

THE BELL SYSTEM TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 57

April 1978

Number 4

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Loop Plant Modeling:

Overview

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(Manuscript received August 20, 1977)

The loop plant is a fruitful area for operations modeling. Because it can have many configurations and detailed structures, and because over 30 percent of the total telephone work force interacts with it, it is physically and operationally complex, and modeling is often the only way to arrive at an understanding of the basic principles underlying its operation. This article provides an introduction to the loop plant modeling papers which follow and includes both a description of the loop plant and brief descriptions of the individual papers.

I. INTRODUCTION

The following ten papers describe various models of the telephone loop plant. The papers cover work done chiefly during the past decade, although the foundations of the work are often much older.

The loop plant, which is described in detail in Section II of this overview, is a fruitful area for operations modeling for two main reasons. First, since the loop network must extend everywhere customers use telephones, it is geographically dispersed and can have many configurations and detailed structures. Second, over 30 percent of the total telephone work force interacts with it, to select network paths and

connect customers, to rearrange and repair the network, to monitor and analyze service and costs, and to design and construct network additions. In such a physically and operationally complex network, modeling is often the best—and sometimes the only—way to arrive at an understanding of the basic principles underlying its operation.

The emphasis in these articles is on concepts rather than implementation, on understanding basic mechanisms rather than on ways these and other models can be used in day-to-day operations. For that reason, as well as limitations on space, no attempt has been made here to describe the many computer programs and operations systems utilizing the models.

The models described here are largely concerned with investment options, work activities, and the tradeoffs between them. This work has been collected at this time both because much of it is recent and has not been reported before and because it has now reached a stage when much of the loop plant has been successfully modeled, and interrelationships have begun to emerge. This is not to imply that the work is complete or that all the critical linkages have been made. Much remains to be done, but an underlying structure can be discerned, and a firm base for future work has been established.

In the next section of this overview a description of the loop plant is provided, both to aid in understanding the models and to avoid repeated definitions of the same terms. In the final section, brief descriptions of the individual papers are provided.

II. THE LOOP PLANT

The loop is the part of the telephone network connecting the customer to the nearest switching office. As used here, the term "loop plant" covers both the physical network, and the activities required to operate it.

2.1 Loop network definitions

AERIAL: Type of construction in which multipair cables are suspended from utility poles. Aerial construction may be used for feeder or distribution networks, but more frequently for the latter. It is less costly to relieve than buried or underground plant, which influences cable sizing¹ but it is more easily damaged. Maintenance and appearance considerations have led to a decline in new aerial construction techniques; in 1977 only 23 percent of the plant added in the Bell System was aerial. Overall, 28 percent of the pair miles are aerial.

ALLOCATION: The process of apportioning spare feeder facilities in groups of 25 or 50 pairs along a feeder route so that the placement of the next relief cable is deferred as long as economically practical. Allocation is a planning step; it does not result in an engineering work order.

ALLOCATION AREA: A geographical region subdividing the area served

by a feeder route. The allocation area is the recommended unit of the distribution network to be analyzed as a unit for relief or revision. Each allocation area is fed by a unique bundle of pairs called a pair group. Pair groups are defined for the analysis of congestion for relief and rearrangement timing² and for allocation of spare feeder facilities.³ Two sets of allocation areas are defined for a route: ultimate and existing allocation areas (q.v.).

ULTIMATE ALLOCATION AREA: A proposal for the ideal network configuration. An ultimate allocation area is a grouping from 1 to 5 distribution areas that have the same feeder transmission requirements (gauge and loading).

EXISTING ALLOCATION AREA: A reflection of the existing configuration of the network for monitoring activities and for establishing the base from which the ultimate design will take place. There may be up to 10 percent multiplying between existing allocation areas, with a goal of no multiplying. In size, existing allocation areas can vary from 500 to 2000 working telephone lines. The size has been defined so that the statistical fluctuation in operating cost information is minimized^{4,5} as well as to accommodate the wide range of actual network configurations encountered in practice.

BROAD GAUGE CABLE COSTS: Term used for the $A + BX$ approximation used in estimating the cost of placing and splicing a cable. In the expression, A is the total labor and material cost per sheath foot, independent of number of pairs; B is the material, placing, and splicing cost per pair foot; and X is the number of pairs. There will generally be a different set of A and B costs associated with the gauge of wire in the cable as well as with the type of construction—aerial, buried, or underground. In addition broad gauge costs will vary from one location to another.

BURIED: Type of construction in which multipair cables are buried directly in the ground. Buried construction may be used for feeder or distribution networks. About 34 percent of the new construction in the Bell System was buried in 1977; at the present time, 21 percent of the pair miles are buried.

COMMITMENT: The process of physically connecting allocated feeder pairs to the distribution network.

CONNECT-THROUGH: An assignment option in which the loop connection between the central office and a premises—feeder, distribution, and drop—is left intact when telephone service is discontinued. In this way no action need be taken in the loop network when a new customer occupies the premises and requests service. The disadvantage is that, depending upon assignment rules, the pair may be designated as unavailable for other customers, increasing the number of idle pairs at relief.⁶

DISTRIBUTION AREA: A subdivision of an allocation area to which

feeder pairs are committed. A distribution area may be an area served by a point of interconnection (e.g., a serving area interface and a control point) or it may be a group of laterals administered together in multiple. A distribution area should contain between 200 and 600 ultimate living units; it is usually a "logical" or "natural" area with common user or geographical characteristics. There are no restrictions on multiplying between individual terminals or between distribution areas within an allocation area, unless the distribution area is administered as a Serving Area (q.v.).

DISTRIBUTION NETWORK: The system of cables and terminals to which individual telephone lines are connected, and which then is connected to the feeder route. Distribution cables are usually small, on the order of 50 to 300 pairs, and follow all the streets where subscribers are located. Most distribution networks are short, with a maximum length under $\frac{1}{2}$ mile. Distribution cables are not sized for periodic reinforcement as the feeder network is, but are constructed initially to satisfy estimated ultimate pair requirements. This minimizes construction activity close to subscribers and eliminates the need to closely monitor a large number of small cables. Individual distribution pairs appear in one or more distribution pedestals or terminals, discussed below.

DISTRIBUTION PEDESTAL: Point of interconnection between the drop leading to the customer's residence and the distribution network in buried plant. Pedestals may contain from 5 to 50 pairs.

DISTRIBUTION TERMINAL: Point of interconnection with the distribution network in aerial plant containing between 5 and 50 pairs.

FEEDER ROUTE: Major network of cables from central office to within $\frac{1}{2}$ mile or so of customers. Area within feeder boundaries is the first and largest subdivision of area served by a central office. For convenience 4 routes are often nominally designated "north," "south," "east," and "west," although in practice office configurations and local design procedures may result in wide variations from nominal. Physically, feeder routes consist of many multipair cables in parallel, which are interconnected by splices. Pairs from the route end cumulate toward the central office, so that at the central office all pairs in the route are concentrated. The reduction in route cross section as it gets farther from the central office is termed "tapering." At various points pair bundles leave the feeder route in laterals which connect the feeder cables to the distribution network. As discussed under "Resistance Design" (q.v.) up to four different gauges of wire may be used in the cables making up a feeder route. Under standard design procedures, an attempt is made to restrict any one loop to only two consecutive gauges (e.g., 26 gauge next to the CO, followed by 24 gauge farther out). This may, however, result in all 4 gauges appearing in parallel close to the central office. As discussed under "Feeder Relief" (q.v.), in the practical case of reinforcing part of

a feeder route, separate relief calculations must be made for all gauges appearing in a given cross section.

FEEDER RELIEF: Broadly, the process of making more pairs available at a given demand point. This may be done either by network rearrangement, so that unused pairs become available where needed,³ or by adding new cables.

When relief is provided, the number of pairs added should be that number that minimizes the total cost of the current plus all future relief projects. Opposing economic forces are at work which tend to both maximize and minimize the number of pairs added. The cost per pair is less with large cables, and the time before relief is required is increased. However, large cables represent large idle investments which will not be compensated by increased service earnings for an extensive period. The process of balancing these compensating forces to reach an economic optimum is termed "economic cable sizing."¹

In general, separate sizing calculations are required for each section of the feeder route, and for each gauge within the cross section. The size and complexity of such calculations often makes mechanized assistance desirable.⁷

The time at which relief should be provided to the network depends on the use of existing facilities. Use is usually characterized by "fill" of the individual feeder sections, where fill is defined as the ratio of pairs in use to pairs available. Two fills may be used: "assigned pair" fill, which includes all pairs connected between subscriber and central office, even if telephone service is not in use; and "working pair" fill, which includes only pairs connected to active customers. The difference between the two is the "idle assigned" level. As the inventory of spare facilities decreases, the probability that a network rearrangement will be required to satisfy an inward service order increases. The optimum time to provide relief occurs when the incremental costs of relief exactly equal the incremental rearrangement costs of congestion.^{2,8}

FEEDER SECTION: Feeder sections are linear segments of feeder routes which have been defined so that the number of pairs in the route may be matched to present and future demand as effectively and economically as possible. Sections may be defined to study duct sizing, to account for gauge requirements, and to accommodate major demand points. As discussed under "allocation area" (q.v.), ideally one feeder route section should be associated uniquely with each allocation area. While the number of sections can be made arbitrarily large, forecast uncertainties and difficulties in constructing and rearranging a feeder network which changes size and gauge frequently make it impractical and uneconomic to define and attempt to administer a network with a large number of sections.

FEEDER LATERAL: A branch cable connecting the distribution net-

work to the feeder route. A lateral may be ultimately sized or it may be relieved as growth exhausts pairs, but then less frequently than the backbone feeder.

LOOP: Connection between the subscriber's telephone and the central office. It takes its name from the pair of wires usually used, which traditionally constitutes a "loop" of direct current from the central office to the subscriber for signaling. A loop extends from the main distribution frame within the central office to the first connection point within the customer's premises, usually a voltage overload device called a "protector." Typically, the components are: "tip" cables from MDF to cable vault; feeder cable from vault to interface or distribution/feeder splice; distribution cable from that point to the distribution terminal; and "drop" wire from the terminal to the residence. The wires for any given loop may appear in only one, two, or all three types of plant (aerial, buried, underground) during the course of their route from central office to customer, and appear in multipair cables from over 3000 to 50 pairs in size.

According to a survey taken in 1973,⁹ the average length of a loop was 11,400 feet; of this, it is estimated that typically 2000 feet is in distribution cable, and the remainder in feeder.

MULTIPLYING: The practice of having a cable pair appear (i.e., be accessible for service) at more than one place. Multiplying may be applied in distribution, feeder, or both networks. It was originally devised to provide flexibility with low service penetration and high party line content; its drawback is encouragement of rearrangements, which leads to increased faults and repair costs. While multiplying is useful in many environments, there are others where its penalties outweigh its advantages.⁵ For that reason, multiplying has been eliminated or sharply reduced in the Serving Area (q.v.) Concept.

PAIR GAIN: The general name applied when electronic systems provide several loops over a smaller number of wire pairs. Such systems employ frequency and time division multiplexing, switching, and other techniques.¹⁰ Various ways are used to specify the system characteristics; for example, in the SLC-40 system 40 loops are obtained from 4 physical pairs; this may be called a "pair gain" of 36 pairs, or a "pair gain ratio" of $36/4 = 9:1$.

PERMANENT PLANT: Term loosely applied to either Serving Area (q.v.) design, or its predecessor, Dedicated Outside Plant.¹¹ In its strictest sense, it has been used to describe loops which are nowhere in multiple and, once connected to a residence, are never severed. As the result of experience, a somewhat more relaxed definition is emerging in which distribution pairs are not in multiple, and are never broken between terminal and interface, but may be disconnected from the feeder pair at an interface.

REARRANGEMENT: The process of disconnecting some pairs in cables at splices and reconnecting them to others. This activity is often required in conjunction with relief and is also required because of shifts in demand patterns.

RESISTANCE DESIGN: The name given to the method of insuring that the resistance and insertion loss of all loops is limited, so that any loop will be able to signal and send dialing information to the central office. In addition, resistance design rules have been chosen so that the resulting loop, trunk, and switching network as a whole provides adequate transmission performance. The standard resistance limit is 1300 ohms total (combined or looped resistance of the two pair wires). To achieve this limit for loops up to 6 or 7 miles in length, 3 wire gauges are commonly used: 26 gauge, 24 gauge, and 22 gauge. If used alone, they would correspond to maximum loops of (approximately) 15,000 feet, 24,000 feet, and 38,000 feet respectively. To conserve copper, the use of two gauges in tandem is recommended; that is, loops between 15,000 and 24,000 feet long, for example, would contain both 26 and 24 gauge conductors. Obviously, every loop cannot be individually tailored; theoretical savings in copper on any individual loop must be balanced against loss of flexibility and fragmentation of the route as a whole. Usually, as a result of such tradeoffs, 6 or 7 gauge change points are defined per feeder route.

Beyond 6 or 7 miles, up to as much as 20 miles, a fourth gauge of cable, 19 gauge, is available. However, both transmission and signaling limits are frequently met using finer gauge cable and electronic supplements to copper pairs.¹⁰ The low customer density and forecast uncertainty in this region of the network imposes restrictions on sectionalization and administration not covered by the following articles. (See Ref. 10 for further details.)

In addition to the resistance limit, resistance design rules include specifications designed to insure adequate transmission performance. The major ones are: loading (the application of an 88 mH inductance every 6000 feet to compensate for capacitance) should be applied on all loops longer than 18,000 feet; and bridged tap (cable in electrical parallel with the loop) should be limited to 5000 feet.

SERVING AREA: A distribution area administered under the Serving Area Concept (SAC).¹² Under this concept multiple appearances in the distribution network are sharply limited, and two or more pairs per ultimate living unit are usually provided from interface to terminal. All connections between the feeder network and the distribution network are made in a cross connection unit called a Serving Area "Interface." The purpose of serving area design is to reduce rearrangement and repair activities in the distribution plant by permanently establishing connections between a residence and the interface. All subsequent activities

then take place in the interface. Once a connection has been made to the feeder, two major operating modes are used: I, in which the connection is permanent, never broken; and II, in which an idle pair may be broken when no unassigned spares are available. At the present time, type II is more commonly encountered in practice.⁶

UNDERGROUND: Type of construction in which cables are pulled through tubes called ducts that are buried in the ground. When ducts are constructed, several are placed in parallel; since digging and street opening costs are large, particularly in the cities, enough are placed at one time so that reinforcement is infrequent. As available ducts near exhaustion, duct capacity can significantly influence the economic cable size.¹ Access points to underground cables and ducts are provided by manholes placed every 500 to 1000 feet. Due to its cost, underground construction is generally reserved for large concentrations of cables such as in a main feeder route. About 43 percent of the pair miles placed in 1977 were in ducts; about 51 percent of the Bell System loop plant is underground.

2.2 Functional description

The loop network must be capable of providing a transmission path between customers and central offices in response to widely varying and occasionally unexpected service requests, without requiring either excessive pairs or excessive work activities. To achieve this goal, the network must be continually monitored and, when activities or pairs exceed proper levels, steps taken to augment or rearrange the network.

Viewed over time, loop network activities are cyclical though aperiodic. Long intervals may elapse between basic reappraisals of allocation area, route, and office boundaries, including reestablishment of long range goals for design changes and area rehabilitations. More frequently, but still at several year intervals, major additions to the network may be designed and carried out. With comparable frequency, though not necessarily linked with cable additions, areas may be converted from multiple to permanent plant, new multiple or permanent distribution networks may be added, and in older ones major amounts of deteriorated cable and terminals may be replaced. Several times a year, small additions to and rearrangements of the network may be made. And, finally, daily reassociations of pairs and residences may occur throughout the distribution plant in response to service requests.

The models to be described were developed in response to the need to understand and quantify these cycles. They address such questions as: How long should the interval be between relief cables? How are op-

erating activities related to fill levels? What should be monitored? How is the level of the items monitored related to decisions to convert to permanent plant?

Although many of the individual models which are described in the papers which follow address individual parts of the overall process just described, none is completely independent. An important consideration underlying this body of work is that all of the functions and cycles of the loop plant be included.

III. OVERVIEW OF THE MODELS

3.1 *Inventory levels*

In the first paper that follows in this issue, a description of one of the first analytical models to be developed for the loop plant is given. In "A Simple Model for Studying Feeder Capacity Expansion," Freidenfelds describes how an inventory viewpoint may be used to determine the optimum size of a feeder relief cable, balancing the advantage of reduced cost per pair for larger cables against the extra "carrying charges" for temporarily unused capacity.

In the second paper, "Economic Evaluation of Subscriber Pair Gain System Applications," Koontz develops equations which expand the options of feeder relief to include electronically derived loops. As the pair gain systems described in the other section of this special issue become more widespread, such analyses will become increasingly important.

The relief of individual feeder routes affects the aggregate number of pairs over many such routes. In "A Model of Pairs Added at the Main Frames for a Large Entity," Blum and Bell develop a model of the combined effect of many independent relief decisions on aggregate pair levels.

How feeder pairs are apportioned among competing demand points can have a major effect on both day-to-day work activities, and on the frequency of relief. In "The Feeder Allocation Process," Marsh discusses models used in establishing broad guidelines for flexible and efficient feeder pair allocation and commitment strategies.

3.2 *Models of operating activities*

In "An Approach to Modeling Operating Costs in the Loop Network," Koontz describes work to date on modeling the level of day-to-day work activities in the loop plant as a function of administrative strategies, inventory levels, and network characteristics. In a related paper, "Optimal Operating Policies for Serving Areas Using Connect-Through Administration," Freedman examines how similar models in permanent plant areas can be used to analyze relief and rearrangement options to serving areas.

In "Loop Plant Work Operation Cost Models Using Semi-Markov Processes," Gibson uses Markov modeling to describe how the work content of one particular activity, the reassociation of pairs among several cable sheaths (a cable "throw") can be modeled as a function of pair status and other information.

In "Economic Design of Distribution Cable Networks," Stiles describes the tradeoffs in the distribution network between initial cost of construction and future costs, and shows how these tradeoffs can affect design decisions.

3.3 Network organization

In "Statistical Analyses of Costs in Loop Plant Operations," Dunn and Landwehr develop some of the statistical considerations governing the basic size of allocation areas, and the interval over which data from them should be monitored, in order for random statistical errors to be reduced to a satisfactory level. Aughenbaugh and Stump in "The Facility Analysis Plan: New Methodology for Improving Loop Plant Operations" then show how such data may be used in making basic decisions to convert geographical areas from multiple to permanent plant. They also describe a monitoring and control system called the "Facility Analysis Plan" which relates many of the work operations just discussed.

IV. ACKNOWLEDGMENTS

Many contributions to this work have been made by individuals not explicitly identified. To all those whose work laid the foundations for the present efforts, grateful acknowledgment is made.

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