An Overview of File Service Using Functional Multiprocessing

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Abstract

This report discusses a computer architecture that delivers the reliability, scalability, availability and performance required of consolidated network file servers. The essential components of this architecture and their impact on the success of corporate IT strategies are presented in the main body of text. The details of the components are given in Appendix A. This brief begins with the *I/O performance gap*, a widespread performance problem that has arisen because surges in workstation performance have not been balanced by similar increases in file server I/O capability. Auspex's Functional Multiprocessing (FMP)® architecture removes network I/O bottlenecks, enables the reliable consolidation of data, and eases administration burdens.

FMP is a unique, patented multiprocessor server architecture that removes the critical network protocol, file, and disk I/O functions from the general-purpose operating system and instead executes them on dedicated, high-throughput I/O processors. Complete user-level transparency and compatibility are maintained by executing UNIX on a separate, general-purpose, peer processor.

Using FMP, Auspex has built a family of NetServers, which have been used in heterogeneous client, mainframe, and super computing networks. Concurrent random disk access, which the NFS protocol demands for these environments, is delivered by multiple storage processors with as many as 30 fully concurrent SCSI storage channels.

Auspex has also incorporated CIFS support into its product line with the addition of NeTservices™ software enabling bilingual support of UNIX/NFS and NT/CIFS clients. This allows both types of clients—UNIX and NT—to access a common set of file data with their native protocol and user interface without the need for additional client software. Auspex also supports standard NT administrative tools to provide ease of management for NT personnel.

NetServers are complemented by a number of unique, optional software products, including DataGuard™, which allows data service to continue when UNIX fails; ServerGuard™, a patented, high-availability solution that allows filesystems to be mirrored between independent servers on the network; DriveGuard™, a RAID 5 solution that leverages the hardware acceleration of the Auspex storage processor; and FastBackup, which takes advantage of the parallelism of FMP to accelerate backup. These products enhance the NetServer hardware to provide the reliability and functionality required by even the most demanding environments.

With over 2,200 Auspex servers in production use worldwide, the FMP architecture has proven to be exceptionally reliable and scalable. Typical systems range between 12 to 18 Ethernets, 4 to 8 100BaseTs, 4 to 8 FDDIs or 2 to 4 ATMs with 50 to 750 GB of disk storage, supporting 40 to 400 active workstations and personal computers. Larger servers with almost 2 TB of disk space and serving 1,000 to 2,000 clients are frequently deployed as well. Systems of this capacity, throughput, and reliability represent a new class of network data server.

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1 BACKGROUND

Over the past fifteen years, remarkable improvements in hardware price-performance have caused a startling shift in technical and office computing environments. Networks of PCs, workstations, and servers have rapidly displaced alphanumeric terminals attached to mainframes or minicomputers. However, client-server computing in the nineties is experiencing growing pains. Client workstation power and productivity is severely constrained by file server I/O limitations. Dramatic jumps in microprocessor performance have not been matched by similar boosts in server I/O performance and reliability. At the same time, new and emerging applications are creating a need for ever-greater amounts of storage—storage that must be uniformly accessible and secure from disaster and security breaches.

Server reliability has become more critical than ever, with many enterprises evolving to 24-hour operations to improve time-to-market in the face of expanding global competition.

1.1 THE I/O PERFORMANCE GAP

Driven by RISC and CISC microprocessor developments, client workstation performance has increased more than ten-fold in the last few years. These extremely fast clients have an appetite for data that conventional servers are unable to satisfy. The dramatic increase in workstation computational power has not been matched by a comparable increase in individual-disk performance or server disk-to-network I/O throughput. The emergence of 100 MB/s FDDI backbones, the adoption of Fast Ethernet and 155 Mb/s ATM, and the promise of Gigabit Ethernet and 622Mb/s ATM do not close the I/O gap. This disparity is illustrated in Figure 1 below.

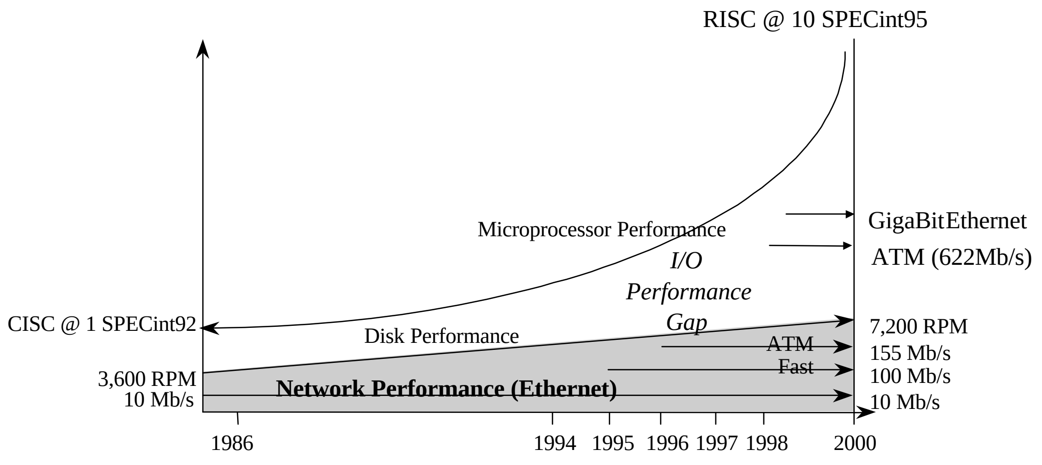


Figure 1: The I/O performance gap that results from mismatched advances in client processor performance and server storage and connectivity performance. This gap has grown so wide that some file servers can be overloaded by as few as ten contemporary client workstations.

In most UNIX environments, clients and servers exchange file data using the Network File System (NFS) [Sandberg 85], a standard distributed file system promulgated by Sun Microsystems and now widely adopted by the entire computer industry. Analysts estimate over 10 million computers are currently NFS-capable, and NFS products are sold by over 100 computer system companies, making NFS almost ubiquitous.

Despite its simplicity and reliability, clients using NFS place considerable demands upon both networks and the servers feeding data to them. To understand the I/O performance gap in the context of NFS, it is necessary to examine the impact of client configuration and NFS network traffic patterns on server performance.

The recent emergence of Windows NT™ as a force in the client/server arena has also resulted in the increased appearance of the Common Internet File System (CIFS) protocol, previously known as Server Message Block (SMB), in many high-performance client/server networks. The CIFS/SMB protocol, part of the LAN Manager suite, has performance characteristics similar to NFS, although it places an additional burden on the server by utilizing connection-oriented transport protocols and maintaining state information. The following discussion will focus on NFS with the understanding that much of what is stated about the use of the FMP architecture for NFS is also applicable to CIFS/SMB.

1.2 WORKSTATION CONFIGURATION AND NFS TRAFFIC CHARACTERISTICS

The two most common types of clients found in NFS implementations today are those containing small local disks for booting and/or paging—*swapfull* or *dataless* clients, see Table 1. The trend towards these client types has been driven by the rapid decrease in disk prices. The swapfull client obtains its boot image and all binaries from the server, but performs paging and stores temporary files on local disk to improve performance.

The dataless client boots and pages from its local disk, but accesses the server for all shared data and, in most implementations, any data that requires frequent backup. Both swapfull and dataless clients may choose to take advantage of *cachefs*, a client-side feature that provides an on-disk cache of data from the server. The use of *cachefs* can substantially reduce loads on both the network and the server, particularly for read-mostly data.

Workstation Type	File System and Description					
	Root System booting	Swap Virtual memory paging	/tmp Temporary files (never backed up)	/usr Applications, documents, etc.	/home /personal Personal files: mail, news, etc.	/home /projects Shared project files
Diskless	On Server	On Server	On Server	On Server	On Server	On Server
Swapfull	On Server	Local Disk(s)	Local Disk(s)	On Server	On Server	On Server
Dataless	Local Disk(s)	Local Disk(s)	Local Disk(s)	Local Disk(s)	On Server	On Server
Diskfull (Standalone)	Local Disk(s)	Local Disk(s)	Local Disk(s)	Local Disk(s)	Local Disk(s)	Local Disk(s) & Server

Table 1: Client workstation type and file system organization. This table defines workstation types as a functions of file system location: either on local disks attached directly to the workstation, or remotely on one or more NFS servers. A diskless workstation mounts all its file systems remotely. A swapfull workstation locates only completely volatile swap and /tmp information on local disk. A dataless workstation is swapfull with a local root for booting, and optionally /usr as well; data requiring frequent backup is still kept on servers. A diskfull workstation is essentially standalone with all files local and requiring local backup; shared files are manually moved to a server as needed.

Table 2 shows typical primary and secondary applications for the various client configurations.

Workstation Type	Primary Application	Secondary Application	Main Advantages	Main Disadvantages
Diskless	Secure environment; universities; low cost/user	Software development; X-windows terminal	Lowest cost; easiest administration; lowest noise; best reliability	Higher network traffic due to swapping; lower performance
Swapfull	Software development; office automation; publishing;	Small CAD	Up to 50% less network traffic; almost no administration; better performance	Disk cost; disk noise; disk unreliability
Dataless	ECAD, MCAD, CAE; large-scale software development	Seismic analysis; animation	Less network traffic than Swapfull; even better performance; only shared files on server	Larger disk needed; each workstation needs individual software updates
Diskfull (Standalone)	Single-user ECAD & MCAD; seismic analysis; visualization	Workstations acting as servers	No network traffic; no server disk traffic; optimal workstation response with fast disks	Contrary to data management consolidation trends, each workstation needs backup and updating; easy for shared files to become inconsistent

Table 2: Typical workstation applications and tradeoffs. The primary and secondary applications are typical, not fixed or comprehensive. Diskless workstation load on the server will decrease as primary memory is increased. The advantages and disadvantages columns are considered from several viewpoints: user, system administrator, and purchaser.

The most demanding NFS clients are diskless workstations with no local disks. *Diskless* clients, defined in Table 1, depend on a file server for application binaries and virtual memory paging as well as data. Because of the decrease in disk prices in recent years, this client type has become substantially less common. However, diskless clients may still be mandated by secure sites that don’t allow data to be stored locally, and they continue to be used at some other sites for ease of administration.

Diskfull configurations, in which all necessary data is stored on local disk, are typically applied to the most demanding application types, particularly when there is little shared data among users. They’re also encountered in networks where legacy NFS servers have not met performance expectations. This configuration, along with the distributed fileserver, is declining rapidly in shared data environments. Duplicated, inconsistent copies of shared data increase the risk of design errors and lost information. This has a negative impact on product quality, cost and profitability and highlights the need for reliable consolidated fileservers.

Network bandwidth contention among powerful workstations limits Ethernet performance. The average number of active *dataless* clients per Ethernet is practically limited to 1-10,depending on both application and client power. Table 3 is an empirical view of hundreds of networks seen by Auspex systems engineers.

It provides rules of thumb for practical client-per-Ethernet ranges, taking into account both client and application type.

Client Type	Application		
	Large E/MCAD and Seismic	Medium E/MCAD and Software Development	OA & Doc
Sun Ultra2, HP J210, IBM 3CT	**100/100 Switched**	**10/100 Switched**	Not Recommended
SS20, HP 735, IBM 390, P6-NT	**10/100 Switched**	**10-15 Shared**	Not Recommended
SS2, HP 715, IBM 390, P5-NT	**10-15 Shared**	**15-20 Shared**	**~25 Shared**
X Terminals (ASCII terminals)	Not Recommended	25-50 Shared	**~75 Shared**

Table 3: Recommended clients per Ethernet. The right number of clients per Ethernet depends on workstation power and application demand. For the fastest workstations and most demanding applications switched Ethernet (either 10BaseT or 100BaseT as required) is the most appropriate choice, aggregated into one or more Fast Ethernet, FDDI, or ATM server connections. In this table, appropriate matches appear in bold text and user access is network intensive.

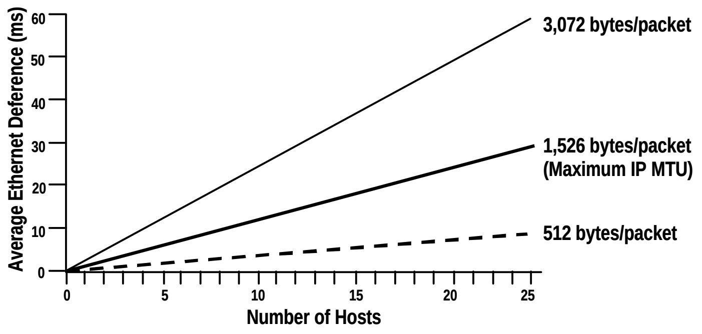


Figure 2: Average-peak Ethernet utilization. On an Ethernet loaded with 15 workstations doing Ethernet-IP-MTU-sized (1,536-byte) transfers, the 15 ms of deference causes a *GetAttr* operation to take 15 ms + 15 ms + 2 ms, or 32 ms total—16 times *GetAttr*'s usual 2 ms round-trip. Since *GetAttr* can be 50% of a software development server's operation load, the negative impact of deference becomes apparent. To reduce this unnecessary queuing delay, keep average-peak Ethernet utilization below 25-30% and the number of clients low. Average peak traffic is the average of all traffic over a 2–3 minute interval—it's not the instantaneous peak utilization, where 100% is fine.

In addition, Ethernet load plays a strong but little-understood role in minimizing NFS response times. Many network administrators consider Ethernet usage of 40–70% acceptable. This assumption is true with respect to fair, round robin Ethernet access by the attached workstations. It is *false* if response times are also assumed to be *low* at high load. David Boggs, co-inventor of Ethernet, extensively studied hardware-level latencies for packet transmissions on loaded Ethernets [Boggs 88]. His study permits the conclusion that for NFS transfers in a data-intensive 15-workstation network, there is a hidden *extra* average response time delay of about 10 milliseconds (each way) as each workstation waits for all the *other* workstations' big packets to fly by (Boggs' Figure I-4, paraphrased in Figure 2). This latency-causing CSMA/CD deference occurs in hardware and is *invisible* to software and various Ethernet analyzers. This 10-ms delay is significant because some frequent NFS operations (e.g., *GetAttributes)* take only *2 ms* on an unloaded Ethernet. Boggs' recommendation for reducing hidden Ethernet delays is simple: Keep unswitched Ethernet utilization to a 25–30% maximum so workstations never wait to transmit. For contemporary networks this recommendation often boils down to *private* (switched) 10BaseT or 100BaseT as Table 3 indicates.

With the deployment of Microsoft Windows NT and Windows-95 in workgroup, department, and even enterprise environments, it is common to see dataless or diskful client configurations. Issues that apply to NFS workstations also apply to CIFS/SMB clients.

In summary, purchasers of high performance clients and servers must make careful choices regarding the network infrastructure to realize the full value of their investment.

1.3 NETWORK ARCHITECTURE EVOLUTION

Contemporary networks, with their mix of clients, servers, bridges, hubs, routers and switches may leave the casual onlooker in a state of bewilderment. A look at history (refer to Figure 3) can help clarify.

- *Every man for himself*

  In the earliest days, experimenters had little or no need to network their workstations together. Many sites implemented a stand-alone model. The casual communications of the day were more than satisfied by a single 10-Mb/s Ethernet.

- *The good Samaritan*

  When files had to be shared within the workgroup, one or more generous users might volunteer their workstations' excess processing and storage capacity to the community: Their workstations thus became part-time data servers.

- *We need a server*

  When NFS load on these good-Samaritan workstations grew, and their users' productivity dropped, early-generation servers were installed. Though no more than rack-mounted workstations with some additional disks and controllers, these low-I/O-power servers would suffice if (1) clients remained first-generation machines with small network appetites or if (2) single-Ethernet contention rose enough to preclude the presentation of inordinately high loads to the servers. In effect, the inability of a single Ethernet to transport much data might hide a server's inherent inability to generate it.

- *Speak softly, but carry a big disk*

  When client workstations were added or upgraded and/or more data had to be shared more frequently, Ethernet utilization would rise to the point of stalling the network. Work could simply not get done in reasonable time. On the surface, a sensible approach to reducing contention was to reduce conversations with the server(s) by augmenting each workstation's local disk configuration. The expedient solution to an overloaded Ethernet was to limit its usage.

- *Segmenting with bridges*

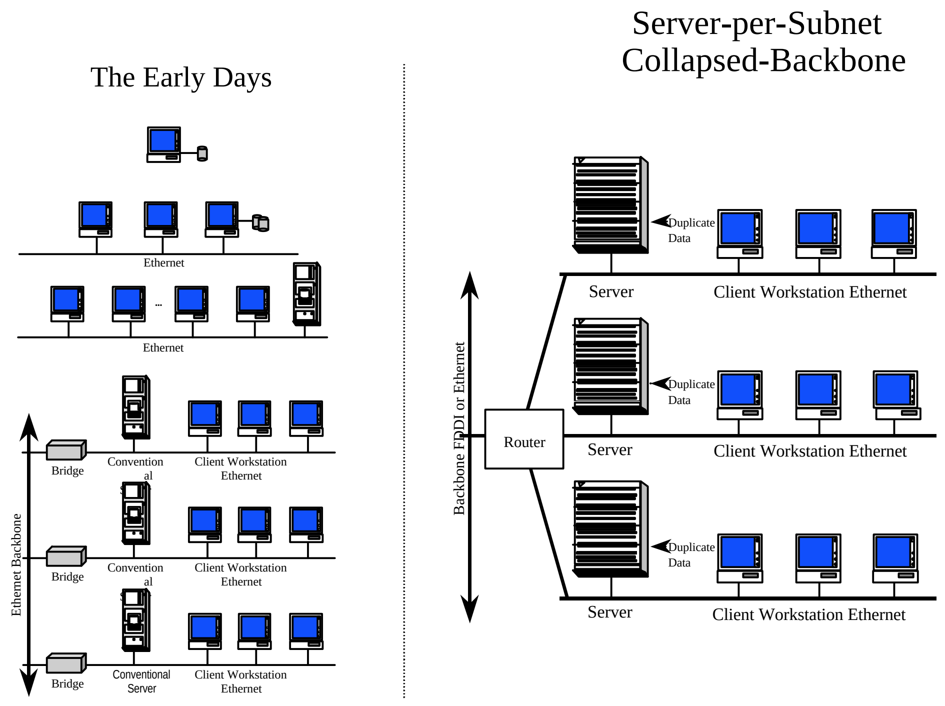
  Unwilling to accept the extra cost and administrative burden of the local-disk solution, some administrators looked for another way to make true client-server networking work. They reduced Ethernet contention by splitting their single network into multiple physical segments connected with bridges.

- *Server-per-segment*

  With Ethernet contention dramatically lower, network analysis revealed a residual problem. The single server was too weak or too many bridge “hops” away to serve the entire active-user community. The next expedient step (see lower left hand corner of figure 3) was to install additional servers on each of the newly created segments. This not only provided more aggregate server power, but also increased the likelihood of achieving locality of reference. The desire was for clients to obtain their data from the server attached to their own segment. The motive to go through the bridge from clients on segment A to servers on segment B was greatly reduced. From a performance point of view, things seemed to be back on track. The administrator would simply accept a new server for every so many workstations on the segment—typical ratios of the day were one server per 10–20 active clients on a segment.

- *Crossing the bridge to routers—server-per-subnet at its best*

  Having “solved” the server problem by deploying them in greater numbers, problems attributed to low-cost, low-function bridging attracted the network administrator’s focus. Administrators would often abandon a flat-net bridged environment, replacing it with a collapsed-backbone router and numerous servers (right side of figure 3).



The Early Days
Ethernet
Ethernet
Ethernet Backbone
Bridge
Conventional
Client Workstation Ethernet
Bridge
Conventional
Client Workstation Ethernet
Bridge
Conventional Server
Client Workstation Ethernet
Server-per-Subnet Collapsed-Backbone
Duplicate Data
Server
Client Workstation Ethernet
Duplicate Data
Server
Client Workstation Ethernet
Duplicate Data
Server
Client Workstation Ethernet
Backbone FDDI or Ethernet
Router

Figure 3: Network architecture evolution. On the left, top to bottom, standalone workstations are grouped onto a single and then multiple Ethernet segments. Initially, NFS service is provided by a “good Samaritan” workstation equipped with extra disks. This gives way to a dedicated server, and as Ethernet contention drives the topology to segmentation, multiple servers are configured to handle the NFS load on their particular segment. In more contemporary installations bridged, segmented topologies have given way to the topology on the right, in which a dedicated router handles the inevitable subnet-to-subnet traffic. In such topologies—often called the *server-per-subnet model*—each client network is limited to 10–20 workstations by server performance, necessitating a complex multiserver configuration. In addition, 15–30% of each server’s disk storage usually contains replicated common files, an expensive redundancy, but one that reduces IP routing load and delays. See the text for more explanation.

1.4 RESIDUAL PROBLEMS

Though more refined than the topologies from which it evolved, the network depicted on the right side of Figure 3 is not trouble-free. Attempts to extend this architecture by converting it from shared to switched Ethernet, do not fix the fundamental problems. Informal surveys taken by Auspex at hundreds of sites around the globe have reported all or some of the following problems associated with this topology:

- *Sharing*

  Development groups of more than 10–20 people overpower any single small server, cannot readily share the same server, and thus cannot easily share files without multiserver file replication and/or NFS crossmounting.

- *Reliability*

  A commonly held notion is that multiple, small servers increase overall NFS availability. This belief stems from the unrealistic assumption that a given server will never be responsible for more than a small fraction of the entire client community. Thus it is hoped the effect of a single server outage will be mostly contained. In practice, the inevitable crossmounting found in contemporary networks destroys any such hope. Every client's dependency on multiple crossmounted file systems actually *reduces* the reliability of the NFS service clients receive overall.

- *Performance*

  With minimal or no sharing, so long as locality of reference and a low client-to-server ratio can be maintained, performance from any given server may be acceptable, but overall performance drops when sharing begins and this delicate balance is disrupted. Individual servers become network performance bottlenecks when hot spots develop on widely shared file systems. These hot spots may "travel" from server to server during the workday. Additionally, inevitable crossmounting adds router latency to average NFS response time.

- *Administration*

  System administrators must maintain many limited-capacity servers rather than one or a few powerful servers. This burden encompasses performance monitoring and tuning, free-disk-space management, hardware maintenance, and user account administration. A classic problem is the treatment of an imbalance in Ethernet subnet utilization. To restore the overloaded subnet to a healthy state, the administrator is motivated to move a certain number of clients from it to another under-loaded subnet. This movement has the effect of perturbing client-server locality of reference, motivating a corresponding movement of data from servers on the overloaded subnet to other servers on the under-loaded subnet. The target servers may lack space on their existing disks or the spare slots to handle disks the administrator is prepared to physically transfer from server to server.

- *File system backup*

  System administrators or operators must conduct multiple file server backups, a time consuming task. It is also expensive to duplicate backup peripherals on each server (or every few servers if slower network backup is used).

1.5 CAMPUS NETWORKING

A combination of factors (starting with those of section 1.4) has driven "large-installation system and network administrators" to implement topologies such as depicted in figure 4 over the past several years and is leading many sites to implement configurations like that shown in figure 5. These factors include:

- Establishment of FDDI and 100BaseT as stable, multi-vendor standards for high-bandwidth, reliable computer communications

- Availability of affordable high-performance 100Mb/s to 10Mb/s switches to provide private Ethernet service to desktops where needed

- Availability of 100Mb/s to 100Mb/s switches to provide high bandwidth to the most demanding desktops, between servers, and to server-room compute clusters

- Accelerated migration of interconnections to new technologies as they mature:
  —Shared Ethernet —> switched Ethernet (major trend)
  —10BaseT —> 100BaseT (major trend)
  —FDDI —> 100BaseT (frequent)
  —FDDI backbone —> ATM (limited)
  —100BaseT —> Ether-channel/Ethernet trunking (emerging technology)
  —Gigabit Ethernet (pre-standard in 1997, standard in 1998)

- Rapid growth in amount of data storage required and the desire to consolidate storage

1.6 THE NEED FOR I/O INNOVATION

The widening I/O performance gap, in conjunction with the administrative and economic considerations of section 1.4 and the special challenges of campus networking, demonstrates a need for higher-performance, larger-capacity file servers with superior reliability. The workstation vendors' traditional approach to server design, repackaging a workstation in a rack as a retrofitted compute server, is inadequate for large networks at current client performance levels.

Conversion of a display-less workstation into a server may address disk capacity issues, but it does nothing to address fundamental I/O limitations. As a file server, the retrofitted workstation must sustain 10–20 or more times the network, disk, backplane, and file system *throughput* than it was designed to support as a client. The addition of larger disks, more network controllers, extra primary memory, or even a faster processor does not resolve basic architectural I/O constraints. They do not substantially increase overall I/O throughput nor are they designed to achieve high reliability. Even today's general-purpose SMP servers are optimized for compute and not I/O; they fail to achieve the real world performance and reliability required of a consolidated data server.

Closing the I/O performance gap and providing high levels of reliability requires a network data delivery-specific architecture that can flexibly balance client data demand with network data server I/O throughput. The new I/O architecture must scale in throughput and capacity just as easily as client workstations scale in performance. The new architecture must focus on optimizing a network data server's most common actions, network file protocol and disk operations, just as router architectures optimize IP routing and RISC processors optimize a CPU's most common instructions.

The Auspex network data server, the *NetServer*, has such an I/O architecture.

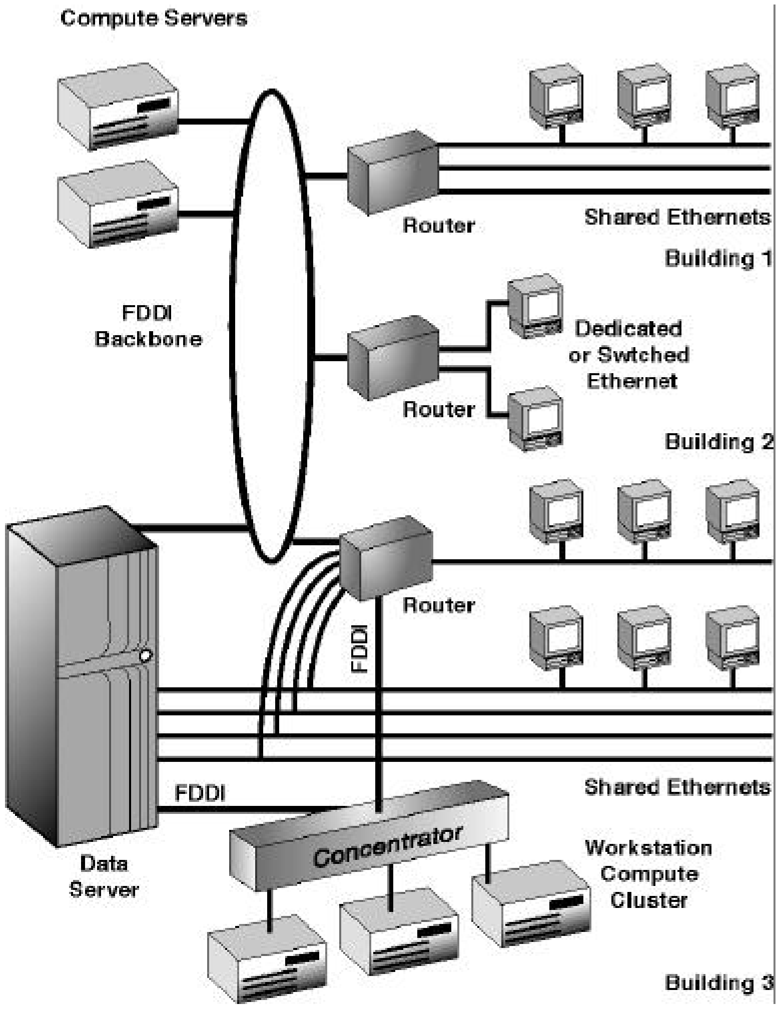


Figure 4. Consolidated server with FDDI and Ethernet ports (typical top 15% network topology, 1994-1995). Combined FDDI and Ethernet internetworking for large installations spread over distances beyond Ethernet's limited maximum. The NetServer replaces multiple conventional servers. Client workstations are connected by Ethernet, driven by cost and the realization that 10 Mb/s remains fast enough for any given individual user, even when equipped with an 80-SPECint92 workstation. Where client-to-server distances are short, direct Ethernet connection to the NFS server is preferred, for reasons of cost and reduced latency. When distances are great, high-performance FDDI-to-Ethernet routers are employed to keep latencies reasonably low. The presence of FDDI also fostered a style of compute- and data-server collaboration discussed in section 4.2.

2 NETSERVER ARCHITECTURAL OBJECTIVES

The Auspex NetServer was designed with the four objectives in mind: scalability, reliability, software compatibility, and performance. By meeting these four primary design goals, Auspex has created a consolidated network filesystem that plays a major role in today's global IT infrastructures. The end result is a data management platform that helps the corporation achieve its business goals.

2.1 SCALABILITY

The server architecture had to support a system that was both flexible and scalable. Flexibility was desired so that FDDI, ATM, 100baseT networks, optical and tape storage media, and multivendor UNIX host processors could be included as appropriate. Scalability was important to accommodate server configurations with not just 2 or 4 networks, but 8, 12, 24, 30 or more networks; not just 5 or 10 disks, but 50, 100, 200, or more disks; and not just one or a few *usable* CPUs, but multiple *usable* CPUs.

A scaleable architecture allows and encourages the consolidation of many individual server-per-subnet workgroups onto a single server that is more cost-effective, reliable, and easily administered. Significantly, scalability implies more than configurability. To meet the growing data demand of an expanding client population, a server's ability to attach a large complement of networks, disks, and processors must be supported by an architecture facilitating the *effective, collective utilization* of these resources. The important distinction being drawn here is between *theoretical* configurability and *practical, real-world* configurability and usability.

2.2 RELIABILITY

Recognizing that the trend toward larger, consolidated servers must be accompanied by increased server reliability, Auspex set the base configuration (excluding peripherals) Mean Time Between Failure (MTBF) goal to 5,000 hours for the original NetServer. MTBF goals for current NetServers exceed 14,000 hours, less than one base system failure every 18 months. Data is collected on a continuing basis to confirm that this goal is regularly exceeded.

2.3 SOFTWARE COMPATIBILITY

For comprehensive software compatibility, the NetServer needed to be compliant with CIFS/SMB, NFS, other Open Network Computing (ONC) services such as NIS and automounter, and SunOS UNIX. Moving into the future the NetServer architecture provides the framework to accelerate a wide variety of network protocols beyond CIFS/SMB, NFS version 2, NFS version 3, and FTP and to provide full compatibility with those environments. These include WebNFS and other internet-related protocols.

2.4 PERFORMANCE

Ten years ago, in 1987, Auspex designers set the target performance level for their first server to be 1,000 NFS 8 KB *read* operations/second. Of the 22 NFS operations defined, NFS *read* operations usually occur less than 25% of the time, but Auspex's performance goal was made more difficult by restricting the load to NFS *read* operations. This was a difficult, data-intensive goal for I/O hardware because it required driving 8 Ethernets at 90% utilization each, achieving a total transfer rate of 72 Mb/s. Of course, excellent performance on the remaining NFS operations is important as well. In benchmark tests using an *average* NFS operation mixture, the NetServer's actual peak performance today exceeds 10,000 NFS LADDIS ops/s. It is important to note that while other vendors claim to deliver higher performance, Auspex is the only vendor willing and able to provide mission critical reference sites with multi-terabyte high-throughput configurations while maintaining required levels of reliability.

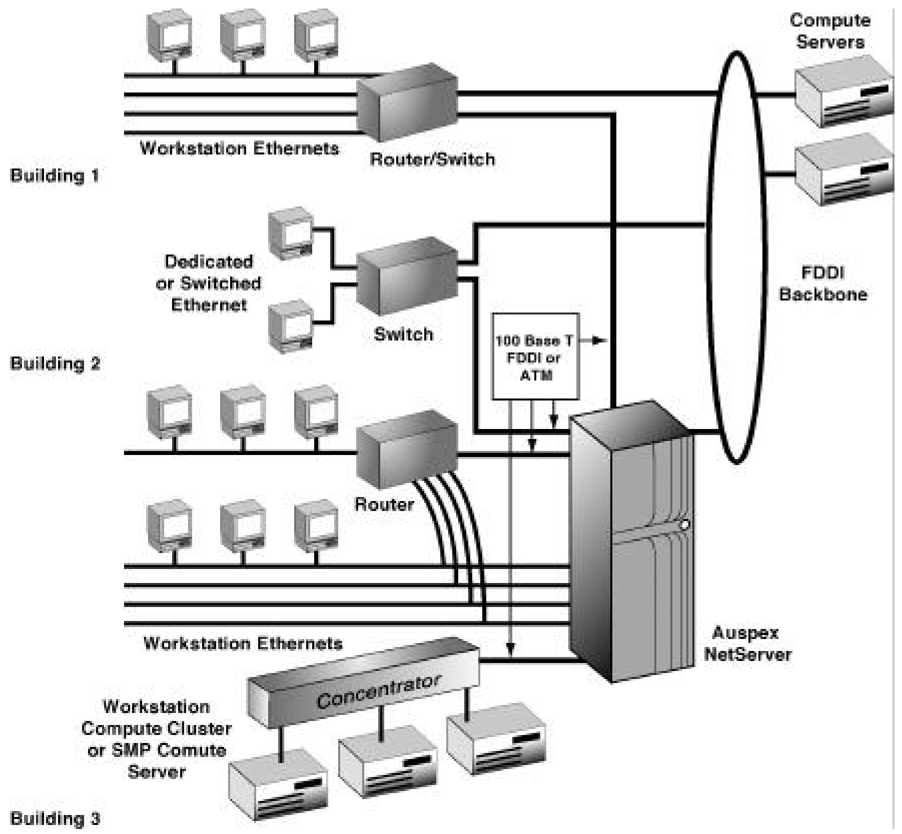


Figure 5: Consolidated server (1996 and beyond). Compared with Figure 4, current networks have a greater emphasis on switching technology with switched 10BaseT or even 100BaseT to the most demanding desktops. Redundant paths are provided between all buildings for greater reliability and to limit the need for the NetServer to act as a router. 100BaseT may replace FDDI where distance is not a constraint. Shared Ethernet is still used where appropriate for lower powered desktops and less demanding applications.

In summary, Auspex's design goal was to develop a network file server that could plug directly and transparently into existing NFS-based networks. It would replace, or offload NFS processing from, all configured conventional servers, attaching to all of their existing networks and replacing their cumulative disk storage. The goal was to design a server uniquely capable of supporting network configurations of the type illustrated in Figure 5.

3 High Availability

To extend the availability of its base file server offerings, Auspex has developed a portfolio of high-availability software products. These products include DriveGuard™, which provides economical RAID 5 storage protection; DataGuard™, which protects against UNIX failures; and ServerGuard™, a unique product that protects against loss of data access in the event of a catastrophic server failure or other disaster. When combined with the highly reliable FMP architecture, these software solutions meet the needs of even the most demanding environments.

3.1 DriveGuard

The use of Redundant Array of Independent Disks (RAID) has become among the most common ways of improving data availability. Along with disk mirroring and striping, Auspex provides the ability to configure RAID 5 disk arrays as an optional feature of the storage processor. DriveGuard allows customers to configure the appropriate number of filesystems (large or small) with the appropriate level of protection—mirroring for maximum data redundancy and protection, striping for maximum performance without redundancy, or RAID 5 to balance cost-effective data redundancy with performance.

The storage processor transfers data in and out of I/O cache memory using a patented ASIC called the Auspex FIFO Controller (AFC). The AFC incorporates the ability to calculate parity as data is being transferred, providing a simple and efficient mechanism for generating RAID parity blocks while placing minimal additional burden on the storage processor CPU and no burden on other system CPUs.

Figure 12 in Appendix A illustrates how RAID fits into the storage processor block diagram. An incoming write request is first processed by the virtual partition code if appropriate (virtual partitions may be constructed on top of RAID arrays if desired) and is then passed to the write cache module. The write is then cached and is subject to coalescing and inode collapsing as described previously. When the block is scheduled to be written, parity is generated by reading the appropriate parity and data blocks from cache or disk. Both parity blocks and data are cached whenever possible to accelerate operations.

RAID arrays can be flexibly configured from the disks managed by each storage processor. Each RAID array optimally consists of from 3 to 6 disk drives. Larger partitions, if required, can be created by concatenating two or more RAID arrays. Spare disks can be configured on a per-array or per-SP basis. An attached 8 MB write accelerator daughter board and Storage Processor 5 (SP5) are required to ensure optimal performance, but no other hardware additions or changes are required.

3.2 DataGuard

Operating system failures cause up to 50% of all server disruptions, the biggest single source of disruptions. Realizing this, Auspex developed DataGuard™, a product that allows UNIX to come to a complete halt without affecting NFS operations. Leveraging the FMP architecture that removes UNIX from the NFS data path, DataGuard builds a logical firewall between the host processor and the data control and delivery path managed by the rest of the system.

With DataGuard, NetServer availability is independent of operating system reliability. Users can run important applications on the host processor, such as backup applications or system administrator scripts, without fear that application instability will interrupt NFS data service. If a UNIX hang or panic occurs, the host processor reboots automatically, independent from the rest of the system, in approximately 2 minutes. Ongoing NFS service continues uninterrupted. The host processor may also be rebooted manually, providing greater administrative flexibility. In practice, this feature is frequently used to install new software releases or patches on the host and to install or de-install SCSI devices connected to the host processor.

DataGuard host-processor-only reboots do not interrupt NFS operations or cause NFS timeouts on the clients. This allows administrators to perform activities during working hours that previously would have had to wait for a planned downtime window. For organizations that require 24x7 operations, these downtime windows scarce. DataGuard provides administrators with the scheduling freedom to install and configure third-party software, modify UNIX kernel parameters, attach hardware to the host processor SCSI port, or simply reboot immediately, as soon as a problem arises. A common example of the latter would be a reboot to kill and restart a set of misbehaving application processes not involved in data service.

Although the initial motivation for developing DataGuard was primarily to reduce unplanned downtime, DataGuard, as exemplified above, impacts planned downtime even more favorably.

3.3 SERVERGUARD

ServerGuard is a unique software product that provides an NFS server solution for environments requiring high availability and disaster recovery. ServerGuard creates and maintains consistent copies of file systems on independent servers. No change is required to the clients or client applications; they simply mount the ServerGuard file system.

A key component of ServerGuard, the fault-tolerant NFS (FTNFS) protocol, is used between servers to ensure consistency. The FTNFS approach differs from traditional two-phase commit algorithms in having lower overhead, and differs from shared-disk solutions by allowing the servers to be physically distributed.

FTNFS performs on-line transaction-consistent duplication of data by using network multicasting to send each client’s NFS request to two servers. The requests are processed simultaneously by the pair of servers. A lightweight acknowledgment mechanism between the two servers provides a guarantee of data redundancy and consistency.

ServerGuard offers the benefits of fully-distributed redundancy with much less overhead than competitive algorithms. The software achieves this by targeting specific NFS architectural features, knowing the relative idempotency, statelessness, and data modification characteristics of each type of NFS request. Figure 6 illustrates a typical ServerGuard configuration. For more information on ServerGuard please refer to Auspex Technical Report 12, *ServerGuard: The Pinnacle of Continuous Data Access* [Gehlbach, Giammarco 97].

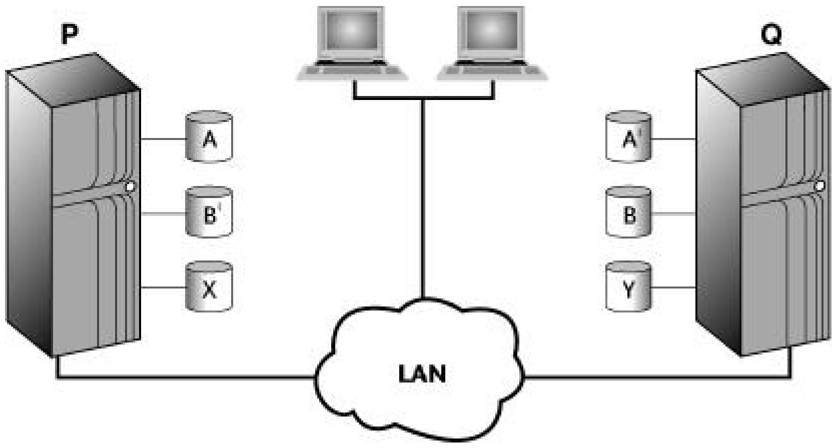


Figure 6: Typical ServerGuard configuration. Server P acts as the primary server for filesystem A and the secondary server for filesystem B, while server Q is secondary for A and primary for B. Each server maintains a complete and consistent copy of requests for each filesystem at all times. Clients mount filesystems from a virtual server consisting of both P and Q and multicast all NFS requests so that both servers receive them simultaneously. The servers respond to NFS requests according to Auspex's FTNFS protocol. Primary and secondary actions differ depending on whether the request is reading or writing data or creating files. Should one of the servers suffer a failure, the other is able to take over the workload almost instantaneously. Recovery is fully automatic and occurs on-line after the failure has been corrected.

4 PERFORMANCE TUNING, SPECIFICATIONS, AND EVALUATION

4.1 PERFORMANCE TUNING

Since NetServers support as many as five network processors and five storage processors, multiple network connections (10BaseT, 100BaseT, ATM and FDDI), and 210 disk drives in a single system, a concise display of server I/O performance data is vital for system managers and administrators. NetServers come with a performance monitor that enables detailed investigation of site- and application-specific server performance behavior. This is possible because the monitor gives a clear and precise view of statistics not normally available to system administrators, and rarely viewed even by system programmers. Such a thorough view is especially important in a functional multiprocessor, where there is considerably more latitude for network, file, disk, and processor cache adjustment and load balancing than in conventional servers.

The NetServer's performance monitoring tool has an extensive view into each NetServer processor type and provides both real-time display and fast-motion replays of significant server performance events. Figure 7 shows a sample performance monitor summary screen. The event-generated statistics include: per-processor CPU utilizations; network and disk I/O rates and I/O types; file system operation loads, mixes, and rates; and individual cache hit rates and age distributions for the network, file, and disk subsystems. The performance monitor's results are reported in two-dimensional windows at user-selected update times. The results can also be written to log files over a extended time base for trend analysis.

Capacity planners routinely use the performance monitor to automatically log peak-hour performance statistics over long time spans. When this data is displayed in histogram form, as in Figure 8, trends become apparent. Existing resources can be rebalanced, or, as the figure illustrates, a NetServer hardware upgrade can be predicted and accomplished well before increased user load demands immediate action.

```
-     1.0  System Summary             mlab              Wed Jun 12 15:20:54 1996
CPU Utilization   Ethernet/FDDI: Bytes/sec                           SP0:OPs/sec
HP  usr     1%     NP0[  6481518] NP2[  7232494] NP4[  7392942]   (0~ 80 in bar)
    sys     1%      f0[  6481518]  f0[  7232494]  f0[  7392942] R1[            ]
    idle   98%        [         ]    [         ]    [         ]   [            ]
                      [         ]    [         ]    [         ]   [            ]
                      [         ]    [         ]    [         ]   [RRWWWWWW    ]
NP0  97%[========]    [         ]    [         ]    [         ]   [RRWWWWWW    ]
NP1  82%[======= ]    [         ]    [         ]    [         ]   [RRWWWWWWW   ]
NP2  82%[======= ]                                                [RRWWWWWW    ]
NP3  83%[======= ] NP1[  7314628] NP3[  7226578]                R2[            ]
NP4  84%[======= ]  f0[  7314628]  f0[  7226578]                  [            ]
                      [         ]    [         ]Total NP Bytes/sec[            ]
FP0  70%[======  ]    [         ]    [         ]  [     35648160] [RRWWWWWW    ]
FP1  60%[=====   ]    [         ]    [         ]                  [RRWWWW      ]
FP2  59%[=====   ]    [         ]    [         ]                  [RRWWWWWW    ]
FP3  60%[=====   ]    [         ]    [         ]                  [RRWWWWWW    ]
FP4  60%[=====   ]     FP: LFS OPs/s(0~1500) DataCacheAge       R3[            ]
                       FP0:2049[GGLLLLLRRR] [AAAAAAABBBI]         [            ]
SP0  50%[====    ]     FP1:2322[GGLLLLLRRR] [AAAAAABBBI ]         [            ]
SP1  83%[======= ]     FP2:2174[GGLLLLLRRR] [AAAAAAABBBC]         [RRWWWWW     ]
SP2  61%[=====   ]     FP3:2256[GGLLLLLRRR] [AAAAAABBBCI]         [RRWWWWW     ]
SP3  98%[========]     FP4:2280[GGLLLLLRRR] [AAAAAABBBCH]         [RRWWWWWW    ]
SP4  68%[=====   ]      [------]  Total LFS OPs/s                 [RRWWWWWW    ]
```

Figure 7: The Performance Monitor's System Summary screen. This screen summarizes the most important performance information about a NetServer.

The performance monitor allows system administrators to accomplish tuning that has heretofore been extremely difficult in UNIX (as opposed to proprietary minicomputers or mainframe) environments. It encourages maximum use of existing hardware before any upgrade purchases. The *Auspex System Manager's Guide* discusses the performance monitor in depth.

4.2 COMPUTE SERVERS WITH REAL PRICE/PERFORMANCE

As mentioned in section 1.2, for optimal response time, contention on Ethernets supporting many concurrently active clients should be kept low; utilization should be restrained to 30% or less. However, in point-to-point connections, collisions and contention are much smaller issues—high Ethernet utilization is both safe and achievable. This fact has inspired an extremely cost-effective means for running computationally intensive jobs on CIFS/SMB or NFS data (see Figure 9). Rather than temporarily copying a bulk of NetServer data to some costly compute server's local disks for the sake of running a job, remote mounting the data from a RAM-rich dataless headless workstation (incorporating the very same RISC CPU) results in virtually the same job execution time for many applications. This seemingly counter-intuitive result is plausible when one considers the following:

- Auspex NetServers are powerful enough to deliver data at 60 to 120 Mb/s (7 to 15 MB/s) over 100BaseT, ATM and FDDI. Compute servers whose main-memory data working set is on the order of hundreds of megabytes rarely have to wait more than a few seconds for fresh data upon which to compute. When job execution time is dominated by computational time, the fraction of time spent waiting for disk data or storing results is essentially negligible.
- The network component of total job execution time can be further decreased if the file system used for writing back results is asynchronously mounted. Asynchronous mounts are typically thought to be unwise—even heretical to some NFS purists. Yet, in this particular case, the impact of a server reboot in mid-job is at most a very rare inconvenience (once per year on a NetServer, to be conservative), since, by definition, the compute node can recreate the results.

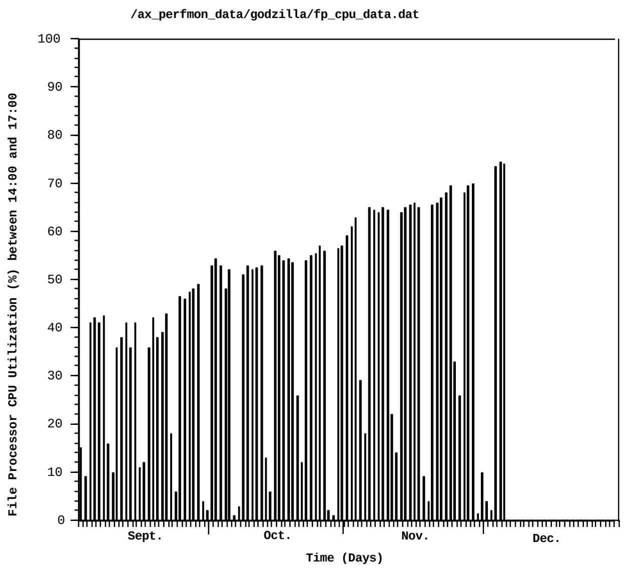


Figure 8: Histogram display of performance monitor statistics. As an example, this histogram displays a log of file-processing CPU data from the performance monitor. Each vertical bar shows average CPU utilization between 2 and 5 p.m., rather than a single instantaneous sample. This 3-hour high-use period was selected, rather than 24 hours, to avoid deflating the values with low nighttime traffic. (Note how utilization drops substantially on weekends and holidays). The histogram shows that adding NFS workstations to the NetServer's networks over a three-month span has increased prime-time file-processing CPU utilization from 40% to greater than 70%. In early December, when this graph was made, the upward trend in user workload was expected to continue—utilization was projected to reach overload levels (above 90%) by the end of February. To avoid this overload condition, an extra file-processing CPU would be added in advance.

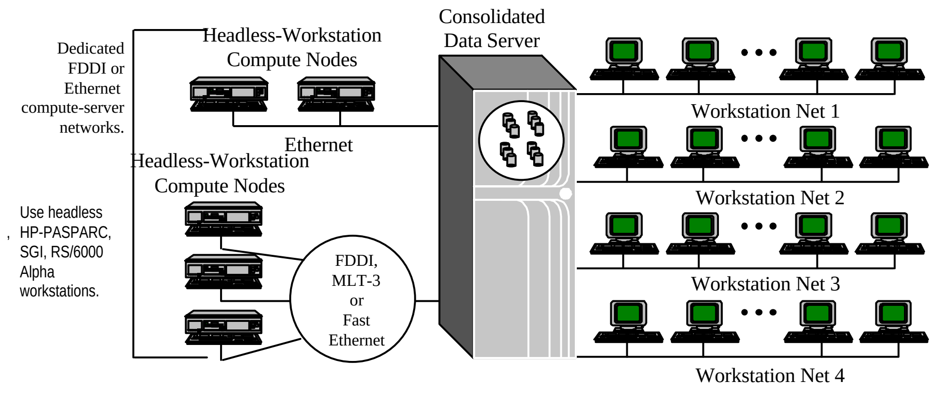

Dedicated FDDI or Ethernet compute-server networks.
Headless-Workstation Compute Nodes
Consolidated Data Server
Ethernet
Headless-Workstation Compute Nodes
Use headless HP-PASPARC, SGI, RS/6000 Alpha workstations.
FDDI, MLT-3 or Fast Ethernet
Workstation Net 1
Workstation Net 2
Workstation Net 3
Workstation Net 4

Figure 9: Compute servers with real price/performance. NetServers have the spare power and connectivity to satisfy the data appetite of powerful workstations direct-connected over dedicated Ethernet or FDDI networks. As experiments indicate (even with today's most powerful workstations), compute-intensive jobs can finish as fast or faster accessing data on a NetServer than when relying on local disk. Compute server cost is thus contained and flexibility gained, since the workstation implementation of a vendor's fastest RISC chip is less costly per SPECint than the general-purpose server version. For best results, the compute node should have 128 MB to 1 GB of memory and a 1 to 4 GB local disk. Jobs demanding data at >1 MB/s may be run on FDDI-connected headless compute nodes.

5 CONCLUSION

The I/O performance gap is a tangible, daily problem for workstation users. The NetServer's functional multiprocessor architecture breaks this bottleneck for NFS clients. FMP eliminates the cost, performance, reliability, and administrative problems of the traditional, server-per-subnet NFS network. FMP is a demonstrably scalable network-server architecture with exceptional throughput and low latency.

The NetServer can be further enhanced with DataGuard software to prevent UNIX failures from affecting client data access, and ServerGuard to provide the greatest degree of data availability and disaster avoidance for environments that require it.

5.1 THE FUTURE OF FUNCTIONAL MULTIPROCESSING

Because of its unprecedented scalability and efficiency, FMP achieves far greater I/O throughput per unit of processing power than conventional, general purpose, compute-oriented architectures. This provides great flexibility for future development. While conventional architectures depend on the latest, hottest CPUs to achieve good results, Auspex can choose to migrate FMP to commodity CPUs, decreasing system cost, while still maintaining the clear advantages in real-world performance that the FMP architecture provides.

Additionally, since FMP is fundamentally independent of the operating system running on the host processor, additional host environments, such as Windows NT, can be implemented in the future without impacting the inherent strengths of the underlying architecture.

The consequence is simple. Auspex has done the hard part—mainframe class I/O at UNIX price/performance—and is quite happy to let the giants battle it out for MIPS.

5.2 OPERATIONAL EXPERIENCE

While this overview report focuses mainly on architecture, Auspex's customers say that the NetServer's high reliability and simplified system administration are just as important. The features and functions of the NetServer that contribute to high reliability and easy administration are:

- Support of both CIFS/SMB and NFS protocols with one server and one copy of data
- CIFS/SMB and NFS bulletproofing through FMP
- DriveGuard, DataGuard, and ServerGuard
- Hot-pluggable disks, CD-ROMs, and tapes
- Disk striping and mirroring
- File system cloning and expansion
- File system fault isolation
- NFS crossmount elimination by consolidating servers
- Single-point file-system backup
- 15-minute replacement time of any component
- N+1 power supplies
- The performance monitor and histogram tool.

Our customers' actual operating experience with NetServers has been extremely gratifying. With over 2,200 systems installed as of this printing, customer response is universally enthusiastic, as the following items illustrate:

- Many customers, especially those in the Fortune 500, have multiple machines both throughout their companies and at single sites. One Fortune 100, semiconductor customer has a NetServer volume purchase agreement that essentially makes Auspex its exclusive worldwide corporate NFS server. This pattern in the United States has repeated itself in Japan and is doing so in Europe.

- NetServer application environments are similar for both large and small customers in industries such as software development, VLSI and PCB design, mechanical CAD, strategic Web site deployment, oil exploration, securities trading, feature-film animation, multimedia, and scientific research (at national laboratories and supercomputer centers).

- NetServer network environments are highly heterogeneous. Equipment from Sun, DEC, HP, IBM, Intergraph, NeXT, and Silicon Graphics appears frequently, often in combination with large numbers of increasingly capable PC clients.

- Typical installations have four to six 100 Mb/s network connections and average >200 GB of disk capacity. Many are configured with eight 100 Mb/s connections and over 400 GB of disk, with high capacity DLT tape libraries for backup. Numerous systems have >1 TB of storage.

- Heavily loaded systems experience exceptional uptime between scheduled shutdowns. For example, one 200-workstation environment exceeded 365 days, and another 100-client environment exceeded 450 days. NetServer uptime is typically governed by customer maintenance schedules; most reboots are voluntary and initiated by system administrators. One administrator reports "on average one crash per year, resulting in about one hour of unscheduled downtime on a server serving 180 clients." He reboots the NetServer once every three months for general housekeeping. A humorous complaint from some of his users is that the NetServer doesn't give them the excuse to take one day off a month, something they could count on with other vendors' products.

- Some power users report that their workstations run faster during the day (sharing a NetServer with 40 other users) than they did previously in the middle of the night (accessing a conventional server as the only user).

- One uptime-conscious customer relocated his NetServer and its user community to a new building in record time. “In just two hours, versus two days. While our servers from other vendors were lying about in pieces on the floor, the NetServer was powered down, transported, reinstalled, and rebooted. Our engineers were up and operating in record time. Consolidating NFS service onto one NetServer meant there was just one server to move, not ten or fifteen. We had even tested our expansion from two to four Ethernets prior to teardown and transported the hot-pluggable disks by hand. We moved the NetServer ourselves. Auspex system engineers were on call, but everything went smoothly without their help.” The speed and smoothness of the move earned the system administrator a standing ovation from his executive staff, as well as a performance bonus.

- A major automotive vehicle design center uses seven Auspex servers, each with DataGuard, 8 FDDI connections, and a total combined mirrored storage capacity of 2 TB (4 TB of total disk). These servers support a user community of over 1,200 engineers doing mechanical CAD. Despite the fact that the entire operation is 24x7, the servers are supported by fewer than 4 administrators.

- In a data-intensive seismic interpretation operation,the customer replaced 4 existing conventional servers with a single NS 7000 NetServer with 350 GB of storage. The customer reports the system, “has eliminated our bottlenecks, our users are satisfied, and everybody is more productive.”

- At a leading Internet service provider, all network News and Web data is consolidated on a single Auspex NetServer, currently with 90 GB of storage. This single server provides all data to a large number of front-end servers that process HTTP and other client requests. The machines are interconnected with FDDI and 100BaseT for redundancy. [Chua 96]
- Some system administrators report that they now lead “normal” lives, working 8 to 5 because they’re no longer fighting multiple-server crossmounts, backups, and updates. They tell us, “I don’t even know the server’s there.”

- Auspex’s well-known dedication to “total customer satisfaction” is proving itself in practice. Especially among Fortune 500 customers, Auspex continues to win business because decision-maker reference checks with Auspex’s existing customers show that Auspex’s customer support, from sales, service, engineering, and manufacturing, is “better than the support we’ve received from any of the UNIX vendors we’ve dealt with.”

At Auspex, we define success as making our customers successful. Regular customer feedback tells us we are meeting that goal by helping customers improve their productivity, time-to-market, and, ultimately, their global competitiveness. We remain committed to continuous improvement in customer satisfaction.

Appendix A: Functional Multiprocessing Architecture

The NetServer achieves its design objectives with a unique, patented *functional multiprocessing* (FMP) architecture that maximizes performance by coupling storage devices to networks as directly as possible. A key FMP notion is that protocol, file, and storage software components *are not run on general purpose UNIX or NT CPUs*. This strategy further boosts performance by cutting unnecessary software overhead to a minimum and dramatically reducing outages that, on a conventional server, are typically ascribed to an overly complex general-purpose operating system. Because processing components have local memories and are loosely coupled via functional multiprocessing kernel (FMK) control messages, system scaling is predictably linear.

FMP Architecture

The lifecycle of a read operation will serve as a tutorial on the operation of FMP. For purposes of this discussion, NFS version 2 (NFSv2) is used. However, with the exception of a few minor particulars, the discussion here also applies to the NFS version 3 (NFSv3) protocol and to WebNFS. More details are provided in the following section, "NFS Version 3 Implementation."

The CIFS/SMB protocol, now implemented under FMP, uses a largely identical process. CIFS/SMB does not require that writes be committed to stable storage before acknowledgment, so all writes are allowed to occur asynchronously.

Although the FTP protocol differs substantially from the protocols mentioned above, FMP has also provides substantial acceleration for the FTP protocol and can provide the basis for a highly parallel FTP server.

Let us begin with an 8 KB NFSv2 read request entering the system via a network connected to the protocol-processing CPU (refer to Figure 10). Running FMK, the protocol CPU processes the read operation through the IP, UDP, RPC, XDR, and NFS layers. It then constructs a control message to send to the file-processing CPU, passing a file handle and data offset. Upon receipt of this control message, if the file-processing CPU's hash tables indicate the read block is already in I/O cache memory, it responds immediately with the address of the requested data. Otherwise, it navigates its locally cached UFS metadata to further refine the file handle request into a disk I/O control message for passage to the storage-processing CPU.

This second, and final, control message also contains the I/O cache memory location reserved by the file-processing CPU for the block. The storage-processing CPU translates the request first to a physical partition request (only necessary when the data resides in a virtual partition) so that it can then drive the appropriate SCSI channel to action. In a single direct memory access, the 8-KB block flows through the storage processor to I/O cache memory. The storage-processing CPU then replies to the file processing CPU that its original request for a direct-memory-access (DMA) transfer has completed. This acknowledgment in turn triggers a reply from the file processing to the protocol-processing CPU. Since the reply contains the I/O cache memory location of the user's requested data, the protocol-processing CPU can initiate a second and final DMA transfer of data, IP-fragmenting it as necessary onto the network. Further elaboration is given in the following subsections.

Elimination of UNIX from the Critical NFS Path

In responding to the NFS operation, FMK, not UNIX, takes over traditional operating system roles providing lightweight process management (multiple NFS requests from a large client community need to be concurrently executed), interprocessor communication, memory management, and device control. Elimination of UNIX from the critical NFS path brings two key benefits: improved performance and enhanced reliability. FMK is further described in a separate Usenix conference paper [Hitz 90].

LOOSE COUPLING OF PROCESSORS

The *control* path is subtly different from the *data path*, which does not include the file-processing CPU itself. Furthermore, control is achieved with interprocessor messages, not shared memory. Such loose coupling of processors significantly contributes to linear scaling when additional protocol-, file-, and storage-processing CPUs are added to the NetServer. Because each processor is functionally specialized and autonomous, there is no need to burden the system buses by requiring full cache coherence between processors as is required on SMP machines.

LOCAL FILESYSTEM

For efficient file-system processing within the NetServer, Auspex designed the *local file system* (LFS), a new, internal filesystem interface. LFS is used for file communication between protocol-processing CPUs and file-processing CPUs, and also between the host-processing and file-processing CPUs. The set of LFS operations is a superset of NFS operations, and these common operations share many semantic properties. LFS has been a strong unifying influence on the NetServer software architecture. But it is important to note that LFS is used only *within* the system; the external network protocol is precisely standard NFS. LFS is described in a separate IEEE conference paper [Schwartz 90].

NO INSTRUCTIONS

The NetServer's I/O cache memory contains no instructions; it is exclusively dedicated to NFS data and transient IP packets being routed between networks under control of the protocol-processing CPUs. Additionally, no instructions flow across the NetServer backplane (except for the minimal amount needed by the Host Processor), reserving this pathway almost entirely for data moving. Although SMP systems may boast impressive speeds on their internal buses, much of this bandwidth is consumed moving instructions rather than data and maintaining cache coherence between CPUs.

SUPPORT FOR FILESYSTEM INTERCEPT EXTENSIONS

To better support Auspex and third party data management products for backup/restore, file migration, compression, and file encryption, the file-processing CPU supports Filesystem Intercept extensions (FIX). This API is functionally similar to the Data Management Interfaces Group (DMIG) API specification. To illustrate the use of FIX, if the file-processing CPU determines that a particular data block is on tertiary, not secondary storage, it sends its request-for-data control message to the host-processing CPU, which is responsible for management of tertiary devices such as optical and tape libraries. The data is then migrated back to primary storage for rapid access.

RAID

RAID is supported on all disks attached to the storage processor. The RAID subsystem is described in greater detail in section 3.

VIRTUAL PARTITIONS

The virtual partition storage manager supports an elaboration of UNIX's traditional physical disk partition. Virtual partitions permit the *concatenation*, *striping*, or *mirroring* of disk data. These capabilities can be selected alone or in combination. Concatenation permits partitions (and thus file systems) to be larger than a physical disk, up to 144 GB, a limit derived by multiplying 16 (the maximum number of contributing partitions) by 9 GB (the current maximum single-disk capacity).Larger partition sizes can be achieved using RAID arrays as the building blocks of concatenated virtual partitions.

Striping interleaves disk blocks across multiple physical disks, easily alleviating *hot spots* in busy file systems or databases. Mirroring duplicates file systems onto two striped or concatenated virtual partitions on two sets of disks, permitting transparent recovery from drive or media failure (in conjunction with file system fault isolation and hot pluggability). Implementing virtual partitions on the storage processor, as close as possible to the disks themselves, injects lower overhead than conventional kernel driver-level approaches and allows benefits to be applied to all disk processing, not just NFS. This is a cursory description of virtual partitions; they are described in more detail in *The Auspex System Manager's Guide*.

FastBackup

In order to better support accelerated backup, the storage processor provides the optional FastBackup API, which takes advantage of the FMP architecture to accelerate and parallelize the backup process. Each storage processor can stream data directly from disk to attached tape devices without the data ever traversing the FMP backplane. With applications written to the FastBackup API, an administrator can quickly create consistent, online image backups of active filesystems while retaining the ability to rapidly locate and restore individual files.

Filesystem Cloning

Filesystem cloning, a feature analogous to virtual partition mirroring, permits metadata-consistent "snapshots" of *online* file systems to be taken, typically to a spare disk partition. Once the data-replication portion of the cloning process is complete, the cloned snapshot is automatically detached from the online file system. The offline snapshot may then be backed up from disk to tape, for which administrators often use an unattended-backup application driving a tape library. After the tape copy is complete, the spare disk partition may be reused to clone-backup the next partition.

Optional Write Accelerator

NFS version 2 normally requires that all writes be *synchronous* (completed to a stable storage medium before sending an acknowledgment to a client). Servers that routinely perform *asynchronous* writes sacrifice data integrity for the sake of performance. The storage processor's optional write accelerator provides asynchronous performance with synchronous data integrity. It accomplishes this in three ways:

- *Write caching*

  Not having to wait for completion of a physical disk write cuts the write operation from 20 ms to under 1 ms (see Figure 12).

- *Data coalescing*

  As mentioned above, NFS version 2 fractures a single client's write operations into successive, 8-KB blocks. When several clients access the same file system in this manner, the data presented to the storage processor takes on a random, not sequential, traffic pattern. By coalescing the 8 KB blocks in the write cache, the accelerator can reorder the eventual disk writes to be physically more sequential, thus greatly reducing disk arm movement and wasted time.

- *Inode collapsing*

  Repeatedly rewritten metadata (inodes and indirect blocks) of frequently accessed files are long-lived in the cache. During that time, the cache accumulates metadata updates that otherwise would be *individually* written to the disk drive. Inode collapsing is particularly worthwhile when data is written to the end of a file with an *append* write, because each new append would normally write an inode to disk. Instead, the inode update is caught in the write cache—avoiding a disk operation. About 90% of all UNIX file write operations are append writes, so inode collapsing is truly valuable.

For an average NFS version 2 operation mix, the system delivers 20% more throughput and 50% faster response time. This means that typical write-intensive applications complete 3 to 5 times faster. The write accelerator is easy to administer. Write acceleration is selected on a per-file system, per-storage processor basis and its behavior is indicated in one of the performance monitor's display screens (see section 4.1).

HOST PROCESSOR

As the protocol-, file-, and storage-processing CPUs are collectively responsible for satisfying NFS requests, the host-processing CPU is free to take on other functions. It is responsible for system booting; ONC functions such as the automounter, Network Information Service (NIS), and lock manager; system error reporting and logging; performance monitor event collection (section 4.1); backup and restore (management only with FastBackup); and virtual partition/file system cloning administration. Even under heavy NFS loads, only a small fraction of the host processor's power is consumed by the above mentioned administrative functions. Consequently, a large and predictable fraction of the host processor's CPU remains available for other services as needed. This balanced behavior is in sharp contrast to so-called general-purpose architectures, wherein NFS performance is achieved at the expense of application processing (and vice versa). The basic design is easily extensible to support other network file access protocols such as FTP, WebNFS or CIFS/SMB, allowing non-NFS clients to realize the advantages of the FMP architecture using their native protocols.

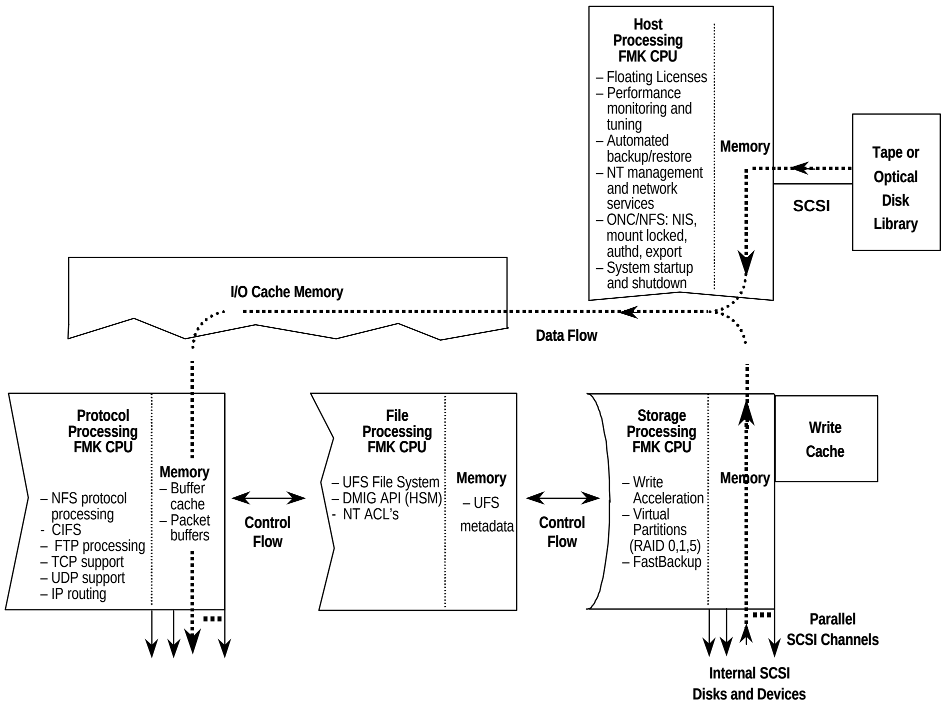


Figure 10: The NetServer functional multiprocessing I/O architecture. All protocol, file system, and storage processing is completely removed from the UNIX host processor. The UNIX host processor, a SPARC-based design, is responsible for system booting, ONC functions, error logging and reporting, performance monitoring, SNMP agent coordination, backup and restore, and virtual partition and file system cloning administration.

NFS Version 3 Implementation

Most of the details discussed in the previous section also pertain to the NFS version 3 implementation on the NetServer platform. However, NFS version 3 does differ in some important details. NFS version 3 includes a number of significant performance improvements that can provide real benefit to many NFS environments.

Version 3 includes a safe asynchronous write protocol. NetServers using NFS version 3 demonstrate twice the write throughput versus the same configurations using NFS version 2. This enhancement mitigates the benefits of the non-volatile write cache (discussed above) to some extent, although early studies show that write caching still provides substantial performance benefits by caching metadata writes (which occur synchronously) [Pawlowski 94].

NFS version 3 also implements fewer on-the-wire operations between clients and servers for improved performance. Version 2 clients check to make sure that their cached data does not become invalid by periodically acquiring the file's attributes, including the date and time of last modification. This requires frequent "Get Attribute" (getattr) requests, which can make up a large percentage of NFS version 2 traffic. NFS version 3 minimizes the number of these requests by returning attribute information with all operations.

NFS version 2 has an 8-KB maximum buffer size limitation, which restricts the amount of data that can be sent over the network in a single read or write operation. In NFS version 3, this restriction is relaxed, enabling NFS to construct and send much larger amounts of data for improved throughput. The Auspex NFS version 3 implementation uses a maximum buffer size of 32 KB.

FMP HARDWARE IMPLEMENTATION

As discussed above, Auspex's FMP architecture distributes performance—limiting I/O functions to multiple dedicated CPUs. Although the architecture calls for four kinds of functional processors (protocol, file, storage, and host) and I/O cache memory, the current generation NetServer implements these five functions on three board types. Each FMP board incorporates 32-bit microprocessors and has multiple internal buses and memories. By storing function-specific instructions and data in local memories, FMP dramatically reduces bus traffic and completely avoids the classic SMP cache-miss bus-contention problem. A base NetServer configuration includes one each of the three board types, along with a rack for the initial SCSI devices. Further details are given in the following subsections.

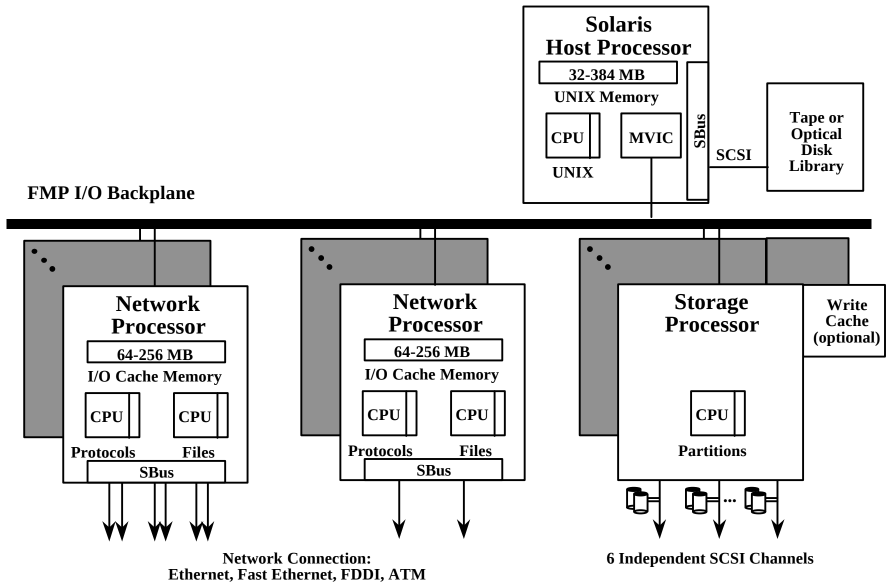


Figure 11: FMP hardware implementation (refer also to Figure 10). Today's NetServer, which evolved from and is backplane-compatible with five previous generations, coalesces the I/O cache memory, protocol processing, and file processing functions onto a single, dual-SPARC CPU network processor.The storage processor handles virtual-partition and SCSI-channel management with 6 independent SCSI-2 channels supporting 42 disks per storage processor. The storage processor may be optionally equipped with a nonvolatile-RAM write accelerator, which reduces write latency and improves overall throughput by deferring, coalescing, and collapsing disk writes. Disk arrays are discussed in section 3.2; SCSI devices are *hot pluggable* (disks, CD-ROMs, and tapes can be added or replaced while NFS and UNIX are running). The local-memory-equipped network, storage, and host processors communicate over a 100 MB/s FMP I/O backplane whose full bandwidth is reserved for user data and lightweight interprocessor control messages. The largest production NetServer can contain 11 boards: 5 network processors (30 Ethernets 10/100BaseT, 15 FDDI or ATM interfaces; or combinations), 5 storage processors (210 disks), and 1 host processor.

Network Processor Board

On one of its two SPARC CPUs, the network processor board performs full protocol processing up to and including the CIFS/SMB or NFS level. This processing includes IP, UDP, RPC, XDR, CIFS/SMB, and NFS. The protocol-processing CPU passes the resulting CIFS/SMB or NFS requests directly to the appropriate file-processing CPU (on the same or different network processor board) through the local file system (LFS) interface.

The file-processing CPU runs the Berkeley 4.3 UNIX Tahoe file system, which has been completely removed from the UNIX kernel. The binary representation of file systems on NetServer disks is identical to the representation in other 4.3 BSD (or SunOS) systems. Each file-processing CPU can manage multiple, independent filesystems, allowing data to be partitioned into the optimal number of filesystems for any environment. Standard BSD quotas are supported for sites that require further disk space management. Filesystems can be expanded on-line, when required.

Every network processor board is equipped with 64 to 256 MB of local memory. The memory is partitioned to contain:

- *The network processor kernel*
- *User data en route to/from the storage processors*
- *IP packets traveling between networks*
- *Metadata—file system structural information like directories, inodes, and indirect blocks that are cached to enable the file-processing CPU to make instant searches without consuming any backplane bandwidth*

With four SBus slots for connection of network interfaces, each network processor can be easily configured with various combinations of 10BaseT, 100BaseT, FDDI (fiber or MLT-3, SAS or DAS), and ATM (155 Mb/s). A maximally configured system with five network processors can support up to 15 high-speed connections (FDDI at 100 Mb/s or ATM at 155 Mb/s) or 30 Ethernet (10/100BaseT) connections.

Complete IP routing is performed between all connected networks without intervention by the host processor. The latest generations of network processor are able to multiplex the data and address lines of existing NetServer backplanes, utilizing 64-bit paths for data movement to and from the latest storage processors. This doubles the bandwidth of the system backplane, while maintaining full backward compatibility with previous system models for investment protection.

Storage Processor Board

The storage processor is responsible for virtual partition management [Cheng 91], RAID array management, file system cloning, file system expansion, write acceleration, SCSI channel management, SCSI disk and tape device control, and disk seek optimization. All I/O channels in a storage processor board may simultaneously perform DMA data transfers to I/O cache memory. These channels are attached to disk arrays (described below). For backup, SCSI tape options include 8-mm helical drives and Digital Linear Tape (DLT) drives in single tape and library configurations. CD-ROM drives are also supported: Auspex distributes its software releases on CD-ROM.

Refer to Figure 12 for a graphical description of the storage processor motherboard.

DriveGuard™ Software

The Auspex RAID 5 implementation, DriveGuard, is supported by special hardware on the storage processor to perform parity calculations and uses the larger 8 MB write accelerator per storage processor to stage and accelerate RAID operations.

Auspex's write accelerator implementation is a logical extension of FMP. Performance-enhancing hardware and software is positioned close to the resource (disks in this case), where they have the greatest impact, not in the UNIX host processor (or its coprocessor). An ancillary benefit of the NetServer's storage processor-based implementation is disk write acceleration for *non*-NFS applications such as FTP, dump and restore, NIS updates, and sendmail.

DISK ARRAYS

Disk arrays are organized in racks of four drawers containing seven, 7,200 RPM,3.5-inch form-factor drives available in capacities of 9.1 GB (formatted). Disks, as well as tape and CD-ROM drives, are hot pluggable (they can be inserted and removed while the system is powered-up and running).

Each SCSI drive has its own internal controller and track buffer for autonomous, concurrent operation and data transfer. Disk array storage organization is vital in high-performance NFS servers because these servers receive independent, largely random, 8 KB I/O requests from potentially hundreds (even thousands) of active workstations. Individual client workstations may exhibit sequential read and write behavior, but in aggregate, the traffic will appear random and independent at the server. The crucial NFS performance role played by the NetServer's storage processor and SCSI disk arrays is described by Cheng and Nelson in a separate Usenix paper [Nelson 92].

TAPE LIBRARIES

Tape library solutions are available from Auspex or third parties for attachment to the host processor or the storage processor. Using a combination of FastBackup and storage processor-attached DLT tape libraries, a NetServer can be configured for fully automated, lights-out backup with unparalleled throughput and performance. Up to 100 GB of data can be transferred from disk to tape per hour.

HOST PROCESSOR

The HyperSPARC-, MBus-, and SBus-based host processors are compatible with Solaris 1.x and SPARC International SCD 1.1.1. The host processor is mated to the FMP I/O backplane by a Fujitsu Microelectronics MBus-to-VMEbus Interface Controller (MVIC) ASIC designed by Auspex. A maximum of 384 MB (ECC) of virtual memory is configurable, with a choice of 16 MB, 32 MB, 64 MB or 128 MB modules. A SCSI-2 port is available for attachment of devices such as optical and tape libraries. Three SBus and two RS-232 ports are also included.

I/O CACHE (PRIMARY) MEMORY

Essentially, I/O cache memory is a huge disk buffer cache for user data en route to and from networks and disks. The I/O cache memory is co-resident on the network processors with the protocol and file processing CPUs. Memory on each network processor is partitioned between instructions, the metadata cache used by the file processor and the data cache, with the bulk of available memory used for data.

To speed an individual client's sequential NFS reads, the file processor initiates asynchronous reads-ahead from the relevant storage processor into the I/O cache. The I/O cache also buffers transient IP packets being routed between different network processors.

FMP I/O BACKPLANE

Using an enhanced VME bus protocol, the NetServer's backplane is capable of performing 32-bit block transfers at 55 MB/s and 64-bit block transfers at 100 MB/s. The latest generation network and storage processors are able to perform accelerated 64-bit transfers between themselves while maintaining full compatibility with older technology using 32-bit transfers. The FMP backplane is electrically compatible with the standard VME interface, though substantially faster. This increased speed provides both improved throughput and sharply reduced latency. Because the backplane is used only for data movement and FMP control messages, the available bandwidth is entirely dedicated to network I/O.

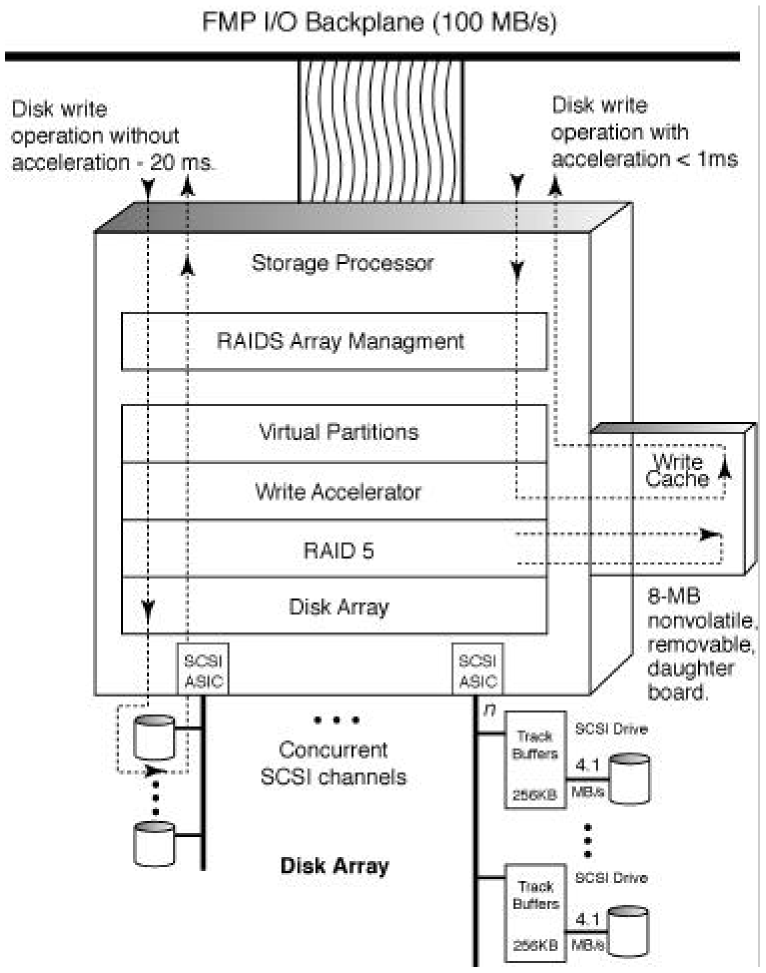


Figure 12: Write accelerator and RAID operation. The write accelerator achieves a 20x speedup for all write operations for which acceleration has been selected. For NFS, these would include *Write, SetAttributes, Create, Remove,* and *MakeDirectory*. Host-processor functions that benefit include FTP (either from the host processor or on the FP), dump and restore, NIS updates, sendmail, and database access. The write-accelerator firmware is interposed between the storage processor's virtual partition and disk array management layers. It controls 2 MB of nonvolatile memory on the *write cache* daughter board. Each storage processor can have its own, independent write cache. The daughter board is removable, and can be switched to a new storage processor (to recover cached data) should an SP fail. Optional RAID software is interposed between the write cache module and the physical disks. RAID can take advantage of a larger 8 MB NVRAM daughter board to provide flexible parity protected storage.

APPENDIX B: GLOSSARY

100BaseT	See Fast Ethernet.
ATM	Asynchronous Transfer Mode. A suite of network protocols providing low-level services spanning local- and wide-area networks. ATM is intended to provide the switching and multiplexing services necessary to carry voice, data, video and multimedia traffic using fixed 53-byte cells. Standards are being defined to allow ATM to emulate traditional LANs (LANE).
b	Abbreviation for bit (e.g., 10 Mb/s Ethernet).
B	Abbreviation for byte (e.g., 120-GB total capacity).
BSD	Berkeley Software Distribution. The major branch of Unix upon which SunOS and other variants are based.
Fast Ethernet	Fast Ethernet or 100BaseT, defined by the IEEE 802.3 committee, provides a 100 Mb/s standard that is compatible with existing 10BaseT installations, preserving the CSMA/CD media access control (MAC) protocol.
FDDI	Fiber Distributed Data Interface. A standard for local area networks that typically uses fiber-optic media capable of data rates up to 100 megabits/second over distances up to 100 km. An FDDI network is a token-based logical ring, and is often constructed as a pair of counter-rotating redundant rings (called dual-attachment mode) for reliability. Ethernet, in contrast, is a bus-based, non-token, 10 megabits/second network standard.
Fibre Channel	Fibre Channel is an ANSI standard designed to provide high-speed data transfers between workstations, servers, desktop computers and peripherals. Fibre channel makes use of a circuit/packet switched topology capable of providing multiple simultaneous point-to-point connections between devices. The technology has gained interest as a channel for the attachment of storage devices, and limited popularity as a high speed network interconnect.
FMK	Functional Multiprocessing Kernel. Communication among the NetServer's multiple hardware processors and software processes is handled by the FMK, a low-overhead message-passing kernel executing on each FMP processor that communicates over the NetServer backplane.
FMP	Functional Multi-Processor. Auspex's multiprocessor architecture distributes I/O activities to parallel processors specifically optimized for particular functions such as protocol processing, storage management and host operating systems. See SMP.
Gigabit Ethernet	Gigabit Ethernet is a draft standard of the IEEE 802.3 committee which when concluded will provide a mechanism for conveying Ethernet format packets at GB/s speeds. The goals of the gigabit Ethernet effort include: preserve the CSMA/CD access method with support for 1 repeater, use the 802.3 frame

	format, provide simple forwarding between Ethernet, fast Ethernet and gigabit Ethernet, support both fiber and copper (if possible), and accommodate the proposed standard for flow control. At the time of this writing it appears that fibre channel will be adopted to provide the physical layer for the first implementations of gigabit Ethernet.
HIPPI	High-Performance Parallel Interface. A short-distance, unidirectional, extremely fast, 100 MB/s interconnect. It is usually used in pairs, providing bi-directional 100 MB/s transfers. HIPPI will be used for connecting supercomputers and minisupers to high-speed networks and storage devices. It is a draft standard formulated by Los Alamos National Laboratory.
LADDIS	An acronym formed by names of the group (Legato, Auspex, Data General, Digital Equipment Corporation, Interphase, and Sun) that has developed and popularized SPEC's vendor-neutral NFS server benchmark of the same name. See SPEC.
LFS	Local File System. A file system type developed by Auspex and used in the NetServer for file-system communication between the network processors and the file processor, and between the host processor and the file processor. LFS provides local file operations similar to NFS remote operations, but without the protocol processing overhead. See VFS.
MAC	Media Access Control.
MAC multicast	MAC multicasting is the transmission of a LAN packet to a group of hosts on the LAN. LAN adapters are configured to recognize a special multicast MAC address and to receive those packets in addition to unicast and broadcast packets. MAC multicasting differs from IP multicasting in that it is implemented at the physical layer. As such, MAC multicast packets are confined to single physical LANs.
MBUS	SPARC International's 280 MB/s (peak rate) primary memory bus into which all CPUs plug (via so-called MBus *modules*). The MBus is one of several buses in Sun's hierarchical bus architecture. See SBus and VME.
MTBF	Mean Time Between Failure. A key component of the availability equation, AVAILABILITY = (MTBF – MTTR) ÷ MTBF. Example: A server which on average fails once every 5,000 hours and on average takes 2 hours to diagnose, replace faulty components, and reboot would have an availability rating of (5,000 – 2) ÷ 5,000 = 99.96%.
MTTR	Mean Time To Repair. Includes the time taken to diagnose the failure, replace or repair faulty component(s), and reboot the system. See MTBF.
NIS	Network Information Service. This is ONC's general name-binding and name-resolution protocol and service, previously called Yellow Pages. See YP.
NFS	Network File System. NFS is an ONC application-layer protocol for peer-to-peer, distributed, file system communication. NFS allows a remote file system (often located on a file server) to be mounted transparently by client workstations. The client cannot perceive any functional difference in service

	between remote and local file systems (with trivial exceptions). NFS is the most popular ONC service, has been licensed to over 300 computer system vendors, runs on an estimated 10 million nodes, and is a de facto UNIX standard. See also VFS, ONC, NFSv3.
NFSv3	NFS version 3. References to NFS generally imply NFS version 2 protocol. NFS version 3 is an update to the NFS protocol. Significant among the many changes made for NFSv3 are the adoption of a safe asynchronous write protocol and the use of block sizes up to 64 KB. Other protocol changes are intended to improve the overall network and client efficiency and provide improved support for client-side caching.
NFS ops/s	NFS operations per second. Typical NFS operations include: *lookup, read, write, getattr, readlink, readdir, create, remove, setattr, and statfs*.
ONC	Open Network Computing. The trade name for the suite of standard IP-based network services—including RPC, XDR, and NFS—promulgated by Sun Microsystems.
RPC	Remote Procedure Call. An RPC is an (almost) transparent subroutine call between two computers in a distributed system. ONC RPC is a Sun-defined session-layer protocol for peer-to-peer RPC communication between ONC hosts. ONC RPC underlies NFS.
RAID	Redundant Array of Independent Disks. RAID is used to increase the reliability of disk arrays by providing redundancy either through complete duplication of the data (RAID 1, i.e. mirroring) or through construction of parity data for each data stripe in the array (RAID 3, 4, 5). RAID 5, which distributes parity information across all disks in an array, is among the most popular means of providing parity RAID since it avoids the bottlenecks of a single parity disk.
SBUS	SPARC International's limited-distance, 80 to 160 MB/s (peak rate, 32-bit or 64-bit) bus linking the central CPU(s) to small physical form factor controllers (e.g., Ethernet, FDDI, SCSI). Typical SBus systems consist of a "motherboard" containing the central processor(s) and SBus interface logic, a number of SBus devices on the motherboard itself, and some SBus expansion connectors. See MBus.
SCSI	Small Computer System Interface. An intelligent *bus*-level interface that defines a standard I/O bus and a set of high-level I/O commands. Each SCSI device has an intelligent SCSI *controller* built into it. SCSI is used for local data communication between a host CPU and an attached SCSI bus that contains intelligent peripheral devices such as disks, tapes, scanners, and printers.
SMB	Server Message Block. A stateful, connection-oriented, network file sharing protocol developed by IBM and Microsoft as part of LAN Manager. SMB is the native file sharing protocol for systems running Windows for Workgroups, Windows95 and Windows NT.
SMP	Symmetric Multi-Processor. A computer architecture in which processing tasks are executed in parallel on multiple, identical, general-purpose CPUs that share

	a common memory. SMP computer systems usually have modified operating systems that can themselves execute concurrently. The SMP architecture offers high computational throughput, but not necessarily high I/O throughput. See FMP.
SNMP	Simple Network Management Protocol. SNMP is a protocol used for communication between simple, server-resident SNMP *agents* that respond to network administration requests from simple-to-sophisticated SNMP *manager tools* running on remote workstations.
Solaris 2.x	Sun's UNIX operating system based on System V release 4.
SPARC	Scalable Processor Architecture. SPARC International's specification for the Reduced-Instruction-Set-Computer (RISC) CPUs found in systems sold by Sun Microsystems, Auspex, etc.
SPEC	Standard Performance Evaluation Corporation. A nonprofit corporation of vendors' technical representatives that develops and certifies accurate, vendor-neutral, computer-system benchmarks. As an example, popular SPEC CPU benchmark metrics include SPECint, SPECfp, and the now obsolete SPECmarks. See LADDIS.
SPECNFS ops/s	A measure of NFS performance standardized by SPEC. This unit of measure is often used interchangeably with SPECNFS_A93 ops/s. The A93 suffix indicates the first of what may evolve into a series of workloads, each corresponding to different LADDIS variations simulating the loads and traffic patterns of application environments like ECAD, MCAD, imaging, etc. The current version is SFS97 and incorporates NFSv3 testing.
SunOS	Sun's UNIX operating system based on Berkeley UNIX. SunOS was originally based on the BSD 4.2 release. The NetServer Host Processor runs a licensed version of SunOS modified to accommodate the LFS file system and FMP software architecture. Also referred to as Solaris 1.x.
UFS	UNIX File System. UFS is the standard file system type in the BSD 4.3 kernel. See VFS.
VFS	Virtual File System. A generic file system interface defined in SunOS that allows convenient and transparent integration of different file system *types*. In the NetServer host processor, all file system requests are sent to the VFS, where they are mapped into NFS, LFS, or UFS calls. LFS calls are routed to the file processor, and UFS calls are routed directly to the storage processor.
VME	A backplane bus conforming to a Motorola specification by the same name. The VME bus specification defines the mechanical and electrical properties of an interfacing system used to connect data processing, data storage, and peripheral control devices in a closely coupled configuration. It is comprised of four groups of signal lines: the data transfer bus (DTB, for high speed asynchronous parallel transfers), the DTB arbitration bus, the seven-level priority interrupt bus, and the utilities bus.

WebNFS	An extension of the NFS protocol to simplify access to NFS servers and permit easier access through corporate firewalls. WebNFS provides: public filehandles (to avoid mount protocol overhead), streamlined path lookups (to reduce network traffic and improve response over slow links), and is registered at a well-known port (to avoid portmapper negotiation). Future web browsers will provide NFS URLs (Uniform Resource Locators) to allow WebNFS to take the place of HTTP for transmission of static Web content. In tests, WebNFS has proven to be up to 10 times faster than HTTP for some applications. WebNFS is expected to complement HTTP, which supports dynamic web-page generation. Although not a requirement, the preferred protocol for WebNFS is NFSv3 over TCP, this helps optimize performance over wide area connections and eases access through firewalls.
XDR	eXternal Data Representation. A Sun-defined ONC presentation-layer protocol for the canonical, serialized representation of programming-language data structures. XDR is used for convenient information exchange between heterogeneous computer systems that may have different byte orderings, floating-point representations, and so forth. XDR is used to marshal ONC RPC parameters and underlies NFS.
YP	Yellow Pages. An obsolete name for NIS. See NIS.

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