Recent advances in distributed systems and transportable software and increasing demand for better quality-of-service (QoS) control in multiservice networks are driving a reexamination of network software architectures. We established the Comet (Control, Management, and Telematic) Group at Columbia University's Center for Telecommunications Research to provide comprehensive understanding of network software architecture for the 1990s and beyond. Led by Aurel Lazar, the group encompasses more than thirty researchers including Henning Schulzrinne and Andrew T. Campbell (faculty), Rolf Stadler (research scientist), visiting researchers, and PhD, MS, and BS students.

Research focus and selected projects

We believe that the development of open programmable multimedia networks represents a key research challenge to the networking community. To address this challenge, the Comet Group has initiated several projects and international forums to promote and address the need for research on open architectures, open signaling, and network programming for ATM, Internet, and mobile networks (see Figure 1).

By open, we mean that the proposed platform must support a set of APIs for resource control and management that third-party service providers can use when developing new services. By programmable, we mean that these APIs should be "high-level" enough to allow the service specification and creation process to be carried out via a high-level programming language using distributed systems technology such as the Common Object Request Broker Architecture (CORBA).

ATM initiatives

The Comet Group's research on ATM-based broadband networks has expanded considerably beyond investigating network architectures and network control and management. New research on open signaling and telematic arises from our simple observation that the prevalent thinking in signaling and service creation dates back to the late 1960s and is based on an assumption that the "intelligence" required for service creation resides only inside the network. We find this assumption outdated and propose taking a fresh approach to the subject.

The Comet Group helped establish an international working group called OpenSig (open sig-
naling) that actively explores network programmability and next-generation open signaling technology for service creation and deployment on ATM, Internet, and mobile multimedia networking platforms. The OpenSig group meets informally every six months to exchange ideas and discuss appropriate forms of collaboration. OpenSig’s tremendous success spurred the IEEE Communications Society to sponsor a new conference on Open Architectures and Network Programming (OpenArch 98).

IETF initiatives

The Real-Time Transport Protocol (RTP), developed by the Internet Engineering Task Force Audio/Video Transport working group, is gaining acceptance as the common transport protocol for delivering continuous media over the Internet. RTP describes a data packet format and a control protocol (RTCP) that allows participants to gauge group size, establish the identities of other group members, and measure the quality of service that members receive. Relevant applications include Internet conferencing, telephony, and media-on-demand. RTP’s adoption by the ITU-T as part of its H.323, a first for an Internet standard, ensures its use for Internet telephony and LAN-based conferencing in general.

Mobile initiatives

The emergence of wireless ATM (WATM) has inspired considerable interest in applying this technology to next-generation mobile multimedia communication systems. We will need wireless extensions to broadband networks to support the seamless delivery of high-quality voice, video, and data. To this end, WATM directly extends the existing ATM network with uniformity of end-to-end QoS guarantees.

In early 1996, the ATM Forum established the WATM working group to address the challenge of providing broadband services over an air interface. The working group primarily seeks to develop a set of specifications for location management, ATM mobility, and a new 25-Mbps air interface. Participating in the WATM working group since its creation, the Comet Group has actively shaped discussions within the working group as well as in the mobile and wireless networking community at large. Our involvement in this new initiative entails tracking the development of new standards, developing software solutions that can exploit emerging techniques, and feeding our research results into the working group.

Open programmable ATM-based multimedia networking

Since Fall 1994 we have experimented with a broadband kernel called xbind. The broadband kernel is a programmable operating platform that supports the creation, deployment, and management of networked multimedia services (such as connection management, route management, admission control, and QoS mapping) and efficient resource allocation mechanisms.

We use the term “kernel” deliberately to draw a parallel between xbind’s role as resource allocator and extended machine and that of a typical operating system. The broadband kernel behaves as a resource allocator in that it arbitrates between various parties’ conflicting requests for system resources. It functions like an extended machine in providing a simplified way to access fundamental system services by abstracting away the operational complexities of service provision.

Resource allocation in xbind employs game theory models. By taking an economic (market based and game theoretic) approach in multimedia network engineering, we hope to develop solutions that provide distributed and thus scalable intelligence and decision making. The induced market dynamics should give us more efficient and fair use of shared resources. Borrowing and adapting game theory tools from economics thus addresses problems of resource allocation (such as admission control, routing, and flow control) in multiservice networks. By viewing a network as a collection of resources for which users selfishly compete, this approach yields efficient, decentralized algorithms and helps us develop network architectures that provide explicit QoS guarantees.

The players in this network economy are software agents rather than humans. Agents acquire resources such as bandwidth and buffer space from the network on behalf of applications (video, voice, data transfer). Following appropriate interaction rules, the agents’ collective actions constitute a distributed intelligence superior to that of any single controller. This lets us analyze noncooperative behavior and algorithmic strategies and design the mechanisms (rules of the game) that will ensure the desired outcomes.

Service modeling

The distributed nature of multimedia networks suggests many possible ways to distribute interactions among different binding algorithms during the service creation process. We have devised a service creation process that consists of five steps:
1. Create a service skeleton for an application (such as a virtual circuit, virtual path, virtual network, or multicast). For example, the skeleton for a virtual circuit might consist of a graph from a source node to a destination node.

2. Map the skeleton into the appropriate name and resource space, thereby creating a network application.

3. Associate (or bind) a media transport protocol to the application, thereby creating a transport application.

4. Bind the transport application to resources, creating a network service.

5. Bind the network service to the service management system, thereby creating a managed service.

As illustrated in Figure 2, we defined four general interfaces: the service factory interface, the service programming interface, the service control interface, and the service management interface. We can use the service factory interface to request the creation of a service instance. The service programming interface allows us to customize or modify the algorithmic component of the server or service instance. The service control interface is the operational interface to the service instance and allows us to monitor and manipulate service instance states during execution. Finally, the service management interface lets us monitor and control the server and set management policies.

**Advanced multimedia Internet services**

Much work remains before truly scalable transport and signaling, protocols, and teleconferencing tools are in place for Internet multimedia teleconferencing. To meet these challenges, the Comet Group will develop a protocol that performs all standard telephony signaling functions, including automatic and manual call forwarding. In addition, we must create new feedback modes for RTCP to address scaling problems that will manifest as the number of participants in an RTP session scales from hundreds to potentially thousands.

Selected projects in advanced multimedia Internet services include the following:

**Conference control tools.** Unlike other conferencing systems, Mbone and RTP are single-media tools used as application building blocks. The same audio tool, for example, can be used as an Internet telephone, an Internet group collaboration tool, an Internet radio receiver, and a receiver for media-on-demand, just by changing the surrounding control programs.

Most tools, however, currently provide rather limited control. We are building a set of tools that communicate via a conference control bus implemented by host multicast so that information generated by one tool can easily be used by any number of other tools. This will make it easy, for example, to build a shared conference roster application that shows all participants and their media rather than having each media tool display its own set of participants. We can even integrate other conference accessories, like talk timers and floor controllers, without modifying the other applications.

**Session initiation protocol (SIP).** Today's multimedia Internet conferences are announced in a global multicast directory. You cannot invite someone to a conference or a phone call short of
sending e-mail. Together with Mark Handley of the Information Science Institute (ISI), we have developed an Internet session initiation protocol (SIP) that performs all the standard telephony signaling functions including automatic and manual call forwarding, call transfer, and automatic call distribution, yet is much simpler than existing telephony signaling protocols.

In companies where most employees have access to a workstation, PC, or network computer, this protocol will make traditional PBXs obsolete because the end systems or a simple call gateway at the corporate perimeter will handle all calls. This approach is also much simpler than the computer-telephony integration (CTI) efforts that maintain a separate network for voice. Since the traditional public switched telephony network will be with us for many years to come, some researchers are investigating interoperability between the two, focusing particularly on gateway selection, billing, security, and addressing.

Real-time stream control protocol (RTSP). The network protocols and applications can be the same for all continuous Internet media, whether stored (media-on-demand) or interactive (telephony and conferencing). Media-on-demand requires additional protocols to retrieve media descriptions and control the media data flow—for example, to pause or fast-forward. We are actively involved in defining the real-time stream control protocol (RTSP) currently being standardized within the IETF.

Among its interesting properties, the protocol reuses many facilities offered by HTTP and thus can share most of the optimized code found in Web servers. It also offers most of the functionality of the MPEG DSM-CC media control suite yet is described in less than one-tenth the space. In the past, conferencing and media-on-demand were strictly separate activities. RTSP supports the integration of media-on-demand sources into ongoing conferences. We are exploring the control and management aspects of this integration.

Wireless media systems

The Comet Group’s research project on wireless media systems investigates QoS provision in mobile multimedia communication systems. Next-generation wireless and mobile communication systems must support the seamless delivery of high-quality voice, video, and data. Large-scale mobility requirements, limited radio resources, and fluctuating network conditions complicate the delivery of hard QoS guarantees in the wireless domain. To address this challenge, we are developing a QoS-aware middleware platform called Mobiware that will support multimedia applications operating over standard and wireless ATM networks.

Mobiware runs seamlessly on mobile devices, base stations, and mobile-capable ATM switches. It employs CORBA and Java technology and is designed to operate between the application and radio-link layers of future wireless media systems. Mobiware incorporates new architecture and novel adaptive algorithms to support QoS-controlled mobility, allowing mobile multimedia applications to operate transparently during handoff and periods of persistent QoS fluctuation. The Mobiware adaptive algorithms transport scalable flows, reduce handoff dropping, and improve wireless resource utilization.

We use the term “controlled QoS” to distinguish it from hard QoS guarantees offered by fixed ATM networks. Implicit in the term is the notion that flows can be represented and transported as multilayer scalable flows at the mobile device. Adaptive algorithms help scale flows during hand-
off based on the available bandwidth and an application-specific flow adaptation policy. This policy characterizes each audio and video flow as having a minimum QoS layer and a number of enhancements. Mobiware promotes the separation of mobile signaling and adaptation management on the one hand and media transport on the other.

As Figure 3 illustrates, Mobiware uses xbind and Java for signaling and adaptation management during handoff or periods of persistent QoS fluctuation. The Java Virtual Machine executes on mobile devices, base stations, and mobile-capable ATM switches and supports the dynamic execution of active transport objects. These objects constitute an active component of the Mobiware transport system called Active Transport System Environment (a-trane). This component can dispatch active transport objects to strategic network points (such as the base station) or end systems to provide value-added QoS support.

Prototyping multimedia networks

To study multimedia networks under various conditions such as different load patterns, network sizes, and management operations, we have built a platform to develop and evaluate control systems through real-time visualization and interactive emulation. The current implementation runs on an IBM SP2 parallel processor at the Cornell Theory Center, which is connected to a graphics workstation in our laboratory at Columbia University via ATM. We currently use the platform in projects that focus on real-time control, as opposed to current work of the Telecommunications Information Networking Architecture Consortium (TINA-C), which is essentially management-based with a focus on data and functional modeling.

The emulation platform consists of four building blocks: parallel simulation kernel, emulation support, real-time visualization and interactive control, and emulated system. The emulated system (illustrated in Figure 4) and the emulation support modules consist of a set of objects that communicate by exchanging messages, using functions provided by the simulation kernel. The simulation kernel controls the execution of these objects and ensures that messages are processed in the correct order. To support real-time visualization and interactive control of the emulated system, the kernel controls the progression of the simulation time, constraining it by the processor's time progression.

The module for real-time visualization and interactive control contains a graphical interface that provides 3D visual abstractions of the system state. Other selected projects in this area include the following.

Broadband virtual private networks. This research seeks to develop a communication architecture that allows the extension of a private high-speed backbone into islands of private component.
networks using a public broadband infrastructure. The management and control system of the resulting global network is independent of the characteristics of the underlying public network services. It guarantees QoS including survivability on an end-to-end basis and uses advanced techniques to manage and control the interconnections of component networks. The results of this effort apply directly to the creation of a virtual enterprise network for a large, geographically dispersed corporation.

Managing real-time services on multimedia networks. This project aims to provide high-level control abstractions to network operators. High-level controls and dynamic visual abstractions will permit network operators to effectively pursue management objectives in a high-speed multiservice environment. We have developed a management architecture to support these capabilities. It manages real-time traffic by tuning the resource controllers in the traffic control system.

We evaluated these concepts on an emulation platform that includes a management station implemented on a graphics computer and a high-performance parallel machine running the control and management systems of a large network in real time. This platform allows us to experiment with control abstractions for network operators and to monitor management operations in real time. The project's next phase will port the developed management algorithms to the xbind platform.

Software

We regularly publish the Comet Group's investigations; a complete list appears in The Comet Annual Report, available on the Web (see the "Resources" sidebar). In addition, we made our software prototypes available on the Web, where the following software can currently be downloaded:

- kStack: a user-space native-mode ATM transport layer with QoS support
- RTP: a transport protocol for real-time applications
- TREX: a telecommunications research exchange
- xbind: a broadband kernel

Summary

In the early 1990s the Comet Group developed the necessary theoretical foundations for engineering QoS in broadband networks. Today, we are developing open programmable ATM, Internet, and mobile networks that will enable new models for future network signaling, control, and management. If you would like further details, all publications, software, and information from the Comet Group appear in full on the Web.

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Resources

For general information on the Comet Group, go to http://comet.ctr.columbia.edu/
Details on open programmable multimedia networking appear at http://comet.ctr.columbia.edu/xbind/
For more information on multimedia Internet services research, see http://www.cs.columbia.edu/hgs/research/
Details on wireless media systems research appear at http://comet.ctr.columbia.edu/wireless
OpenSig documentation appears at http://comet.ctr.columbia.edu/opensig/
To find out more about OpenArch, see http://comet.ctr.columbia.edu/openarch/
Details on building open programmable multimedia networks appear at http://comet.ctr.columbia.edu/publications.html