

ARACHNE: Weaving the Telephone Network at NYNEX

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The NYNEX Corporation invests hundreds of millions of dollars each year to enhance the telecommunications services provided to its customers. Extensive planning and construction are required to meet the ever-increasing demand for better service and provide the latest in sophisticated equipment throughout the telephone network. Engineering groups plan changes to network facilities five years ahead, with constant adjustments for changes to forecasted service demand, changes in the economy, changes to NYNEX company policies, or the availability of new technologies.

ARACHNE is an expert system that automates interoffice facilities (IOF) network planning in New England Telephone and New York Telephone, NYNEX subsidiaries. ARACHNE was deployed for planning the IOF networks in the New York City metropolitan area and most of New England. It dramatically reduced the overall planning time and improved the quality of the network plans. In its first production run, it identified potential capital savings of over \$10 million in Massachusetts alone through expense avoidance and capital recovery.

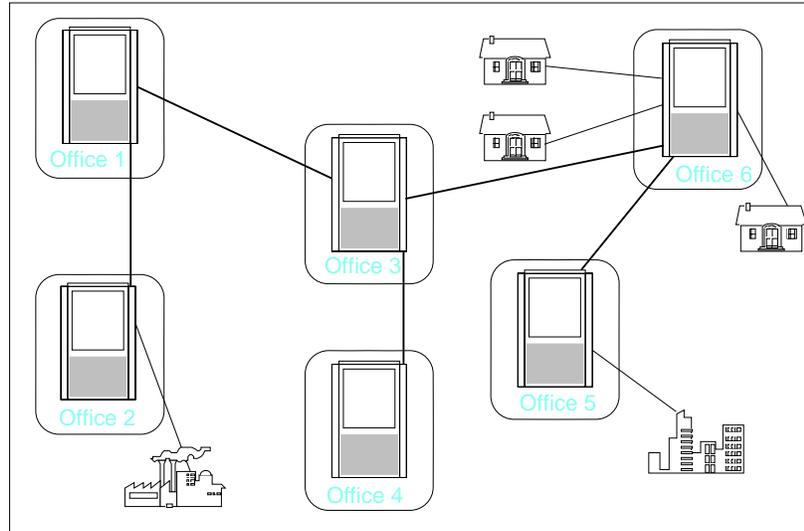


Figure 1. A Simple Telephone Network.

ARACHNE Overview

A simple telephone network is shown in figure 1. Switching equipment is located at nodes called *central offices*. These offices are connected to customer premises (forming the *local loop*) and each other (forming the *IOF network*). The physical links between nodes can be copper cables, fiber optic cables, or microwaves. The transmission on these links can be digital or analog.

ARACHNE uses a five-year forecast of expected IOF network demand—together with information specific to each central office, data about the existing network, and expert planning rules—to create a carrier program. A completed *carrier program* is a plan to meet the forecasted demand between any two central offices in the network. The plan includes transmission facilities that must be added or disconnected to satisfy the demand in an economical way together with the schedule for implementing these changes, a design for routing the services, and the equipment to be used.

We had to address several major technical and business issues for ARACHNE to be successful. Chief among these issues was the complexity of the planning domain. To be planned properly, the IOF network must be viewed as composed of several levels, corresponding to the digital services hierarchy shown in table 1. Each level of the digital hierarchy requires its own transmission equipment (for multiplexing and demultiplexing at the nodes) and uses available channel capacity at the

Table 1. Digital Services Hierarchy.

Signal Level	Bit Rate	Channel Capacity
DS0	64 Kbs	1 voice circuit
DS1 (T1)	1.544 Mbs	24 DS0
DS3 (T3)	45 Mbs	28 DS1
Optical System (HICAP)	90 Mbs–1.1 Gbs	Nonstandard

next signal level. Planning the IOF network requires providing sufficient capacity at each level.

The overall plan for any level is composed of plans for the individual links between pairs of nodes. The plan for each link involves many decisions, including *sizing* (determining needed capacity), *timing* (determining when to add capacity or when to remove excess capacity), routing onto transmission facilities at the next level, selecting the technology to use, and selecting the equipment to use. The IOF planner's objective is to come up with the most cost-effective solution for satisfying demand that takes into account such considerations as the demand, the existing capacity, engineering considerations, evolving network technologies, competitive positioning in the industry, maintenance costs, network reliability, and internal company policies.

Developing an ideal network plan is an inherently recursive problem in that the plan created at one level of the digital service hierarchy has implications for the ideal plan created at both higher and lower levels of the hierarchy. A purely algorithmic solution is not possible because the problem is nonlinear, nonnumeric, and qualitative. A purely heuristic approach cannot be used because there are no heuristics for achieving global optimization. We needed to develop a planning approach that combined heuristic and algorithmic solutions.

Another issue was the size of the network. NYNEX's network has a large number of central offices and an even larger number of links. The sheer volume of information precludes the possibility of working with all the network data simultaneously. We needed to find a way to partition the problem into manageable-sized pieces if we were going to be able to develop a solution.

Integrating ARACHNE with the existing corporate database systems was also a critical issue. NYNEX's databases record both the current and planned state of the network. ARACHNE had to be able to obtain input from these databases and return output to them. The databases involved are external products (from Bell Communications Research, Inc., [Bellcore]) and have new releases several times a year. This setup created a serious risk of obsolescence if ARACHNE could not keep pace

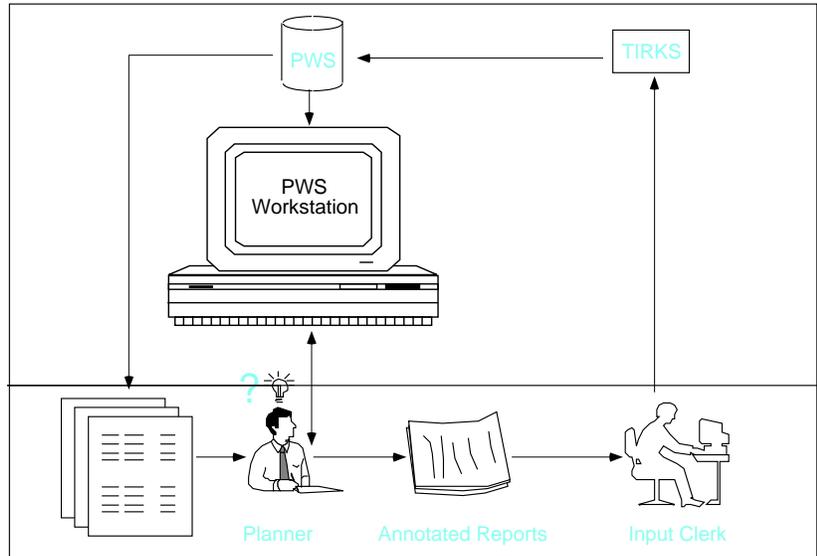


Figure 2. Planning before ARACHNE.

with these changes.

A final important issue was the impact of planning decisions. Implementing network plans can take from several months to more than a year. At any point in time, many future planning decisions are at least partially committed and have already incurred expenditures. Therefore, it is highly desirable that the plans not be too sensitive to minor changes in the business environment. ARACHNE had to be able to respond to changes as well as know when not to respond to changes.

All these issues meant that developing a working system would be a challenge; it would clearly be a long-term effort with uncertain results. However, the shortcomings of the pre-ARACHNE planning process indicated the effort would be worthwhile.

Planning before ARACHNE

The manual planning process used before ARACHNE is shown in figure 2. The trunks integrated record-keeping system (TIRKS) and the planning workstation (PWS), both Bellcore products, were used by the planners. TIRKS, an IMS-based system running on IBM mainframes, contains the facility inventory and network plans, and is a major database system used throughout NYNEX. PWS is a front end to TIRKS that serves as a re-

porting mechanism for the planners; it is a RAMIS-based database system also running on IBM mainframes.

NYNEX's forecasting group creates a forecast of the IOF network demand twice each year. The forecast is loaded into PWS at the start of the network-planning process. When planning was done manually, the planners reviewed reports generated by PWS for each link at each level of the network. They compared the forecasted and planned supply and altered the plan as needed. Changes were marked on the PWS reports and given to clerks for entry into TIRKS. There were several problems with this process:

Time: Manual review of the plan took months. It was difficult for planners to complete the process on time.

Quality and consistency: The planners have varying levels of expertise (many experienced personnel recently retired), which resulted in plans of inconsistent quality. There was no way to ensure that planners followed the company's guidelines and policies consistently.

Incompleteness: Because of the network's large size, the planners concentrated their efforts on planning the critical parts of the network, where there was insufficient supply to provide service for the forecasted demand. They often didn't have time to review oversupplied links that have equipment that could be disconnected and used elsewhere in the network.

Localized views: Each planner was responsible for only a limited part of the network. This approach made it difficult to ensure good global results.

Changing environment: The business, technological, and regulatory environment the telephone companies operate in changes rapidly. In the absence of automated planning tools, the planners' ability to react to change by modifying plans was limited.

All these reasons indicated that an automated planning process would have major benefits for NYNEX.

Previous Automation Attempts

To our knowledge, ARACHNE is the first and only expert system to address the domain of IOF network planning in the telecommunications industry. Although partial system support for planning existed previously, ARACHNE is the only system that addresses the complexity of the planning process and provides the flexibility required by the planning organizations at NYNEX.

PWS currently provides an automatic planning feature. However, it performs only the sizing and timing part of the planning, and it does

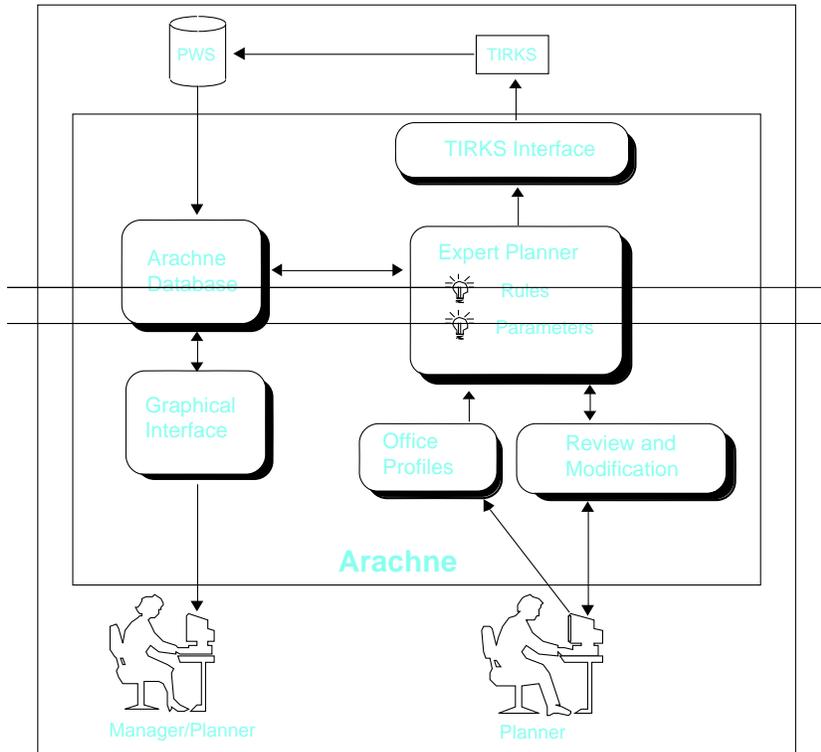


Figure 3. Planning with ARACHNE.

so in an incomplete manner. It plans to disconnect facilities only if the demand drops to zero and remains there until the end of the five-year planning period; it does not plan disconnects if demand is only reduced, not eliminated. It does not check the route used by the facilities it adds; it simply uses the old design without looking for a better design. Additionally, automatic planning in PWS is guided strictly by the forecast of network demand. However, there are known errors in the forecast that the planners must correct. Neither New York Telephone nor New England Telephone used the automatic planning feature of PWS. Because ARACHNE was tailored to the needs of New York Telephone and New England Telephone, it provides the capabilities and flexibility they require.

ARACHNE Architecture

ARACHNE was developed using a combination of traditional programming techniques and advanced technology. Figure 3 shows an overview

of the system architecture. This architecture enabled us to address the issues identified earlier.

ARACHNE runs on a SUN workstation. Its major components are three expert system modules developed with Common Lisp and KEE (an expert system shell that provides both rules and objects): an internal relational database implemented in ORACLE; a C-based graphic interface for viewing the IOF network and plans; and an interface to TIRKS for uploading ARACHNE's plans, also developed in C.

ARACHNE's three expert system components plan different levels of the digital service hierarchy. One module plans the DS0 level, one module plans the DS1 level, and one module plans the DS3 and high-capacity optical system (HICAP) levels of the IOF network. These three modules are independent and communicate only through the ORACLE database. They have similar internal architectures. Each has two knowledge bases, one containing information about central office characteristics (called *office profiles*), the other containing the planning rules.

The rule base is implemented in Lisp. Early prototypes of ARACHNE used KEE's rules, but as the development process continued, we decided to stop using the rule language and implement the rules as functions in Lisp. Much of the planning must be performed in a certain order. A complex set of metarules would have been required to ensure that the rules executed in the correct order. Also, the rules are complex and require many support functions and mechanisms, also written in Lisp. They combine heuristics with greedy bin-packing algorithms and operations research techniques such as dynamic programming.

ARACHNE's planning heuristics incorporate long-term strategies to ensure that the network continues to grow according to strategic plans and not be overly reactive to local or transient fluctuations. Other heuristics guide the planning process to achieve corporate objectives such as quality of service and modernization of facilities.

The issue of domain complexity is addressed through the partitioning into three expert systems and through the combination of heuristic and algorithmic techniques. ARACHNE's DS0 and DS1 modules, where the volume of data is exceptionally large, try to achieve optimization on only the local level. The DS3-HICAP module, which deals with a smaller volume of data, is able to optimize network planning globally as well. Although this simplification does not result in a fully optimal plan, it does improve the plans produced by the network planners, who were responsible for planning geographically defined areas and were never able to address issues of global optimization. Because major capital costs are incurred at the DS3 and HICAP levels of the network, even this partial optimization is a significant benefit.

ARACHNE's combination of programming techniques addresses the

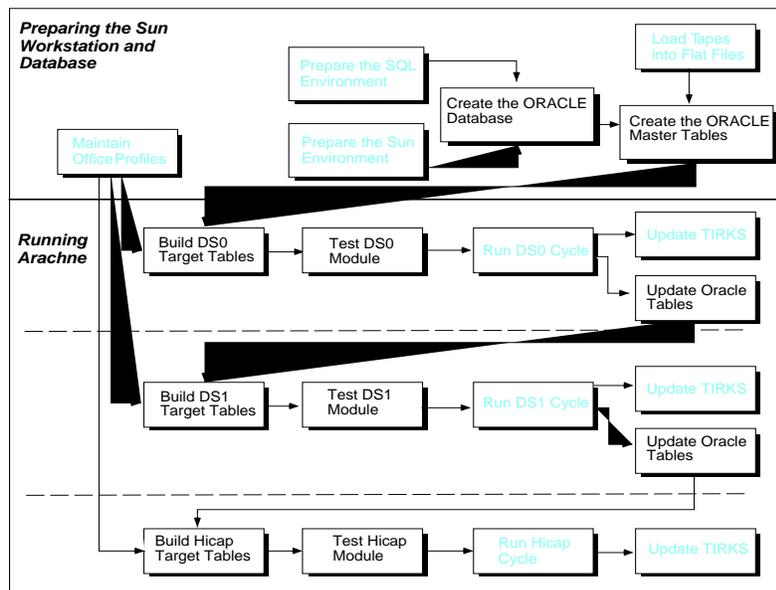


Figure 4. ARACHNE Planning Process.

conflicting objectives inherent in network planning: increasing overall network use while achieving local optimization. Dynamic programming techniques were employed for global optimization, but heuristics were used for local optimization. The methodology and algorithms developed at NYNEX for ARACHNE have been awarded a patent by the U.S. Patent Office ("Method and apparatus for planning telephone facilities networks," patent number 5,067,148).

The partitioning of ARACHNE into three expert systems addresses the size consideration as well. Not all nodes in the network need to be considered in all the levels of planning. Additionally, because the DS0 and DS1 modules focus on local optimizations only, they never require data about the entire IOF network simultaneously. This partitioning makes the volume of data tractable.

ARACHNE is loosely coupled with the external systems TIRKS and PWS. The expert system modules do not directly interact with the corporate databases, allowing most changes in the external systems to be addressed by ARACHNE's interface modules only. ARACHNE's input (the demand forecast and current network plans) comes from PWS as ASCII files, which are loaded into the ORACLE database. The expert systems use KEE LINK to download relevant data from ORACLE and create appropriate data structures (often KEE frames). ARACHNE generates SQL trans-

actions to update the ORACLE database; thus, the input at the next level of ARACHNE correctly reflects the new plan. ARACHNE also creates files of transactions to be uploaded to TIRKS through screen emulation. These transactions place network plans (suggested adds, disconnects, and designs) into the corporate database where they can be accessed by other users. Planners can review, accept, reject, or modify any plans prior to updating the databases. The planners, not ARACHNE, retain the final authority and responsibility for the network plans.

ARACHNE Planning Process

Planning with ARACHNE begins after the demand forecast has been loaded into PWS. Figure 4 shows the ARACHNE planning process. At the start of the planning cycle, the ARACHNE system administrator (a member of the planning department who is responsible for running ARACHNE) collects central office information and updates the office profiles. The system administrator also sets various parameters for each module's planning. These parameters include such items as thresholds for triggering various rules.

The DS0 module is run first. For each central office to be planned, the DS0 module downloads the forecast of demand and the existing routes from ORACLE. Based on the demand, the DS0 module routes the circuits onto DS1 facilities. After the DS0 planning is completed, DS1 planning begins.

The DS1 module downloads the forecast, designs, and current and planned supply of each central office to be planned. There are four subtasks within DS1 planning: demand analysis, design analysis, augment analysis, and disconnect analysis. The *DS1 demand analysis* compares the forecasted demand to the supply in the network and proposes to add or disconnect DS1 facilities as needed to satisfy demand. When the expert system was first built, this algorithm was simple: ARACHNE always ensured the minimum supply needed to satisfy the demand. Since this time, several heuristics have been added because there is activity in the network that is not included in the forecast. One heuristic increases the forecasted demand to provide some buffer in case of unanticipated growth; the amount added depends on the forecast for that link and a parameter set by the system administrator. Another heuristic looks at current activity in the network initiated by a human being and ensures that ARACHNE does not plan contradictory actions; people have access to outside information and might have reasons for the activity that ARACHNE does not know about.

The *DS1 module's design analysis* routes the DS1 demand onto DS3 fa-

cilities. The *augment analysis* then schedules the addition of new facilities and determines their characteristics (using information from the office profiles). The *DS1 disconnect analysis* schedules any needed disconnects and selects the specific facilities to be disconnected, considering both the technology and the amount of work required.

After DS1 planning is complete, the DS3-HICAP planning module is run. At this level of planning, the volume of data is small enough to allow the KEE module to handle all the network information at once. Thus, the planning module is allowed to achieve global optimization rather than the local optimizations achieved by the DS0 and DS1 modules.

DS3 planning has three parts: demand analysis, design analysis, and demand allocation. The *DS3 demand analysis* looks at the utilization of each DS3 link (measured as demand/capacity) and attempts to keep it within a certain range. There is a tolerance period during which the use can be outside this range, limiting the volatility of ARACHNE's plans. DS3 facilities are added or disconnected, as required, to keep the use within the desired range.

The DS3 design analysis routes the DS3 facilities onto HICAP facilities using information from the profiles and a recursive algorithm guided by a set of heuristics to determine the ideal route. The routing algorithm has two phases, which are applied iteratively until equilibrium is reached (both recommend the same route). The first phase augments the topology of the network by creating new links between central offices. The second phase improves capacity use by carrying out local or nonlocal optimizations.

The *DS3 module's demand allocation* adjusts the HICAP demand for new or disconnected DS3 facilities. Then, the HICAP level is planned. HICAP planning has three parts: demand analysis, technology selection, and routing onto fiber. The *HICAP demand analysis* provides the minimum supply to meet DS3 demand and determines which HICAP technology will be used (*technology selection*). Two designs are formed for the HICAP facilities using the same recursive algorithm and heuristics as the DS3 routing. One design is called the *service route* and is the best route; the other, a *protection route*, uses entirely different fiber cables and enhances network reliability. After the HICAP routes are created, the fiber level of the network is planned, requiring a demand analysis and the addition of new fiber, as needed.

Development and Deployment Experience

ARACHNE's development took approximately 2-1/2 years. An estimated

15 person-years of developer time, plus 2 to 3 person-years of expert time, have been spent developing and supporting ARACHNE. The three expert system modules were developed in parallel. Each module had a different programmer, although the experts were shared across modules. The modules finished development at approximately the same time, although the DS3-HICAP module took slightly longer because of its greater complexity.

ARACHNE was developed through an informal prototyping methodology. The experts were located in Massachusetts, but the developers were in New York, so extensive telephone contact, as well as occasional meetings, was used to refine the rule base. The prototypes were tested several times during the development process, and numerous corrections and enhancements to the rules resulted from the experts' review of the modules. In some cases, the experts agreed that ARACHNE was correctly applying rules they themselves used, but once they were able to see the impact of the rules on a more global scale, they realized that the rules did not produce the best plan. New rules were created and experimented with until the experts were satisfied. Thus, ARACHNE's development did not merely capture expert knowledge; it enriched and enhanced this knowledge as well.

One drawback to the informal prototyping process and the lack of a formal specification or requirements document was that it was difficult to tell when development was done. When the experts and their managers saw the capabilities of early versions of the system, they requested more and more functions. Coding the extra functions delayed our testing of the final release, system version 1.0. Finally, we were told by the managers that they liked the system, and they wanted—needed—to use it immediately.

Therefore, we were forced to deploy ARACHNE before the system had been tested to our satisfaction. The individual modules had been tested, both through unit testing of the Lisp code and function testing with the experts, but no integration testing or validation of the database updates had been done (these tasks had been scheduled for the end of the development process, which never came). We proceeded extremely cautiously because of the incomplete testing and because procedures for running ARACHNE had not been finalized, formalized, or documented.

The first two runs of ARACHNE became combined test-production runs. Test cases were selected prior to the runs after a careful review of the domain. Each module's plans were reviewed for about a week, and rule changes, including several major ones, were implemented on site. Only after the experts were satisfied with ARACHNE's plans for the selected cases was it run for the entire region and its output uploaded to the

corporate database. Approximately six weeks were spent on each of these ARACHNE runs. By the third use of ARACHNE (July 1991), planner confidence in ARACHNE was high. Only a few hours were spent reviewing output, no major code changes were considered, and planning each level required only a few days. The most recent runs have been similarly short, with planning concluded within three weeks.

The initial development of ARACHNE focused on New England Telephone. Following its first run there, our emphasis shifted to modifying the rules as needed by New York Telephone. The two companies use similar but not identical rules. Currently, there is one set of code, with parameters specifying whether to use the New York or New England rules. Some rule changes under consideration for New York Telephone might eventually lead to two distinct sets of code. Two code sets is a serious maintenance issue that has not yet been resolved.

Another serious issue that has not yet been resolved concerns ARACHNE's basic structure. Although the current architecture successfully addresses the design challenges identified three years ago, changes in the planning process have added dependencies between the different levels of the IOF network as well as among links within a level. It is not certain that we will be able to address these issues within the current architecture.

Impact of ARACHNE

Following each run, a significant effort was made to analyze the impact and benefits of the ARACHNE plan.

ARACHNE has had significant monetary benefits for the telephone companies. Operational savings of \$2 million have been identified. However, the major savings from ARACHNE result from reduced capital expenditures (ARACHNE suggests new construction only where needed) and opportunities for capital recovery identified by ARACHNE (the company can remove unused equipment and use it elsewhere in the network). In its first run at New England Telephone, ARACHNE identified \$10 million in potential capital savings; total savings identified to date are over \$20 million. Quantifying the actual benefits is difficult because the planning environment is so dynamic that the plan created by ARACHNE might not be carried out fully because of changes in the forecasted demand.

Other monetary savings are anticipated. ARACHNE's speed of planning allows a long lead time for equipment recommendations, thus reducing the likelihood of incurring premium charges for unanticipated rush jobs. The reduction of errors also saves costs because less rework

is required. The reduced planning load results in work force savings.

In addition to providing financial benefits, ARACHNE's plans improve the quality of the network. The improvements to existing planning rules, the introduction of new planning rules, and the consistent and exhaustive application of the best planning rules resulted in superior carrier programs. The new designs created by ARACHNE improve a network measurement called *routing efficiency*, making better use of the existing base network, and improve network use. These improvements should eventually reduce network maintenance costs. Through the designs it creates, ARACHNE also promotes routing diversity in the network, improving its reliability.

ARACHNE also assists with the introduction of new technologies and new services. The rapid dissemination of new planning rules and strategies shortens the interval between the availability of new technology and its effective use in the network. Company policies, such as replacing copper cable with fiber and the use of optical systems, were incorporated into ARACHNE's planning strategies and implemented throughout the network.

ARACHNE has had a qualitative impact on the planning process itself. Because of ARACHNE, the planners feel they are able to make decisions based on quality rather than expedience. Because ARACHNE's plans are accurate and are completed quickly, better annual budget estimates can be prepared; the reduced planning interval allows the construction program to be more closely aligned with the forecast. Planners are able to react more quickly to internal and external changes. They now have time to review the impact of the plans on the network and make changes and are able to concentrate on solving new problems and investigating new network technologies. The reduced planning time yields a longer lead time for allocating resources and carrying out the plans.

The planners have begun to use ARACHNE for tasks in addition to the routine planning. Although ARACHNE does not currently have true what-if functioning, the planners identified a way to use ARACHNE to help them perform a study of network survivability and diversity issues. We anticipate that such studies will become more common in the future as the users become more experienced with the system.

Conclusion

Although the major development of ARACHNE is complete, there is a strong possibility of continuing work. Some work is necessary simply to keep up with the changing environment; for example, a new technolo-

gy, SONET, is being introduced into the network in 1992 and requires different planning strategies. Other potential work includes the implementation of true what-if capability to allow the planners to experiment with different rules. We are also investigating demand forecasting; because the forecast drives the planning process, an improved forecast has obvious benefits. A generalized network-planning platform is also being considered.

We also plan to expand the use of ARACHNE throughout NYNEX. Its first use was in the state of Massachusetts and the New York City metropolitan area. New England Telephone has since expanded its use to Rhode Island, New Hampshire, Vermont, and Maine, and New York Telephone is considering its use in upstate New York. Some rule modifications might be necessary at that time.

ARACHNE's success is largely owed to its hybrid approach to problem solving. Its effective combination of heuristics and algorithmic approaches enables it to efficiently augment capacity in a network without a fixed topology. It has now become a routine part of the planning process, and we anticipate enhancing its capabilities to ensure that its benefits will continue to be realized in every planning cycle.

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