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THESIS

A FRAMEWORK FOR APPLYING ASYNCHRONOUS TRANSFER MODE (ATM) TECHNOLOGY TO COMMAND, CONTROL AND COMMUNICATIONS SYSTEMS

by

Carolynn A. Luce

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Thesis Co-Advisors: Carl Jones
Myung W. Suh

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A Framework for Applying Asynchronous Transfer Mode (ATM) Technology to Command, Control and Communications Systems

by

Carolynn A. Luce
Lieutenant, United States Navy
B.A., University of Rochester, 1988

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June 1994

Author: Carolynn A. Luce

Carolynn A. Luce

Approved by: Carl R. Jones

Carl R. Jones, Co-Advisor

Myung W. Suh

Myung W. Suh, Co-Advisor

Paul H. Moose

Paul H. Moose, Chairman
Command, Control, and Communications Academic Group

ABSTRACT

Asynchronous Transfer Mode (ATM) has great promise for supporting bandwidth-intensive, delay-sensitive requirements that will be typical of future command, control and communications (C3) systems. There are many factors to be considered in implementing ATM in a C3 system, making this a complex decision process. Since information technology decisions by their nature are inherently complicated, the use of a framework helps to structure this decision problem. In the context of systems engineering, the author introduces a decision framework for applying ATM in C3 systems and choosing among alternatives. An overview of C3 and an introduction to ATM technology, including current implementation issues, provides the reader with basic concepts. A brief review of alternative and competing technologies is covered to provide a baseline for comparison with ATM. The decision framework is developed using trade-off, risk, performance and cost analyses. Scenarios and network architectures form the alternatives considered in the framework. The Analytic Hierarchy Process (AHP) is used in the framework to synthesize the results of the analyses and helps to select a preferred network architecture.

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I. INTRODUCTION

A. PURPOSE OF THESIS

The purpose of this thesis is to introduce a decision framework for implementing Asynchronous Transfer Mode (ATM) technology in Command, Control and Communications (C3) systems. The capabilities of ATM have great promise for increasing the scope of command and control. However, the way in which ATM can be implemented in C3 system architectures is constrained by several factors. First, the performance requirements of any given C3 system dictate many aspects of a C3 system design. Secondly, the environment and mission for which a C3 system is designed limits some physical aspects of a system (i.e., network topology and type of transmission media used). Even with these constraints, there are many different forms which ATM take on in a C3 system. Furthermore, if ATM is used in combination with other telecommunications and networking technologies, the options are potentially limitless.

Telecommunications and networking technologies like ATM are generally considered "information technology". Decisions involving information technology can be characterized by several qualities. First, information technology is a rapidly evolving area of development; and new technologies and products enter the industry on almost a daily basis. Another aspect of information technology is a large range of alternatives. There are not simply one or two technological methods for achieving a certain telecommunications or networking function; there are many. Lastly, some aspects of information technology are qualitative versus quantitative. This makes the cost benefit comparison of one technology versus another difficult in that measuring benefits requires a more subjective approach. In general, information technology decisions involve many different options, and the method for choosing one technology over another is not straightforward.

Since information technology decisions by their nature are inherently complicated, the use of a framework helps to structure the decision problem. In addition, since ATM can be implemented in C3 systems many different ways, an organized approach to its implementation allows for a relatively better and more objective decision.

B. BACKGROUND

Until recently, separate networks have been developed for voice and data. The Integrated Services Digital Network (ISDN) allows for voice, data and video to be transmitted on the same physical transmission infrastructure at the user-network interface. But because of its limitations, primarily its lack of support for broadband video, newer technology has superseded it. Broadband ISDN (B-ISDN) evolved from ISDN and supports voice, video and data. In addition, B-ISDN supports burst and continuous traffic; making it a flexible solution for different types of users. B-ISDN uses a new transfer and switching technology called ATM. ATM has been touted by some as a revolution in networking (Feltman, C., 1993, p. 52). It has been selected for use by the public B-ISDN network but it also has applications in private networks for organizations like the Department of Defense (DOD).

From experience gained in the Gulf War, it is apparent the future holds a much more extensive distribution of video, high-resolution images and computer files (Donahue, M., 1992, p. 538). This requirement is in addition to the more traditional voice and low data rate prerequisites. The distribution of bandwidth-intensive information is required at national, theater and tactical levels. ATM technology has promise in supporting these C3 requirements in a more efficient manner than currently available.

The extent of DOD's initial commitment to ATM is evident in several efforts underway. The Navy Research Laboratory has numerous ATM switches set up in a testbed environment and is conducting extensive research in various areas. Two other initiatives also support the view that the military is going to employ ATM technology in the future (INCA, 1993, Tab 1,p. 2). The first is that of the Defense Information System Network (DISN) which is primarily a fiber based system intended to support ground based users. The second initiative, called the Defense Global Grid (DGG) concept is an effort to interconnect DOD "information sources" with "information users" anywhere in the world. Both initiatives plan to use ATM technology in their infrastructures.

In addition to initiatives within the United States, the use of ATM has been considered by our Allies. The North Atlantic Treaty Organization (NATO) post-2000 information transport architecture studies have mandated the use of ATM in tactical allied/NATO post-2000 communications networks (Tracy, R. P., 1993, p. 57). This has implications for coalition forces and would suggest that to maximize interoperability, ATM should be considered by any military organization.

C. METHODOLOGY

An overview of command and control is presented to familiarize the reader with the basic concepts behind the design of C3 systems. The five basic functions of C2 are discussed. All five functions are supported by information flow and this functionality can be physically implemented by telecommunications. Finally, it is argued that C3 systems are categorically supported by telecommunications and any future C3 system will have some degree of telecommunications in its physical infrastructure. Hence, the framework concentrates on telecommunication network decisions.

In order to fully understand the implications of utilizing ATM technology in C3 systems, an introduction to the technology itself is provided. This is intended to familiarize the reader with the basic concept of its operation. In addition to the ATM introduction, a discussion of implementation issues is presented. This provides background information on issues which remain unresolved and also addresses the tactical application of ATM. Some issues like congestion control and interoperability are particularly important to the successful implementation of ATM in C3 systems. A brief review of alternative technologies is covered and provides a baseline for comparison of alternatives to ATM. The prime focus of the thesis is on ATM since it appears that this is the way of the future for telecommunications and networking. However, it is essential that current systems using older telecommunications and networking technologies be supported, and therefore the ability of ATM to interoperate with "legacy systems" is essential. This issue is addressed along with other implementation factors for ATM.

In comparing alternatives, trade-off, risk and performance analyses are necessary in any information technology decision problem. As part of the development of the framework, a discussion of these types of analyses is included and is presented with reference primarily to ATM technology. The framework makes use of the decision analysis method known as the Analytic Hierarchy Process (AHP). AHP is a methodology for dealing with complex situations and avoids the need to make simplifying assumptions to suit quantitative models (Saaty, T., L., 1980, p. 1). Appendix A provides a more detailed explanation of the process.

D. EXECUTIVE OVERVIEW OF FRAMEWORK

In order to set the stage for the body of the thesis, an overview of the decision framework follows. The framework is established on the premise that a C3 system is either in existence or is in the process of being developed. The top level system requirements (TLSRs) have been established and top level warfare requirements are known. The boundaries of the system in question have been established and define what is internal and external to the system. Furthermore, the environment for which the C3 system is being designed has been delineated. Environmental aspects of systems are concerned with physical conditions (i.e., weather, geography, and terrain) as well as the degree of hostility C3 systems may endure. The framework also assumes that the functional analysis of the C3 system has been completed and functional architectures developed. It is at this point of the system engineering process (defined in Chapter VII) that the framework is applicable.

The first step of the framework is to review the competing and alternative technologies to eliminate those that do not meet minimum performance requirements or environmental constraints. Based on the feasible technologies, scenarios and network architectures are considered using trade-off and risk analysis. Trade-off and risk analysis is discussed specifically in the context of telecommunications and networking. These trade-off and risk considerations covered are applicable to almost any information technology today. Scenarios and network architectures are not specifically developed in the context of this thesis but their generic characteristics are outlined. Following the completion of trade-off and risk analysis, a smaller set of alternative scenarios and network architectures results, and these are reviewed to ensure that top level system requirements and any other constraints are met.

For the given set of scenarios and corresponding network architectures, performance and cost analysis is conducted in the next step of the framework. Performance criterion are discussed and they focus on those aspects of telecommunications that are particularly important. Cost analysis involves the estimation of life cycle costs and the components are briefly introduced. The actual calculation of life cycle costs is not covered in this thesis but is assumed in the development of the framework. Finally, with performance and cost analysis conducted, the AHP process is used to combine these results. The AHP process results in the prioritization of the alternative scenarios and network architectures relative to their performance and cost analysis. In addition to these rankings, the scenarios and network architectures are ranked again using AHP but within the context of their expected utility for the future. Given both sets of rankings, they are combined resulting in an overall ranking, with the highest ranked as the preferred scenario and network architecture for implementation.

II. THE COMMAND, CONTROL, AND COMMUNICATIONS (C3) SYSTEM

A. INTRODUCTION

Command and control (C2) has evolved in terms of technology it uses as well as its implementation. Its implementation has grown to become a warfare area, one of increasing importance in an era of "Information Warfare". The technology used in C2 has become increasingly sophisticated. C2 is now more of a force multiplier when applied successfully in war. Warfare has evolved and is now generally fought over thousands of miles versus hundreds of miles in days past. In addition, military headquarters and center of operations may be far removed from the battlefront but they can have greater influence on subordinate commanders because technology can bring the battlefield to the homefront. One could say that technology has facilitated this change in the way wars are fought. However, the fundamentals of C2 remain the same.

An overview of C2 terminology and its' derivatives is presented to provide a baseline view of C2. To give an understanding of the command and control process, Lawson's C2 process model is introduced with a description of the functions involved. The composition of system architectures along with an overview of the hierarchy of architectures is given. Finally, a look at C3 systems and their components provides a profile of systems within the Department of Defense.

B. WHAT IS C2?

1. Joint Chiefs of Staff (JCS) Definition of C2

The Department of Defense defines command and control as follows:

> The exercise of authority and direction by a purposely designated commander over assigned forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission (Coakley, T., P., 1992, p. 17).

This definition is all encompassing and provides a general picture of C2; yet the topic of C2 is very broad and the JCS definition means different things to different people. To the Navy, C2 might mean control of a battlegroup and to the Air Force, control of an air wing. However, inherently common to both views is the organization's primary objective of successfully completing their mission using something called C2. A C2 system is a collection of personnel, equipment, communications, facilities arranged in a particular architecture with a specific boundary where the system interacts with the environment and vice versa.

2. How Does C2 and Its Derivatives Fit Into the Picture?

There are many definitions with a foundation of C2. Some have been derived as the result of more advanced technology and its effect on C2. Others have been coined from the aggregation of functions supporting C2. Some are:

- Command, Control, and Communications (C3)
- Command, Control, Communications, and Intelligence (C3I)
- Command Control, Communications, Computers (C4)
- Command, Control, Communications, Computers, and Intelligence (C4I).

They are all related and their basic premise relies on the baseline definition of C2. As C2 systems evolve, they have encompassed other aspects fundamental to C2. In the past, communications and intelligence were functions which were really too slow to be used in real time situations. Therefore, they did not have much effect on the outcome of battle. For this reason, commanders had to decentralize command so that subordinate commanders could make decisions at the battlefront in real time. In the mid to late 1960's, information was handled in a distributed manner across large distances. This implied use of communications and the role it plays is now considered essential (Davis, R. M., 1989, p. 162). Because of the fundamental role that communications plays in C2, the term C3 is used. Communications has allowed for real time strategic and operational decision making over much greater distances. Today the National Command Authority (NCA) as well as Headquarters based in the continental United States (CONUS) play a larger role in decision making, reducing the decentralization of command. As the nature of warfare and technology changes, the nature of C2 changes. Communications is now a prerequisite for adequate support of the C2 process.

Information is also a fundamental part of C2 and most would consider intelligence to be information. Technology has allowed operational commands at the front line to directly receive some forms of intelligence. Previously, intelligence agencies had to process the information and then disseminate the intelligence to users. In the past, the intelligence did not always reach operational and tactical units. Some would argue that this change (capability for front line forces to receive intelligence directly) is an aggregation of C3 and intelligence and thus C3I. Still others argue that intelligence is an entity in itself and has substance, unlike communications (Davis, R. M., 1989, p. 164). Because of its value by itself, intelligence should not be aggregated with C3 given the understanding, of course, that intelligence is part of the "information" used in C2.

The development of computers and their increasing processing power has guaranteed their place in C2 systems. Computers bring the capability to process more information faster. Any C2 system today has computers as part of the physical architecture. As new systems are introduced and developed, they too will have computers. Hence, C4 and C4I are in the C2 family.

The area of C2 is dynamic in terms of its own characteristics as well as the environment it is employed in. Therefore, C2 now has derivatives which incorporate the changes occurring in the areas of technology, warfare and C2. These changes reflect components of C2 that are essential to its successful implementation. The evolution of C2 has also changed the way battles are fought. Commanders in Washington and CONUS can get a bird's eye view of the battlefield along with the front line troops. Contrasted to a time when information was available only to limited numbers and locations of people, C2 now has greatly advanced.

For purposes of this thesis, C3 will be used throughout to refer to the function and process of C2.

3. Lawson's C2 Process Model

There has been much work done on defining the process of C2. In fact, the actual process implemented in different scenarios with different force structures may result in many different variations. But the basic concepts are the same and can be understood by looking at Dr. Joel S. Lawson's model (Orr, 1983, pp. 23-4). The flow chart of the model is shown in Figure 1 (Orr, 1983, p. 24). As shown, there are five functions as well as their interfaces to the environment. It should be noted that this is an iterative process with some functions being performed in parallel with other functions. Lawson expanded the C2 process to take into account the intelligence aspect of the C2 process.

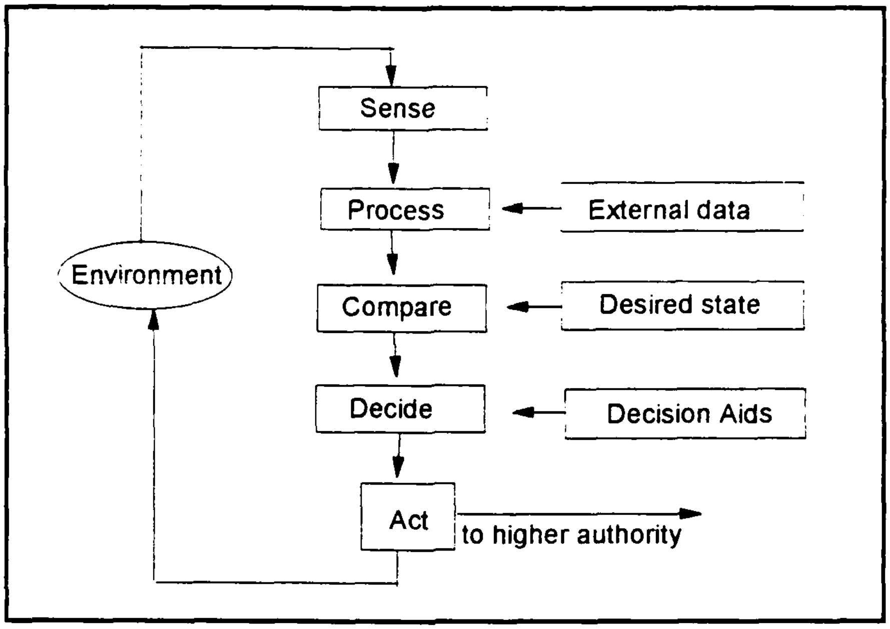

Figure 1. Lawson's C2 Process Model

Figure 2 shows the modified C2 process model or the C3I model (Orr, 1983, p. 25). As shown in the diagram, the intelligence aspect interacts with C2 at the compare and decide phases. The ΔT phase symbolizes projection and

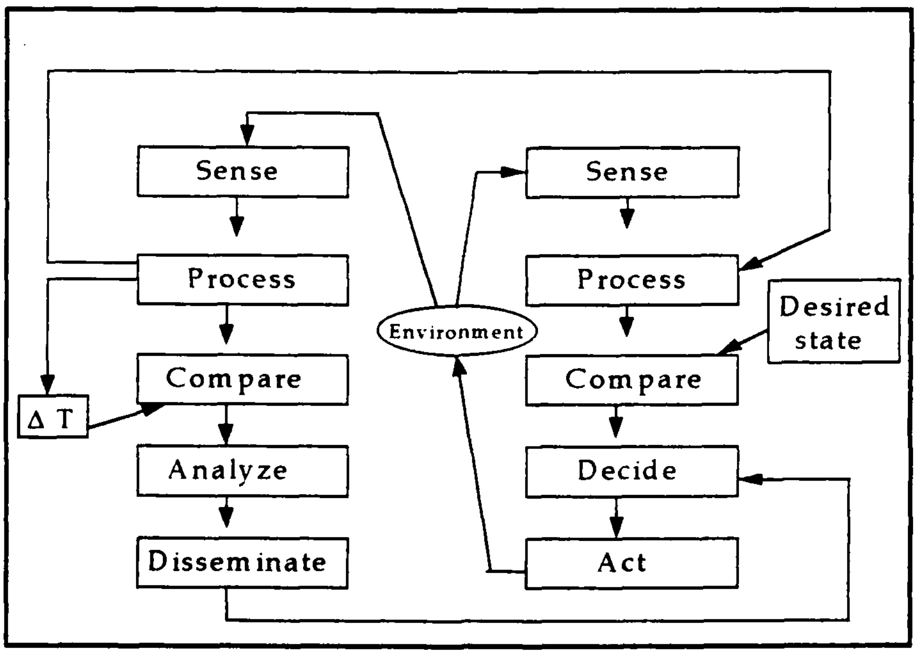

Figure 2. Lawson's C3I Process Model

should only be used at the decide phase. This model is a good example of how intelligence is an aspect of C2 in terms of the information component.

a. Functions

As shown earlier, the C2 process model involves five basic functions (Orr, 1983, p. 25). These functions are all supported by information flow and physically implemented in some way by telecommunications.

The function of sense corresponds to the data gathering aspect of C2. Signals and emissions external to the system are sought after and tracked. Physical implementation of this function could involve radars, reconnaissance, and human observation. Once this data is collected it must be forwarded to sites for processing and dissemination. Telecommunications and data communication networks can achieve this end.

In processing, the data gathered in the sense step is processed to find out what it means. Information from the environment, not directly under surveillance, may be used in achieving a final analysis of data gathered. This is typical of the intelligence process where previously gathered data may be combined with other data to result in a single piece of information. Again, telecommunications can be implemented in this process to provide for shared information resources or cooperative processing using mainframe or central processing computers.

The compare function involves the comparison of the external environment with the desired state. The desired state may be the mission objective or a degree of certainty in information gathered about the enemy. For instance, if the desired state was to establish the enemy's order of battle, several iterations of this C2 process may be required to determine this with some degree of certainty. Network resources and communications with various commands and assets are needed at this stage of C2 process to compare and share data.

The function of decide is to determine what needs to be done to the actual state to reach the desired state. This may involve numerous levels of the chain of command and requires communications horizontally and vertically in the command hierarchy. Strategic, operational, and tactical decisions are possible and support for these decisions is provided by telecommunications. The telecommunications infrastructure will allow for exchange of suggested courses of action and recommendations.

At the function of act, the decision(s) from the previous stage are carried out. This could be thought of as the point where orders are passed. Certainly, telecommunications is used here. The commander's order to deploy or fire at a target rely on the transfer of the order.

b. *Functional Decomposition of Systems*

Any system can be disaggregated functionally through functional decomposition and the result would include the five functions outlined above. However, in addition to the generic functions from the C2 process model, there are other functions that will be present in any C3 system.

The transfer of data is becoming increasingly important in today's atmosphere of data intensive systems. This function refers to the transfer of a digital or analog signal which may or may not have been processed and thus may be information or raw data. This appears to be the same as information flow, but in this case the data may be processed and therefore is actually considered information.

Voice communications is a common backup to data transfer and is practically a given requirement in many C3 scenarios. This can involve personnel across hundreds of miles or thousands of miles and is required in virtually any scenario. This function can also be viewed as a subset of information flow.

Much strategic and operational level planning and decision making is enhanced by face to face interaction on the commander's part which equates to the function of group discussion and meeting. Technology available today enables this without the requirement for personnel to be physically located in the same location. More and more systems provide this functionality and it may soon became a standard capability required of systems.

C. C3 ARCHITECTURES

1. Definition

A C3 system architecture is a conceptual framework describing the physical, operational, procedural, or functional structure of a C3 system or set of interoperating C3 systems (Lacer, D., A., 1991, p. 5). As discussed above, a system architecture will have characteristics driven by the level of DOD for which the system is designed for. For instance, the architecture of national level system will have unique physical characteristics compared to those of a Service level system.

2. System Architecture

This architecture is the most basic and any system, regardless of the environment or mission it is designed for, can be based on this concept. The system architecture may be seen as a black box. By taking off the top of this black box, the following components can be found.

a. Information Flow

This is driven by the organizational concept of the organization that a system is supporting. By looking at the decision making process of an organization, the information required by each element in organization can be outlined and the flow as well as direction of information will be evident.

b. *Connectivity*

The physical implementation of information flow can be regarded as the connectivity in an architecture. Links between elements in an organization will require communications connectivity.

c. *Capabilities*

Measures of performance measure the capabilities of a system. A capability may also be manifested in the environmental aspects of a system. For instance, a system that is designed or used for operations covering thousands of miles versus hundreds of miles requires a longer operating range capability.

d. *Operational Concept*

The doctrine used in designing a system will play a large part in this aspect. In addition, the mission and scenario chosen as the most likely future will help to define this aspect of the system architecture. Another way to think of this aspect is to ask how the system will be used with forces in a given scenario.

System architectures literally used to be black boxes in that they were designed without any thought to external systems requiring interface or data exchange. Previously it was not an issue if a system could not interoperate with another system. These type of systems are referred to as stovepipe systems. The emphasis has now changed. When designing or modifying a system today, attention is paid to the various architectures to ensure that systems are interoperable and can be integrated throughout different architectures.

3. Other Architectures

Four other architectures in the hierarchy of C3 system architectures remain to be explained(Lacer, 1991, pp. 6-7). The National Military Command System (NMCS) is concerned with the strategic aspects of C3 and is the basis for support to the National Command Authority. Theater architectures aim at the unified and specified command level and include joint task forces. They provide the framework in which future C3 systems and their procedures are designed. Similar to the theater architecture, the Component Command architecture, is the framework in which C3 systems and procedures interrelate to support the Component command's responsibilities. It should be noted that joint task forces are operationally assigned to the unified command but are composed of forces from component commands. Finally, the last architecture in the hierarchy concerns the mission area. This provides the setting for which future C3 systems are designed. A mission is a specific warfare area as in air defense or surface warfare. The integration of C3 systems is also considered at this point. Figure 3 is an adapted version of Lacer's hierarchy of C3 system architectures.

These architectures provide a framework for defining the context of existing or evolving C3 systems. They are also important in defining the environment of C3 systems. A well defined environment leads to systems that support the commander in fulfilling his/her mission most effectively.

D. THE C3 SYSTEM

The C3 system is made up of physical entities used by the commander to accomplish the assigned mission. As stated in the JCS definition, some of these entities include personnel, communications, etc. Again, as C3 and technology evolve, the physical entities used in C3 systems have employed more technologically advanced equipment.

1. The Components of C3 Systems

LCDR J. Crooks and MAJ C. Wigley look at C3 systems in the context of standardization (Crooks and Wigley, 1991, p. 156). They break the C3 system down into three components which are applicable to any study of C3 systems.

It should be noted that their view of components does not include humans. However, humans do represent a component known as "man-in-the-loop" and

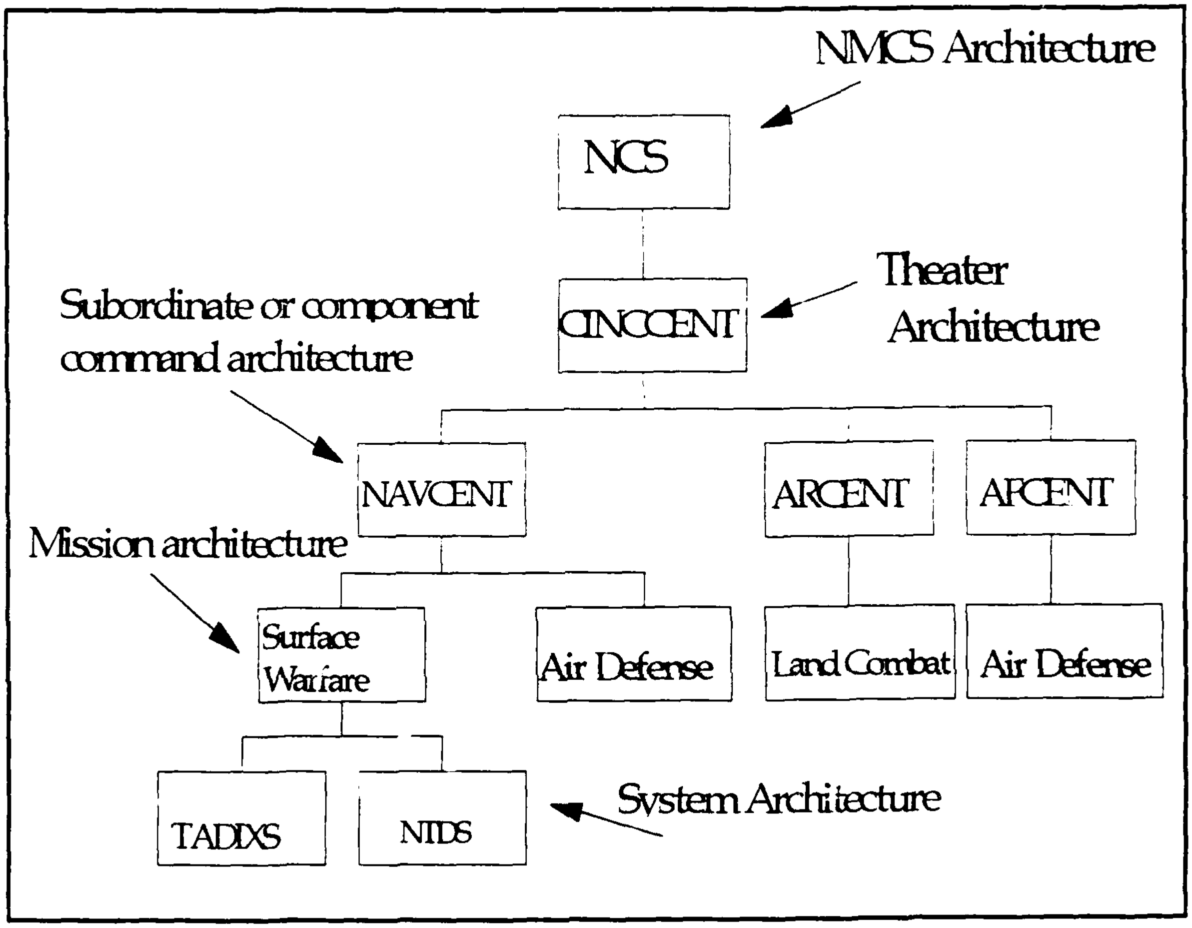

Figure 3. Hierarchy of C3 System Architectures.

are present in any C3 system, no matter how advanced the technology involved.

Other descriptions of C3 systems break down the system into different components. However, Lieutenant Commander CDR Crook's and Major Wigley's view of components is suitable for the framework discussed in this thesis.

a. *Information*

This is the data derived from some source for use by the C3 system. The transformation of data to information occurs simply by virtue of any sort of processing. Therefore, data from some source may undergo the simple translation from satellite signal to analog signal. This is a crude translation but value has been added. Information is critical to C3 and C3 is information intensive.

b. *Information Processing*

This is the process that the C3 system uses to translate the **information** provided to it into a useable product. Computers play a large part in facilitating this translation.

c. *Telecommunications*

This represents the paths over which the **information** flows to and from the system. The physical implementation of this could involve any sort of physical transmission media. Typically, fiber optics and copper are used. Although telecommunications usually use tangible media, microwave and satellite signals are also used as paths for information.

2. How Components Fit Together

Many different analogies have been used to show how the components of C3 systems work together. They range from the likeness to the nervous system of a human to a football team (Coakley, T., P.,1992, pp. 18-22 and pp. 41-43). Telecommunications could be thought of as the supporting infrastructure of the C3 system. The information processing occurs at the nodes on the infrastructure with information being passed from node to node in raw or enhanced states.

3. Components at National, Headquarters and Service levels of Department of Defense (DOD)

The components outlined above will be present in any sort of C3 system. However, the missions and requirements will be different depending on the level of DOD for which the system was designed.

a. National Level Systems

Several factors characterize National level systems. First, strategic connectivity is at the heart of these systems. At this level, systems are required for the National Command Authorities and the commanders in chiefs of the unified and specified commands to direct the operations of U.S. forces. In addition, this level requires C2 to control the nuclear aspects of national security.

Usually, these types of systems service land based commands and sites spread across large distances. Because of these distances, vulnerability to attack or failure is widespread and is a primary concern. Therefore, "hardened" security must be introduced. An example of this is the World Wide Military Command and Control System (WWMCCS). A survivable element was built in by using airborne platforms to guarantee some level of communication. Furthermore, due to the strategic aspect of these systems, single points of failure are not acceptable.

For purposes of illustration, a good example of a National system is the WWMCCS. This system is made up of subsytems which service the National Military Command System, Unified and Specified commands and the C2 systems of service headquarters and component commands. Numerous C2 systems use WWMCCS as their data processing and communications support infrastructure. One example, is the Joint Operations Planning and Execution System (JOPES). Senior level decision makers use JOPES to conduct joint planning, operations and deployment. WWMCCS is being phased out and replaced with the Global Command and Control System (GCCS). The new system is taking advantage of Commercial off the shelf software (COTS) and the latest telecommunications technology.

b. Headquarters' Level Systems

As in National level systems, connectivity between Headquarters is generally across large distances. However, the emphasis is not on strategic connectivity. At this level the Headquarters of different services require connectivity as well connectivity between service Headquarters and their subordinate commands. Furthermore, some situations may call for connectivity between a given Headquarters and various platforms (i.e. ships, aircraft).

c. Service Level Systems

These types of systems support C2 within a single service. Again, this may require communications among various platforms. The distances involved are not as great and usually are within one area of responsibility (AOR).

d. Joint Task Force (JTF) Systems

Systems supporting JTFs require flexibility because the requirements as well as the missions are dynamic. Often, little or no lead time is available to establish C3 systems for JTFs. Because of the joint nature of these systems, connectivity and interoperability between services is required. Furthermore, tactical connectivity at lower level units will require extensive links between different platforms. Systems supporting JTFs may need some degree of transportability for deployment.

E. BASIS FOR FRAMEWORK

In the author's opinion, C3 systems are categorically supported by telecommunications. Furthermore, as telecommunications technology matures, any C3 system of the future will have some level of a telecommunication infrastructure. Therefore, the focus of the decision framework is that of telecommunication network decisions.

The environment for which a system is designed for or modified for has boundaries established by the various architectures. Characteristics of the architectures and unique features constrain the design requirements of the system. This is manifested in the Top Level System Requirements. Requirement determination will be further discussed in Chapter VI.

III. ATM BASICS

A. INTRODUCTION

1. Purpose of Chapter

This chapter introduces the basic concepts of ATM. The standardization of ATM is reviewed and an overview of ATM implementation schemes is presented. Information presented is intended to give only a broad overview of ATM. Additional references are provided for readers wanting more detailed information on ATM.

a. ATM and Broadband-Integrated Services Digital Network (B-ISDN)

B-ISDN is intended to be a universal, public network integrating a wide range of telecommunications services. Current plans provide for variable transmission rates which allow for numerous different types of telecommunications traffic to be carried over the same physical medium. The emphasis in B-ISDN is for a public network. In 1988, the International Consultative Committee for Telecommunications and Telegraphy (CCITT), now the International Telegraph Union Telecommunication Standards Section (ITU-TSS), decided that ATM, a cell relay technology, would be used as the transfer and switching technique for B-ISDN (Delisle and Pelamourgues, 1991, p. 39). Note that the term CCITT will be used in lieu of ITU-TSS throughout the remainder of this thesis. To some, the term ATM is synonymous with B-ISDN. However, ATM technology is not limited to use in public networks. It can be used in private local and wide area networks.

b. *Sources for Further Information*

Many periodicals provide coverage of ATM. In addition, some books have been published on the topic of ATM and B-ISDN. The background material and fundamentals of ATM remain the same: but, because the technology is not fully mature, books typically are out of date or overcome by events by the time they are published. The area of ATM technology is very dynamic and therefore the latest information is usually found in periodicals. The following list of periodicals usually have some degree of monthly coverage on ATM:

- IEEE Communications
- IEEE Networks
- IEEE Transactions on Communications
- Telecommunications (US edition)
- Data Communications

Asynchronous Transfer Mode: Solution for Broadband ISDN, second edition, by Martin dePrycker is the most current book on the subject. In addition, any of the references used in this thesis for material covering ATM are also good sources. On-line information is abundant on the INTERNET and is an inexpensive starting point if access is available. Generally this information is focused on the research aspect of the technology versus the business/vendor approach. If access to a Gopher server is available, there is an archive on the cell relay at the University of Indiana. Its address is *cell-relay.indiana.edu* under the *pub/cell-relay* directory. Entry is also available via telnet to the University of Minnesota Gopher at *consultant.micro.umn.edu*. Once connected, login as *gopher*. Available at this archive are research papers, frequently asked questions/answers, and the archives of the cell-relay news group. Additionally, the ITU has a public access file transfer site and access is most easily gained via the cell relay archive at University of Indiana. Information concerning working groups, scheduled meetings, and publications is available.

2. Evolution of Transfer Modes

Transfer modes are methods of switching ,multiplexing and transmitting information in a network. In order to help understand the advantages and incentive for the development of ATM, a brief look at the growth and change of transfer modes is presented. As technology has matured and user requirements for bandwidth and speed have increased, transfer modes have been developed that meet these increasing demands. It should be noted that every one of the transfer modes presented is still used in some way in public or private telecommunications networks. There are many new applications requiring higher bandwidth and better quality of service and the new transfer modes support these requirements and more. However, some situations are well served by the older, slower technologies.

a. Circuit Switching

This type of transfer mode has been used for telephone networks for many years. The Plain Old Telephone System (POTS) is based on circuit switching and any person using a telephone has accessed this network. In this approach, a circuit or connection is established for the entire duration of the call. On the trunk circuits, interconnecting switches and different calls have different time slots and can be combined or multiplexed into one continuous stream. This is called time division multiplexing (TDM). Throughout the duration of a call, the same time slot will be used and therefore is not available for any other caller. Because a time slot is allocated to a connection for the entire duration, this can result in inefficient use of the available bandwidth.

Circuit switching has traditionally been used for voice but is now widely used for data. The use of circuit switching is most suited for traffic that requires transmission at regular intervals, is time-sensitive, and is generated at a fairly constant rate, not in bursts. Private networks may be established by businesses or individuals when the user has requirements for a consistent, steady transfer of traffic and requires availability of circuit on demand.

The advantages of circuit switching are twofold (Stallings, W., 1992, p. 28). First, it is transparent in that once the connection is established, no additional processing is required by sending or receiving station. Second, during the data transfer phase, routing, flow control and error control are avoided allowing for simplicity in software.

b. Packet Switching

This form of information transfer evolved partially as a result of an increase in the use of circuit switched networks for data transfer with subsequent inefficiency This type of transfer mode is used to transmit information in the form of packets. Additional information is appended to the packets and contains instructions for routing, error correction and flow control. The packets can vary in size and also in rate of generation. The size of the packets are variable and can be thought of as self contained. They do not need a continuous path, like circuit switching, to arrive at their intended destination. Instead, the packet must be stored and forwarded at each node on the path traversed through the network. Each node must determine the best route for the next leg of the journey. A disadvantage of this is that it requires additional processing time and increases the delay for individual packets through the network.

Because of the variable size of the packets, relatively lengthy delays are possible. Therefore, this transfer mode is not entirely suitable for time-sensitive traffic like voice and video.

Many different types of packet switching networks (PSNs) evolved resulting in proprietary and incompatible systems. Therefore the CCITT developed a standard to a common interface between users and PSNs. This standard is commonly known as X.25. The standard defines the interface between user's equipment and the network equipment. It outlines the physical, link and packet layers of operation which are equivalent to the three lower levels of the Open Systems Interconnection (OSI) model. (Muller and Davidson, 1990, pp. 166-8)

c. *Frame Relay*

This is one type of fast packet switching which closely follows the concept of packet switching but uses high speed transmission facilities. In frame relay, there is no addressing, link-by-link flow control or error control. These functions are moved to the end devices. Because the transmission media used have better error rates, error control on each link is not necessary.

Addressing or routing is accomplished by the establishment of permanent virtual circuits. Once the permanent virtual circuit is established, software intensive and time consuming processing at each node is avoided.

d. *Cell Relay*

Cell relay is synonymous with ATM and is the second type of fast packet switching. In contrast with earlier technologies where variable length data packets were used, relatively small, uniform cells are used to compartment data for transmission. Additional information is included in the cell header which provides routing information. In addition, prioritization of cells is supported for cases of network busy periods. This transfer mode is often considered the best of two worlds of circuit and packet switching. It takes the advantages of circuit switching and packet switching and combines them to maximize efficiency and transmission speed and throughput.

In terms of the connection mode or means of transfer through a network, cell relay is midway between the extremes of packet and circuit switching. Whereas circuit switching establishes permanent connections for the duration of transmission, packet switching does not establish any one path for communication. In order to maximize efficiency, ATM uses virtual connections between ATM switches. Unlike the packet scheme, ATM cells travel the same virtual path throughout the network and for that reason this transfer mode is considered connection oriented. However, these virtual paths are not reserved solely for one user. If a user is not using a connection (i.e. a source is waiting for response), another user can make use of the path. Routing is done via tables in the switch using addressing information in the cell header. This aspect of hardware implemented routing, like circuit switching, allows for greater throughput and less processing delay. (Lane, J., 1994, pp. 42-3)

Like packet switching, the cell holds data in its payload and has its own routing information contained in the header/address portion. The difference between the two is the cell or packet size. Cell relay and packet switching are similar in that both give users access to a transmission channel for as long as required, In both, the routing information is self-contained in the "datagram".

e. Synchronous Transfer versus Asynchronous Transfer

This concept is presented in the context of multiplexing and each of the transfer modes above can be characterized by one of these modes. With synchronous techniques, the bandwidth of a transmission path is divided into channels. The data passed across the channels is identified by its position in the path. Synchronous transfer is constrained by these predefined channel paths and transmission rates. This is contrasted to asynchronous transfer where data is referenced by its virtual channel and could be found in any position on the channel. In the context of ATM, asynchronous refers to multiplexed transmissions where the rate the information is placed in cells and on a connection is according to demand which is not necessarily at regular intervals.

Because the placement of data on physical path is not in reference to its fixed channel but occurs by virtue of its occurrence, transmission bandwidth can be dynamically allocated according to the service needs required by data (i.e. constant bit rate and time sensitive, etc.). Efficiency is gained because idle transmission paths are available to other users and bandwidth is provided on demand. Figure 4 depicts the two transfer modes. (Handel and Huber, 1991, pp. 13-7)

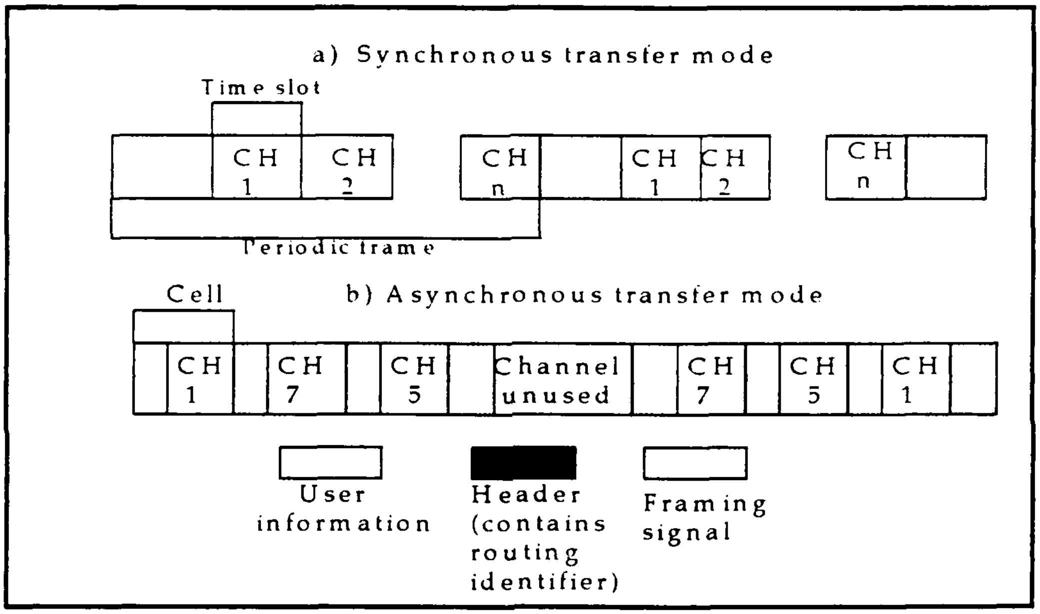

Figure 4. Synchronous and Asynchronous Transfer Modes.

B. ATM PRINCIPLES

1. ATM Cell

a. Cell Header

The cell header consists of 5 bytes and is considered overhead to the actual data payload. The 5 unique fields in the header are generic flow control (GFC), routing, payload type, cell loss priority, and header error control. The

GFC field will be used for flow control and allows for 16 different states (2^4). Virtual channels (VC) and virtual paths (VP) are identified by 24 bits in the routing field. The type of information contained in the payload is classified by the payload type. Priority of the cell, in terms of potential cell discard, is set by the cell loss priority field. Finally, error control, for the header only, is accomplished by the header error control field.

b. Cell Payload

The payload consists of 48 bytes of information. Some cells may be empty and are used for filling unused bandwidth. The ATM cell structure is shown in figure 5.

<table>
<tr><td>Generic flow control</td><td colspan="3">Virtual path identifier</td></tr>
<tr><td>Virtual path identifier</td><td colspan="3">Virtual channel identifier</td></tr>
<tr><td colspan="4">Virtual channel identifier</td></tr>
<tr><td>Virtual channel identifier</td><td>Payload type</td><td>Reserved</td><td>Cell loss priority</td></tr>
<tr><td colspan="4">Header error control</td></tr>
<tr><td colspan="4">Information field
48 bytes</td></tr>
</table>

Figure 5. ATM Cell format.

2. ATM and Open Systems Interconnection (OSI) Model

As in the OSI model, a layered approach to ATM functions is used. However, the ATM relevant layers do not map directly to those of the OSI model. For purposes of this thesis, the B-ISDN protocol model is used in comparison to the OSI model. Regardless of the implementation of ATM, be it public (B-ISDN) or private, the ATM functions remain the same. Figure 6 depicts the ATM hierarchy and the OSI model (INCA, 1993, Tab 1 p. 5). The

ATM physical layer is most equivalent to layer 1 of the OSI model. The ATM layer can be likened to the lower level of the data link layer or OSI layer 2.

B-ISDN Protocol Layers	OSI ISO Reference Model
Application Layer	Application Layer
Higher Layer	Presentation, Session, Transport Network Layers
ATM Adaption Layer Convergence Sublayer Segmentation & Reassembly Sublayer	Datalink Layer
ATM Layer	
Physical Layer Transmission Convergence Sublayer and Physical Medium Dependent Sublayer	Physical Layer

Figure 6. ATM/B-ISDN Model and OSI Model.

3. ATM Physical Layer

a. Sublayers

The physical layer is further broken down into two sublayers; the physical medium sublayer and the transmission convergence sublayer. The physical medium sublayer supports functions concerned with the actual function of movement of bits across the medium via transmission and reception. The function of proper bit timing reconstruction at the receiver is accomplished at this layer as well. The transmission convergence sublayer provides for five functions and they are summarized as follows:

- Generation and recovery of transmission frames based on a given data rate.

- Adaptation of cells into transmission frames.
- Cell delineation to allow for recovery of cells at destination.
- Header error-control (HEC) codes are present in every cell. This layer generates the HEC code and checks it for errors at receiving node.
- Cell rate decoupling is performed to adapt rate of valid ATM cells to payload capacity of the system. This is achieved by inserting and suppressing idle or "empty" cells.

(Stallings, W., 1992, p. 523)

b. Error Control

As mentioned earlier, there is no link-by-link error control. The two end nodes on any connection provide the error control at the physical layer. The eight bits set aside in the header provide error detection and some actual error correction. The receiver has two modes, correction mode and detection mode. In correction mode, cells with single bit error are corrected. In detection mode, those with multiple bit errors are discarded and require retransmission (DATAPRO, 1993, p. 7). Figure 7 shows how the receiver conducts error detection.

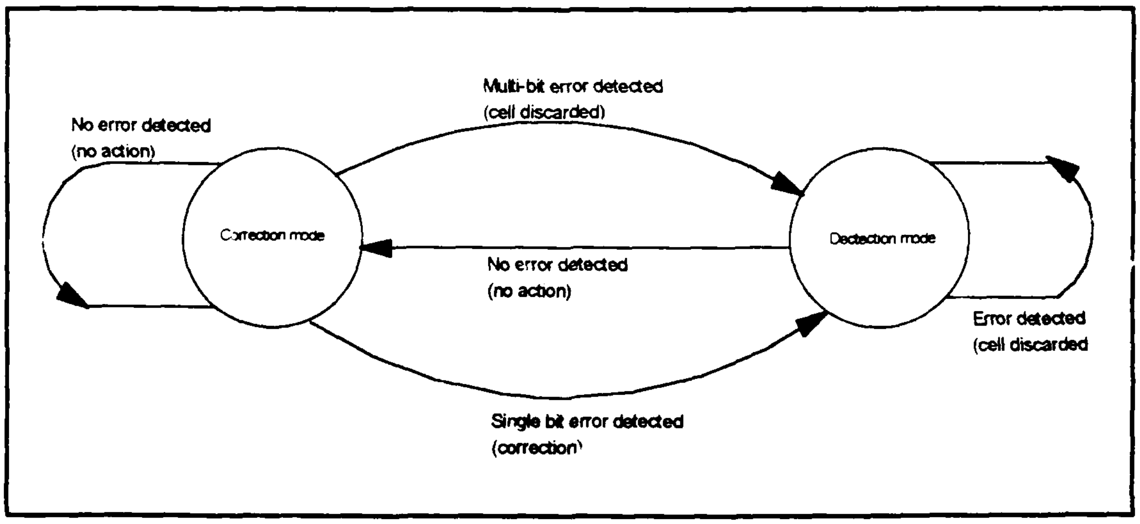

Figure 7. Error detection at the receiver.

c. *Transmission of ATM Cells*

Three different frame adaptation schemes have been specified by the CCITT. The Synchronous digital hierarchy (SDH) interface uses fiber optics with transmission rate of 155 Mbps or 622 Mbps. With data rates of 622 Mbps, single mode fiber is required. It should be noted that other transmission media such as coaxial cable are being considered. Ranges of 100-200 meters and 800 to 2000 meters are possible with electrical and optical line interfaces, respectively. The SDH hierarchy is compatible with the SONET interface standardized by the American National Standards Institute (ANSI). (dePrycker, M., 1993, pp. 115-6)

The second interface, cell based interface, also requires optical fiber and provides for the same transmission speeds. Thirdly, a plesiochronous digital hierarchy (PDH) interface uses the existing transmission foundation. This would eliminate the costly need to deploy new SDH equipment. The fourth option has been introduced by the ATM Forum and is a Fiber Distributed Data Interface (FDDI) based option (this interface is also known as the Transparent Asynchronous Transmitter/Receiver Interface (TAXI)). A 125 Mbaud multimode fiber interface is specified for the private network interface based on the FDDI physical layer. The maximum transmission rate possible is 100 Mbps. (dePrycker, M., 1993, pp. 118-21)

4. ATM Layer

a. *Functions*

As in the OSI model, this function is independent of the physical layer. The main functions are listed below:

- Multiplexing and demultiplexing of cells from different connections into a single stream of cells on physical layer.
- Translation of cell identifier. Usually done at each point a cell is switched from one physical link to another.

- Support of Quality of Service classes.
- Management functions via information in the cell header.
- Extraction and addition of cell header before and after the cell is delivered to/from the adaptation layer.
- Flow control implementation at the user-network interface. GFC bits in cell header support this function.

(dePrycker, M., 1993, pp. 114-5).

b. *Characteristics*

CCITT recommendation I.150 outlines the ATM functional characteristics. There are four altogether and they apply both to virtual channels as well as virtual paths. First, quality of service is supported by parameters establishing thresholds for cell loss ratio and cell delay variation. Switched and semipermanent virtual circuit connections are to be supported allowing for dedicated connections as well as switched or on-demand connections. Within a virtual channel, the sequence of the cells transmitted is preserved. Finally, traffic parameter negotiation and use monitoring is to be supported. The traffic parameters may include maximum and average transmission rate, degree of burstiness, and maximum duration of transmission. The monitoring aspect will ensure that the negotiated traffic parameters are not violated and in some cases may terminate connections where parameters are exceeded. Finally, one characteristic is applicable to virtual paths only. Some virtual channels within a virtual path may be reserved for network management or signaling and therefore are not available for user information. (Stallings, W., 1992, pp. 532-3)

5. ATM Adaptation Layer (AAL)

This layer is divided into two sublayers, the segmentation and reassembly sublayer (SAR) and the convergence sublayer (CS). The SAR sublayer is responsible for the segmentation of higher layer information into appropriate size units for the payloads of consecutive ATM cells of the same virtual connection. The reversal of this process is also achieved at this level. The CS layer performs the functions of message identification, time/clock recovery, etc.(dePrycker, M., 1993, p. 115-6)

Some users may find that ATM services are adequate for their requirements. On the other hand, users may need specific types of service, for example guaranteed real-time video. In these cases, the AAL layer provides enhanced services to the next higher layer. To transition to the next protocol layer, user information is mapped into protocol data units (PDU). Four types of AAL protocols are used to perform the mapping and they support four classes of service.

a. Classes of Service

ATM is designed to support different types of traffic. These different traffic types have different requirements with respect to timing between source and destination, their inherent bit rates, and connection mode. Four services classes have been designated and cover the range of possible requirements. The four classes are as follows:

- Class A: timing required, constant bit rate, and connection-oriented.
- Class B: timing required, variable bit rate and connection-oriented.
- Class C: timing not required, variable bit rate, and connection oriented.
- Class D: timing not required, variable bit rate and connectionless.

Uncompressed voice or video is an example of Class A traffic and compressed voice or video is an example of Class B traffic. Data traffic across multiple local area networks (LAN) is typical of Class C traffic and data traffic across a single LAN is characteristic of Class D traffic.

b. AAL Protocols

The AAL protocol determines the class of service being given to user data by the network. The protocol suite is responsible for taking data from higher level protocols and packaging it into 48 byte payloads in a manner appropriate for the type of data being transmitted. Theoretically, any AAL protocol can support all four classes of traffic. However, some protocols handle specific types of traffic better and more efficiently than others. Table 1 delineates the service classes and the corresponding AAL types. (Feltman, C., 1993, p. 22)

TABLE 1. ATM CLASSES OF SERVICE AND CORRESPONDING AAL TYPES

Class	Description	AAL Type
Class A	constant bit rate, connection- oriented, synchronous traffic	AAL 1
Class B	variable bit rate, connection- oriented, synchronous traffic	AAL 2
Class C	variable bit rate, connection-oriented, asynchronous traffic	AAL 3/4 and AAL 5
Class D	connectionless packet data	AAL 3/4

6. ATM Connections

Before any information is transferred across the network a logical or virtual connection is established. Once all the information has reached its final destination, the connection is broken down. This type of switching is also referred to as connection oriented. In ATM, these logical connections are referred to as virtual channels. Virtual channels can be further broken down into virtual paths. A brief discussion follows.

a. Virtual Channels

This functionality is supported by a subfield in the header consisting of sixteen bits. The virtual channel identifier (VCI) is applicable only on a link-by-link basis. At each ATM node the VCI is translated and new VCI's are designated. A virtual channel is analogous to a virtual circuit in X.25 or frame relay logical connection (Stallings, W., 1992, p. 531).

b. Virtual Paths

Eight bits are reserved in the cell header for virtual path identification (VPI). A virtual path is a bundle of virtual channels that have the same endpoints (Stallings, W., 1992, p. 532). This functionality allows for different types of traffic between two endpoints to travel over the same logical connection resulting in network simplification. Figure 8 depicts the relationship between virtual paths and channels (Stallings, W., 1992, p. 532).

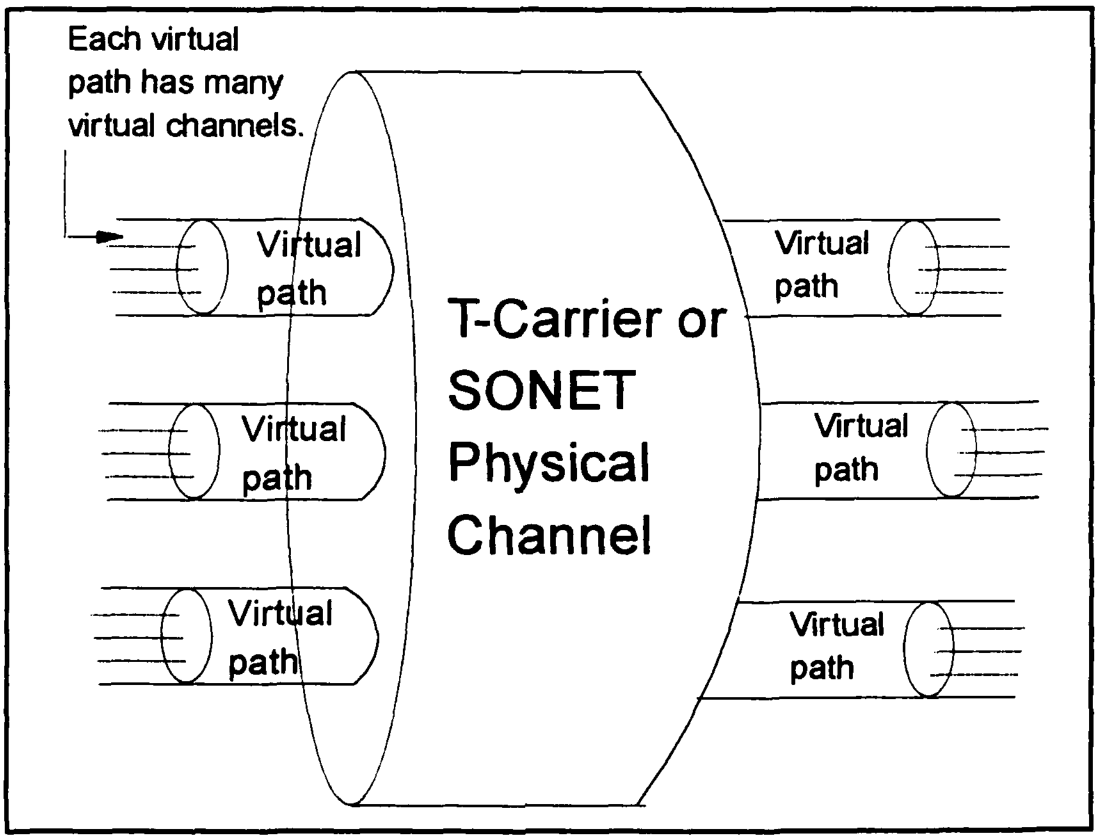

Figure 8. Relationship between virtual channels and virtual paths.

c. *Control Signaling*

This function supports establishment/disestablishment of virtual channels and paths, controls traffic parameters in establishment of connections as well as modifying already established paths. Transmissions from one point to numerous endpoints, also known as multicast, is also supported by signaling. CCITT has specified methods for establishment/release of virtual channels and paths and they are summarized in Table 2 (Stallings, W., 1992, p. 534).

TABLE 2. METHODS FOR ESTABLISHMENT AND RELEASE OF VIRTUAL CIRCUITS AND PATHS

Virtual paths	Virtual channels
1. A virtual path can be established on a semipermanent basis by prior agreement and therefore no control signaling is required.	1. Control signaling can be supported by a semipermanent virtual channel.
2. A network customer may request a virtual path using a signaling virtual channel. This is referred to as customer-controlled establishment and release.	2. A permanent channel is used to set up a virtual channel for call control. This is called a meta-signaling channel since it is used to set up signaling channels.
3. Path establishment and release may be network-controlled using a network established virtual path. The path can be network-to-network, user-to-network or user-to-user.	3. The meta-signaling channel is used to set up connection between user and the network for call-control signaling. This is called a user-to-network signaling virtual channel.
	4. The meta-signaling channel is also used to set up user-to-user signaling virtual channels. This type of channel allows two end users to establish and release user-to-user channels without network intervention.

7. Standards

Several organizations play a role in the standardization process. Internationally, CCITT publishes standards, in the United States, ANSI generates public network telecommunications standards. The standardization of ATM for the most part has been developed in the context of B-ISDN and in the interest of a universal, public network. Standards from these organizations tend to be slow in coming. Furthermore, these standards tend to be insufficient in themselves for a designer to build equipment (Vickers, R., 1993, p. 62).

Nonetheless, these international and American standards provide the base guidelines for the development of B-ISDN.

Industry has taken an initiative in establishing a "de facto standards" organization. It is called the ATM Forum. Current membership includes over 400 vendors, users and researchers (ATM Forum, 1994, p. 11). DOD is a full member and the Navy Research Laboratory is an active participant (NRL, 1993). Unlike previous technologies, this show of industrial support and commitment is unparalleled.

There are several motivations for this endeavor. First, they are moving the CCITT standards to the implementation and specification stage. The ATM Forum is primarily comprised of vendors and it is in their best interest to produce equipment that is compatible. Furthermore, the motivation for a unified approach is also driven by their interests in getting products to the market as soon as possible. Finally, the Forum focuses primarily on customer premise equipment, whereas the ANSI committees and CCITT tend to focus on the public network aspects (Amy, R., M.,1994, p. 54).

Appendix B is a summary of the CCITT recommendations to date. The ATM Forum has also published several specifications as listed in Table 3.

TABLE 3. ATM FORUM SPECIFICATIONS

Specification	Description
User to Network Interface (UNI) Last updated 26 September 1993	Addresses physical and network management aspects of UNI, including physical layer interfaces, local area management, ATM bearer services. The last update added details on signaling protocols for switched virtual circuits (SVCs)
B-ISDN Inter Carrier Interface (B-ICI) Version 1.0 released 7 December 1993	Details support of intercarrier ATM services via inter-carrier connectivity between public ATM network providers.
ATM Data Exchange Interface (ATM DXI) Released 31 August 1993	Details the use of special data service units to connect existing equipment such as routers, bridges, hubs and front end processors to an ATM network.

8. ATM Implementation

Implementation schemes have been developed for many different scenarios. These include use of ATM in LANs, wide area networks (WAN), and metropolitan area networks (MAN) also known as campus wide networks. There has been much speculation as to where the initial use of ATM will prevail. Much of the argument centers around when public carriers will offer the service as well as the extent of its deployment. While this has minor implications for the military, the use of ATM in DOD will be driven more by the maturity of standards and the interoperability of vendor products. The potential stumbling blocks will be discussed in more detail in the next chapter. The use of ATM will primarily be found in three areas.

a. LAN Use

The use of ATM in LANs will provide unprecedented bandwidth to the desktop. ATM can provide much greater capacity to individual users than the existing shared medium LANs. With ATM, the shared medium is replaced with a centralized switch that provides dedicated connections for users. Figure 9 shows an example of the use of ATM in the local area.

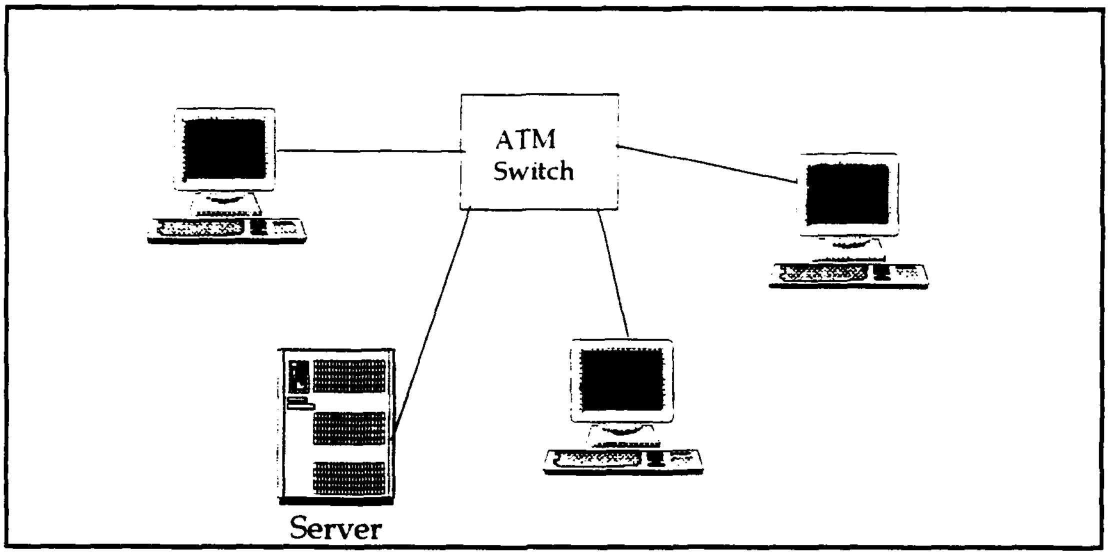

Figure 9. Implementation of ATM in local area.

Some argue that to successfully implement ATM in the local environment, it must offer LAN-like service for data traffic and be compatible with existing data protocols, applications, and equipment (Newman, P., 1994, p. 86). Much research is being devoted to this issue and many solutions have been proposed to date

b. WAN Use

ATMs use in the WAN allows for more efficient use of long haul transmission resources and also can be used to create a seamless network across many miles. The ability to combine different types of traffic (voice, video, and data) and transmit on one network provides for increased efficiency. Another advantage, is that billing on a per cell basis is possible (Lane, J.,1994, p. 44). While perhaps not as big an issue for DOD as the commercial sector, this will provide for cost savings in cases where the military can replace leased T-1 lines with ATM service. Figure 10 is shows the use of ATM in the wide area.

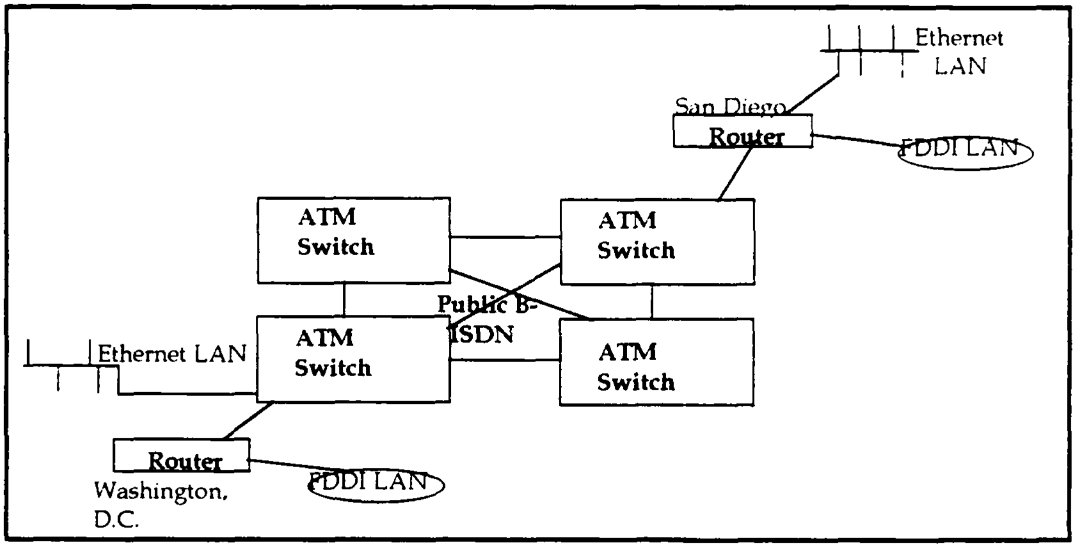

Figure 10. Implementation of ATM in the wide area.

c. MAN

This is also known as a campus wide network. Its implementation is ideal for the Washington, D.C. area or any location where many DOD commands are located. MANs are usually spread across a range of 5 to 50 kilometers and provide high speed connectivity (> 1 Mbps) (dePrycker, M.,1993, p. 259). Hosts, file servers, high performance workstations and LANs can be interconnected to extend the range of LANs. Different protocols are used in MANs to allow the different types of systems to internetwork. A MAN using ATM is shown in figure 11.

DOD's Advanced Research Projects Agency (ARPA) has awarded a contract to Bell Atlantic Federal Systems to establish a MAN in the Washington, D.C. area. A critical goal of this Advanced Technology Demonstration Network (ATDNet) is to gain hands-on experience in using ATM technology. Six ATM switches will be installed at a number of government agencies. The switches will be connected to an experimental SONET network operating at 2.4 Gbps.

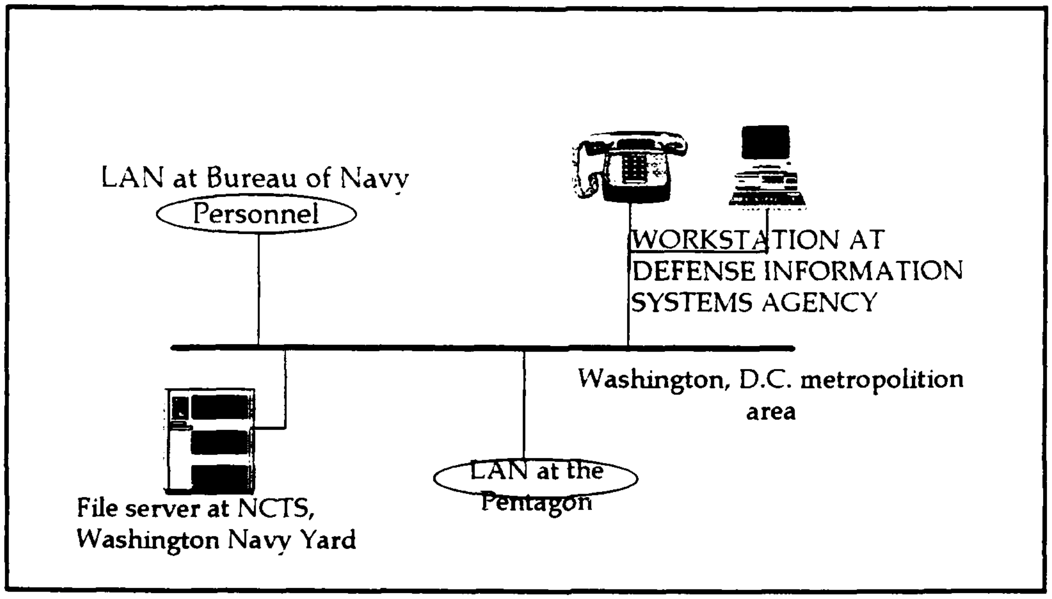

Figure 11. Implementation of ATM in the metropolitan area.

9. Summary

ATM has several advantages over existing transfer modes. Perhaps the most touted is its capability to provide transmission for multiple types of data. It also is scaleable. The ATM standard defines only the cell format without specifying data rates, framing or physical bearers (Lane, J.,1994, p. 43). Therefore, many different systems can use the same format at whatever rate is required. Bandwidth is available on demand versus a fixed rate approach. This means that when users have large files to transfer this can be accomplished and once completed the transmission channel is available for another user. Finally, ATM can provide high throughput rates by using high quality transmission paths which eliminate the need for error detection and correction.

IV. IMPLEMENTATION ISSUES FOR ATM

Although ATM technology is not really new (conceived in the late 80's), its standardization and implementation are still in immature stages. However, there are enough standards published for vendors to market ATM products and provide very primitive ATM services. The catch is that vendors are using proprietary solutions for those areas where standardization is lacking. Even with proprietary ATM equipment, there are aspects of ATM which require attention before they will fully meet military requirements. In the author's opinion, the topics presented here represent critical issues which are currently unresolved. Over time, if adequate solutions are not reached, some of the unresolved issues will present potential stumbling blocks to the successful implementation of ATM. It should be stressed that new developments arise almost daily and, in a period of less than 2 months, the field of ATM will have greatly changed. Some issues presented here may be solved in the short term and will be irrelevant. On the other hand, new issues may arise. Therefore, when looking at ATM as a potential C3 technology, a current survey of ATM and standardization status is recommended.

A. STANDARDIZATION

1. Standards Not Fully Defined

In 1988, CCITT issued the first two interim recommendations relating to B-ISDN. As of late 1988, recommendations I.113 and I.121 represented the consensus of the future of B-ISDN. As the demand for high speed networking increased and the increase in technology available to support this increased, CCITT released an interim set of recommendations on B-ISDN in an attempt to preempt a flurry of proprietary implementations. Usually it takes four years to develop standards and CCITT knew that this would take too long. Therefore, interim standards were released. (Stallings, W., 1992, p. 496)

Following the interim standards release, the base standards were completed in 1992. These standards further detailed specific aspects of B-ISDN and ATM, but many areas are still not fully standardized. While most of the outline of the process or procedure for accomplishing ATM functions has been laid out, the details are lacking. Since the ATM framework is established, the work does not lie so much in the basics but involves the specification of exactly how things will be done. Therefore, the drive of standards has moved away from ATM itself to other standards required for full ATM/B-ISDN capabilities: signaling, Operations and Maintenance (OAM), and interworking with other networks (Vickers, R., 1993, p. 70).

There are several standardization areas that the standards organizations and implementors are considering. First, many different network protocols already exist and in order to provide seamless networks, multiplexing of ATM and legacy LANs is required. Second, the CCITT has specified the methods for establishing ATM connections but the signaling process has not been agreed upon. Finally, in order to support internetworking of different networks, support for ATM addressing in different environments is required. Each of these factors alone are important to the success of ATM and B-ISDN. Without fully specified standards, vendors implement proprietary solutions which can result in incompatibility.

2. Proprietary Aspects of ATM Equipment and Components

There are numerous reasons why vendors produce equipment and components with proprietary aspects. Vendors are motivated by opportunities in gaining large market shares and profits. Furthermore, they generally are concerned with the production of equipment used in customer premises versus public providers like telephone carriers. For these reasons alone, vendors may not wait until standards for a given technology are available and this is where DOD should be cautious, particularly as DOD fully supports Non-Developmental Items (NDI) and Open Systems standards[1] .

As discussed earlier, the ATM Forum was conceived to make specifications work versus drafting standards and its key charge is to ensure interoperability (INCA, 1993, Tab 1, pp. 5-6). Its primary focus is on the private environment. In that regard, the ATM Forum has taken an initiative in drafting specifications for customer premise equipment and private switching. Although the ATM Forum is as susceptible to delays in release of standards as CCITT is, it has established a unified approach for solving some unresolved issues and uses a two-thirds vote rule for passing standards recommendations. With such a large group of vendors and users in the ATM Forum, commitment to standardization and compatibility is much more prevalent than would be without such a consortium. Although vendors will always be concerned with being the first to market regardless of the technology involved, the incentive to introduce proprietary concepts is not as great with ATM technology as with others. Evidence of this is the commitment that vendors have made to the ATM Forum. It is almost becoming a de facto requirement to be a member of the organization because membership in the ATM Forum symbolizes a certain level of credibility in the world of ATM. Another reason for the slower rush to proprietary solutions is that B-ISDN is intended to be a universal network and when that time comes users will want equipment that lets them network with the rest of the world (which will be using B-ISDN).

[1] Congress identifies NDI as: (1) any item available in the commercial marketplace, (2) any previously developed item in use by the U.S. government or cooperating foreign governments, or (3) any item of supply needing only minor modifications to meet DOD requirements (Defense Systems Management College, 1992, p.3)

3. Interoperability

The term interoperability can be thought of in several different ways. To some, interoperability simply means two computers can talk to each other. What it really boils down to is the requirement for different protocols to work with protocols above and below a given layer in the OSI model. In the world of standardization, interoperability is achieved when different implementations of the same specification correctly provides the intended service or application. There are two phases to interoperability with the first being conformance testing against the given standard. Secondly, testing two different implementations of the protocol to ensure that they interwork confirms the system as a whole meets its functional requirements.

In an effort to validate interoperability and facilitate demonstrations of such, several efforts have been undertaken. The first U.S. laboratory dedicated to multivendor ATM interoperability testing was established by Bellcore. Bellcore plans to provide the physical facilities, technical support and test equipment to vendors who participate in the lab. Under this scenario, vendors have a central location and independent party to test each other's products. Another effort has been undertaken by the University of New Hampshire. Disparate vendors' equipment will be tested there with a focus on workgroup equipment. The lab intends to publish test results with general conclusions about interoperability without revealing details about specific vendor equipment. (INCA, 1993, Tab 1, p. 9)

The implications of interoperability or lack thereof are far reaching in the DOD. The emphasis on joint warfare has made interoperability a key issue in any discussion of communication networks. The potential for use of ATM in all the services and across many echelons of command is great. In the interest of multi-service, multi-echelon operations, equipment from different vendors must be interoperable. The option of a DOD sole source procurement for ATM equipment is not a practical solution for interoperability. In reality, services buy from different contracts resulting in the use of equipment from multiple vendors.

The trend in DOD networks is towards a global infrastructure and to support that, ATM equipment interoperability is critical. Therefore, it is imperative that DOD purchase equipment that wholly meets the international standards as well as interoperates with other vendors equipment. Not unique to DOD only is the issue of interoperability of existing networks with new ATM networks. Many users currently do not require ATM speeds to their desktop and are best supported by existing network technology. Others may need 155 Mbps to their desktop. The trends show that user requirements increase over time so there will be some point where everyone needs the transmission rates that ATM provides. Therefore, good clean interoperability will allow users to gradually evolve their networks to ATM as their requirements increase (Feltman, C., 1993, p. 26).

B. SIGNALING

1. Definition

The functions of signaling involve the following:

- Establish, maintain, and release Virtual Channel Connections (VCC) and Virtual Path Connections (VPC) for information transfer. This can be on-demand, semipermanent, or permanent.
- Support for communication configurations on a point-to-point, multipoint or broadcast basis.
- Ability to negotiate the traffic characteristics of a connection at connection-establishment time.

- Ability to renegotiate the traffic characteristics on an already established connection.

(DATAPRO, 1993, p. 10)

B-ISDN provides for signaling virtual channels at the user access as follows:

- Point-to-point signaling virtual channel. For point-to-point signaling, one virtual channel connection in each direction is allocated to each signaling endpoint.
- Selective broadcast signaling virtual channels. One virtual channel connection for selective broadcast signaling is allocated to each service profile.
- General broadcast signaling virtual channel. The general broadcast signaling virtual channel connection is used for broadcast signaling independent of service profiles. Channel is identified by a standardized VPI and VCI value.

(DATAPRO, 1993, p. 11)

As discussed earlier, two types of virtual connections have been standardized: VCCs and VPCs and these are identified with their VCIs and VPIs, respectively. Table 2 summarized the standardized methods for establishing and releasing these connections. VPCs and VCCs can be semi-permanently established between two endpoints and without requiring signaling. Semi-permanent virtual circuits (PVC) are like leased lines. The disadvantage of this is that the connections may not always be fully occupied and therefore poor utilization results. In addition, in the case of large networks and demanding users, network management becomes a headache, requires much human interaction, and results in inefficiencies. The ultimate solution is to have bandwidth on demand with requirements driven by the user when connections are required (dePrycker, M., 1992, p. 27). ATM has been advertised as having on demand capability to provide for dynamic allocation of bandwidth. To provide this functionality, switched connections are required. Switched virtual circuits (SVC) are similar to circuit switched connections. The methods defined by CCITT call for use of signaling channels as delineated above and in Table 2. The protocols used on these channels is what is unresolved and is a major factor in implementing ATM with "bandwidth on demand".

2. Problem

Currently only PVCs are supported and in order to fully gain the benefits of ATM, SVCs are necessary. This in turns requires signaling and because CCITT has not standardized the protocol, ad hoc solutions are being implemented by vendors. In the near future, CCITT will release a standard for this aspect of ATM but in the mean time proprietary solutions are being brought to market.

One example of proprietary development is that of Fore Systems' simple protocol for ATM network signaling (SPANS). Fore Systems argue that because multiple signaling schemes can easily coexist, early adopters of ATM will not be penalized for their foresight. Once the standard signaling protocols are available they can be implemented in ATM LANs by using different reserved signaling channels (Biagioni, Cooper, and Sansom, 1993, p. 35). An argument against this approach is that using additional signaling channels results in poor utilization of resources. In addition, extensive vendor support would be necessary once new signaling protocols are available to ensure that they are added to existing ATM equipment.

3. Timeline for Solution

CCITT is currently working on Q.93B Release 1 signaling protocol which supports call-by-call setup of point-to-point connections. An enhanced version, Release 2/3 is due to support point-to-multipoint and multiconnection calls. This signaling protocol will be an enhancement of Q.931 used in NISDN[2]. Standardization is expected in the 1994-1995 timeframe[3]. (dePrycker, M., 1993, pp. 107-8)

The ATM Forum published an implementation agreement in July 1993 which details a new signaling specification based on CCITT's Q.93B. It allows individual end points to dynamically establish, maintain and clear ATM switched virtual circuit connections in a multivendor environment. This agreement is based on a subset of the Q.93B Broadband signaling protocols from the CCITT. (Sammartino, F.,1994, p. 27)

C. CONGESTION CONTROL

1. Definition

Congestion is defined as a state where network elements are unable to guarantee the negotiated quality of service to existing connections and to new connection requests. It is caused by traffic overload and/or control resource overload. Unpredictable fluctuations in traffic and/or fault conditions in the network may cause congestion. Congestion control is defined as a set of actions taken by the network and all applicable elements to minimize congestion effects and to avoid congestion state spreading. (Minoli, D., 1993, p. 567)

The basic traffic and congestion control functions specified for ATM networks are Connection Admission Control (CAC) and Usage Parameter Control (UPC). CAC is a set of actions taken by the network at call set-up in order to accept or reject an ATM connection. A connection is granted only if

[2] Narrowband ISDN (NISDN) is also referred to as ISDN and is the precursor to Broadband ISDN. ISDN provides for the integration of voice and data over a copper medium with Nx64 kbps channel rate.

[3] At the time of writing, the signaling standard was not available. However, recently the ITU-T has published Q.2931 (which replaces Q.93B) and the ATM Forum adopted this signaling for the UNI specification. (FORE Systems, 1994)

adequate resources are available over entire network for a required Quality of Service (QOS). In addition, QOS must be able to be maintained for existing connections before new connections are granted. During procedures for connection establishment, the following information must be agreed to by the user and network to allow the CAC to make accurate acceptance/rejection decisions on connection admission:

- Specific limits on the traffic volume the network is expected to carry in terms of well-chosen traffic descriptors.
- A requested QOS class with respect to cell transfer delay, delay jitter, cell loss ratio and burst cell losses.
- A tolerance to accommodate cell delay variation introduced by equipment outside network, for example, Customer Premises Equipment.

(dePrycker, M., 1993, p. 290)

The UPC and Network Parameter Control (NPC) is accomplished at the User Network Interface (UNI) and the Network-Node Interface (NNI), respectively. This represents the set of actions taken by the network to monitor and control traffic in terms of cell traffic volume and cell routing validity. The primary purpose of these actions is to ensure that ATM connections comply with their negotiated traffic contract. The lack of this type of control can result in detrimental affects on other network traffic. Three main features should be found in an ideal UPC/NPC algorithm: (1) capability of detecting any illegal traffic situation; (2) rapid response time to parameter violations; (3) simplicity of implementation. (dePrycker, M., 1993, p. 290)

2. Problem

Congestion control is probably the largest unresolved issue in ATM. There are no inherent flow control mechanisms in ATM, so that must be built on top of ATM by enforcing certain algorithms to reduce data flow when necessary. (Sammartino, F., 1994, p. 28)

In wide-area ATM networks, congestion conditions will tend to be very dynamic and will require innovative solutions requiring more than simple reactive mechanisms. In addition, once switched virtual circuits are widely available, network conditions will become more dynamic. This means that real-time congestion management will become even more critical (Heckart, C., 1994, p. 38). In the local area, congestion is less likely because of the immense amount of bandwidth available to less users than in the wide area. Therefore, it can be handled with a simple, reactive scheme (Feltman, C., 1993, p. 52). The topic of congestion control is being actively researched. Many different solutions have been developed. While some are proprietary, others are vendor independent. In addition to CAC and UPC/NPC, other congestion control functions may be implemented. These include priority control (selective cell discard), traffic shaping, network resource management, and feedback controls (i.e. explicit forward congestion indication) (dePrycker, M., 1993, p. 305).

3. Timeline

Even though congestion control is an intense research area with many alternatives being developed, trial implementations are required. The general consensus is that final standardization of congestion control is several years away. Within the standards groups, there has been much discussion on the subject but no agreement has been made on specific control mechanisms (Knowles, G., C., 1993, p. 145). The implications for DOD in this area are critical. Although both the commercial sector and DOD depend on timely, error-free transmission of information, the military tends to face more crucial, even life or death situations. Therefore, DOD cannot withstand uncontrolled and potentially excessive congestion in networks; consequently the control of congestion in a network is of the utmost importance. Solely because of this weakness and lack of maturity, DOD should be cautious in implementing ATM. Work on CCITT recommendation I.371, traffic and congestion control, is expected to continue until June 1995 (Knowles, G., C., 1993, p. 145).

D. PERFORMANCE

1. Problems

There are some questions regarding the performance of ATM with regards to the heavy processing overhead of segmenting and reassembling large numbers of cells. Moreover, the specific cell size of 53 bytes many not assure that echo on voice circuits (Class A and B traffic) will not occur. These can be considered problems but they are not necessarily show stoppers in implementing ATM. Rather they constitute issues that should be addressed in weighing the trade-offs of different technologies.(INCA, 1993, Tab 1, p. 17)

In the data link layer processing of X.25 and frame relay packet-switched frames, user data can occupy as much as 4,096 bytes with a default of 128 bytes. When adding bytes for address and control the resulting overhead is as little as .08 percent and averages at 3 percent overhead. With ATM, 5 bytes of the total 53 bytes are for addressing and control resulting in 9 percent overhead. Furthermore, at the ATM adaption layer, timing information may be added to cells thus increasing overhead to a potential 13 percent. This equates to a large portion of transmission channels being used for overhead and results in wastage of bandwidth. The bottom line is that the price paid for low latency (short delay through network) is inefficiency. (Derfler, F., J., 1993, p. NE1)

It can be said that ATM is most economical for video and sound requiring synchronized delivery. For situations where the bulk of traffic is variable rate data, a penalty will be paid for the all the overhead. More efficient technologies like frame relay are better suited for data where millisecond synchronization is not required (Derfler, F., J., 1993, p. NE1). Frame relay maximizes use of available bandwidth by packaging data in variable length packets and this is best suited for the bursty nature of data traffic.

A brief background on the reasons behind the choice of 53 bytes for the ATM cell size is presented here. This is to facilitate in understanding the problem of echo with voice transmission. CCITT decided that it was best to use a fixed length cell. Once this was decided, the next issue was that of cell length (dePrycker, M., 1993, pp. 80-1). Each type of traffic (voice, video, data) is best suited by a certain data unit size. In order to integrate all 3 traffic types on one network, a compromise on the size was required. To support voice, the overall network delay cannot be too lengthy. Echo cancellers can be used to reduce this problem but this has far reaching costs and implementation issues for a universal network. Several options were possible in the choice of the cell length:

- A short cell length (32 bytes or less) so that in almost all situations voice connections can be supported without echo cancellers.
- A longer cell length (64 bytes or more) requiring either: (1) installation of echo cancellers for most of the voice connections or (2) fill cell partially for voice so that packetization delay is small enough to eliminate need for echo cancellers. However, the second solution reduces transmission efficiency.
- Intermediate cell length (between 32 and 54 bytes). In this case echo cancellers could be avoided in most cases where the number of nodes, the number of transitions between ATM and non-ATM, and the transmission distance are not too large. In addition, partially filled cells is also a possibility.

(dePrycker, M., 1993, p. 81)

In CCITT, various members had preferences for different cell sizes for numerous reasons. In the end, a compromise of 48 bytes was reached in the CCITT SGXVIII meeting of June 1989 in Geneva (dePrycker, M., 1993, p. 84).

dePrycker works an example to calculate total transmission delay using a distance of 1000 km between source and destination, various cell sizes and 2 transmission speeds (150 and 600 Mbps) (dePrykcer, M., 1993, pp. 66-8). It was found that cells larger than 64 bytes and distances more than 1000 km would introduce the need for echo cancellers[4] As stated above, the cell size was chosen at 48 bytes and therefore this size minimizes delay problem with respect to size of information payload. This example presents an issue requiring further work. Transmission distances will not always be less than 1000 km and therefore echo may become a problem requiring repeaters or some other solution.

2. Solution

There are no immediate solutions to the issues of high overhead or echo delay. In the case of ATM overhead and inefficiency, this is a trade-off issue in the choice of technologies. The support of isochronous traffic (i.e. voice) originating from legacy systems and the potential for echo delay is an area of research which is particularly of concern to DOD. It can be said that this is an area of primary importance for the military because voice communications are the ever prevalent "back-up means" to fault control. Analysis is being conducted with respect to current military systems including TRI-TAC and radio frequency (RF) media and no firm conclusions have been made as yet.(Mitre, 1993, pp. 110-7). It is hard to put a timeline on the development of solutions for adequate support of voice traffic. More experimentation is required in order to fully examine the alternative courses of action.

[4] Echo cancellers are required for voice transmissions if delays are larger than 24 milliseconds.

E. SUPPORT FOR EXISTING LAN TECHNOLOGIES

ATM/B-ISDN can be used in LANs as well as in the backbone to interconnect LANs. But before either of these options are fully supported, several factors need to be resolved. ATM networking products will have to provide services like multicasting, LAN emulation, and address mapping. Furthermore, ATM does not inherently have provisions to support connectionless service with point-to-point, multicast, and broadcast transmission. Current standard LANs provide for this connectionless functionality. Again, like most unresolved issues of ATM, the area of technology coexistence has been the subject of much research. In the absence of standards for the protocols required to achieve much of the required functionality, vendors have developed proprietary solutions. A brief look at the individual factors is presented below.

1. Factors Required for Support of Existing LAN Technologies

Multicasting can be defined as the function of providing information from one source to many destinations. Broadcast is defined as the provision of information from one source to all destinations. Implementation of these functions occurs in the switch using signaling protocols. In shared-medium networks (e. g., Ethernet), multicasting is essentially free; but in switched networks it makes additional demands on the switch hardware and software (Feltman, C., 1993, p. 52). Most vendors have implemented multicasting in the switch fabric[5]. In situations where multicasting and broadcasting occurs across arbitrary topologies of switches and nodes, signaling protocols are required. The protocols needed to provide this functionality have not been standardized (Mitre, 1993, p. 85).

[5] A switching fabric is composed of identical basic switching building blocks, interconnected in a specific topology (dePrycker, M., 1993, p. 151)[5]

LAN emulation allows LAN protocols, different from ATM, to talk to the ATM network directly. LAN emulation is needed for three basic reasons: (1) existing LAN protocols need a broadcast media; (2) they use 48-bit Medium Access Control (MAC) address; and (3) existing LANs "switch" packets (Backes, F., 1994, p. 12). The function of LAN emulation will provide broadcast and multicast functionality, address resolution, and a way to break packets into cells.

Connectionless service is a means of LAN interconnection and has gained popularity in recent years. Because ATM does not provide any such functionality at the network layer, it is by virtue a connection-oriented technology. The information used for routing connectionless data (i.e. destination address and QOS parameters) is found at the network layer. Therefore, in order to provide connectionless service like most LANs do today, new equipment must be introduced (Delisle and Pelamourgues, 1991, p. 42). This would be the connectionless server. Users requiring connectionless service will be linked to the server via an ATM connection. The users' information is then transmitted to the server and from there it is forwarded to the final destination. Connectionless service can be likened to the existing Switched Multimegabit Data Service (SMDS). SMDS and its benefits will be discussed in the next chapter.

2. Solutions and Timeline

Many solutions have been introduced in response to the need for support of existing LAN technologies. Since many of the alternatives are proprietary, caution is in order. Standardization of support for legacy LANs will eventually result but part of the problem is in choosing the most efficient solution. Because the issue largely involves requirements for additional functionality, extra processing and overhead may be inevitable and therefore efficiency should be a key concern

There is an emulation specification for the TCP/IP protocol but no specification exists for the rest of the existing LAN traffic. Solutions exist which take either the bridging or routing approach. There are advantages and disadvantages to both and the best solution requires more work before a resolution can be reached. An additional factor in the LAN emulation problem rests in internetwork address mapping. Several methods for address mapping are under consideration and they include the Address Resolution Protocol (ARP), directory lookup, algorithm mapping and administrative mapping (Cisco, 1993, p. 18).

The timeline for the area of LAN interconnection and support of existing network technologies is probably shorter than many of the other areas. One of the reasons for this is that the success of ATM is largely dependent on how well it can support the current infrastructure. Furthermore, most users in the commercial sector and/or DOD cannot afford to scrap all current technology and start afresh with ATM. Therefore, the concerned parties in making ATM work with legacy LANs need to solve the unresolved issues before users can jump on the ATM bandwagon.

F. AAL COMPATIBILITY

The CCITT has standardized four classes of service and these are referred to as Class A through D. The ATM adaption layer (AAL) provides the services to the higher layers of the OSI model that support these four classes with the primary function being segmentation and reassembly. Segmentation of upper layer information into cells is done at the transmitter with reassembly of cells accomplished at the receiver. Four types of AALs have been specified: AAL 1, AAL 2, AAL 3/4, and AAL5. As with most aspects of the standardization for ATM, the standards for these AAL types are not fully developed.

1. Problem

In the area of AALs, several problems exist and until fully resolved there is potential for incompatibility and proprietary implementation. First, the specification for AAL 2 is still under study. Since AAL2 is designed to support variable bit rate, traffic additional functions are required to handle cases where cells are not completely filled (dePrycker, M., 1993, p. 132). AAL 5 was introduced to support bursty data traffic more efficiently than AAL 3/4. Users found that the high overhead associated with AAL 3/4 was not efficient. Furthermore, it provides functionality for error detection less robust than needed for transmission of long blocks of data. The ATM Forum implemented AAL 5 and CCITT is considering the recommendation of AAL5 for class C services. Again, the problem here lies in the fact that CCITT has not standardized the use of AAL 5.

A fundamental issue in supporting the four classes of traffic is that, in order for ATM equipment to receive cells, it must support the type of AAL cells sent to it. In the LAN environment this may not be an issue because there is a good chance that the majority of the network switches and network interface cards (NIC) all come from the same vendor and will be matched (Lawton, S., 1993, p. 47). Inherent to this type of scenario is the issue of vendor support with respect to AALs. Not all vendors are marketing equipment that support all four AAL types. For instance, Digital Equipment Corporation supports only AALs 3/4 and 5 (Lawton, S., 1993, p. 47). It means that a Digital switch could decode only AAL 3/4 traffic. Connecting computers that use different AALs is somewhat analogous to connecting computers on different shared medium LANs (i.e., Ethernet and Token Ring) (Cisco, 1993, p. 11). Since CCITT does not require all four service classes to be supported by ATM equipment there will be some incompatibility inherent among vendor products.

2. Solution

The obvious solution is to have all standards complete with compatible vendor implementation. In reality, this is not likely in the short term. As with many of the factors previously discussed, industry has an interest in getting products to market as soon as possible. Typically this results in proprietary solutions and incompatible equipment. The connection of ATM equipment that is supporting different classes of service and thus different AAL types is one area where solutions are not clear. Cisco Systems state that a router/bridge or other internetworking device will be required to convert between two cell types (Cisco, 1993, p. 11). This in an area that requires more research before adequate solutions are proposed.

G. TACTICAL APPLICATION OF ATM

The ability to use ATM technology in an operational and tactical environment is a prerequisite for most C3 systems. Tactical systems must operate under conditions requiring mobility, reliability in a severe environment, and survivability when parts of the system may be destroyed (Donahue, M., 1992, p. 21.4.1). Because military forces find themselves conducting battle over much greater areas and travel large distances in short periods of time, the need for mobility is paramount. For this reason, networks established in support of, or as part of C3 systems cannot be based solely on fixed terrestrial transmission lines. Support for transmission of information to forces afloat, airborne or many miles away in the field does not lend itself to miles and miles of fiber optic or copper cable. Moreover, it is not physically feasible to run transmission lines to forces afloat or airborne. Consequently, the use of ATM is required over satellite and radio frequency (free space) systems where terrestrial connectivity does not exist.

1. Requirements and Military Application of ATM

Support for legacy equipment like the Mobile Subscriber Equipment (MSE) System, the Army's area wide cellular telephone-like communication system, is nec essary. Furthermore, existing systems using radio and satellite links need to be able to access ATM systems. Two initiatives in particular will have a major affect on the architectures/concepts used to develop and deploy future military C3 systems utilizing ATM[6] . The Defense Information System Network (DISN) is based primarily on the use of ATM/B-ISDN and uses terrestrial, radio, and satellite links. The North Atlantic Treaty Organization (NATO) post-2000 information transport architecture studies have mandated the use of ATM switches and SDH network connections for tactical allied/NATO communications networks (Tracy, R., P., 1993, p. 57). Figure 12 shows how ATM will be implemented in the Defense Global Grid (INCA, 1993, Tab 1, p. 15). The Global Grid concept is a starting point for the development of tactical and legacy system interfaces.

[6] In addition to these initiatives formal consideration has been documented. The use of ATM is one of the options noted in SECNAVNOTE which accompanies SECNAVINST 5200.32A, Acquisition Management Policies and Procedures for Computer Resources. Furthermore, the request for proposals to contractors concerning the tactical workstation, TAC 4, includes the ordering option for an ATM interface and switch supporting AAL 5 traffic. (Green, D., T., 24 May 1994)

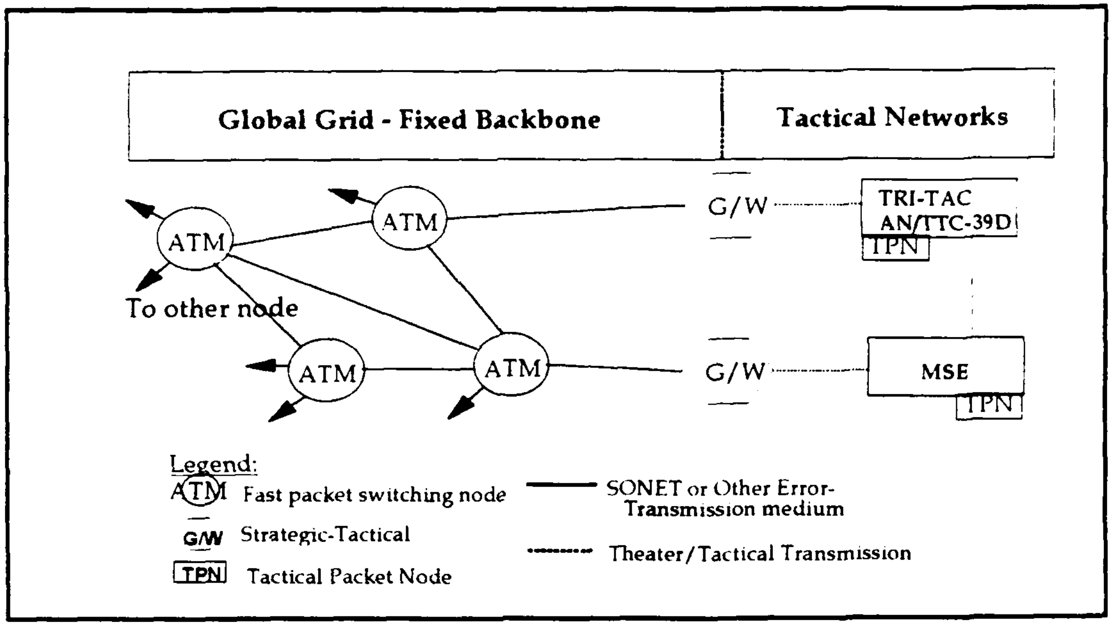

Figure 12. Defense Global Grid Concept Using ATM/SONET.

Some people in the field have entertained the idea of using fiber optical cable on the battlefield. One communications systems engineer suggests that short haul links not requiring range extension could be attained by using disposable fiber optic cable (Tracy, R., P., 1993, p. 58). ATM equipment brought to the theater of operation requires additional protection than that used in the commercial sector. Extreme environmental conditions are possible in any military system and tactical equipment must withstand these circumstances. AT&T Bell Laboratories and the U. S. Army CECOM developed the Tactical Fiber Optic Cable Assembly (TFOCA) for use in extremely severe tactical field environments (Kalomiris V., E., 1993, p. 858). Assemblies were developed which allow for transmission distances from one to eight kilometers without repeaters. Several factors were kept in mind when the TFOCA was developed. First, the requirement for deployment and retrieval of fiber optic cable was considered. Second, circumstances where fiber optic cables are driven over, stepped on or pulled on were taken into account. The TFOCA solution and others like it will be crucial in successfully bringing ATM to the field.

2. ATM over Satellites

a. Issues and Problems

Satellite links carrying ATM will be imperative in extending the range of telecommunications into any theater of operation regardless of the type of platform (air, ground, sea) involved. However, in order for a global grid and theater network to perform satisfactorily, a number of problems need to be resolved. These problems ensue because the bit error characteristics and the inherent satellite propagation delay on typical links have an adverse impact on the operation of ATM/AAL protocols and the SDH transport mechanism. (Chitre, D., M., 1993, p. 258)

A random distribution of bit errors is assumed for most terrestrial microwave and fiber optic based transmission systems. This is generally valid for these type of systems, but the assumption is not valid for satellite transmission systems. Bit errors usually occur in bursts over satellite channels and this has an impact on the SDH transport signal and the ATM cells contained within the signal. COMSAT Laboratories has developed a proprietary solution called ATM link enhancement (ALE). ALE uses a selective interleaving technique that improves the cell discard probability. (Chitre, D., M., 1993, pp. 258-9)

Satellite delay introduces another problem area. ATM via satellite introduces relatively large propagation delays. These delays can substantially increase the latency of feedback mechanisms which are fundamental for congestion control. Unless robust feedback mechanisms are introduced congestion control will become ineffective at a certain point. Reliable data transport via ATM over satellite is also affected by the satellite delays introduced. The error correction required for reliable transfer of data is usually accomplished by means of a coding or retransmission protocol. As discussed earlier in the chapter, the areas of congestion control and error correction are lacking in specification and require more work.

b. Demonstrations

Several programs have been underway to test the feasibility of using ATM over satellite and radio links. Some have had some degree of testing and had success for the most part. But there are issues that remain unresolved with respect to use of ATM over satellite and radio. Because of a fairly large effort by DOD to implement ATM in tactical and operational situations, the next couple of years should produce conclusive results and implementation scenarios.

The Air Force has a contract with GTE Government Systems for the Secure Survivable Communications Network (SSCN). The purpose of the program is to verify the effectiveness of ATM in tactical environments. In addition, the contracts includes development of a low-rate interface card that will enable testing using existing tactical and communication assets. Table 4 is a list of the sites involved in the program. The SSCN program is due to end in November of 1994 and its results will be influential in the issue of ATM for tactical use.(Klaus, L., A., 1994, p. 26)

TABLE 4. Sites involved in SSCN program

Rome Laboratory, Griffiths AFB, NY
Naval Research and Development Division (NRAD), San Diego, CA
Joint Interoperability Test Command (JITC), Ft Huachuca, AZ
US Army CECOM, Monmouth, NJ
480th Intelligence Group, Langley AFB, VA

The Defense Information Systems Agency's (DISA) Commercial Satellite Communications Initiative (CSCI) sponsored a demonstration of ATM over a satellite channel. COMSAT conducted the demonstration using a scenario of mission planning between sites scattered across several continents. One of the key hurdles was burst errors prevalent to satellite communications. COMSAT solved this problem using interleaving. (INCA, 1993, Tab 1, p. 16)

H. CONCLUSION

The issues discussed above represent critical areas to the successful implementation of ATM. The majority of work required is not necessarily unique to DOD requirements. Many of the problems are important to both the commercial and military sector. For this reason, DOD is not in a position where it needs to invest large amounts of funding in the research/use of ATM technology. The commitment that industry has made to the development and implementation of ATM is tremendous and reduces the risks involved for DOD.

The timeframe estimates for widespread use of ATM range from several years to ten years. It will be at least a few years before the required standards are released and from that point the implementation begins. DOD is currently active in the ATM Forum and is conducting much research of its own. This needs to continue until conclusive test results are documented. The use of ATM has already been validated by the high bandwidth requirements arising out of Desert Shield/Desert Storm and the potential for widespread ATM use in the DOD is great.

V. COMPETING AND ALTERNATIVE TECHNOLOGIES TO ATM

A survey of technology used in local, wide, and metropolitan area networks is presented below. Its purpose is to provide a baseline for the comparison of ATM to existing technologies. Further details can be found in any of the references used throughout the chapter. It should be noted that not all the technologies provide the same functionalities. For instance, ATM supports voice, data, and video whereas frame relay supports data only.

Depending on the requirements for a particular C3 system, one network technology in particular or a mix of technologies may best provide the functionalities required. Ideally, local area requirements are met using local area technologies and wide area requirements are supported using the appropriate wide area technology. Some argue that ATM is the "end all, be all" because it will provide seamless, global connectivity thus eliminating the need for any other type of technology. However, as discussed in the previous chapter ATM is not fully mature and has some details requiring work before widespread implementation is likely. Therefore, for the short to mid-term, a mix of technologies may be required depending on the requirements and architecture of the C3 system in question.

A. LOCAL AREA NETWORK (LAN) TECHNOLOGY

LANs typically service small areas within an office or floor of a building. Generally, transmission rates between 1 to 100 Mbps are supported over numerous types of transmission media. Copper, twisted pair and fiber optic cables are used to connect nodes on a network and provide the means for physical transmission of information. The physical transmission medium is usually shared by all stations attached to the network. The common topologies used in LAN environments are the ring, bus and star configurations. LANs are designed so that any node can send information to another node without the permission of a master control node. Medium access control (MAC) is required to arbitrate between nodes when simultaneous access or transmission occurs over the shared medium. The MAC standards are typically used as the common names for local area networks (i.e., Token bus or Ethernet).

1. Ethernet

This technology is officially known as the Institute of Electrical and Electronics Engineers (IEEE) Carrier Sense Multi Access/Collision Detection (CSMA/CD) standard. The IEEE 802.3 specification calls for transmission rates of 1 and 10 Mbps over a bus topology. Typically, Ethernet LANs use 10 Mbps. For the most popular standard, Ethernet, the maximum bus length is 2500 meters (1.5) miles and the bus consists of 500 meter segments connected by repeaters. Table 5 details the physical cabling options developed for Ethernet (Stallings, W., 1994, p. 412).

TABLE 5. PHYSICAL LAYER SPECIFICATIONS FOR IEEE 802.3 (CSMA/CD)

Cable Plant	Bit Rate	Standard	Max segment length (meters)
"Thick" coaxial	10 Mbps	10BASE5	500
"Thin" coaxial	10 Mbps	10BASE2	185
Unshielded twisted pair	10 Mbps	10BASET	100
Unshielded twisted pair	1 Mbps	1BASE5	250
Coaxial cable	10 Mbps	10BROAD36	3600

This standard requires that the transmission time for a data frame must exceed the round-trip bus delay. This in turn will drive the minimum frame size depending on transmission speed and distance. The disadvantage to the minimum frame size is that in some cases this may require frame stuffing where the data requiring transmission is smaller than the minimum frame size. The maximum frame size is 1500 bytes.

The operation of CSMA/CD works similar to the concept of "every man for himself". The stations on the network operate without knowledge of what the other stations are doing. Each node can attempt to use as much of the shared bandwidth that it needs. In order to prevent mass congestion and error-filled transmissions, the CSMA/CD medium access control mechanism is used. This mechanism provides a method of sensing when the network is free and available to handle transmissions. In the case of multiple stations attempting use of the network at the same time, a collision is detected and the sending stations are notified. Once collision is detected, further transmission is stopped until the physical medium is free.

The disadvantages of Ethernet include a decrease in efficiency when large amounts of traffic require transmission across network. The CSMA/CD mechanism is best suited for light traffic loading. Secondly, since the transmission medium is shared, bandwidth limitations are not only characterized by the size of the "pipe" but also by the number of users/nodes on the network. As the number of network nodes increase, efficiency decreases. Although Ethernet's quoted transmission speed is 10 Mbps, the CSMA/CD mechanism causes user to have access to about 3 Mbps of usable information bandwidth (INCA, 1993, Tab 2, p. 3). One way to increase the available bandwidth per user is to connect fewer users per LAN segment and divide the network into more segments. The downside to this is that network management requirements increase. The advantages of Ethernet include support from a broad commercial base and relatively low cost for the given transmission rates available.

2. Fast Ethernet

As the name implies, this is a faster version of Ethernet. Fast Ethernet supports a data rate of 100 Mbps and runs over unshielded twisted pair cable. The maximum length from workstation to hub is 100 meters and the maximum diameter of 250 meters. A star topology is specified and requires a central repeater or hub for each leg of the star. Like the first Ethernet version, it uses CSMA/CD for control of access to the transmission medium and makes use of the IEEE 802.3 frame format. Currently, Fast Ethernet is not standardized but two different proposals have been presented to IEEE. One proposal comes from Grand Junction Networks with a backing of 15 industry vendors and is referred to as 100BASE-X. The Grand Junction approach calls for use of the CSMA/CD mechanism and uses category 5 unshielded twisted pair cabling. Category 5 cabling is of higher quality than category 3 UTP. One of the disadvantages of this proposal is that most places have category 3 UTP installed.

The second proposal called 100 BASE-VG is from AT&T Microelectronics and Hewlett-Packard. Category 3 UTP is called for along with a different mechanism for access control. This new mechanism, called Demand Priority Access, uses a centralized architecture with request/grant protocol to eliminate collisions and maintain some level of predicable network performance. This approach is designed to support delay-sensitive traffic like multimedia. (Axner, D., H., 1993, p. 16)

Both proposals have been assigned IEEE working groups to preserve the 802.3 standard. Currently, 100 Mbps Ethernet is not a formal standard. Some argue that it is extremely likely that Fast Ethernet will remain a non-standard through the majority of 1994 (Naegle J., H., 1994, p. 21). It is likely that vendors will market equipment prior to the release of standards and therefore interoperability problems may result. Because prices are falling for competitors of Fast Ethernet and ATM is quickly coming from the background, the window of opportunity for the success of Fast Ethernet is small.

3. Token Bus

This networking technique is standardized under IEEE 802.4. It uses a token, essentially a control packet, to regulate access to the transmission medium. A physical bus topology is used with a logical ring topology and stations are assigned network positions in an ordered sequence (Stallings, W., 1994, p. 376). Transmission [illegible] at 1, 5, 10, and 20 Mbps using coaxial cable (broadband [illegible] band) or optical fiber[7]. The maximum segment length is 7600 meters when using a carrierband system over coaxial cable. In the case of broadband and optical fiber systems, no maximum length is specified.

Token passing regulates how network stations share the common transmission medium. When a station receives a token it is given the right to transmit information until finished or at an earlier point if the specified token holding time is exceeded. Once the [illegible] finishes transmitting or runs out of time, it passes the token on to the next station. The disadvantage of this technique and downfall to token ring bus networks is the additional logic required for this token passing functionality. There are several advantages to token passing that outweigh the added complexity. First, stations can be assigned different priority by allowing multiple token holding times within the network. Second, there is an upper bound to the time a station may have to wait before it can transmit. This provides for deterministic conditions on networks. Third, there is no minimum frame size as in CSMA/CD. (Stallings, W., 1994, pp. 376-82)

[7] Broadband systems use analog signaling with frequency division multiplexing which allows for multiple channels over one cable. Carrierband systems are also known as single-channel broadband systems. They allow for a signal transmission path for analog signals.

4. Token Ring

IEEE 802.5 standardizes the use of a ring access technique and is called token ring. Physically the topology is a star and logically the cabling is a bus. A multi-access unit (MAU) is at the center of the network and connects all the segments of the "star-like" cabling. Either shielded twisted pair or unshielded twisted pair can be used supporting 1, 4 or 16 Mbps. The maximum number of repeaters allowed is 250 and there is no maximum distance between them.

Like token bus networks, token ring networks use a token to control access to the transmission medium. In a token ring, instead of physically receiving the token, the station must detect a "free" token passing by. Once detected the station changes the status of the token to "busy" and starts transmitting information. When completed the station will insert a new free token on the ring. The difference between token bus and token ring operation, is that in the later the token returns after sequentially traveling across the entire ring and all systems in between. In the bus, the token is sent to a specific station using addresses. Many of the advantages of token rings are the same as token bus networks. One disadvantage of token ring operation is the requirement for token maintenance to ensure that tokens are not lost or duplicated.(Stallings, W., 1994, pp. 382-84)

5. Fiber Distributed Data Interface (FDDI)

FDDI is standardized by the American National Standards Institute (ANSI) and the International Standards Organization (ISO). It is similar to token ring operation but provides high speed transmission. Optical fiber is the specified transmission medium and it supports a data rate of 100 Mbps[8] The topology consists of dual-counter-rotating rings supporting up to 500 stations each (1000 total attachments). Stations can be spaced up to 2 kilometers apart

[8] ANSI FDDI standards groups and several industrial consortiums are assessing twisted pair technology (both shielded and unshielded) for its potential as a transmission medium for FDDI (Mirchandani and Raman, 1993, p. 41).

with a maximum 100 kilometer circumference[9]. Each of the dual-rings is designated as either the primary ring or the secondary ring. Usually all traffic is distributed on the primary ring. The secondary ring acts as a backup in case of a network node failure or ring break. Prior to transmission, data is segmented into 4500 byte maximum frames with each frame having unique starting and ending delimiters.

The FDDI protocol operates by passing a single token from station to station in a sequential fashion. If a station wants to transmit packets it seizes the token and proceeds to transmit. At the end of the transmission the station passes the token on to the next station. In FDDI, the MAC protocol maintains control of the token rotation time (TTRT) in order to bound the maximum time around the ring. This is done by setting a limit to the amount of data a station can transmit on each token rotation. As data packets circulate around the ring, each station checks to see if it is addressed to it and if so copies it to its buffer. Once the packet reaches its originating station, it is removed from the ring.

The use of a token in FDDI differs from token ring operation in two ways (Mirchandani and Raman, 1993, p. 66). First, FDDI places a limit on the token rotation time where token ring does not. Second, in token ring operation, the token is not released until the transmitted data reaches its originator. Whereas in FDDI, once the data is transmitted the token is released to the next station. For this second reason, FDDI is more efficient than token ring because transmission access delay is reduced and multiple data packets are allowed on the ring at the same time. This modified token passing operation gives the user access to more of the actual LAN-transmission bandwidth (80 to 90 percent). (INCA, 1993, Tab 2, pp. 1-3)

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[9] FDDI is presented here as a LAN technology. But it should be noted that FDDI can be used to interconnect LANs in a campus environment across numerous buildings. In addition, FDDI can be used for LAN interconnection across multiple campus locations. (Mirchandani and Raman, 1993, pp. 18-9)

The token rotation protocol supports three classes of traffic:

- Synchronous data traffic with guaranteed bandwidth and response times.
- Asynchronous data traffic with multiple traffic priorities.
- Restricted token data traffic, which supports multiple traffic priorities.

(Mirchandani and Raman, 1993, p. 10)

It is argued that although FDDI can truly support synchronous traffic using "design tweaks", it is improbable that it can realistically support real-world needs of isochronous voice/video traffic. A sufficiently small TTRT is required to support voice and video. The specified TTRT value stated in the standard is 4 milliseconds. Ideally, a TTRT of 125 microseconds is desired to provide high quality voice and video. Even if the standard TTRT was decreased below 4 milliseconds, extended transmission distances and heavily populated networks will increase delays and decrease network efficiency. Therefore, FDDI is suited best for data. In response to needs for voice and video, FDDI-II has been developed to support such traffic and is introduced in the next section. (Mirchandani and Raman, 1993, p. 125)

Disadvantages of FDDI include lack of scalability and shared bandwidth. Every station attached to a FDDI network must transmit and receive at exactly the same rate. Like any shared bandwidth network (all those discussed so far), as the number of stations attached to the network increase, the efficiency and individual station effective bandwidth decrease.

6. Fiber Distributed Data Interface-II (FDDI-II)

This is a follow on to FDDI and is designed to support isochronous (equally timed) traffic allowing for the transport of multimedia and video. Asynchronous and synchronous traffic are also supported as in FDDI. The use of FDDI-II allows for the integration of data, voice, and video into a single access interface over a single cable plant (Mirchandani and Khanna, 1993, p. 119). The data rate, topology, and maximum number of nodes found in FDDI are the same in FDDI-II. Enhancements made to the original FDDI MAC protocol allow for the additional support of isochronous traffic. FDDI-II is still under development and currently no standards have been released.

7. Fibre Channel

ANSI's committee X3T9.3 is developing the standards for this technology. Fibre channel makes use of a high-speed serial data channel that can connect nodes point-to-point or through a switch or switch network. It almost acts like a pipe in transferring data between source and destination devices without regard to the format or meaning of the data (Kessler, G., 1993, p. 69).

Three topologies are supported by fibre channel operation: point-to-point, an arbitrated loop, and a fabric topology. The point-to-point topology is the simplest connection and involves the direct connection of two ports between two devices. Multiple devices can be connected in a ring and this is referred to as an arbitrated loop topology. This type of topology supports a maximum of 238 devices with attached devices sharing the available loop bandwidth. The third topology makes use of a "Fabric" into which communications are directed. The Fabric consists of a single switch element or a collection of interconnected elements. Devices are connected to the fabric switches much like a switched network. Any device attached to the Fabric can transmit or receive data from any other device on the Fabric (Mitre, 1993, pp. 49-51).

Data rates of 133, 266, 531 and 1063 Mbps are supported over optical fiber, coaxial cable or shielded twisted pair. Maximum distances depend on the physical medium used. They range from 10 meters for mini coaxial cable to 10 kilometers for optical fiber. Fibre channel supports Ethernet, Token ring, FDDI and ATM by using an encapsulation technique. Data is segmented into frames which can range in size from 36 to 2148 bytes with actual data payloads of 1 to

2112 bytes. Connection and connectionless data transfer is supported using three classes of service. Table 6 summarizes the three types of service (Mitre,1993, pp. 51-60).

TABLE 6. FIBRE CHANNEL SERVICE CLASSES

	Class 1	Class 2	Class 3
Connection mode	Connection-oriented	Connectionless	Connectionless
Guaranteed bandwidth	Yes	No	No
In order frame delivery	Yes	No	No
Acknowledged Frame receipt	Yes	Yes	No
Guaranteed Latency	No	No	No

Fibre Channel is not yet widely implemented but several vendors are actively working on the development and design of products. There is a Fibre Channel test bed at Lawrence Livermore National Laboratory and tests have been conducted with success reported in transfer of video images. Some argue that Fibre Channel will be a direct competitor of ATM. (Kessler, G., 1993, p. 69)

B. METROPOLITAN AREA NETWORKS (MAN)

MANs are essentially huge LANs that encompass a metropolitan area or city and generally provide transmission rates that qualify as high speed. The operating range of LANs can be extended by connecting numerous LANs together using fiber optic cable. IEEE standard 802.6 provides the specification for MANs and defines Distributed-Queue, Dual Bus (DQDB) as the architecture and protocol for medium access control. DQDB is but one implementation scheme for MANs. In addition, FDDI and Switched Multi-Megabit Data Service

(SMDS) are other methods for achieving metropolitan area networking. An overview of DQDB and SMDS are presented below and FDDI was discussed earlier.

1. Distributed-Queue, Dual Bus (DQDB)

DQDB is the medium access control specified in the 802.6 standard. This protocol is independent of the physical layer and therefore a number of different data rates can be implemented over dissimilar transmission systems. Currently only one of the 3 specified transmission systems has functionality defined for the physical layer translation and this is the ANSI DS3 specification. It calls for either optical fiber or coaxial cable providing a data rate of 44.736 Mbps. (Stallings, W., 1994, p. 415)

The topology used is a dual bus arranged in a ring. There is a provision that the ring can be arranged in a star similar to the token ring standard. Each station on the network is connected to both buses allowing for simultaneous receive and transmit capability.

By providing for isochronous and nonisochronous service, voice, data and video can all be supported. Isochronous traffic is possible by the use of fixed-size slots on the dual buses. The size of the slots is 53 bytes and there is little coincidence that this is the same size as ATM cells. Nodes read and copy data from the slots with control over this access maintained by the DQDB protocol (Stallings, W., 1994, p. 390).

The DQDB protocol is very efficient under a range of loading conditions. With light network traffic, delay is insignificant and access to the bus is quick. Under heavy loading, network efficiency approaches 100 percent and the delay in waiting for a slot is predictable. The combination of quick access and predictable delays makes it possible to support a mix of bursty and constant bit rate traffic. (Stallings, W., 1994, pp. 395-6)

2. Switched Multimegabit Data Service (SMDS)

As stated in its name, SMDS is a service and not an actual hardware implementation or technology. It provides a public packet-switched connectionless service available from several Bell Operating Companies. SMDS is based on the IEEE 802.6 DQDB standard. However, there are some differences between SMDS and IEEE 802.6 . First, SMDS provides network management functionality and access classes which are not supported by 802.6 protocols. Secondly, 802.6 supports isochronous traffic and connection-oriented services while SMDS does not.

Data sent using SMDS is encapsulated into SMDS packets. Variable size service data units are used with a maximum size of 9188 bytes. Each SMDS packet has a source and destination address for the information contained in the payload allowing for connectionless service. SMDS packets are further segmented into cells (via IEEE 802.6) for transmission over the physical transmission medium. Because of the large SMDS packet size, this service best supports bursty traffic.

C. WIDE AREA NETWORK (WAN) TECHNOLOGY

WANs allow for the exchange of information over thousands of miles or even across continents. The majority of these technologies started out using metallic transmission media. But as the public carriers upgrade their facilities, the bulk of transmission media will soon be optical fiber.

1. Circuit Switching and Dedicated Services

Voice grade telephone lines using circuit switching (discussed in Chapter III) is one method of sending voice information over large distances. If data transmission is required, a modem is required to convert the data from a digital to analog signal prior to transmission over voice grade lines. Voice grade lines can be leased to allow for dedicated services. Dedicated services guarantee access by way of permanently establishing a connection between the two desired end points. This type of service is most efficient where routine transfer of data is required.

Leased data lines are also an option particularly in fulfilling high speed communication requirements. T1 leased lines provide an aggregate data rate of 1.544 Mbps. Individual channels at 64 kbps rate can be multiplexed up to a total of 1.544 Mpbs within a single T1. Leased lines at the T3 or 44.73 Mbps transmission rate are also available. Switched 56 service also can provide high speed services using 56 Kbps channels with aggregation of up to 24 channels where required. This service provides for high speed data communications and supports full-motion video by using digital circuit switching.

2. Packet Switching

Packet switching is another way to achieve the transfer of information across large distances. It supports data transfer only and most often the X.25 protocol is used to give virtually any two computers the capability to transfer data between each other. The details of packet switching were discussed in Chapter III.

3. Frame Relay

Frame relay developed out of the advent of high speed transmission facilities which support lower error rates. Since transmission lines were no longer producing as many errors, error detection and correction was no longer as necessary of a function as in packet switching. Because of the reduced functionality required during transmission, the overhead appended to information payloads could be reduced. With less need for link by link error detection and processing plus less overhead, the delays incurred throughout transmission are greatly reduced.

Data is segmented into frames which can be variable in size up to a maximum 4096 bytes in the information payload. Header and trailer control information is appended to the payload and varies in size from six to eight bytes. Frame relay uses logical connections to transfer information across a network. Multiple logical connections can be multiplexed onto the same physical channel. The physical medium used is typically fiber optic cable supporting access speeds of 56 kbps, N x 64 kbps (N=1, ...24), and 1.544 Mbps.

Several recommendations exist which standardize frame relay. CCITT has published two on the subject:

- 233: ISDN Frame Mode Bearer Services (1991).
- 370: Congestion Management for the Frame Relaying Bearer Service (1991).

(Stallings, W., 1994, p. 803)

Frame relay has been the subject of more attention in the United States than in other countries. As a result, ANSI has released three standards:

- ANSI T1.606: Architectural Framework and Service Description for Frame-Relaying Bearer Service (1990).
- Draft ANSI T1.617: Signaling Specification for Frame Relay Bearer Service (1991).
- ANSI T1.618: Core Aspects of Frame Protocol for Use with Frame Relay Bearer Service (1991).

(Stallings, W., 1994, p. 803)

D. SUMMARY

Of the alternatives to ATM presented here, there are only a few that come close to supporting the same range of traffic types. FDDI requires tweaking to support good quality voice and therefore FDDI-II is more promising. However, FDDI-II is still in the development stage. SMDS is primarily for data but is considered a good intermediate step prior to full scale implementation of ATM. One factor to keep in mind concerning SMDS is that it is a commercially provided service available over terrestrial transmission lines. Therefore, it may have limited applicability to the military. Finally, frame relay does not support voice and video but provides an efficient transport mechanism for data. Furthermore, it can be used to access an ATM backbone from locations with lower bandwidth data requirements (INCA, 1993, Tab 1, p. 18).

Several things should be kept in mind when considering these telecommunication technologies. First, in one way or another, each option provides to some degree an evolutionary path to long-term implementation of ATM. Secondly, in some scenarios and C3 system architectures, the functionality and speeds ATM supports may never really be needed. Therefore, alternatives to ATM and perhaps a mix of technologies should be considered. Tables 7, 8 and 9 are included below to provide a comprehensive review of LAN, MAN, and WAN technology in terms of their characteristics and types of traffic they support.

TABLE 7. LAN OPTIONS

Attribute	Ethernet	Fast Ethernet	Token Ring	Token bus	FDDI	FDDI-II	Fibre Channel
Media BW	Shared	Shared	Shared	Shared	Shared		Dedicated
Delay	Variable	Variable	Variable	Variable	Variable	Constant	Variable
Data unit	0-1500 bytes	variable	variable	variable	0-4500 bytes	0-4500 bytes	0-2148 bytes
Data rate (max)	10 Mbps	100 Mbps	20 Mbps	10 Mbps	100 Mbps	100 Mbps	1063 Mbps
Traffic type	———	———	———	———	———	———	———
Voice	No	No	No	No	Marginal	Yes	No
Data	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Video	No	No	No	No	No	Yes	Yes

TABLE 8. MAN OPTIONS

Attributes	DQDB	SMDS
Data rate	45 Mbps	45 Mbps
Delay	Fixed	Variable
Data unit	53 byte cell	0-9188bytes
Traffic Type	———	———
Voice	Yes	No
Video	Yes	No
Data	Yes	Yes

TABLE 9. WAN OPTIONS

Attributes	Circuit Switching	Packet Switching	Dedicated Services	Frame Relay
Delay	Minimal	Variable	Minimal	Variable
Data rates	56 kbps	56 kbps	N X 64 kbps, 1.544 or 44.73 Mbps	56 kbps, N x 64 kbps, 1.544 Mbps
Traffic type	----------------	----------------	----------------	----------------
Voice	Yes	No	Yes	No
Video	No	No	Yes	No
Data	Yes	Yes	Yes	Yes

VI. A FRAMEWORK FOR IMPLEMENTING ATM

A. INTRODUCTION

1. Information Technology Decisions

Generally speaking, any technology used to accomplish networking or telecommunications falls under the umbrella of "information technology". To some, the term "information technology" implies fixed plant transmission systems and support for more administrative functions (i.e, database management and word processing) versus operational functions (processing and data transfer of military sensor information or data). As the use of computers infiltrates every aspect of the commercial and military sector, the technology used in a broad range of areas from administrative support to transfer of military intelligence can generally be classified as information technology. This is generally true, whether it be for generation of financial documents or distribution of operational reports.

Decisions involving information technology can be distinguished by several characteristics. First, information technology itself is very dynamic. Given the rate at which computer processing technology advances today the decision environment is extremely complex in terms of the technological choices at hand. Generally speaking, the number of options or alternatives in information technology is immense. Choices are not usually limited to one or two options.

Ordinarily, cost is an issue in any type of decision, be it buying an aircraft or buying medical supplies. Alternatives are usually compared by their cost-effectiveness for a given set of attributes or characteristics. The difficulty with information technology decisions is that the costs and benefits from information technology are not straightforward and are hard to quantify (Remenyi, Money, and Twite, 1991, p. 46). Furthermore, intangible benefits will not be quantified, though they may be an important factor in justification for one option over another (Remenyi, Money, and Twite, 1991, p. 46). Intangible benefits could include such things as more productive personnel due to a relatively better user interface with given computer communication system.

In summary, information technology decisions are typically wrought with many choices. They do not have a given, quantifiable set of criteria from which to evaluate, and some benefits may not be quantifiable. As a result of these factors, decisions regarding information technology usually tend not to be straightforward. Furthermore, alternatives cannot be chosen simply because they meet criteria. Some options must be analyzed to determine the degree to which they meet a given measure of performance. In other words, there may not be one optimal answer as in a mathematical problem.

2. Use of Heuristics in Decision Making

Heuristics can be defined as criteria, methods or principles used for deciding among several alternatives with the end objective of choosing an alternative which will be the most effective in achieving some goal (Gass, S., I., 1985, p. 19)[10]. Regardless of the type or level of decision, heuristics are useful in making more objective and rational decisions. Furthermore, heuristics help to structure a problem that is not necessarily straightforward. The framework developed in this chapter is intended to serve as a heuristic for implementing ATM technology in physical architectures for C3 systems.

[10] The American Heritage Dictionary defines a heuristic as usually a speculative formulation which serves as a guide in the investigation or solution of a problem (Morris, W., 1982, p.610).

3. Introduction to the Decision Process

Figure 13 presents a flowchart of the ideal decision-making process (Hill, P., H., 1979, p. 22). This is an abstract view of the decision making process which is generic and can be applied to any decision problem.

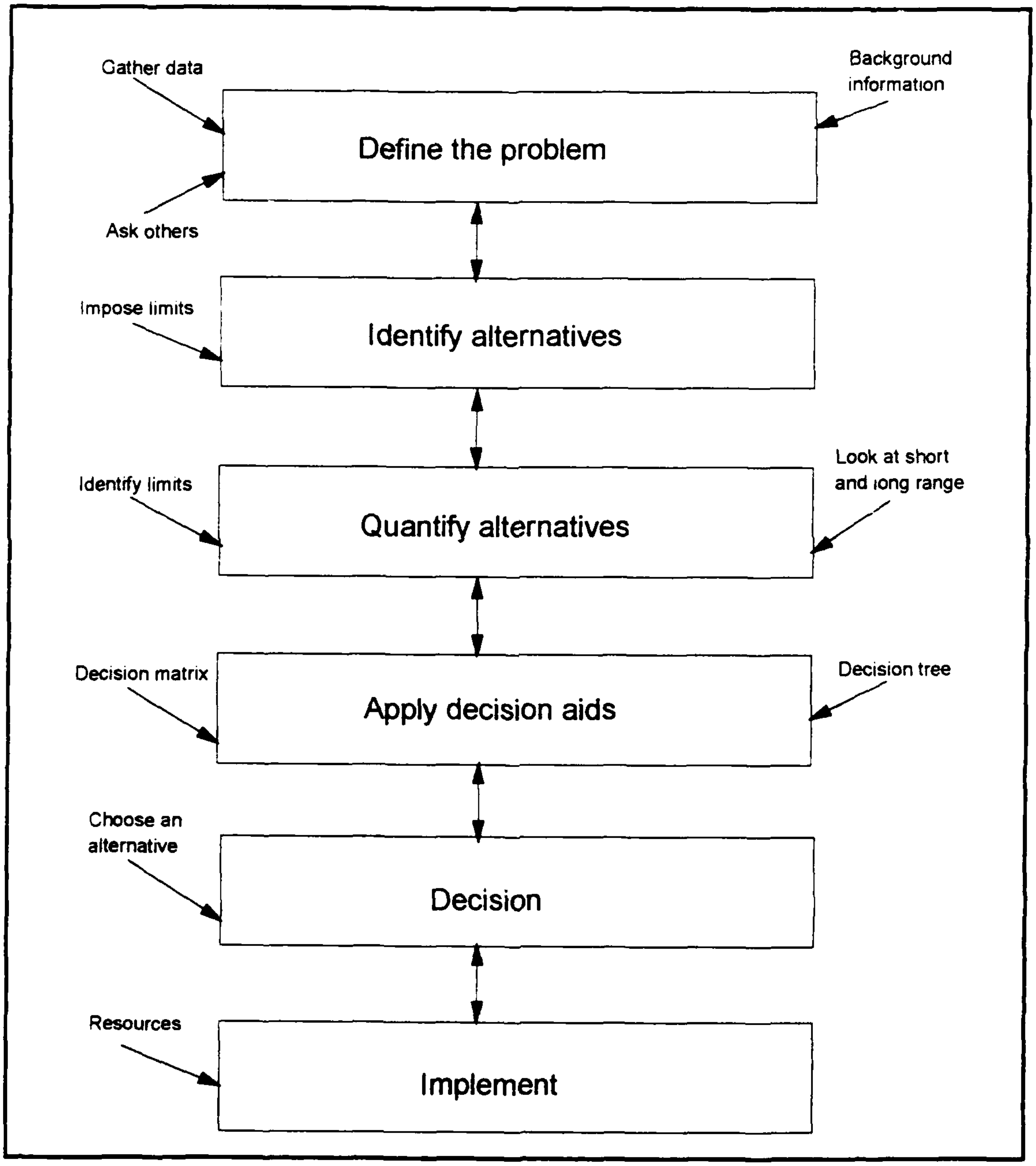

Figure 13. The Decision Making Process.

Figure 14 presents a modified decision-making process which is specific to the information technology decision problem of this thesis. The process presented delineates a prescriptive heuristic that can be followed when deciding how ATM should be implemented in current and potential C3 systems.

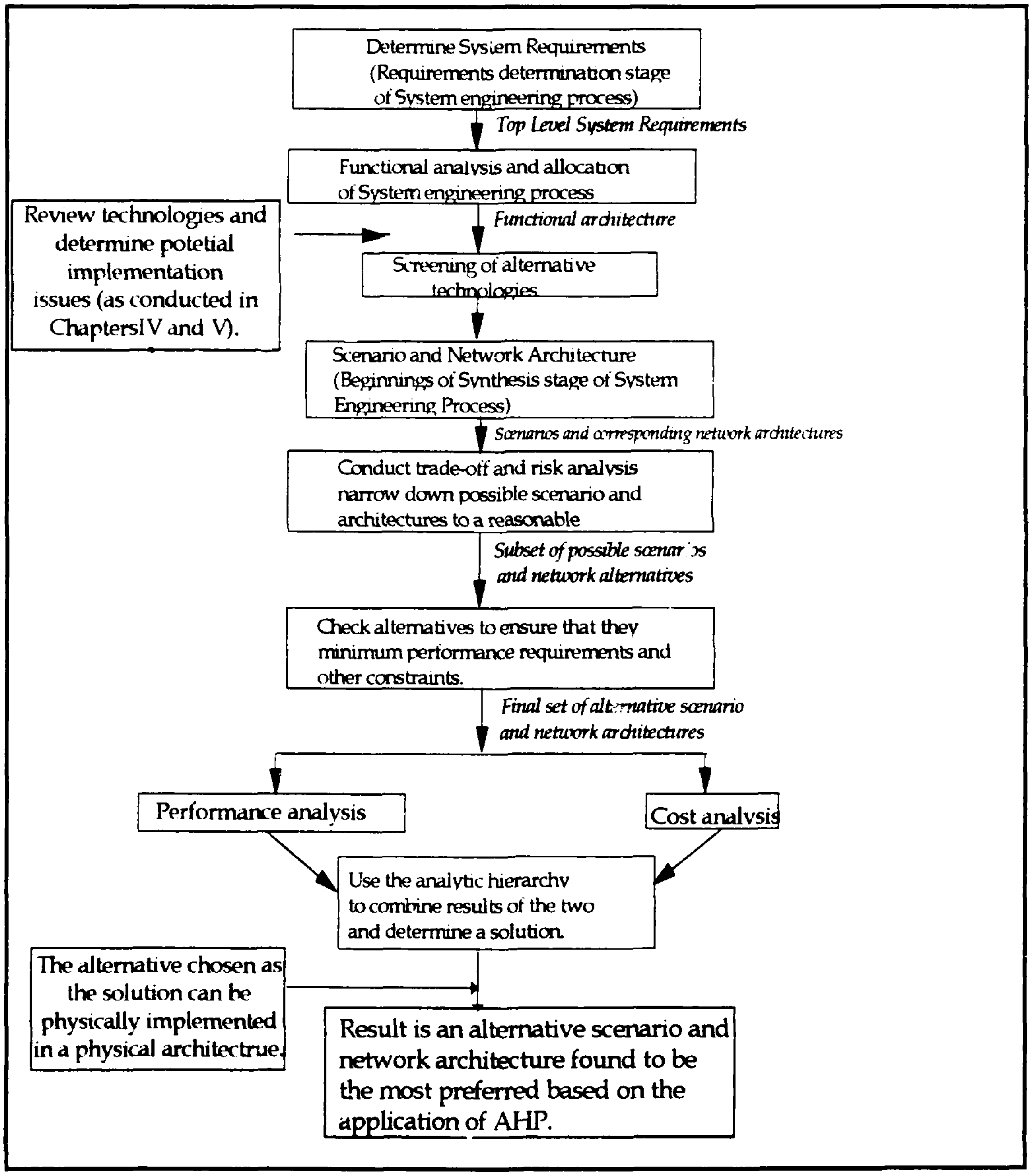

Figure 14. Decision-making process for ATM implementation.

The system engineering process is shown in Figure 15 and is provided to help define the context in which the framework is applicable (DOD MIL-STD-499B, 1992, p. 4).

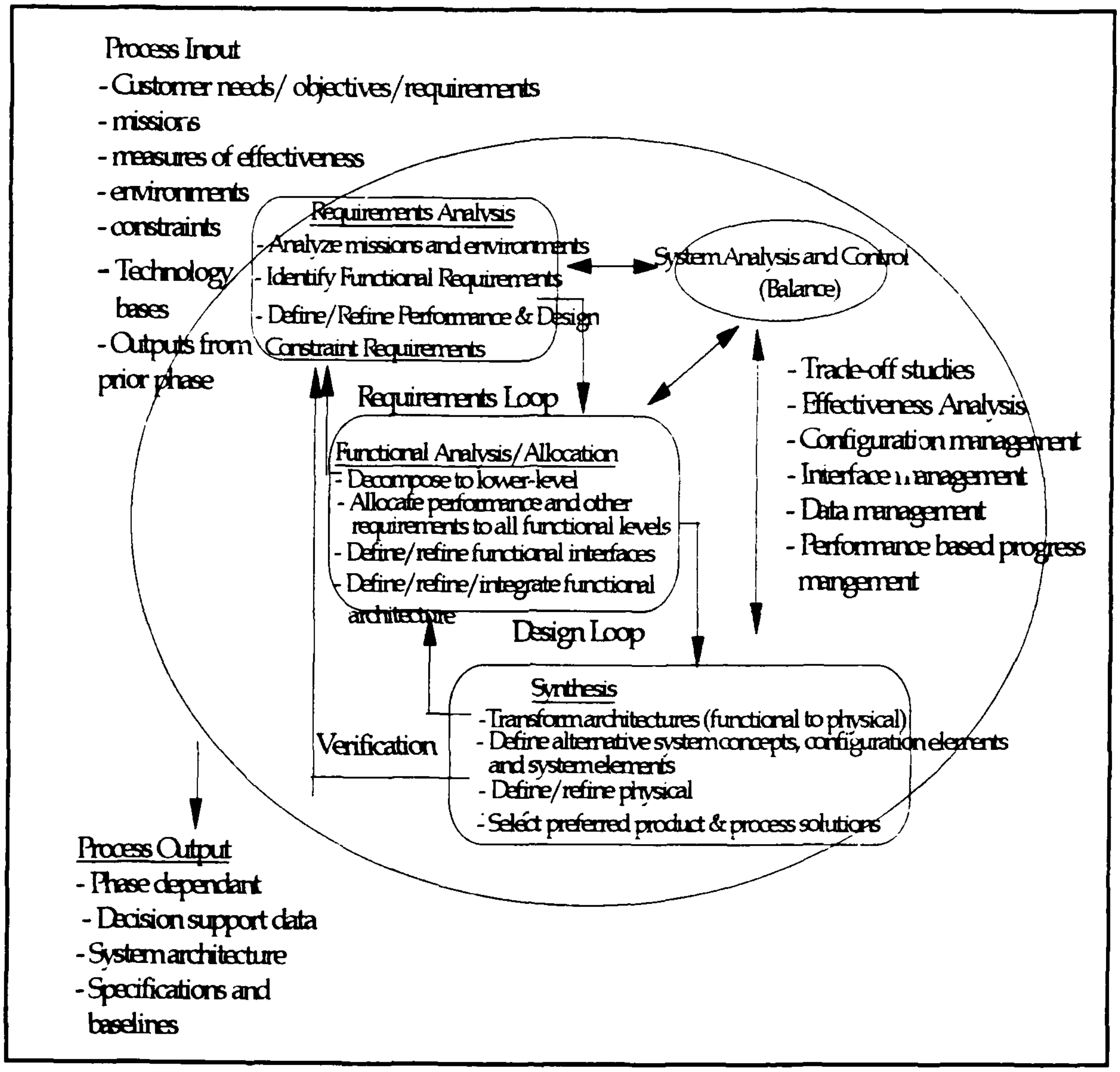

Figure 15. The system engineering process.

The following discussion establishes the starting point for the framework. For a given C3 system, it is either in existence or is being developed. The system engineering decision problem has been established with one of two objectives: (1) minimize life cycle cost of the C3 system constrained by at least the minimum required top level system performance; or (2) maximize top level system performance constrained by at least the maximum allowable life cycle cost (Jones, C., R., 1993, p. 2). The C3 system concept has been studied in detail to determine its boundaries and the environment has been established. Top Level System Performance Requirements have been established as well as the measures of performance (MOP) which quantify these requirements. This first step occurs under the requirements analysis step in Figure 15. Secondly, the functional architecture has been developed under the functional analysis/allocation step in Figure 15.

Following the functional analysis step, the synthesis process begins within the design loop (see Figure 15). It is at this point that the framework is applicable. Each of the potential alternative technologies is examined with respect to how well they meet or exceed the performance requirements. As stated above, this will generally not result in <u>one</u> feasible answer. Therefore several different methods of analysis are used to select the preferred solution. Under the system analysis & control (balance) component in Figure 15, some of these methods of analysis are listed. For purposes of this thesis, risk, trade-off, performance and cost analysis will be discussed. In exploring alternative technologies, alternative system concepts are developed within a given scenario. Inherent to this step is the beginning of the transformation of functional architectures to physical architectures (Blanchard and Fabrycky, 1990, pp. 64-75). With the development of physical architectures, C3 system concepts will become further defined. This results in network architectures which are unique to each scenario. The translation of functional architectures to physical architectures corresponds to the synthesis process and involves some iteration of previous system engineering process steps to ensure that requirements are met. The framework development in this thesis is applicable to the synthesis stage of the system engineering process (see Figure 15).

B. SYSTEM REQUIREMENTS DETERMINATION

This discussion is presented to provide a broad understanding of the requirements process. Also it provides a baseline view of how specific system requirements are established. Within the requirements analysis process, the actual system requirements are determined in order to define the interface of the system-in-focus with all the pertinent aspects of the environment (Jones, C., R., 1993, p. 1)[11] . These requirements are also referred to as Top Level System Requirements (TLSRs). In order to ascertain what is required of a system, several different areas require some level of analysis and definition. These are in addition to those requirements established by the user which are referred to as Top Level System Performance Requirements[12] . First, the environment of the system-in-focus must be detailed. Second, the potential users of a system may have specific functional needs which are to be met or supported by the system being designed. Lastly, systems are generally designed to be used in a specific scenario. This scenario has characteristics which may constrain certain aspects of the system-in-focus. These characteristics include potential manning levels. Within manning levels and force structure, there are various levels of readiness and experience which have a bearing on a potential scenario. A brief discussion of the areas of concern to requirements determination is presented below. It is

[11] The concept of a "system-in-focus" is a way to define the system that is of concern and allows for the differentiation between details or issues internal and external to the system in question.

[12] Top level system performance requirements are measures of performance that users require a system to meet. They are quantitative in nature and can be set at a specific level (i.e., with reference to time or speed) or they can establish a probability which a system must meet in terms of its performance.

intended to provide only an overview of the factors involved in the system requirements determination process.

1. Environment of C3 System-in-Focus

The environment of the system-in-focus is important for several reasons. Since the system interfaces with it, this has implications for system design and choice of technology. The interaction between the system and its environment must be forged so that the system performs as required. Furthermore, any environmental limitations must be accounted for in system design and supported by the technology implemented.

One environmental factor requiring discussion is at what level of DOD the system is to be tailored. Levels of DOD refer to the type of command level like those discussed with systems architectures in Chapter II. For instance, a system may be designed to be used by a Joint Task Force (JTF) and inherent to this are some additional requirements that may be unique to JTFs. Within the domain of level of implementation, potential end points or nodes in a system introduce another issue which must be considered. If a system is going to be implemented in a JTF, then communications between an afloat unit and an airborne unit may be required. Or in the case of system use within a U.S. Navy battlegroup, communications between numerous ships may be required. These are very generic and fundamental examples but they suffice for illustrating potential requirements. The level of implementation has implications for transmission media requirements. For example, if communications between an afloat unit and an airborne unit are required, the system-in-focus cannot rely on fixed, terrestrial media only.

Another area which is of concern in defining a system's potential environment is operational deployment and use. The expected operating times (i.e., day/night) and degree of use (i.e., requires operation over 12 hour period) are important factors in ensuring a system will meet its required operating conditions. In addition, the issue of transport requires consideration. If the operational environment demands quick reaction, a C3 system supporting such a mission may need to be put on a helicopter for instance. This would have implications for size and weight limitations. Finally, the physical environment within which a system will be used requires delineation. The expected temperature, humidity and terrain characteristics are at issue here.

2. Telecommunications Functions Required of C3 Systems

As stated in Chapter two, any C3 system of the future will have a global, broadband telecommunications infrastructure. Therefore, many sophisticated functions supported by telecommunications will become a standing user requirement in virtually any C3 system. The range of these functions is limited only by the imagination of users. The mission for which a C3 system is designed for drives some of the requirements. For instance, if a mission involves an unified attack by forces from many different units, detailed coordination will be required. In turn, this coordination may require the use of video teleconferencing to achieve the desired level of coordination needed to successfully initiate the attack. Furthermore, large amounts of intelligence may be required and that in turn calls for high capacity data transfer capabilities.

In the age of information warfare, three primary telecommunications functions will be required of most systems: voice, video teleconferencing, and data transfer. These functions are not necessarily new in concept, but their introduction onto the battlefield is certainly a recent development. The importance of "information" and the quantities requiring transmission manifested itself like never before in the Gulf War. The extent to which video teleconferencing, data transfer and voice communications is to be supported is also driving at a global telecommunications infrastructure. The bottom line is that commanders want more information faster and they need it delivered to their "troops in the foxhole". Therefore, system requirements for modified and new C3 systems will generally include voice, video teleconferencing and data transfer.

3. Future Scenario Risks

Generally speaking, systems are devised to be used in a specific scenario. Scenarios have characteristics which may constrain certain aspects of the system-in-focus. Force structure, readiness and various levels of personnel experience are all factors in the manpower aspect of scenarios. Other characteristics of a scenario include the geographical setting of mission, degree of hostility expected of enemy, state of industrial and technology base, and political environment in terms of potential coalition forces. Each of these attributes has many different potential configurations. For financial as well as technical reasons, it is not possible to build a C3 system to support all the possible scenario-mission and force combinations. Therefore, a plausible and realistic set of combinations must be chosen and taken into consideration in establishing system requirements. The question is how do we know if we planned for the right scenario or future? This is where risk analysis comes into play along with "expert decision makers". In general, risk analysis is a means of identifying potential risks in terms of costs, state of the military and industrial base and other factors which may influence expected futures. By conducting risk analysis, the possibility of planning for the incorrect future is reduced.

4. Top Level System Requirements (TLSR's)

From the final set of combinations, system requirements will be established that meet Top Level Warfare Requirements (TLWRs) for each of the mission-force level-scenarios considered[13] . These requirements are known as TLSRs, and system performance measures (MOPs) are established for each of the scenarios developed and represent discrete requirements. In order to develop

[13] TLWRs establish levels of performance for a given force (i.e., a JTF) with respect to the established mission success criteria which are measures of a units effectiveness.

quantitative specifications that can used in the design and physical implementation of systems, a scalar index is required to represent system requirements across the range of possible scenarios. One way to achieve this is to use the analytic hierarchy process (see Appendix A). The AHP process can be applied to requirements determination and results in a single overall TLSR which can be used to provide system design specifications for designers.

C. METHOD FOR CHOOSING ALTERNATIVES

After system requirements are determined, functional architectures are developed to provide models of the C3 system. These models can also be referred to as functional flow diagrams. Blocks within the diagrams illustrate what is to be accomplished versus the realization of how something should be done (Blanchard and Fabrycky 1990, p. 57). Once this is completed, the process of synthesis begins and eventually results in physical solutions which support system requirements (and are based on the system's functional architecture). In the case of telecommunications and network functional architectures, there is a broad range of technological solutions.

Technologies which support telecommunications and networking are numerous, and combinations of them further broaden the possibilities to an infinite number. As shown in Chapter V, there are many different solutions to telecommunications and networking. Furthermore, new technologies are being developed which will add to the pool of choices. Primarily because of the enormous range of options, a preliminary review and assessment of technologies is necessary to narrow down the field of possibilities. Some technologies may not meet a given need and others may provide much more functionality and performance than is required. By examining technologies in this fashion, some possibilities can be eliminated as not technologically feasible or more than that required. This process could be thought of as a screening process to establish a baseline set of technologies which meet a given set of criteria.

1. Criteria Used in Screening Alternatives

Some of the criteria are listed below and are applicable in choosing a set of telecommunication and networking technologies:

- Open system technology: technology that is either available in the public domain or can be easily licensed at nominal costs; this type of technology should also be a standardized to a degree such that proprietary implementations do not result.
- Commercial acceptance: products implementing a given technology are or appear likely to be avai... ..ultiple vendors.
- Available port bandwidth: the information rate in bits per second which can be delivered to an individual user connected to the network.

(Green, D. T., 1994, pp. 9-10)

Other criteria might include factors such as survivability, fault tolerance, and portability. In addition, there may be some very basic system requirements set by the potential users. If a techno... does not and is not expected to meet these basic requirements or criterion , it can be eliminated from the field of choice. As a result of preliminary screening, the range of potential telecommunication and network methods will be narrowed down to a manageable size.

2. Constraints Unique to Military Systems

In addition to TLSRs and criteria discussed above, unique military requirements may limit the possible alternatives. DOD frequently has requirements particular to the military which may not be supportable by a commercial system or by a given technology. For instance, SMDS (discussed in Chapter V) is a commercial service and its design makes use of primarily a terrestrial infrastructure. This service can support shore based military units but it cannot provide telecommunication services to airborne or afloat units. Furthermore, because SMDS is a commercial service, DOD cannot control the points of failure as it can with systems used solely by the military (an issue of susceptibility, survivability and reliability). When choosing a set of alternatives, characteristics unmatched by commercial requirements require careful consideration. This will ensure that appropriate alternatives are examined for military C3 systems.

3. Scenario and Network Architecture Development

A given set of requirements (TLSRs) and boundaries of a "system-in-focus" drives and constrains the different mixes of technology that are suitable for a particular system. Supposing a C3 system is required for a JTF, the following requirements are established for the C3 system:

- Communications connectivity required for platoons in field approximately 200 - 300 miles away from JTF headquarters.
- Communications connectivity require between platoons approximately 50 miles apart.
- Communications connectivity between JTF headquarters and surface ship with varying range between 100 - 1000 miles.
- Video teleconferencing connectivity between JTF headquarters and surface ships.
- High resolution image transfer between JTF headquarters and platoons but not required between platoons themselves.
- Minimum data transfer rate = 1.5 Mbps.
- Bit error rate = 10^{-9}.
- System efficiency = maximum six percent overhead for given information payload.

The requirements listed above can be considered part of a scenario and they influence the network architectures that can be considered. More generally, scenarios can be characterized by several factors. First, they reflect operational characteristics which must be supported. These include the types of units (ground, air, sea) which will use the C3 system and potential size of the force using system. The mission and objectives of the forces for which the C3 system is being designed play a role. The distances over which the C3 functions will be conducted are also a factor in the scenario. In addition, technological demand is reflected in the scenario. This involves the bandwidth, transmission speed, and bit error rate desired. Time phasing of the various futures of technology is detailed. Two examples of technology futures follow:

- ATM is fully available in 1994 and FDDI is in widespread use.
- ATM is not fully available until 1996. Currently ATM is available in private networks with some proprietary signaling aspects.

Each scenario has a specific network architecture that supports its attributes. Network architectures specify the particular aspects such as the mix of technologies , transmission media, and topologies to be used.

4. Determination of Final Set of Scenarios and Network Architectures Using Trade-off and Risk Analysis

By conducting trade-off analysis, a set of scenarios (and network architectures) can be narrowed down. In order to cover all risks or technology and performance combinations, each and every possible combination of the technology alternatives requires analysis. This is not feasible nor is it cost-effective in finding a solution. Therefore, a limited number of alternatives are considered and these are arrived at by looking at the risks and trade-offs involved.

a. *Trade-offs Requiring Consideration*

The first trade-off is between the types of technology themselves. For instance, a network architecture using all ATM is possible. This can be contrasted to a network architecture using ATM between the JTF headquarters platoons, and ships, with Ethernet between the platoons themselves. Each one of the possible combinations is different and brings with it advantages and disadvantages. The combinations can be compared by their network performance and transmission effectiveness and usually the combinations with the highest levels of such are the preferred solutions.

The choice between transmission media is a second trade-off. In the broadest terms, there is a trade-off between the amounts of terrestrial and free space transmission media used. The feasible "mixes" of fixed and free space media will depend on several factors including the mobility required and the types of units involved (airborne, ground or sea). It is possible to utilize satellites for an entire system but this may introduce too many burst errors and may not be feasible due to limited satellite resources. On the other hand, complete use of fixed media is not possible because most situations involve some forces other than ground forces. Consideration must also be given to the tactical issues involved in using ATM (discussed in Chapter IV). For a given amount of terrestrial transmission medium in a C3 system, there can be a mix of fiber optic and metallic cabling. Figure 16 is a graphical representation of the possible combinations of terrestrial transmission media for various performance levels (X_1 through X_4).

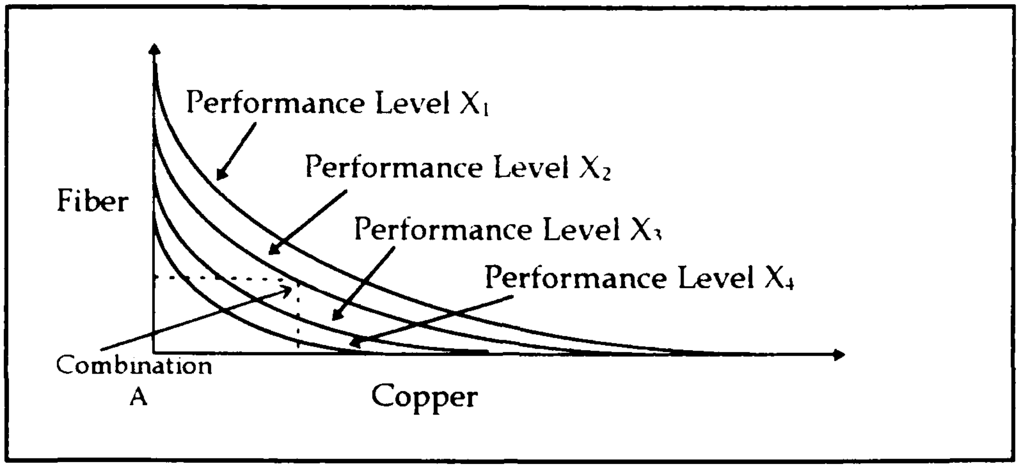

Figure 16. Trade-offs between terrestrial transmission media.

It is emphasized that each curve in Figure 16 meets a particular set of performance requirements; and the curve which meets the established C3 system requirements would be chosen. Each curve is made up of discrete points which represent discrete combinations of transmission media(alternatives) Figure 16 shows a specific point (for combination A) on the curve for performance level X_2. To avoid a confusing figure other combinations are not labeled but suppose that combinations A through C are being considered. Combination A could be the use of fifty percent fiber optics and fifty percent copper. Suppose combination B suggests the use of seventy-five percent fiber optics and twenty-five percent copper. Finally, combination C intersects the x axis and uses one hundred percent copper. Depending on the transmission distances involved, the use of copper versus fiber may mean the difference between mandatory repeaters and no requirement for repeaters. Copper has a more limiting transmission distance than fiber before the use of repeaters is required. Another trade-off between optical fiber and copper is the bit error rate introduced with each. Unanticipated requirements and ease of future upgrades or modification may favor the use of primarily fiber optic cabling. In summary, when comparing alternative combinations of terrestrial media, the issues introduced above must be taken into account.

In addition to the trade-off between fixed, terrestrial media (copper and fiber optic) there are trade-offs between "free-space" media (satellite transmission) and the frequency ranges used (i.e., high frequencies (HF) versus super high frequencies (SHF)). Issues germane to this trade-off include any limitations on resources available and environmental factors which may affect transmission quality.

Cost is another big factor and is a trade-off issue of particular weight in the telecommunications arena. The transmission chip sets that are required for network nodes range widely in price depending on the technology. For instance, the prices of chip sets for Ethernet networks are well below those for ATM networks. In addition, the network interface cards vary depending on the use of Ethernet, FDDI, ATM or any other technology. Generally speaking, equipment for technology that is fairly new to the commercial market will be priced higher than mature technologies such as Ethernet.

Finally, there is the trade-off between network performance and transmission efficiency (i.e., overhead in frames and packets). Each of the different technologies discussed in Chapter V have a certain amount of overhead. For a given amount of information, the additional bytes required for processing introduce overhead. This reduces the effective amount of user information transmitted at any one time. In some cases this may not be especially important, for instance, in communications between the JTF headquarters and the afloat units where less time-sensitive information or administrative traffic may be involved. Whereas, information transmitted between the platoons may be more time critical and be better supported by a more efficient technology.

Also inherent to the trade-off between network performance and transmission efficiency, is the issue of the type of information being transmitted (i.e. voice, video, or data). If a C3 system is being designed to support mostly data traffic, then overhead is not necessary for timing and synchronization control. On the other hand, a C3 system intended to be used for mostly voice traffic will dictate additional overhead to support timing and synchronization required for voice transmission. In cases where a system is designed to support all types of traffic, efficiency may be a compromise when using one technology. However, with a certain integration technology, a compromise may not be necessary and therefore a higher level of efficiency may be achieved.

It is important to note that these trade-offs are not independent of each other. For example, by choosing ATM, the requirement for fiber optic transmission media is mandated, and a metallic transmission medium it is not an option. On the other hand, by choosing copper as the preferred transmission medium, the opportunity to upgrade to technologies requiring fiber optics is forgone.

b. Risk Analysis

Inherent to the trade-off analysis discussed above, there is some risk analysis involved. Risk analysis involves the identification of risks that may have an impact on system cost and performance. Furthermore, there is risk inherent to the technologies themselves and this needs to be assessed. A discussion of risks, specific to the decision involving the implementation of ATM to C3 systems, is presented below. In addition to the risks identified below, the ATM issues discussed in Chapter V are accompanying areas of uncertainty.

The first risk considered involves the possibility that in choosing one technology the opportunity to migrate to another technology (in the future) is blocked. The ability to migrate or evolve to other technologies depends on the technology itself, the transmission medium used and the network architecture implemented. In terms of technology, the manner in which information (voice, video or data) is segmented and encapsulated into units (frames or cells) affects potential interfaces to other systems (using different technologies). For instance, the Distributed-Queue, Dual Bus (DQDB) standard for MANs specifies the use of 53 byte cells as well as the ATM standard. Therefore, systems following the DQDB standard should be able to interface with an ATM system without as much translation required if different size data units were used. This is of course dependent on the provision that the specifications were implemented properly.

The second aspect of migration capability lies in the type of transmission medium chosen. Generally speaking, the newest (also the fastest) networking and telecommunications technologies specify the use of fiber optics. It is most likely that future technologies will also require fiber optics or another medium not yet discovered[14]. Therefore, if transmission media other than optical fiber is used, it is likely that the opportunity to use newer technologies will be lost. On the other hand, some consideration must be given to the effort to improve metallic transmission media. Higher transmission speeds and reduced bit errors are becoming a possibility on copper and twisted pair transmission media.

Finally, the network architecture chosen, in terms of its logical and physical configuration, will have implications for future migration possibilities. If a physical star architecture is used, evolution to future technologies using centralized management and control will be simple. On the other hand, a physical ring architecture would not allow for an easy transition to a centralized management and control architecture. In this case, it is most likely that additional cabling would be required. In summary, there is risk in choosing one network technology, transmission medium and topology over another. In order to minimize the risk of having to completely replace a network in the future, consideration should be given to future needs and potential replacement technologies.

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[14] In the author's opinion, the use of fiber optics as a transmission medium will become almost universal because it provides unprecedented bandwidth and the lowest bit error rates.

The second area of risk involves the amount of vulnerability a particular technology brings to a system. Vulnerability in telecommunication networks and computer networks is dependent on several factors. First, the topology a particular technology employs can increase or decrease the vulnerability to system failure. In a star architecture, failure of one of the nodes will not affect the other nodes but if the central node (or switch) fails the entire network is ineffective. FDDI is designed so that failure of a network node results in a self-healing mechanism where the network reconfigures itself to bypass the failed node. Vulnerability to unauthorized access is another factor that should be considered.

Finally, in an increasingly joint and coalition oriented defense posture, the issue of incompatibility is a risk that must be minimized. To reach the ultimate state of compatibility, the entire DOD and the United States' potential Allies would have to all agree on what technologies and architectures to use in the designing of C3 systems. This is highly unlikely and a more realistic approach should be followed. In the assessment of technologies the degree to which standards are followed should be a prime consideration. If the bulk of systems employ "open system" technology, interoperability problems can be diminished.

c. *Subset of Alternatives*

After trade-off and risk analysis have been conducted, a smaller set of possible scenarios and network architectures results. By eliminating those alternatives which introduce too much risk, the most practical solutions are considered for final selection. In addition, trade-off analysis results in a subset of solutions which are most effective or feasible for any two given parameters (i.e. performance as a function of types of transmission media used). The final subset of scenarios and network architectures should be reviewed to ensure that the TLSRs and TLWRs established in the requirements phase are met. In addition, the potential solutions must satisfy any additional constraints placed on the C3 system.

4. Summary

In summary, the first step is to conduct a screening of telecommunications and networking technologies which are possible solutions for the physical implementation of a C3 systems. The unfeasible or inappropriate alternatives are eliminated from further review. From the pool of screened technologies, a set of scenarios and network architectures are developed which provide solutions for physical architectures. Trade-off and risk analysis is conducted with respect to these scenarios and architectures and results in a smaller subset of alternatives. This step is needed to restrict the range of possibilities to a manageable size. A final review of the scenarios and network architectures ensures that TLSRs and TLWRs are satisfied and that any additional constraints are accounted for. With the resulting scenarios and network architectures, a cost and performance analysis can be conducted to assist in reaching a final decision on the physical architecture.

D. EVALUATION CRITERIA AND PERFORMANCE ANALYSIS

The criteria discussed here are only a sample of possible factors which have potential implications for the overall performance of a system. The discussion presented below focuses on some of the most important considerations in telecommunication and networking technology today. In addition, the discussions in Chapter IV and V present background information on potential performance problems and issues. Prior to using this heuristic a review of the telecommunications and networking technologies is recommended in order to gain an understanding of the current situation and status of technologies (to be familiar with the most current problems and issues).

1. Bit Error Rate and Information Accuracy

This is largely a function of the transmission media and hardware used in a system. Metallic transmission media typically have higher data rates than optical fiber. In addition, the introduction of satellite links in any given transmission path is likely to increase the bit error rate. Furthermore, bit errors generally occur in bursts over satellite channels which changes the environment in which error control must be handled. If given transmission path involves large distances, it is likely that numerous legs will be traveled. This results in the transfer of information through many different switches or network nodes; more than is required in point-to-point transmission. If the highest level of information accuracy is required, then high bit error rates cannot be tolerated. On the other hand, if a greater degree of bit errors can be accepted, then which transmission media to use is not such an issue.

Information accuracy must be regarded in terms of the mission and objective that the C3 system is due to support. For example, if a C3 system is being designed to support ground warfare, then large amounts of imagery is usually involved and this implies a particular level of information accuracy. On the other hand, a C3 system designed to support voice transmission only, can tolerate a different degree of information accuracy. Therefore, when comparing scenarios and their given network architecture, bit error rates and the resulting information accuracy should be considered in light of the mission and system objective at hand.

2. System Efficiency in Terms of Data Overhead and Total Frame Size

As discussed in Chapter IV and V, telecommunications and networking technologies segment information into various different formats and use different amounts of overhead to achieve routing, error and flow control processing. Some formats are better suited to certain types of traffic. For instance, data traffic does not necessarily need timing synchronization like voice traffic. Therefore, data traffic will not require the extra overhead required to provide for the function of synchronization.

In the case of a C3 system designed for support of ground ops requiring transfer of large data files and some voice traffic, network architectures should aim to transmit the data traffic in as efficient as a manner as possible. Because the voice traffic requires synchronization, it will drive requirements for processing overhead. Depending on the potential amount of data in this scenario, it may be more efficient to use different technologies for the voice and data traffic. It is in this context that the alternative scenarios and network architectures should be considered.

3. Scalability

There are two factors of concern here. First, most network technologies have a limit to the number of network nodes they can support as well as the maximum distances which can be covered. Both of these limits have potential implications for the scalability of a particular network architecture. This could be thought of as a "room to grow" issue. C3 systems are designed to support a given number of nodes but some degree of network growth must be possible to cover any change in requirements or mission.

The second factor involved in scalability is the degree to which the available bandwidth of a system can be scalable to the various needs of users. For instance, FDDI technology requires all nodes on the network to use the transmission speed of 100 Mbps. Therefore all nodes must use network interface cards that support that particular transmission rate. Other technologies such as ATM, Ethernet and Token passing support transmission rates which correspond to the user's need at any particular time. It is obvious that scalable technologies can be more responsive to unanticipated changes in system requirements.

4. Flexibility

The flexibility of a system includes the degree to which it allows for mobility and how well it can adapt to changing requirements. This factor is particularly important in today's military posture. Scenarios requiring C3 support are not as straightforward as in the Cold War era. C3 systems must be able to meet the needs of c[illegible]s and limited warfare in any area of the world (INCA, 1993, introduction p. 2). Furthermore, the flexibility of a system in meeting unanticipated requirements will increase the range of scenarios over which it can support command and control. This is not to say that a system should or can be designed to support many different scenarios. This is not an affordable option. However, by implementing technology which has some degree of flexibility a wider range of futures have the potential for effective C3 support.

5. Status of Standardization and Technology Maturity level

Technologies which have been in the marketplace and previously implemented by DOD generally have known performance levels. Furthermore, the degree to which they are standardized and non-proprietary is known. This further affects the success of interoperability. With new and emerging technologies, standardization is not necessarily complete (as shown in Chapters IV and V).

6. Commercial Acceptance and Conformance to Standards

The commercial sector is not bound to the implementation of standards within products manufactured by its vendors. But certainly the degree to which vendor's products conform to standards has a direct bearing on the market share they will hold. Large organizations may not be concerned with proprietary solutions because equipment within the establishment will usually be from the same vendor and therefore interoperable. On the other hand, DOD and smaller organizations generally look for equipment which follows standards. Commercial acceptance of a standard affects the amount of standard/uniform implementations and minimizes DOD funding required in acquisition costs.

7. Ease of Integration with Other Technologies

As stated earlier, today's military needs to be able to adjust to a dynamic environment. This includes the ability to integrate various technologies used within a system. Furthermore, in case unanticipated requirements develop, the ability to makes changes to a system is an important factor. These changes may entail use of a different technology or may call for additional interfaces with other C3 systems (which may use a different technology).

E. COST ANALYSIS

Cost analysis is conducted to support decisions and identifies the economic consequences of product and process alternatives (DOD MIL-STD-499B, 1992, p. 20). Cost information is collected in these type of analyses and is used in system cost effectiveness and trade-off studies. For purposes of this thesis, it is assumed that cost data has been collected. Furthermore, the system engineering decision problem has established whether the C3 system will be designed to cost for a given level of performance or designed to maximize performance with an established maximum life cycle cost.

1. Life Cycle Costs (LCC) and Its Components

LCCs refer to all the costs associated with a system over its life cycle (which is usually defined in fiscal years). The following outlines the components of total LCC:

- Research and development cost: initial planning; market analysis; feasibility studies; product research; engineering design; design documentation; software; test and evaluation of engineering models; and associated management functions.

- Production and construction cost: industrial engineering and operations analysis; manufacturing (fabrication, assembly, and test); process development, production operations, quality control, and initial logistic support requirements (i.e., initial customer support, manufacture of spare parts, the production of test and support equipment).
- Operation and support cost: consumer or user operations of the system in the field, product distribution, sustaining logistic support throughout the system life cycle.
- Retirement and disposal cost: disposal of nonrepairable items throughout the life cycle, system retirement, material recycling and applicable logistics support.

(Blanchard and Fabrycky, 1990, p. 504)

For each C3 system alternative, LCCs are estimated and determined based on the collection of cost data for all the LCC components. Several methods are used for cost estimation and they include: (1) the analogy method; (2) the engineering method (bottom-up approach); (3) the parametric method (top-down approach); and (4) the extrapolation method (Hoviak, T., H., 1992). The author assumes that estimation of LCCs for each of the C3 system alternative has been completed[15].

2. Potential Risk of Each Component of LCC

In addition to the determination of estimated LCCs for each alternative, analysis of the risks involved in an alternative's LCC should be conducted. By examining the potential cost risks for a particular technology, a better understanding of the implications for each alternative can be gained. Risks

[15] Additional information on cost estimation can be found in Blanchard and Fabrycky's *System Engineering and Analysis.*

involving cost can include such things as uncertainty in cost estimates, the possibility of unanticipated additional costs, DOD budget uncertainties and slow growth in commercial sector for a given technology. Uncertainty in a cost estimate may be a factor of how new a technology is or the lack of use in existing systems (which can provide a baseline estimate). For each of the cost components, a brief discussion of some potential risk areas is outlined.

Research and development (R&D) costs for C3 systems using telecommunications and networking technology will generally be borne by the commercial sector. In particular, ATM technology currently is the focus of much attention by the commercial sector. A large degree of financial commitment has been made by vendors to ensure the success of ATM. Evidence of this is seen in the growth of the ATM Forum. Furthermore, numerous vendors have sponsored testbed efforts to demonstrate the use and interoperability of ATM products (discussed in Chapter IV). Other technologies such as Ethernet and FDDI for instance, have been available on the commercial market for some time and the bulk of their R&D costs have been invested already.

In addition to R&D costs borne by the commercial sector, some research on the part of DOD is required in the implementation and integration of ATM. Current efforts by several DOD agencies (see Chapter IV) is being conducted to research the feasibility of ATM in tactical environments and over satellites. Even with these efforts, R&D costs will play a role in the development of C3 systems in order to analyze the feasibility of specific utilization and design issues with respect to ATM. Because of limited use of ATM in the commercial and DOD sector, historical cost estimates are minimal. As a result, there is some uncertainty in the potential research costs for the integration of ATM with existing telecommunications and networking technology.

Production and construction cost risks will generally be borne by the commercial sector. Most of the telecommunications and networking technology is bought "off the shelf" and, therefore, DOD avoids the program management aspects of production and construction costing and control. Yet, some additional costs may be incurred by the military in cases where NDI items require modification to support DOD requirements. In cases where major modifications are required, additional costs may be unbounded by the risk that modifications require further changes to ensure that the system operates as required.

Operations and support costs for the newest telecommunications and networking technologies (i.e., ATM and frame relay) is an area that is somewhat new to DOD. Certainly support for C3 communications networks is not new to the military but network management on a global scale is a different story. Support for networks using ATM will be required across greater distances and involve more networks nodes than ever before. The seamless and global connectivity that will be possible with ATM will demand a greater degree of network management than DOD has supported ever before. Therefore, the costs involved in operating C3 systems with such a capability are unfamiliar and may range greatly in cost.

Retirement and disposal costs for C3 systems are unlike large scale weapon systems in that the former is composed of many more individual parts capable of use on their own and the later tends to consist of parts built to be used in a system, not on their own. Since C3 systems tend to contain reusable parts (particularly telecommunication oriented systems), the retirement and material recycling costs will not be as large. If the majority of transmission media is copper, future reuse may not be as likely as if fiber optical cable is used. Therefore, the cost of retirement and disposal for the transmission media of a system has some dependency on the future requirements of other technologies.

G. OVERALL EVALUATION OF SCENARIOS AND NETWORK ARCHITECTURES

1. Introduction

Following the performance and cost analysis of a given set of alternatives, a method is needed to combine these findings to choose the best solution. This section presents such a method using the AHP process (the specific details of the AHP process are presented in Appendix B). By combining the results of the performance and cost analyzes, a single measure or priority ranking is created which results in an "optimal" solution.

As stated in the chapter introduction, in formulating the system engineering decision problem one of two overall objectives will have been established: (1) maximize performance of the C3 system while holding cost below a maximum level; or (2) minimize cost of the C3 system while holding performance at a level which satisfies TLWRs and TLSRs. Given this, the individual importance of performance and cost must be established with respect to the overall objective. Within that context, the scenario and network architecture is chosen which best supports the objective. As discussed in the previous sections, cost and performance each have sub-criteria which contribute to a system's total performance and cost. The method used to integrate these sub-criteria into the system criteria of overall performance and LCC cost is AHP.

In addition to the performance and cost analysis of each alternative, analysis of the expected utility of the alternative scenarios and the supporting network architectures is conducted. This can be thought of as the value a specific scenario and network architecture may bring to the C3 system. The term "value" should not be confused with monetary value but with a more subjective concept uniquely determined by individuals (Hill, P., H., 1979, p. 108). Realistically, a system can be built to support only one set of performance requirements and corresponding scenario. Therefore, the scenario and supporting network architecture bringing the most utility should be used in the physical architecture of the C3 system. Again, AHP is used to gather expert judgments for the subjective measure of utility.

2. First Step: Establish Priorities of Alternative Scenarios and Network Architectures

In order to use the AHP process, the decision problem must be organized into a hierarchy. Figure 17 details the hierarchy of this specific problem. The sub-criteria of cost and performance shown in Level three

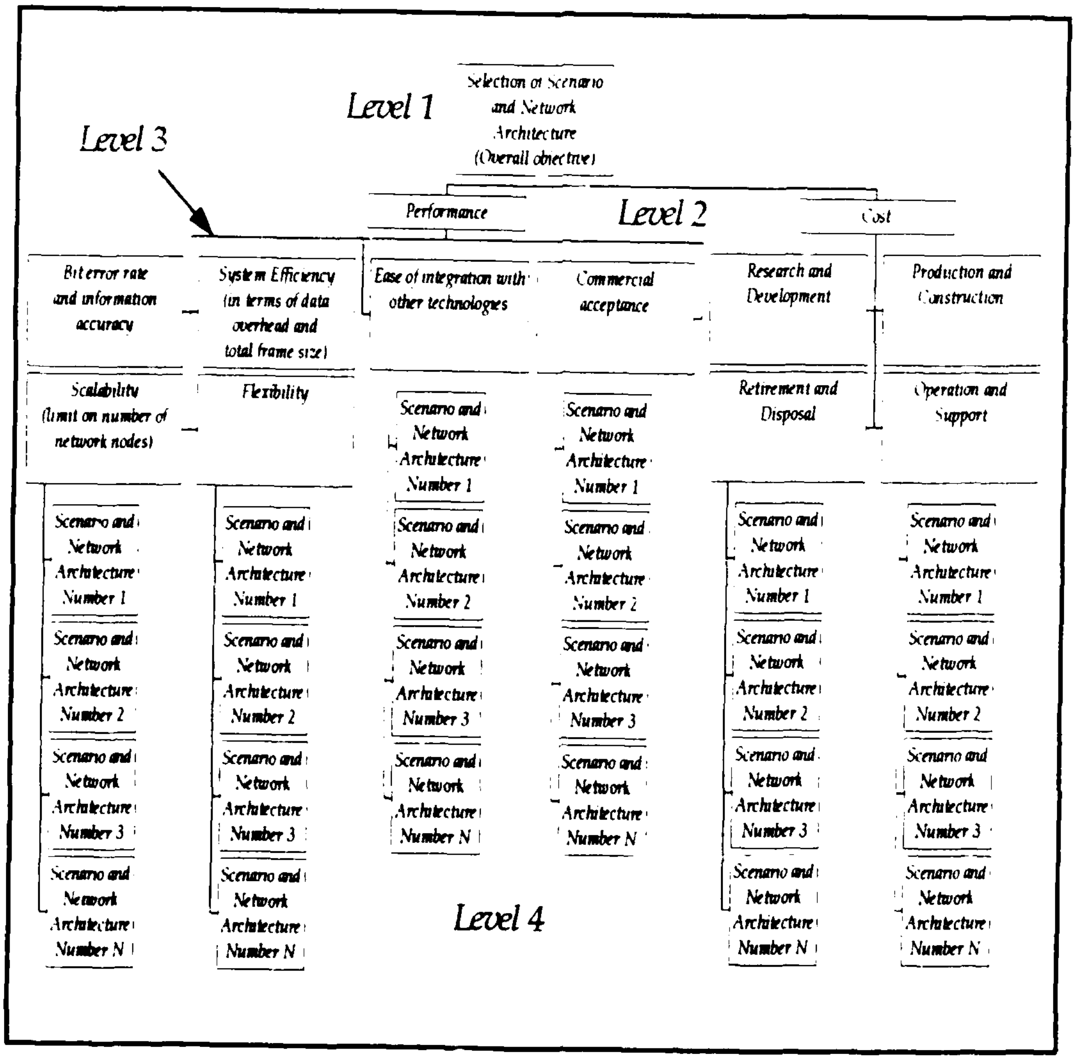

Figure 17. The hierarchy of decision problem.

correspond to the performance and cost analysis discussed earlier in the chapter. Level four consists of the scenarios and corresponding network architectures (alternative solutions to the decision problem in Level 1). The number of alternative solutions considered is dependent on the result of trade-off and risk analysis conducted earlier.

As shown in Appendix B, priority vectors are established for each level of the hierarchy. These priority vectors are developed from the data collected from the pairwise comparisons made by the decision makers. First, each one of the alternatives (Level 4) is prioritized with respect to each and every one of the sub-criteria (Level 3). Next each one of the sub-criteria (Level 3) are prioritized with respect to the objectives of performance and cost (Level 3). Third, the cost and performance criteria (Level 2) are prioritized with regards to the overall objective of the decision problem (Level 1). Figure 18 provides the pairwise comparison scales that should be used at each level of the hierarchy. Once the priority vectors have been established for each level of the hierarchy, they are used in the determining the overall priority of the alternatives.

3. Second Step: Establish Utility of the Alternative Scenarios and Network Architectures

In this step, expert decision makers take into account several factors: (1) how dynamic is the world?; (2) how dynamic or quickly is technology evolving?; and (3) what is likely to happen to force levels and composition based on the "downsizing" of force structure?. Usually decision makers involved in the process of planning for DOD will have an opinion (which is subjective) on the utility that entities will bring to a given system or scenario. These subjective "measurements" are collected by using AHP and judgments are made to establish some order of expected utility. Figure 19 provides a schematic of the decision problem involved at this step. The pairwise comparison scale is also included.

Pairwise Comparison Scale for Level 4:	Pairwise Comparison Scale for Level 3:	Pairwise Comparison Scale for Level 2:
1: Scenario and Network Architecture X and Y contribute equally to Level 3 objective. **3**: Scenario and Network Architecture X contributes slightly more than Scenario and Network Architecture Y to the Level 3 objective. **5**: Scenario and Network Architecture X contributes more than Scenario and Network Architecture Y to the Level 3 objective. **7**: Scenario and Network Architecture X contributes much more than Scenario and Network Architecture Y to the Level 3 objective. **9**: Scenario and Network Architecture X contributes the most to the Level 3 objective versus Scenario and Network Architecture Y. **2, 4, 6, 8**: Intermediate values to those listed above.	**1**: Performance criterion X and Performance criterion Y contribute equally to Level 2 objective. **3**: Performance criterion X contributes slightly more than Performance criterion Y to the Level 2 objective. **5**: Performance criterion X contributes more than Performance criterion Y to the Level 2 objective. **7**: Performance criterion X contributes much more than Performance criterion Y to the Level 2 objective. **9**: Performance criterion X contributes the most to the Level 2 objective versus Performance criterion Y. **2, 4, 6, 8**: Intermediate values to those listed above.	**1**: Performance and Cost are equally valued with respect to the overall objective. **3**: Performance is valued slightly more than Cost (Performance) with respect to the overall objective. **5**: Performance (Cost) is valued more than Cost (Performance) with respect to the overall objective. **7**: Performance (Cost) is valued much more than Cost (Performance) with respect to the overall objective. **9**: Performance (Cost) is valued the most in the overall objective. **2, 4, 6, 8**: Intermediate values to those listed above.

Figure 18. Pairwise comparison scales to be used at each level of hierarchy.

4. Final Ranking of Alternatives

Once the priority of all the alternatives is established (with respect to performance and cost criterion), their final rankings are weighted by the utility priority vector found in the previous step. An example is provided for illustration. Suppose that alternative one has an overall rank of .12 (with respect

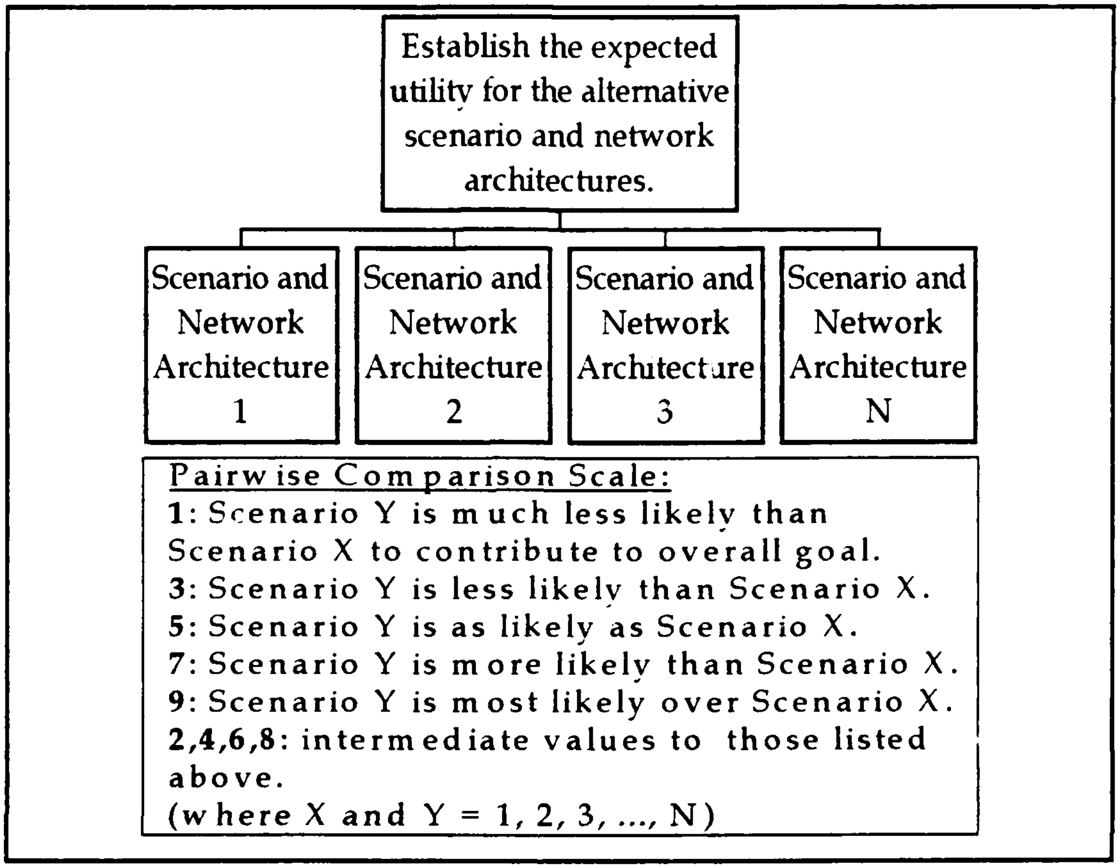

Figure 19. Hierarchy for establishing expected utility of alternatives.

to performance and cost criteria). The expected utility of scenario one was judged to be .56 and therefore its final ranking equals (.12) x (.56) or .0672. The final ranking is calculated for each alternative following this manner. The scenario and network architecture with the highest numerical ranking is the preferred solution to the decision problem.

H. SUMMARY

The framework presented above included a focus on the current issues and implementation factors that are currently important in the implementation of ATM. In summary a more generic framework is provided as a step by step guide or heuristic:

- *First step*: screen the potential telecommunications and networking technologies to eliminate those that are not feasible or those that do not meet the TLSRs and TLWRs.
- *Second step*: ensure that telecommunication and networking technologies (or services) meet unique military requirements or constraints.
- *Third step*: develop scenarios and network architectures based on C3 system requirements and their functional architectures.
- *Fourth step*: conduct trade-off and risk analysis to narrow down the set of possible scenarios and network architectures.
- *Fifth step*: ensure that scenarios and network architectures meet the TLSRs and TLWRs.
- *Sixth step*: to gain an understanding of the current situation and status, conduct a review of telecommunication and networking technologies.
- *Seventh step*: conduct performance and cost analysis for each scenario and network architecture. Particular attention should be paid to background information gathered in step six.

Eighth step: develop a hierarchy for the overall objective of selecting a scenario and network architecture. Cost and performance are level two criteria. Sub-criteria of cost are the four components of life cycle costs. Particular implementation factors for telecommunications and networking technologies found in step six constitute sub-criteria of performance. Additional performance criteria should also be included as sub-criteria. Figure 20 is provided as a generic hierarchy.

- *Ninth step*: use the AHP process to determine the priorities of the alternatives (scenarios and network architectures) established in the lowest level of the hierarchy.
- *Tenth step*: using AHP, establish a priority ranking for the expected utility of each of the scenarios considered to be an alternative.

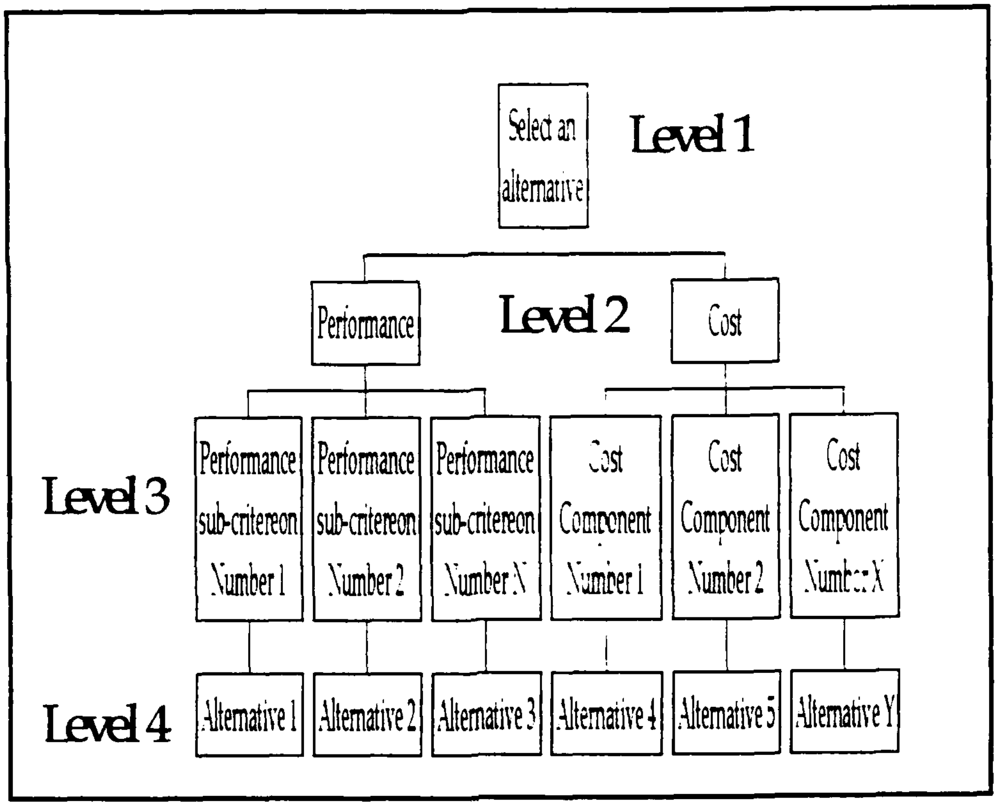

Figure 20. Generic hierarchy.

- *Eleventh step*: using the priorities found in step ten, multiply the priorities found in step nine these numbers. This results in the overall ranking of the alternatives.
- *Twelfth step*: choose the alternative with the highest priority ranking as the preferred scenario and network architecture for implementation.

VII. CONCLUSION

A. RECOMMENDATIONS

1. Use of Alternative Decision Analysis Methods

For several reasons, methods other than AHP may warrant consideration. First, there is no one "right" way to conduct decision analysis. Therefore, a group of decision makers may use a particular method that is more amenable than the alternative decision analysis methods. Second, the willingness or unwillingness of decision makers to place probabilities on possible futures influences which type of decision analysis method can be utilized. Third, a disadvantage of the AHP process warrants consideration.

A disadvantage of AHP that some consider controversial is the phenomenon of rank reversal. This occurs when the ranking of alternatives, determined by AHP, are altered by the addition of another alternative. One critic argues that this is simply a symptom of a much larger problem; that the rankings arrived at by the AHP methodology are arbitrary. It is argued that arbitrary results occur when the principle of hierarchic composition is assumed (i.e., the weights on the criteria do not depend on the alternatives under consideration). Several solutions have been suggested to remedy this situation and are relatively simple to implement. (Dyer, J. S., 1990, pp. 257)

As detailed in Chapter VI, the ATM implementation decision problem can be organized hierarchically and solved using AHP. There are methods of decision analysis other than AHP which can be used to help structure a given decision problem. In cases where decision makers are willing to make judgments about the future (decisions under risk) the following decision analysis methods can be used:

- The *aspiration level criterion* compares alternatives based on a required level of success or performance objective. The alternative which maximizes the probability of reaching the desired level of success or performance is selected.
- *The expected utility criterion* compares alternatives based on their expected "value" if implemented. This method requires decision makers to calculate or determine the expected value of each alternative being considered.

(Blanchard and Fabrycky., 1990, pp. 133-136)

In some situations decision makers may be unwilling or consider it inappropriate to assign probabilities to the numerous futures possible for a given situation. Decisions made under these circumstances are considered "decisions under uncertainty." Several criteria can be used for this type of decision making including the *Laplace* criterion; *maximin* and *maximax* criteria; and the *Hurwicz* criterion. (Blanchard and Fabrycky, 1990, pp. 137-139)

2. Review of Technology

As mentioned previously, it is recommended that a review of technologies be conducted prior to implementing the framework presented in Chapter VI. New developments occur almost daily in the field of telecommunications and networking; and the status of technologies can dramatically change over a short period of time. While ATM is the newest telecommunications and networking technology available, competing technologies are emerging (e.g., Fibre Channel and Fast Ethernet) and should also be considered.

Because of ATM's immaturity many technological aspects are still being studied. Furthermore, ATM is not fully standardized and some of those standards currently published require further specification. Consideration of the unresolved factors discussed in Chapter IV should particularly be of concern in conducting a technological review. DOD and many academic organizations including vendors are actively participating in research efforts concerning ATM. The results of these efforts can be found in many different references (see Chapter II).

3. Estimations of Costs

Because ATM is such a new technology, a relatively limited number of products are available in the commercial sector. Furthermore, the current hardware and software implementations of ATM are not mature yet. Equipment that fully supports ATM, as it has been envisioned and touted, is slow in coming to the market. For these reasons, estimating life cycle costs for systems using ATM may be difficult. Studies of the commercial market and availability of ATM equipment should place considerable emphasis on the risk involved in cost estimating for system alternatives.

4. Use of a Heuristic in Decision Making

Decisions regarding information technology and its implementation are not necessarily straightforward. Generally they involve qualitative and quantitative aspects of performance and other criteria as needed. Because qualitative factors are hard to measure, there is some degree of subjectivity involved in making choices about information technology. In order to structure a problem and limit the amount of bias introduced, the use of an effective heuristic (as developed in Chapter VII) is recommended. An additional benefit to the use of a heuristic is that simply by detailing the decision process, decision makers better understand all the aspects of the decision at hand.

B. FURTHER RESEARCH

1. Development of Network Architectures

The framework introduced in Chapter VII includes a step in the decision process for developing network architectures. These network architectures are characterized by the mix of technologies, transmission media, and the topologies used. In terms of the framework, each network architecture supports a given scenario and its top level system requirements. Further research and development of specific network architectures in support of C3 top level system requirements would be beneficial in future implementation of ATM technology.

2. Specific Applications of ATM

Several DOD programs currently are scheduled to incorporate ATM technology into the physical infrastructures of C3 systems. In addition to these DOD applications, the capabilities that ATM promise have far reaching possibilities for expanding the C3 realm. Analysis and research into specific uses of ATM for support of C3 functions would be effective in advancing the efforts to bring information to the warfighter.

3. Modeling of ATM Networks

The potential success of ATM would benefit from additional efforts in the simulation and modeling of ATM networks. As demonstrated in the Gulf War, the rapid transfer of large amounts of information is a basic requirement of any C3 system. Since military requirements and contingencies are dynamic in today's world, systems need to be able to support a large range of circumstances. For these two reasons, simulation and modeling of networks with numerous degrees of traffic or information loading will benefit the design of C3 systems.

APPENDIX A: THE ANALYTIC HIERARCHY PROCESS

This appendix provides an introduction to the Analytic Hierarchy process (AHP) developed by Thomas L. Saaty in 1977. His book, "The Analytic Hierarchy Process" provides and in-depth development of the process and also includes examples of its application. AHP provides a method for including and measuring all important tangible and intangible, quantitatively measurable, and qualitative factors (Saaty, T., L., 1980, p. 1). Furthermore, it allows for the handling of differences in opinion and for conflicts which occur in the real world of decision making. AHP can be used in many different applications ranging from the social sciences to systems engineering. The cognitive processing limitations of humans makes decision problems with numerous criteria difficult to follow. AHP provides a framework in which complex or multi-criteria problems can be structured to assist in overcoming cognitive limitations.

The method involves four steps: (1) setting up the decision in the form of a hierarchy; (2) collecting input data by pairwise comparison of decision elements; (3) using the "eigenvalue" method to estimate the relative weights of decision elements; and (4) aggregating the relative weights of the decision elements to arrive at an outcome (Zahedi, F., 1986, p. 96). The first step involves the decomposition of the decision problem into a hierarchy. Generally, the overall goal or decision is placed at the top of the hierarchy. Below the main objective are criteria which contribute to the overall decision or goal. Depending on the complexity of the problem, lower levels may be required which further detail aspects of the criteria. The very last level of the hierarchy contains the alternatives or choices. Figure 1 is an example hierarchy and will be referenced throughout this Appendix (Gass, S. I., 1985, p. 364).

Step two uses human judgment to make assessments between two entities at each level of the hierarchy. This is called pairwise comparison. The scale is used in the comparison and can be called the pairwise comparison scale . It is

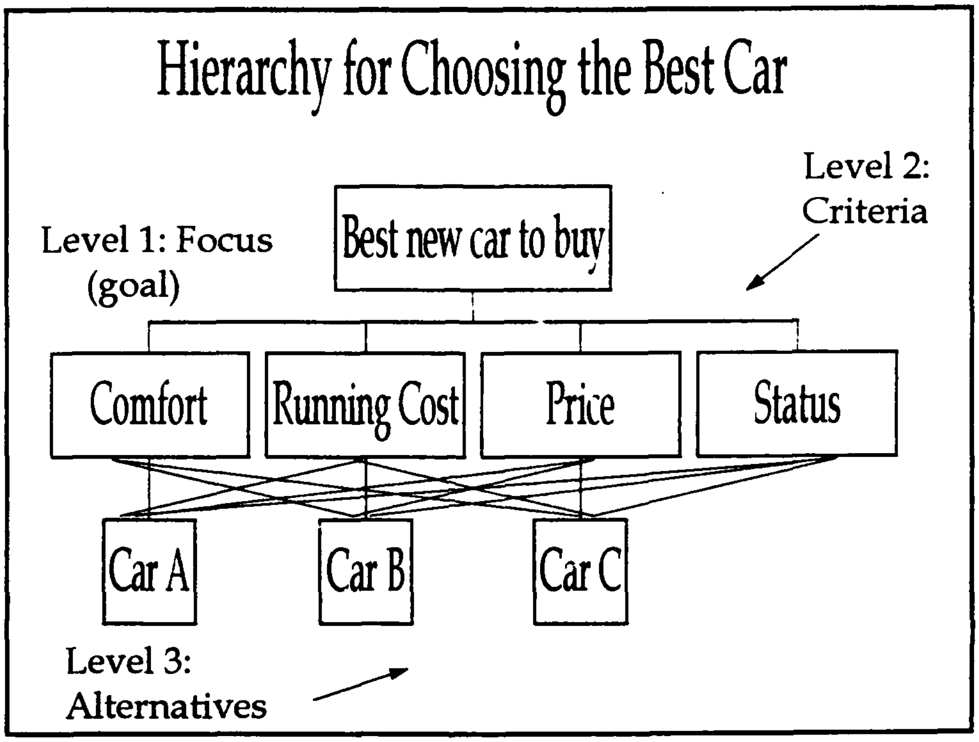

Figure 1. An example hierarchy.

used to "measure" the relative preference or importance of one entity over another. The recommended range for this scale is one to nine and an example is shown in Table 1 (Saaty, T., L., 1980, p. 54). It should be noted that the verbage used in a pairwise comparison scale need not be exactly as shown in the table. Scales can be modified to fit the decision problem as appropriate. For example, in assessing the likelihood of decision elements at a particular level, each point on the scale would represent some degree of likelihood.

The data for the decision problem results from the pairwise comparisons for each level of the hierarchy. For each level, a matrix is created using the elements at that particular level. Comparisons are conducted with respect to the next higher level or criterion. An example is presented in Figure 2 for purposes of illustration and refers to the hierarchy presented in Figure 1.

Looking at the criteria in level 2, each element is compared to the all the other criteria. As illustrated in Figure 2, price compared to running cost is considered to be of absolute importance (9) (Gass, S. I., 1985, p. 365). When running cost is compared to price the reciprocal (the inverse) is entered in the matrix. When an element is compared against itself it must be considered of equal importance or preference.

TABLE 1. Pairwise Comparison Scale

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another.
5	Essential or strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong or demonstrated importance	An activity is favored very strongly over another.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between adjacent scale values.	When compromise is needed.

Decision to buy a new car	Price	Running Cost	Comfort	Status	p_i
Price	1	3	7	8	0.586
Running Cost	1/3	1	5	5	0.277
Comfort	1/7	1/5	1	3	0.088
Status	1/8	1/5	1/3	1	0.049

Figure 2. Level 2 comparisons.

Once all the pairwise comparison matrices have been developed, the relative weights of the decision elements are calculated for each level. This results in priority vectors for each level of the hierarchy (see Figure 2, p_i is priority vector for criteria) and they reflect the order in which specific criteria relate to the overall goal or decision objective. Saaty suggests four methods for calculating these vectors and they are summarized here in order of accuracy:

- Sum the elements in each row and normalize by dividing each sum by the total of all the sums, thus the results add up to one. The first entry of the resulting vector is the priority of the first activity; the second of the second activity and so on.
- Take the sum of the elements in each column and form the reciprocals of these sums. To normalize so that these numbers add to unity, divide each reciprocal by the sum of the reciprocals.
- Divide the elements of each column by the sum of that column (i.e., normalize that column) and then add the elements in each resulting row and divide this sum by the number of elements in the row. This is a process of averaging over the normalized columns.
- Multiply the n elements in each row and take the nth root. Normalized the resulting numbers.

(Saaty, T., L., 1980, p. 19).

Included in the second step is a process to check the consistency of judgments made in developing the pairwise comparison matrices. Saaty refers to consistency not only as the traditional requirement of the transitivity of preferences but also the actual intensity with which preferences are expressed transit through the sequence of elements in the comparison (Saaty, T., L., 1980, p. 7). Generally speaking, consistency is more of an issue in decision problems that are more complex (many different criteria). The mathematical details for calculation of the consistency index can be found in Saaty's book (Saaty, T., L.,1980, p. 179).

The final step in the AHP process is the calculation of the overall priority ranking of the alternatives. One way to view this is to think of each criterion or element as a weight which reflects its importance to overall goal or decision objective. This step is depicted in Figure 3. Once the overall priorities are calculated, the highest ranking alternative is chosen as the solution to the overall objective or decision problem. In the car selection example, Car B would be chosen with a priority of 0.442.

Criteria	Price	Running Cost	Comfort	Status	Composite hierarchical priorities (p_i)
Level 2 Priorities	0.586	0.277	0.088	0.049	
Alternatives (Level 3 alternatives)					
Car A	0.540	0.106	0.627	0.188	0.410
Car B	0.297	0.744	0.280	0.731	0.442
Car C	0.163	0.150	0.093	0.018	0.149

These are the priority vectors for each alternative with respect to the criteria.

Composite priority for Car A = 0.540(0.586) + 0.106(0.277) + 0.627(0.088) + 0.188(0.049) = 0.410

Composite priority for Car B = 0.297(0.586) + 0.744(0.277) + 0.280(0.088) + 0.731(0.049) + 0.442

Composite priority for Car C = 0.163(0.586) + 0.150(0.277) + 0.093(0.088) + 0.018(0.049) = 0.149

Figure 3. Calculation of Overall Priority Ranking.

In addition to the manual AHP method presented above, a software package is available for use on personal computers. Produced by Decision Support Software, Expert Choice provides an interactive method of collecting information concerning the decision problem as well as all the details of pairwise comparison. In addition to Saaty's book several periodicals contain articles which provide further discussion and application of AHP:

- Moshe Zviran presents a comprehensive methodology for computer family selection (Zviran, M., 1993, pp. 17-26).
- Ami Arbel and Abraham Seidmann provide a selection methodology for choosing a computer for process control and data acquisition (Arbel, A., and Seidmann, A., 1984, pp. 73-80).
- Fatemeh Zahedi provides a review of AHP and a survey of its applications (Zahedi, F., 1986, pp. 96-108).

APPENDIX B: CCITT RECOMMENDATIONS ON BROADBAND ISDN

Number	Title	Description
I.113 April 1991	Vocabulary of terms for Broadband Aspects of ISDN	Defines terms basic to the understanding of B-ISDN
I.121 April 1991	Broadband Aspects of ISDN	Covers the basic principles of broadband aspects of ISDN.
I.150 April 1991	B-ISDN ATM Functional Characteristics	Describes functions of the B-ISDN ATM Layer.
I.211 April 1991	B-ISDN Service Aspects	Classifies services and provides guidelines for development of detailed B-ISDN service recommendations
I.311 April 1991	B-ISDN General Network Aspects	Networking techniques, signaling principles, traffic control, resource management. Defines ATM virtual section, virtual path, and virtual channel concepts.
I.321 April 1991	B-ISDN Protocol Reference Model and its Application	Expands Narrowband ISDN reference model to cover B-ISDN.
I.327 April 1991	B-ISDN Network Functional Architecture	Expands the narrowband ISDN functional architecture to include B-ISDN.
I.356 July 1993	B-ISDN Layer Cell Performance	Defines the performance parameters and objectives for the ATM layer.

I.361 June 1992	BISDN ATM Layer Specification	ATM cell specification, coding, and header formats. Describes ATM protocol procedures.
I.362 June 1992	BISDN ATM Adaption Layer (AAL) Functional Description	Classifies services requiring AAL and describes the services/functions provided by layer
I.363 June 1992	B-ISDN ATM Adaption Layer Specification	Describes the interactions between the AAL and the next higher layer. Defines four AAL types.
I.363 Section 6 July 1993	same as above	Adds AAL type 5.
I.364 June 1992	Support of Broadband Connectionless Data Service on B-ISDN	Lays the groundwork for connectionless services and establishes requirements for AAL type 5.
I.371 June 1992	Traffic and Congestion control in B-ISDN	self-explanatory
I.413 April 1991	B-ISDN User-Network Interface (UNI)	Describes the reference configuration for a broadband UNI.
I.414	Overview of Recommendations on layer 1 for ISDN and BISDN customer accesses	
I.432 April 1991	BISDN User-Network Interface - Physical Layer Specification	Defines interface structures applicable to specific points identified in I.413. Describes possible physical media and error control.
I.610 April 1991	OAM Principles of B-ISDN Access	Outlines the minimal functions required to maintain broadband UNI.

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