Introduction

In the aftermath of the 1987 San Francisco earthquake, the telephone network in California was swamped with calls. Rather than crashing under the load, the phone system kept working. Not only did the system stay up, it also automatically gave preference to calls originating in California, ensuring that people in California could make essential calls. Moreover, the voice quality of those calls was indistinguishable from those placed on a more placid day.

Californians stayed in touch thanks to decades of research and development that built the smart systems that manage today’s telecommunications networks. Callers in California were able to get dial tone because various operations support systems (OSSs) were proactively managing congestion control. However, OSSs do much more than ensure the reliability of today’s telephony networks. These systems touch every aspect of a service provider’s business, both during normal operations and in extreme situations such as the California earthquake. They help design the network, handle customer orders, keep the network running at the designed reliability level, bill for the services provided, and support customer service applications. OSSs have enabled the growth of large, complex, yet cost-effective and reliable telecommunications business.

While OSSs have served the needs of telecommunications providers for many years, we are entering a period in which great changes will be required in the systems that manage our networks and network-based services. Fundamental and disruptive technologies are driving new networking applications, and these new applications are creating new demands for telecommunications services well in excess of that...
experienced by the circuit-switched voice telephony of the past decades. The systems that manage these services and the underlying network must change to handle these new applications, as well as the new load. In this paper we examine the roots of the aforementioned change and outline several Bell Labs research projects aimed at addressing these new challenges. Some of these projects have been incorporated into generally available Lucent products; others are still in their formative, exploratory stages.

The Changing Face of Telecommunications

A few years after the 1987 earthquake, a handful of researchers at CERN—the European Laboratory for Particle Physics Research—released code that enabled hypertext applications on the Internet, launching the World Wide Web. Their goal was to make information already available on the Internet more easily accessible and to make it possible to put even more information on the Net. The revolution in Web-based applications begun then is still being played out.

The explosion of the Web brought greater public awareness of the Internet, but the Web was merely the latest in a series of innovations that have characterized the spread of the Internet. Even before the Web, the Internet had been doubling every year for more than 20 years. Much of this growth has been fueled by new applications: first by FTP, e-mail, and telnet; then by Netnews; more recently by the Web and e-commerce; now by cable and other broadband access-enabling Internet telephony and video; and soon by wireless mobile applications. The engine of all this innovation is the open, distributed architecture on which the Internet is built. This architecture has encouraged individuals and small entrepreneurial firms to create innovative networking applications.

But an engine needs fuel, which in this case is the continuing, dramatic increase in bandwidth capacity. Advances in optical transmission have doubled bandwidth every year and promise to continue to do so. This growth rate surpasses the doubling of CPU speed every 18 months, which has fueled the computing revolution for the past 20 years.

These fundamental drivers are changing the nature of telecommunications. Internet applications are both computing and communications applications. As such, there is a need to manage application content in the network. Increasingly, this content is and will become more complex, requiring not only simple hosting, but also intelligent access and search mechanisms. The ways that customers interact with the network are also changing. Today’s Internet applications primarily run on traditional computers, but already hand-held personal devices that will run new mobile Web-based applications are being created. We can expect further innovation to create new, as yet unforeseen, modes of interaction with the network. Moreover, the spread of cable modems and digital subscriber lines (DSLs) promises to finally fix “the last mile” problem. We can expect new applications to arise that rely on this broadband access to the home.

Panel 1. Abbreviations, Acronyms, and Terms

- ACID—atomicity, consistency, isolation, and durability
- CPU—central processing unit
- DHCP—dynamic host configuration protocol
- DSL—digital subscriber line
- DWDM—dense wavelength division multiplexing
- FTP—file transfer protocol
- HTTP—hypertext transport protocol
- IN—intelligent networking
- IP—Internet protocol
- IPNC—IP Network Configurator
- ISP—Internet service provider
- MATE—MPLS adaptive traffic engineering
- MPLS—multi-protocol label switching
- OC3—optical carrier digital signal rate of 155 Mbs on optical facility, SONET
- OSS—operations support system
- PEP—policy enforcement point
- QoS—quality of service
- RADIUS—remote authentication dial-in user service
- RAE—real-time analysis engine
- SAE—service authoring environment
- SLA—service-level agreement
- SONET—synchronous optical network
- UWU—Understanding Web Usage
- VPN—virtual private network
and small businesses. Cable providers will also require telecommunication-level support systems to achieve telephony-like reliability for these new applications.

The proliferation of Internet usage is also driving an increased expectation for on-line access to customer service. Customers who are already on line expect to be able to obtain technical and other service support and to review bill details on line. New customer care applications must be deployed that enable this kind of customer support.

As bandwidth gets cheaper, new bandwidth-intensive applications are migrating to the Internet. These applications are leading to the convergence of voice and data networking, changing the fundamental design of the Internet in the process. The Internet was originally designed for “best-effort” service, which cannot meet the requirements of voice and video applications. New protocols and new traffic control systems will be required for these applications. A related trend putting pressure on the Internet’s traditional best-effort model is the increasing use of the Internet for business-critical applications. As businesses migrate to the Internet, they are demanding more rigorous service-level agreements (SLAs), providing another impetus for management systems that can ensure more predictable and reliable performance.

Along with more reliable service levels, customers and providers are demanding more sophisticated pricing and accounting controls. In its original form, use of the Internet was free to end users, with the actual costs being absorbed into the budgets of various research institutions, corporations, and government agencies. Initially, there was no requirement to collect usage data at the level of individual users, and therefore such data has usually been unavailable. Today’s Internet increasingly deviates from this original model. Service is provided by a variety of for-profit corporations. Furthermore, the Internet has been used to construct virtual private networks (VPNs) with complex SLAs and private “intranets” that require accounting controls. As a consequence, commercial network operators now need detailed usage data that tracks services delivered to individual users.

The rapid increase in bandwidth at lower prices, coupled with open IP-based networking, continues to fuel ongoing innovation in services. As services change, the systems that manage the services must adapt. Flexibility has been a buzzword in the design of OSSs for some time. What is new is the rapid pace of change in services to which management systems must adapt. Bandwidth is expanding faster than the rate of change in computing power, yielding an even faster rate of innovation within the Internet than that experienced in the computing industry. Management systems must be created at the same speed as the services they control.

Given the magnitude of change sweeping the telecommunications industry, we can be certain that the systems that manage today’s networks (both circuit-switched and IP-based) will have to change to meet these new demands. In the remainder of this paper, we outline various efforts in Bell Labs aimed at creating the foundations of next-generation management systems. Our review is organized by looking first at service planning, then at service assurance, and finally at service management systems. Service planning systems enable the provider to plan and build networks that can support these new services and demands. Service assurance systems manage the relationship between the customer and the service provider, including customer service and billing systems and SLA management systems. Service management systems operate and control the underlying network infrastructure and/or provide the network-level tools used in building new services.

**Service Planning**

Service planning systems encompass systems that support the technical design, service pricing, and investment decisions that are prerequisites to providing services. Not surprisingly, the twin drivers—rapid application innovation, which is driving new demand, and rapid reduction in the cost of bandwidth—are playing havoc with existing planning systems. In the next section, “Business Planning,” we look at a new approach to network investment planning that was created to address these new drivers. This approach jointly optimizes prices and investment decisions and incorporates technologically aware forecasting for equipment prices. The rapid evolution of optical
technology is enabling new approaches to the design of optical layer transport networks. In the section “Optical Network Design,” we describe a tool designed to help providers select among competing architectures.

**Business Planning**

The twin drivers of rapid cost compression for bandwidth and the innovation engine of the Internet are disrupting the long-term investment planning of carriers. It should be clear that carriers face a major tradeoff in making network deployment decisions. Rapid deployment of current systems allows a carrier to collect revenue in the short term, but it may rule out future opportunities to exploit cost savings. What may be less obvious is that carriers must improve their demand forecasting in order to optimize network deployment decisions.

The usual practice of telecommunications planners is to take traffic requirements as inputs and to produce a cost-minimizing network. Because voice applications are relatively stable and the price-demand relation for voice services is relatively inelastic, such an approach has approximated the profit-maximizing solution reasonably well. However, experience indicates that the price-demand relation for data services is more elastic. Conventional forecasting has consistently underestimated data demand. A typical history of forecasts looks like the graph shown in Figure 1. The branch, or lower, curves represent forecasts for total capacity in successive years. The topmost curve represents the actual history of traffic growth.

This consistent underestimation helps account for the continuing inability of providers to fill all the demand for data services. When technology innovation is fast, as it is in optics, and demand is elastic, as it appears to be for data services, then traditional practice will yield overly conservative deployment plans.

The Teranet planning system, described in Panel 2, offers an alternative planning model. Unlike traditional models that view future demand as externally given, the Teranet model allows demand to be determined by prices using a constant-elasticity demand function; prices are then optimized jointly with capacity investment decisions. The formulation of a constant-elasticity demand function represents current communications technology trends reasonably well. Depending on the elasticity value assumed, a carrier will adopt either a rapid or conservative deployment strategy. Our results show that in an environment of high elasticity and large reductions in the per-unit cost of technology, frequent deployment of newer systems is optimal.

These results fit well with existing practice in the industry. For voice networks, where demand elasticity is low, price reductions do not increase revenues. Under such conditions, the main objective of network planners is cost reduction. Cost consciousness leads to using legacy equipment for a sufficiently long time to allow the service provider to spread costs over many years, thereby lowering unit costs. Without a revenue incentive, the time to consider lower-cost equipment is at the end of the useful life of legacy equipment. This fact explains the traditional 10- to 25-year lives of circuit-switching equipment.

Conversely, when elasticity is high (1.3 or greater), price reductions yield a revenue reward sufficiently large to justify investment in new equipment almost every year. The notion of a shorter economic life becomes more significant than the longer useful life of the equipment.
Optical Network Design

With the advent of dense wavelength division multiplexing (DWDM) hardware and optical cross connects that enable efficient switching at the optical layer, network providers face new tradeoffs in the design and deployment of core transport optical networks. In particular, differing restoration strategies can present dramatically different costs for network construction and operation. The Spider design tool provides alternative next-generation optical network designs that differ in cost, robustness, restorability, and reconfigurability. Network providers can sort through these alternatives and select network designs that best meet their objectives.

The Spider tool produces a series of optical layer network designs for routing and wavelength assignments among nodes in the network. For each architecture, the tool minimizes the fiber capacity and the
number of wavelength cross connects. In some designs, wavelength conversion is allowed everywhere in the network, while in the remaining architectures, wavelength continuity is assumed. Even for the designs with wavelength conversion, the tool favors solutions that maximize wavelength continuity in order to minimize the number of converters. In the current version, the tool takes as input the capacity demands and load estimates in terms of wavelengths between locations in the network and produces designs that vary according to the restoration architecture. Future work will integrate the Spider tool and the demand forecasting capabilities of the Teranet planner to enable more flexible demand modeling.

The most costly architectural option provides the fastest restoration, as well as flexible reconfigurations and 100% protection. In this design, each demand between a source and a destination is serviced by an active path and a path providing “dedicated protection.” These two paths traverse disjoint sets of links and nodes. The use of completely disjoint paths ensures that, in the event of a single failure affecting the primary path, the protection path is not affected. The design maximizes bandwidth utilization and can yield restoration times in the tens of milliseconds, but at the cost of a 30 to 40% reduction in capacity.

At the other end of the spectrum, a fully shared restoration architecture relies on a mesh network architecture to connect all the nodes in the network, thus allowing restoration capacity to be shared among all nodes. Such a design will have slower restoration times but the highest capacity utilization. Moreover, restoration on a fully mesh architecture is operationally more complex. In such an architecture, a preplanned reconfiguration map may be generated and stored at each node. The map provides an optimized set of restoration routes that can be used in the event of failure of a normal route. This map must be updated whenever the network topology changes and, equally important, when new demands are added to the network. Distributed implementations of mesh restoration with low computation and storage requirements are also reaching performance parity with centralized implementations. These schemes would be appropriate for light path circuits with lower than premium—that is, with best-effort—recovery requirements.

A third alternative, partial sharing of optimally designed logical rings, yields better capacity utilization than the fully dedicated designs, at the cost of modestly increased restoration times. This architecture groups node pairs into logical rings, each of which carries no more than a predefined number of wavelengths for active as well as protection wavelengths. Active paths are defined for all node pairs on the ring, and protection wavelengths are reserved in the complementary routes for each node pair. Non-overlapping demands on the same ring can share protection wavelengths.

Service Assurance

Service assurance systems manage the interaction between the customer and the provider regarding the services for which the customer has contracted. These systems include traditional applications, such as billing and customer care, but they also cover new applications, such as those that ensure that contracted service levels are achieved. As customers migrate online, existing care and billing systems are changing radically to support new modes of interaction with the customer. Similarly, as businesses rely increasingly on the Internet for e-commerce, internal mission-critical applications, and VPNs, they are demanding higher reliability and more consistent service levels. In the first three sections below—“Web-Based Customer Care,” “Network-Based Call Centers,” and “Knowledge Discovery”—we discuss several research projects aimed at supporting new kinds of customer service. In the remaining three sections we review work directed at providing and supporting more rigorous service levels.

Web-Based Customer Care

Coincident with the spread of e-commerce is the need to redefine customer care strategies and systems. E-commerce customers are, by definition, online and expect online care. However, early experience indicates that solely Web-based customer care systems are not in themselves sufficient. Customers want and expect to be able to interact with a live agent. Stair 9, whose architecture is shown in Figure 2, is a Web-based customer care system that enables direct customer-agent interactions.
The system operates with standard off-the-shelf browsers and hardware. It supplements an enterprise’s Web pages by enabling chat sessions between the customer and the customer service agent. The system automatically synchronizes browsing between the agent and the customer, which allows the agent to direct the customer to the appropriate Web pages for answers to questions and for additional information.

Along with providing on-line interaction between agents and customers, the system supplies routing capabilities to match customers to available agents. Routing decisions can be used both to avoid queuing delays and also to pair a customer to the agent with the best skills match for that customer’s queries. The system can manage multiple queues across multiple customer care sites simultaneously.

**Network-Based Call Centers**

As more customers migrate to e-commerce and its associated on-line care systems, providers face the need to offer both on-line and traditional telephony-based customer care. Looking to the future, it will be some time before all customers migrate to the on-line world, and some will want to use both on-line and traditional means of interacting with their suppliers. As a result, companies will face the need to provide telephony-based care and on-line care for the foreseeable future. In a desire to launch quickly, early e-commerce entrants typically have tended to establish separate care centers for on-line customers. As e-commerce matures and becomes more fully integrated with the existing enterprise, companies will want to integrate on-line and traditional voice-based care systems. The network call center, shown in Figure 3, provides the network routing support to enable this kind of integration.

The system integrates routing of both Web-based and telephone-based access to integrated customer care call centers. It provides high-level rules to specify routing decisions, and it supports customer relationship management-based routing and advocate routing algorithms. Access to local, on-site care centers and to remote agents is supported. The system provides fully Web-based administrative tools for specifying routing and for collecting and reporting on call center data.

![Figure 2. Stair 9 architecture.](image-url)
Knowledge Discovery

The advent of the Web makes available a tremendous amount of information for analyzing customer behavior, but the sheer volume of the data makes meaningful analysis extremely difficult. Traditional data mining techniques are of limited utility in dealing with such data, because the amount of genuine information is small relative to the total amount of data that must be analyzed. The Bell Labs Customer Data Analysis team has devised various techniques that have proven effective for extracting a weak signal from a large amount of information, where the information is generally buried in huge heterogeneous, incompatible databases. In the past, these knowledge discovery techniques have been applied to such diverse problems as real-time scoring for fraud control and customer profiling for retention. These techniques are now being extended to the analysis of on-line information.
For example, the Understanding Web Usage (UWU) project has applied techniques similar to those used in fraud control and customer retention to the problem of analyzing user Web sessions. UWU takes users’ click streams as input and annotates Web pages with the analysis results. Various visualization techniques enable Web designers to understand exactly how users interact with their site; this information can then be used to improve site design. Because the techniques support real-time analysis, dynamic customization of pages in response to users’ navigation is also possible. Similarly, these techniques can be integrated with Internet-based call centers, such as Stair 9, to support routing of calls to agents. The agents can be provided with the click stream history of a user’s session.

Service-Level Agreements

Traditionally, network design and capacity planning tools have been independent of the systems that provision and control the network. Design tools helped designers lay out the network topology, select network elements, and determine link capacities, but other unrelated systems managed the deployment and provisioning of the network elements. This separation is no longer feasible for providers who wish to support VPNs that specify quality of service (QoS) guarantees. These VPNs run on a shared IP infrastructure, so service providers must now plan for the allocation of these shared facilities to meet SLAs. Coupled with the resource allocation problem is the need to produce an associated routing design that must be propagated to the network elements. Once provisioned, the network must be controlled to ensure that, to the extent possible, SLAs are achieved.

The VPNStar system integrates the design and provisioning of VPNs. First, VPNStar translates the QoS characteristics of an SLA into a set of flow specifications, which specify attributes such as end-to-end delay and loss rate. The system then verifies that the network can accommodate the SLA and, for each demand, it generates QoS-aware routes and allocation of resources (that is, bandwidth and buffers) along the routes. As part of the provisioning process, the system also communicates with the network elements and—in networks with multi-protocol label switching (MPLS)—it sets up the explicit routes.

To ensure compliance with the provisioned SLAs, the MPLS adaptive traffic engineering (MATE) system performs automated real-time load balancing across the routes that VPNStar has designed. The system relies on a set of real-time probes to determine the state of the network. This probe data is useful for detecting both fault conditions and traffic congestion. MATE processes the probe data to measure congestion in alternate explicit routes for common ingress and egress points and then uses these measurements to distribute flows on the routes.

Revenue-Aware SLA Management

The challenge to today’s operators is to provision and meet QoS-based SLAs. Once providers can confidently do so, we expect they will want to optimize their traffic management to take SLAs into account. For example, when SLAs cannot be met, traffic congestion controls should minimize penalties and maximize revenues when deciding which traffic to admit. The D’ARTAGNAN system proposes a template for defining SLAs and an associated control system that optimizes net revenue for these SLAs. The system is design assisted, real time, and measurement based, as illustrated in Figure 4.

The SLA template stipulates offered and carried bandwidths for each stream. The ratio of the load carried to the aggregate load offered is the contracted flow acceptance ratio for each stream. Tacit to SLA crafting must be an appreciation of the fact that, as this ratio approaches unity, the corresponding amount of network resources that must be made available approaches infinity. Revenues are earned for all bandwidth that is carried. If the customer is requesting an amount of bandwidth less than the contracted offered load, then the carrier is expected to carry the fraction of the offered load proportional to the flow acceptance ratio. If the monitoring process indicates that this obligation is not being satisfied, then the service provider is “non-compliant” and every lost flow contributes to the penalty for the stream.

Similar to the operation of VPNStar and MATE, the D’ARTAGNAN system includes design, provisioning, and control processes. The design system decides which SLAs the network can handle and generates routes and trunk allocations appropriately. This data is automati-
cally passed to the network for use in routing and admission control. The design data is supplemented by near-real-time measurements that determine whether a particular route is undersubscribed or oversubscribed. New flows are preferentially allocated to under-subscribed routes in accordance with a resource management concept known as “virtual partitioning.”

**IP-Based Billing**

Being able to craft SLAs, design and provision the network to support them, and then control the network to ensure that the service levels are achieved is not sufficient. Clearly, providers also need to be able to bill for these service-level guarantees. If providers are to bill for these service levels, then customers will expect to see detailed accounting that verifies the promised levels of service were indeed delivered. Both billing and reporting require detailed usage collection within the network.

The Internet, however, originally designed as a research network, lacks standards for collecting detailed usage records. Moreover, there is no mechanism for mapping usage to individual users. Creating such a mechanism poses three key problems:

- Handling the huge volume of events (either packets or flows),
- Associating usage with the users that generated it, and
- Providing detailed measurements of the service type and quality that individual users received.

In general, there is an important tradeoff between the first two problems. In particular, some accounting systems reduce data volumes by aggregating within the network, based on IP addresses. However, IP addresses are often assigned dynamically. As a result, these systems may inadvertently combine usage from two or more different users, thereby making it impossible to perform accounting at the level of individual users. This fact suggests that, in order to achieve effective aggregation within the network as well as to retain detailed usage data for individual users, traffic must be associated with users within the network before it is aggregated.

The NetCounter, described in **Panel 3**, is a special-purpose in-network device designed to address these problems. The NetCounter can operate as a passive “sniffer” of packets or as an active network element (that is, a bridge). In either case, the NetCounter is transparent to other devices at levels 2 and above. Transparency is important since it makes it possible to install and uninstall NetCounters without introducing transit subnets or reconfiguring adjacent switches and routers. The key innovation in the NetCounter is its ability to associate packets immediately with the individual users that generated them within the network.
The Problem
Gathering usage data for individual users in order to perform detailed accounting and to verify adherence to SLAs.

Challenges
The challenges that exist in gathering this type of usage data include:
- Contending with a huge volume of events (packets or flows),
- Properly mapping usage to the users that generated it in the face of dynamic assignment of IP addresses, and
- Measuring the service levels and quality that individual users receive over multi-service networks.

Solution
The solution to this problem is the NetCounter, shown in Figure 5, an in-network accounting device that sits on the network between the user and the backbone and associates each packet with a user. Software authentication monitors resident in authenticating servers, such as dynamic host configuration protocol (DHCP) or remote authentication dial-in user service (RADIUS) servers, notify the NetCounter when users log in and are assigned a new IP address. This data enables the NetCounter to map dynamic IP addresses to actual users. The NetCounter also:
- Performs in-network aggregation to reduce the volume of data that must be processed;
- Collects data such as jitter and delay to measure quality-sensitive and time-sensitive services; and
- Collects raw usage data, such as counts of bytes, packets, or flows.

Results
The NetCounter’s initial PC-based implementation, which is fast enough to keep up with fully utilized, full-duplex Fast Ethernet links, will handle up to OC3 networks. A line-card version of the NetCounter is under development for line-speed packet processing in hardware to scale to larger and faster networks.

The NetCounter generates between two and four orders of magnitude less usage data than flow-logging systems. In-network aggregation varies significantly with the data collection interval (by as much as two orders of magnitude), implying that network designers can trade off between aggregation and frequency of data collection.

Latency is increased by between 50 and 60 µs, which is comparable to (or slightly less than) the latency introduced by an Ethernet switch and 1/4000th of the 200-ms end-to-end latency generally considered acceptable for IP telephony.

Further Refinements
The next step in the evolution of the NetCounter will be to integrate it with VPN provisioning and billing systems to provide an end-to-end VPN solution.

Panel 3. NetCounter: Collecting Detailed Usage Records from IP-Based Networks

User
POP network
RADIUS
M
DHCP
M
User/IP address association sent to NetCounter(s) when user logs onto network

User

NetCounter
Packets associated with users within the network

Figure 5. The NetCounter dual-ported accounting device within an IP network.
This allows substantially more aggregation to be done, without losing user-level accounting information. NetCounters can also record other useful measurements of service type and quality, in addition to counts of packets, bytes, and flows.

**Service Management**

Service management systems keep the network running and provide network-level building blocks for advanced network-based applications. Because these systems manage the underlying infrastructure, it is not surprising that many of the trends outlined at the beginning of this paper are driving the creation of new service management tools. For example, the increased role of content and computing in networking applications is reflected in the IPWorX™, NetBlitz™, and QTM™ projects, discussed below in “Content Management,” “Accelerated Access to Web Content,” and “Real-Time Transaction Processing.” The need for greater reliability in IP-based networks and the requirement that management systems themselves be flexible and easy to change underlie work on the IP Network Configurator (IPNC), discussed in “Router Configuration,” and on the Policy-based IP Network Monitoring System, described in “Network Monitoring and Control.”

**Content Management**

There are numerous issues associated with the advent of content-rich communications applications. These issues span requirements more traditionally aligned with computing—for example, managing server farms either in the network or remotely at customer sites—to those more clearly associated with traditional networking—for example, managing the location and distribution of content sites within the network to optimize access and network throughput. The IPWorX solution addresses the latter problem, optimizing content distribution.

While bandwidth is becoming cheaper, it continues to be a scarce resource. Service providers are struggling to cope with the explosion of Internet usage, even while they are worrying about more bandwidth-intensive applications to come. One way of dealing with bandwidth scarcity is to cache content closer to users, thereby reducing the bandwidth needed to distribute the content to its users. Existing enterprise caching products do not provide for sharing among caches. Users are assigned to a particular cache, and if the information they desire is not there, then a network query must be made to obtain it. Such schemes fail to exploit the great amount of information available at the cache sites to optimize content distribution to caches within the network.

The IPWorX system, illustrated in Figure 6, solves both of these problems by supporting a distributed network of caches under centralized control. A central component of the IPWorX architecture is the WebDirector, an intelligent layer 4/7 switch. The WebDirector automatically routes users to the nearest cache most likely to contain the information requested, thus ensuring that cache resources are fully utilized. The central switch is controlled by a management and control system called the IPWorX WebController. This controller performs continuous analysis of cache load and traffic patterns to identify “hot” sites and content. It achieves optimal load balancing for hot sites by performing a nonlinear optimization on the actual usage data measured by the distributed caches. The Activator module of a WebController checks for modification of hot pages, fetches them from the origin servers if they are modified, and pushes them to the relevant WebCaches. Measured against industry standard benchmarks, IPWorX intelligent caching achieves a 40 to 70% improvement in response time when compared to stand-alone caches. The IPWorX caches can also sustain 25% more network traffic load than stand-alone caches, thus reducing the cost of deploying caches within the network.

**Accelerated Access to Web Content**

As the volume of data transferred over the Web has grown, networks and servers have often become overloaded, resulting in painfully slow response times. Response time is often so poor that the Web has been dubbed the “World Wide Wait” by the popular press and others. Slow downloads are particularly trying for dial-up users, most of whom use low-bandwidth modems to connect to the Web and therefore also have to wait while data is transferred over this slow connection. One of the primary causes of the Web's...
performance bottleneck is the growing popularity of byte-intensive data types, such as images. Images are used not only for page decoration, but also in advertisement banners to make products attractive. Various surveys have shown that images account for more than 70% of the traffic on the Internet. Clearly, accelerating the delivery of images would minimize browsing delays considerably. This is exactly what the NetBlitz system does.

The aim of the NetBlitz system is to eliminate browsing delays by delivering data customized to the client’s desired preferences. Images are compressed to use fewer colors (for example, 8-bit rather than 24-bit color) and lower resolution, with the degree of compression controlled by the user. The NetBlitz system performs semantic compression “on-the-fly.” This technique significantly reduces the size of images (in number of bytes), thereby speeding up their download considerably, with a negligible loss of quality.

The NetBlitz system is a proxy-based solution designed as a “plug-n-play” application. It requires no
changes to the browser, Web server, proxies, or any protocols such as HTTP. Figure 7 shows the default architecture of the NetBlitz system. Briefly, it functions as follows. On receiving a request from the client browser, NetBlitz gets the document from the Web server via the Internet if it is unavailable in the cache. Next, the NetBlitz system performs resolution reduction and delivers the preferred lower-byte image to the client. All these actions take place on-the-fly and are transparent to the user.

The NetBlitz system has obvious benefits for the end user in reduced waiting times. For example, using a 56-KB modem to read the home page of one of the Fortune 100 companies takes, on average, 37.6 seconds. Using NetBlitz cuts the download time to 22.7 seconds, a savings of 40%. Of course, this improvement in download speed means that fewer bytes are being transferred to the user. For Fortune 100 home pages, NetBlitz reduced the number of bytes transferred by 50%. This reduction in traffic means that Internet service providers (ISPs) or enterprises that install the NetBlitz system also benefit by this reduction in the volume of traffic.

**Router Configuration**

IP systems were first used in sophisticated research environments. In these environments there was little demand for tools that simplified administrative tasks or made them resistant to errors. Despite the size and importance of IP-based networks, there is still little attention paid to making administrative tasks easy to perform and hard to get wrong. As IP-based networks move into mainstream telecommunications operations centers, it is essential that operations personnel be able to handle these tasks reliably.

As an example, configuring routers is a poorly automated and highly error-prone process. Routing changes are made to the live network, and it is nearly impossible to “test” router updates before deploying them. The IPNC solves this problem by automating the job of provisioning routers. Using IPNC reduces the task of configuring routers from hours to minutes. More importantly, the system uses a network model to detect errors before routing changes are deployed into the network, thus reducing errors that occur when routers are configured manually. The system allows both subnets and individual network elements to be configured. Once a configuration has been verified, the system generates the router-specific commands necessary to update the routing tables. IPNC knows how to configure most popular routers and therefore can be used to configure a heterogeneous network.

**Network Monitoring and Control**

Modern networks are increasingly complex, heterogeneous, distributed systems that must support rapidly changing applications and traffic patterns. Monitoring such networks requires flexibility in two dimensions: The monitoring code must be device and protocol independent in order to manage heterogeneous networks, and the monitoring logic must be easy to modify in order to cope with sudden changes in traffic or to manage unique application-specific functionality. The Policy-Based IP Network Monitoring System, distributed with the Lucent Softswitch, is an example of this kind of flexible monitoring and control system. Built on the Directory-Enabled Policy Server, the monitoring system allows service providers to monitor for complex events and take corrective action when problems occur.
The Policy-Based IP Network Monitoring System provides a high-level declarative language for specifying complex events using logical and temporal composition. Events such as congestion or switch overload can be quickly detected, and appropriate corrective actions can be launched to resolve the problem. Because the system is a pure software solution, new events can be added to handle new requirements and to respond to new conditions. The use of a formalized event specification language allows the system to analyze policies to determine their execution complexity before loading them into a running network.

Events are stored in a centralized directory and downloaded into policy enforcement points (PEPs) distributed throughout the network. Each PEP includes a device mapper that maps events into device-specific monitoring and control code for the individual network elements, thus enabling device independence. These device servers allow monitoring of multi-vendor networks using existing administrative interfaces.

Real-Time Transaction Processing

Since the advent of intelligent networking (IN) services in the 1980s, telecommunications systems have required real-time transaction processing during call setup. IN calls are routed through the network based on a database lookup that maps a dialed number to a physical phone. The increasing use of toll-free numbers and call forwarding—along with the advent of debit-based billing, local-number portability, and the popularity of wireless systems with roaming capabilities and follow-me services—are causing a rapid increase in the proportion of calls that require number translation, redirection, or other transaction services. As voice and data networks converge, these applications (and their associated need for real-time event handling) must be moved to the converged network. Moreover, Internet-based services increasingly have their own requirements for transaction processing at session initiation, such as route selection based on customers’ profiles regarding QoS guarantees.

Because these transactions are handled during session startup, they must be performed in real time and may consume at most a few milliseconds. Conventional database technology—in which the costs of invoking a high-level database operation over a client-server interface or the costs of a single access to secondary storage can account for hundreds of milliseconds—cannot meet the requirements for real-time applications. Instead, most telecommunications applications have relied on custom databases to meet these high performance requirements.

Of course, custom solutions are expensive to build and tend to be inflexible. The QTM real-time transaction processing system is a general-purpose event-processing system developed to strike a balance between the performance benefits of custom databases and the flexibility and maintainability of conventional database systems. At the heart of the QTM system is the DataBlitz™ main memory storage manager, which offers transactional access to persistent data at main memory speeds. QTM retains many features of conventional database systems, including a high-level, declarative programming interface and the correctness properties of atomicity, consistency, isolation, and durability (ACID) for transactions. These features enhance the reliability, robustness, usability, and maintainability of both the QTM system and the applications built on it.

The QTM architecture consists of two primary entities aimed at achieving the required performance and flexibility. The real-time analysis engine (RAE) provides a fast, in-memory data store, while the service authoring environment (SAE) supplies the tools needed to allow service providers to design and build applications to run in the RAE.

The QTM system allows multiple RAEs to work in parallel. Each RAE has its own CPU, its own memory, and its own instance of the memory store (with its own recovery log). Every memory store table is either replicated across all sites or partitioned across sites. This shared-nothing approach to parallelism harnesses the aggregated memory and CPU resources of several machines. Shared-nothing parallelism is well suited to real-time, “rifle-shot” transaction processing, allowing nearly linear scale-up of throughput.

Additional speed is gained because the QTM system is not a client-server system in the traditional sense. Instead, application-specific services and the RAE execute within the same process address space. Moreover, the QTM system does not admit ad hoc
queries, so all the costs of selecting a query plan are incurred once, statically. The safety of the application code sharing the RAE process space is guaranteed by the use of the SAE. The SAE provides high-level, declarative programming tools that can validate event handlers statically and compile services in a way that either avoids or handles possible error conditions.

**Continuing Change**

In this paper we have outlined various efforts under way within Bell Labs to provide some of the building blocks for next-generation communications management systems. As should be clear from the breadth of the efforts described, the revolution in communications is having a profound impact on the systems that manage today’s networks, whether they are circuit switched or IP based. Looking further into the future, we can see that communications systems are just embarking on a set of changes that will continue to transform our networks, the systems that manage them, and the applications that run on them.

The current revolution is largely fueled by rapid increases in bandwidth. When coupled with open networking protocols, these rapid increases are enabling an innovation pace that exceeds the remarkable innovation stream that has characterized the computing industry for the past 20 years. At times it seems that the industry has its hands full just responding to these new applications and the resulting new demands for service. However, as this bandwidth-fueled revolution continues, the communications industry will face a continuous stream of rapid change.

In particular, the reality of “living on Internet time” will spread to larger and larger segments of the industry. The kind of time compression that characterizes telecommunications today is having profound impacts—from investment life, to development and deployment intervals, to customer expectations for rapid response to inquiries, to requests for new services, and even to billing cycles. As we look towards the future, we can see two primary consequences of this time compression that call out for better solutions.

First, the rapid pace of change means that we must design systems and networks for replaceability. As we saw earlier, in “Business Planning,” even the network itself is facing more rapid obsolescence, with advances in technology and increases in demand justifying replacement of network elements as frequently as every 3 to 5 years, instead of the more traditional life span of 10 to 25 years. Similarly, the industry will need some mechanism for retiring old applications and replacing them with new ones. The current telecommunications tradition of maintaining existing features and applications beyond an economically viable life will become increasingly untenable as the number of such applications proliferates.

A subtler, but perhaps more pressing, need is the ability to contend with the design pressures inherent in the time compression being experienced. It is not surprising that the extreme time-to-market pressures that characterize the Internet industry all too often lead to design compromises. Such compromises often yield applications that are either hard to scale, hard to make reliable, and/or hard to evolve. To see the effects of these design shortcuts, we need look no further than the ever-present and well-publicized examples of crashed Web sites. In their rush to market, many sites have experienced problems, ranging from an inability to handle the volume of traffic to unreliable system architectures that were not resilient in the face of inevitable hardware failures. Even though these sites had problems, they met their time-to-market goals and in many cases achieved important business objectives. What is needed are architectures and components that will let the industry marry the robustness of traditional communications applications to the speed of development that has characterized the spread of Internet applications over the past decade.

Another fundamental shift taking place, but not yet fully digested, is the impact of integrating back-end systems (billing and customer care) with the network. Traditionally, both data- and circuit-switched network service providers had fairly complete isolation between the network and the support systems with which customers interacted. At worst, customer orders could be taken and provisioned manually, and customers would wait to see the details of their usage at the end of the billing cycle. Increasingly, services are provisioned on line directly by customers, who demand (nearly) instant access to their usage records.
so they can proactively manage their communications expenses. Moreover, the need to open up “back-end” systems directly to customers goes beyond service providers. Every enterprise that launches an e-commerce site is a service provider and, as such, it will face this same need to integrate account management and fulfillment systems with its e-commerce applications. However, making back-end systems part of the customer experience has profound implications. Back-end systems now must operate in a 24 × 7 mode, with the same reliability and ease of use that are expected from the network services themselves. The systems must be kept 100% current with the deployment of new services; it is no longer possible to rely on manual patches to work around missing system support. Security can no longer be assumed, as it has been in the past, just because the systems run unconnected to the outside world. The industry is only beginning to deal with these implications.

A related trend is the increasing demand by customers to control their interaction with the network. They want to self-provision in order to control the speed with which changes are made to the network. They expect to be able to monitor compliance with service levels themselves. They want to dynamically switch between pricing alternatives to ensure that they are obtaining the best possible price for their current usage. Essentially, customers will expect to be able to share in the active management of “their part” of the network. Management systems will have to be designed to give end customers access and control over parts of the network, while protecting it from unauthorized changes.

The end result of these changes will be that there is no end in sight. Innovation in network-based applications will continue and with it will come demand for new systems to manage those applications. This is perhaps the greatest challenge of all: the need to build systems that can grow and change with the networks and applications they support.

Conclusion

In this paper we have outlined a number of research projects undertaken within Bell Labs that address the needs of next-generation management systems. Existing telecommunication management systems face enormous challenges unleashed by the combined effects of the innovation engine of the Internet, coupled with the rapid and continuing decrease in the cost of bandwidth. These fundamental forces are changing the nature of telecommunications.

The rapid expansion of bandwidth and the effects of Internet-fueled demand have a direct impact on network planning systems. Among the projects at Bell Labs that will help providers plan in the face of these changes are the Spider DWDM design tool and the Teranet long-range investment, pricing, and technology planning system.

Increasingly, networking applications are computing applications, requiring new facilities to manage content and new building blocks to support network-based applications. The IPWorX content distribution system, the NetBlitz system, and the QTM real-time transaction processing system are examples of some of the Bell Labs work addressing these issues.

As customers migrate on line, new service models are required. Similarly, once customer interactions are on line, there is more data available that, properly analyzed, can lead to improved customer service. Bell Labs projects providing these new capabilities include the Stair 9 Web-based customer care system, the network-based call center, and the UWU project.

As the Internet enters the mainstream, customers are requiring a greater level of both reliability and service assurance. A number of projects at Bell Labs are designed to help bring greater, more predictable service levels to IP-based networks and applications. In this paper, we described several such efforts, including the IPNC, which automates router configuration; the Policy-Based IP Network Monitoring System, which monitors complex, heterogeneous networks; VPNStar, which designs and provisions QoS-based SLAs; MATE, which performs traffic engineering to support SLAs; D’ARTAGNAN, which enables revenue-aware SLAs; and the NetCounter, which supports the detailed usage accounting required to bill for service assurances.

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DEBASIS MITRA, director of the Mathematical Sciences Research Center of Bell Labs in Murray Hill, New Jersey, holds a Ph.D. in electrical engineering from London University. Dr. Mitra is currently directing work in traffic engineering for IP and ATM networks and has collaborated in developing new scalable analytic techniques and incorporating them in the TALISMAN and VPN DESIGNER software packages. For some time his interests have been focused largely on broadband networking, in the areas of statistical multiplexing, feedback-based flow control, admission control, service scheduling, and traffic shaping for data networks. Dr. Mitra has been the recipient of awards given by the Institution of Electrical Engineers, the Bell Labs Technical Journal, and the ACM Sigmetrics/Performance Conference; he also received the Steven O. Rice Prize Paper Award and the Guillemin-Cauer Prize Paper Award of the IEEE and is co-recipient of the IEEE Eric E. Sumner Award. A Bell Labs Fellow and an IEEE Fellow as well, Dr. Mitra has been a member of the editorial board of the IEEE/ACM Transactions on Networking and is currently a member of the editorial boards of Queueing Systems (QUESTA), Performance Evaluation, and the Journal of High Speed Networks.

KENAN E. SAHIN is president of Kenan Systems, a subsidiary of Lucent Technologies in Cambridge, Massachusetts, and vice president of software technology for Bell Labs. He earned a B.S. from the Massachusetts Institute of Technology in Cambridge and completed his Ph.D. at the MIT Sloan School of Management, where he received fellowships from Sloan and the Ford Foundation. Dr. Sahin’s doctoral work and subsequent research led to worldwide patents in areas relating to computer communication networks and massively parallel computation. A member of the board of trustees of MIT and recognized for significant achievements in scholarship and teaching at Harvard University, MIT, and the University of Massachusetts, Dr. Sahin was the recipient of the Clark Scholarship, the MIT Sloan School Salgo Noren Outstanding Teacher Award, and the Harvard University Teaching Award. He also received the Ernst & Young New England Entrepreneur of the Year Award in software, and in two consecutive years he and Kenan Systems won awards for “Most Innovative Product” and “Best Contributions to the Billing Industry” from the Institute of International Research.

RAVI SETHI is vice president of Communications Sciences Research at Bell Labs in Murray Hill, New Jersey. He earned a B.Tech. degree in mechanical engineering from the Indian Institute of Technology in Kanpur and a Ph.D. degree in electrical engineering from Princeton University in New Jersey. Before joining Bell Labs, Dr. Sethi was a faculty member of the Computer Science Department at The Pennsylvania State University in University Park and then a professor at the University of Arizona in Tucson. For his technical contributions to compilers and programming languages, he received a Distinguished Member of Technical Staff award early in his career at Bell Labs, and recently he was named an Association for Computing Machinery Fellow. A co-author of the textbook Compilers: Principles, Techniques, and Tools and author of the textbook Programming Languages: Concepts and Constructs, Dr. Sethi has also written more than 50 scientific papers on compilers, algorithm analysis, and the semantics of programming languages.

AVI SILBERSCHATZ is executive director of the Information Sciences Research Center at Bell Labs in Murray Hill, New Jersey. He holds a Ph.D. degree in computer science from the State University of New York at Stony Brook. Prior to joining Bell Labs, Dr. Silberschatz held a chaired professorship in the Department of Computer Sciences at the University of Texas in Austin. His research interests include operating systems, database systems, and distributed systems. Dr. Silberschatz is an ACM Fellow and an IEEE Fellow. His writings have appeared in numerous ACM and IEEE publications, other professional journals, and conference publications. He received the ACM Karl V. Karlstrom Outstanding Educator Award, the ACM SIGMOD Contribution Award, and the IEEE Computer Society Outstanding Paper Award for the paper “Capability Manager,” which appeared in the IEEE Transactions on Software Engineering. He is the co-author of two well-known textbooks, Operating System Concepts and Database System Concepts.