IDA MEMORANDUM REPORT M-305

SDI BATTLE MANAGEMENT/C^3 NETWORKING TECHNOLOGY PROGRAM PLAN

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The Institute for Defense Analyses (IDA) has collected and analyzed information on network technology that is relevant to Battle Management Command, Control, and Communications (BM/C^3). This memorandum report represents a program plan that will provide the SDIO BM/C^3 directorate with administrative and technical insight into network technology.

This program plan focuses on C^3 network concepts and provides information and analysis to the SDIO to be used in formulating budget requirements for FY 1988 and beyond. Based upon analysis of network requirements and ongoing programs, recommendations have been made for research areas that should be funded, including both the continuation of current work and the initiation of new tasks. While emphasis here is on the SDIO-funded tasks, other relevant government-sponsored and commercial efforts, such as packet radio networks, also have been examined.

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PREFACE

The purpose of this memorandum report is to assist the SDIO Battle Management/ Command, Control, and Communications (BM/C^3) directorate in the development of a program plan for network technology. This memorandum report, which has been subjected to formal review, is a revision of an earlier draft program plan and incorporates changes suggested by the several reviewers.

In the future, the conduct of studies such as this one in support of the SDI Phase I program will be within the purview of the Phase One Engineering Team (POET) Network Technology Panel.

ABSTRACT

The Institute for Defense Analyses (IDA) has collected and analyzed information on network technology that is relevant to Battle Management/Command, Control, and Communications (BM/C^3). This memorandum report represents a program plan that will provide the SDIO BM/C^3 directorate with administrative and technical insight into network technology.

This program plan focuses on C^3 network concepts and provides information and analysis to the SDIO to be used in formulating budget requirements for FY 1988 and beyond. Based upon analysis of network requirements and ongoing programs, recommendations have been made for research areas that should be funded, including both the continuation of current work and the initiation of new tasks. While emphasis here is on the SDIO-funded tasks, other relevant government-sponsored and commercial efforts, such as packet radio networks, also have been examined.

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CONTENTS

EXECUTIVE SUMMARY

Given that the personnel of the SDIO BM/C^3 directorate must be fully cognizant of the technical content and programmatic issues of all of the BM/C^3-funded efforts and of related programs, a means must be devised to enable the BM/C^3 staff to access this information in a concise and timely manner. Such a means is a program plan; this document establishes such a plan for the networking technology efforts of BM/C^3.

Creating a program plan involves establishing requirements, analyzing current programs, comparing requirements with current programs, and providing guidance for future efforts. Chapter III provides network requirements for SDI BM/C^3 which are fully in support of the SDS Phase I architecture. Chapter V details the in-depth analysis performed on the FY87 networking programs, while Appendix A presents a quick reference on the status and objectives of each effort. Recommendations and guidance are found in Chapter VII. Appendix B updates accomplishments on two of the programs since the earlier draft version of this report was prepared.

The FY87 networking programs have accomplished a great deal with respect to networking algorithms and modeling. Highlights from several of these programs follow.

1. Harris Corporation, under contract to NRL, has developed, coded, and tested a backbone adaptive routing algorithm and a backbone link assignment algorithm. One particularly creative avenue Harris undertook for the SDI networking problem was the use of load-splitting in their adaptive routing algorithm. Load-splitting helps to improve the stability of the algorithm, to provide improved throughput by balancing the load on alternative routes, and to increase system robustness by finding disjoint message paths.
2. As part of a wide-ranging effort, SRI, under contract to RADC, has developed a loop-free, shortest-path routing algorithm. The advantages of this algorithm are that it is dynamic (i.e., it adjusts to abrupt topology changes), is loop-free (i.e., messages will not go around in circles), and uses only local information from neighboring nodes.
3. Harris Corporation, under contract to RADC, is developing an Internet System Model which will evaluate ground, air, and space battle management techniques for communications networks. One of the key design accomplishments of this effort is the modular construction of the system that

will allow communications networking characteristics to be "mixed and matched" according to different architectures. Of particular interest to SDI BM/C^3 is the possibility of evaluating different SDI system architectures with respect to communications networking.

Some of the technical recommendations for the communications networking efforts are briefly summarized below; expanded descriptions are found in Chapter VII.

1. Follow and support research on distributed processing currently under way. This research is addressing problems that must be faced in the SDI network management area.
2. Pursue the use of parallel processors for the implementation of network management and control functions, such as link assignment, adaptive routing, topology update, and congestion control.
3. Develop more robust distributed algorithms capable of functioning with only limited knowledge of network topology.
4. Explore the integration of network routing and reconstitution, focusing on *distributed* and *approximate* network control algorithms.
5. Encourage the development of heuristic algorithms to arrive at good networking strategies when handicapped by inconsistent or incomplete information.
6. Investigate the use of hybrid routing algorithms to exploit the advantages of different types of algorithms.

Some of the procedural recommendations for the communications networking efforts are as follows.

1. Develop a mechanism for promoting meaningful technical interchanges between contractors working on similar problems. This might take the form of workshops involving technical, not managerial, personnel.
2. Require contractors developing models and algorithms to make them compatible with a specified common simulation testbed. This would allow comparisons to be made between the models and algorithms.
3. Require all of the networking technology efforts to adhere to the SDS Phase I (baseline) architecture requirements.
4. Develop mechanisms to insert results of the network technology program into the Experimental Versions (EVs) to avoid duplication of effort and to ensure use of the best available networking techniques.

I. INTRODUCTION

A. PURPOSE

Given the intricacies of managing an enormously complex program such as the networking technology for SDI BM/C^3, a program plan is a vital tool. Ideally, a program plan provides a quick overview of and insight into the technical and administrative aspects of a given program.

The creation of a program plan for the BM/C^3 networking technology program is divided into six major steps.

1. Define networking requirements.
2. Identify and analyze the currently funded tasks.
3. Compare steps one and two.
4. Identify deficiencies between the two steps.
5. Identify programs that are not currently funded by BM/C^3 but which may contribute to the networking technology for SDI BM/C^3 and may eliminate some of the deficiencies.
6. Provide recommendations for structuring the BM/C^3 networking technology program.

A program plan is a living document that needs to be updated periodically as architectures and requirements change, as funding profiles change, and as new networking accomplishments are announced.

This memorandum represents a program plan for the BM/C^3 networking technology program. The above six steps used in creating a program plan have been performed in varying depth, based on available information and resources. Recommended changes received from reviewers of an earlier draft of this report have been incorporated.

B. BACKGROUND

The Battle Management/Command, Control and Communications (BM/C^3) directorate of the Strategic Defense Initiative Organization has two principal divisions:

technology and experimental systems. This draft memorandum concentrates on the technology portion of BM/C^3.

The objective of the BM/C^3 technology portion of the overall SDI effort is to develop the technologies needed to support responsive, reliable, survivable BM/C^3 for strategic defense. These technologies are grouped into five areas:

- Battle-management algorithms,
- C^3 network concepts,
- Processors,
- Communications,
- Software engineering.

This document focuses on C^3 network concepts and provides information and analysis to the SDIO to be used in formulating budget requirements for FY 1988 and beyond. Based upon analysis of network requirements and ongoing programs, recommendations are made for research areas that should be funded, including both the continuation of current work and the initiation of new tasks. While the emphasis here is on the SDI program, other relevant government-sponsored and commercial efforts, such as packet radio networks, are also examined in brief. Some of the design concepts being developed in such programs may be applicable to SDI; if so, the SDIO can avoid duplicating this work and concentrate its resources on areas critical to SDI that are not being addressed elsewhere.

C. DEFINITION OF NETWORKING

Because they are so highly interdependent, the SDI BM/C^3 technology areas listed above do not have clearly defined boundaries. To avoid ambiguity, the definition of networking to be used in this document is set forth below.

The SDI C^3 network consists of the collection of entities, called nodes, that must send to and/or receive from other nodes information and data together with the transmission paths, called links, used to effect this exchange of information and data. Nodes may be located at ground command posts, on aircraft, on ground-launched missiles or sensors, and on satellites in earth orbit. Corresponding links may be established using antennas, wire, coaxial cable, or optical fibers, as appropriate. The C^3 network concepts address the mathematical and logical processes and procedures that control and manage the C^3 network and its associated processors and communication links. This network provides the high-performance, fault-tolerant, secure, and survivable C^3 environment within which the battle-management algorithms function. Topics addressed as part of the C^3 network concepts include protocols and distributed control concepts as well as distributed operating systems and management of distributed data bases. These concepts are elaborated below.

First, a distinction needs to be made between networking and communications. Communications is concerned with establishing links between node pairs which have sufficient capacity, acceptably low bit-error or packet-error rates, and acceptably high resistance to unauthorized interception or insertion of data. The means of accomplishing these objectives include choice of transmission medium, multiple-access techniques, modulation and detection schemes, error-correction codes, and link-encryption techniques. To increase system robustness to jamming, data interleaving and spread-spectrum techniques may be used as well. In the terminology of the International Standards Organization's Open Systems Interconnection (OSI) architecture, communications functions occupy the physical and data-link layers. See Figure 1.

The next-higher layer in the OSI reference model is the network layer, which manages communication resources so that messages are delivered reliably, with minimum delay. A robust network is desirable so that it can function even in the event of multiple node and link failures and under heavy traffic conditions. These objectives are met through algorithms for (1) specifying the location of point-to-point links, (2) implementing adaptive routing strategies, (3) providing message flow and congestion control, and (4) updating network topology to accommodate the relative motion of nodes and hostile actions against the network, both of which result in temporary or permanent unavailability of certain network nodes and links. These communication-related issues fall in the realm of networking and are the focus of this report.

The other aspect of networks in the SDI context relates to the distributed nature of the system, which addresses problems associated with maintenance and interoperation of data bases, operating systems, and processors that exist at distinct locations but must operate in a highly coordinated, consistent fashion. Related programs are included in the descriptions of current program funding and status but are not included in the expanded discussion of networking efforts.

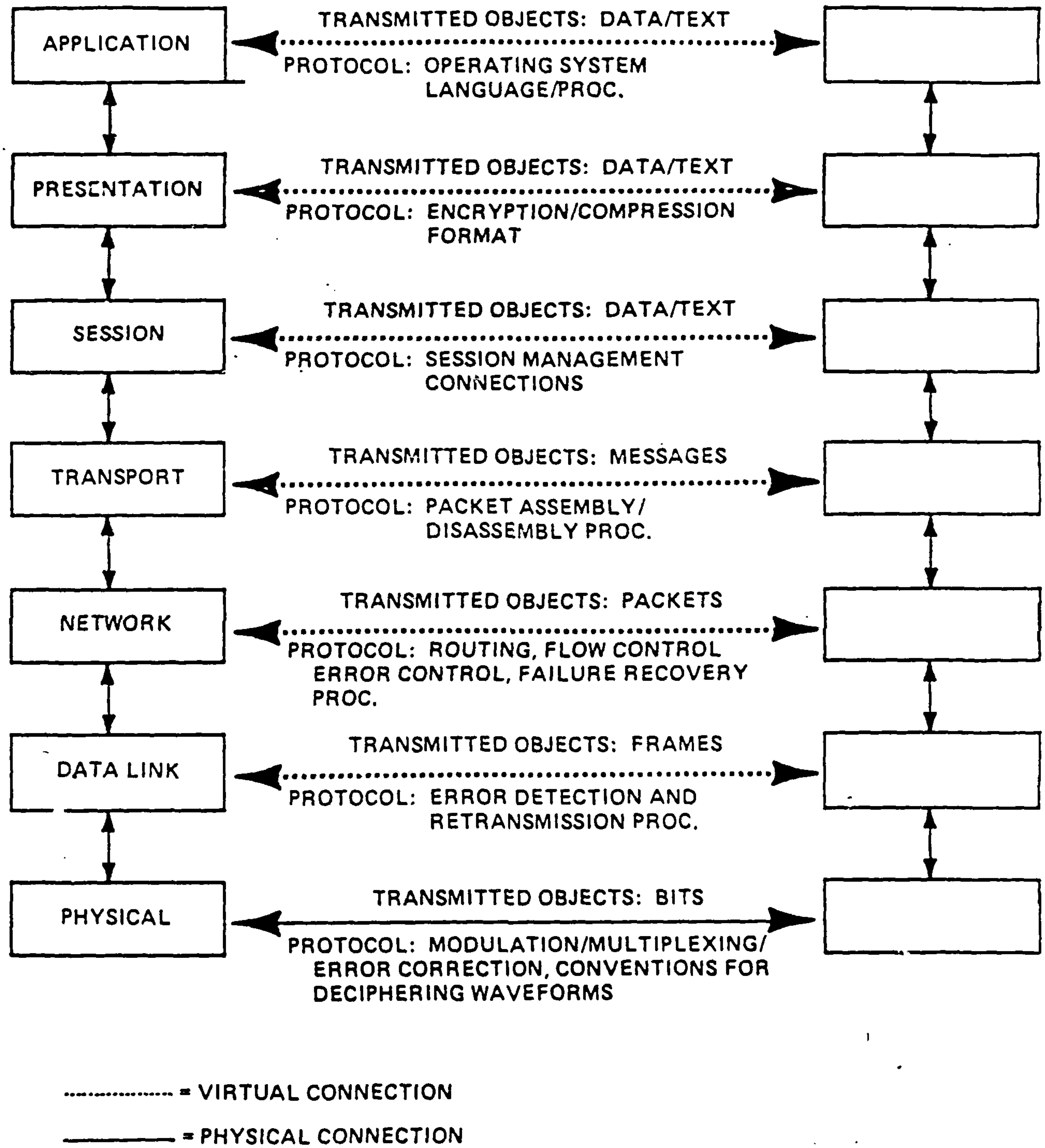

Figure 1. International Standards Organization Open System Interconnection Reference Model.

D. ORGANIZATION OF SUCCEEDING CHAPTERS

Chapter II presents the methodology used in conducting this study. The requirements that must be satisfied by the SDI network are discussed in Chapter III. A summary of the status of current SDI-funded network programs is presented in Chapter IV. The information provided includes the contracting agency, contract number and title, contractor, funding, schedules, and a list of deliverables. In addition, a brief description of contract objectives is given. In this draft document, Chapter V contains an in-depth discussion and analysis of some of the efforts summarized in Chapter IV. Critical comments are offered for each effort, including the identification of any weaknesses or errors. Chapter VI presents a discussion of non-BM/C^3 networking technology programs, both government and commercial, that share some of the complex attributes of the SDI system. Network control and operating concepts used in these other systems, though they may not be directly applicable, may be of value in designing the SDI BM/C^3 network. Finally, Chapter VII contains recommendations based upon the findings of this study. These recommendations focus on changes and refinements to the ongoing programs and on important areas that are not being investigated at present. These recommendations are intended to assist the SDIO in formulating its FY 1988 program plan by identifying areas critical to SDI that are not being funded elsewhere.

II. METHODOLOGY

The task of creating this report consisted of two major activities: information gathering and analysis. The primary sources of information on current SDI networking technology efforts were the various military services and government agencies that are administering SDIO-funded contracts. These include NRL, RADC, USASDC, and DARPA. Appropriate individuals in these organizations have been contacted and interviewed and have been requested to provide summary information on their programs, including technical descriptions, schedules, milestones, status, and a list of deliverables. In a few cases, copies of relevant documents, such as interim and final reports and copies of briefing materials from program reviews, have been provided. This information has been clarified and augmented through follow-up visits and telephone conversations.

Seven efforts funded under the BM/C^3 technology program in networking were chosen for analysis. These contracts were chosen because their content matches our definition of communication networking as stated in the preceding section. In some cases, additional information was obtained through attendance at scheduled program reviews, and visits to contractor facilities. All site visits and attendance at program reviews were coördinated with and approved by the appropriate contracting organizations. For the efforts covered in this study, these organizations were NRL, RADC, and ESD.

Relevant information concerning networking requirements, concepts, and systems employing these concepts was also obtained from government documents and the open technical literature. Information on network algorithms, open questions regarding distributed networks, terrestrial networks, satellite networks, and packet radio networks was obtained in this way.

After gathering the available information, work conducted by the contractors was analyzed. This entailed understanding the work performed to a depth sufficient to evaluate the adequacy of the approaches taken and the reasonableness of the assumptions made within the scope of the effort and in view of the time constraints within which the work was done. This analysis process led to the identification of aspects of the networking problem that are not being adequately addressed by current programs and which should be pursued by the SDIO in its BM/C^3 research plan.

In parallel with the analysis effort, the information gathered was used to develop a top-level set of networking requirements by considering the complex global conditions within which the SDI system must operate. These conditions include the need to interoperate with other systems, both U.S. and Allied, and with command authorities, and the need to function both in peacetime and during a nuclear conflict.

III. NETWORK REQUIREMENTS

Network requirements for the SDI BM/C^3 must be created with full awareness of the attributes required for the SDI system architectures in addition to specific networking attributes. Defining the system architecture within which the SDI BM/C^3 network operates establishes the framework for network requirements: network management (routing, flow control, error control, failure recovery, and network reconfiguration), security, diagnostics and maintenance, and performance metrics. This section suggests the types of network functions that must be included in the development of quantitative requirements for the SDI BM/C^3 network.

A. SYSTEM ARCHITECTURE

The design, implementation, testing, control, and management of the SDI BM/C^3 networks are highly dependent on the system architecture in which the networks must perform. This section briefly describes an architecture, loosely based on the Strategic Defense Systems (SDS) Phase I architecture (Ref. 1) and defines the impact of this architecture on SDI BM/C^3 networks.

1. Description

The desirable attributes of an SDI architecture are evolution, scalability, robustness, endurance, survivability and testability (Ref. 1). To obtain these attributes, the SDI architecture will strive to reduce the complexity and need for extensive cooperation among multiple elements. The environment in which the architecture will operate varies across peacetime, alert, conflict, and reconstitution. To attain such stringent attributes, networks which are robust, testable, evolvable, and secure (Ref. 2), must be created to manage and control voice and data traffic.

The elements composing the SDI system include a diverse repertoire of ground, air, and space components with equally diverse operational missions. Some of these elements, such as ERIS and SBI, are unique to SDI while others, such as GBR and BSTS, may have missions in addition to SDI. Timely and accurate information exchange must be performed among and between all of the elements that comprise the SDI system, regardless of their uniqueness to SDI.

The geographical dispersion of the elements encompasses space, air, and ground (the United States and its Allies). The command and control of these distant elements must be maintained through the multiple layers of the existing infrastructure such as the National Command Authorities, the Joint Chiefs of Staff, and the Unified and Specified Commanders.

The communication requirements to meet the SDI battle management command and control requirements encompass mixed communications media including laser, RF, microwave, and fiber optics with a wide range of frequencies such as 60/44/20/10/2/1.56 GHz and 300 MHz. Information carried over these media and frequencies will be generated from unique SDI components and from external sources such as intelligence sources, DSP, GPS, MILSTAR, and DSCS.

2. Impact on SDI Networks

Given the four environmental states, the multitude of SDI elements, command authorities, geographical dispersion of resources, communications media, and communications frequencies, the networking aspect of SDI is extremely complex and unparalleled. The probable impacts on the networks for SDI BM/C^3 include the following items. The term topology as used here refers to the time-varying collection of active satellite nodes and channels linking those nodes.

- The SDI system must be able to communicate reliably both voice and data traffic in a volatile, real-time topology. New elements must be capable of being added to the configuration through regulated plans, while existing elements may be lost through hostile actions.
- The amount of communications will vary during each of the four environmental states from a forecastable level during peacetime to unpredictable traffic during conflict.
- The data rates will vary, based on the source and destination of the information.
- Multi-level security will be required based on the content, source, and destination of the traffic. For example, command and control voice traffic during peacetime may be unclassified while information from intelligence sources may be compartmented. All of the data will flow through the SDI BM/C^3 networks.

- The SDI system must interoperate with existing systems such as the MEECN and the WWMCCS. The existing systems have established standards and protocols with which the SDI must interface. However, the SDI must establish its own network standards and protocols in addition to interfacing with existing systems.
- The SDI system must have the capability to manage and control partitioned or fragmented networks. For example, battle groups may be arranged in clusters with their own subnetworks.
- Highly distributed networks must be managed and controlled. Given the wide dispersion of assets and the requisite communications, a diverse set of networking algorithms and practices must be invoked.
- Network management will vary between automated, semi-automated, and manual with varying degrees of autonomous and semi-autonomous operations.
- Mobile and fixed elements must be serviced through the SDI BM/C^3 networks. Ground units may be mobile while some space units may be geostationary, each of which necessitates different networking considerations.
- Different routing techniques may be required at different tiers/levels in the networks. In some instances, flooding may be the best routing technique, while point-to-point may be appropriate in other instances.
- Local and remote diagnostics and maintenance will be mandatory. For those ground- or air-based elements local testing may be adequate, but for space-based assets remote testing and repairs will be required.

B. NETWORK REQUIREMENTS

Network requirements for the SDI BM/C^3 are arranged into four main groups: network management, security, diagnostics and maintenance, and performance metrics.

1. Network Management

The network management section of this document focuses primarily on the network layer of the International Standards Organization Open Systems Interconnection (ISO OSI) reference model that deals with routing, flow control, error control, and failure recovery procedures. Routing is the choice of path(s) through the network(s); flow control regulates traffic entry into the network; error control guarantees that messages are passed to higher layers correctly and in order; and failure recovery and network reconfiguration adapt to node or link failures and the relative motion of the nodes (Ref. 3).

It is the responsibility of network management techniques to determine the logical link connectivity and to control the parameters to assure that the link connectivity is maintained and managed appropriately while maximizing the overall network throughput.

a. Routing

Routing deals with the guidance of information from its origin to its destination(s) through the network. Aspects of routing that pertain to the SDI BM/C^3 networks through all environments are detailed below.

- Message formats need to be established for each facet of the SDI BM/C^3. The message structure, content, and the assignment of labels used in the preamble and data portions of the message must be standardized to operate within the SDI and to exchange information with systems external to SDI.
- The labels must be disseminated throughout the network and maintained locally and globally.
- Procedures/algorithms must be established to update local and global tables that maintain routing information.
- Algorithms, such as link assignment, must be created for defining the network topology.
- Synchronization of links upon initial net entry or reacquisition of links is required for a dynamic topology.
- A distributed routing process should provide enough information to each node so that each node can simply compute for itself the best total route and then take action locally that is commensurate with the global optimum.
- A process must be established such that each node can inform its neighbors about the current state of the routing table.
- Addressing and naming conventions for internal and external use must be formalized, particularly for rapidly changing topologies.
- A directory of users and hosts must be maintained locally and globally.
- Frequency and bandwidth allocations must be formally established through international and national organizations.
- Procedures for nodes entering the network for the first time and for those nodes reentering after temporary failure must be established.

b. Flow Control

Flow control regulates the flow of traffic into and through the network. Preventing the overloading of network capacity and the resulting poor performance is the responsibility of flow control techniques. Specific requirements for SDI BM/C^3 are discussed below.

- Means to detect and correct congestion must respond rapidly to bulk data flow as well as to bursty traffic. Algorithms must be available to detect the presence of increasing congestion.
- Buffers allocated to queues must be of sufficient size to retain incoming messages until they can be processed.
- Information that is required to initiate, cancel, and reroute traffic must be disseminated throughout the network.
- Algorithms for retransmission requests, for example, due to data link error control or end-to-end error control, must be provided.
- Algorithms for distributed flow control which adapt to network variations need to be established.
- Preferential treatment of message classes, for example for weapon release authorization versus sensor report, must be available.
- The reduction of contention through algorithms that stipulate *a priori* fixed assignment of channel resources or a dynamic channel access algorithm--which defines when users are permitted to transmit based on channel conditions and traffic--is mandatory.
- Positive termination of the propagation of redundant or "old" messages must be developed to prevent system saturation.
- Mechanisms for handling priority traffic from flash override through routine must be established.
- Channel access protocols and code assignment algorithms must be determined.

c. Error Control

Errors may occur at many points in the network, for example, packets can be lost or garbled or data links can fail or be destroyed. Error control requirements for the SDI BM/C^3 networks are defined below.

- End-to-end error control techniques are required which ensure that node failures do not result in lost or duplicate messages, and that accurate delivery of messages is accomplished or time-out mechanism is invoked to prevent deadlock.

- The order of packet receipt from end to end must be preserved.
- Error detection and correction algorithms must be employed.
- Notification of error detection back to the source must be provided.
- Identification/prevention of deadlock or livelock must be performed. "If a process is blocked, waiting for an event that will never occur, it is said to be deadlocked. If a process is blocked, waiting for an event that may not occur for an arbitrarily long time it is said to be livelocked." (Ref. 4)
- The system should be biased to "fail live," that is, initiate a restart after a short period of inactivity. A system override may be necessary to positively shut down a failed node.

d. Failure Recovery and Network Reconfiguration

The longevity requirement of the SDI BM/C^3 networks and the dynamic topology mandate rigorous requirements for failure recovery and network reconfiguration. Some of the requirements are outlined below.

- To establish connectivity, choose links that are optimal with respect to appropriate metrics.
- Optimize the topology of dynamically changing networks.
- Provide rerouting algorithms in event of failures or reconfiguration with the appropriate dissemination of topology information.
- Constrain the amount of requisite overhead in order to maintain speed of recovery.
- Establish link determination and control procedures.
- Determine information required to establish existence of link.
- Determine appropriate responses to lost link such as increasing power, retransmitting, or trying different route.
- Provide alternative strategies to be used locally to try to rapidly correct for localized topology changes.
- Provide detection/correction of lost connectivity between previously connected nodes.
- Create algorithm for rapid reconfiguration under attrition.
- Provide identification of permanent or temporary loss of connectivity.
- Provide positive control of nodes, e.g., turn on or off, for system trouble-shooting and testing.

2. Security

The SDI will be the target of hostile agencies during all four phases of the life of SDI. Provisions must be made to protect the networks from intrusion and the disruption or capture of information. Some of the security requirements are provided below.

- Provide rapid authentication of commands and links.
- Provide jam/spoof resistant links and nodes.
- Minimize jamming effects by spreading the spectrum of a message through use of frequency hopping or pseudo-noise coding.
- Determine amount of data encryption required. For example, should the header of the message be encrypted and if so, should a unique route be established that is not entirely decoded even by participating nodes.
- Provide rapid access authorization.
- Provide access control at internal as well as external entry points.
- Provide key management for key distribution and rekeying.
- Provide multi-level security for unclassified through compartmented traffic.
- Determine the amount of networking countermeasures needed.

3. Diagnostics and Maintenance

Maintaining a positive operating status of the SDI BM/C^3 networks through benign and hostile environments over an extensive period of time for space-, air-, and ground-based assets will be extraordinarily complicated. Some of the actions for diagnosing and maintaining the SDI BM/C^3 networks are enumerated below.

- Provide the ability to diagnose faults in a given or neighbor node.
- Establish the required amount of reporting of faults.
- Determine the required amount of remedial action.
- Establish procedures for the detection of whether or not a given node or neighbor node is operational.
- Establish the appropriate chain of reports for node failures.
- Establish procedures for keeping track of existence and status of all nodes in network.
- Be able to detect the difference between a failed node that requires repair or a node that has moved out of range and requires relocation or replacement with another node.

- Provide recognition of intermittent failures.
- Perform self-diagnostics and built-in-testing.
- Perform internal tests and cross-net diagnostics and debugging.
- Perform internal monitoring and diagnostics.
- Perform remote diagnostics and maintenance.
- Be able to disseminate new networking software to nodes while preserving software integrity.

4. Performance Metrics

Network performance is difficult to gauge, particularly for dynamic network topologies. Once the networks are designed, the concept must be proven; once the networks are operational, the users must be assured of the networks' ability to continue to perform. Several user-oriented performance metrics (Ref. 5) that can be used in mathematical simulation are provided below.

- Availability --the fraction of time that a connection is available.
- Delay--the end-to-end transit time through the network.
- Priority--differential handling of information based on its relative value in the user community.
- Throughput--bits per second accepted and correctly delivered by the network.
- Coverage--the average area from which information can be transmitted or received.
- Mobility--the maximum speed at which a unit can travel and still open and maintain a connection with useful throughput.
- Accuracy--the overall error rate as seen by the receiving equipment.

Several architecture-oriented performance requirements--robustness, survivability, testability, security, evolvability, reliability--must be addressed with respect to networks. Corresponding performance metrics that can be used in simulation must be determined.

C. CONCLUSIONS

This section has identified network requirements for the SDI BM/C^3 networks. While this section represents an initial set, requirements will be added and refined based on further knowledge about and definition of the SDI environment and the required communications between components.

In addition to the documents referenced in this section, several other briefings and reports were reviewed for information on network requirements. See Refs. 6, 7, and 8 for further details on SDI BM/C^3 network requirements.

IV. NETWORK PROGRAM STATUS

To determine the current status of the BM/C^3 network technology program, attempts were made to collect information on each funded task. Personal telephone calls were placed, messages were left on the ARPANET, Services and Agencies were visited, and uniform questionnaires were generated and distributed. The completeness of the information collected varies considerably between the Services and Agencies.

A. FY87 NETWORK TECHNOLOGY FUNDS

For fiscal year 1987 (FY87), the SDIO BM/C^3 directorate has allocated $19.6 million for network technology. These networking funds are distributed as follows:

WPD	Service/Agency	Dollars ($M)
B412	Army	2.5
B413	Air Force	8.0
B414	Navy	4.5
B417	NSA	2.4
B418	DARPA	2.2
	TOTAL	19.6

Within each WPD, the network funding allocations are subdivided into separate tasks. These tasks are summarized below.

WPD	Task Title	Dollars($M)
B412	Distributed Data Management System	1.3
B412	Management of Distributed Systems	1.2
B413	Communications Network	.7
B413	Distributed Information Processing	3.5
B413	Distributed Databases	.4
B413	Distributed System Security	3.4
B414	Track File Data Base Management System	1.2
B414	Adaptive Communication Networking	1.4
B414	Communications/Graphics	1.9
B417	Security Architecture Studies	2.4
B418	Trusted Real-Time Operating System	2.2
	TOTAL	19.6

B. NETWORKS QUESTIONNAIRE

To be able to compare information on each funded network task a networks questionnaire was created. The questions which were asked of each Service/Agency point-of-contact are enumerated in Figure 2.

A set of supplemental questions were asked that pertained to possible networking efforts outside of the BM/C^3 FY87 program. These questions are enumerated in Figure 3.

C. NETWORKS DATA BASE

To capture all the information and to be able to present the information in multiple reports, the collected data has been entered into a dBASE III Plus data base on an IBM PC. All of the information that has been made available is presented in Appendix A.

1. What current contracts use BM/C^3 funds and involve networks?
2. Who is the COTR and what is his/her phone number?
3. What is the title of the effort?
4. What is the contract number?
5. Who is the prime contractor?
6. What is the address of the prime contractor?
7. What is the technical point of contact at the prime contractor ? (TPOC's name, phone number, and address)
8. Who are the subcontractors?
9. When did the contract begin?
10. What is the contract completion date?
11. What are the FY87 dollars? (Any FY88 or FY89 dollars?)
12. Have there been any contract deliverables to date? (SOW, progress reports, milestones, IPRs?)
13. What are the titles of the deliverables?
14. Are there any upcoming TIMs that we should/could attend?

Figure 2. Networks Questionnaire

1. Are there any networking efforts that might be proposed for FY88 funds?
2. Do you know of any other networking efforts within the (Service/Agency) that are funded by SDIO?
3. Do you know of any other networking efforts within the (Service/Agency) that might be pertinent to BM/C^3?
4. Do you know of any networking efforts within the Services or Government Agencies that might be pertinent to BM/C^3?
5. Is there any person or organization that you would recommend we contact regarding networks?

Figure 3. Additional Networks Questions

V. ANALYSIS OF NETWORKING EFFORTS

A. INTRODUCTION

This chapter contains discussions of the technical content of SDIO-BM/C^3 funded networking efforts being carried out for various services and agencies, as summarized in Chapter IV and Appendix A. The objectives, technical approach, and plans for future work are presented for each program, followed by a critical evaluation and suggestions for expansion or improvement. The information below is based upon examination of contract deliverables and personal visits to the contracting agency and, in some cases, the contractor. The order of the descriptions parallels the data in Appendix A.

B. DESCRIPTIONS OF EFFORTS

1. Communications Networking For SDI Applications

WPD Number:	B413
Contracting Agency:	Rome Air Development Center (RADC)
Contract Number:	F30602-85-C-0272
Contractor:	Harris Corporation, Melbourne, FL.

a. Overview and Status

This program was an eighteen-month effort to evaluate network techniques that may be applicable to SDI and to identify any deficiencies in those technologies required to meet the SDI mission objectives. The study began in October 1985 and was completed in March 1987, with the final technical report dated April 1, 1987. Specific objectives of the study were to define communications requirements for multiple SDI architectures; propose potential network solutions; recommend communications networking approaches by performing functional adequacy assessments, trade-offs, and sensitivity analyses; and assess technology deficiencies. The material below was obtained primarily from a contract deliverable (Ref. 19).

Two architectural frameworks were developed by Harris with inputs from ESD and RADC. Architecture candidate one featured sensor-based battle manager (BM); architecture candidate two featured a CONUS-based battle manager. Both frameworks had the following satellite constellations where the BSTS/BM or SSTS/BM indicates the colocation of the battle manager with the spacecraft in accordance with architecture candidate one:

- BSTS/BM sensor spacecraft:
  - -- 9 geosynchronous spacecraft
  - -- 9/9/3 (Walker orbit configuration)
  - -- 51-deg inclination
  - -- circular orbit.
- SSTS/BM sensor spacecraft:
  - -- 48 MEO (medium earth orbit) spacecraft (5000-km altitude)
  - -- 6 rings of 8 satellites per ring
  - -- 90-deg inclination (polar orbits)
  - -- circular orbit.
- Weapon carrier vehicle spacecraft:
  - -- 900 spacecraft (total) in LEO (low earth orbit) (1000-km altitude)
  - -- 30 rings of 30 satellites per ring
  - -- 70-deg inclination
  - -- circular orbit.

The node connectivities for the candidate architectures are summarized below.

- For architecture candidate one:
  - -- All nine BSTSs have continuous LOS (line of sight) to each other,
  - -- SSTSs have links among themselves to allow fusion of sensor data by any SSTSs within a battle group,
  - -- Global Battle Manager (GBM) has communication path to all space-based weapon platforms, either LOS or via communications relay,
  - -- GBM has direct LOS communications path to all BSTSs and SSTSs within its FOV (field of view); not all of these paths are necessarily active simultaneously,
  - -- All space-based BM have path to and from the GBM,

- -- BSTSs and SSTSs have communications paths to and from weapon platforms, either directly or via relay.

- For architecture candidate two:
  - -- All nine BSTSs have continuous LOS to each other,
  - -- SSTSs have necessary links to allow fusion of sensor data by any SSTS within a battle group,
  - -- Each command center has a communications path with any space platform (sensors and weapons),
  - -- Command centers have communications paths to all other command centers.

b. Communications Requirements

Given the two candidate architectures and the corresponding nodal connectivity, Harris identified and quantified top-level communications requirements to support the boost, post-boost, and midcourse phases of the Strategic Defense System (SDS). While the study concentrated on networking, Harris pointed out other factors that could affect the network. For example,

- Space diversity through beam- and null- steering antennas,
- Time diversity through forward-error-correction-coding and time-hop techniques,
- Frequency diversity through frequency management,
- Code diversity through spread-spectrum techniques,
- Path diversity through network (i.e., packet) switchng and redundant transmissions,
- Adaptation to the threat through adaptive techniques in antennas, transmit modulation, receive filtering, network routing, power control, and data rates,
- Acquisition, link handover, and recovery modes,
- Security.

A brief summary of communication requirements as defined by Harris is presented below.

- Delay--99 percent of messages shall be delayed no more than 3 s and 99.9 percent of messages shall be delayed less than 10 s.
- Transmit power for 60 GHz crosslinks--assumed the following EIRP (effective isotropically radiated power):

- power amplifier output = 100 W
- antenna diameter = 1 m (dish)
- efficiency = 0.70

therefore, EIRP = 74.4 dBW.

- Transmit power for laser crosslinks--assumed the following EIRP:
  - power = −10 dBW
  - optics = 20 cm
  - wavelength = 10.6 μm

  therefore, EIRP = 84 dBW.
- Number of antenna apertures for BSTS and SSTS antennas:
  - 5 active laser crosslinks plus 1 backup
  - 2 active 20/44 GHz up/down links plus 1 backup
  - 2 active 60 GHz crosslinks plus 1 backup
  - 1 active SGLS (space-ground link system) with dish antenna, and
  - 1 backup SGLS with omni antenna.
- Number of antenna apertures for weapon antennas:
  - 4 active laser crosslinks plus 1 backup,
  - 1 active 60 GHz TDM (time division multiplex) crosslink plus 1 backup,
  - 1 active SGLS with dish antenna, and
  - 1 backup SGLS with omni antenna.

c. System Trade-Offs

Harris performed system trade-offs on BM to weapon platform communications, weapons network, BSTS network, physical layer, link layer, network layer, internetwork layer, and network security. Each trade-off will be discussed separately.

BM to Weapon Platform Communications. The issue being analyzed was whether or not a distinct weapons network should be required as part of the communications path between weapon platforms and the battle managers. The analysis was performed with respect to architecture candidate one, but is equally valid for architecture candidate two. Two cases were defined and analyzed: case one had no weapons network whereas case two incorporated a weapons network. The characteristics of two cases are briefly summarized below.

Case 1. Characteristics of No-Weapons Network

No crosslinks among weapons platforms

BMs communicate directly to final destination weapons platform

No weapons platform used as relay.

Each BSTS and SSTS has broadcast antenna with 20-deg beamwidth

Lower complexity and cost since platforms need not contain transceivers for crosslinks nor network switches with complex protocols

No beam steering required for broadcast

No store-and-forward queuing delay

No isolated nodes as a result of outage or jamming of neighboring relay nodes

More susceptible to uplink jamming since a single jammer (per BSTS) could be pointed up into the BSTS antenna

Case 2. Characteristics of Weapons Network

Crosslinks among weapons platforms (carrier vehicles)

Point-to-point links were used between battle manager satellite and particular weapon platform which acts as 'entry point' into weapons network

Each message relayed through weapons network

Used narrow beam RF (radio frequency) or laser links between BMs and weapons network as well as between weapon platforms

Much lower vulnerability to uplink jamming due to narrow beam antenna on BSTS

Use of laser links offered robustness with respect to nuclear effects, and extremely narrow bandwidths (anti-jam and low probability of intercept properties as well as low transmitter power required)

Higher complexity due to addition of network between weapons platforms and requirement for antenna/laser pointing and tracking

Supported higher data rates

Supported lower power

Had no contention on uplinks

Considered two cases, a flat grid with three links per node and a network with four links per node

Battle group contains 300 weapons platforms which were divided into two subnets containing 150 weapons platforms; a subnet contained only those nodes orbiting in the same direction

The performance characteristics were measured via simulation in terms of the following communication parameters: communication delay (mean, standard deviation, peak), communication throughput, and number of isolated nodes. Performance was measured on the basis of the probability of node failure/destruction, large areas of disrupted communications from nuclear effects, and communications traffic loading. The analysis was considered complete if case one could be proved qualitatively to be quite inferior in terms of susceptibility to jamming and if case two could be proved quantitatively to be quite adequate in terms of performance and survivability.

The primary conclusion reached through this analysis was that a totally point-to-point network is feasible for the battle managers' command and control of weapons platforms. Other conclusions were as follows:

- Increasing the number of links per node, providing adaptive routing, and providing a link reconfiguration algorithm did improve the survivability of the network. Adding more links per node resulted in the least improvement, while use of the simple link reconfiguration algorithm with the adaptive routing provided excellent performance even when greater than 50 percent of the network nodes failed.
- The critical survivability factor was the number of isolated nodes. The communications delay was not significant as long as reasonable link capacities were provided.
- Clustered node failures have fewer isolated nodes than unclustered node failures.
- The use of one entry node is viable for reconfigurable links, marginal for adaptive routing, and unacceptable for fixed routing.

Weapons Network. Assuming that the conclusions in the previous analysis would be accepted, Harris designed and analyzed a weapons network. In particular, the contractor designed a physical layer, a link layer protocol, and a routing and flow control, and discussed a laser communication approach to the weapons network. Architecture candidate one was used as the framework for the analysis.

For the physical layer design, Harris proposed using a 60-GHz RF channel with a coherent data modulation technique overlaid with a direct-spread modulation to provide a moderate amount of processing gain against a space-based jammer. However, slow frequency hopping was also considered since it could provide much greater tracking accuracy and processing gain at lower overhead cost. The recommendation for the forward error correction coding was a convolutional in conjunction with a pseudo-random interleaver which would be done on a burst basis to limit throughput delay.

The analysis for the link layer protocol design assumed fixed length packets and included the evaluation of five protocols: pseudo-random scheduling, mutually exclusive scheduling, master frame, master frame with more restrictions, and master frame with no collisions. Each of these prospective protocols was simulated and the performance measured in terms of traffic, throughput, and power efficiency. The results of the simulation showed that random scheduling of mutually exclusive receive slots, combined with a master frame structure which divides time between incoming and outgoing packets can yield greater than 84 percent efficiency for throughput up to 22 percent. If a complete time division between transmission and reception is implemented, 100 percent efficiency can be obtained at much lower throughput.

In a top-level description of a routing and flow control concept, Harris suggested using a geocentric coordinate system to eliminate the need for global routing tables; optimizing subnet areas such that accurate knowledge of state information of the total subnet was computationally feasible, using a modified Gallager's routing algorithm; having individual nodes communicate simple flow control information via a small field in the acknowledgments that would indicate to increase, decrease, or maintain the present sending rate; and using a circuit switch approach to resolving blocked traffic flow.

The laser communications approach to the weapons network provided trade-off information about laser versus RF characteristics followed by the recommendation that the space-to-space communications medium should be laser. However, RF transceivers should be included on each platform for backup media, diversity, and space/earth communication. For the weapons network connectivity, Harris recommended four transceivers per node, where each link follows an inclined path (with respect to the equatorial plane) to avoid looking into the sun.

BSTS Network. According to the analysis of BM-to-weapons platforms communications requirements, a BSTS network is necessary to: exchange 2-D track information for processing into 3-D track files (sensor fusion), to transmit network management, security, and status information, and to provide redundant paths for communicating between BSTS and weapons platforms. Harris performed an analysis to determine the number of links required, to formulate a network, and to evaluate the performance of the network. The performance measure was a function of the number of failed nodes. The recommended number of links was four and the recommended topology was a battle group network rather than a homogeneous network. The network performed best when a shortest-path message routing scheme of four short links and four long links was employed.

Physical Layer. Harris performed an analysis and technology trade-off of the physical layer to determine any constraints that might be imposed on the upper layers by the physical layer. The attributes of different antenna types were discussed in conjunction with the effects antennas have on communication performance. The effects of nuclear scintillation and mitigation techniques were discussed. For example, four fundamental mitigation techniques are proper choice of link frequency, stronger links, repetition of messages, and proliferated links and nodes. Some of the more sophisticated mitigation techniques involve the design of modulation schemes and signal waveforms that include interleaving and coding, signalling scheme, frequency hopping, adaptive equalization, and acquisition strategy and tracking loop design. General observations during this analysis include the following.

- Laser technology is sufficiently mature to support high-rate crosslinks, particularly those involving satellite-to-satellite communications. This is due to the absence of atmospheric effects.
- Space-to-ground links may be subject to dust and weather attenuation. Therefore, higher frequencies (60 GHz and optical) are not suitable, whereas SDLS frequencies (20/44 GHz) are suitable.
- Laser crosslinks between satellites offer high data rates and reduced scintillation effects, but pointing and tracking may be a difficult problem because of the relative motion of the satellites.
- Interleaving figures prominently in most mitigation schemes for RF links, but a significant delay penalty is incurred.

Link Layer. An overview of the networks used in this portion of the study are as follows: the members of each sensor subnet are linked by four laser crosslinks and one 60-GHz crosslink per satellite; the weapon carriers are linked by four laser crosslinks per satellite; RF links with phased-array antennas are used for communications between weapons and sensors; and the space/ground links operate in the SDLS (satellite data link standard) format. As a result of its analysis, Harris made the following recommendations concerning the link layer.

- PPM (pulse position modulation) frame structure using the SDLS direct detection laser crosslink (DDLC) standard is feasible for SDI if extended to accommodate higher data rates.
- Data rate and timing can follow the same general format as the DDLC in addition to the coding overhead associated with an Iwadare-Massey convolutional code having 3/4 rate and constraint length 6.
- HDLC could be used as the link layer protocol for the SDI space network in the following manner:
  - Where hop-by-hop acknowledgments are needed, use "information frames" with "selective reject" and an increase in window size.
  - For high-volume traffic over long propagation paths (e.g., sensor traffic) use "unnumbered frames." Not only does this alleviate the need for huge buffers at satellite nodes, but also allows efficient forward communications even if the return (acknowledgment) link is impaired.

Network Layer. The study on the network layer analyzed characteristics unique to SDI. These characteristics include:

- A very large number of nodes organized into a hierarchical structure,
- Frequent reconfiguration due to environment and node mobility,
- Long propagation delays between some nodes,
- A wide variety of traffic types and loads.

This network requires an adaptive routing algorithm capable of detecting changes, a communication protocol to disseminate information about the changes, and a computational method to update routing tables accordingly. The algorithm must be distributed and have redundant routes to increase survivability and be robust so that the malfunction of some nodes would not impede the function of the whole network. Nodes should be able to compute their own routing table independently without the assistance of a central routing control. Harris undertook an evaluation of nine algorithms most suitable for the SDI applications. The algorithms were the following:

- The Gallager routing algorithm,
- The Thaker-Cain-Bradley version of a modified Gallager routing algorithm,
- The Chang-Wu version of a modified Gallager routing algorithm,
- The original ARPANET routing algorithm,
- A minimum-hop routing algorithm,

- A PRNET (packet radio network) distributed routing algorithm,
- A PRNET hierarchical routing algorithm, and
- the ADMNS (adaptive, distributed network management system) routing algorithms developed specifically for SDI.

The conclusion was that none of the existing non-SDI algorithms possesses all of the attributes necessary for SDI. Harris recommended making a composite algorithm generated by putting together several of the ideas present in the algorithms listed above. Specific ideas to be examined include the use of distance tables from the "minimum-hop routing algorithm" to reduce routing traffic and storage requirements; multiple routing tables from the "ADNMS routing algorithm" to create the effect of split routing; cluster organization from the "hierarchical routing algorithm for packet radios" to handle the problem of a very large network; and the implementation of different algorithms for different classes of messages.

Internetwork Layer. This portion of the study specified the internetworking requirements, technologies, and assessments for a candidate SDI architecture. Traffic analysis, technologies for gateway interconnection, and SDI internetworking assessments were performed.

The traffic analysis considered data flows for command and control data, track files, status monitoring and reporting data, raw sensor data, and configuration and control data such as software uploads, system parameters, routing tables, and network management configuration commands. Analysis was performed for each of these data flows with regard to source/sink, traffic type, duty cycle, delay requirement, criticality, priority, error control, comments, and network service (datagram or virtual circuit).

A major design goal for the SDI with respect to the gateway interconnection is the use of a common suite of communication protocols that would help assure a coherent, efficient internet. Ideally, all networks to which SDI subnets must be connected should use the same internetworking protocol. In those instances where interconnection within SDI is necessary, the internetworking layer could be incorporated into the network layer which could employ the DOD's Internet Protocol (IP) or a separate protocol could be developed just for use between relay nodes. Interconnection to other networks could incorporate a common subnet approach, use a common internet protocol such as DOD's TCP/IP (transmission control protocol), use common network access interfaces such as CCITT's

(International Telephone Telegraph Consultative Committee) scheme using X.25, or use protocol translation gateway.

The results of the interworking technology assessment were the following:

- Datagram service is recommended at the network layer; on top of this may be placed a connection-oriented transport protocol (e.g., TCP) or a non-connection-oriented transport protocol (e.g., UDP), or both.
- Multiple-hop internet/subnet paths are required in only a limited number of circumstances.
- The internetworking protocol should be eliminated for all traffic between space-based elements during boost and mid-course.
- A common subnet approach should be used such that all subnets be considered a single, coherent network.
- IP or IP-like protocol should be used for SDI gateway traffic; however, the fragmentation/reassembly feature should not be required.
- The transport layer protocol must provide end-to-end error control and recovery procedures; the OSI class 4 transport protocol (TP4) should be used.
- Out-of-order packet detection and resequencing facilities are unnecessary in the transport layer during alert and attack states since very little traffic consists of more than one packet.
- A unique SDI-specific network layer protocol should be developed due to the unique nature of SDI applications.
- Priority forwarding (i.e., multiple transmit queues) at gateways and relays should be investigated.
- Routing and status-monitoring information exchanged between space-based elements should be accomplished through extensions of the adopted network layer protocol rather than by specifying separate protocols.
- Work should proceed on SDI addressing plans.

Network Security. This analysis examined the trade-off between the addition of security methods and network performance. Harris looked at the current capabilities and projected capabilities with respect to key management and authentication for their technology assessment. Several security measures were proposed for BSTS-to- weapon, SSTS-to-weapon, BSTS-to-ground, and BSTS-to-ground links.

- Both end-to-end encryption and link encryption are required for data integrity since data may be subject to multi-hop transmission path.

- Authentication and validation procedures should be performed to prevent masquerading and spoofing of critical weapons and target assignment in addition to protecting key distribution.
- Acknowledgment and message sequencing are required to assure that all critical messages are received and correctly interpreted.

However, link encryption should be sufficient for BSTS-to-BSTS, SSTS-to-SSTS, and BSTS-to-SSTS links.

The impact of security measures on the network include acquisition delays (i.e., authentication transaction or access transaction request, and synchronization of encryption devices), authentication delay, encryption delay (i.e., time to establish encryption mode and propagation delay through encryptor), and key variable transfer time (i.e., authentication delay, protocol transaction, and synchronization time).

d. Conclusions

The conclusions drawn by Harris from their analyses and simulations as well as from observations made throughout the study covered four major topics: communications network architectures, protocols and algorithms, hardware, and recommendations for further work. Each topic is discussed below.

Communications Network Architectures. Recommendations and observations regarding the communications network architectures are briefly summarized below.

- The primary conclusion of the analysis was that a totally point-to-point network for command and control of weapons platforms by the battle manager is survivable.
- A combination of a very simple link reconfiguration algorithm along with a shortest-path adaptive routing algorithm made the network extremely robust to loss of nodes. More elaborate algorithms should further enhance survivability.
- Fewer nodes were isolated as a result of N nodes in a cluster than when N nodes had been independently destroyed.
- For the resolution of contention, when broadbeam antennas are used on the BM satellites, the problems associated with conventional multiple-access protocols can be avoided via use of a proposed command/response link scheduling technique.
- Both RF and laser communications equipment should be included on the dynamic SDS platforms to provide for media diversity.

- The pseudo-random scheduling (PRS) link protocol and the associated transceiver have general applicability to SDS needs.
- Links between pairs of satellites traveling in counter-rotating rings should be avoided due to the increased difficulty of software and hardware, particularly with laser links.
- The requirement for relaying communications should be incorporated into the essential SDS nodes (sensors, weapons, BMs) instead of introducing dedicated relay satellites.
- The communication network design should be made up of several subnets, one for satellites at each altitude.
- Full duplex links are preferred over half-duplex links, especially where high link utilization efficiency is required.

Protocols and Algorithms. A brief summary of the recommendations for protocols and algorithms is presented below.

- Delays associated with establishing and authenticating links or circuits discourage network designs that use agile beam antennas (or lasers) that repoint on a packet-by-packet basis.
- Delays associated with existing links affect the link layer and transport layer protocols in terms of window sizes used to limit the maximum number of outstanding packets at any one time. These delays also affect the network layer in terms of stability of routing algorithms and the network management in terms of stability of link reconfiguration algorithms.
- End-to-end (transport layer) acknowledgments alone should be used in the SDS unless the hop-by-hop acknowledgments can be sent over a highly jam-resistant link. Furthermore, the end-to-end acknowledgments should not be restricted to follow the same (return) path as the messages they are acknowledging.
- The SDLS can be used for many of the relatively static, low-to-moderate-data-rate SDS links; however, SDLS does not currently accommodate high-data-rate links.
- While the PRS protocol requires no global synchronization, the PRS links never achieve a throughput greater than approximately half of the throughput achievable with perfectly synchronized TDMA (time division multiple access) links.
- An adaptive, distributed, survivable routing algorithm is mandatory for a large, highly dynamic network operating in a stressed environment.

- Network designs using an even number of links per node allow link reconfiguration after node loss without wasting available link resources.
- A new network-layer protocol probably should be designed for the SDS since no existing network-layer protocol seems well suited for the SDS.
- A communications network for SDS should have a minimal requirement for an internetwork protocol. If one is needed provide an to interface between ground-based and space-based assets, DOD's IP would be suitable if it could be streamlined to eliminate unnecessary overhead.
- A virtual circuit service for sensor traffic is feasible, but since packet sequencing is not necessary it does not appear to be beneficial.
- A datagram-like service with the option of end-to-end acknowledgments is appropriate for weapons command and control messages since packets will have a high probability of being sent to destinations different from the preceding packet.
- The transport layer must provide end-to-end acknowledgments for all weapons command and control traffic.

Hardware. Considerations for communications hardware are presented below.

- Electronically steerable antennas can be steered much more rapidly than mechanically steered beams and are generally more reliable in space applications than mechanical apparatus.
- The maximum data rates required for SDS communications links were estimated to be within 10 to 100 Mb/s and are well within the current state of the art for RF and laser hardware.
- Frequency hopping is the most viable candidate for gaining AJ protection on very-high-data-rate, survivable space links.
- No known existing packet network switches are designed to handle the high traffic volumes anticipated in SDS.
- The existence of high-data-rate encryption/decryption devices on a single integrated circuit eliminates the technical challenge for high-data-rate encryption/decryption devices.
- Nd:YAG and GaAs diode lasers are currently among the best available for space-to-space applications.

Recommendations for Further Work. Harris provided a commentary on work that should be examined for SDI and is summarized below.

- A common set of algorithms and protocols should be developed for the SDS, based on current techniques if possible (e.g., link layer) and using new techniques where appropriate (e.g., network layer and network management).
- If each SDS satellite node is equipped with both RF and laser transceivers, algorithms must be developed that choose the appropriate medium to use, depending on the situation.
- Situation assessment techniques (potentially heuristic techniques) need to be developed that could be used in conjunction with multi-media resource control.
- A resolution must be made about whether or not a network operating system is required.
- Key parameter trade studies should be performed on routing algorithm time constants (for both RF and laser links), unacknowledged packet window sizes (transport and link layers) as a function of the various link delays, optimal packet and Automatic Repeat Request (ARQ) block sizes, and performance versus amount of excessive link capacity.
- Communications network security protocols need to be established and should be tailored to specific SDS needs, such as fast authentication to support real time network reconfiguration under massive nodal attacks. A procedure for remote key distribution and redistribution is of prime importance.
- Fast acquisition techniques need to be developed to support fast network configuration/reconfiguration.
- Fast spatial-search techniques are required for directional antennas and especially for laser links.
- Efforts should be expended to advance the technology for electronically steered antennas for 60 GHz and laser optics.
- Techniques for the rapid synchronization of decryption devices need to be developed to support real time link and end-to-end circuit reconfiguration.
- An SDS communications network must be designed to operate against projected countermeasures (for RF and laser links) that will be responsive to the deployment of SDS.

e. Comments and Concerns

This study has concluded with no direct follow-on identified. Indirectly, the information generated from this analysis will provide a foundation for Harris's "BM/C^3 Communications Network Design" effort, discussed in paragraph B.4 of this chapter.

Harris has done a good job of identifying potential communications issues for SDI and understanding the problems of the space-based assets. With this background, Harris did an excellent job of performing technology assessments and trade-offs. The observations and recommendations which were made throughout the analysis were extremely insightful and pertinent to SDI BM/C^3.

More analysis would have been useful in two areas.

1. At the beginning of the analysis, RADC requested that Harris perform trade-off studies on two candidate architectures selected by RADC. Basically, all of the technology assessments and trade-off studies were performed on architecture candidate one and applied to architecture candidate two unilaterally. To postulate communications requirements and network configurations for each architecture and rigorously analyze each set would have generated useful information regarding trade-offs on the BM/C^3 architecture suite with respect to communications networking.

2. Communications requirements are a central part of a communications networking study. While Harris provided some general communications requirements and information flows, the requirements were too skeletal. A comprehensive set of communications networking requirements versus the state-of-the-art technologies would have provided traceability into key communications networking issues and needs.

2. Internetted System Modeling

WPD Number:	B413
Contracting Agency:	Rome Air Development Center (RADC)
Contract Number:	F30602-86-C-0217
Contractor:	Harris Corporation, Melbourne, FL.

a. Overview and Status

This program is a twenty-four month effort which began in September 1986. The primary objective is to build upon the Distributed System Simulator (DSS) in order to build modeling tools that can be used to evaluate ground, air, and space BM techniques.

The objective of the DSS was to permit a user to define a network, in terms of nodes, protocols, circuits, topology, and traffic, and to perform simulation analysis to evaluate network performance. Between 1982 and 1984, DSS Version 1.0 was built by General Electric Corporation to evaluate ground-based networks and required the users to write simulation model computer programs. Between 1984 and 1986, Harris Corporation built DSS Version 2.0 adding an interactive user interface. DSS Version 2.0 runs on a VAX 11/785 and is written in Simscript II.5.

The Internetted System Modeling (ISM) effort uses DSS Version 2.0 as its foundation and will be installed on the VAX 8650 system at RADC. ISM will make improvements to DSS by adding the following features:

- Ground, air, and space nodes,
- Heterogeneous, internetted systems of networks,
- Dynamic networks with network reconfiguration, and
- Routing algorithms.

Information for this review was obtained primarily from a contract deliverable (Ref. 20).

b. System Description

ISM is to provide an interactive and user-friendly tool to evaluate the performance of internetted, heterogeneous networks. The simulation model will collect statistics on the flow of messages as they contend for resources in the system. These statistics will be available to the user in the form of reports and graphs that will summarize the system performance. Data entry is through a system of menu and input screens, with user-selectable output reports and graphs. On-line help as well as a directory display of existing parameter files will be available.

The functional requirements that are collected in order to run ISM are divided into seven functions: topology, protocols, channels, message, node messages, node hardware, and executive. These functions have input requirements and output parameter reports associated with each. Separate discussions of each function are provided below.

Topology. The topology function of ISM describes which nodes in the system are allowed to carry on direct communication with each other. The ISM will dynamically determine whether two nodes are within LOS (line of sight) and can communicate. For input, the user specifies the initial conditions (node name, channel name, connection, gateway name, and network name) for the topology and specifies whether the connections are broadcast or point-to-point. ISM allows input to be either textual or graphical.

Once the characteristics of the topology are entered, the simulation model checks the topology for consistency and completeness. The positions of the satellites are simulated to move in circular orbits according to user-input parameters and orbital mechanics. The node connectivity uses an algorithm based on maximum island size and then nearest neighbor. To determine whether to establish connectivity with another node, each node will have knowledge of the positions of all the nodes with which it can connect and has a table indicating the status of each node.

The output report will contain a graphical or textual report on the specified topology and the number of operational channels. Statistics will be collected on network congestion, as measured by the overall utilization of packet buffers and by the overall utilization of message buffers for the entire network, and on message throughput across the network.

Protocols. The protocols function describes the rules and conventions used in organizing and controlling the flow of data traffic. The ISM uses DOD's internet model of communications layers and not ISO's; Figure 4 displays the differences between the protocol layers. For input, the user must enter information about each protocol layer (i.e., higher, transport, internet, network, link, and physical). The required inputs are detailed below.

ISO Model	DoD Internet Model	ISM Model
Application	Application	{ Higher
Presentation	Utility	Layers
Session	Transport	Transport
Transport	Internetwork	Internetwork
Network	Network	Network
Link	Link	Link
Physical	Physical	Physical

Figure 4. Layer Comparisons

- **Higher**. For the higher layer protocol, the user must enter the number of overhead bytes, protocol processing time, data compression time, text modification ratio, end-to-end encryption and decryption times, and number of batched messages.

- **Transport**. For the transport layer, the user must enter the number of overhead bytes, maximum and minimum data unit size, acknowledgments decision (if yes, acknowledgment length, acknowledgment priority, time-out period, maximum number of retries, maximum resend time, send window size, and piggy back outgoing message decision must be entered), connection oriented decision (if yes, maximum number of messages sent per connection, handshake message length, and maximum time allowed for open connection must be entered).
- **Internet**. For the internet layer, the user must enter the number of overhead bytes, protocol processing time, time to convert packets from the network protocol to the internet protocol form and vice versa, conversion times, maximum and minimum internet packet size, acknowledgments decision (if yes, same input as the transport layer).
- **Network**. For the network layer, the user must enter the maximum and minimum packet size, maximum number of packets per message, number of overhead bytes, and protocol processing time.
- **Link**. For the link layer, the user must enter the number of overhead bytes, protocol processing time, acknowledgements decision (if yes, user must enter acknowledgment length, acknowledgment priority, time-out period, maximum number of retries, and send window size), local area network (i.e., token ring passing) decision (if yes, then user must enter maximum number of transmission retries).
- **Physical**. For the physical layer, the user must enter the number of overhead bytes; protocol processing time; indicate whether time division multiplexing (TDM) or frequency division multiplexing (FDM) will be used; if TDM, user must enter number of transmission queues, associations between transmission queues and frame slots, associations between reception windows and frame slots; if FDM, user must enter the number of transmission queues, associations between transmission queues and subchannels, associations between reception windows and subchannels.

The output report for the protocols function will be the average, minimum, maximum, standard deviation, and number of observations for the job queue time for each node and for each protocol layer.

Channels. The channels function describes the physical connection between nodes. The user must input the following information: channel type (broadcast or point-to-point); if broadcast, TDM, FDM, or non-multiplexed; if TDM, number of slots per TDM frame, size of TDM frame slot in bits, overhead bits per TDM frame; if FDM, number of subchannels on channel, capacity for each identified subchannel; if point-to-point, data link protocol; indicate whether channel is dynamically or statically allocated; types of nodes that can be connected by dynamically allocated channel; allocation of capacity to different subchannels on channel; error rate for every specified channel; propagation delay for statically allocated channels; duplicity and total capacity for every subchannel; power level, synchronization time, and antenna pointing delay for every dynamically allocated link type; and maximum queue size for subchannels on every specified channel.

The output report for each channel will include the average, minimum, maximum, standard deviation, and number of observations for each of the following: channel-induced delay; channel utilization; packets rejected due to lack of buffer space at receiving node and due to sequence number errors; number of packet retransmitted; time between failures; time to repair; throughput; utilization of channel capacity by information packets, control packets, and supervisory packets; total packets transmitted on channel; total packets transmitted; packets with errors; subchannel throughput and utilization; total packets transmitted by subchannel; packets with errors, queue length, outstanding acknowledgments, number of retries, lost packets, total packets queued, percent of time empty, and queue time by subchannel. Graphical output for channels and antennas will be the following statistics versus time: channel-induced delay, channel utilization, channel throughput, utilization of channel capacity by information packets, utilization of channel capacity by control packets, utilization of channel capacity by supervisory packets, subchannel throughput, subchannel utilization, and queue length by subchannel.

Message. The message function describes the characteristics and flow of all types of data. The user will describe message name, message type, and expiration time. The output report will contain statistical output on messages generated at each node.

Node Messages. The node messages function describes the characteristics of messages generated at each node. The user must input the following information: component of source node that generates the message and final destination node and node component, final destination of all nodes, data processing time as relates to sending and receiving (i.e., encryption and error checking), order of preference for being served, names of transport and internet layer protocols, fixed routing scheme (if desired), multiple frequencies for message generation (start, stops, and interarrival time distribution), interdependencies among messages (number of messages to be received and message type), and message expiration time.

The output report will include the average, minimum, maximum, standard deviation, and number of observations on the following: number of messages generated, number of messages sent, number of interdependent messages sent, number of messages received, number of messages received with errors, and number of interdependent messages received for a host component, communication switch component, sensor component, and weapon component. The report will also contain message length, outstanding acknowledgments for a message, number of retries for a message, number of late messages, number of early messages, and network-induced delay time for each message. The percent of messages early and the percent of messages late will also be collected.

Node Hardware. The node hardware function describes the physical characteristics of a node. The user must input the node composition (weapon, sensor, host processor, communications switch), processor rate in millions of instructions per second (mips), message storage capacity for host processor, packet storage capacity for communication switch, maximum size received storage queue, transmit message storage queue, storage queue access time, percentage of time processor busy with non-network jobs, random or non-random failure distribution, time to repair distribution for random failures, time of failure and time to repair for non-random failures, node position (space, air, ground), stationary or moving node (moving node described as space, air, ground), maximum number of point-to-point channels supported, maximum number of broadcast channels supported, and mobile ground or air (position in longitude, latitude, and altitude), course expressed as points on surface of earth, velocity, number of point-to-point and broadcast channels.

The output report will contain the average, minimum, maximum, standard deviation, and number of observations on CPU utilization, time between failures, time to repair, non-network queue, queue length, queue time, packet buffer utilization, and message buffer utilization for the host component, communication switch component, sensor component, and weapon component. The report will also contain memory utilization for the node, node throughput, and node-induced packet delay time. The following list of statistics will be output graphically versus time: CPU utilization for the host component and communication switch and the queue length, packet buffer utilization, message buffer utilization for the host component, communication switch, sensor component, and weapon component. The graphical output will also contain memory utilization for the node, node throughput, and node induced packet delay time.

Executive. The executive function will process all user interactions as well as direct activity to underlying subsystems with ISM. The executive facilities will be the menus, the HELP facility, and the directory. The directory allows the user to review all the defined topologies, nodes, channels, protocols, user-defined distribution, graphs, and messages.

The performance requirements for the ISM will be certified using a Strategic Air Command (SAC) C^3 experiment in addition to scenarios provided by RADC and by Harris. The Harris scenario will consist of three phases. The first phase will model a peace time situation through the build-up to alert. This phase will last long enough to ensure topology reconfiguration has been achieved. The second phase will model the engagement situation that will begin with the boost phase and end with the terminal phase of an SDI situation. The third phase will model post-engagement situation that explores reconstitution from engagement back to peace time. This phase also must last long enough to ensure topology reconfiguration.

The test simulation will consist of an internetted system of communications networks containing at least 125 nodes with proportional numbers of battle managers, sensor platforms, and weapons platforms all of which will be resident on air, ground, and space platforms.

Two classes of messages will be modeled. The first class will contain messages which have a high volume, are perishable, and require only moderate assurance of delivery. The second class of messages will contain messages which have low volume but need a high assurance of delivery.

Stressing of the network will be accomplished by:

- Physical destruction of 20 percent of the nodes,
- Temporary loss of 30 percent of nodes due to electromagnetic pulse (EMP),
- Media disturbances such as scintillation, and
- Jamming.

c. Comments and Concerns

Harris is performing a herculean job of modifying an existing simulation model (i.e., DSS) to encompass all aspects of a communications network while incorporating characteristics of SDI BM/C^3. One of the key design accomplishments is the modular construction of the system. Since the user-specified information is written to libraries associated with each function, it is possible to "mix and match" communications networking characteristics and to update the libraries as new functional descriptions become available. Of particular interest to SDI BM/C^3 is the possibility of testing new concepts for or new combinations of BM/C^3 communications and networking suites. Once ISM is tested and on-line, it may be possible to evaluate and analyze different SDI system architectures with respect to communications networking.

According to the current design, ISM should be a valuable tool for BM/C^3. However, there are areas where ISM could be improved.

- ISM requires an exhaustive amount of detailed information; therefore, the user must be extremely sophisticated. While ISM is mandated to be user friendly, an inordinate amount of work must be performed to allow a user of the ISM to be less than a communications engineer.
- Although the draft functional description document (Ref. 20) indicates that default values will be available for most of the input requirements, it would be highly beneficial if a pre-established repertoire of libraries could be available to users such that the users would only need to select among the choices. For example, the protocol library could have pre-established choices for TCP, IP, UDP, HDLC, and RS422 protocols.
- Current estimates of the time required to run ISM vary from two hours to two days. ISM could accommodate more "what if" drills if the run time was significantly reduced.
- ISM is scheduled to be installed on the VAX 8650 at RADC. Since ISM may prove to be a valuable tool for SDI BM/C^3, more processors, such as the SUN workstation, should be targeted for implementation.

3. Wideband Satellite Support

WPD Number: B413

Contracting Agency: Rome Air Development Center (RADC) (MIPR to DARPA)

Contract Number: None

Contractor: BBN, Cambridge, MA.

Overview and Status

The purpose of this contract is to provide a five-node, wideband satellite network to support technology validation experiments for the National Test Bed (NTB). The network nodes are located at RADC, Lincoln Laboratory, and BBN. The network uses Western Electric ground stations and operates over the Westar-3 satellite. Network gateways and management are provided by BBN. The sole function of the network is to establish satellite links between the above-mentioned facilities. The dollar amount of the contract represents RADC's share of a utility payment to BBN for providing the service.

4. BM/C^3 Communication Network Design

WPD Number:	B413
Contracting Agency:	Rome Air Development Center (RADC)
Contract Number:	F30602-86-C-0224
Contractor:	Harris Corporation, Melbourne, FL.

a. Overview and Status

This project is a 30-month effort that began in September 1986. The major objective is to develop a design methodology for an SDI communication network and to gain an understanding of the advantages of different design techniques and tools. Harris Corporation was asked to do a complete network design that will result in useful algorithms and design concepts, although there is no intent to actually build the resulting network. The design will culminate in the creation of C-level software specifications that will be implemented in a computer simulation of the network to validate the designed subsystems and networking concepts.

The design methodology is expected to incorporate the following features:

- Flexibility to accommodate new technology
- Flexibility to permit varied use
- Software portability
- Redundancy and fault tolerance
- Excess capacity
- Extensibility
- Use of standard approaches, where feasible
- Use of artificial intelligence
- Use of existing studies and research.

To date, the following contract deliverables have been produced:

Interim Technical Report	January 1987
Draft System Segment Specification	January 1987
Initial Design Review	May 1987

As part of the effort, a systems requirements analysis will be conducted covering traffic demand, threat assessment, network management, survivability, security, protocols, and gateways and internetworking.

The design verification phase will utilize a contractor-developed Ada language network simulation tool called GENESIS (Generic Evolutionary Network Simulation System). Algorithms and protocols developed in the design phase will be specified using an Ada pseudo-code. The Ada pseudo-code will be compiled and integrated with the GENESIS program for simulation and design verification.

b. Accomplishments to Date

This section contains a summary of the work performed to date as presented in the contract deliverables. The first part of the discussion focuses on material contained in the Interim Technical Report and the Draft System Segment Specification.

As a starting point for the contractor's efforts, a description of the SDI system based upon both near-term and far-term architectures was developed based upon the current documentation on SDI requirements. Architectures were chosen to give visibility to communication data flows. The features of each architecture are summarized below.

<u>Near Term</u>

9 Boost, Surveillance, and Tracking Satellites (BSTS) in geosynchronous orbits

100 Carrier Vehicles in 500-km orbits

<u>Far Term</u>

18 Space-Based Battle Managers in 50,000-km orbits

9 BSTS in geosynchronous orbits

80 Space Surveillance and Tracking Satellites (SSTS) in 2,000-km orbits

16 Spaced-Based Radars in 1,000-km orbits

2500 Carrier Vehicles in 500-km orbits

4 Ground-Based Lasers

16 Relay mirrors in geosynchronous orbits

81 Fighting mirrors in 5,000-km orbits.

For the near-term and far-term architectures, a detailed functional description was developed for each major system element. For example, in the near-term architecture, a Strategic Defense Control Center is defined that is responsible for all Command and Control functions. Its top-level functions consist of combining data from multiple platforms, making battle arrangements, monitoring/assessing the system and selecting appropriate responses, and coordinating operations. Each of these functions, in turn, is shown to be composed of a number of subfunctions. Based upon these system functions and the attendant interconnection of system elements required, data flow specifications were developed for the types of data that must be exchanged, such as kill assessment, sensor status, track files, weapon assignment, weapon release, and so forth. These flows are based upon an assumed number of bits per message and an assumed message frequency.

Very rudimentary tables of security requirements were constructed, showing for each identified data flow the security threat resulting from detection, identification, modification, or deletion of the corresponding flow. The degree of threat is given as low, medium, or high.

A high-level description of the enemy threat was presented in terms of number of boosters, launch sites, launch profiles, and target sites. This threat description was developed by the contractor using materials obtained from open sources.

Communication network requirements were developed in some detail. Quantitative data rates were presented for the various data flows such as BSTS-to-BSTS single-sensor track files, weapon-allocation messages to carrier vehicles, and inflight guidance updates to weapons. The traffic statistics were generated via computer simulation for an assumed worst-case spike launch and assumed sensor scan cycle durations. The resulting traffic requirements include type of traffic, volume of traffic, traffic arrival statistics, traffic timelines, data rates, bandwidths, and so forth. A tutorial presentation addressed various enemy threats to communication, including electromagnetic pulse (EMP), nuclear scintillation, and jamming. Some techniques for mitigating the effect of these threats were presented.

Functional requirements for managing the communication network were developed. These requirements are grouped into categories called monitoring and assessment, configuration and control, and testing. These categories were subdivided into 8, 12, and 3 subfunctions, respectively. For example, some of these subfunctions are fault detection and isolation, periodic monitoring of nodes, adaptive message routing, rapid reconfiguration, control of protocol and communication parameters, and path verification and loopback testing. A brief discussion of factors involved in network survivability was presented, supported by an appendix containing previous work done by the contractor on network survivability and its measurement. Various types of network protocols, including data link, network, transport, and upper level protocols, were discussed in detail, together with their respective functions.

An Initial Design Review was held in May 1987 which elaborated upon some of the design areas included in the Interim Report and discussed above. An extensive section on overall design methodology included as key design criteria minimizing complexity, maximizing flexibility, and maximizing use of available technology. An updated functional design flow was presented, together with a methodology for developing the baseline communication architecture. This architecture methodology used results from an earlier contractor study for RADC entitled *Communication Networking for SDI Applications*, which is also reported upon in this document. The top-level functions that make up the baseline architecture methodology are the following:

- Specify type and number of links per node
- Develop link topologies
- Analyze and select baseline architecture
- Calculate link budgets
- Size links
- Specify node design requirements
- Revise specification as necessary.

This methodology is iterative, with both feedforward and feedback paths existing between many of the above steps.

A more detailed treatment of network security requirements, both in terms of type of threat and security levels, was given. A list of security techniques was presented and a baseline security architecture proposed. This baseline model consists of a top-level functional description of component security functions, component-level key management issues for multilevel security, an approach for establishing crypto-synchronization, and a process for crypto key distribution.

General requirements and features of link reconfiguration, network routing, and networking protocols were discussed. Examples of algorithms for the first two of these functions were given. The algorithms presented were developed by Harris Corporation under contract to the Naval Research Laboratory; they are described in this document under the corresponding contract. The protocol discussion covered the functions of the various protocol layers, interfaces required between different networks, and packet formats for both the International Standards Organization (ISO) and Department of Defense (DoD) protocols. Issues and alternatives concerning choice of a particular protocol were presented for some of the protocol layers.

The work performed by the contractor to date, summarized in the preceding paragraphs, has been preliminary in nature, concentrating on system requirements and characteristics of alternative approaches to network management rather than developing substantive designs or detailed methodologies. The lack of mature results is a reflection of the early stage of the program which was only eight months old at the time the work described here was completed. To indicate the level of treatment, the initial methodologies proposed for link reconfiguration and protocol selection are summarized below.

Link-Reconfiguration Methodology

- Define requirements
  - network wide
  - subnet level.
- Preliminary analysis
  - research needs versus existing algorithms
  - analyze needs versus existing and projected technology
  - pose attributes of desired algorithms.
- Select candidate algorithms
  - formulate candidates from requirements, desirable attributes, and existing algorithms
  - pose reasonable applications of each candidate.
- Identify trade-offs
  - enumerate strengths and weaknesses
  - identify traits specifically suiting or preventing application of each algorithm to the problem at hand

- construct uniform performance measures for comparing trade results.

- Simulate network operation
  - transform algorithms into executable code
  - choose appropriate traffic and threat models
  - provide for appropriate performance measures
  - execute simulation
  - process results into a meaningful form
  - analyze results.
- Modify candidates
  - iteratively adjust algorithms to better suit problem at hand
  - rerun simulations and repeat trade-off analyses as necessary to improve performance.
- Select resulting algorithms
  - fit algorithms best suiting requirements into a cohesive, network-wide, link-reconfiguration algorithm.

Protocol Design Methodology

- Determine services needed for each protocol
- Identify required functions
- Develop formal specifications of services and protocols
- Prove correctness of protocol design formally
- Develop formal protocol conformance tests
- Implement protocols
- Validate formally correct implementation of protocols
- Test interoperability of protocols
- Assess protocol performance.

Since this program is still in its early stages, much work remains. Plans for future work include constructing a network design including routing, synchronization, and other network management functions, developing C-level subsystem specifications, implementing the design via computer simulation, verifying the design, and performing a communication vulnerability assessment. The ultimate goal of this effort is to use the methodology developed to design the actual SDI communication network. Of course, the actual design may be carried out by a different contractor.

c. Comments and Concerns

A substantial amount of work has been done in the first eight months of this project. Most of the work, however, remains to be done. Further information on accomplishments of the last quarter-year will be presented to RADC in a briefing on October 7, 1987.

There are some concerns about the objectives of this project. The primary output of the effort will be a document presenting a design methodology. This document will have limited utility if, as is likely, the contractor chosen to do the ultimate communication system design is different from the contractor who developed the methodology. Indeed, every organization with communications expertise probably has its own approach to system design which has helped it to achieve its expert standing and which it will continue to use. It is not likely that a contractor will invest the time and effort required to understand and adopt a methodology developed by someone else, especially if it involves poring through a multi-volume design handbook. Such a methodology would be more likely to find use if it were installed on a computer system, perhaps in the form of an expert system communication design tool.

Although the actual network design developed in this study is not intended to be used, many of the subsystem-level tradeoff analyses may be more useful in future efforts than the actual design methodology. The methodology developed so far seems to be little more than the standard systems engineering approach to large-scale system design, i.e., define the problem, develop requirements, formulate alternative solutions, perform tradeoff studies, evaluate alternatives against performance measures, and select the best solution. In fairness, it is possible that as more experience and insight are gained, more mature and sophisticated methodologies may emerge. The maximum benefit from this experience, however, will result only if the contractor who develops the methodology also conducts the actual system design.

System design algorithms developed in this project could be some of the more useful products of the effort. Algorithms for network routing, flow control, capacity allocation, network security, and so on, could be made available as network design tools to any subsequent contractor working on SDI network design. Such algorithms should, therefore, be designed as separate modules with as much flexibility as possible, be easy to learn and use, and be well documented.

Since a design methodology is very general, many aspects of it will be applicable to a broad range of communication system designs, not just SDI. Consequently, this effort could be funded by non-SDI sources, at least in part. There are aspects of the SDI network that are unique, so it is appropriate that SDI continue to fund part of the effort.

See Appendix B for a brief description of more recent accomplishments on this effort.

5. Distributed System Topology

WPD Number:	B413
Contracting Agency:	Rome Air Development Center (RADC)
Contract Number:	F30602-85-C-0199
Contractor:	Advanced Decision Systems (ADS), Mountain View, CA.

a. Overview and Status

This project was a two-year effort that concluded in September 1987. The work was done in response to a PRDA requesting assistance in a number of areas of BM/C^3 for SDI and had as its major objective advancing the state of the art in network architecture and control through the use of creative approaches to overcome limitations of current technology. During the same time period, a parallel effort was undertaken by SRI International which is also discussed in this chapter. SRI was chartered to take a traditional approach to the network management task, while ADS was instructed to take a new look at the problem, unconstrained by prior approaches, to seek innovative, non-traditional solutions, and to formulate their own set of requirements and candidate system topology to respond to those requirements. The approach taken was intended to be revolutionary rather than evolutionary.

The initial objective of the effort was to try to define unique areas of battle management where novel approaches could be applied. Focus was placed on two areas: active process migration and knowledge-based routing. The former concept concerns the transfer of computation from one platform to another while the latter addresses the application of artificial intelligence to the adaptive message routing problem. Specific task areas identified for study were:

- Review existing studies (e.g., Fletcher and Eastport) and derive communication system requirements,
- Generate candidate network topologies (i.e., strawmen),
- Frame a network protocol model,
- Create a distributed computing testbed,
- Study active process migration, in particular triggering mechanisms that initiate the migration, and
- Investigate knowledge-based routing concepts.

ADS produced an Interim Report in October 1986 covering the first year of their effort and gave a progress review in December 1986. The final project briefing and Final Report were due in September 1987.

RADC does not plan to continue this effort. The study results will be provided to SRI and incorporated into their anticipated continuation studies.

b. Accomplishments to Date

The following summary of accomplishments, derived from available reports and briefing materials, reflects only the first 15 months of the contract period.

ADS reviewed the open literature, including the Fletcher and Eastport studies, to arrive at a set of system requirements. Their review included consideration of several previously proposed topologies. One of them, suggested by the Naval Research Laboratory, consists of 200 weapon platforms in 500-km orbits, 6 groups of 6 sensor platforms in 1,000-km orbits, and 2 groups of 6 battle management satellites in 50,000-km orbits. Based on their derived system requirements and their study of other topologies, ADS developed a topology consisting of 6 battle management clusters in geosynchronous orbits and a large number of weapon/sensor clusters in low earth orbits. In addition, they included a layer of communication nodes in orbits between the battle management and weapon/sensor clusters whose sole function is to establish connectivity between the two types of clusters.

ADS addressed SDI security issues, particularly those related to protocol architectures. They identified a number of security requirements such as privacy of messages, authentication of messages, network access control, distribution of crypto keys, and prevention of traffic analysis.

In the protocol area, ADS developed a set of general protocol requirements and proposed studying routing, data rate control, and authentication-connection strategies in more detail. Their approach to applying knowledge-based system concepts to protocols includes choosing relevant protocol problems, such as situations where nodes disappear and reappear, deciding which aspects of communication to include in a knowledge-based model, developing prototype knowledge bases, and demonstrating the use of knowledge-based protocol management. Likely candidates cited by ADS for application of knowledge-based techniques include message routing, addressing, flow control, and maintenance of virtual circuits. ADS stated that in applying knowledge-based concepts, one should provide the communication system with a model of its structure and function as well as general reasoning techniques and a model of communication goals to be achieved. In addition, a set of values should be provided to guide the mapping of communications requirements into measurable criteria to be met, e.g., reliability, data volume, and delay. A distributed knowledge-based communication manager would then select particular communication techniques based on available resources and problem requirements and constraints.

The work reported so far has been concerned primarily with formulating system requirements, identifying a number of alternative approaches, and proposing areas for future investigation. Few substantive results were obtained. More significant progress has been made in the area of a distributed computing research testbed. Such a testbed has been implemented using the Scheme dialect of LISP. The testbed hardware consists of Sun-3 work stations connected via both an Ethernet and a packet radio network. In addition to the Sun-3, the testbed runs on VAX, Pyramid, and Butterfly machines. The testbed is capable of supporting knowledge-based communication algorithms, making it useful for experimenting with architectures and evaluating protocols. In order to achieve this capability, ADS modified Scheme by adding some communication protocols.

A final area of work described by ADS is the use of active process migration to enhance system survivability. Suppose, for example, that a node suddenly ceases functioning due to a system failure or hostile action. Any processing that was in progress is then lost. Active process migration is a technique to mitigate or avoid such a loss. The approach taken differs from previous ones in that ADS considers an unreliable, distributed system operating in a hostile environment and composed of heterogeneous equipment. Active process migration attempts to increase system survivability by insuring that important functions are accomplished, regardless of the particular node at which the function is performed.

A *process* is a computing entity that consumes such system resources as Central Processing Unit (CPU) seconds, communication channels, and memory locations. *Process migration* refers to moving and copying processes from one node in a distributed system to another node. For process migration to succeed, it is necessary that the state of the process be captured, the process be capable of transmission, and the target processor be able to execute the process copy.

ADS has implemented some mechanisms and policies to support process migration. They have developed and demonstrated in their Scheme LISP environment the ability to transmit arbitrary LISP objects from one machine to another. An implementation of heterogeneous process migration via datagram was near completion at the time the available documentation was prepared. The goal is to be able to autonomously migrate, under software control, a process started on one node to another node while the process is executing. Triggering mechanisms, i.e., those events that initiate the migration process, also have been under investigation.

c. *Comments and Concerns*

ADS was assigned the task of developing a creative approach to tackling the problems associated with an SDI communication network. An attempt was made to apply artificial intelligence concepts to appropriate areas of BM/C^3 design. Few concrete results were obtained during the first year of the effort but that is, perhaps, a reflection of the difficulty of the problem. The first year was spent largely in problem definition, proposing work to be done in the second year, and developing some methodologies for addressing the identified problems. Unfortunately, the work done during the second year has not yet been reported so it is not possible to fully evaluate the effort based upon the end products.

Although the intent of this study was to encourage creative, new approaches, the initial work done on defining a system topology was of questionable value. Many groups had already studied that problem, including the original ten system architecture contractors. With that much prior work, it was not likely that a radically new approach would be found and, in fact, the topology proposed by ADS differed little from those available to them at the outset. It might have been better to start with a given system topology and concentrate the creative efforts on developing knowledge-based protocols, routing concepts, and so forth.

The relevance of the process migration effort to SDI presupposes that it will be necessary for processing to be shared by geographically separated nodes. Current emphasis, however, is on distributed processing and increased platform autonomy which also enhance system survivability. In these concepts, essential processing is performed independently at various nodes of the system, often nearly simultaneously. Under these circumstances, the need to migrate processes from one node to another would be minimal or nonexistent.

Since RADC does not plan to continue this effort, it is not appropriate to offer suggestions for changes to the study plan.

6. Distributed Processing System Topology

WPD Number:	B413
Contracting Agency:	Rome Air Development Center (RADC)
Contract Number:	F30602-85-C-0186
Contractor:	SRI International, Menlo Park, CA.

a. Overview and Status

This project was a two-year effort that concluded in August 1987. The work was done in response to a Program Research and Development Announcement (PRDA) requesting assistance in a number of areas of BM/C^3 for SDI and had as its major objective advancing the state of the art in network architecture and control through the use of creative approaches to overcome limitations of current technology. During the same time period a parallel effort, which will be discussed later in this chapter, was undertaken by Advanced Decision Systems (ADS). SRI was chartered to take a traditional approach to the network management task, while ADS was instructed to seek innovative, non-traditional solutions.

A final project briefing of the SRI effort was given to RADC on August 6, 1987. A summary of the first year's effort is contained in an interim report delivered in September 1986. The focus of effort was changed somewhat for the second year of the contract and this latter work is the subject of the ensuing discussion. Brief mention will be made of some areas covered in the first year's work that were not covered by the second year's efforts.

The study conducted by SRI encompassed four main task areas:

- Routing algorithms--optimal and suboptimal, quasi-static and dynamic, central and distributed.
- Topology control (link assignment) and link scheduling (multi-access).
- Packet resequencing with multiple channels and multicast.
- Object-oriented programming environments.

The final report for this contract is due approximately mid-September 1987. A follow-on contract is planned to continue the work, subject to the availability of adequate funding.

b. Summary of Algorithms

For SDI network application, one would ideally like to have network routing algorithms that are distributed rather than centralized. Such algorithms are more robust and, if based upon limited local knowledge rather than global knowledge of the network state, reduce the amount of communication overhead that the network must carry. Another desirable attribute is that an algorithm be cooperative (i.e., consider the needs of neighboring nodes) rather than selfish. Furthermore, it is often advantageous to develop suboptimal algorithms to reduce the required processing time and amount of communication overhead needed. The algorithms discussed below were designed to address some of these concerns.

Nearly Optimal Quasi-Static Algorithm. This algorithm attempts to minimize a cost function which is a linear combination of strictly convex, differentiable functions of the individual link flows, i.e., the link traffic. Satisfaction of a local condition on link traffic guarantees a sub-optimal solution. Advantages of the algorithm include limiting the number of required iterations and basing the solution on a condition depending on local information only. This condition involves the value of a defined parameter called the *node potential.*

Each node has knowledge of the potential of its neighboring nodes. If the node's traffic flow pattern cannot be modified to satisfy both the feasibility and local conditions, the node changes its potential. When the local condition has been satisfied by all nodes, the algorithm terminates. Since only enough iterations are used to satisfy the local conditions, the algorithm achieves reduced overhead at the expense of suboptimality. Nodes require local information about their neighbors only, not global knowledge of the network.

Heuristic Dynamic Routing Algorithm for Multiple Destinations. The objective of the heuristic dynamic routing algorithm is to minimize the maximum message delay. The proposed new algorithm solves a series of multicommodity maximum flow problems. While each iteration of the algorithm requires only polynomial time and provides an improved message flow (i.e., intermediate solutions are feasible), the entire algorithm could require an exponential number of iterations. The sclution is obtained by satisfying a time-dependent set of state equations subject to capacity constraints on the network links.

The algorithm proceeds by choosing a cutset (i.e., a set of links whose removal isolates the originating node from the destination node) and computing the minimum time required for the associated data to traverse the cutset. The corresponding multicommodity flow problem is then solved. Based upon the results, the algorithm chooses another cutset and repeats the process. When the same bound on the transit time is achieved twice, the algorithm terminates. Termination is guaranteed since there are only a finite number of cutsets. This algorithm actually yields the optimal solution for the case of two message destinations.

Quasi-static/Dynamic Hybrid Algorithm. The hybrid approach is proposed to avoid several intrinsic limitations of dynamic algorithms: (1) the state of the queues at all network nodes must be known by each node, requiring extensive communication, (2) queue state information from distant nodes may be obsolete when received, (3) computational complexity effectively limits dynamic algorithms to networks with fewer than 100 nodes. To avoid these difficulties while maintaining the benefits of dynamic algorithms, SRI suggests grouping network nodes into clusters of maximum size 30.

Each boundary node in a cluster maintains the time-averaged delay to the destination via each link exiting the cluster. A dynamic centralized algorithm is used within each cluster to minimize over all routings the sum of (1) the time for the slowest message packet to leave the cluster, and (2) the time-averaged delay expected to be encountered by the packet after leaving the cluster. Only the quasi-static, time-averaged delay information needs to be exchanged between clusters.

The run time of the algorithm at each node is proportional to the product of the fourth power of the number of nodes in the corresponding cluster and the number of outgoing links. SRI claims that this algorithm can accommodate topological reconfiguration between clusters as well as within clusters. Because of the partitioning of network nodes into clusters, the proposed hybrid algorithm is suboptimal.

Loop-free Shortest Path Routing Algorithm. Although one would prefer to have cooperative, multiple-path routing algorithms, the need for SDI networks to rapidly adapt to changes in network topology makes shortest path algorithms attractive because of their ability to accommodate abrupt topological changes. Existing algorithms either involve no coordination among nodes or else require an excessive amount of coordination. Moreover, they do not completely avoid the phenomenon of looping where messages may travel around a circular path or bounce back and forth between a pair of nodes. The new algorithm will be outlined after defining some needed terminology.

An *update message* consists of a destination ID, the shortest distance to the destination, and a synchronization flag (SF). A *feasible successor* node must have a finite distance to the destination that is less than or equal to the distance from the current successor to the destination. The *updated shortest distance* is the shortest distance reported by a feasible successor node. The updated successor is the feasible successor reporting the shortest distance.

The steps in the algorithm are outlined below:

a. If the routing table needs updating and a feasible successor is found, perform update and send a message to each neighboring node with SF set to zero. (This step involves no coordination among nodes and is the same as the classical Bellman-Ford algorithm.)

b. Otherwise, freeze the successor entry, update the distance entry, and send an update message with SF = 1, which indicates that an acknowledgment is required from each recipient. (This requires coordination with neighboring nodes.)

c. Send acknowledgments to SF = 1 update messages received from other nodes that are not the current successor node.

d. Send acknowledgment to SF = 1 update message received from current successor if the acknowledgments from own updates with SF = 1 have been received from all neighbors.

e. Unfreeze successor entry when acknowledgments are received from all neighbors.

This algorithm is dynamic, loop-free at all times, and uses only local information obtained from neighboring nodes. Full topological information about the network is not needed by the nodes. It has been assumed that the only changes that a node can detect by itself are the deletion or addition of a link and this information is imparted through a link-level protocol. The link layer notifies the network layer of changes in adjacent links one at a time. Nodes learn of the addition or deletion of other nodes through the routing-table update mechanism described above.

This algorithm is claimed to outperform existing algorithms in terms of the number of iterations required. Both this claim and proofs of the algorithm's correctness, loop-freeness, and convergence are based upon mathematical arguments, not simulation experience.

Hierarchical Routing. A hierarchical algorithm is proposed to reduce the overhead information that must be sent throughout the network and the amount of routing information that must be stored at each node. The notion of clustering nodes is used together with a regional-node routing scheme. The routing algorithm is an extension of the one described in the preceding paragraph; its goal is a reduction in the required frequency of update information.

Several levels of clusters are used, organized into a tree structure. There are two types of nodes: simple and regional. The address of a simple node is the name of the corresponding regional node. The address of a regional node is its name. Regional nodes are known throughout the network. Some simulations of this algorithm done at BBN Corporation indicate that worst-case performance is at least as good as other hierarchical algorithms. The complexity of the proposed algorithm is less than for any previously reported hierarchical schemes for land-based networks. The time required for the new algorithm is proportional to the diameter of the network, while the number of operations required is proportional to the product of the number of nodes and the average number of neighbors per node.

The algorithm is attractive for routing in networks characterized by a large number of nodes or multiple types of transmission media such as would occur in a large internetwork involving multiple gateways. Loop-free performance is guaranteed at all times and SRI claims that the algorithm performs better than any previous hierarchical approaches.

Random Connection Algorithm for Topology Control. This algorithm addresses the problem of establishing connectivity among network nodes to produce a connected network (i.e., one in which any pair of nodes can communicate) where the maximal degree of any node is specified (i.e., the maximum number of neighbors to which it can have a direct link.) A distributed algorithm is desirable to reduce the amount of communication overhead required. In the proposed scheme, links are chosen at random subject to the maximal degree constraint. With such a scheme, of course, network connectivity is assured only with some probability.

The algorithm begins with a collection of isolated nodes. A given node chooses a particular neighbor at random and attempts to establish a link between them. If the attempt is refused by the neighbor, another neighboring node is randomly selected and the process repeated. This process continues until the maximal degree of the initiating node is reached or until there are no more neighboring nodes.

Computer simulations were run with nodes located at random on the unit square. These nodes had no connections at all initially. Runs were made for a range of network parameters including number of nodes, maximum distance to neighbors, maximal nodal degree, and procedure for bringing up the network. One hundred runs were made for each combination of parameters. The relative frequency of connected networks obtained in this way was used to approximate the probability of network connectivity. A threshold effect was observed. When the maximal nodal degree was greater than a critical value, the network was connected with a probability approaching unity. Conversely, for values lower than the critical value, there was a high probability that the network was disconnected. The observed threshold value ranged between 4 and 8, depending upon the total number of nodes in the network. The particular order in which links were added was not observed to have a significant effect on the connectivity of the resulting network.

The work presented is still in the early conceptual stages; much work remains. For example, nodes that enter the network late may not have available neighbors to connect with because those neighbors may already have maximal degree. While the new node may be included by having a nearby node break one of its links and add a link to the new node, care must be taken not to isolate the older node in the process. The phenomenon of isolating one node while adding another node is termed oscillation. It was found experimentally that when operating the network with maximal degree above the threshold value, oscillation did not present a problem. Oscillation could result, however, for maximal degree values below threshold.

Techniques must also be developed for responding to the loss of nodes in the network. The existence of a partitioned network following node loss will be detected when a node on the boundary of a partition observes neighbors that do not appear in its routing table. One approach to reestablish connectivity might be to randomly break existing links and add new ones, taking care not to perform the deletions and additions simultaneously.

This process would be facilitated if the original network had nodal degree less than maximal but still above threshold.

Areas for further investigation include development of algorithms that (1) perform well with maximal node degree below the threshold value, (2) accommodate unequal link costs, (3) employ a more sophisticated strategy for adding new links, and (4) reflect anticipated node traffic patterns.

Although having less than guaranteed connectivity may not be acceptable for SDI networks, the random scheme proposed for establishing network links is interesting because of its simplicity.

Optimal Link Scheduling. This algorithm addresses the problem of establishing communication when the available number of transceivers at a node is less than the number of potential links so that all links cannot be active simultaneously. A procedure for establishing link transmit and receive schedules in such a situation is needed to assure efficient link utilization. Although deterministic Time Division Multiple Access (TDMA) can provide the best utilization, the simple heuristics that are often used instead result in low link utilization. The same is true of widely used random access protocols. The proposed centralized algorithm uses a network decomposition technique to produce an optimal TDMA schedule for half-duplex links. It is the fastest known such algorithm. For a highly connected network, the time required to run the algorithm is proportional to the product of the number of links and the fourth power of the number of nodes.

The problem is formulated as a generalized scheduling problem. The required separating hyperplanes used in the mathematical programming solution are found using a method developed by Padberg and Rao. The solution is simplified by decomposing the original network into two subnetworks. The optimal schedule for the original network can be obtained by first finding the optimal schedules for each of the subnetworks.

A related algorithm is also suggested to improve the performance of the Adaptive Receive Node Scheduling (ARNS) protocol proposed for the Multiple Satellite System (MSS). The current algorithm is simple but is expected to yield a utilization of less than 20 percent. SRI proposes as an alternative, grouping the network nodes into clusters, using a centralized greedy scheduling algorithm within clusters, and retaining ARNS for inter-cluster transmissions. The greedy algorithm would assign the link with the largest demand to transmit in the first time slot, the link with the next largest demand to also transmit in the first slot, and so forth, as long as subsequent links do not interfere with previously assigned links. The process would then be repeated for the second and subsequent time slots until all the demands have been satisfied. The algorithm is simple, requiring little overhead when performed within a cluster. Simulation results have shown that when propagation delays can be assumed to be negligible, the greedy algorithm produces optimal schedules in 90 percent of the cases tested. Of course, in the SDI network, propagation delays will be large for some links. Further testing of the algorithm when propagation delays are finite is therefore needed.

Packet Resequencing. When a message is divided into multiple packets, some channel protocols may result in correct packets arriving at their destination out of sequence. Provision must then be made for sorting such packets into the proper order. A performance analysis was conducted for a multi-channel, multi-destination selective repeat Automatic Repeat Request (ARQ) protocol. In this arrangement, parallel channels are available for transmitting packets so that packets may traverse different channels, and each message transmitted may be addressed to more than one destination. A quantitative analysis of the protocol's performance showed the effects of system parameters which include error probabilities in the forward and feedback channels, number of receivers, and propagation delay. This analysis extended earlier work for a single channel with a single transmitter-receiver pair. Graphs were presented of resequencing buffer occupancy versus channel error probability and versus propagation delay.

In performing the analysis, the following assumptions were made. All channels had the same speed and propagation delay, were divided into time slots, and had possibly different probabilities of successful packet transmission; the service policy was first-come, first-served and packets were assigned to the available channel having the greatest probability of successful transmission. Future directions for this work include a study of resequencing in high speed, high delay, lossy networks such as those of interest to SDI.

Object-Oriented Programming Environments. Object-oriented programming is a software development methodology that attempts to simplify the design of large systems. The drawbacks of standard layered protocols such as Open Systems Interconnection (OSI) include a duplication of services at different network layers (e.g., both network-layer checksums and data link-layer error correcting codes) and lack of flexibility to bypass unneeded layers or services in some applications. The object-oriented approach employs entities called *objects* which can be thought of as data structures manipulated by particular operations.

SRI has conducted a study of object-oriented programming and investigated how it might be applied to the SDI. A summary of their work follows.

A method of applying object-oriented programming in the SDI environment is through use of Remote Operation Invocation (ROI) whereby one host processor can request operations to be performed by another host. Benefits for SDI are claimed to include: (1) elimination of procedural programming inefficiencies, (2) use of modularity to meet demands imposed by system size, complexity, and reliability requirements, (3) improved performance and sharing of resources, (4) concurrent access to objects, (5) reduced equipment and memory costs, and (6) current availability of object programming languages and affordable hosts.

A sample object-oriented system architecture and model of operation were developed. An example illustrates the use of ROI to operate across dissimilar programming environments involving two processors, one using the SmallTalk language and the other using the C++ language.

SRI has developed some specific conclusions concerning the advantages of object-oriented programming, but the terminology and concepts are tied to their architectural model and would require stating many definitions and elaborating details of the model. Consequently, we will not present these results. They can be found in the final project report.

Other Areas. For completeness, we now mention two topics included in SRI's interim report but not pursued further during the second year of the effort.

In the area of self-organizing networks, two quasi-static, heuristic schemes were developed for establishing network connectivity by making assignments between ports at one node and ports at neighboring nodes. The existence of a topology update algorithm providing information on operating nodes, number of ports, and number of network partitions is assumed. Both schemes attempt to minimize the path lengths between all pairs of nodes. They employ a minimum disturbance criterion which requires that existing links not be broken during network reconfiguration: only link additions are permitted. The first scheme, called the Replicated Port-matching Algorithm (RPA), is a centralized algorithm that is used when complete information about the network state is available to all nodes. When only inconsistent or incomplete information is available, a distributed Vote-based Port-matching Algorithm (VPA) is proposed. Although it was assumed that the RPA/VPA and network routing algorithms operate independently, it would be better if they were integrated into a single topology/routing algorithm.

An extensive discussion is given of a session-level service called Multi-destination End-to-end Reliable Services (MERS), focusing on a multidestination network architecture and corresponding session- and transport-layer protocols.

c. Comments and Concerns

It is apparent the SRI has done a substantial amount of high-quality work within the scope of the current contract. Nonetheless, there are several concerns. While the work certainly represents valid contributions to networking technology in general, the relevance of some of it to SDI is questionable. Some specific concerns, followed by more general comments, are listed below.

1. The random connectivity algorithm may not be appropriate for SDI. While having less than assured connectivity may be tolerable for some networks, such a condition may be considered unacceptable for SDI.

2. Link scheduling will probably not be a key issue in the design of the SDI network. Many of the links, certainly the most important ones, will be supported by dedicated point-to-point transceivers, obviating the need to establish link schedules.

3. A drawback of the proposed link-scheduling scheme is that it uses a centralized algorithm, although SRI feels that a distributed implementation is possible. Furthermore, it is not clear whether the proposed algorithm can accommodate changing traffic demands.

4. Packet resequencing may not be relevant to SDI since most of the critical message traffic will consist of datagrams (i.e., single-packet messages.)

5. The relevance of object-oriented environments to SDI is limited. Distributed processing concepts may be applicable to different processors occupying the same platform, but the emphasis on platform autonomy and minimizing communication overhead would seem to militate against extensive inter-platform processing.

6. A global concern is that, for the most part, the algorithms that have been developed exist only in the form of mathematical constructs. They have not been coded and tested even in isolation, much less in a realistic test-bed incorporating simulated threats and message traffic. Most of the claims for correctness and convergence of the algorithms and performance comparisons with previous algorithms are based solely upon mathematical arguments. (See also Item 10 below.)

7. The manner in which the algorithms and concepts developed respond to SDI networking requirements should be emphasized. The work SRI has done to date is quite abstract in nature with virtually no reference to a particular network structure or system architecture. In any future work, they should relate their results to the current baseline architecture.

8. The wealth of material presented could be better integrated. At present, for example, it is not clear how the different types of routing algorithms are related to one another, and when each should be used.

9. The work to be performed in any follow-on study should be more focused in those areas of particular concern to SDI. Suggested topics include (a) development of distributed and approximate routing and reconstitution algorithms, (b) integration of routing and topology/reconstitution algorithms, and (c) development of hybrid routing algorithms combining shortest-path, quasi-static, and dynamic elements.

10. In any follow-on contract, coding and testing of network algorithms should receive high priority. The testing should be conducted in a simulation environment that causes links and nodes to fail in order to assess performance and stability of the algorithms. More credibility will result if performance claims are corroborated by realistic simulation experience. (See also Item 6 above.)

7. Adaptive Distributed Network Management System

WPD Number:	B414
Contracting Agency:	Naval Research Laboratory
Contract Number:	N00014-86-C-2056
Contractor:	Harris Corporation, Melbourne, FL.

a. Overview and Status

This program is in the second year of a planned three-year effort. Its objective is to establish the technical feasibility of controlling a space-based BM/C^3 network and to develop and test appropriate communication network management algorithms. For the purpose of designing these algorithms, an architecture of 2073 orbital nodes was assumed, consisting of:

- 12 battle-management platforms in 50,000-km orbits
- 36 sensors in 1000-km orbits

- 2025 weapons platforms in 500-km orbits.

Since it was recognized at the outset that frequent changes to the BM/C^3 architecture were likely, one of the design goals was to make the network management algorithms as insensitive as possible to the underlying architecture. This philosophy results in a robust set of algorithms that can accommodate a range of evolving architectural options. Additional principles guiding the design include the use of existing algorithms insofar as possible, design of unique algorithms where necessary, and rapid development of prototypes for testing. The priorities guiding the algorithm design were (1) functional adequacy, (2) robustness of the algorithms, and (3) computational efficiency of the algorithms.

The overall effort consists of:

- Development of networking techniques and protocols
- Development of a software simulation facility to test and refine the various network algorithms
- Definition of measures of performance
- Design of statistical testing procedures for the developed algorithms
- Algorithm testing via simulation and statistical analysis
- Incorporation of networking algorithms into the NRL test bed.

The main functional areas of network management addressed in the algorithm development effort include:

- *Link assignment*--determining the placement of links joining pairs of nodes, which defines network connectivity. This involves developing schedules for establishing and disconnecting satellite crosslinks in response to both planned and unplanned changes in satellite-to-satellite availability.
- *Adaptive routing*--for a given topology and distribution of message traffic, determining the best sequence of nodes for a given message to traverse in going from its point of origin to its destination. The routing strategy must permit recovery from planned and unplanned link and node outages.
- *Failure recovery/topology update*--maintaining consistent network topology data bases at each of the nodes in the network. This algorithm is responsible for sensing, collecting, and distributing status information for all network links and nodes.
- *Congestion/flow control*--avoiding the development of extremely long message delays due to network bottlenecks while maintaining reasonable levels of

system throughput. This algorithm must both control the network flow and avoid the occurrence of deadlock conditions which cause resources to be unavailable and from which recovery is not possible.

During the first year, or Phase 1, of the contract, attention was focused on developing and testing algorithms for link assignment and adaptive routing. These areas were considered to be of prime importance and also the most difficult. Along with algorithm development, Phase 1 also addressed creation of a simulation environment and statistical procedures for testing algorithms as they were developed. The initial algorithmic concepts were subjected to one-day reviews by each of three noted academic researchers active in the networking area: Professors Gallager of MIT, Hajek of the University of Illinois, and Livny of the University of Wisconsin.

In the second year, current algorithms will continue to be refined while attention is directed to the areas of failure recovery/topology updating and congestion/flow control. In addition, an Engineering Change Proposal (ECP) calls for examining the issue of modifying the network control algorithms for implementation on a parallel processor. This ECP has the potential for greatly speeding up the run time of the algorithms.

It is appropriate at this point to discuss a key assumption used during the Phase 1 effort. A hierarchical arrangement of the 2073 space-based nodes under consideration was employed. The 48 battle-management and sensor nodes were grouped together as elements of a backbone network that requires high-capacity links to accommodate the high-rate sensor data as well as the lower rate command-and-control and system-status data. The 2025 weapon platforms were formed into overlapping clusters associated with backbone nodes so that each platform had access to the backbone network through more than one backbone node. This two-tiered arrangement was adopted to ease the computational burden on the network management algorithms, which grows rapidly with network size. As part of the Phase 2 effort, it is planned to consider a so-called "flat" topology where no distinction is made between the different types of nodes. The algorithms developed during Phase 1 addressed the networking problems for the 48 backbone nodes only. The weapon platform clusters will be included in the Phase 2 work.

During Phase 1 of the program, development of backbone network link assignment and adaptive routing algorithms, development of a simulation test facility, and development of algorithm test plans proceeded in parallel. Simulation times on a Sun-3 work station were about seven hours per run corresponding to a battle of 15 to 20 minutes duration. (Recent improvements have drastically decreased the required simulation time.) After coding and checkout, the algorithms were installed and tested on the simulation test bed with the simulation results subjected to statistical testing. A summary of current program status is shown in Tables 1 and 2. In the tables, BB refers to the backbone network, LA is link assignment, and AR is adaptive routing.

b. Summary of Algorithms

The algorithm design effort was guided by the following requirements:

- Mobile platforms and hostile environment require frequent reconfiguration of links,
- Message routing must adapt to congestion and link reconfiguration,
- Distinct types of traffic (e.g., sensor data, command and control messages) require different classes of service,
- Network organization and topology should reflect expected traffic loading,
- Algorithms should be distributed rather than centralized.

An effective topology updating scheme is essential for successful operation of link assignment and adaptive routing algorithms. The adopted approach requires that global topology information be made available to each node. With the assumed hierarchical network organization, this information can be distributed by periodic updates without excessive communication overhead. Periodic updates were chosen over asynchronous updates to simplify the routing and link assignment problems. The requirement for global knowledge of network topology, however, is restrictive. A more robust system would result if nodes only required knowledge of a limited subset of the network, perhaps only of their neighboring nodes and incident links. It would seem worthwhile to examine the feasibility of such algorithms either in the present effort or through another project concerned with the development of robust network algorithms. In the current scheme, network topology is updated every five seconds by having each node broadcast its local connectivity by a "flooding" arrangement wherein the information is sent out on all links with each receiving node retransmitting the message on all of its links except the one on which it arrived. The advantage of flooding for topology updating is that no routing tables are required. The overhead required on each link is proportional to the number of nodes and the frequency of the updates.

A more detailed discussion follows of the two key algorithms developed in Phase 1: the backbone adaptive routing algorithm and the backbone link assignment algorithm.

Table 1. Summary State of the ADNMS Program

TASK CATEGORIES	RESULTS	RELATED DOCUMENTS
1. Algorithm Development	Designed & implemented BB LA & AR algorithm in detail, other facilities at functional level	ARR (2 versions) SAD
2. Simulator Development	Designed & Implemented Harris Simulator	HSDD HSD (2 versions)
3. Test	Developed test plan and used it to test algorithms	ATP FRAT RADC
4. Program Management	Program run per plan, on cost, on schedule	PSSP MR (12) PR (4)

Also: 4 joint NRL/Harris papers
- MILCOM 2
- Simulation Conference 1
- BM/C3 Conference 1

Abbreviations

ARR - Algorithm Research Report
SAD - Selected Algorithm Description
HSDD - Harris Simulator Design Description
HSD - Harris Simulator Documentation
ATP - Algorithm Test Plan
FRAT - Final Report on Algorithm Testing
RADC - Recommended Algorithm Dsn Changes
PSSP - Program Schedule and Spending Plan

Table 2. Summary State of the Network Management Algorithm

	DEFINITION	TEST
1. LINK ASSIGNMENT (LA)		
1.1 BB LA	D	I
1.2 CLUSTER LA	F	-
2. FAILURE RECOVERY/TOPOLOGY UPDATE		
2.1 FAILURE RECOVERY	F	-
2.2 TOPOLOGY UPDATE	F	-
3. ADAPTIVE ROUTING (AR)		
3.1 BB AR	D	I
3.2 WP ROUTING	F	-
4. FLOW/CONGESTION CONTROL		
4.1 BUFFER MANAGEMENT	F	-
4.2 END-TO-END FLOW CONTROL	F	-
5. NET ENTRY/CONTROL CHANNEL		
5.1 NET ENTRY *	D-	S
5.2 CONTROL CHANNEL *	D-	S
6. STATUS MONITORING	F	-
7. MULTI ACCESS CHANNEL CONTROL *	D-	S
8. END-TO-END ERROR CONTROL	F	-
9. SECURITY	F	-

LEGEND: F=FUNCTIONAL DEFINITION; D=DETAIL DEFINITION; S=STANDALONE TEST; I=INTEGRATED TEST; *MSS - DERIVATIVE

The material below was obtained through briefings from the contractor, contract deliverables (Refs. 9, 10), and papers prepared by the contractor for presentation at technical conferences (Refs. 11, 12).

Backbone Adaptive Routing Algorithm. This algorithm dynamically determines the path a particular message takes to get from its point of origin to its destination. A recently improved algorithm has been implemented, replacing the original algorithm described in the Phase 1 contract deliverables. The new algorithm is synchronous and provides multiple routes to the destination. Some of the difficult issues associated with adaptive routing are self-reference, choice of metric, algorithm stability, and the use of heuristics. Self-reference is the problem of using links and nodes that are themselves subject to failure to disseminate information about network topology changes. Some measure of the relative worth of alternative routes must be provided to guide the search for an optimal route and this choice of metric is difficult. Stability is necessary to avoid oscillatory swings in the routing and is enhanced by techniques such as averaging link flows over several iterations of the algorithm and by load-splitting among alternative routes. Because computational complexity of optimal algorithms grows rapidly with the number of nodes and the number of links per node, and because of the frequency of changes in network topology, sub-optimal, heuristic approaches are attractive for load balancing, selection of disjoint alternative paths, and minimization of transients due to outages.

The multiple-path routing algorithm developed provides rapid failure recovery, near-optimal loop-free routes for load balancing, and fast adaptation to load variations. The algorithm also provides the basis for implementing immediate local adaptation to failures, for path diversity for redundant transmissions, and for multicast routing. The last of these features refers to the ability to address a single message to multiple destinations. To update its routing tables, each node must have global knowledge of the network topology. This is accomplished by providing status updates at five-second intervals. The updates are total rather than incremental; they do not consist only of changes since the previous update. Immediately after receiving a topology update, each node updates its routing tables and the new tables become effective simultaneously at all nodes.

The routing metric used in Phase 1 was a weighted sum of the propagation delay and the expected queueing delay on each link. Since the propagation delay term dominates, except for high-traffic loads, a modified metric is being investigated in Phase 2 that reflects both types of delay at all loads and leads to more stable algorithm performance. For each node, the routing algorithm calculates the "shortest" path to each destination--that is, the path that minimizes the chosen metric. The source and each of its neighbor nodes (those to which it is connected by a direct link) are then assigned a weight equal to the minimum distance to the destination. The only paths considered feasible from source to destination are those that pass through nodes whose distance to the destination is less than that of the source. This last criterion insures the generation of consistent routes with no loops. The stability of the routing algorithm is enhanced by splitting the traffic probabilistically among candidate paths in inverse proportion to a metric based upon the expected path delays. It was found that in some instances this load-splitting resulted in oscillatory behavior of the algorithm. A modification was made to the path metrics to minimize this effect.

Backbone Link Assignment Algorithm. The purpose of this algorithm is to establish the network topology by determining as a function of time which node pairs are to have communication links joining them. This is accomplished by creating schedules for establishing and disconnecting links. In creating these schedules, the algorithm seeks to optimize some specified network performance measure. In addition to deciding where links should be placed, the algorithm must provide a protocol by means of which two nodes that are not connected can determine where to point their antennas and quickly establish a connection. Because of the highly dynamic environment of the space-based SDI network, frequent topology changes must be accommodated in a timely fashion. The network must also be capable of rapidly reconstituting itself after extensive link and node failures. Consequently, the algorithm must be able to find a good topology with only a small amount of searching. To be successful, heuristic methods rather than exhaustive search are needed. The resulting topologies will then be good, though suboptimal.

Some candidate performance measures for use with the link-assignment algorithm are the following:

- Ability to accommodate a specified traffic-flow matrix,
- Delay for a specified traffic-flow matrix,
- Distribution of the number of node disjoint paths between all source and destination nodes (connectivity),
- Network diameter and average minimum distance between sources and destination nodes.

A traffic-flow matrix is a representation of the amount of traffic that the network must carry for each possible pair of source and sink nodes. The diameter of a network is the maximum over all node pairs of the minimum distance between two nodes; informally, it is the distance between the pair of nodes that are farthest apart. The actual link assignment algorithm used is not metric-limited and so can be used with any of these measures. The Phase 1 algorithm was evaluated against the third (connectivity) metric.

During the development of the backbone link-assignment algorithm, the following assumptions were made:

- Each satellite knows the orbital parameters of all other satellites in the network.
- Each satellite has accurate global timing.
- A low-bandwidth control channel is available on which to exchange the protocol information and certain status data between satellites in line of sight of each other.
- CRC codes provide error-free reception of protocol information.
- The network management scheme provides topology update information over the high-bandwidth channels to all nodes within an island.

In the last assumption, an island is a set of nodes which can communicate with each other via the high-bandwidth links. Through node and link failures, it is possible for the network to become partitioned or fragmented into two or more such islands with no communication possible between them other than over the control channel. Techniques for rejoining islands must have high priority in any acceptable link-assignment algorithm.

To minimize the computational burden, a heuristic "hill-climbing" algorithm was chosen for selecting link assignments. In this scheme, links are added or deleted only if doing so improves the value of the chosen metric. The only way the metric can degrade is as a result of links disappearing because of hostile actions or because nodes move out of communication range of each other. The algorithm is distributed in that it is carried out at each node. Two basic operations are available: (1) adding a link, and (2) breaking a link and adding another link. Criteria used in making the decision include trying to maximize island size, to maximize the minimum pairwise node connectivity, and to minimize the number of node pairs with minimum connectivity. Links can be added by all nodes simultaneously as long as the addition reduces neither connectivity nor island size. However, during a break-and-add-links operation, control is rotated among the nodes to prevent a reduction in connectivity or island size from occurring. The timing of the link assignment functions is controlled through the use of frames consisting of multiple subframes. The subframes of the Break and Add Links Frame, for example, are Join Islands, Update Topology, Improve Connectivity, and Update Topology.

The implemented algorithm was tested for the case where all 48 nodes of the backbone were within communication range of each other but no links existed initially. This is the so-called "cold start" condition. The algorithm achieved a single-island network of 4-connected nodes in approximately two minutes. Connectivity improved rapidly after the second iteration of the algorithm, with the network becoming 3-connected after the fifth iteration and 4-connected just after the start of the sixth iteration. For the test case, the maximum possible connectivity was four.

A number of improvements are planned for the link assignment algorithm during Phase 2. The Phase 1 algorithm only attempts to provide robust connectivity. That metric will be augmented in Phase 2 to include accommodation of the specified traffic load matrix. Another goal is to reduce the time required by the algorithm.

Although initial effort is concerned solely with developing a good algorithm, this algorithm eventually must interface with other network management functions, notably failure recovery/topology update and adaptive routing. The link-assignment algorithm will influence the approach taken for failure recovery/topology update. Indeed, some failure recovery mechanisms are now contained within the link assignment algorithm. The adaptive routing algorithm may be subjected to large transients as a result of the deletion and addition of links. Interactions such as these must be carefully considered in the final choice of a link-assignment algorithm.

c. Comments and Concerns

The work done by Harris Corporation on this project has been outstanding. They have done an impressive amount of work in the first year with a fairly small staff and relatively small budget. Along with the development, coding, and testing of the algorithms, they have produced a substantial amount of high-quality documentation. They are familiar with the state of the art in network algorithms and have been creative in attacking the SDI networking problem. For example, the use of load-splitting in their routing algorithm helps to improve the stability of the algorithm as well as provide improved throughput by balancing the load on alternative routes. In addition, load-splitting has the potential to increase system robustness by finding disjoint message paths. Finally, Harris is aware of the limitations of their algorithms and has suggested many areas where improvements to existing approaches or the implementation of alternatives should be studied (Ref. 13).

Despite the above favorable comments, there are a number of features of the implemented algorithms that cause some concern and should be examined in subsequent phases of the contract. Some of these concerns have been recognized by Harris and some have not been. A listing follows:

1. Current algorithms work well with the proposed backbone network consisting of 48 nodes. Whether these algorithms can be modified to handle a full constellation of possibly thousands of nodes in a reasonable time is unclear. Since the computational complexity of the current approach varies as a power of the number of nodes, this is a potentially serious problem.

2. The present approach makes use of heuristic algorithms and accommodation of larger numbers of nodes will likely make their use even more imperative. It is important to have some means of ensuring the "correctness" of such heurisitics to guarantee that good solutions will be obtained in all cases and that the algorithm will not get hung up. Techniques for establishing such proofs need to be developed.

3. The routing algorithm's robustness is limited by the need for each node to have knowledge of the global topology of the network at all times. It would be better if only local connectivity information were required. For example, a node might only be required to know the state of other nodes in some limited neighborhood. Such a restriction may limit the quality of the routing but achieve acceptable results while reducing communications overhead and increasing robustness of the network. (See Comment 8 below.)

4. The current link-assignment algorithm assumes the existence of a separate low-rate control channel that is needed for rejoining islands formed as a result of network failures. Dependence on this additional channel obviously increases the vulnerability of the network. A link-assignment algorithm that does not require the existence of a separate channel would be preferable.

5. It is assumed that global timing is available at all nodes. Such timing is important in the operation of the link-assignment algorithm since the breaking and adding of links must be highly coordinated. Although it is claimed that extreme accuracy is not required, it is not clear whether synchronization is achieved through the exchange of messages or if the clocks resident at each node are sufficiently accurate. If message exchange is necessary, the robustness of the network is diminished.

6. In carrying out statistical testing of the implemented algorithms, more simulation runs than used at present should be conducted to increase the reliability of the results. In addition, since simulations are time-consuming, sophisticated variance-reduction techniques should be used to obtain the maximum utility from each run.

7. Because of their computational complexity, attempts should be made to develop network algorithms that can be implemented on parallel processors. This has the potential for greatly speeding up current algorithms and will probably be absolutely essential for the successful implementation of algorithms for a network containing thousands of nodes.

8. Algorithms should be sought that minimize the communications overhead imposed upon the network. In addition to freeing up communication resources to handle more message traffic, the increased autonomy of the nodes will improve system robustness by reducing the amount of coordination needed for network management. (See Comment 3 above.)

See Appendix B for a brief description of more recent accomplishments on this effort.

VI. RELEVANT NETWORKING EFFORTS

Because of the complexity of the SDI networking problem, it would be advantageous to exploit relevant concepts and algorithms that may have been developed for other systems. The SDI situation is unique because of the combination of network size, platform dynamics, and time criticality of the functions that must be performed. Nevertheless, some of these features are shared by other systems and networking solutions used by them may be applicable to SDI, either directly or in modified form. This Chapter takes note of a number of systems whose networking concepts may be transferable to SDI. While these systems are representative of other efforts, no claim of completeness is made; there may well be additional relevant networking efforts that we were not able to identify within the time and resource limitations of this study.

A. PACKET RADIO NETWORKS

These networks are used to provide store-and-forward operation to terminals via radio transmission. They are intended to serve mobile terminals, though in many applications the terminals are fixed. The January 1987 issue of the *Proceedings of the IEEE* (Ref. 5) was a special issue on packet radio networks. The relevance of such networks to SDI is apparent from the following excerpt taken from the paper by Leiner, Nielson, and Tobagi (Ref.5):

> There are a number of common issues involved in the design of these networks. These include .... methods for determining connectivity and using that connectivity to route data through the network, methods for achieving reliable communications in a typically noisy radio environment, and methods for managing and controlling the distributed network.

An example of such a packet radio network is the Navy's High Frequency Intra Task Force (HF ITF) Network (Refs. 14, 15). This network has a maximum of about 100 mobile nodes and its design is heavily influenced by the characteristics of the HF channel. Despite these dissimilarities to the SDI network, similar network-management functions are required. A fully distributed algorithm enables the network to reconfigure itself when it is affected by connectivity changes such as those caused by jamming. Study of the network control techniques used in this system may be of value in designing SDI network-management algorithms.

Some features of the DARPA Packet Radio Network (PRNET) design (Ref. 16) also may be useful for SDI. This system can accommodate networks of about fifty nodes with limited mobility operating via a common radio channel. Fully automated, distributed network management algorithms and protocols to organize, control, maintain, and move traffic through the packet radio network have been designed, implemented, and tested. These algorithms dynamically determine optimal routes and control congestion in an environment characterized by changing link conditions, node mobility, and varying traffic loads. Although a node can have many neighbors, the algorithms employ a logical hierarchical structure that limits the number of logical neighbors to a manageable size.

In addition to the above two examples, there are other packet radio systems that should be examined for relevant ideas, such as the Battlefield Information Distribution (BID) Network. This network is based upon an adaptation of the PRNET concepts and employs a hierarchical structure with distributed control.

B. COOPERATING SATELLITE SYSTEM (CSS) EXPERIMENT

Although this effort falls within the SDIO BM/C^3 Experimental Systems Program Element, it is worth mentioning since it will provide a near-term test bed for candidate network control algorithms. At present, there is nothing approaching a realistic space-based network that can test such algorithms. Airborne platforms cannot adequately emulate orbital ranges and dynamics and they are subject to much more vibration than would be experienced by an orbiting platform. Even though the CSS experiment will only have eight nodes, the ability to test link-assignment and routing algorithms, for example, in an orbiting network should lead to significantly better algorithms.

C. DIRECTION CONTROL AND WARNING COMMUNICATION SYSTEM (DCWCS)

This is a large-scale system, similar in complexity to SDI, being developed for the Federal Emergency Management Administration (FEMA). The program has been ongoing for about two years, with Harris Corporation as the prime contractor.

D. DEFENSE COMMUNICATIONS SYSTEM

The Defense Communications Engineering Center (DCEC) is responsible for maintaining and improving the Defense Communications System. This system encompasses both voice and data networks distributed worldwide. Techniques used for managing such large networks may be applicable to SDI.

E. COMMERCIAL NETWORKS

Many privately operated commercial data communications systems employing satellites exist. Some are operated by corporations to link geographically separated locations, while others are used by television and radio broadcasting companies to provide programming to their local affiliates nationwide. Because of their size and the data rates involved, network-management concepts for these systems should be examined as part of the SDI networking efforts.

F. MITRE BM/C^3 NETWORK ARCHITECTURE AND SIMULATION

The MITRE Corporation, in Bedford, Massachusetts, is being funded under the SDIO BM/C^3 Experimental Systems program at the Air Force Electronic Systems Division (ESD) to establish an in-house prototyping capability to provide design guidance for the Experimental Version (EV) and NTB programs and quick insight/resolution of critical BM/C^3 issues. Part of this activity includes the demonstration of rudimentary interplatform communications.

1. Network Architecture

MITRE is using a BM/C^3 architecture that is loosely based on the Zero-One Architecture and that uses the following structure for initial deployment;

- 378 platforms
- 9 planes, 42 platforms per plane
- 800 km altitude, 88 deg inclination
- Each platform has sensor, weapon, and battle management suite.

The sensor suite is composed of 4 sensor cubes; 2 SWIR and 2 UV per cube; 30 deg by 60 deg FOV; and 1-km resolution at 2000 km. The weapons suite is composed of 10 KKVs, 10 defense weapons, 6 km/s ΔV for initial deployment and 8.5 km/s ΔV for final deployment. The BM/C^3 suite contains one lasercom, or 60 GHz, link (TBD) for

BSTS connectivity; four lasercom, or 60 GHz, link for terrestrial-space connectivity; and processors for track-association and weapon-allocation functions. Each platform is a member of four different sensor groups (one for each sensor) and each group has one group leader. Additionally, each platform knows the alive/dead status of other platforms, has synchronized clocks, and knows ephemerides of all platforms with which it may link. Platform-to-platform link-acquisition time is approximately 1 s.

The network topology for this strawman architecture is a simple grid where platforms are connected in-plane plus neighbor planes with no links near the poles. The routing is minimally adaptive, with flooding for high-priority broadcast traffic and directional for point-to-point traffic.

2. Network Simulation

The objective of the communications networking simulation (COMSIM) that MITRE is creating is to analyze and evaluate SDI communications architectures through simulation focusing on platforms (addresses and dynamics), communication ports (data rates and point-to-point/omni-directional links), routing protocols (hop-by-hop and end-to-end), and message sources (threat and battle management). The framework is to provide simulation features or pieces common to most or all SDI architectures, is written in C, and runs on a PC. A demonstration of Block 1 of COMSIM will take place in September 1987 and will feature:

- A rough approximation of orbital dynamics;
- Platforms with multiple ports; full duplex, point-to-point links; and subject to attrition;
- Links modeled as propagation, transmissions, and queueing delays, and with/without errors;
- Routing limited for flooding up to N hops and retransmit out all other ports;
- Addressing limited to point-to-point, broadcast, and with or without acknowledgments (acks) but no negative acknowledgments (nacks); and
- Messages repeated regularly or randomly, source or destination addressing with either one randomized, and no content or no specific scenarios (i.e., uniform message size).

Output from the COMSIM will be displays of message delay distribution by type; maximum/mean delay per clock tick; queue lengths; delay per hop; undeliverable messages; and simulation time. No graphic displays are currently planned.

VII. RECOMMENDATIONS

This section presents recommendations for topics that should be pursued by SDIO in the area of BM/C^3 networks during the next fiscal year. Some of the recommendations concern changes or refinements to ongoing programs while others identify areas of importance that are not currently being pursued. Some of the suggestions concern technical networking issues, while others concern management of the network technology program. The technical issues are presented first. These recommendations are intended to guide the SDIO during preparation of the FY 1988 budget.

1. Examine networking concepts from other large-scale networks, both government-funded and commercial. Some relevant examples are contained in Chapter VI.

2. Gain visibility into black programs that are likely to involve networking. This potentially has a large payoff in terms of acquiring advanced technology, saving time, and saving money.

3. Address the complicated issues of interfacing SDI network and communication protocols and hardware with that of other systems, e.g., Milstar. This will be a non-trivial exercise and must be incorporated early in the system design.

4. Recognize the need for SDI to interface with Allied communication systems. This requirement will likely be even more difficult to meet than interfacing with other U.S. systems. In addition to the technical issues involved, there are thorny security concerns that must be addressed.

5. Follow and support research on distributed processing currently underway. This research is addressing problems that must be faced in the SDI network management area. Some of these issues are discussed by Bertsekas and Gallager in their recent book (Ref. 17). In addition, Kleinrock (Ref. 18) has identified the following underlying principles of distributed-systems behavior which serve as a guide to the types of studies needed in this area:

    - Developing innovative architectures for parallel processing,
    - Providing better languages and algorithms for specification of concurrency,
    - More expressive models of computation,
    - Matching the architecture to the algorithm,

- Understanding the trade-off among communication, processing, and storage,
- Evaluation of the speed-up factor for classes of algorithms and architectures,
- Evaluation of the cost-effectiveness of distributed-processing networks,
- Study of distributed algorithms in networks,
- Investigation of how loosely coupled self-organizing automatons can demonstrate expedient behavior,
- Development of a macroscopic theory of distributed systems,
- Understanding how to average over algorithms, architectures, and topologies to provide meaningful measures of system performance.

6. Pursue the use of parallel processors for the implementation of network management and control functions, such as link assignment, adaptive routing, topology update, and congestion control. These functions must be performed continuously to insure network connectivity in a hostile environment. At present, for large networks these functions are prohibitively time-consuming. Parallel processing, together with the use of heuristics, holds the promise of reducing these times to acceptable values.

7. Develop more robust distributed algorithms capable of functioning with only limited knowledge of network topology but not overloading the communication channels with redundant messages.

8. Define meaningful network performance measures for SDI. These measures should reflect system robustness, connectivity, and ability to accommodate evolutionary changes in addition to the more traditional measures of throughput and delay. Even these last two metrics may need to be defined in non-traditional ways to insure that the resulting network will perform satisfactorily. The adopted metrics must have operational value in the sense that observed network behavior can be translated into a score, preferably quantitative, that can then be used to rank-order alternative network concepts.

9. Give more attention to the space-ground and space-air portions of the network. The former area involves internetworking considerations, while the latter is characterized by less predictable inter-platform range and range rate which complicates the network management task. Most of the networking efforts to date have focused on the space-based or ground-based portions of the network.

10. Analyze alternatives for rapid link synchronization and command authentication, crypto key distribution, communication protocols, and link

reconfiguration algorithms. These items determine the rapidity with which links can be placed in service and so affect network performance measures.

11. Expand the preliminary work on crypto key management and distribution and on message authentication. These network security features affect the ability to reliably and securely transmit messages throughout the network.

12. Develop techniques for rapid link acquisition to support adaptive networking algorithms. The ability of the network to accommodate topological changes depends upon being able to quickly add links when needed.

13. Explore the integration of network routing and reconstitution, focusing on *distributed* and *approximate* network control algorithms. Distributed techniques require less communication overhead since global information is not needed by each node and approximate algorithms take less time to execute. Simultaneous consideration of routing and reconstitution should yield better solutions than are available at present.

14. Encourage the development of heuristic algorithms to arrive at good networking strategies when handicapped by inconsistent or incomplete information regarding the state of the network. In particular, encourage the application of innovative artificial intelligence concepts to network management problems, e.g., creation of expert systems for adaptive routing and network reconstitution.

15. Investigate the use of hybrid routing algorithms to exploit the advantages of different types of algorithms, e.g., quasi-static and dynamic, or centralized and distributed.

The foregoing recommendations focus on technical concerns. The following suggestions are of a procedural nature, intended to guide the management of the networking technology program.

16. Develop a mechanism for promoting meaningful technical interchanges between contractors working on similar problems. This might take the form of workshops involving technical, not managerial, personnel. Direct SDIO involvement may be needed to overcome contractor or service reluctance to discuss ideas and products openly. If successful, a beneficial synergism of ideas and avoidance of duplication of effort should result.

17. Require contractors developing models and algorithms to make them compatible with a specified common simulation testbed. This would allow comparisons to be made between the models and algorithms. At present, such comparisons cannot, in general, be carried out. Such a common testbed is needed prior to the availability of the National Test Bed (NTB).

18. Require all of the networking technology efforts to adhere to the Phase I (baseline) architecture requirements. All results should specifically relate to that architecture and their contribution to satisfying associated requirements should be made clear.
19. Require that all networking efforts emphasize simulation and testing of models and algorithms in addition to mathematical proofs of correctness. Insofar as possible, project deliverables should be tools that are modular and can be incorporated into later network design studies.
20. Develop mechanisms to insert results of the network technology program into the Experimental Versions (EVs) to avoid duplication of effort and to ensure use of the best available networking techniques.

REFERENCES

1. The Strategic Defense Initiative Organization and SRS Technologies, *Zero-One Study Report,* 20 March 1987.

2. The Strategic Defense Initiative Organization and SRS Technologies, "Strategic Defense Battle Management Command, Control, and Communications Briefing Master," March 1987.

3. Sandell, N.R., "Research Issues in Network Control for Strategic Defense," presented to SDI Networks Committee Meeting, 20 November 1986.

4. Institute for Defense Analyses, "Network Communications," *SDI Preliminary Software Technology Program Integration Plan,* 02 July 1986.

5. Leiner, B.M., D.L. Nielson, and F.A. Tobagi, "Issues in Packet Radio Network Design," *Proceedings of the IEEE,* Vol. 75, No. 1, January 1987.

6. Sowa, P., "SDI BM/C^3 Communications," briefing to the SDI Advisory Committee BM/C^3 Working Group, January 1987.

7. The Armed Forces Communications and Electronics Association, "Network Technology Section," *Strategic Defense Initiative Battle Management/Command, Control and Communications Technology Study Phase I,* 1 December 1986.

8. U.S. Army Strategic Defense Command, "Networks," *SDI Large-Scale System Technology Study Final Report,* 28 March 1986.

9. Cain, J.B., and S.L. Adams, "Selected Algorithm Description," *Harris Corporation ADNMS Technical Report,* prepared for Naval Research Laboratory, Contract No. N00014-86-C-2056, August 20, 1986.

10. Cain, J.B., "Algorithm Research Report," *Harris Corporation ADNMS Technical Report,* prepared for Naval Research Laboratory, Contract No. N00014-86-C-2056, February 16, 1987.

11. Cain, J.B. et al., "A Distributed Link Assignment (Reconstitution) Algorithm for Space-Based SDI Networks," unpublished paper, April 1987.

12. Cain, J.B. et al., "A Near-Optimum Multiple Path Routing Algorithm for Space-Based SDI Networks," unpublished paper, April 1987.

13. Knoke, P.J., "Recommended Algorithm Design Changes," *Harris Corporation ADNMS Technical Report,* prepared for Naval Research Laboratory, Contract No. N00014-86-C-2056, February 16, 1987.

14. Ephremides, A., J.E. Wieselthier, and D.J. Baker, "A Design Concept for Reliable Mobile Radio Networks with Frequency Hopping Signaling," *Proceedings of the IEEE,* Vol. 75, pp. 56-73, January 1987.

15. Baker, D.J., A. Ephremides, and J.A. Flynn, "The Design and Simulation of a Mobile Radio Network with Distributed Control," *IEEE Journal on Selected Areas in Communications,* Vol. SAC-2, pp. 226-237, January 1984.

16. Jubin, J.D., and D. Tornow, "The DARPA Packet Radio Network Protocols," *Proceedings of the IEEE,* Vol. 75, pp. 21-32, January 1987.

17. Bertsekas, D.P., and R.G. Gallager, *Data Networks,* New Jersey: Prentice-Hall, 1986.

18. Kleinrock, L., "Distributed Systems," *IEEE Computer Magazine,* Vol. 18, pp. 90-103, November 1985.

19. Lawandales, E.F., and A.L. Polivka, "*Communications Networking for SDI Applications,*" Harris Corporation Draft of Final Technical Report, prepared for AFSC Rome Air Development Center, Contract No. F30602-85-C-0272, March 10, 1987.

20. Harris Corporation, "*Draft Functional Description Document for the Internetted Systems Modeling,*" prepared for Rome Air Development Center, Contract No. F30602-86-C-0217, April 13, 1987.

APPENDIX A

NETWORKS DATA BASE REPORTS

APPENDIX A
NETWORKS DATA BASE REPORTS

The structure of the dBASE III Plus data base is as follows:

FIELD	DESCRIPTION	SIZE	NAME IN REPORT
IDA-ID	Unique identifier for each effort	5	IDA-ID
WPD	Work Package Directive	4	WPD
WPD-SEQNUM	Unique identifier for each task that relates back to another IDA data base which collects information on WPDs	5	WPD-SEQNUM
EFF-TITLE	Title of the effort as present by the Service/Agency	100	Effort Title
EFF-FY87	Contract dollars	8	FY 87 under Task Title
EFF-FY88	Contract/proposed dollars	8	FY88$ under Effort Title
TASK-TITLE	Title of the task as presented in the WPD	100	Task Title
TASK-FY87	Allocated FY87 dollars	8	FY 87$ under Task Title
SERVICEORG	Service organization having contracting authority	6	Service Organization
SERV-POC	Service/Agency point-of-contact	50	Point of Contact
SERV-PHONE	Phone number of POC	12	Phone Number
PRIMECONTR	Prime contractor	50	Prime Contractor
PRIME-ADDR	Address of prime contractor	100	Address

PRIMETPOC	Technical point-of-contact for the prime contractor	50	Technical Point of Contact
PRIME-PHON	Phone number for TPOC at prime contractor	12	Phone Number
CONTRACTNO	Contract number for prime contractor	20	Contract Number
CONTRBEGIN	Beginning date of contract	8	Contract Begin Date
CONTREND	Ending date of contract	8	Contract End Date
SUBCONTR	Subcontractor	50	Subcontractor
SUB-ADDR	Address of subcontractor	100	Address
SUB-TPOC	Technical point-of-contact for subcontractor	50	Technical Point of Contact
SUB-PHON	Phone number for TPOC at subcontractor	12	Phone Number
OBJECTIVE	Objective of effort	1000	Objective
ACCOMPLISH	Accomplishments to date	1000	Accomplish-ments to Date
RELE-BMC3	Relevance of effort to BM/C3	1000	*
CONCLUSION	Conclusions about this effort	1000	*

An additional data base was created to capture information on CDRLs, document titles, and due date of the deliverables for each effort. This information is *related* back to the data base described above through the use of IDA-ID.

A third data base was created to capture information on subject and due date of technical meetings. IDA-ID *relates* this information back to the primary data base.

Three types of reports were generated from these data bases. The first report presents adminstrative data from the primary data base; all funded efforts should have one

* Not included in revised draft report.

of these reports. The second report presents technical documentation about contract deliverables (CDRLs, documents, and due dates) with data from the second data base and schedule of technical meetings (subject and due date) with data from the third data base. The second report is generated only if there is information on a specific effort. The third report produces a technical summary from the objective and accomplishment data fields in the primary data base. This report is also generated only if information exists.

It is very important to recognize the difference between FY87$ under Effort Title and FY87$ under Task Title. FY87$ under effort refers to the contract dollars while FY87$ under task refers to WPD dollars. There is not a one-to-one mapping. For example, WPD B413 has four tasks which spawned fifteen efforts.

The following pages represent the reports from the data base.

IDA-ID: 00002	WPD: B412	WPD-SEQNUM: 00158

EFFORT TITLE	Conceptual Design of a Distributed Data Management System (DDMS)
FY87 $:	1,300,000
FY88 $:	1,300,000
TASK TITLE:	Distributed Data Management System
FY87 $:	1,300,000
SERVICE ORGANIZATION:	USASDC
POINT OF CONTACT:	Virginia Kobler
PHONE NUMBER:	205-895-3857
PRIME CONTRACTOR:	Softech
ADDRESS:	460 Totten Pond Road, Waltham, MA 02254
TECHNICAL POINT OF CONTACT:	Rueben Jones
PHONE NUMBER:	
CONTRACT NUMBER:	DASG60-86-C-0033
CONTRACT BEGIN DATE:	Apr 86
CONTRACT END DATE:	Apr 89
SUBCONTRACTOR:	Nichols Research Corporation
ADDRESS:	Huntsville, AL
TECHNICAL POINT OF CONTACT:	Alice Brown
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
A001	Cost/Schedule Status Report	
A002	Research Plan	
A003	Software Requirements Documentation	
A004	Special Technical Reports	
A005	Software Design Document	
A006	Software Test Definition	
A007	DMS Workbench Test Report	
A008	BM/C^3 Functional Simulation Test Report	
A009	Quarterly Progress Report	
A010	Final Report	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

TECHNICAL SUMMARY

OBJECTIVE: Perform a conceptual design of a DMS to support SDI. This evaluation will require examination of underlying data structures, data flow requirements, and analysis of data graphs, to support the operational aspects of weapons, sensors, and computing platforms, as well as the higher level architecture to support BM/C^3. The effort shall include the development of requirements for a DMS, to include new requirements in view of the BMD environment. Specific design concepts will be developed for alternative approaches. These concepts will be evaluated and recommended approaches will be provided. The viability of the proposed design will be demonstrated by the implementation of a prototype system.

ACCOMPLISHMENTS TO DATE: Have developed the techniques and algorithms for control of a distributed computing system.

IDA-ID: 00003	WPD:B412	WPD-SEQNUM: 00157

EFFORT TITLE:	Controllers for Distributed Computing Systems
FY87 $:	
FY88 $:	
TASK TITLE:	Management of Distributed Systems
FY87 $:	1,200,000
SERVICE ORGANIZATION:	USASDC
POINT OF CONTACT:	Virginia Kobler
PHONE NUMBER:	205-895-3857
PRIME CONTRACTOR:	Unisys (formerlySystems Development Corporation)
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
A00B	Controller Development Plan	
A001	Controller Functional Requirements	
A002	Workload Model Evaluation	
A003	Experiment Plans	
A004	Controller Designs	
A005	Controller Evaluation Report	
A007	Controller Implementation Technology Report	
A008	DCDS/PDL Evaluation	
A00C	Global DCS Controller Analysis	
A00D	Conceptual Design of DCS Controller	
A00E	Conceptual Designs and Performance Projections of DCS Employed Controller Concepts	
A00F	Oral Technical Discussions	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

TECHNICAL SUMMARY

OBJECTIVE: Develop and demonstrate a central philosophy which will support the effective utilization of tightly coupled distributed computing resources within various BMD defense regimes. The desire is not only to meet throughput performance requirements, but also to exhibit a high degree of robustness and fault tolerance. The control to achieve these goals is envisioned as closed loop, employing feedback to optimize desired performance characteristics. Control includes aspects of task scheduling, task creation and deletion, task control, response to exceptional conditions, resource allocation, protection, communication, etc. These functions also include normal operating system (OS) functions as well as resource management functions normally allocated to the applications. It is also believed that to achieve these capabilities, the distributed system controller will function at two levels; a policy level, and an implementation level. Interfaces with the applications programs and a minimum kernal operating system will be defined as part of the research effort. It is planned that the technology will evolve from control of fixed interconnection topologies to those of a more dynamic nature.

ACCOMPLISHMENTS TO DATE:

IDA-ID: 00004	WPD: B413	WPD-SEQNUM: 00076

EFFORT TITLE:	Communications Network for SDI Application
FY87$:	352,546
FY88 $:	
TASK TITLE:	Communications Network
FY87 $:	700,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger
PHONE NUMBER:	315-330-2066
PRIME CONTRACTOR:	Harris Government Aerospace Systems Division
ADDRESS:	P.O. Box 37, Melbourne, FL 32902
TECHNICAL POINT OF CONTACT:	E.F. Lawandales
PHONE NUMBER:	
CONTRACT NUMBER:	F30602-85-C-0272
CONTRACT BEGIN DATE:	Oct 85
CONTRACT END DATE:	Apr 87
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Final Technical Report	01 Apr 87

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

TECHNICAL SUMMARY

OBJECTIVE: To assess network techniques which may be applicable to the Strategic Defense Initiative (SDI) and identify any deficiencies in those technologies which are required to meet mission requirements. Specific objectives are to:

- Define the communication requirements for multiple SDI architectures,
- Propose potential network solutions to meet the requirements,
- Perform functional adequacy assessments, trade-offs, and sensitivity analyses to develop recommendations for communications networking approaches,
- Assess technology deficiencies, and
- Recommend follow-on technology and test bed programs.

ACCOMPLISHMENTS TO DATE:

Contract is complete.

IDA-ID: 00005	WPD: B413 WPD-SEQNUM: 00076
EFFORT TITLE:	Internet System Modeling
FY87 $:	417,800
FY88 $:	
TASK TITLE:	Communications Network
FY87$:	700,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Mary Denz
PHONE NUMBER:	315-330-2066/315-330-3623
PRIME CONTRACTOR:	Harris Government Information Systems Division
ADDRESS:	505 John Rodes Blvd., Bldg 1, Melbourne, FL 32935
TECHNICAL POINT OF CONTACT:	Joe Lugo
PHONE NUMBER:	305-242-5649
CONTRACT NUMBER:	F30602-86-C-0217
CONTRACT BEGIN DATE:	11 Sep 86
CONTRACT END DATE:	10 Sep 88
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
A001	R & D Status Report	
A002	Contract Funds Status Report	
A003	Presentation Material	
A004	Functional Description	
	Draft Functional Description	09 Dec 86
A005	Users Manual	
A006	Program Maintenance Manual	
A007	Test Plan	
A008	Test Analysis Report	
A009	On-the-Job Handbook	
A010	Technical Report	
	Software Development Plan for the Internet System Model	18 Dec 86

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
IPR at RADC	09 Dec 86
IPR at Harris	28 Apr 87

TECHNICAL SUMMARY

OBJECTIVE: Using the Distributed System Simulator (DSS) as a baseline;

- Define the requirements of modeling tools to support the analysis and system design of an internetted, distributed data processing system appropriate to the SDI environment;
- Develop the means to perform detailed system performance analysis to match physical implementation against functional requirements; and
- Demonstrate the utility of the tools for evaluating ground/air/space battle management techniques.

This effort shall define the requirements, limitations, and scope of modeling tools for an air/ground/space system for the purpose of performing detailed system performance analysis. The effort shall include the design and development of modeling tools based on the requirements identified in the definition phase and utilize the available assets of the DSS. The DSS shall be extended to consider the traffic flow and system functionality associated with multi-cluster, internetted configuration of ground, airborne, and satellite nodes. Consideration must be given to protocols, functional partitioning, data load, data sharing, and reconfigurability. The result shall be highly interactive and completely accomplished within computer programming. The modeling tools shall be able to accept real world data to serve as a testing device. It is essential that the modeling tools include graphics routines which are user-friendly and provide insight for the system analyst to determine measures of system effectiveness, system requirements and recommended solutions.

ACCOMPLISHMENTS TO DATE:

IDA-ID: 00006	WPD: B413	WPD-SEQNUM: 00076

EFFORT TITLE:	Wideband Satellite Support (MIPR to DARPA)
FY87 $:	285,000
FY88 $:	285,000
TASK TITLE:	Communications Network
FY87$:	700,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger
PHONE NUMBER:	315-330-2066
PRIME CONTRACTOR:	Bolt Beranek & Newman
ADDRESS:	30 Moulton Street, Cambridge, MA
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	Dec 85
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL SUMMARY

OBJECTIVE: Ground station and satellite channel access with all support. This is part of an effort which maintains and operates a five node satellite communications network.

ACCOMPLISHMENTS TO DATE:

IDA-ID: 00023 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	BM/C^3 Communication Network Design
FY87 $:	375,000
FY88 $:	505,000
TASK TITLE:	Communications Network
FY87 $:	700,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger
PHONE NUMBER:	315-330-2066
PRIME CONTRACTOR:	Harris Government Aerospace Systems Div.
ADDRESS:	P.O. Box 94000, Melbourne, FL 32902
TECHNICAL POINT OF CONTACT:	Paul Julich
PHONE NUMBER:	305-729-3196
CONTRACT NUMBER:	F30602-86-C-0224
CONTRACT BEGIN DATE:	Sept. 1986
CONTRACT END DATE:	March 1989 (30 mos.)
SUBCONTRACTOR:	Clarkson University
ADDRESS:	Electrical and Computer Engineering Dept. Potsdam, NY 13676
TECHNICAL POINT OF CONTACT:	Dr. Robert Meyer
PHONE NUMBER:	315-268-6541

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT		DUE DATE
	Interim Technical Report		Jan 87
	System Segment Specification (A Spec)	Draft	Jan 87
		Final	Feb 87
	Data Base Design Document	Draft	Feb 88
		Final	Feb 89
	Software Top-Level Design Document	Draft	Feb 89
		Final	Mar 89
	Software Detailed Design Document	Draft	Feb 89
		Final	Mar 89
	Final Technical Report		Mar 89
	Technical Status		Monthly
	Funding Status		Monthly

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
Initial Design Review	Mar 87
Final Design Review	Mar 88
Quarterly Reviews	Oct 87 & every 3 mos.
Final Project Briefing	Mar 89

TECHNICAL SUMMARY

OBJECTIVE: The major objective is to develop a design methodology for a SDI communication network and to develop an understanding of the advantages of different design techniques and tools. The design methodology is expected to incorporate the following features:

- Flexibility to accommodate new technology,
- Flexibility to permit varied use,
- Software portability,
- Redundancy and fault tolerance,
- Excess capacity,
- Extensibility,
- Use of standard approaches, where feasible,
- Use of artificial intelligence, and
- Use of existing studies and research.

ACCOMPLISHMENTS TO DATE: To date the following contract deliverables have been produced:

Interim Technical Report	January 1987
Draft System Segment Specification	January 1987
Initial Design Review	May 1987

1. For the near-term and far-term architectures, developed a detailed functional description for each major system element.
2. Developed data flow specifications for the types of data that must be exchanged.
3. Held an Initial Design Review in May 1987 which elaborated upon some of the design areas included in the Interim Report.
4. Developed an overall design methodology that includes as key design criteria minimizing complexity, maximizing flexibility, and maximizing use of available technology.
5. Developed a methodology for designing a baseline communication architecture using results of an earlier study.

IDA-ID: 00007	WPD: B413	WPD-SEQNUM: 00231

EFFORT TITLE:	Distributed Systems Topology
FY87 $:	306,000
FY88 $:	
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Richard Sweed
PHONE NUMBER:	315-330-2066/315-330-2805
PRIME CONTRACTOR:	Advanced Decision Systems
ADDRESS:	201 San Antonio Circle, Suite 286, Mountain View, CA 94040
TECHNICAL POINT OF CONTACT:	Andrew Cromarty
PHONE NUMBER:	415-941-3912
CONTRACT NUMBER:	F30602-85-C-0199
CONTRACT BEGIN DATE:	23 Aug 85
CONTRACT END DATE:	23 Aug 87
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	"SDI Distributed Topology-Project Review"	Dec 86

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
Monthly progress reports	Monthly

TECHNICAL SUMMARY

OBJECTIVE: Address current limitations in networking technology in areas of critical importance to SDI. Take a new look at the battle management problem, unconstrained by prior approaches, and formulate a set of requirements and candidate system topology to respond to those requirements. Define unique areas where novel approaches can be applied. The approach taken should be revolutionary rather than evolutionary with a focus on two areas: active process migration and knowledge-based routing.

ACCOMPLISHMENTS TO DATE:

1. Reviewed the open literature, including the Fletcher and Eastport studies, and developed a set of system requirements.
2. Based on derived requirements, developed a system topology
3. Identified a number of security requirements.
4. Developed a set of general protocol requirements.
5. Implemented a distributed computing research testbed using the Scheme dialect of LISP.
6. Developed and demonstrated in their Scheme LISP environment the ability to transmit arbitrary LISP objects from one machine to another.
7. Completed implementation (nearly) of heterogeneous process migration via datagram.

IDA-ID: 00008 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	Distributed Processing System Topology
FY87 $:	453,000
FY88 $:	
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Mark Zonca
PHONE NUMBER:	315-330-2066/315-330-2805
PRIME CONTRACTOR:	SRI
ADDRESS:	333 Ravenswood Ave., Menlo Park, CA 94025
TECHNICAL POINT OF CONTACT:	Nachum Shacham
PHONE NUMBER:	415-859-5710
CONTRACT NUMBER:	F30602-85-C-0186
CONTRACT BEGIN DATE:	14 Aug 85
CONTRACT END DATE:	13 Aug 87
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
A001	Monthly Status Reports	
A002	Interim Technical Report	Sept. 86
A003	Final Technical Report	Sept. 87

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
Semi-annual Progress Briefings	Feb. 86
	Aug. 86
	Feb. 87
	Aug. 87

TECHNICAL SUMMARY

OBJECTIVE: To address current limitations in networking technology in areas of critical importance to SDI. The focus is on:

1. Algorithms for dynamic message routing and link scheduling,
2. Developing an environment to accommodate object-oriented programming using remote operations,
3. Distributed algorithms for establishing network connectivity,
4. Algorithms and protocols for ensuring loop-free routing of messages.

ACCOMPLISHMENTS TO DATE:

1. Routing algorithms:
   - Nearly optimal quasi-static routing algorithm
   - Heuristic dynamic routing algorithm
   - Hybrid hierarchical routing algorithm (quasi-static and dynamic)
   - Dynamic loop-free shortest path algorithm
   - Hierarchical routing algorithm for large networks.
2. A random distributed algorithm for network link assignment.
3. A link scheduling (multi-access) algorithm for large dynamic networks.
4. Performance analysis of packet resequencing scheme for multi-packet messages transmitted to multiple destinations over parallel channels.
5. A comprehensive examination of the advantages and implementation of Remote Operation Invocation for use in an object-oriented distributed processing environment.

IDA-ID: 00009 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	Decentralized DOS
FY87 $:	57,000
FY88 $:	
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Thomas Lawrence
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	Carnegie Mellon University
ADDRESS:	Computer Science Dept., Pittsburgh, PA 15213
TECHNICAL POINT OF CONTACT:	E. Douglas Jensen
PHONE NUMBER:	412-578-2574
CONTRACT NUMBER:	F30602-85-C-0274
CONTRACT BEGIN DATE:	22 Aug 85
CONTRACT END DATE:	29 Aug 88
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Technical Report-final	
	Technical Reports-interim	
	System/Subsystem Specification	
	Program Maintenance Manual	
	Functional Description	
	Users Manual	
	Computer Operations Manual	
	Software	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

IDA-ID: 00010 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	Distributed System Fault Tolerance
FY87 $:	711,000
FY88 $:	
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Thomas Lawrence
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	Honeywell Inc., Corporate System Dev. Division
ADDRESS:	Golden Valley, MN 55427
TECHNICAL POINT OF CONTACT:	Jon Silverman
PHONE NUMBER:	612-541-6825
CONTRACT NUMBER:	F30602-85-C-0300
CONTRACT BEGIN DATE:	30 Aug 85
CONTRACT END DATE:	29 Aug 87
SUBCONTRACTOR:	IIT Research Institute
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Technical Report-final	
	Technical Report-interim	
	Users Manual	
	Software	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

IDA-ID: 00011 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	CRONUS ADM
FY87 $:	1,700,000
FY88 $:	1,470,000
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Thomas Lawrence
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	Bolt Beranek & Newman
ADDRESS:	10 Moulton St., Cambridge, MA 02238
TECHNICAL POINT OF CONTACT:	Richard Schantz
PHONE NUMBER:	617-497-3550
CONTRACT NUMBER:	F30602-86-C-0051
CONTRACT BEGIN DATE:	17 Feb 86
CONTRACT END DATE:	17 Feb 88
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Technical Report-final	
	Technical Report-interim	
	System/Subsystem Specification	
	Program Maintenance Manual	
	Computer Operation Manual	
	Users Manual	
	Functional Description	
	CSSR	
	Test Plan Procedures	
	Software	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

IDA-ID: 00012 WPD: B413 WPD-SEQNUM: 00231

EFFORT TITLE:	SDI CRONUS Application (RFP)
FY87 $:	250,000
FY88 $:	1,000,000
TASK TITLE:	Distributed Information Processing
FY87 $:	3,500,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Charles Schultz
PHONE NUMBER:	315-330-2066/315-330-3623
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00013 WPD: B413 WPD-SEQNUM: 00082

EFFORT TITLE:	Real-Time Data Architectures for SDI (RFP)
FY87 $:	100,000
FY88 $:	800,000
TASK TITLE:	Distributed Databases
FY87 $:	400,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Emilie Siarkiewicz
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00014 WPD: B413 WPD-SEQNUM: 00082

EFFORT TITLE:	Very Large DB Processing
FY87 $:	500,000
FY88 $:	259,000
TASK TITLE:	Distributed Databases
FY87 $:	400,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Raymond Liuzzi
PHONE NUMBER:	315-330-2066/315-330-2643
PRIME CONTRACTOR:	Martin Marietta Aerospace
ADDRESS:	P.O. Box 179, Denver, Jefferson County, CO 80125
TECHNICAL POINT OF CONTACT:	Ron Peterson
PHONE NUMBER:	303-971-6810
CONTRACT NUMBER:	F30602-86-C-0237
CONTRACT BEGIN DATE:	Dec 86
CONTRACT END DATE:	Dec 88
SUBCONTRACTOR:	Database Technology Transfer Corp.
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00015 WPD: B413 WPD-SEQNUM: 00232

EFFORT TITLE:	Security for the SDI BM System
FY87 $:	800,000
FY88 $:	1,094,000
TASK TITLE:	Distributed System Security
FY87 $:	3,400,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Emilie Siarkiewicz
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	Unisys - System Development Group
ADDRESS:	2500 Colorado Ave., Los Angeles, CA 90406
TECHNICAL POINT OF CONTACT:	Anita Skelton
PHONE NUMBER:	805-987-9300
CONTRACT NUMBER:	F30602-86-C-0048
CONTRACT BEGIN DATE:	11 Sep 86
CONTRACT END DATE:	10 Sep 89
SUBCONTRACTOR:	Trusted Information Systems
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Security Issues in the Generic SDI Battle Management Architecture	
	Progress Reports	Monthly

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
TIM	Apr 87

IDA-ID: 00016 WPD: B413 WPD-SEQNUM: 00232

EFFORT TITLE:	Secure Distributed Systems Specification/Verification Tools
FY87 $:	864,000
FY88 $:	877,000
TASK TITLE:	Distributed System Security
FY87 $:	3,400 000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Emilie Siarkiewicz
PHONE NUMBER:	315-330-2066/315-330-2158
PRIME CONTRACTOR:	Sytek, Inc.
ADDRESS:	1945 Charleston Rd., Mountain View, CA 94043
TECHNICAL POINT OF CONTACT:	Daniel Halpern
PHONE NUMBER:	415-960-3400
CONTRACT NUMBER:	F30602-86-C-0263
CONTRACT BEGIN DATE:	19 Sep 86
CONTRACT END DATE:	18 Sep 89
SUBCONTRACTOR:	Odyssey Research Assoc.; Computer Corp of America; RCA
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00017 WPD: B413 WPD-SEQNUM: 00232

EFFORT TITLE:	Secure Distributed DBMS
FY87 $:	120,000
FY88 $:	480,000
TASK TITLE:	Distributed System Security
FY87 $:	3,400,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Joseph Giordano
PHONE NUMBER:	315-330-2066/315-330-2643
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
	Security Policy	
	Formal Model	
	Descriptive Top Level Specification	

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE

IDA-ID: 00018	WPD: B413	WPD-SEQNUM: 00232

EFFORT TITLE:	Intelligence Database Systems
FY87 $:	339,788
FY88 $:	358,783
TASK TITLE:	Distributed System Security
FY87 $:	3,400,000
SERVICE ORGANIZATION:	RADC
POINT OF CONTACT:	Richard Metzger/Joseph Giordano
PHONE NUMBER:	315-330-2066/315-330-2643
PRIME CONTRACTOR:	SRI International
ADDRESS:	333 Ravenswood Ave., Menlo Park, CA 94025
TECHNICAL POINT OF CONTACT:	Matthew Morgenstern
PHONE NUMBER:	415-859-5613
CONTRACT NUMBER:	F30602-86-C-0088
CONTRACT BEGIN DATE:	19 May 86
CONTRACT END DATE:	19 May 89
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00001	WPD: B414	WPD-SEQNUM: 00009

EFFORT TITLE:	Development of an Adaptive Distributed Network Management System for SDI Communications
FY87 $:	700,000
FY88 $:	700,000
TASK TITLE:	Adaptive Communication Networking
FY87 $:	1,400,000
SERVICE ORGANIZATION:	NRL
POINT OF CONTACT:	Steve McBurnett/Ed Althouse
PHONE NUMBER:	202-767-3567/202-767-2586
PRIME CONTRACTOR:	Harris Government Special Programs Operation
ADDRESS:	P.O. Box 95000, Melbourne, FL 32902
TECHNICAL POINT OF CONTACT:	Peter Knoke
PHONE NUMBER:	305-729-7401
CONTRACT NUMBER:	N00014-86-C-2056
CONTRACT BEGIN DATE:	20 Feb 86
CONTRACT END DATE:	20 Feb 88
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

TECHNICAL DOCUMENTATION

CONTRACT DELIVERABLES:

CDRL	DOCUMENT	DUE DATE
A001	Network Control Algorithms and Protocols Description	Jul 87
A002	Network Control Algorithm Source Listing and Code	Dec 87
A003	Design-related Research Topics Memorandum	Aug 87
A004	Network Simulator Design Description	Feb 88
A004	Network Simulator Design Description	Oct 87
A005	Algorithm Testing Plan	Feb 88
A006	Recommended Design Changes	Feb 88
A007	Graphic Demonstrator Description, Documentation, and Software	Dec 87
A008	Project Schedule and Spending Plan	Mar 87
A009	Monthly Technical Status Report	Mar 87 & monthly

SCHEDULE OF TECHNICAL MEETINGS:

SUBJECT	DUE DATE
Quarterly Program Review	May 87 & quarterly

TECHNICAL SUMMARY

OBJECTIVE: Refine and enhance the capabilities and scope of the algorithms developed during Phase 1 of contract. Specifically, these algorithms include dynamic routing, backbone link configuration, link entry and reconstitution (following a major disruption), and flow and congestion control. The contractor shall concentrate the effort on issues/algorithms that pose the greatest problem to development of a successful adaptive communications network for SDI BM/C^3. New algorithms that must be developed include the protocols and network-management schemes for communicating with clusters of nodes (such as weapons platforms) that may not be capable of participating directly in a backbone network of high-capacity, point-to-point links. The contractor shall explore the use of broadcast techniques for these algorithms, refine the implementation of all algorithms on the network simulator developed during Phase 1, and identify any newly found design/performance problems that must be solved to insure the success of BM/C^3 networking but are beyond the scope of the Phase 2 effort.

Conduct performance and sensitivity analyses on the algorithms in a manner that is adequate to quantify baseline performance and to identify required design changes. This effort is expected to exercise the test-plan procedures and simulator software developed during Phase 1.

ACCOMPLISHMENTS TO DATE:

1. Designed and implemented an adaptive message routing algorithm.
2. Designed and implemented a link assignment algorithm.
3. Design and implemented a simulation testbed for testing the developed algorithms.
4. Developed a test plan and used it to test the adaptive routing and link assignment algorithms.
5. Documented the results in a series of technical reports.

IDA-ID: 00019	WPD: B414	WPD-SEQNUM: 00012

EFFORT TITLE:	
FY87 $:	
FY88 $:	
TASK TITLE:	Track File Data Base Management System
FY87 $:	1,200,000
SERVICE ORGANIZATION:	NRL
POINT OF CONTACT:	Steve McBurnett/Sushil Jajodia
PHONE NUMBER:	202-767-3567/202-767-3596
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00020	WPD: B414	WPD-SEQNUM: 00006

EFFORT TITLE:	
FY87 $:	
FY88 $:	
TASK TITLE:	Communications/Graphics
FY87 $:	1,900,000
SERVICE ORGANIZATION:	NRL/ONR
POINT OF CONTACT:	Steve McBurnett/Dick Lau
PHONE NUMBER:	202-767-3567/703-696-4316
PRIME CONTRACTOR:	ISI
ADDRESS:	Marina Del Rey, CA
TECHNICAL POINT OF CONTACT:	Danny Cohen
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00021 WPD: B417 WPD-SEQNUM: 00287

EFFORT TITLE:	(Task 6.6 Phase IIC Architecture Studies)
FY87 $:	
FY88 $:	
TASK TITLE:	Security Architecture Studies
FY87 $:	2,400,000
SERVICE ORGANIZATION:	NSA
POINT OF CONTACT:	Maj. Charles Morgan
PHONE NUMBER:	301-688-6031
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

IDA-ID: 00022 WPD: B418 WPD-SEQNUM: 00281

EFFORT TITLE:	
FY87 $:	
FY88 $:	
TASK TITLE:	Trusted Real-Time Operating System
FY87 $:	2,200,000
SERVICE ORGANIZATION:	DARPA
POINT OF CONTACT:	Dennis Perry
PHONE NUMBER:	703-694-4002
PRIME CONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	
CONTRACT NUMBER:	
CONTRACT BEGIN DATE:	
CONTRACT END DATE:	
SUBCONTRACTOR:	
ADDRESS:	
TECHNICAL POINT OF CONTACT:	
PHONE NUMBER:	

APPENDIX B

PROGRAM UPDATES

APPENDIX B
PROGRAM UPDATES

Since the first draft of this report was prepared, two of the efforts discussed in Section V, BM/C^3 Network Design and Adaptive Distributed Network Management System, have been monitored through attendance at scheduled program reviews. Progress on these programs reported during the reviews is summarized in the following edited trip reports.

1. BM/C NETWORK DESIGN

a. October 1987

On October 7-8, 1987 Harris Corporation presented their fourth quarterly progress review to RADC on the above contract. The purpose of this memo is to highlight the work reported during the briefing.

The current phase of the program involves using the initial design methodology to carry out a network design. Simulation will then be used to verify the design. Highlights of the fourth quarter include:

- functional decomposition of the network manager
- completion of AI design methodology
- identification of candidates for application of AI
- definition of spans of control
- partitioning of the layer managers
- definition of synchronization/authentication approach
- Ada pseudo-code for network and data link layers and for network manager
- standalone simulation of data link layer
- integrated simulation of network and data link layers.

A brief overview was presented of the near-term and far-term baseline architectures used for the study. These architectures are based on information available in October 1986 and are summarized in the document cited above. Discussions are currently underway between RADC and Harris to decide whether the Harris results will be modified to reflect the SCP baseline architecture. At present, the near-term architecture being used employs a ground-based battle manager which must receive all multi-sensor track data generated by the BSTS satellites.

A functional decomposition of a systems management architecture was presented. It consists of multiple networks--BSTS, CV, SSTS, BM--with connecting gateways and uses the OSI model as a guide while anticipating that departures from that model will be made as work progresses. The decomposition was guided by the questions: (1) what services are provided to users?, (2) what resources, processes, operations are being managed?, (3) what functions and/or algorithms are being performed?, and (4) which operations are performed locally and which ones are distributed or remote? These functions were further decomposed to a second level.

Issues related to establishing a time-of-day (TOD) reference for the transfer of encrypted data were presented. A network synchronization algorithm was developed that requires no central time reference, can be initiated from a totally unsynchronized state, and is resistant to spoofing.

Under subcontract, Clarkson University developed a methodology for applying artificial intelligence concepts to SDI communication management. Their focus was on the application of knowledge-based systems to network management. They designed methodological guidelines for knowledge-based systems and for SDI network design. Six generic problem-solving tasks were presented and a matrix developed relating these tasks to the identified SDI network functions. For each major function, the benefit to be obtained through use of AI was assessed in terms of its criticality to the mission and the estimated payoff at the levels of node management, network management, and overall communication system management. Key areas where AI may be beneficial were found in the areas of fault diagnosis (failures, security violations, and nuclear effects), configuration management (reconfiguration, routing, and congestion/traffic control), and performance assessment (situation assessment and communication system threat analysis). It was found *not* to be worthwhile to use AI at the node level of network management. As an example of using the methodology guidelines, for fault diagnosis it was concluded that a breadth-first search of possible approaches should be used, pruning the search tree based on a generate-and-test approach or on the use of a ranking function.

Link-layer protocol requirements were presented and two such protocols were examined: The HDLC (High-level Data Link Control) protocol and an enhanced MSS (Multiple Satellite System) link protocol. Analysis revealed that a sequenced protocol, such as HDLC, should not be used for high volume traffic, such as sensor track data, because of the large delays encountered and the high buffer sizes required. The enhanced MSS protocol can provide hop-by-hop acknowledgment without the sequencing problems that occur with HDLC. The conclusion was that HDLC may be needed at network gateways for compatibility with other systems, but otherwise is not needed for the SDS space network.

To illustrate a proposed algorithm design procedure, a routing algorithm was selected and implemented as Ada pseudo-code. Ultimately, the design procedure will consist of algorithm selection, functional description, PDL generation in Ada pseudo-code, Ada code generation in the GENESIS simulation environment, and, finally, simulation of the algorithm.

Preliminary efforts at simulating the BSTS network, focusing on the network layer, were reported. Implementation was carried out completely in Ada on the GENESIS network simulator developed at Harris. The network management functions modeled to date are adaptive routing, topological updates, and link monitoring. A DDN area routing scheme was used. Among the entities modeled were a system performance monitor and a scenario processor that scheduled link and node failures. The simulation output consisted of end-to-end delays resulting from input levels of sensor track traffic.

Early experience with a data-link layer simulation was also presented. This simulation incorporated queues, acknowledgment messages, timeouts, and a transmission time model. Link delays using the HDLC protocol were examined. The results demonstrated the problems, mentioned above, that HDLC has in handling high traffic levels. During the next quarter, the MSS protocol, which avoids the sequencing delays and queue build-up characteristic of HDLC, will be simulated.

b. January 1988

On 20-21 January 1988 Harris Corporation presented their fifth quarterly progress review to RADC on the above contract. The purpose of this memo is to highlight the work reported during the briefing.

Accomplishments during the fifth quarter include:

- Enhancements to the BSTS simulation model
- Simulation of the Carrier Vehicle (CV) network
- Definition and simulation of a Redundant Acknowledgment Non-Sequenced (RANS) link-layer protocol
- Simulation of a time-of-day (TOD) synchronization algorithm for the case of initial total time uncertainty among nodes
- Testing of a k-nearest neighbor link assignment algorithm for the BSTS ring network
- Introduction of an on-line documentation technique to record significant decisions and issues occurring during the design process
- Adoption of the Ward-Mellor real-time structured analysis methodology for network management
- Adoption of the BCD BM/C^3 architecture for the remainder of the project.

These accomplishments are discussed in more detail below:

1. The introduction of an **on-line documentation** technique is responsive to the need for a systematic procedure to document decisions, provide traceability of the design process, reduce paperwork, and minimize the impact on the design effort of producing documentation. The adopted solution is a modification of a method used successfully by Harris on proposals and on several other programs. Each document deals with a single issue and is short, generally less than two pages in length. Each document is numbered using a matrix numbering scheme that identifies it according to several categories, such as function and program element. The documents are stored in a computer data base so that they are easily accessible by all members of the study team.

2. The **current architecture** consists of a BSTS subnet with one ring of nine satellites and a CV subnet of ten rings of ten satellites each. There is a single ground-based battle manager which must receive all multi-sensor track data generated by the BSTS satellites. Each BSTS generates single-sensor data every three seconds and exchanges these data with its two nearest neighbors. Each BSTS then forms multi-sensor tracks using the information obtained from its neighbors and sends these tracks in bursts once every three seconds destined for the ground-based battle manager.

3. The **network simulator** is implemented completely in Ada using the GENESIS communication network simulation language developed at Harris. The features simulated include high-fidelity link and network layer protocols, adaptive routing, TOD synchronization, and orbital dynamics. The BSTS subnet has been modeled in detail. A preliminary version of CV subnet entry point routing is also implemented. So far, **the CV subnet** has been tested only with a simple scenario that includes random entry points and random destinations. Work is under way on evaluating the performance and optimizing the CV subnet using a realistic scenario.

A **k-nearest neighbor algorithm** for link reconfiguration has been added. At present, four-connectivity of the BSTS nodes is maintained. If a node is eliminated, its adjacent nodes seek out other nodes and establish new links so as to remain four-connected. Constrained flooding is used to communicate the link status changes to other nodes. Future work will include comparing this algorithm with the link assignment algorithm developed for the NRL program at Harris, and integrating BSTS link assignment with CV entry point assignment.

A new **adaptive ring routing algorithm** incorporating split-path routing has been developed and implemented for the BSTS subnet. It has been compared with the new Arpanet routing algorithm which uses single path routing with no load balancing. The new ring routing algorithm is very simple, requires no routing tables, uses multiple paths, and performs load balancing. In tests of end-to-end message delay, it did much better than the Arpanet algorithm. It exploits the very simple topology of the BSTS ring and provides continuous adaptation to traffic changes.

A new redundant acknowledgment non-sequenced (RANS) **link-layer protocol** has been introduced. It reduces the number of unnecessary message retransmissions required by other protocols. This is especially important to reduce the size of buffers needed on links characterized by long propagation delays. So far, only limited testing using a very simple network has been done on this new protocol.

An **animated graphics capability** has been added to permit network performance to be visually tracked. This is the same capability that is being used by the related NRL network management project. It has proven to be an effective tool for network designers, enabling them to quickly spot errors in algorithm behavior that would have been much harder to detect by analyzing printed output data.

An algorithm for accomplishing **TOD synchronization** among the BSTS satellites has been completed, coded, unit tested, and integrated into GENESIS. The total time uncertainty (TTU) mode, where each satellite initially has a different time, was simulated for a simple scenario and convergence of the local times to a common time occurred. Future efforts will include testing the TTU mode in a dynamic environment and then coding and testing a related time-refine mode algorithm which is used for maintaining synchronization once the network nodes have agreed on a common time.

4. As a result of your 1 December meeting with Tom Blake/RADC and Harris Corporation representatives, Harris plans to **transition to the BCD Architecture** for the remainder of the current project. They have obtained a copy of the BM/C^3 portion of the 18 December version of the BCD from a sister group at Harris supporting the USASDC architecture studies. Harris plans to take the basic battle management and command and control architecture from the BCD and to develop the corresponding communication architecture in their studies, i.e., perform tradeoff analyses and select the most promising design.

Certain assumptions regarding the system architecture will be made by Harris in areas where information is not supplied in the BCD. These assumptions include some data from the Army BM/C^3 Architecture Study as well as the following:

a. The BCD talks of partitioning SSTS traffic in the mid-term architecture when the network becomes overloaded. Harris will do this by assigning priorities to various classes of messages such as C^2, IFGU, health and status, mono tracks, cluster tracks, etc. Track data will be further prioritized depending upon such factors as whether they are mono or cluster tracks, frequency of transmission, and sensor-target geometry.

b. BSTS and SSTS monotrack messages will be transmitted continuously as they are generated throughout the scan periods of three and ten seconds, respectively. Cluster track and cluster attribute traffic will be sent in short bursts at ten second intervals.

c. The threat will be taken as 1400 boosters with 20,000 RVs, 600,000 decoys, and 300,000 pieces of "junk." In addition, 2,000 friendly objects in space will be assumed.

d. Harris will tentatively assume that a CV network will form a communications backbone but they will also look at the possibility of networking the SSTSs to form such a backbone. The latter approach would involve adding sensor fusion/BM capability to the SSTSs to perform the message partitioning mentioning in (a) above.

e. While Harris' study is concerned with the space-based network only, consideration will be given to the impact of the ground-based elements. For example, CVs will need to send IFGUs to ERIS after missiles are out of range of the ERIS/BM since Harris assumes that earth-space links cannot be depended upon for reliably delivering the IFGUs.

f. Harris will decide the extent to which the BM/C^2 architecture needs to be modeled for the purpose of devising a workable communication architecture.

g. Analyses to be performed using the BCD architecture include re-examining the link assignment and routing algorithms that have already been developed, and studying performance as a function of the number of links per communication node. Sensor message traffic will be simulated using Harris' KEWSTAR and BOOSTAR threat-generation tools.

5. Harris is applying the Ward-Mellor real-time **structured analysis methodology** to the problem of creating the functional flow breakdown of the network management task for this project. This approach was chosen after examining about ten different methodologies. It is a computer-based system for structuring the network management task, allowing all essential functions to be defined and related to other functions, while it keeps track of all the various inputs and outputs to ensure consistency and completeness, e.g., eliminating redundancy, ensuring that outputs of one function feed into inputs of other functions, etc.

Details of the methodology can be found in the three-volume set of books entitled *Structured Development for Real-time Systems*, by Paul T. Ward and Stephen J. Mellor, Yourdan Press, New York, 1985.

c. October 1988

On 6 October 1988 Harris Corporation presented their eighth quarterly progress review to RADC on the above contract. The purpose of this memo is to highlight the work reported during the briefing.

Areas covered during the eighth quarter include:

- Selection of a link assignment algorithm
- Implementation of a transport layer protocol
- Plans for the simulation verification phase

- Plans for vulnerability assessment using the distributed network vulnerability assessment (DNVA) methodology
- Resolution of an action item concerning timeout in the Redundant Acknowledgment Non-Sequenced (RANS) link-layer protocol
- Resolution of an action item concerning the performance of the Flood and Forward (FAF) network routing algorithm.

These items are discussed below.

1. After considering a number of candidate algorithms, the Global Constraint Link Reconfiguration (GCLR) algorithm was selected because of its relative simplicity and applicability to SDI subnets and internet connectivity. The algorithm operates in distinct phases during which similar links are assigned, e.g., entry-point links such as BSTS/CV, SSTS/CV, BSTS/SSTS. Within each phase, a set of candidate nodes is chosen and feasible links are identified. A set of constraints is applied to reduce the size of the search space. These constraints include line-of-sight restrictions and estimated link lifetime. Links are selected by attempting to optimize a set of objectives that includes such items as: (1) fully utilizing BSTS and SSTS down links, (2) maximizing expected longevity of the network topology, and (3) minimizing the total link distance. If high priority objectives are not met, breaking certain links may be necessary followed by reformulation of the set of feasible links. The selection process is then repeated. This algorithm requires that a copy of the global database be maintained at each node. This database is updated when needed as a result of link changes as well as periodically in the absence of forced updates. There is a lag time before the new database becomes active to ensure consistency among the nodes. The algorithm has been coded in Ada and run for a network of 323 nodes, each maintaining its own copy of the global network database.

2. A transport layer protocol, similar to TCP with a reduction in the size of some data fields, has been designed and coded in Ada but is not yet fully debugged. A number of applications remain to be coded, and policies for message acceptance, delivery, and retransmission must be developed for a space-based network.

3. Objectives for the verification-phase tests include measurement of key parameters that demonstrate the ability of the communication network to support the SDI mission, examination of the sensitivity of network management algorithms to database inconsistencies, and identification of improvements needed in algorithms and supporting technology. Proposed measures of system performance include average and maximum

end-to-end queueing delay and message delay, and message survivability in terms of the number of packets delivered correctly. Preliminary results for a 299 node CV network having 3 links per node indicate that even a packet error rate of about 0.25 will result in only 5 of the nodes failing to receive a topology update message. For packet error rates less than 0.08, essentially all nodes receive the update messages.

4. Plans for network vulnerability assessment include a top-level analysis of the entire network, identifying such vulnerabilities as susceptibility and interceptibility. It will be followed by an in depth analysis of an interesting portion of the network, such as the BSTS/SSTS/GEP subset. This strategy permits the focus to be placed on the most important aspects of the system architecture while permitting more and longer simulation runs because fewer nodes are involved. The analysis to be performed will be based upon a distributed network vulnerability assessment (DNVA) methodology developed by Harris for RADC under a separate effort. This methodology characterizes system vulnerability along three orthogonal axes representing environment, threat class, and network form and function.

5. A problem existed with the RANS protocol that resulted in a large number of excess repeat messages. It was caused by a timeout setting (used to determine when a message should be repeated) that was too small. The problem was resolved by increasing the timeout interval to account for all anticipated delays in the transmission path plus an additional ten percent cushion.

6. The flood and forward (FAF) routing algorithm retains the desirable properties of constrained flooding while making more efficient use of system resources. It is based upon the observation that the routes established during a constrained flood constitute minimum spanning trees from the origin to each destination. FAF operates by occasionally sending out a packet on a constrained flood, recording the corresponding paths in routing tables maintained at each node, and then sending subsequent messages by the appropriate path. Simulated performance of the algorithm showed much lower link utilization compared to constrained flooding and somewhat lower end-to-end delays. Packet survivability in terms of the percentage of destinations reached versus packet error rate was essentially the same for both routing methods up to a packet error rate of 12 percent.

2. ADAPTIVE DISTRIBUTED NETWORK MANAGEMENT SYSTEM

a. January 1988

On 7 January 1988 Harris Corporation presented its quarterly progress review to NRL on the above contract. The purpose of this memo is to highlight the work reported during the briefing. In attendance were Ed Althouse (the NRL COTR), Kepi Wu of SDI/IST, and a group of people from the University of Florida, under contract to IST, performing studies in the area of satellite communications.

The review consisted of a program overview, current status, and discussion of recent activity. A newly developed capability of graphically depicting events during a simulation run was demonstrated. The University of Florida contingent gave a short briefing on their activities.

New work focused on two areas: refining earlier work to create so-called second generation link assignment and adaptive routing algorithms, and developing first generation algorithms for weapons platform communications and network flow/congestion control.

Highlights of the briefing follow:

1. During the past quarter, fourteen technical notes were written and delivered to NRL. These notes were not formal CDRLs.

2. Capabilities to handle local, event-driven failure recovery and to provide virtual circuit service were added to the adaptive routing algorithm. The former was developed to provide for instantaneous response to failures that occur between the synchronous network routing update epochs (nominally occurring every five seconds.)

3. Changes to the link assignment algorithm include: (a) decoupling of the "join islands" and "improve connectivity" operations, (b) simplification of the message frame structure, (c) dynamic control of the link-breaking operation, (d) integration of delay and connectivity metrics, and (e) elimination of a separate control channel. The last item was in response to our criticism of Harris' earlier version which relied on a separate order-wire channel for reconnecting isolated nodes to the network. The current concept assumes the existence of a search antenna (or time-sharing of one of the communication antennas when a search operation is needed to reconnect an isolated node to the network.)

4. Work has begun to develop network management algorithms that can handle a large number of weapons platforms. Previously, the network was considered to consist of

a backbone of 48 nodes. Unfortunately, the assumed architecture for the weapons platforms (WP) does not resemble the BCD. Each BM/sensor in high earth orbit has an associated WP cluster. Each WP belongs to several such clusters to provide redundancy. The WPs do not talk to each other. It is assumed that multiple beam antennas operating at a 10 MHz burst rate are located on each BM and WP. Cluster-oriented, link-level algorithms are currently under development.

5. Early work has begun on flow and congestion control algorithms. Flow control is associated with a single flow, while congestion control deals with the competition between multiple flows. Both packet-oriented and stream-oriented approaches are under study. Congestion control occurs in the network layer. It is based on buffer allocation and smart discarding of packets. Multiple buffers are used to provide a means of imposing a priority structure on messages so that when congestion occurs, intelligent decisions can be made.

6. In response to an ECP from NRL, Harris is investigating the parallel implementation of link assignment algorithms for potential speed-up in processing time. To date, they have coded and tested certain computationally intensive parts of the first generation algorithms on the Concert and NRL Butterfly computers. Results have not yet been analyzed fully, but as processors were added a maximum speed-up factor of about 10 was achieved for the first generation maximum flow algorithm applied to 20 pairs of nodes. As the number of node pairs analyzed increases, the speed-up appears to be almost linear. Conversion of second generation algorithms will begin with those aspects of the link assignment process that seem to offer the most potential for benefitting from the use of parallel processors. Additional work to exploit the benefits of parallel processing may also be pursued.

7. Harris has developed some approaches, such as hierarchical control, to be used in third generation algorithms that will consider a flat network structure of up to 10,000 nodes. Previous work on hierarchical routing for large networks has been studied. This earlier work needs to be extended to handle highly dynamic networks such as the space-based portion of the SDS.

8. A number of changes have been made to Harris' simulator to reduce run time. Weapon scaling involves reducing the number of WPs while correspondingly increasing the weapon message size so that the total level of traffic remains constant. Simulation results were found to be very insensitive to such scaling, while run time was reduced from

39 hours to 14 hours. The duration of the simulated battle and the sensor message packet sizes were also reduced. The latter had little effect on message survivability and end-to-end delay but resulted in a large reduction of CPU time. As a rusult of all the implemented changes, the run time was lowered to 4.5 hours.

9. Limited testing has been done on the first generation WP algorithms. When compared to simple test-case heuristic algorithms, performance was about the same. A test was performed to assess the utility of having a node identify node-disjoint paths to a destination when next-link routing decisions are made independently at each subsequent node. Duplicate sensor messages were sent on different initial links from the source and their respective paths to the destination noted. Sixty percent of the time the two paths taken were node-disjoint.

10. An interesting demonstration was given of the use of graphical displays of the progress of a simulation. These displays are generated on a SUN workstation as a post-processing operation to allow analysts to see what was happening during the simulation. The playback speed can be chosen so that the simulation can be viewed at any fraction or multiple of actual simulated time. The display shows currently active nodes and links with traffic levels and queue sizes represented via colored lines and bars. At each time step, changes in traffic and queue size on the various links can be tracked visually. If a node or link fails, it disappears from the screen and one can see the changes that take place as the network attempts to accommodate the traffic that was carried on the disrupted links by exercizing the adaptive routing and link assignment algorithms. Certain incorrect network behaviors are much easier to spot on the screen than by poring through output data statistics. This graphical tool has been used by people working on the NRL program as well as by the group working on the RADC Network Design Handbook program. Analysts have used the graphical display capability to aid them in debugging their network algorithms.

11. The group from the University of Florida gave a short briefing on their work, funded by SDIO/IST, dealing with routing and link assignment in satellite communication networks. This work is part of IST's program in satellite communications. They considered a low-altitude network of satellites (*à la* MSS) with connectivity determined largely by line-of-sight considerations. Connectivity is treated probabilistically rather than calculated using actual orbital parameters, i.e., each link has a probability associated with it. The work had an academic flavor--simple models with emphasis on precise

mathematical analysis. Link assignment and two-level hierarchical routing are among the areas under investigation. More detailed information about the activities of the University of Florida group can be obtained from Kepi Wu/IST.

b. September 1988

On 15 September 1988 Harris Corporation presented its quarterly progress review to NRL on the above contract. The purpose of this memo is to highlight the work reported during the briefing. In attendance, besides contractor personnel, were Ed Althouse (the COTR) and R.K. Nair from NRL, and Randy Chow, R.E. Newman-Wolfe, and Charles McLochlin from the University of Florida. The latter group was also present at an earlier quarterly review.

Ken Kilburn has recently taken over as the Harris program manager, replacing Pete Knoke. The review consisted of a program overview, current status, and discussion of recent activity. In addition to the scheduled presentations, one of the attendees from the University of Florida gave a short talk on some networking routing algorithms that he has developed.

Activity during the past quarter included refining earlier work on so-called second generation link assignment, adaptive routing, and flow/congestion control algorithms for the 48-node backbone network. Conceptual design was completed on routing and link assignment algorithms for a flat (i.e., non-hierarchical) architecture that could include thousands of nodes. A simplified link assignment algorithm and an algorithm to distribute topology update information needed by both the link assignment and routing algorithms were implemented and underwent initial testing. Testing of second generation algorithms continued. All of the foregoing activity relates to network simulation. In addition, work was begun on the development of a parallel processor-based emulator. After the last review, Harris was directed to expand their efforts in this area, possibly at the expense of additional work on the algorithms. The emulator will be a major focus of the work carried out in Phase III of the contract.

Highlights of the briefing follow:

1. Testing of the Second Generation Link Assignment (SGLA) algorithm showed little sensitivity to network size over a range of 8 to 104 nodes. Convergence to a three-connected network from a cold start (i.e., a one-connected network) was achieved within about 4 iterations of the algorithm. Assuming that in the actual SDS network link

assignments would be updated about every 5 seconds, this means that every node would have at least 3 node-disjoint paths to any other node within about 20 seconds. The corresponding time beginning from a previously three-connected network subjected to node or link failures should be no worse and probably shorter. Modifications were made to the Second Generation Adaptive Routing (SGAR) algorithm to correct undesirable behavior detected in earlier testing. An optimized version of the heuristic-based SGAR that provided better steady-state performance displayed very poor transient behavior and so was not considered further.

2. Implementation of flow and congestion control techniques was completed. Flow control is associated with a single flow, while congestion control deals with the competition between multiple flows. Congestion control is based on buffer allocation and smart discarding of packets. These features are provided by management of the buffer pools at each node. By translating the code for these algorithms from Simula to C, a 40-50 percent improvement in run time was achieved. An interface was built to allow the flow/congestion control algorithm to be used with either the simulator or emulator. End-to-end flow control remains to be added.

3. In the link assignment and adaptive routing work done previously, it was assumed that the necessary updating information was available at all nodes in a timely fashion. The actual distribution of the update messages was not modeled. Such modeling has now begun. Preliminary studies carried out by Florida Institute of Technology under subcontract indicate that topology update message error rate can be as large as 0.1 before inconsistencies in the databases maintained by the separate nodes occur. It takes about 0.5 seconds for update messages to be received by all nodes in the 48 node backbone network. These studies used a simplified link assignment algorithm (not SGLA) with constrained flooding used for the update messages. Further work in this area will study alternative update schemes, the impact of inconsistent data on ADNMS algorithm performance, and the extension to flat architectures.

4. The goal of a simplified link assignment scheme (SMLA) was to preserve the good performance of the SGLA while reducing the run time of the algorithm to 25 percent or less of the run time required by SGLA. One approach that was effective was simply to run the SGLA with a strict time limit. In effect, this corresponds to prioritizing the candidate changes (link additions and deletions) and examining as many as possible within the time limits. Since the most promising candidates are examined first, not much

performance is lost by discarding the possible changes that are low on the list. Unfortunately, work in this area will probably not be pursued further even though the development of simplified algorithms is of interest to SDS Phase I.

5. Testing of the second generation link assignment and adaptive routing algorithms versus the corresponding first generation algorithms was completed. The newer algorithms outperformed the older ones in terms of end-to-end delay and message survivability (defined as the percentage of messages sent that were received prior to a preset deadline time.) Several three-dimensional plots were shown that allowed performance measures to be viewed as a functions of two variables, such as link capacity and traffic load. An overall (or integrated) test of all algorithms remains to be completed to finish the Phase II testing.

6. Link assignment and adaptive routing concepts were developed for the so-called flat system topology. These concepts are intended to accommodate networks ranging in size from 1,000 to 10,000 nodes. The nodes are organized into regions with a representative node being designated as the Regional Node. A two-stage process is involved where global tables are used to direct a message toward the correct destination region followed by local tables to reach the desired node once the message has entered the correct destination region or an adjacent region. While previous work on routing for large networks has been reported in the literature, no results for link assignment have appeared. The concepts being developed have some similarities to work in the literature but also contain unique features. Objectives of the design include: (1) close to optimum delay, throughput, and robustness, (2) linear or slower growth of link overhead and algorithm time complexity with number of nodes, and (3) responsive to dynamic topology changes due to orbital motion and failure conditions. Prototyping has just begun on the routing algorithm. The link assignment algorithm will next be integrated with it and subsequent testing will lead to refinement of the algorithms.

7. The final block of presentations dealt with development of the emulator which is just getting under way. The goals are to achieve a real-time distributed emulation using a parallel processor. The work at Harris will be done on their Concert machine and transitioned to NRL's Butterfly. First, a substrate is being designed to provide flexibility and transparency of the mapping of node processes to actual hardware. The substrate will also handle such things as orbital dynamics, line of sight restrictions, and link propagation delays. Design of substrate interfaces includes the definition of data types to provide a

machine independent layer in the model which will permit largely machine-independent implementation of network management algorithms. A preliminary test plan for the emulator was presented. It will consist of three stages: (1) emulator verification, (2) emulator performance, and (3) ADNMS performance under emulation. The first stage will check that system measures of performance do not vary with the number of processors used for the emulation, and also will compare results obtained on the Concert and Butterfly machines. In the second stage, such factors as execution time and memory size will be explored as a function of the number of processors used. The third stage will examine the actual performance of the network management algorithms using measures such as end-to-end message delay, throughput, and message survivability. The specific tests to be run and the format for displaying the results will closely parallel the testing that was done in Phases I and II.