Management and Control for Giant Gigabit Networks

Using virtual-world technology for the human interface to a management system brings high bandwidth directly to the user.

Laurence Crutcher and Aurel A. Lazar

LAURENCE CRUTCHER is a software engineer with Market Vision Corporation.

AUREL A. LAZAR is a professor of electrical engineering at Columbia University.

The research, development, and implementation of network management systems has progressed to the point where we are now seeing the availability of standards-based management software from commercial vendors and the deployment of these products in operational networks. Similarly, hardware vendors for network components such as switches, bridges, and routers are incorporating management interfaces into their products. Together, these trends are leading us to a communications environment that is interoperable in the management domain as it already exists today in the user transport domain.

To date, the discussion of approaches to network management has been dominated by the debate over competing standards, based on the simple network management protocol (SNMP) and common management information protocol (CMIP). Although there is a clear complexity/performance trade-off between these two standards, it is likely that they will coexist in the future. Given that the current generation of management systems will be based on these standards, it is appropriate to investigate their limitations. In particular, are these systems appropriate for the management and control of the emerging broadband integrated services digital network (B-ISDN)?

The importance of defining management functions for B-ISDN at an early stage has been recognized. There are activities in progress in the International Consultative Committee for Telephone and Telegraph (CCITT) [1], and other groups such as the Asynchronous Transfer Mode (ATM) Forum, which focus on defining management capabilities in the ATM layer. This work will lay the basis for making the broadband network manageable through the definition of operations, administration, and maintenance (OA&M) cells for functions such as traffic monitoring. Just as the subject of user-transport protocols is progressing from compatibility issues alone to considerations of their suitability in a high-speed network, we see that a similar advance will be required in solutions for network management and control of giant gigabit networks. We call these networks giant because of the scale on which they are expected to be built and gigabit because it is assumed that the end-to-end sustained throughput supported by these networks will be in the multigigabit range. The focus in this article is on the architectural requirements of a management system that can cope with the inherent complexity of these networks. The distinction between management and control made here is only in terms of the time scales on which these mechanisms act. Control operations act on the fast time scale of milliseconds and below, whereas management operations act on a time scale of seconds or above.

In this article, we describe the new challenges presented for the management of broadband networks and outline the framework of the COMET research group at Columbia University for finding solutions to these challenges. Finally, we review a prototype that implements some of the requirements for managing the broadband networks of the future. In the COMET framework, management operations are defined in terms of primitives with a much higher semantic level than that typified by get and set in the open systems interconnection (OSI) management model, and the user interface to the managed system is based on virtual worlds that allow the manager to directly visualize and interact with the network. The impact that this new environment may have on existing management architectures is discussed.

This article is organized as follows. Challenges for managing broadband networks, and the advances needed to meet these challenges, are presented next. A framework to meet these challenges will follow. The discussion includes a brief presentation of a reference model, high-level primitives for monitoring and control, and a virtual-world-based environment for information presentation. The authors then discuss ongoing work on a prototype system and its implementation.

Management in the Broadband Network

In this section, we first outline the new challenges faced in the management of broadband networks and describe the characteristics of the type

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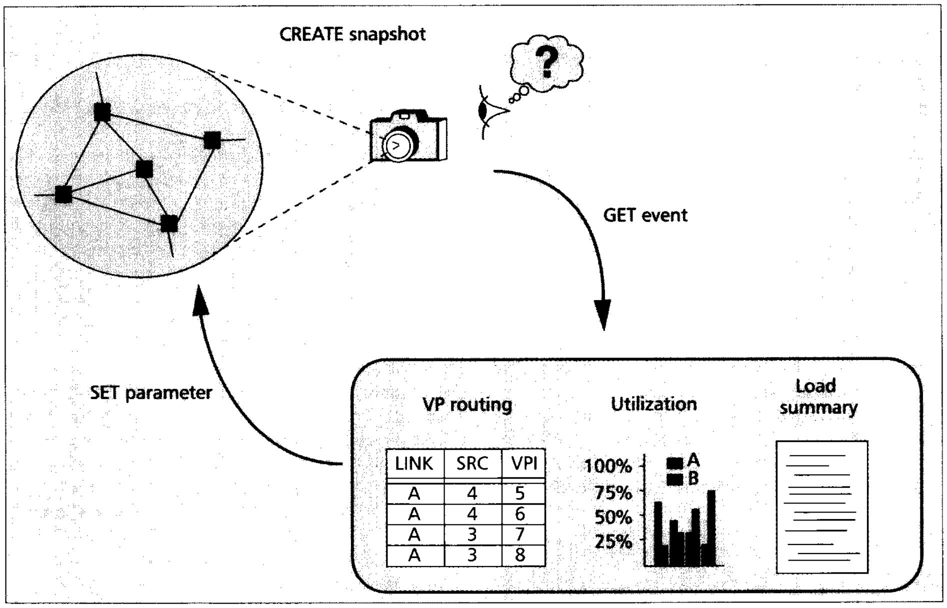

LINK	SRC	VPI
A	4	5
A	4	6
A	3	7
A	3	8

■ Figure 1. *Conventional management cycle.*

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Future integrated networks will be "giant" in that they will contain a very large number of physical and logical entities, services, and users to be managed and controlled.

of system needed for enabling effective management of these networks. We then describe some typical network management scenarios in this environment and outline the technical advances required for its realization.

The Challenges

There are two fundamental properties of broadband networks that lead us to conclude that the behavior, and the management and control of this behavior, of these networks will be qualitatively different from that of existing networks. These qualitative properties are a reflection of quantitative shifts in speed/latency and scaling.

As link speeds move up to gigabits per second and beyond, it becomes more difficult to follow changes in the state of the network because of the shift in the bandwidth/delay product. This shift is due to the ever-increasing capacity of fiber optic links and the physical limitation imposed by the finite speed of light. The corresponding impact on issues relating to the transport of user information, such as end-to-end flow control, are well recognized [2] and have led to proposals of new transport protocols that are able to perform efficiently in this environment. From the point of view of network control, the high-speed environment leads to a situation in which the controller's window of observation is severely out of date with respect to the true state of the network. At best, this leads to situations where control actions are less than optimal, while at worst it creates the possibility of such actions leading to instability in the network.

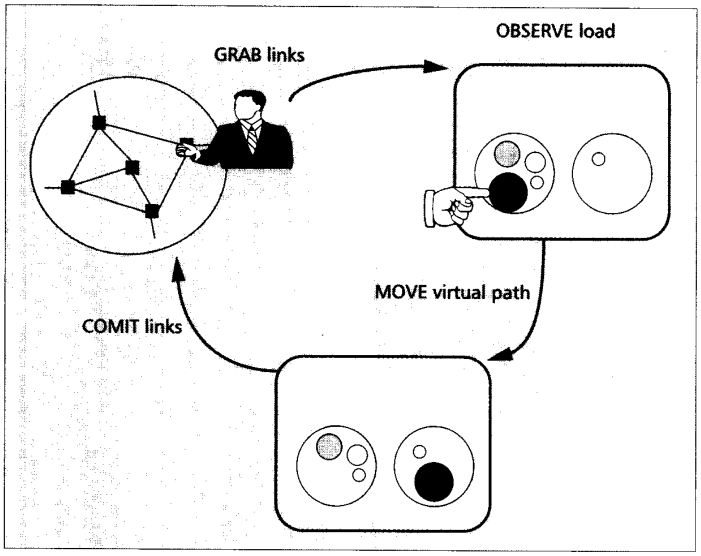
While the speed/latency issue leads to difficulties in making the state of the network available for control, scaling relates to problems concerning the integration of an ever-growing number of services with different quality-of-service requirements and the large number of users these networks will support. Future integrated networks will be "giant" in that they will contain a very large number of physical and logical entities, services, and users to be managed and controlled. The fixed network alone will present enormous complexity in this respect, and this will be amplified by the expansion of mobile networks. Thus, the network management system is faced with an information explosion in which the state space becomes too large to be correlated and controlled within an acceptable time frame.

The management cycle in use today is characterized in Fig. 1. It can be summarized as observation and control at a distance. The manager is given periodic snapshots of the state of the network, and effects management actions through a monitoring and control cycle based on getting events and setting parameters. These operations are low-level and slow. Much of the information presented to the manager is gathered off-line in textual reports and two-dimensional (2D) graphics abstractions; similarly, the ability of a manager to act on the network is often restricted to issuing reports and instructions to other operators.

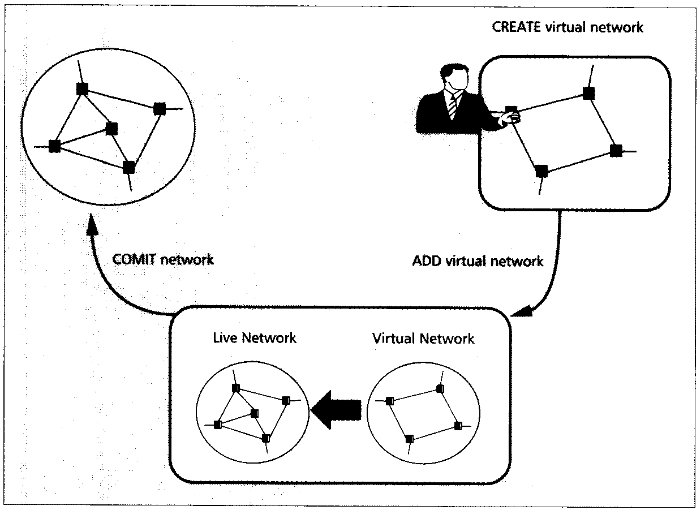
Even in today's networks, there have been many cases where this style of management has led to significant problems. In January 1990, an equipment failure combined with a software bug robbed the United States of much of its telephone service for a large part of one day [3]. During that time, the network was in an unstable state, able to handle less than half of its normal traffic load. While there are many parts of the total management practice, including nontechnical factors such as organization of personnel, there is a fundamental deficiency in the technology that is the basis of this practice; that is, the system to be managed is not truly observable or controllable.

From our considerations of the speed/latency and scaling issues in a broadband network, we conclude that these problems will be greatly magnified in these networks and that fundamental advances will be required in the way in which we approach network management and control. For this purpose, we will discuss a new paradigm in which the network is managed through the exchange and processing of multimedia information. Just as high-speed networks will enable users to communicate more efficiently and naturally through multimedia, the same advances can be made in network management and control by similarly exploiting increased bandwidth and computing power. In contrast to the cycle in Fig. 1, this paradigm is one of direct observation and control. This is distinguished from that of Fig. 1 by three fundamental characteristics:

- The manager can actively navigate through the network and directly observe the state of the system at many levels of abstraction. Information is structured so that the manager is automatically guided through the hierarchy of network states. The manager can access any piece of information at any time.
- Control actions are effected directly through commands with a semantic level that very closely matches their intended purpose.
- The user interface to the network naturally represents the system being managed and allows management operations to be effected rapidly and easily.



■ **Figure 2.** *Direct manipulation of VP configuration.*



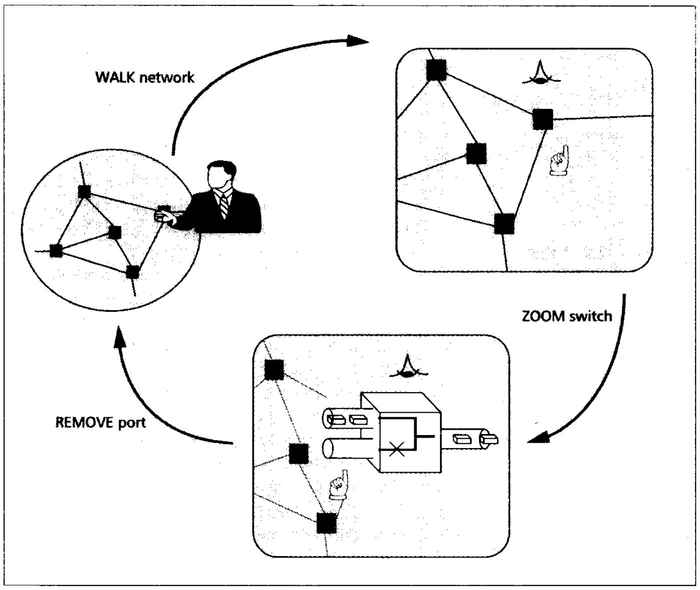
■ **Figure 3.** *Creation of a virtual private network.*

We illustrate this with some examples below.

Scenario 1: Performance Management — For planning and live management, the manager needs to carry out experiments interactively with different network configurations and assignments so that in each case the behavior of the network can be observed. For this purpose, the assignment of virtual paths (VPs) plays a key role in B-ISDN [4]. An example is illustrated in Fig. 2. Here, the user is observing the load on a set of VPs inside the network, and as a result of these observations has decided to reroute some of the VPs. This is a typical scenario that may occur during fault or performance management in an ATM network, where the manager wishes to alter the resource allocation in the network in response to abnormal conditions or the observation of continual high or low utility in different parts of the network. The VPs inside a link are investigated by GRABbing the link in question and observing the paths that are in place, abstractly represented as a set of cylinders inside the cylindrical link. The capacity of a VP is proportional to the diameter of its cylinder in this case, and its utilization is indicated by color coding. To relocate the VPs, the manager GRABs the VPs in question and MOVEs them to the alternate link. A final COMMIT operation translates the changes from the manager's world to the real network.

Scenario 2: Management of Private Virtual Networks — Related to the first scenario is the management of private virtual networks through the allocation or bandwidth adjustment of a network of VPs on request. This is likely to be a major application of broadband networks, where operators lease out logical networks on demand, with guaranteed quality of service. In Fig. 3, an operator is shown CREATEing an image of the virtual network through the direct manipulation of nodes and VPs, leading to a single object that embodies it. The virtual network can be overlaid on the operational network through a single ADD operation that takes this object and moves it into the network of switches and links. The impact of adding the new VPs on the performance of the entire network can be immediately observed, enabling the operator to experiment off-line with different options before finally COMMITting the allocation to the network. When the private network is to be decommissioned, the operator can similarly GRAB a single object that embodies the entire set of VPs in that network, and simply REMOVE that object from the physical network. Should it be necessary to reconfigure the private network, for example, in response to faults or changes in the network load distribution, the operator can MOVE the VPs in the way described in the previous scenario during live operation.

Scenario 3: Test and Measurement — A user wishes to test the flow of a packet through the network. This may be for the purpose of performance measurement or part of fault diagnosis, and is typically carried out today with specialized instruments such as network analyzers. These functions can be incorporated into the management domain. An example is illustrated in Fig. 4. Using a topology map of the network, the user selects a portion of the network to be tested. He can then pick up a packet, place it into the network at any point in the chosen path, and instruct the packet to begin its journey. The trace of the packet's journey is recorded in real time and can then be played back by the user at any speed. On a macro level, the journey is indicated by color highlighting on the topology map. The user may WALK through the journey of the packet and can designate an area of the journey to be observed in more detail. If a single switch is selected, for example, the user can ZOOM inside the switch and see the movement of the packet from the input to the output, passing through the queues inside the switch. In the example of Fig. 4, a fault is observed in one of the routes through a switch. The manager responds by disabling the faulty route with a REMOVE command.



■ **Figure 4.** *Direct manipulation of switching configuration.*

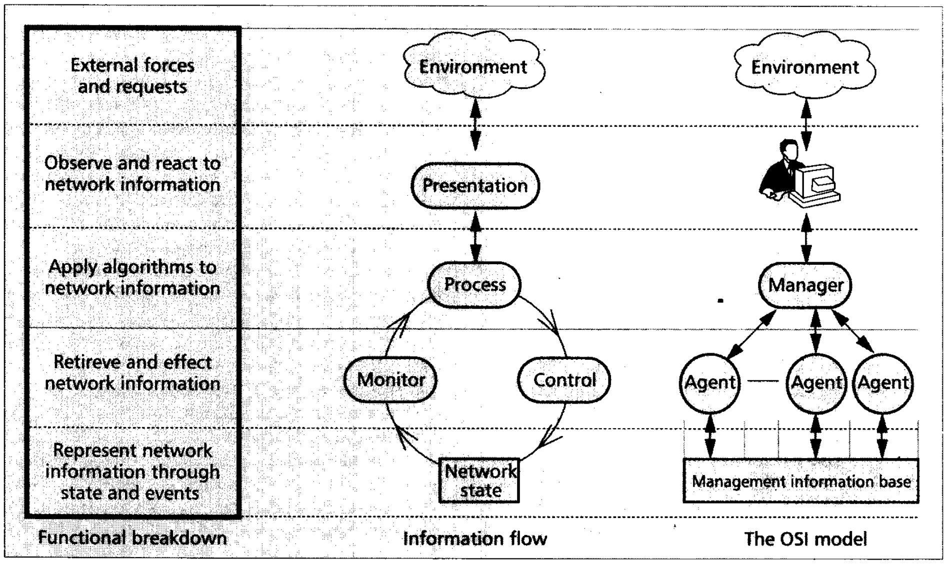
The Required Advances

Having outlined the features of the environment that we consider appropriate for the management of broadband networks, we consider here the advances required from the state of the art in management systems. For this purpose, we look at each of the five basic components of the management cycle, shown in Fig. 5.

This figure depicts management and control in a generic fashion. Whether we are considering network management, which typically refers to operations on a slow time scale, or network control, which in contrast implies actions with real-time demands, the cycle of events is the same. In each case, there is some information in the network that represents the state of the system, and the task is to monitor this state, interpret the state in the context of the specific problem at hand, and to effect this state through control actions in cases where action is required. A fifth component of the cycle is human presentation, allowing for the manual intervention of a network manager or operator. Finally, external to the closed loop of information flow are environmental factors, which can take many forms, such as user requests for the installation of a private network.

To enable the type of powerful management environment we have described, we see that advances are required in each component of the management cycle. Specifically, we see major obstacles in the presentation of the network to the human operator, and in the monitoring and control capabilities provided to the manager. These requirements imply that novel methods of modeling information representation about the network are needed.

The importance and difficulties in providing effective human-machine interfaces for a large network are becoming a significant research issue [5]. 2D displays, with mouse and keyboard input, are



■ **Figure 5.** *Management cycle.*

The centerpiece of the IRM is the network telebase (D-plane). In it, all information supporting the operation of the network is represented.

inadequate for interfacing to a complex multidimensional system. A more powerful interface that incorporates this multidimensionality and allows a human being to interact with the system more naturally is required. An interface based on virtual-world technology is ideally suited to this application. This will allow us to extend the capabilities for input and output in the interface, but this is just one aspect of the problem. The second area to be addressed is providing the appropriate models for human-machine interaction so that the manager is able to cope with the range of modes of interaction presented through the interface.

Our experience with OSI management has shown that the flow of management information experiences low throughput and high delay. To enable the user to readily exploit the potential of high-speed access to state information, we need ways of increasing the monitoring bandwidth so that we can support high-level monitoring commands such as ZOOM and WALK, as illustrated in the earlier examples. Similarly, the control primitives provided by management services such as CMISE are low-level operators. Just as for monitoring, we would like to increase the level of abstraction of control by enabling high-level management primitives such as GRAB, MOVE, and REMOVE.

This approach places great importance on the role of the human operator in the overall management process and the mechanisms provided to this operator. An alternative, or complimentary, approach is to reduce the complexity of the manager's task by capturing that person's knowledge in the form of an expert system, located in the processing component of the management cycle in Fig. 5. There is considerable research into the incorporation of expert systems in the management cycle. We believe that there is a role for such systems in the management process, but that this does not diminish the importance of advancing the user interface in the way described herein. The main points that lead us to this conclusion are:

- Complexity — the increasing size, speed, and sophistication of networks means that with the current level of knowledge it will never be possible to apply automated solutions to all of the problems of network management. An expert system may be useful in handling a problem in a limited knowledge domain, and this will assist in the overall management process.
- Confidence — the critical nature of many decisions in network management require a level of confidence that is beyond that to be trusted to an automatic process that is itself subject to errors.
- The unexpected — no system is ever perfect. The ability to deal with unforeseen problems is a primary requirement. Many of the "external forces" in Fig. 5 are unpredictable.

Finally, we emphasize that these advances call for complementing the high-level operations provided by the virtual world with equivalent capabilities in the management structure. Whatever the balance between automated and manual management, the requirements of the monitoring and control cycle are the same. Whether the knowledge is within management software or a human operator, the complexity of a broadband network places the same demands on this aspect of the management architecture.

In the next section, we outline a possible realization of these advances. We discuss our research into the management architecture, focusing on ways of extending the monitoring and control capabilities of the system, and describe a user interface based on virtual worlds under development in our laboratory as part of the COMET project.

Realizing the Advances

In this section, we describe the features of a management system proposed by the COMET group that supports the interactive and high-level capabilities of management through the virtual world. First, we describe the overall model within which management, control, and information transport are integrated. Although we are specifically concerned with network management here, it is important to appreciate that the management system is just one component of the total network system. A structured approach to integrating the management components with the other elements of the system is crucial for building a manageable and controllable network. Following a description of this model, we discuss how the management architecture can be extended in order to support the powerful monitoring and control features of the virtual world. Although our emphasis here is on the levels of abstraction for monitoring and control, the components of the management cycle in Fig. 5 are closely coupled. Hence, we will also relate this to work on information representation. Finally, we discuss the virtual-world user interface.

The Integrated Reference Model

The management and control architecture is encapsulated in the integrated reference model (IRM) [6]. This model has been developed by the COMET group to provide a network-independent view of the structure and dynamics of the system to be managed, and the services required for control and management on a range of time scales. The IRM is shown in Fig. 6.

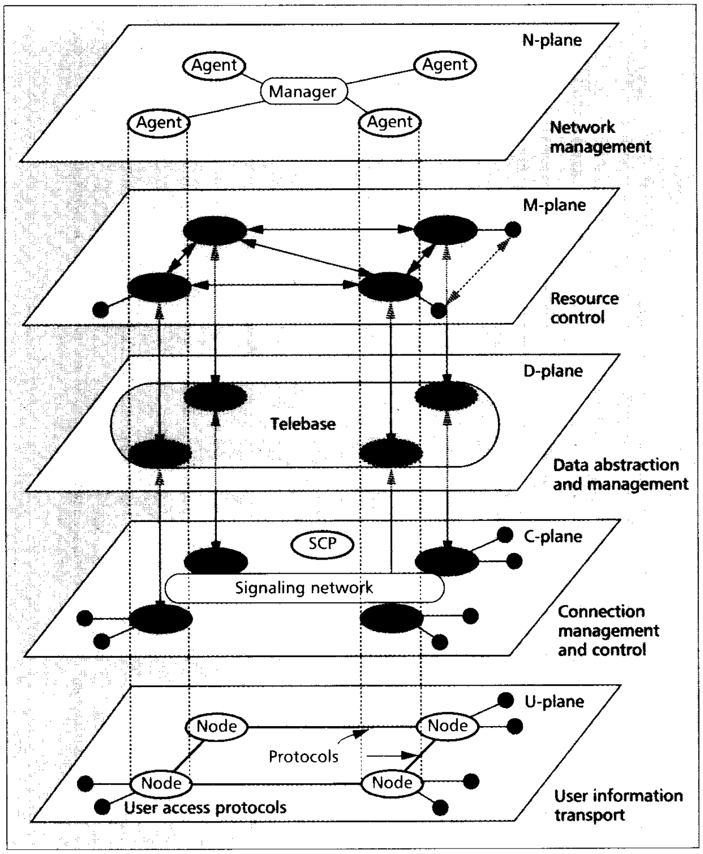
The centerpiece of the IRM is the network telebase (D-plane). In it, all information supporting the operation of the network is represented, including static, dynamic, and statistical information. In practice, the telebase comprises objects that are distributed throughout the network; conceptually, the telebase represents a single information repository where network subsystems can read and write data for their own specific purposes, using D-plane data abstractions that suit their function. Two such elements are the resource control (M-plane) and network management (N-plane) planes. The M-plane embodies a set of distributed asynchronous algorithms that operate in real time to manage network resources. Routing algorithms are an example of a component of this plane. By contrast, the N-plane is perceived as operating on a longer time scale, using a centralized view of the network. Fault management and accounting are examples of components of this plane. The C- and U-planes represent the connection management and user transport, respectively. Thus, the C-plane embodies the algorithms and protocols associated with the signaling network, while the U-plane contains the protocols for transport of user services.

Further details of the IRM can be found in [6]. For the purpose of our discussion here, we note that the model allows us to systematically design and implement the network control and management system in a way in which the complexity of these systems is reduced and made manageable. The functional division according to time scales and the unified representation of network information are the key elements of the model in this respect. The inherent complexity of broadband networks means that attempting to build the management and control system without a structured approach such as that formulated in the IRM is analogous to providing a set of user protocols without a model such as the OSI reference model. Furthermore, successful management requires the coordinated management of all elements of the network, both physical and logical. As described in the following sections, one significant area of attention is the ability to present to the manager a distributed view of each plane of the IRM. This calls for agents and managed objects associated with the C-plane, for example, so that the manager can easily navigate from the user plane to the signaling plane and is able to visualize and control each plane within a unified framework. In this way, the WALK command provided in the virtual world should be effective not just within a plane (e.g., from node to node) but also vertically between planes. The user may therefore WALK from the U-plane to the C-plane, and the view in the virtual world would change from that describing the flow of user information to one describing the state of connections and calls.

Monitoring and Control

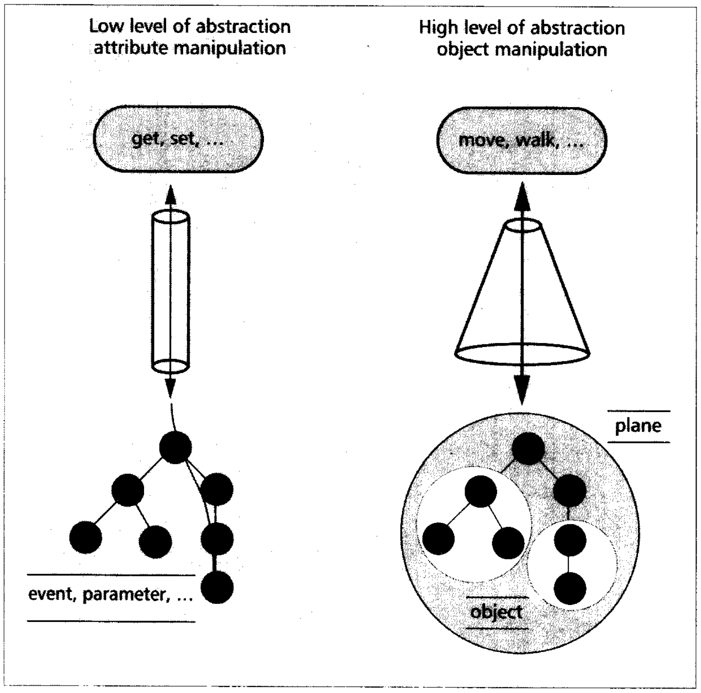
Using an analogy with programming terminology, the services provided by CMISE are equivalent to assembly language instructions, because they enable the manager to manipulate the MIB at the finest level of granularity. By contrast, the services that we have described are high-level language commands. A first approach to realizing these services is therefore to define them in a generic fashion with appropriate parameters and formulate a compilation process in which we can translate each of the high-level services to a set of low-level instructions. Functionally, this is a realistic path. However, consideration of the complexity of CMIP and the overhead associated with each protocol exchange raises doubts that this process will be adequate to satisfy the throughput and delay requirements for monitoring and control of broadband networks.

The focus of the research in the COMET group involves the encapsulation of high-level services such as GRAB and MOVE within the generic get and set primitives. The low-level primitives would be polymorphic in that they would be interpreted differently by different agents. This retains compatibility with existing systems, at least across the manager/agent interface, and allows the high-level primitives to be addressed directly to the agents as an atomic action. Operations are thus devolved to other entities in the network. There is some similarity here to the delegation proposed in [7]. However, our model implies a view of the agent that is different from that we have at present. In order to MOVE a VP, for example, we could issue a set command to an agent that resides in the signalling plane of the network and allow the MOVE operation to be effected under the control of the connection management protocols. The implication here is that get and set in this case would be referring to entire objects, groups of objects, or an entire plane of the IRM, in the MIB, as opposed to simple attributes of objects. (Alternatively, agents could effect the same action in the management plane through peer-to-peer communication in response to a single manager command to one such agent. However, Peer-level agent communication is not supported in the OSI model).



■ **Figure 6.** *The integrated reference model.*

The essential issue here is that the OSI model incorporates a view of distributed data through multiple agents and the MIB, but does not support a consistent view of distributed processing. Aside from their ability to filter data for event notification, agents are seen as passive entities, the main purpose of which is to provide a uniform interface between the manager and the data in the MIB. Investigations are currently underway for incorporating a model of distributed processing within the management model (i.e., within the control loop shown in Fig. 5) so that greater intelligence can be devolved from the manager to the network itself. (Note that this is distinct from the object management framework in the OSF distributed management environment, which is concerned with application-level peer-to-peer communication.) In order to retain compatibility with the OSI model, the best place to do this is within an MIB supported by an extension of the existing manager/agent protocol that allows a richer set of transactions across this interface.



■ **Figure 7.** *Expanding the monitoring and control bandwidth.*

With reference to the IRM, this indicates that we require a better understanding of how to represent network information in the D-plane. The realization of the D-plane is a distributed object-oriented database, but the structure of this database is a subject of ongoing research for the COMET group [8-10]. The correct choice of structure here will greatly assist the monitoring process. Navigation in the virtual world, through ZOOM and WALK commands, is much easier to achieve if the object hierarchy in the MIB reflects that presented to the user. Objects in the network can be self-navigating by adopting an appropriate structure and the incorporation of methods that allow objects to be aware of their relationship to one another. One immediate benefit to be gained is a significant reduction in the large overhead of object identification and location as currently defined in the OSI model. The integration of the naming directory and the managed objects within the MIB is currently not well understood [11]. Just as we conclude that more powerful models of managed objects are required to increase the level of abstraction for control, a similar advance is required to support effective monitoring. This is illustrated in Fig. 7.

Presentation — A Virtual World for Network Management

Within the COMET group, a user interface is being built using virtual-world technology. The multidimensional and interactive nature of this type of interface is ideally suited to the task of visualizing and controlling a complex system such as a broadband network. The use of virtual-world technology with powerful workstation and graphics hardware provides the capability to raise the semantic level of the display so that the behavior of the network can be directly interpreted. This will allow for quicker understanding of, and navigation through, large data sets and spatial networking structures, thereby significantly increasing the monitoring bandwidth to the operator. The operator will be able to observe the behavior of the network in real time, at various levels of abstraction. The level of abstraction is controlled by the operator as he navigates through the network. The navigation is both horizontal, from node to node, and vertical, between different components of the network architecture (i.e., between different planes of the IRM). Furthermore, the capability for powerful forms of direct interaction with the system under observation will enable operations on the network to be effected rapidly and naturally.

Virtual-world technology is in its infancy, and is therefore often awkward to use. Hence, we do not yet consider it applicable to a commercial environment. In terms of network management, the state of the art is presently represented by powerful 2D graphical interfaces that allow visualization of network activity [12-14]. However, technological progress is rapid, and we are beginning to see successful applications of this technology in real-world situations [15]. We see the eventual deployment of interactive three-dimensional (3D) interfaces as a natural progression from first-generation pure textual interfaces and second-generation 2D interfaces, combining text and graphics, of the type in common use today. The virtual-world interface will allow the user to directly exploit the increase in input/output bandwidth that will be achieved through high-speed interfaces between workstations and the network.

There are two main research thrusts that are being addressed for developing an effective virtual world for network management. The first is the development of a set of 3D interaction and visualization techniques that are appropriate for the domain of large networks. This includes a set of 3D spatial metaphors for visualizing and manipulating different aspects of a network's structure and behavior, with extensions of directed-graph models to address behavior over time and facilities for eliding unneeded detail. Because of the massive amounts of data involved and the speed of the network, facilities are being built to journal significant stretches of network activity, and to run journaled activity, at varying speeds, both forward and backward. Also, sonic displays are incorporated in conjunction with graphical displays to help the user gain a better sense of network activity than can be achieved through purely visual virtual worlds. Together, both visual and audio media could be used to form a consistent spatial model of network activity. The second area of research is the creation of a knowledge-based framework within which these techniques can be deployed to automatically customize the information being presented and controlled in a complex and highly volatile environment so that it meets the user's needs.

Further details on the virtual-world interface can be found in [16, 17], and related work appears in [18]. The prototype developed by the COMET group is described in the next section.

Prototype

The current prototype comprises a visualization engine connected via Ethernet to a network engine that executes an emulation of the IRM. This is illustrated in Fig. 8a. The visualization engine

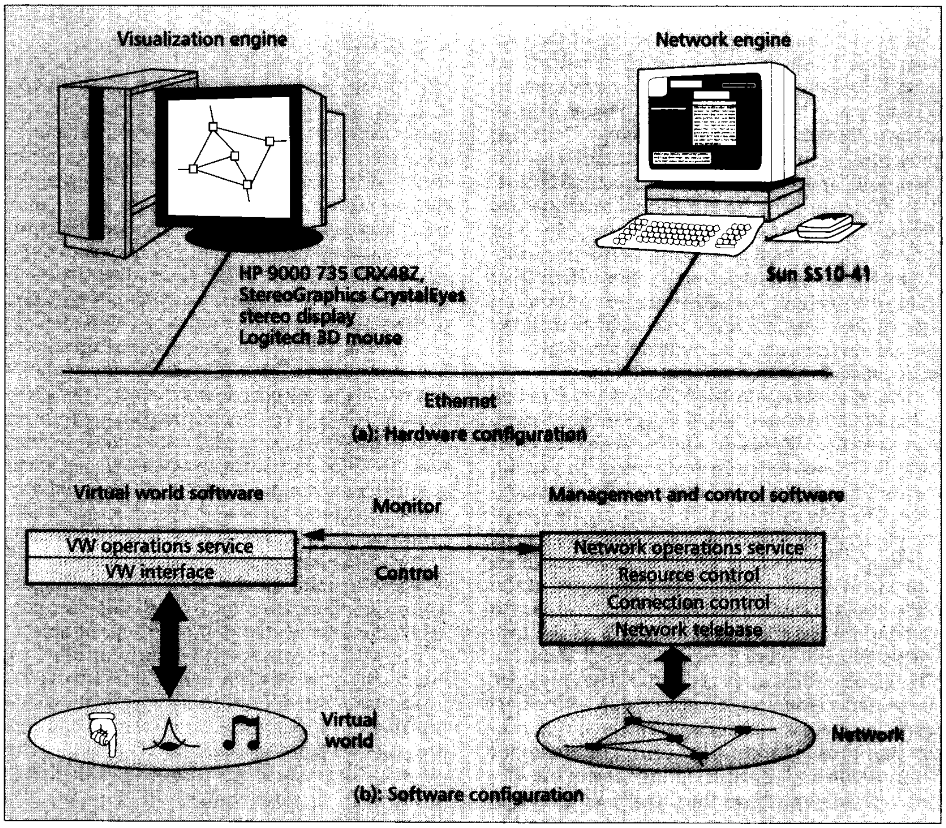


Figure 8. *Prototype system.*

In the visualization engine, the network operations are mapped into the virtual world through the virtual world operations service.

comprises a high-performance graphics workstation with a liquid crystal stereo display system and an ultrasonic 3D mouse that tracks the user's 3D hand position and orientation. This engine presents the user with several different views of the network being maintained by the emulator and allows interaction with the network through the 3D mouse.

The network engine executes a software emulation of a subset of the IRM. The emulation is initialized with a user-specified configuration of physical (e.g., switches and links) and logical (e.g., VPs and calls) entities that are organized into a network database according to the principles of the D-plane in the IRM. The emulator contains a set of control and monitoring modules for the network, and a management interface through which a remote entity can observe and interact with the emulated network.

The structure of the software is shown in Fig. 8b. The lowest layer in the emulator is the network itself, which for emulation purposes is initially specified by the configuration file. This file is written by the user in a high-level syntax and is compiled into the network telebase of the D-plane during the emulation load phase. The remainder of the emulation component of the software is essentially an implementation of a subset of the IRM. The connection control is a minimal representation of the C-plane that allows connections and VPs to be set up between specified hosts and with a specified quality of service, and to be deleted. C-plane services can be invoked directly, so that connections are set up and closed individually, or via traffic generators, which generate connections on a continuous basis with a user-defined arrival and lifetime distribution. The resource control provides some M-plane functions to monitor the network and to change routing tables in the D-plane when appropriate.

The top layer in the network emulator is the network operations service (NOS). This provides services to manage the network. It is deliberately not referred to as the "management" layer since, although it encompasses typical management services that enable reading and writing of network data, the NOS layer also invokes higher-level actions on this data and, potentially, sets of such data. These may relate to any object in the network, from a particular element, such as a call, to the entire network itself, and can be either active or passive. Examples of active operations are "remove node" and "create virtual path," while passive operations include monitoring a specified call or path. This layer can be viewed as providing the language interface through which the network telebase is manipulated and monitored. Thus, the NOS layer directly provides the high-level functions that we feel are appropriate for effective network management.

In the visualization engine, the network operations are mapped into the virtual world through the virtual world operations service. This layer defines the relationship between data and actions in the virtual world and those in the network world. The functions in the NOS layer can be called directly since the interface between the two engines is implemented with remote procedure calls. Finally, there is an interface to the components of the virtual world through which the user can interact with the network.

Within the medium of this article, only the visualization and navigation facilities of the prototype can be shown. Some control facilities that allow GRABbing and MOVEing of entities such as VPs have also been implemented. Figure 9 shows a view of the network's physical topology. Nodes are presented as spheres, links are presented as thin cylinders, and labels are presented as 3D text. The 3D mouse can be used to manipulate the network or camera to obtain a better view. The mouse's 3D position and orientation dynamically determine the position and orientation of the object being controlled. An additional button on the side of the mouse serves as a "clutch" that allows the user to translate and rotate objects relative to their previous position and orientation.

The 3D mouse can be used to select a node or link to be examined in more detail. For example, the user may view the VPs inside a physical link, or complete VP from source to destination. In Fig. 10, the user has selected one specific VP to be examined. The thin cylindrical link representation of the physical topology view is replaced with a thick cylindrical link, and the VP is shown as a cylinder contained within the link. The diameter of the VP is proportional to its capacity with respect to the diameter and total bandwidth of the link within which it is contained. The view shown in Fig. 10 also illustrates the MOTIF framework presented to the user. For each view of the network, the main window is supplemented with others that present additional context-dependent information and controls. In the view of the VP, one such window shows the capacity of the VP in terms of a plane defining the maximum number of calls of each traffic class that can be accommodated inside the VP. The current load can then be shown as a point inside the cube containing this plane.

In Fig. 11, the user has zoomed to observe the VP within one link in its route. Supplementary windows show the route taken by the VP within the switching nodes at each end of the link.

If the user chooses to examine a link in detail, all VPs associated with a selected link can be displayed, as shown in Fig. 12. This view shows how the relative sizes of the VPs can be observed, and how the user can get a quick indication of how much of the total link bandwidth is utilized. A further zoom operation takes the user inside the link, as shown in Fig. 13, from where the individual VPs can be examined in more detail. From this position, it is possible to grab individual VPs, for moving or more detailed inspection, for example. A zoom from this position would take the user inside a VP, from where the individual calls, or even cell-level operation, could be examined.

Although the prototype described here operates in a mock networking environment, it has proven valuable in demonstrating the power of the concept of management through high-level primitives. Further, the design of the network emulator has provided valuable insight into a number of aspects of the management structure, such as the organization of objects in the D-plane and the correct choice of high-level primitives and their parameters, that will guide the construction of the management system for a real network. The transition to such an environment, exploiting the ideas outlined earlier, is a work in progress in the COMET group.

Summary

Although network management is usually considered as operating on a slow time scale, the complexity and speed of broadband networks will demand more powerful and responsive management environments. We have described the type of environment that we consider to be appropriate for this purpose, incorporating high-level management primitives that allow the manager to monitor and control the network in a natural way, and outlined the issues to be solved in realizing such a system. A prototype of this system, based on a network emulator and a user interface with 3D input and output capabilities, has been built, and the design and implementation of a system that will operate in a real networking environment is in progress. For this purpose, we are investigating extensions to the OSI management architecture that allow distributed processing among intelligent entities within the network, and high-speed interaction between a manager and the managed objects inside the network. We feel that it is quite possible to make these extensions without changing the fundamental definitions or principles of the OSI model. The main area for attention is in defining more powerful objects, and cooperating groups of objects, in the MIB, together with agents suitable for interfacing between the manager and such objects.

The use of virtual-world technology for the human interface to a management system is a natural progression from textual and 2D graphics displays. It essentially brings high bandwidth directly to the user. To complement this advance, it is necessary to build management systems that can also deliver this bandwidth to and from the system being managed. Independent of the choice of interface technology, progress in this area is required in order to cope with the scale and speed of broadband networks.

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■ **Figure 9.** *View of physical topology.*

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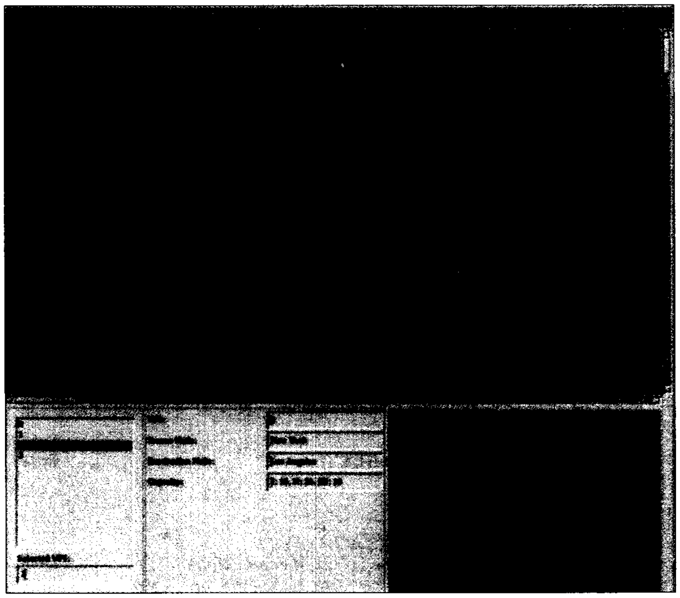
Biographies

LAURENCE CRUTCHER [M'90] received B.Sc. (1985) and Ph.D. (1989) degrees from the University of Bristol, U.K., where he conducted research on computer architectures for the implementation of communication protocols and lectured in the fields of computer architecture, real-time systems, and communication systems. In 1989, he joined Hewlett Packard Laboratories, where he worked in a number of areas in the network technology group, including work on protocols for high-speed networks and carrying real-time traffic over the Internet. In 1992, he joined the Center for Telecommunications Research at Columbia University, working on network control and management for large gigabit networks. He is currently employed as a research scientist with Market Vision Corporation, New York City. His e-mail address is: laurence@mvision.com.

AUREL A. LAZAR [F'93] has been a professor of electrical engineering at Columbia University since 1988. His research interests span both theoretical and experimental studies of telecommunication networks and intelligent systems. Theoretical research he conducted in the '80s pertains to the modeling, analysis, and control of telecommunication networks. He formulated optimal flow and admission control problems and, by building upon the theory of point processes, derived control laws for Markovian queuing network models in a game theoretic setting. He was the chief architect of two experimental networks, generically called MAGNET. He is currently leading a research effort dealing with the foundations of the control and management architecture of future giant gigabit networks. This research pioneered the application of virtual reality to management and control of gigabit networks. He is the director of the Telecommunication Networks Laboratory of the Center for Telecommunications Research at Columbia University.

■ **Figure 12.** *Examination of link.*



■ **Figure 10.** *Examination of VP.*

■ **Figure 11.** *Zoomed view of VP.*

■ **Figure 13.** *Zoomed view of link.*