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at the National Test Bed*

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MIGRATION TO A DISTRIBUTED SYSTEM ARCHITECTURE AT THE NATIONAL TEST BED

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Randy Hoebelheinrich

ABSTRACT

This is a study to consider the mission of the Strategic Defense Initiative Organization's National Test Bed (NTB) and the current directions of gigabit networking and distributed computing research and to produce a report describing a 5- to 10-year vision of an NTB computing architecture and migration path to that architecture.

1.0 Introduction

This report is the result of investigations in the literature and experience in the fields of distributed systems, high-performance computing, and gigabit networking. One is struck by the volume and variety of research and development in these areas. One is also reminded of the model of change by Thomas Kuhn.¹ In this model, we see three stages of change. In the first stage, there is no standard way to do something. There are only competing models with duplication. Current work in distributed operating systems is an example. In the second stage, a standard exists and efforts focus on more specific details of the model. The very mature study of Ethernet is an example. The third stage is the revolutionary step. In this stage, inadequacies appear in the model. One group of people attempts to extend and improve the model while a minority of others take a fresh approach by stepping back, looking at fundamentals, and producing a new model to match new requirements. The best example in the current context is high-speed protocols. It would seem we are currently well into Stage 3, if not Stage 1, of a computing technology revolution. This report suggests a distributed system architecture of the near future implementing various methods, mechanisms, hardware, and software from the previously mentioned fields. No pretense is made that this is the wave of the future or the only way to proceed. It is intended to stimulate thought, discourse, and, hopefully, action to realize the potential the next generation of computing holds for everyone.

The outline of this report is as follows: Section 1 provides the charter and goals of the report. Section 2 provides some background and configuration information on the National Test Bed (NTB), its requirements, and a reference to a system description

document. Section 3 discusses current progress in distributed gigabit networking including issues, a brief discussion of the literature, and test bed projects planned or in progress. Section 4 will describe a proposed NTB distributed system architecture. Section 5 will describe a migration path to that architecture. Section 6 lists research initiatives to help facilitate that migration. Sections 7 and 8 provide a summary and conclusion.

1.1 Charter

The charter for this study is to consider the mission of the NTB and the current directions of gigabit networking and distributed-computing research and to produce a report describing a 5- to 10-year vision of an NTB computing architecture and migration path to that architecture.

1.2 Goals

The goals for this report include the following items.

- 1) Compile background references for future discussions of an NTB architecture.
- 2) Describe a distributed system architecture (DSA) for the NTB.
- 3) Describe a migration path to that DSA.
- 4) List crucial research initiatives needed to realize that DSA.

2.0 NTB Background and Configuration Information

Information in this section is general in nature and a result of discussions with members of the NTB, the Strategic Defense Initiative Organization (SDIO), NTB users and a study of the System Description Document NTB-242/442-006. ²

2.1 Strategic Defense Initiative

The Strategic Defense Initiative is a program to produce a defense from ballistic missile attack. The program is administered by SDIO in the Pentagon. A significant portion of the program is dedicated to computer simulation of defensive technologies and threats to specify a Strategic Defense System (SDS) architecture integrating these technologies into a defensive shield.

The SDS architecture consists of some combination of platforms. Components such as weapons systems, sensors, communications, and battle managers combine to form a platform. For example, a platform may have a real weapon system with its associated sensor, battle manager, and communication unit at the same location in space, on the ground, or in the sea. Platforms grouped together form either a blue defensive or red

offensive capability. Both offensive and defensive platforms make up the SDS and this architecture is, by definition, of global extent.

Selection of the appropriate combination of platforms and components on those platforms is not an obvious process. New technologies are being explored and tested. Integration of these technologies into a real working system is expensive in terms of time, money, and effort. Simulations of individual and interacting systems provide a far more reasonable environment for testing. SDIO created the NTB to provide this simulation environment.

2.2 National Test Bed

The NTB was established to test and analyze instances of system architectures for the SDS. The NTB is made up of a set of computing research sites. These sites are geographically distributed, represent various organizations, and focus on specific systems proposed for the SDS. Computing communication is currently accomplished with satellite and terrestrial links. The topology is a star. The National Test Facility (NTF), located at Falcon Air Force Base near Colorado Springs, is one of these sites. It acts as the control and coordination site for NTB experiments sponsored by SDIO. Figure 1 shows the configuration of an extended Local Area Network (LAN) at the NTF.

2.3 National Test Facility

The NTF acts as the heart of the NTB configuration. It is a major computing and simulation facility for development and execution of SDIO-sponsored simulation programs in the NTB network. It is responsible for simulation experiments from design to final analysis. There are currently several simulation programs of varying capabilities resident at the NTF. Data for simulations, including threat, environment, parameter, and scenario information, are kept at the NTF. The computer network and communication framework are constructed from commercial LAN, High-Speed Local Network, bridging, routing, and fiber-optic equipment. The NTF is essentially an extended LAN constructed from bridges and passive star couplers. This configuration will be discussed further in Section 5. NTB users access the NTF network either on site or through remote access set (RAS) equipment.

2.4 Remote Access Set Sites

NTB users are located at sites geographically distributed around the NTF. These sites are known as Special Program Offices (SPOs) or elements. An SPO is a contractor

Figure 1. Extended LAN at the Network Test Facility.

responsible for building a specific piece of hardware or component of the SDS. The SPO is also responsible for providing a computer model of the component to the NTB for testing and integration into the SDS.

The RAS provides an SPO computing access to NTB resources, specifically the NTF. A RAS consists of a set of equipment including two workstations, a disk, a tape drive, a printer, communication and encryption equipment, a network interface unit, and a LAN. The LANs are Ethernets using the Institute of Electrical and Electronic Engineers' (IEEE) 802.3, 802.2, and the Defense Data Network's Transmission Control and Internet (TCP/IP) protocols. Network routers connect SPO LANs to the RAS node.

2.5 NTB Requirements

The mission of the NTB is to execute geographically distributed supercomputing simulations. These distributed simulations run on multiple mainframes at various sites. A stated requirement is to be able to run a distributed simulation with dedicated links for up to 36 hours without interruption. At the same time, the usual science and engineering development should also receive sufficient resources on the same mainframes.

Other computing requirements at the NTB include the usual set of items such as reliability, performance, development tools, and a straightforward user interface. Management, status, auditing, and accounting are also required by administrative users. Two additional requirements stand out from all the rest. These are security and communication latency. Because this is a defense program of strategic importance, every precaution is necessary to safeguard information at the NTB. This is an especially challenging problem because of the wide area extent, number of organizations, and planned multinational membership of the NTB. Issues of link encryption, data storage, compartments, partitions, need-to-know separation, and multilevel secure systems are necessary topics for later discussion. For further details, refer to the NTB INFOSEC Security Strategy Working Paper-6962 published by Mitre. ³

Latency in distributed simulations is another challenge. This is a requirement that will be dealt with at many fronts including the communication framework, system efficiency, and application algorithms. For purposes of this report, the first two will be dealt with in some detail. Application algorithms are left for another effort.

2.6 NTB Architecture

Further details, such as main frame equipment, communication equipment, and layout, can be obtained by reviewing the System Description Document NTB-242/442-006. ²

3.0 High Performance Computing

The past 10 years have seen a rush of reports, panel discussions, and calls for new initiatives in the area of high-performance computing. Congressional inquiries and opportunities made possible with new technology have prompted these efforts. The Federal Coordination Council on Science, Engineering and Technology, in response to Congress, had also recommended that expert panels assess needs and activities in high-performance computing. The reason can be summed up as economic motivation. The potential progress in science, engineering, and industry is clear. Modeling and simulation, in close association with theory and experiment, act as the third member of scientific research. ⁴ Benefits include insight, feedback, and cost savings. Even though rapid development has occurred, the consensus is that far more needs to be done. For example, a call for a national initiative costing on the order of \$1.5 billion over a 5-year period has been made. Background information on these reports can be found in References 4 and 5.

Recommendations from panels for a national computing initiative ⁴ covered three areas including applications, advanced systems, and parallel computing. Panels of these areas agreed that access to a national gigabit network was crucial to organizing distributed supercomputing into an integrated, coherent system. Recommendations from another gigabit-working group ⁵ focused specifically on national high-performance or gigabit networking.

High-performance computing encompasses applications, system software, and a transport network to provide information transfer. The necessity for a network framework is a critical first step for the support of communicating applications and distributed simulations. For purposes of this report, further discussions will concentrate on the network framework, supporting protocols, and system software. This will establish the necessary basis for the goal of a DSA as proposed in Section 1.2.

3.1 Distributed Gigabit Networking

A number of workshops and ad hoc working groups have produced reports and recommendations concerning issues, architectures, protocols, and related system software for very high-speed networks. Two good examples of these reports can be

found in References 5 and 6. They provide excellent food for thought on issues and the revolutionary stage of networking in which we find ourselves.

3.1.1 Recent Efforts

The National Science Foundation's National Supercomputing Centers were implemented after 1985 following the Lax Report ⁷ and later the Bardon-Curtis Report⁸ recommending research, development, design, and implementation of new supercomputing systems. A number of these centers now exist across the country. A list of current research and development activities related to gigabit networking can be also be found in Appendix A of RFC 1077. ⁵ Since that list was compiled progress has continued. For example, the Corporation for National Research Initiatives is coordinating a gigabit test bed research program with results contributing to research needed for the proposed National Research and Education Network. Five test beds are proposed for installation during 1990. ⁹ These test beds include academic, industrial, and national laboratory collaborations. This program is slated to research issues in wide area networking (WAN), metropolitan area networking (MAN), high-speed protocols, switching, optics, systems software, and security among others. A brief overview of each of these test beds will be discussed in a later section. This next section will describe major issues of gigabit networking.

3.1.2 Issues

The three most notable issues in a distributed gigabit environment are the impact and extent of parallelism, distribution at all levels, and integration of heterogeneous systems. Parallelism is the answer to increased needs in performance at all levels including applications, system architectures, protocol structures, switching, and transmission medium. Distribution aids parallelism and provides for better sharing of capital intensive resources and access to specialized processing needs. Given the heterogeneous nature of specialized systems, integration of the elements into a single system with a uniform user and I/O interface is necessary. ¹⁰⁻¹⁵ Thus, the mainframe, workstations, disk farms, graphics stations, and specialized devices will be integrated to form a logical single distributed computer managed by a single distributed operating system. This has been referred to as the metacomputer. ¹⁴ See Figure 2 for a conceptual view. We begin to see the network as a backplane, or resource, of a larger system or metacomputer which also includes hosts as special purpose devices or peripherals. These hosts are no longer autonomous but components of a larger system. The NTB's SDS is representative of this larger system.

This distributed simulation architecture and environment abstractly mirror the real world system of the entire globe and surrounding space populated with subsystems, or platforms. We now discuss the overall architecture breaking it down into hardware, controlling software, and service characteristics.

3.1.2.1 Hardware Issues

The primary hardware issue in the near future will be consideration of fiber-optic technology and all of its ramifications. This includes switches, interfaces, holographic memory, multiplexing methods, and standards. Another more immediate hardware issue is incorporation of fast packet switches into the network fabric. By far, the most immediate, critical issue facing commercial computer vendors is the impact of massively parallel processing and communication on the architecture of their mainframes, workstations, and devices. These systems can no longer act as autonomous entities that happen to have I/O devices to communicate with others. An abstract uniform interface is desirable. Their architectures would best be served by opening up and developing a multiprocessor/multicomputer frame of reference.

Growth and evolution is a certainty in computing networks. Hardware components such as switches, backplanes, and, especially, mainframes are best designed to be modular, scalable, and extensible. Something of the characteristics of crystal morphology and the flexibility of a Tinkertoy set is useful. Modular construction of a network, as the need dictates, helps in managing and maintaining such a potentially complex system. Scalability allows growth without undue impact on the currently existing structure. Scalability is also a function of link and switch discipline. Examples are the networks assembled with point-to-point links or a shared broadcast medium like Ethernet. Extending the Ethernet network into a hierarchy is possible but not easy. In a parallel environment, significant help can be gained by the use of richly connected hardware not inherently restricted to one dimension or sequential access. A structured topology, rather than an ad hoc amorphous conglomeration of equipment, lends itself to better understanding and management of the network framework. Extensibility through flexibility is also a necessary quality, for, without a plan and carried too far, extending a network becomes chaotic and virtually unmanageable.

Finally, both switches and interface adaptors present challenges in a gigabit environment because they will be temporary bottlenecks for gigabit fiber-based networks. They do have, however, the most potential for contribution to network backplane simplicity. Protocol implementations in silicon are also expected to

contribute to better performance in switches and interfaces. Photonic wave division multiplexing (WDM) and frequency division multiplexing also play in the picture of simplicity in a network backplane.

Figure 2. Conceptual view of a metacomputer.

3.1.2.2 Software Issues

The most critical issue, from a software perspective, is the operating system bottleneck in a gigabit environment. This again is actually a part of the greater issue of architecture. From the software standpoint, if we step back and realize that we'll eventually be dealing with and evolving to an integrated entity, we can no longer think of operating systems on hosts using network communication services as a loosely related collection of functions and policy for communication between a multitude of autonomous objects. The software for this system is no longer a communication tool between peers. The various operating systems and network functions end up being a distributed operating system managing all resources such as the backplane (network), the peripherals (hosts and devices), data storage (mass storage), and user access (concentrator terminal front ends). In this way, we move from a set of hosts with their own autonomous operating systems to a single operating system. 12,13

Important elements of software are the protocol for data transmission, interfaces to the system software, the system operating, or managing, software itself, and the services provided. The use of interfaces and layering needs to be explored and expanded as an avenue for cooperation and integration of these elements into a synergistic system which would otherwise be unattainable. 5,16-17

Another fundamental and challenging problem within the distributed system will be management of simultaneous pairwise transmissions. Virtual circuits have been the traditional mechanism up to now. A very promising variation of this will be the use of WDM with its extremely high capacity for channel assignments to users. It may very well be a natural choice for switching data as the technology reaches maturity. Many technological barriers currently exist, however.

3.1.2.3 Service Issues

Services exist to identify, locate, allocate, protect, maintain, and manage the use of objects in this system. Naming, addressing, and routing serve to identify and locate objects. A directory service acts as the clearing house for registration of an entity's identity, location, and characteristics or capabilities. By careful selection and assignment of namespace, need-to-know separation, partitioning, and general access control can be exercised over users of system resources. Once location and access have been established, other services aid in reserving bandwidth, minimizing delay, and managing faults and errors as well as traffic management such as flow and congestion control or redundant and alternate routing.

Security deserves special notice here. In the past, security has been largely ignored in operating systems. In a distributed system, security will be an absolute requirement to maintain the integrity of the system within itself. It will be necessary for resource allocation, protection from accidental or malicious activities, and even maintenance by temporarily limiting access to objects. Security, unlike in the past, will be an implicit part of the system infrastructure by requiring registration, allocation, and authentication of objects with a need to communicate or interact in any normal way with other objects. This would be accomplished by association of objects into a logical set by means of dynamic logical addressing. Logical group membership can then be determined at the entrance and exit of the network. This provides separation at the host level. The final separation is achieved for transaction protection by use of subsets of logical addressing as well as key and encryption separation as specified by communities of interest (COI) in Reference 3. COIs, logical addressing, and the directory service provide an integrated security

structure for the DSA. Multilevel secure (MLS) systems are critical and need investigation into their relation to a distributed operating system environment. MLSs are outside of the scope of this report.

3.1.2.4 Complexity Issues

Gigabit networking will force one to review, and in many cases rethink, the solutions and methods successful in past network technology. Time becomes much more critical. For example, consider the volume of potential data transferred from one or more sources during retransmissions, acknowledgements, connection setup, context switching, data copies, reassembly and disassembly of messages, buffering, store and forward switching, overhead from administrative protocols like the Routing Information Protocol (RIP), sequential access of the LAN media such as a bus, and the media access routine itself. One then realizes, you cannot afford to have such an impact on data transfers and, consequently, application software because of mechanisms successful in the past. A much more efficient, simple, and natural approach is in order. Piecewise integration and explicit or ad hoc methods of network management suddenly seem futile and woefully inadequate in the context of gigabit environments. Explicit manipulation of data transfers becomes complex and awkward. Networks dealt with as complex, dynamic, and physical systems utilizing implicit characteristics of management from self-organizing phenomena seem far more elegant and effective as a means of providing data transfer and management services. 18-20

As an example, consider flow and congestion control of data. Back pressure has been used as a method of flow control. ²¹ Thinking of the network backplane as a fluid pipe, one can visualize messages backing up to a number of sources. The latency of flow information back to a source is a function of the elasticity of buffers and return flow signaling. ^{22,23} This is a considerably shorter period of time than explicit control through windowing methods for flow control and source quench of message flow from the source for congestion. Windowing seems artificial compared with the use of back pressure which takes advantage of information passing implicitly through the system itself. Cars in freeway traffic provide an excellent analogy of flow control. For congestion, dumping packets is another artificial method that in fact defeats the system by bleeding off pressure that can act as feedback information to sources at the entrance of the network.

3.1.3 Interconnection Network

The network is the major resource of a distributed system. ²⁴ As the communication resource between processors, memory, and devices, this resource, or Interconnection Network (IN), has received considerable attention in the literature. Primary areas of concentration include the switching method, network topology, mode of operation, control strategy, and the transport medium used. The IN can use a shared medium, shared memory, or a crossbar switch. The IN can also use a multistage switch made up of component switches of buses, shared memory, or crossbars.

The actual communication between processors is accomplished with either message passing or shared memory. Message passing is the most common and best understood method. Shared memory is flexible but has expensive overhead in terms of hardware implementation and cache coherence algorithms to maintain a consistent view of data in memory for all processors. A short comparison of the pros and cons of shared memory vs. message passing is in Reference 25. Message passing in multicomputer networks is discussed in References 26 and 27.

Finally, crossing the network is only part of the story. Moving data into and out of a host constitutes a significant portion of transport latency. Anyone who has traveled to and from airports should have some sympathy for this problem. Work in the area of network adaptors and network access is a rapidly growing area of research particularly in light of the growing interest in distributed systems and gigabit networking. For good examples refer to References 22 and 28.

Transport media, switches, and network adaptors make up the hardware portion of IN technology. Understanding the INs themselves is important because of their potential for fault management. Due to the sheer volume of literature on switch and network adaptor strategies, this section will largely serve as a brief introduction and point the interested reader to other sources for detailed descriptions. Very good surveys of interconnection networks can be found in References 29-32. Two good sources of information on high-performance switching techniques can be found in References 33 and 34. A survey of Very Large-Scale Integration (VLSI) implementations of protocols is found in Reference 35.

3.1.3.1 Transport and Storage Medium

Fiber, coaxial cable, parallel copper cable, and shared memory are examples of the transport media available for communication. It is well known that it is only a matter of research, time, and effort before fiber will be the mainstay medium of choice.

Interesting work is also being done in optic holographic memory ^{*} and optical disks. For architectural issues in photonic networks refer to Reference 36. Buffer and storage device work is being done with video random access memory (VRAM) for pipeline protocol processing and content addressable memory (CAM). The most notable issue concerning physical layer entities is limited availability of high-performance standards necessary for supercomputing data transfers at gigabit rates. This becomes an extremely important issue when considering connectivity to commercial supercomputers. The Synchronous Optical Network (SONET) is a physical protocol currently receiving widespread interest especially by the telecommunications industry. It does not easily interface to commercial supercomputers. As will be evident later, the High-Performance Parallel Interface (HIPPI), ³⁷ a proposed ANSI standard, is being proposed in many projects to fill this need.

3.1.3.2 Switching

Most people are used to the packet switching of Ethernet even though they may not think of it as a switch. The switching is passive and done by a distributed method of packet recognition. Traditional packet switching has been done on general purpose computers programmed for a special purpose. With progress in VLSI technology and the ever-increasing need of applications for greater performance, a new generation of switches has been developed. These switches are known as fast packet switches. They take advantage of distributed control and parallelism by moving the intelligence for packet control to the link or channel level and communicating with each other over various possible internal interconnection network backplanes. Notice the similarity to the interconnection network of the gigabit network itself. By generalizing this equivalence, you can consider hosts, clusters of hosts, and networks of clusters identical entities from a system software standpoint. This point will be elaborated further in Section 4.

Switching falls into the two categories of packet and circuit switching. Advantages and disadvantages exist for each technique. The traditional method of gaining the advantages of both is called the virtual circuit. Other more recent methods are described in References 38 and 39. These methods describe switching and data transport services that combine characteristics of both packet and circuit

^{*} This information was presented at Frontiers of Supercomputing II: A National Reassessment, Los Alamos National Laboratory, Los Alamos, New Mexico, August 1990.

switching. Examples include virtual cut through, wormhole and circuit staging methods. Ideally, an evolution to a service providing a continuum between full circuit and packet transfers at the physical level will provide the simplest and most flexible data transfer service.

3.1.3.2.1 Multistage Switches

The largest class of switch types are the spaced division switches. These include multistage interconnection networks (MINs) such as banyan and delta networks, crossbars, and disjoint path switches. The MIN work has been the result of research in telecommunications.³³ They are noteworthy for the use of self routing and the ability to take advantage of the fault tolerant characteristics of a regular topology. Fast packet switches of this design include the Starlite⁴⁰ and one by Turner.⁴¹ One of the critical issues of designing a switch is where to do the buffering of data while a physical connection is established. The three choices include input, internal, and output queues. The preferable choice is output queuing.⁴² This design feature has been incorporated into at least two switches of the disjoint path type including the Knockout⁴³ and Integrated Switch Fabric.⁴⁴

3.1.3.2.2 Crossbar Switches

Crossbar switches have always been popular because they are internally nonblocking. They are, however, subject to concern about placement of buffer queues, external blocking, and exponential growth in crosspoint hardware. Crossbar switches with associated interfaces have recently been implemented at Los Alamos National Laboratory (LANL) and as commercial products by Network Systems Corporation and Ancor Communications. Today these commercial products provide supercomputer connectivity using HIPPI.

3.1.3.2.3 Shared Memory Switches

Shared memory fast packet switches are also being built. Work on shared memory communication networks can be found in References 45-47. These switches are characterized by all input lines feeding data into a single input stream for storage and subsequent transfer to the correct output line. The Prelude switch is an example of this type. A good description can be found in Reference 48. NASA has installed a memory-based network designed and built by two commercial firms.⁴⁹

3.1.3.2.4 Shared Medium Switches

The shared medium switch is similar to the shared memory switch in this respect and has been realized in the design of the SCPS,⁵⁰ ATOM,⁵¹ and PARIS switches.⁵²

3.1.3.2.5 Bus Switching

To deal with the increased call for performance, multiple-bus architectures are also receiving considerable attention. Ultra Network Technologies probably has the best example of a commercial switching product using this type of architecture. The multiple-bus architecture is surveyed in Reference 53.

3.1.3.2.6 Optical Switching

Finally, one must consider optical switching and networks. Optical crossbars, interconnection networks, and switching with WDM are particularly interesting to industry as an integrated framework for voice, video, and data transmissions. Optical switching and networking topics are discussed in References 36 and 54-58.

3.1.3.3 Network Interface Adaptors

Network interfaces to hosts and fast packet switches are also under investigation. They serve two purposes. They provide access to the internal backplane of the host and access to the network transport media, which, as we have stated, is another backplane. Interfaces on switches are really no different. Again, we can see the equivalence when we consider that no matter where an interface is located its fundamental purpose is to move data over a transport backplane. The other purpose is to translate between dissimilar backplanes. Related responsibilities include buffering, address translations, routing, flow control, security, and other protocol functionality up to and including internet gateway translations. At some point, the network adaptor will evolve into a communication coprocessor, or peer, in a multiprocessor environment. This is already evident in the iWarp⁵⁹ implementation of nodes with computation and communication processors.

A number of network interface adaptors have been built. One is the Communication Accelerator Board (CAB) in Carnegie Mellon University's (CMU) Nectar Network.²² It processes protocols up to the transport level. Another well-known adaptor designed and built at Stanford for the Versatile Message Transport Protocol (VMTP) is the Network Adaptor Board.²⁸ This protocol will be discussed in the next section. The original CrossBar Interface (CBI)⁶⁰ is a HIPPI-based protocol processor built in a collaborative effort by LANL and Digital Equipment Corporation

(DEC). It processes protocols at the local network layer and expects the host to handle the transport and internet layers. A commercial adaptor has been built by Ultra Network Technologies. It is designed with a flow-through architecture for protocol processing. It processes a variation of the International Standards Organization's (ISO) Transport Protocol Level 4 (TP4) transport and Connectionless Network Protocol (CLNP) protocols or TCP/IP. The final adaptor mentioned here is designed to process the Xpress Transfer Protocol (XTP)³⁹ of Protocol Engines. XTP was designed by Greg Chesson and is a pipeline protocol combining the network and transport layers into what is called the transfer layer.

3.1.3.4 High-Performance Protocols

High-performance protocols can be classified into two groups at this point in time. The first is existing protocols that are being worked with to improve implementations and extended to meet new requirements. This includes TCP/IP and TP4/CLNP. The other is the group of new protocols designed with very high performance in mind. These include VMTP,⁶¹ XTP,³⁹ Network Block Transfer (NETBLT),⁶² Asynchronous Transfer Mode (ATM),⁶³ Switched Multi-Megabit Data Service (SMDS),⁶⁴ Frame-Relay,⁶⁵ and the Scalable Coherent Interface (SCI).^{66,67} A continuing debate exists over the comparative advantages and disadvantages of the groups. The reader is reminded of the discussion on change presented in the introduction of this report. Since the characteristics of TCP/IP are fairly well known, attention here will concentrate on a few key issues regarding the latter group.

Other interesting protocol issues, such as packet switching as opposed to circuit switching or use of source routing, are discussed in References.⁶⁸⁻⁷⁰ Performance and latency are the overwhelming concerns of newer protocols. Improvements include the use of virtual cut through routing,⁷¹ wormhole routing,⁷² self routing,⁷³ and alternatives to retransmissions and the use of feedback mechanisms for flow control. Another weakness with current protocols is the lack of cooperation between layers of protocols for passing useful information, such as notification of errors and congestion.^{5,16,17} It is also possible to reduce data copying by providing pointers to memory for appropriate placement of data as it is read in from the network.^{22,74} A broadened set of services, such as carrying voice, video, and data, are new requirements over the past. Additional flexibility to existing services, by including the advantages of both packet and circuit switching, is also an issue.

3.1.3.4.1 High-Performance Transport Protocols

VMTP is a transport protocol designed for transaction communication and remote procedure calls (RPC). NETBLT is another transport protocol designed for transfer of large blocks of data. Transport protocols are of interest here because of their relation to the lower network framework protocols optimized for high-speed network communication such as ATM.

XTP is designed for VLSI and works in a pipeline fashion so as to complete processing of a header in a packet's arrival time. It also combines packet and connection services to take advantage of both types of data transfer.

3.1.3.4.2 High-Performance Framework Protocols

ATM is the telecommunication industry's version of a packet-switching protocol. Traditionally a circuit-based industry, ATM uses 53-byte packets with virtual path and virtual channel identifiers to implement virtual circuits. One hurdle for this protocol is packet assembly/disassembly, which is a related issue to fragmentation of datagrams. Fragmentation has recently come under scrutiny for performance reasons. 75

The Fiber Distributed Data Interface (FDDI) protocol is currently available and expected to act as the follow-on to Ethernet and will be the mainstay protocol for LANs of the near future. It is a specification for the physical and media access layers of a token-passing ring. At 100 Mbit/s, it is an order of magnitude increase in bandwidth over Ethernet.

SMDS is actually a public packet switched data service rather than a protocol and expected to be offered in 1991. It acts as a subnetwork communication framework providing packet communications between LANs, computers, and workstations. The actual network providing SMDS is transparent to all users and only visible at the network interface as the SMDS Interface Protocol (SIP). SIP is divided into three protocol layers for addressing, framing, and transport equivalent to a media access control (MAC) and physical layer protocols. Currently, these levels are based on the Distributed Queue Dual Bus MAC protocol defined in IEEE 802.6, and physical signal speeds of 1.544 (DS1) to 44.736 (DS3) megabits per second. Considerable effort and merit are being put into SMDS as a new public carrier network.

Frame-relay is another form of packet transmission similar to a streamlined X.25 functionality. Frame-relay relies on improved transmission media to eliminate some of the expensive overhead involved in transmission error recovery. It is assumed

that very few errors will occur and those that do will be handled by end system protocols at the applications.

SCI is a proposed interface standard for high-performance multiprocessors. It supports a coherent-memory model for a multiprocessor backplane. The interface defines physical and logical layers. This work is being conducted in an IEEE working group. For an introduction refer to Reference 66. Several standards documents can be obtained with an overview in Reference 67.

Other framework protocols are sure to appear as technology advances. One example of a missing requirement is a protocol for combining packet, message, and circuit switching as service options to a distributed operating system. This is an area for further research. An attempt to fill this need is being addressed with the Switched Distributed Data Interface (SDDI).⁷⁶

3.1.4 Processors

Processors are mentioned here to point out two very significant observations within the context of a DSA. First, the impact of parallelism is now fully evident in commercial system architectures. The impact of the Connection Machine's CM-2 and N-Cube's massively parallel machines has been felt at LANL and Sandia National Laboratories in Albuquerque as well as a number of other sites nationwide. Massively parallel machines have demonstrated the capability to solve problems previously thought to be in the realm of the traditional serial supercomputers. At LANL, portability of old code has also been demonstrated to require a surprisingly minimal amount of work. The most important issue is the significant performance that has been achieved with real problems, such as QCD and three-dimensional hydrocodes.

The second item of note is the end of the era of autonomous supercomputers. Previously, supercomputers drove requirements for network design. In the future, the distributed environment will drive requirements for supercomputer architectures. It is now necessary to have the capability to access networks with a standard interface and provide the software support necessary to cooperate in distributed applications. The high-performance processors of the future will be components of a larger system. The major impact will be on design of system architectures of the future. Special consideration will be necessary for design of the internal backplane and I/O systems. Failure on this point will likely prove very costly to commercial vendors.

It is also worth mentioning the potential of clustering workstations for cost-effective solutions to large applications.* Such a configuration will provide an easy mechanism to divide the efforts of workstations, as is necessary, and allow small incremental increases in power at minimal cost. Finally, the impact of very different architectures for physical system modeling, such as the CAM-6⁷⁷ and iWarp,⁵⁹ should not be overlooked. Systems like this take full advantage of parallelism and apply it to physical systems in general.

3.1.5 Projects and Test Beds

As stated earlier, five gigabit test beds sponsored by NRI are underway to research high-performance networking, switch design, network adaptors, protocols, system software, system security, performance, optics, and distributed applications. These test beds are entitled Aurora, Blanca, Casa, Vistanet, and Nectar. The Aurora, Blanca, and Casa Test Beds will concentrate on WANs while Vistanet and Nectar are concerned with MANs. Information about these test beds was taken from Reference 5.

3.1.5.1 Aurora

Members of the Aurora Test Bed include the Massachusetts Institute of Technology (MIT), University of Pennsylvania, Bellcore, and IBM. Collaborators include Bell Atlantic, MCI Telecommunications and Nynex. Their primary investigation, will be in network services. In particular, MIT will focus on network resource control, University of Pennsylvania on distributed virtual memory, Bellcore on protocols and network architecture, and IBM on a joint architecture effort. The network framework proposed uses SONET with the PARIS and SUNSHINE switches. PARIS was mentioned earlier and SUNSHINE is a self-routing Banyan switch with output queuing and recirculation queues for higher reliability. The protocol used will be ATM. The applications will center around collaborative business effort and virtual worlds.

3.1.5.2 Blanca

Blanca members include AT&T Bell Laboratories, Lawrence Berkeley Laboratory, the National Center for Supercomputing Applications, the University of California at Berkeley, the University of Illinois at Urbana-Champaign, and the University of

* From a talk by Bill Joy of Sun Microsystems, Inc. at Frontiers of Supercomputing II: A National Reassessment, Los Alamos National Laboratory, Los Alamos, New Mexico, August 1990.

Wisconsin. Collaborators include Ameritech, Astronautics, Bell Atlantic, Cray Research, Norlight, and Pacific Bell. The network protocol used in this test bed will also be ATM. The switch will be the Experimental University Network, or XUNET-2, initiated by AT&T. Other links will utilize HIPPI, FDDI, and DS-3 standards. Applications included in this test bed are multiple remote visualization and control of simulations in atmospheric modeling, radio astronomy imaging, a multimedia digital library, and medical imaging.

3.1.5.3 Casa

Casa test bed participants include LANL, the California Institute of Technology (CIT), the Jet Propulsion Laboratory, and the San Diego Supercomputer Center. Industrial participants include MCI, Pacific Bell, and US West. The emphasis for this test bed is distributed applications in three areas. They include a tightly coupled chemical reaction dynamics computation, an interactive visualization program in geophysics with input data from Landsat, seismic and topographic databases, and a climate model combining atmosphere and ocean models. The network framework will include physical layers using HIPPI and SONET. The transport layer will choose from TCP, VMTP, NETBLT, and Ultra's ISO TP4. System software will be chosen from LINDA,⁷⁸ STRAND88,⁷⁹ or CIT's Express.⁸⁰

3.1.5.4 Vistanet

Vistanet members include Bell South, the Microelectronics Center of North Carolina, the University of North Carolina at Chapel Hill and GTE. Their network is ATM and SONET based with HIPPI network access for supercomputers. The application will be a 3-D interactive imaging program to aid physicians in planning radiation doses for patients.

3.1.5.5 Nectar

Nectar²² constitutes the fifth test bed. Members include CMU, the Pittsburgh Supercomputing Center, Bell Atlantic, and Bell of Pennsylvania. Their research focuses on high-speed networks. It is a fiber-optic network using a gigabit switch designed at CMU. Protocol processing is done by a CMU's CAB. HIPPI will also be installed on the CAB. System software and protocol issues are a primary interest in this test bed. Processors will include a Cray YMP and the iWarp also developed by CMU and Intel.

3.1.5.6 Autonet

Another project of special note is the Autonet.⁸¹ This is a high-speed, self-configuring, switching LAN developed at the Systems Research Center in Palo Alto. The interesting feature of this network is threefold. First, it is based on active switches rather than the passive switching of Ethernet. Secondly, it configures itself into a spanning tree at initialization or upon a link or node failure. Finally, the addressing and host software has been designed to make Autonet look indistinguishable from an Ethernet. This final item is important when considering migration paths of currently installed Ethernet-based networks. Autonet-II will be an implementation using HIPPI as the physical layer protocol. Encryption is also part of their design. It is expected to be implemented in 1991.

3.1.5.7 Multiple Crossbar Network

A network project associated with HIPPI was started at LANL 3 years ago. This was called the Multiple Crossbar Network (MCN).¹⁴ This amounted to development of a HIPPI-based switch with associated protocol processors. The switch was a standalone unit called the Crossbar Switch (CBS) while the protocol processors were designed and built by DEC and called CBIs.⁶⁰ The CBS and CBI combine to form the CrossPoint Star (CP*) switch. Combinations of CP* form the MCN. A fair amount of testing experience was gained on the CBS. Experience was also gained on the CBI. Connectivity and data transfers were achieved between an IBM 3090 HIPPI, the DEC CBI, and a framebuffer. Later efforts demonstrated successful data transfers on a Cray YMP and Thinking Machines CM-2. A HIPPI tester exists to test HIPPI implementations. It has completed technology transfer channels to Input Output Systems Corporation and is available to industry.

Unfortunately, changing priorities at DEC prompted the cancellation of a second generation CBI. Consequently, LANL has taken what it learned from the collaboration and is now designing and will build an implementation of its own version of the CBI. The CBS success resulted in Network Systems Corporation designing and producing the P8 Switch. Today, this is a HIPPI compatible 8 x 8 crossbar switch providing supercomputer connectivity. The MCN is now being realized by installation of P8 switches and HIPPI hosts in the Casa Test Bed mentioned earlier and the Advanced Computing Laboratory (ACL) at LANL.

Other noteworthy commercial efforts using HIPPI include the Ancor Communications switch being developed in association with Lawrence Livermore National Laboratory (LLNL) and the Ultra Network Technology Corporation's

UltraNet. The Ancor switch was designed to replace LLNL's graphics capabilities and is due for installation and testing in March 1991. UltraNet is available today. It processes protocols at the transport level.

3.2 Distributed System Software

Given a gigabit network framework and supporting transfer protocol, the second element of a DSA is the system software. Here again, the field is rich in research with no clear winning candidate. Distributed software means different things to different people. The spectrum ranges from RPCs to windowing to an all-encompassing distributed operating system (DOS). This discussion considers no less than the DOS as an essential element of a DSA. Refer to Watson ¹³ for a description of a future operating system architecture. It also discusses the shortfalls of UNIX in this context. Responsibilities of a DOS are virtually identical to single-host operating systems. The complexities are another matter. Issues such as latency, error control, fault management, resource control, access control, and table coherence are magnified and complicated by the sheer volume of equipment and interactions of system entities.

Quite a few distributed systems have been developed and tested extensively. They are simply listed here for reference. Mach ⁸² was developed at CMU, ISIS ⁸³ at Cornell, Athena ⁸⁴ at MIT, Express ⁸⁰ at CIT, Chorus, ⁸⁵ at the Institut National de Recherche en Informatique et Automatique and V-Kernel ⁸⁶ at Stanford. LINDA and STRAND⁸⁸ are also distributed environments available today. The V-Kernel is an example of a DOS with security designed into the system. Examples of commercial systems of interest include IBM's Transparent Computing Facility and Hewlett Packard/Apollo's Network Computing System.

3.3 Distributed Applications

The third and final element of the DSA is the set of applications. The requirements of applications affect the first two elements. Given increased use of parallelism, architecture models such as single instruction multiple data (SIMD), multiple instruction multiple data (MIMD), and data flow need to be supported. Reconfigurable architectures such as those represented by the Texas Reconfigurable Array Computer (TRAC), ⁸⁷ Partitionable SIMD/MIMD (PASM), ⁸⁸ and Configurable Highly Parallel (CHIP) ⁸⁹ are highly desirable to allow tailoring of the architecture to the application rather than the reverse. Providing this capability in a gigabit DSA is an extension of scale similar to that of multiprocessors and multicomputers. Another

characteristic of this architecture is the ability to partition the framework. This gives applications guaranteed resources, limits access to need-to-know users, aids fault isolation and tolerance, and, most importantly, provides a virtual SIMD or MIMD machine for a number of users.⁷⁷ Finally, the ability to connect heterogeneous systems to this DSA allows special purpose machines connectivity as a kind of peripheral device. This applies to disk farms, frame buffers, special simulators, or whatever is needed. That device then becomes an object with known capabilities to interested users. Combining these systems allows multilevel applications. An example of this is speech recognition with raw data acquisition, data rendering, image display, and expert system analysis done within the context of a single application.^{22,90} Most all of these characteristics are applicable to the NTB applications. Consequently, this fits very well into the mission of the NTB as a system simulator of defense technologies.

4.0 NTB Distributed System Architecture

The DSA has been characterized as a metacomputer. Characteristics include 1) a modular, richly connected communication framework of links, switches, and network adaptors; 2) a simple, streamlined framework protocol; 3) a distributed operating system; and 4) an object-oriented directory service for resource management and access control. The central theme for this architecture is a synergy of processors, communication, managing software, services, user interface, and applications to produce an image of uninterruptible service from a single logical entity available to users of the system.

When considering a DSA, three things come to mind. They are the need for a standard interface to attached supercomputers, the multitude of choices in switching methods and system software, and the observation that backplanes of hosts and networks from local to wide area extent are virtually identical. The first point is extremely important for connectivity. Fortunately, a proposed standard supercomputer interface now exists in the form of HIPPI and in the form of SCI in the near future. The second point begs for a structure that will accommodate the experimentation and use of these technologies independent of each other and yet contributing a uniqueness to the system as a whole much as the special purpose processors attached to the system. The last point is relevant to the design of a seamless network backplane necessary for distributed computation. It represents quite a change in perspective with interesting implications. A network is no longer a group of autonomous hosts connected by links and switches but clusters

communicating as peers. The clusters are devices communicating over an internal cluster backplane. One or more of the devices on each cluster provide intercluster communication. At the final destination, or traditional host, data is delivered to the final device whether it be memory, a frame buffer, or some form of controller such as for a disk.

Rather than discuss the various reasons for building a framework a particular way, a process of building a framework through description and figures will be pursued here. Throughout this process, relevant features of interest will be pointed out to the reader.

4.1 Hardware Framework

Given that HIPPI is a commercially implemented, proposed standard supercomputer interface, it will be used as the link component of the DSA. The switch elements will be a generalization of the CP* switch. The switches themselves are not restricted to a HIPPI-based physical layer; however, HIPPI-based switches will be used here for simplicity. Some interface adaptors exist, most notably a VME/HIPPI adaptor card. Interface adaptors are depicted in the logical layout of Figure 3. Sequencers move data into and out of memory, such as the video random access memory (VRAM) in Figure 3, which may be configured as multiple queues for efficiency. The Protocol Processor (PP) acts as the intelligent forwarding, or protocol translation, agent. These adaptors are expected to be more than mere translators.

Figure 3. Simple Logical Diagram of an Interface Adaptor.

They are in fact coprocessors. Their functionality, however, is single purpose. That is to provide an intelligent communication agent at bifurcation points in the IN. To begin the process a short description of HIPPI is in order.

The signaling for HIPPI is shown in Figure 4. As a simplex point-to-point link, the protocol is straightforward. A physical connection is established with a REQUEST from the source and acknowledgement of a CONNECT by the destination. Transmission of data is signaled as a PACKET. Actual data is transmitted as a BURST. The destination signals that it is READY for a burst of data. Multiple READYS can be sent by the destination. As part of the connection sequence, one word of data may be transmitted with the REQUEST for connect. This is switching information for an intermediate controller or switching mechanism.

Figure 4. HIPPI Signaling.

Figure 5. Logical hierarchy of HIPPI structures.

Figure 6. Packets passing over a connection through a switch.

The resulting logical hierarchy of data structures is shown in Figure 5. There is no limit to the number of packets within a connection nor the number of bursts within a packet. An illustration of data passing through a switch is depicted in Figure 6, which applies to buffered or bufferless transmissions.

The simplest case for connectivity immediately brings a HIPPI point-to-point link and interface adaptor cards into play as seen in Figure 7. For additional connectivity a crossbar switch can be introduced as depicted in Figure 8. Supercomputers, workstations, and device controllers can then be attached using appropriate adaptors to form a simple cluster. Expanding the capacity of the cluster is a matter of connecting crossbars into a multistage network. The number of ports can then be

Figure 7. Simple configuration requiring two adaptors and cables.

Figure 8. A cluster with a crossbar interconnect.

scaled to suit the need. At this point, a distinction will be made between a host and a node. The purpose is to encourage the image of equivalence between a node and cluster as communicating multiprocessor entities rather than atomic systems like the traditional network host. The difference between a node and cluster is that a node is the final destination for data transfers.

To expand the framework to multiple clusters, communication adaptor cards are added to the cluster. At this point, topology becomes an issue. Many topologies are possible including a line, ring, mesh, or more complicated structure such as hypercube ⁹¹ or n-star. ^{92,93} It is also possible to have an irregular topology. Ad hoc connectivity, however, is considered unnecessary and, ultimately, unmanageable in a gigabit framework. The potential utility of a regular topology for simplified routing, fault management, and security should not be ignored. For illustrative purposes a hypercube topology has been selected for this discussion. A hypercube of clusters is depicted in Figure 9. Now consider a blown-up view of a cluster within this hypercube. See Figure 10. There are four intercluster links in this example with a hypercube interconnection network within the cluster itself. Node adaptors fill remaining slots of the cluster and provide backplane translations and encapsulation

if necessary. It is not a requirement that these adaptors be in a single cabinet or in close proximity. Problems may arise when considering the combined requirements of the node and cluster backplanes.

Figure 9. Clusters in a hypercube topology.

Finally, note that the intracluster network is not restricted to crossbars, hypercubes, or even HIPPI. A generalization of cluster INs is possible by building appropriate interface adaptors from HIPPI to other local network or bus architectures. Ethernet or FDDI are examples of intracluster INs which might be used. See Figures 11 and 12. Packets traversing this type of IN would be encapsulated with the appropriate protocol header. This allows flexibility beyond HIPPI-based networks. The pros and cons of this method will be briefly discussed in the next section on software.

Figure 13 is an example of the cluster connection to the node. Data arriving at this point is delivered to the appropriate device by the node communications adaptor. Buffering may or may not occur here. If a device is ready or can be readied in time, the virtual cut-through or wormhole technique will be used and data sent directly on to the final device. A frame buffer is a good example of this. Private memory and disks on the other hand may present a few more complexities, requiring data staging

before an appropriate controller moves the data to a final destination. Generally speaking, a shared memory node architecture is most appropriate as a final destination, as depicted in the figure, although various message-passing topologies are possible.

Figure 10. Expanded view of a cluster of the physical framework.

Figure 11. Cluster with Ethernet interior IN.

Figure 12. Cluster with FDDI Token Ring interior IN.

Figure 13. View of a node beyond the communication framework.

4.2 System Software Support

4.2.1 Framework Protocol

An early implementation of the DSA would probably consider TCP/IP or ISO's TP4/CLNP as the transport and internet protocols of choice. As new protocols, XTP and VMTP should be given serious consideration as end-to-end protocols. ATM is a candidate for a framework protocol; however, it is not entirely appropriate since it only provides a packet switching service. XTP was designed as a streamlined VLSI implementation of a fast network protocol and is part of an ANSI standardization effort; however, implementation experience is still needed. VMTP has been designed

and used with the V-Distributed System. ATM is the protocol of choice by the telecommunications industry and expected to be used over SONET (fiber) networks. These protocols could probably use HIPPI directly; however, at least some form of simple glue protocol would be better to optimize the use of HIPPI services.

No protocol or software implementation currently exists over HIPPI. An early suite of protocols were specified and implemented as part of the LANL/DEC CBI collaboration.* Although little experience has been gained nor much experimentation or testing done with protocols over HIPPI, the ANSI/HIPPI Working Group has attempted to specify protocols to run over HIPPI. The HIPPI Framing (HIPPI-FP) and Link Encapsulation (HIPPI-LE) protocols will provide an interim solution until an appropriate framework protocol is developed. The HIPPI-FP and HIPPI-LE protocols are designed to run under the IEEE 802.2 Logical Link Control Protocol, which is the same method used on IEEE LANs. By taking this course of action, considerable software will be saved and porting efforts to HIPPI-based networks minimized. The capability to utilize TCP/IP with or without these intermediate protocols is still an option. Finally, as is evident in the literature, panels, and workshops, new approaches to high-speed network protocols are being sought. Experimental protocols are also an option for a HIPPI-based network. A simple, effective distributed backplane protocol is possible and is currently being described coincident with the completion of this report. 76

The remainder of the software aspect of the DSA will describe services and characteristics that may or may not be available in an existing protocol. The minimal service of unreliable datagram transmission is all that is required for the overlying system software. This can be provided by TCP/IP over HIPPI. Some of the services described below, however, cannot be provided by TCP/IP.

4.2.1.1 Switching Types

Three types of switched communication have been common practice in data communications. They are 1) circuit switching, 2) packet switching, and 3) message switching. HIPPI is not strictly a circuit-switching mechanism nor strictly a packet- or message-switching mechanism. It can provide any and all of these mechanisms to an overlying protocol. This is accomplished by maintaining appropriate signaling over multiple hops of a network. HIPPI is also not restricted to store and forward

* The specifications, "Protocol Suite for the Multiple Crossbar Network", were written by Randy Hoebelheinrich and Richard Thomsen at Los Alamos National Laboratory.

networks. It can support virtual cut-through and wormhole routing. The difference between cut-through and wormhole routing is in the buffering and responses to blocked paths.²⁶ Cut-through routing will degrade to a store and forward network when blocked while wormhole routing blocks a message over multiple links and switches. Hot potato,⁹⁴ desperation,⁹⁵ voluntary misrouting,⁹⁶ and derouting⁹⁷ all use no buffering and always selects an ongoing path through the network regardless of whether or not it is the most appropriate path for forwarding data. Experimentation with these types of switching and routing in a HIPPI environment is worthy of consideration. Figure 14 illustrates the possible movement of data through a network when using HIPPI.

4.2.1.2 Physical Addressing and Routing

Addressing in the past has been either flat or hierarchical. Relative addressing can be either ordered or random. Flat addressing is expensive in terms of hardware cache and look-up overhead when routing because global knowledge of all addresses is necessary. A hierarchical structure has proven useful in many areas of human endeavors. In the case of addressing, it aids routing decision efficiency and simply breaks the problem of locating nodes down to a manageable scale. Ordered addressing is similar to hierarchies by limiting the scope of necessary work within a local context. Random addressing requires a global scope. Explicit information about all nodes is necessary to locate a given node. This may be irrelevant on a single broadcast network segment; however, as soon as bridging is required, random addressing has a performance impact due to learning overhead. Ethernet uses flat, random addressing because addresses are not associated with location as might be expected. Instead, the addresses are associated with an interface which can be moved resulting in an amorphous address space. The result has been a need for extensive overhead in global table updates, which is a drain on network bandwidth.

Physical addressing in the DSA is hierarchical and ordered. Both routing hardware and software are simplified with this method. This is the reason for the regular topology. Administrative routing overhead is unnecessary because no look-up tables for the physical routing framework are used. The size of hardware cache for tables is reduced. Most importantly, self-routing techniques are possible. As seen in the literature, much of the current fast packet switches use self-routing techniques. Note that HIPPI does not require a regular topology nor preclude the use of an irregular topology and the consequent table-driven routing techniques.

Self-routing has advantages because it specifies alternate paths in a permutation or routing tag derived from node addresses. Deadlocks are also preventable by an appropriate selection of paths.⁷⁰ This routing tag is a permutation of possible switch settings at each stage of an IN and is derived from the address of the destination node. Figure 15 is a good illustration for a comparison of Ethernet and a multistage local network (MSLN). Ethernet can rely on broadcast and passive address recognition as its switching mechanism. A switched LAN needs the routing tag for active switching at each stage of the IN. The I-Field in the HIPPI specification is intended to contain this routing tag for each connection request. In this way, a HIPPI connection can be made over one or more stages of intermediate switches between the source and destination adaptors. This tag is determined at the interface adaptor to each cluster in the network. To an external user, the end result is the appearance of a switched local network similar to Ethernet. This comparison becomes important later when considering migration and standards.

4.2.1.3 Flow and Congestion Control

Flow and congestion control are subjects of research and interest to many in data communications. In the DSA, traditional methods can be used as a fallback position. This is undesirable because gigabit rates will not tolerate the traditional methods of window-based flow control and congestion mechanisms such as source quench. Streamlining the flow and congestion control will become necessary. A back pressure flow control mechanism, similar to that used in TYMENET,²¹ is possible by appropriate implementation of the HIPPI READY signal. READY signals act on a link-by-link basis; however, given message switching with cut-through or wormhole routing, these signals can be propagated back to the source through interface adaptors. When using HIPPI, a problem does exist over long lines. The source is only required to account for up to 64 READYS at a time. The result is either underutilization of long links or overflow. Two remedies are possible. One is explicit flow control in the overlying protocol and the other is to enhance the HIPPI specification at some later date. At any rate, flow control is aided by determining the propagation delay per link and allocating buffers for that delay. In this way, the physical parameters of a link are considered in order to emulate fluid flow. Minimizing the buffers limits the elasticity in the system and results in more timely feedback to the source.

Figure 14. Multiple clusters with data transfers in progress.

Figure 15. Comparison of Ethernet vs. switched LAN.

For internal congestion, an aging mechanism associated with messages and wormhole routing is possible to produce a global backpressure mechanism to limit entry of too much data into the network. The aging mechanism is expected to prevent livelock and insure that data leaves the network. * Both of these methods are attempts to mimic the behavior of physical systems in order to control flow and congestion. As requirements grow, redundant links, or extra stages, to the network may be needed for chronic congestion. Multiple, or redundant links, are groups of physical lines with the same logical port number. The intermediate controller selects a free physical link for any given logical port connection request providing additional bandwidth and multiplexing over these lines where needed. External congestion is handled by multiple links both into and out of the nodes.

4.2.1.4 Logical Addressing and Partitioning

Logical addressing provides mobility for entities such as servers, users, special purpose processors, or whatever object becomes a part of the network. It provides a mapping to multiple physical addresses. Consequently, the flexibility to be independent of geographic location as well as a multihoming capability exists for multiple links to an object. It has been shown how physical addresses benefit routing. In a similar way, logical addressing benefits the manipulation of groups of objects with identical, or mutually exclusive, capabilities. For example, users of a particular organization or project can obtain a suitably registered logical address that associates them as members of a set, or group, independent of their respective locations. Separation is established from other users. Refer to Figure 16. This represents two different logical groups, each with three logical to physical associations to the communication framework. For actual communication, logical addresses for objects are queried, cached, and translated to establish current location and transfer data across the network. The logical address space can be taken one step further by mapping it to a regular abstract topology. This would result in a logical structure that is similar to the structure of the physical addresses. Consequently, the logical and physical address spaces and associations could look like Figure 17. Note that it is not necessary that the logical and physical topologies are identical. The most useful characteristic for the logical structure is the use of masks in comparisons at the source and destination node adaptors to determine the right for members of two

* Private communication with and unpublished report of Vance Faber, C-3, Los Alamos National Laboratory.

Figure 16. Two logical groups, connected physically at six points.

logical addresses to communicate. Appropriate selections of logical addresses and masks will provide need-to-know separation, partitioning, and hierarchical access to appropriate members of a given logical address. Figure 18 demonstrates partitioning of logical addresses into four groups with four possible members in each group. Larger 64-bit addresses are expected to be used for logical addressing. Logical addresses can be based on organization, function, or capabilities such as read/write access to objects or information. The result is a partitioned regular topology for the logical address space. An example of a four-partition hypercube of clusters is in Figure 19. At this point, the security dominance relationship for reading down and writing up described in Reference 3 is a natural consequence of the architecture.

4.2.1.5 Error Control

4.2.1.5.1 Data Transmission Errors

Data transmission error rates on HIPPI have been reported to be very low. Currently HIPPI uses a longitudinal and vertical redundancy check (LRC/VRC) error detection scheme. This results in possible undetected errors. A 64-bit cyclic redundancy check (CRC) has been proposed by DEC to replace the LRC/VRC. An optical version of HIPPI would use forward error correction (FEC). Again, gigabit rates will not be tolerant of traditional retransmission schemes for transmission error recovery. For DSA, an error-correcting code is proposed, and error detection and notification of the packet and fault location within each packet is also required.

Figure 17. Logical address space connected to physical address space.

0000	0100	1000	1100
0001	0101	1001	1101
0010	0110	1010	1110
0011	0111	1011	1111

Figure 18. Sixteen logical addresses partitioned into four groups.

Figure 19. Logical address space partitioned into four groups.

4.2.1.5.2 Link and Node Failures

Fault location is extremely important as a proactive management mechanism for the system. This will be accomplished by the error notification scheme above and the monitoring network described below. Another characteristic of error detection is a requirement that error information must be propagated through a node or adaptor to determine failures within that node or adaptor as opposed to a link failure. Before a failure is found and corrected, other data must be redirected and continue moving. Consequently, alternate paths are required and a method to switch to them is implicit in self-routing.

4.2.2 Heterogeneous Cluster Protocols

The advantage of having heterogeneous non-HIPPI INs in clusters is the ability to use various technologies already in existence and experiment with new technologies. Dissimilar addressing and routing do not present problems since all that is required is a cache of external address to internal address translations on the local cluster alone. These translations can be obtained within the local environment and do not require global knowledge of all addresses. The relation of how to route to a distant node is implicit in regular topology addressing. The disadvantage is that the IN will

not necessarily provide all the services that the protocol over HIPPI provides. This results in the well-known interworking problem that must be dealt with when disparate services are used over a logical link. For example, HIPPI packets may be longer than an internal clusters packet size and may require packet fragmentation. Data arriving on the other side of the cluster may no longer be in sequence. The protocol over HIPPI will then need to provide for packet reassembly and sequencing. The option to include an internet protocol such as IP on the adaptors does exist. In any case, one can keep a homogeneous HIPPI network similar to current extended LANs to minimize interworking problems.

4.3 Operating System Software

This section will not deal with the operating system software explicitly, except to say that the purpose of any underlying distributed backplane protocol and framework was intended to support the needs of the system software. With the establishment of the framework, the operating system has the foundation necessary to communicate with any object of the system it finds necessary and provide the services it has to users requesting them. Instead, a short discussion of the services available to users follows. These services are provided by a framework protocol on behalf of the system.

Services provided by the system include resource management, allocation, and access control. This includes fair access to scarce resources. Resources include explicit objects, such as a visualization frame buffer or a particular processor, for example. Other resources include implicit system elements such as network bandwidth and clear paths through the network. Explicit resources can be handled by allocation and queuing mechanisms. The implicit resources need a scheme for fair usage of bandwidth and paths. HIPPI and an appropriate framework protocol can provide this.

Communication services have traditionally used a connection-oriented or connectionless service for pairwise transmissions. This translates to one- or two-way circuit switching and packet or message switching. Circuits provide dedicated paths but waste bandwidth and block paths for other transmissions. They can even partition the network without sufficient redundancy in internal network links and multihomed nodes. Packet switching allows an optimal interleaving of data by many transmissions to minimize blocking and optimize utilization of network bandwidth. As stated earlier, HIPPI can provide a spectrum of transmissions from packet-to-circuit switched data by appropriate use of signaling and intermediate-switching

technology. Recall Figure 14. That figure shows a two-way circuit and two examples of message switching using wormhole routing. In one case, the message tail is shown leaving the source before the header has arrived at the destination. The second case shows a message spanning the length of the distance from source to destination. The third case shows a connection maintained for greater than a round trip delay. These cases demonstrate the simple continuum of data transfer service alluded to earlier. Coupled with system software and administration of the network, the HIPPI capability can be used to provide all of these services within a single network.

This is accomplished as follows. Explicit resources or objects such as visualization platforms have permissible services, such as circuit switching, associated with them. When a user needs this resource the visualization object is either requested or reserved. The DOS queues or schedules this request. The user may or may not be blocked from further work while waiting for access to the object. As the request is serviced, the user is given the go-ahead to connect to the resource or it is reserved for a later time. In any case, upon execution, the framework protocol will have a service type, such as circuit switching, attached to the request and use HIPPI appropriately to set up the necessary circuit. A service, such as retrieval of a file or E-mail, would only be allowed to use the message-switching service. In the case of a massive simulation, multiple objects could be reserved for a particular time. These reservations need not tie up an entire machine. With multiple links into a node, multiple sessions could be time shared with periodic message traffic on one link and dedicated traffic on the other link. Using this method will provide, and yet limit, the use of services to a level that will not deteriorate the system to the detriment of other users. To summarize: 1) objects have service capabilities attached to them, 2) a user requests access to an object, 3) the DOS queues, allocates, and grants access, and 4) the system then controls explicit use of the service that is provided by HIPPI. This method may also be expanded to include requirements for reliability as well as throughput and delay.

Given packet switching over the backplane, an end-to-end transport protocol is necessary to insure sequential data. One possible alternative mechanism is to provide a header and trailer on each packet with pointers relative to other packets in the same message. At the destination, a linked list is formed that is updated and completed as data arrives. Upon completion, missing data is requested, either errors are corrected or selectively retransmitted (that were specified in the trailer), and the data is delivered to the end object. In delivering this data, either the data is stripped of headers and trailers and moved to the final location or the end object can be passed

the head of the list and access the data indirectly much as is done in virtual paging systems now. It is, in fact, expected that the packets will be distributed virtual memory pages or cache blocks of data with associated system parameters and pointers resident in the block.

4.3.1 Directory Service

As stated earlier, the directory service acts as the clearinghouse for locations and capabilities of objects in the system. An object can be a device, user, server, or application. These objects can be members of a logical set of objects, such as members of a project. Functions performed by the directory include registration of an object to establish its existence, authentication of users requesting to enter the system, controlling access to objects by users, and providing information about objects to authorized entities. The directory would also be closely tied to key distribution, event logging, auditing and accounting systems. The most difficult function would be maintaining cache coherence for logical address caches on outlying nodes.

4.3.2 Monitoring Service

The monitoring service is intended to provide a real time display of the data traffic as well as load and status of links and nodes in the system. This is accomplished by an orthogonal network made up of high-speed serial links out of each interface adaptor to a collection site. A prespecified set of information is sent out on a periodic basis by interface adaptors. This information is written to a grid of parameters. These parameters are used by a cellular automata machine to compute and display data movement as well as link and node status. Given buffering, it is conceivable that buffer levels could also be monitored and color displayed on a screen. This provides a qualitative feel for load, hot spots, and link or node failures.

4.3.3 Accounting

Accounting for services takes advantage of the integration of coherent distributed operating system structures, user to resource allocation mechanisms, and the message stream characteristic of the transport framework. Specifically, upon allocation of a resource by a user, costs are accrued as data passes the origin of communication from the head to tail of a message or request to hangup of a connection. Type of service factors affecting cost are also considered at the origin. These factors include the system effort to insure reliability, or security, the length of time a path is locked due to large images or unused bandwidth, and initial priority

assigned to a message or connection. Consequently this provides the mechanism to impose varying costs due to dynamic usage patterns and changes in policy. Some semblance of management and conservation of scarce resources is then possible.

4.4 Security

The security policy is implicit in the architecture of the system with incorporation of logical addressing and capability-based access through a directory service. The logical addressing and associated capabilities tie closely with the COIs discussed in Reference 3. These security policies can easily be enhanced in this architecture by a cooperative directory and key distribution service. The architecture provides checks of these COIs in interface adaptor hardware and software upon entrance to and exit from the network backplane. Encryption provides protection on a session basis. Encryption at gigabit rates is a fairly new endeavor. This level of protection will provide separation, although the inclusion of an MLS system is also a requirement. MLS is out of the scope of this report.

5.0 Migration Path

Migrating from the current NTB to the DSA described above is fairly straightforward. The nature of the equipment allows a phased, modular approach to migration. Migration would progress in three major phases. Phase 1 is development and testing of equipment and protocols. Phase 2 is replacement of mainframe LANs with clusters and the implementation of intercluster links and adaptors. Phase 3 is attachment of workstation LANs to clusters that are in turn linked to mainframe clusters. Phase 3 also includes implementation of long-haul links to RAS clusters. Pieces of this migration path follow development of the modules and hierarchy of the hardware framework described in the previous section. The major pieces are 1) interface implementation on the hosts, 2) software (drivers and protocols) development, 3) point-to-point link check-out including long- and short-haul links, 4) switch test and checkout, 5) individual Ethernet replacement for mainframes with an intermediate gateway replacing appropriate bridges, 6) intercluster adaptors, 7) directory and monitor service implementations, and 8) a distributed operating system implementation.

As an example of NTB topology, the hypercube pictured earlier would partition such that the NTB domain would be divided into eight RAS regions with a cluster assigned to each region. Connections to the RASs would be with HIPPI/SONET links. Each RAS SPO within a region would connect local LANs or nodes to one or more links

of the RAS regional cluster. The internal cube of the hypercube would correspond to NTF clusters. The four upper NTF clusters would be assigned as red partition clusters while the lower four would be black partition clusters. Each cluster is similar to an Ethernet as seen in Figure 1. Intercluster links and adaptors correspond to bridges. That completes the physical framework. See Figure 20. The logical framework would be superimposed over the physical framework and is almost entirely a software issue that includes a framework protocol and overlying system software.

To summarize:

1. Implement host HIPPI interface implementations.
2. Develop, test, and install software drivers and protocols.
3. Test and install point-to-point links, both short and long.
4. Test and install a cluster.
5. Test and install an intercluster adaptor.
6. Test and implement a directory server.
7. Test and implement a monitor server.
8. Research, test, and install distributed operating system software.

A few added items are worth noting. There is no requirement to use a hypercube topology. The n-star is another excellent choice of topology for the framework. Recall that each cluster is not restricted to any particular topology or number of ports. Individual links need to be installed both locally and long haul.

Interface cards into the internal bus of the specific systems are necessary. Vendor support is available for the interface implementations and drivers. Other items include the HIPPI/SONET interface and gigabit encryption. Efforts are currently underway to produce HIPPI/SONET links. At least one design and forthcoming implementation is known for gigabit encryption at this time.

The software requires the bulk of the effort of the migration. The first step involves implementation of a simple link protocol over HIPPI between two workstations. The second step will implement TCP/IP over HIPPI. Finally, an application can be implemented during Steps 1 and 2. Initially, the directory server can be simulated with appropriate static logical-to-physical address translation tables. Applications can be developed throughout the migration although it may mean interim throwaway code development as the migration progresses.

Figure 20. Example NTB DSA.

6.0 Research Initiatives

The research effort parallels the migration effort. At each stage of the migration, a certain amount of experience needs to have been gained with equipment and software prototypes or implementations. Some similar efforts are ongoing elsewhere; collaborative efforts are possible and strongly encouraged. Research initiatives are necessary in three areas. They are 1) design and development of interface adaptor cards for mainframes, workstations, and controllers, 2) protocol implementations between HIPPI and the transport level such as TCP/IP, and 3) hardware link technology development for a serial fiber implementation of HIPPI, a HIPPI/SONET interface, and transparent gigabit-rate security encryption units for insertion on the link.

A four-year project is proposed. The first year would deliver an implementation of TCP/IP over HIPPI between two workstations or a workstation and a framebuffer. Applications served would be file and image transfer. This establishes connectivity and the potential for useful work. The second year would deliver a cluster of

workstations and a frame buffer using the previous implementation communicating over a HIPPI crossbar switch. This would test the execution of multiple applications executing and device contention. In addition, framework and alternative transport protocols would be explored and tested. The third year would deliver intercluster communication and an initial directory service. Distributed operating systems would also be explored and tested. The fourth year would be devoted to implementation of a distributed operating system with associated directory and visual monitoring services. This is just a general overview of a set of research initiatives needed for the full architecture described in this report. A modified architecture would require less ambitious efforts. An example would be development of single mainframe or workstation clusters.

7.0 Summary

I began by describing the mission of the NTB as a distributed simulation test bed of heterogeneous defense technologies interacting over a global extent. A description of the current movement of computing technology toward unification into a distributed framework environment was presented. The timely creation of the former, with the potential and momentum of the latter, provided the basis for a target NTB architecture for the near future. A modular and progressive migration path, with associated research initiatives, will work hand-in-hand toward achievement of that goal.

8.0 Conclusion

The mission requirements of the NTB provide the impetus to contribute to development of a computing technology central to the revolution and evolution of computing for the next generation at the dawn of the twenty-first century. The NTB provides the forum, opportunity, and focus for a national initiative to produce a real system beneficial, directly and indirectly, to a great many aspects of scientific and engineering endeavors.

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