Overview of Digital's Open Networking

1 Abstract

The principal element of Digital's open networking family of products is the DECnet computer network. In its latest form, DECnet supports very large networks of more than 100,000 nodes and incorporates industry standards such as OSI and TCP/IP. To meet the design goals of the Digital Network Architecture, the structure of DECnet is divided into layers with defined relationships between layers. Since its introduction in 1974, DECnet has evolved in parallel with the standards for open networking. Digital has contributed to the formation of networking standards, and the standards have, in turn, influenced the design of DECnet.

In 1974, Digital shipped the industry's first general-purpose networking product for distributed computing. The DECnet computer network was the embodiment of the vision that small systems working together could become an alternative to mainframe computing. Prior to that time, networking products had been aimed at solving some specific problem and had often been closely integrated with a particular application. In contrast, DECnet allowed any application to share data with all others. Whereas previous networking products in the industry had concentrated on connecting terminals to hosts, DECnet provided peer-to-peer networking for the first time. By doing this, it anticipated the client/server computing style that is now commonplace and established client/server computing as a viable approach.

DECnet built on work that had been done in the research community. The internet protocol, funded by the Advanced Research Projects Agency (ARPA), was of particular relevance.[1] This too was aimed at providing general-purpose distributed computing and later evolved into the well-known TCP/IP (transmission control protocol/internet protocol) protocol suite. In 1974, however, it was still a research topic.

In the same year, International Business Machines Corporation announced its Systems Network Architecture (SNA).[2] The comparison between SNA and DECnet is interesting because SNA was designed, not surprisingly, to support mainframe computing. It focused principally on connecting many relatively unintelligent devices, such as terminals and remote job entry stations, into a single computer. Only after several years did SNA allow more than one mainframe to exist in the same network. Its original goal was to address the proliferation of application-specific protocols that allowed a terminal connected to the network to use one application only.

This paper presents a short history of the DECnet networking product, defining each phase of its evolution in terms of its contribution to distributed computing. It explores the development of DECnet Phase V, the current implementation, and discusses the principles of Digital's layered architecture. The paper then describes the layers of DECnet, the importance of naming services, and the role of network management.

2 A Short History of DECnet

The development of DECnet has proceeded by phases. Each phase has represented a major step in the evolution of the product family. The initial products, later referred to as Phase I, revealed some unexpected problems in building a range of products across different systems that would all work together. One of the consequences was the creation of a distinct Network Architecture Group. Their job was to produce detailed specifications of the protocols and interfaces to be used without constraining the implementers to build products in some particular way. At that time, software portability was practically unheard of, and each different hardware or software environment had its own completely separate implementation. Phase II of DECnet, introduced in 1978, provided full interoperability between the different implementations, thanks to adherence to a rigorously specified architecture.

At this stage, systems still had to be directly connected to each other if they were to communicate. Phase III, which appeared in 1981, introduced the ability to route messages through any number of links and intermediate systems to reach a destination. DECnet again used a technique from the research networks, a dynamic adaptive routing algorithm, which computed the best route to a destination automatically as the physical connectivity of the network changed. Competing products at the time (such as SNA) required routes to be computed and entered manually, including backup routes for use in the event of failure of a link or a system in the network.

Phase III also included full remote management and reflected the gradual emergence of standards for computer networking by supporting X.25 packet switching networks as one means for connecting systems.[3] A Phase III network could contain up to 255 nodes.

The invention of local area networks (LANs), and in particular the Ethernet, was to have a huge impact on the use of networking.[4] For the first time it was cheap and simple to connect a system to the network. Prior to LANs, only wide area network technology was used, even when the systems were physically next to each other. DECnet Phase IV, which appeared in 1984, added support for the Ethernet and allowed networks to contain up to 64,000 nodes.

3 The Evolution of Open Networking

When DECnet appeared in 1974, all its networking protocols were "proprietary," that is, they had been developed by Digital and remained under Digital's control. At that time there were no standards or publicly defined network protocols. Work on standards for this purpose began during the 1970s, and in 1978 the Comité Consultatif Internationale de Télégraphique et Téléphonique (CCITT) published its Recommendation X.25.[3]

This document defined a standard way of connecting a computer to a network that would permit free communication between all attached computers. X.25 networks were typically expected to be provided by a public carrier such as a telephone company.

The appearance of this standard prompted the question, "Now that our computers can talk to each other, what are they going to say?". Simply permitting them to send data to each other was of no use unless they could also understand it and make some use of it. DECnet, for example, included protocols for transferring files and for remote terminal access as well as the base protocols for transferring data.

Thus the idea of open systems interconnection (OSI) was born. OSI was the most ambitious effort in the history of standards. Its goal was to develop a complete set of standard protocols that would allow computers not only to exchange data but also to make meaningful use of it in their applications. The work was undertaken by the International Organization for Standardization (ISO). This organization has representatives from all major countries and is thus able to draw upon their extensive experience in research and commercial networking.

By 1984, when DECnet Phase IV became available, the work on OSI had made substantial progress. The architectural model had been published as an international standard, and standardization of many of the protocols was at an advanced stage.[5] It was also becoming clear that the future of computer networks depended on the ability to communicate without regard to who was the supplier of a system. Ad hoc solutions, such as the DECnet/SNA gateway, existed for communication between different network architectures.[6] OSI, however, held the promise of being a general solution. It was feared that the alternative to OSI would be the adoption of a vendor-specific architecture as a de facto solution, and that that architecture would inevitably be SNA. The internet family of protocols, colloquially known as TCP/IP, had not yet become the force it is today.[7]

Detailed examination of the OSI protocols showed that they formed a suitable basis for the evolution of DECnet. This was not surprising, since the ISO had incorporated Digital's basic concepts into OSI, rather than the different ideas put forth by the public network operators. A number of deficiencies were identified, but these could be remedied by contributing more of Digital's technology to the standards process. For example, all the network-layer routing protocols used in OSI were contributed by Digital. Thus the decision was made that the next phase of DECnet, Phase V, would use the OSI standards as much as possible. The existing proprietary protocols would be retained only for the purpose of backward compatibility.

During the development of the architecture and products for Phase V, another event of great significance took place. During the 1980s, TCP/IP emerged as an alternative solution for open networking. This development was prompted by the explosion in the use of workstations based on the UNIX system style of computing. The architectural model of Phase V allowed a relatively straightforward integration of these protocols into the products, although a great deal of necessary software was written. Since OSI and TCP/IP were never designed to work together, allowing them to coexist in the same network demanded considerable creativity.[8]

4 Goals of DECnet Phase V

The design of DECnet Phase V had three principal goals:

- To allow networks to grow to be very large, with one million systems as a practical target

- To use standard protocols to the maximum extent possible

- To support a distributed-system mode of operation in which the systems cooperate more closely than in traditional networking

The 64,000-node size limit of Phase IV was far from posing a practical problem in 1984, but it was then foreseen that computer networks in large enterprises would approach this limit by the end of the decade. Indeed, this happened with Digital's internal network, which grew to over 100,000 nodes on Phase IV with the use of innovative management techniques. The node size limitation was imposed primarily by the size of the addresses used, which was 16 bits. Addresses in OSI networks can be as long as 20 bytes, which removes the immediate limitation. Very large networks, however, need more than large addresses to support 100,000 nodes or more. For example, the Phase IV routing algorithm has certain inherent weaknesses that start to appear for networks at the Phase IV size limit. For this reason, Phase V employs a different routing algorithm, which readily supports networks of millions of nodes.[9] This algorithm has subsequently been adopted as the international standard for routing in OSI networks and, with modifications, for TCP/IP networks.[10,11].

Management of very large networks also requires special attention. DECnet has always provided a high degree of automated management compared to other network architectures, but as a network increases in size, the burden of tracking the configuration increases disproportionately. Assigning addresses to nodes was a manual procedure in Phase IV, and maintaining the correspondence between node names and their addresses was performed separately in each system. A goal for Phase V was to provide a robust, distributed naming service throughout the network. Furthermore, nodes would be allowed to generate their own addresses in a reliable and unambiguous way and to register themselves in this naming service. Thus a new system can be connected to the network without any administrative procedure, if network security policies permit.

At a more detailed level, the architecture has a set of goals that have evolved over time to include the following.

- Conceal network operation from the user. The internal operation of a large network is inevitably complex, but to the user it should appear simple.

- Support a wide range of applications.

- Support a wide range of communications facilities: LANs, wide area leased lines, X.25 networks, etc.

- Support a wide range of network topologies.

- Use standards wherever feasible rather than proprietary protocols. For cases in which standards are evolving but are not yet finished, ensure that future migration is as smooth as possible.

- Require minimum management intervention.

- Be manageable. Not all functions can be automated; for example, some depend on the organizational policy of the user. In such cases management should be as simple as possible and should not impose any particular style of management.

- Permit growth without disruption.

- Permit migration between versions. Each phase of DECnet is guaranteed to work with the next and previous phases, so that the systems in the network can be upgraded over a long period. It would be inconceivable to upgrade thousands of systems overnight.

- Be extensible to new developments in technology.

- Be highly available in the face of line or system failure or even, to the extent possible, operator error.

- Be highly distributed. The major functions of the Digital Network Architecture (DNA), such as routing and network management, are not centralized in a single system in the network. This in turn increases availability.

- Allow for security functions, such as authentication of remote users and access control.

5 Architectural Principles

DNA is a layered architecture. The necessary functions are divided into related and logically coherent groups called layers. The layers are built on top of one another, so that each layer makes use of services provided by the one below it. To meet the goals of DNA, particularly those relating to flexibility, the structure of a layered architecture is essential.

Figure 1 illustrates the principles of a layer in the terminology of the OSI reference model.[5] These principles apply to any layer; in Figure 1 they are shown applied to the transport layer. Each communicating system contains its own element of the layer, called the transport entity. These entities communicate with each other through the transport protocol. This protocol is conveyed using the services of the next lower layer, in this case, the network layer. For this purpose the most important service is the one that conveys data without regard to its contents. Other services are also provided, for example, connection management services. The transport layer also provides a well-defined transport service to its user, in this case, the session layer. The detailed mechanisms and protocols of the layer are hidden from the layers above and below, so that the layer above sees only a well-defined service.

This independence of the mechanisms used permits substantial changes to be made to the mechanisms and protocols of a layer without affecting the adjacent layers. This very important property is called layer independence. It has been extensively exploited in the development of DECnet to allow protocols to be enhanced or even completely replaced.

The principles of layered architecture were defined in a rigorous way by the OSI reference model, building on previous work such as DECnet and the TCP/IP protocol family. The original layer structure of DNA was defined in Phase I and has changed only a little since then. It corresponds to the lower layers of OSI as well as the layers of TCP/IP.

6 The Layers of DECnet

Figure 2 shows the layers of DECnet Phase V. The lower layers are the physical, data link, network, and transport layers. They provide a universal, reliable service for moving data from one system to another. Many different underlying means of physical communication can be used, with their associated protocols, including:

- Ethernet LANs and the equivalent standard (IEEE 802.3, ISO 8802-3)
- Token ring LANs (IEEE 802.5)
- Wide area links running over leased links at any appropriate speed
- X.25 wide area networks

The network and transport layers unify the service provided by these disparate physical networks and allow communication across any mixture of different facilities.

Protocols from different protocol suites may be used, including OSI, TCP/IP, and DECnet Phase IV, but the structure of the layers is the same in each case. This facilitates interworking in mixed-protocol networks.

The upper layers of DECnet, the session, presentation, and application layers, make use of the reliable transport service to provide application-oriented functions, such as file transfer or electronic mail. Again, different protocol suites are supported, although in this case there are historical reasons for the different layer structures that exist.

The Physical Layer

The physical layer is concerned essentially with the electrical or other physical aspects of communication. It converts electrical or other signaling into binary data (i.e., bits) and vice versa.

In DECnet, this layer has always been viewed as the province of standards for devices such as modems and LANs. These standards may have an extremely complicated internal structure, as is the case for some of the emerging high-speed, wide area network standards, but this complexity is not visible to the layers above.

The Data Link Layer

The data link layer provides a reliable communication path between directly connected systems in the network. Its protocols can detect errors introduced by the physical layer (for example, from electrical disturbance). For media known to exhibit a high error rate, such as analog links, the data link layer also provides error-correcting mechanisms.

DECnet supports a variety of protocols in the data link layer, depending on the nature of the physical link and the need to accommodate existing technologies.

The Network Layer

The network layer provides the means to move data from one system to another, without regard to the nature of the connections between them. It finds a route through multiple systems and physical paths as necessary for any particular pair of communicating systems. In DECnet, systems that move data through the network without being involved in the details of the communication are called routers.

A key element in this layer is the network address. Every system in the network has a unique address. Every system can communicate with every other system in the network, whether it is adjacent or located on the other side of the world. OSI provides an addressing scheme that allows every system in the world to have a unique address.[12] It may also give some hints to find a route to the system. Previous versions of DECnet (Phase IV and before) used a different addressing scheme. Phase V includes a way to map these addresses into the OSI scheme.

In addition to protocols for carrying user data between communicating systems, the network layer also contains protocols for finding routes between systems. The routing protocols used in DECnet Phase V are international standards, but the technology was developed by Digital and subsequently submitted to the relevant standards organizations.[10,11,13]

The network layer has a complex internal structure that allows one network to use the connections provided by another. For example, some of the links in a DECnet network may be provided by a public X.25 network, which is also providing links in other private networks.

The Transport Layer

The transport layer provides a reliable end-to-end service between two communicating systems, concealing from its users the detailed way in which this is achieved. Unlike the layers below it, the transport layer is present only in the end systems communicating with each other. Thus it allows the end systems to take full responsibility for the quality of the communications. The functions of the transport layer include

- Recovery from data loss, for example, when the network layer fails to deliver a packet due to congestion

- Flow control, so that the transmitter does not send data into the network faster than the receiver can accept it

- Segmentation and reassembly of user messages, so that the necessary division of data into distinct messages sent through the network does not limit the size of messages as seen by the user

- Congestion avoidance, so that data transmitters can adjust their rate of transmission into the network in reaction to congestion indications from the network layer

DECnet supports three protocols in the transport layer: the network services protocol (NSP), defined for previous phases of DECnet; the OSI transport protocol; and TCP from the internet protocol suite.[7,14]

Upper Layer Protocols

The OSI model defines three distinct layers above the transport layer: the session, presentation, and application layers.

- The session layer organizes the structure of message exchanges. For example, it provides half-duplex semantics and allows checkpoints to be established for recovery from system failure.

- The presentation layer deals with the existence of different data representations in different systems. It allows a mutually acceptable transfer syntax to be established which each communicating system will be able to convert to and from its internal representation.

- The application layer contains protocol elements specific to a particular application, such as file transfer. It also provides a structure that allows applications to be built that use multiple protocols in a coordinated fashion.

The DECnet Phase IV and TCP/IP protocol stacks, which are also supported by

DECnet Phase V, do not have this structure. Rather, the functions of the session and presentation layers are built into the application protocols as needed.

All three protocol suites support a wide variety of applications, in addition to allowing a user the flexibility to develop custom applications. Typical applications include

o File transfer and access

- o Virtual terminal
- o Electronic mail
- o Remote procedure calls

7 Naming Services

The protocols in the lower layers operate in terms of addresses which are, for practical purposes, simply bit strings. Their format is heavily constrained by the protocols, and their value is constrained by the network topology or hardware. These addresses are not at all user friendly, nor are they intended to be. The human users of a network need access in terms of something which they can remember and which makes sense to them, which is to say a name. Computers in the network therefore need to be able to take a name and change it to an address, and vice versa for incoming traffic.

DECnet Phase IV had a very simple approach to this problem. Since it was aimed at small- to medium-sized networks, it was practical for each system to store the complete set of names and addresses. Administrative procedures, such as regular file transfers, could be used to ensure that all systems were kept up-to-date.

DECnet Phase V was designed to allow much larger networks to be built, while both OSI and TCP/IP are designed to support networks on a global scale. The administrative problems and storage requirements of the Phase IV approach make it unusable for very large networks. A further complication arises as networks span multiple organizations, since no single central site can have management responsibility for the complete set of names. Therefore, a different approach is needed.

The limitations of the Phase IV approach were recognized when this version of DECnet was in the design phase, and work was started on the Digital Distributed Name Service (DECdns). DECdns has been available as an optional component of DECnet Phase IV for some time. It provides

- o Distribution: All naming information does not have to be stored at a single point in the network.
- o Replication: Information can be held in more than one place, giving resilience in the face of system or network failures.
- o Dynamic updating: Information can be changed at any time.
- o Automatic updating: Changed or new information is automatically propagated throughout the network.

- Hierarchical naming: A name can have multiple components to reflect an administrative or other organizational structure.

The development of the DECnet and DECdns products has been closely linked, and each is designed to make maximum use of the other. When they are used together, DECnet can provide complete autoconfiguration of a new node in the network, such that no manager or user needs explicit knowledge of the address of a node. Once a name is assigned, the node can keep the naming service up-to-date both with the initial assignment of an address and any subsequent changes. It is also possible for a DECnet system to operate without DECdns.

The TCP/IP protocol suite also includes a naming service, with similar properties to DECdns. It is called the domain name system, or DNS. At the highest level, names are assigned by a global authority to countries and to other large groupings of organizations. Within countries, they are assigned to particular organizations such as companies. These organizations can then assign names that may have further components reflecting their internal structure.

Work on a naming service for OSI has lagged behind the other protocol suites, but the most important elements have been available since 1988 in a standard generally called X.500 (after the first of a series of CCITT recommendations that define the OSI directory). The X.500 standard defines the structure of names and the protocols to be used to access the naming service, but it does not include the mechanisms required for automatic updating and maintenance of the service itself.[15] Work on standards for these functions is currently at an advanced stage. Like the DNS system for TCP/IP, the X.500 standard allocates the highest level of the structure to countries and then to organizations within countries. Its design pays particular attention to the needs of electronic mail (the X.400 protocol family). In contrast to DECdns and DNS, which assign names to computer systems, the structure of X.500 names extends to the level of naming individuals within a coherent naming framework.

DECnet supports all these naming services, in conjunction with their respective protocol stacks.

8 Distributed Network Management

In early computer networks, management was performed "out of band." This meant that if any communication between sites was needed to keep the network running, some means other than the network (for example, the telephone) was used. It was soon realized that much of the time, the network itself provided the most effective way to communicate management information, either to investigate a problem or to modify the configuration. DECnet has included the ability to manage itself in this way since Phase III.

The most obvious requirement for such a scheme is a protocol that can carry management information through the network. Such a protocol fits naturally into the application layer, where it can make use of the services provided by the other layers.

A further requirement is a well-defined structure for the information that is to be conveyed. A network architecture is constantly evolving, and it must be possible to add new information (for example, for a new kind of data link) into the protocol.

Finally, the specific information elements, such as the fault counters to use in conjunction with a particular protocol, must be defined.

The management model and protocol used in earlier versions of DECnet were unsuitable for the needs of Phase V due to the many different protocol combinations that were to be supported. Hence, a new management model was defined. For a long time, this was called the Entity Model and was subsequently published as Digital's Enterprise Management Architecture (EMA).[16] This model takes an object-oriented approach to modeling the information needed for management. It is completely flexible and is not restricted to the management of the network itself; it has since been applied to management of the computer systems themselves.

At the same time, Digital adopted an early draft of the protocol under development for OSI management, the common management information protocol (CMIP). The structure of the CMIP protocol accommodates the flexibility allowed in EMA.

The management information needed for each protocol is defined in the same architecture document as the protocol itself. The modular structure of EMA allows this to be accomplished without conflict between management information defined for different protocols. In addition to the information specific to particular protocols (such as parameters of the protocol operation or counters), there are also representations of the relationship between protocol elements, such as user to provider.

EMA provides a clear distinction between two roles in the management of a network: the agent and the manager. The agent corresponds to the thing being managed and is part of the same system. The manager is typically elsewhere and communicates with the agent using the network and the management protocols. The manager role is taken by user interface programs. These may be simple, like the network control language (NCL), a basic command line utility appropriate for simple networks, or they may be extremely powerful. DECmcc, for example, is a Digital product that provides the facilities appropriate to the management of networks throughout an enterprise.

If the network is being used to manage itself, the possibility exists for a kind of "deadly embrace," in which the communication path needed to fix a problem is itself unavailable due to that same problem. DECnet has been designed to minimize the likelihood and practical impact of this risk. The operation of the network layer is of vital importance in this regard.

As long as a physical communication path is working, it will virtually always be able to correct a fault, even if the fault is due to a previous incorrect management operation.

The TCP/IP protocol suite also provides a management capability through the simple network management protocol (SNMP).[7] Although both the protocol and the information model underlying it are considerably simpler than EMA, comparable facilities exist for many purposes. To the extent possible, DECnet implementations are designed to be managed through SNMP as well as through using the DECnet management protocol.

The standards for management associated with OSI protocols are still under development. Digital has made extensive contributions based on its own architecture, and the resulting standards bear a strong resemblance to EMA. Standards exist for the CMIP protocol and for the management model, but specification of the specific elements of management information needed for particular protocols have yet to be completed.

9 Conclusions and Future Capability

In 1974, DECnet was the first networking product to provide general-purpose, peer-to-peer communications. With the availability of Phase V, DECnet has become the first fully standards-based family of network products. It incorporates all available standards from the OSI and TCP/IP protocol suites in a way that provides the system integration and the performance traditionally associated only with proprietary network products. Achieving this migration to standards has involved a phenomenal effort, but this price has now been paid. Technology and the standards that reflect it are in a constant state of development. The future of DECnet will consist of relatively frequent and modest incremental changes that incorporate these new developments. Already major developments in areas such as naming (X.500), transaction processing, and management are finding their way into the products.

At the same time, there is an increasing need for Digital networking products to incorporate widely used, nonstandard protocols, especially for interconnection with personal computers and other desktop devices. Fortunately, the modular architecture developed for Phase V makes it relatively easy to do this in the same incremental fashion.

DECnet has changed out of all recognition from its early versions, yet it can still support the same application programs that were built in the 1970s, as well as client/server applications that are still emerging. The basic physical technology that supports networking has also undergone enormous changes, from 2,400-bit-per-second modems to Ethernet and fiber distributed data interface (FDDI), yet DECnet makes this all transparent to the user. In another 20 years we can expect these technologies to have developed as much again, or more, and we can expect too that DECnet will continue to adapt to match them.

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