Computer Aided Planning of the Telephone Network of Rural Areas

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ABSTRACT
A new computer program for the economic optimization of rural telephone networks and its application to a real life planning study is presented. The paper first analyzes the experience gained with previous programs as the starting point for the specification of the new program. Next, the main characteristics of the new program are described, including its input/output data and logic. The first application of the program is a planning study in Norway, which has a double purpose: to make the planning study itself and to evaluate the applicability of the program. Both subjects are analyzed in the last sections of the paper.

1. BACKGROUND

1.1 GENERAL
Within the field of telephone network planning, the planning of rural areas constitutes a well defined problem, because of its special characteristics. Among these characteristics, the following are most relevant: low subscriber density; subscribers irregularly distributed in zones separated by distances ranging from some hundred metres to more than 10 km; traffic dispersion mainly radial; i.e., traffic tends to be oriented to the commercial/administrative center of the area.

To meet the network planning study objectives, i.e., to determine the most economic network that satisfies a forecasted demand under a set of constraints (technical, topological, etc.) for a rural area, requires the solution of a complex problem. This is because of the variety and volume of data involved as well as the number of alternative solutions from which the most appropriate one must be selected.

1.2 FIRST GENERATION COMPUTER PROGRAMS
The use of the computer as a tool to solve network planning problems is not new. During the last decade, telecommunication entities in different parts of the world have been active in the development of computer aids to network planning. In particular, in 1970, Laboratorios ITT de Standard Electrica, S.A. (ITTLS) completed the development of a computer program (1) for the economic optimization of rural telephone networks; more specifically, the aim of the program is to determine the economic optimum number of terminal exchanges, their placement, and the subscriber assignment to each exchange of the network that satisfies a given service demand. The program is only able to treat networks with a tree structure; consequently, the study of a rural area usually requires its previous subdivision into independent sections which are separately studied. The model which the program is based upon is cross sectional, i.e., the economic optimization is carried out for a given moment in time. The optimizing algorithm follows a combinatorial procedure based on a quasi-enumeration of the solutions; total enumeration was avoided in the subscriber assignment of exchanges, due to the tree structure of the subscriber plant and for heuristic reasons. Because of this, the running time grows exponentially with the number of subscriber distribution points which for this reason was limited to 20.

In 1974, Televerket Forskningsinstitutt (NTARE), the Norwegian Telecommunications Administration Research Establishment, developed a computer program (2) based on the network model of the ITTLS program. Its general optimization algorithm, based also on a combinatorial process which may be controlled by means of a flexible set of input data, enables the program user to disregard those solutions that a priori can be considered uneconomic. This drastically reduces the running time and has made it possible to increase the number of distribution points of the networks that can be studied. A practical value of 72 was chosen. Another significant difference between the NTARE and the ITTLS programs is in the subscriber assignment process where the NTARE program uses a method based on a direct cost evaluation of the alternatives for subscriber assignment, using a predefined curve of subscriber cost as a function of the distances between distribution points and local exchanges and between local exchanges and the primary center.

1.3 EXPERIENCE GAINED FROM USING THE FIRST GENERATION COMPUTER PROGRAMS
From using the first generation programs as tools for planning rural telephone networks in several completed and ongoing projects, the Norwegian Telecommunications Administration (NTA) has gained considerable experience in this type of work. This experience shows that:

- From a general point of view, the use of computer aids in network planning has produced changes in the approach to the network planning problem. As an example, the procedure of data collection has been vastly improved when using a computer compared with conventional planning methods. This is due to the program algorithms which work with exact numbers and cannot utilize the "engineer judgment" experienced in conventional planning. Computer aided planning therefore demands of the planning engineer more precise thinking, particularly in terms of subscriber density and forecast, leading to considerable more accurate registration of the demand for telephones.

- The first generation programs show up some limitations which incur relatively heavy manual calculations for assessing the economical optimum network considering the existing plant and transmission systems other than voice frequency (VF). It is therefore felt that great savings in time and manpower may be achieved by producing a computer program which can consider the value of existing plant, and can calculate the most economic solution taking into account both VF and multiplex systems.

- An advantage was seen in dimensioning the junction network from traffic values, instead of basing the size of the junction group on the number of lines, as was done in the first generation programs.

- An increase in the maximum network size that the ITTLS program could consider was seen as desirable.

The NTA views were in full agreement with these experiences by ITTLS. In addition, ITTLS saw an advantage in including the possibility of considering the use of concentrators and satellites.

1.4 THE SECOND GENERATION COMPUTER PROGRAM
Based on the experience gained with the use of the first generation programs, it was felt appropriate to computerize the treatment of the factors mentioned in the previous section. The introduction of these factors would
have significantly increased the program running time if the same optimization algorithm were used. Thus, ITTLS decided to develop a new program based on a new optimization algorithm capable of handling these factors. In addition, the new algorithm would permit the study of the rural area as a whole rather than by subdividing the area into sections, as was usually necessary in most cases with the previous programs.

2. PROGRAM DESCRIPTION

2.1 THE PROBLEM

The problem treated by this computer program can be stated as follows. Given, in the rural telephone area under study:

- Network topology;
- The placement of the primary center;
- Telephone demand, characterized by: number and location of the subscribers, and traffic;
- Characteristics (capacities, mode of use, etc.) of the telephone elements (switching, cables, carrier systems, poles, etc.) to be utilized;
- Network design rules for the transmission media (for instance, the subscriber loop design rules);
- Cost parameters of the telephone equipment;
- Existing plant facilities: switching, cables, open wire lines and structures (poles, conduits, etc.);
- Restrictive conditions, if any;

then, the problem is to determine:

- The number and placement of switching centers;
- The subscribers assigned to each center;
- The telephone equipment required in the telephone network that satisfies the demand at a minimum cost.

Network sections connecting two network points are unique in the model. Therefore, in case there are two possible ways to go from one point to another, as in Fig. 1, from TAU to ALPHA, a previous decision should be made to define only one path to the computer program, as in Fig. 2. Another characteristic of the model network sections concerns the uniformity of installed facilities (cables, sizes and gauges, structures, etc.) on them. This means that a physical network section may be composed of several model network sections.

To provide telephone service in a rural area, it is economic in general to use a star type network structure. This is the type of network the computer program model considers. From the switching hierarchy point of view, three levels may be considered by the computer program: primary center, rural centers and satellites. A satellite center may home on the primary center or on a rural center. Fig. 3 shows a network serving the area of Fig. 2. The route joining a distribution point or a switching center (rural centers or satellites) to the center they home on is that of shortest length, in the computer program model.

The term "cost" should be understood in the program model in a wide sense. It may actually refer to first cost, present value of annual charges (PVAC), etc. depending on the cost optimization aim.

Only lumped (or concentrated) carrier systems are considered. The computer program model is cross-sectional, as it was for the first generation programs.

The junctions are bothway.
2.3 INPUT DATA

The basic information required as input data by the computer program is as follows:

- Placement of the primary center;
- Minimum and maximum number of switching centers. The program will study all the networks having a number of switching centers between these limits, both included;
- Initial placement of the exchanges for the minimum number of exchanges;
- For each section: length; existing structure description (capacity, extension possibility and cost parameters); existing cables (number of cables, and for each cable: number of pairs, gauge, cost parameters); existing open wire lines (number of pairs and cost parameters);
- For each point: number of subscribers; total traffic (originated and terminated); existing switching equipment (rural exchange or satellite) description (capacity, extension possibility, cost parameters);
- Traffic flows between the distribution points;
- Traffic grade of service for junction calculations;
- VF design rules for the subscriber loop and for junctions;
- Carrier systems (subscriber and junction) description: number of channels per system, number of pairs required per system, number of service pairs, distance between repeaters for each gauge;
- Characteristics of the switching equipment (rural exchanges and satellites) available for installation: maximum number of lines and junctions;
- Cost parameters for new installations of switching equipment, cables, carrier equipments, structures, etc.;
- Restrictive conditions that may be imposed on the solution: fixed location for an exchange; location forbidden for exchange placement; area served by a given exchange.

2.4 OUTPUT

The program prints out all the input data. Afterwards, a full description of the optimum network is printed out for each number of switching centers from the minimum to the maximum number specified by the user. The description includes:

- Placement of the switching centers;
- Description of the service area of each center;
- Description of the switching equipment required at each center, indicating if it is a rural or a satellite center and its cost;
- Description of the points where carrier equipment terminals are required, specifying the necessary equipment and its cost;
- Description of transmission equipment required (cables, open wire lines, etc.) and the cost for this equipment per section;
- Total cost of the network;
- Résumé of the new and existing plant used and costs.

2.5 PROGRAM LOGIC

The program starts working with the given minimum number of switching centers. The optimum network is then obtained for this number and printed out. Next, a new switching center is automatically added at a point having the highest number of subscribers (excepting those points where a switching center is forbidden or there already is an exchange). A new network optimization is then made and results are printed out. The process continues until the given maximum number of switching centers is reached.

The optimization process for a certain number of switching centers is an iterative algorithm consisting of two main phases:

1. Calculation of a feasible solution.
2. Optimization of the feasible solution by means of two main steps that are reiterated until a minimum cost network is obtained. These steps are:

- Relocation of the switching centers.
- Reassignment of the subscribers.

Intercalated with these steps, there are two secondary processes for the optimization of the installation of carrier systems and satellite exchanges.

Fig. 4 illustrates the program logic which will be analysed in detail in the following paragraphs. The method of calculation of the telephone equipment requirements and costs is the subject of the last part of this section (see 2.5.6).

2.5.1 DETERMINATION OF A FEASIBLE SOLUTION

To find a feasible solution is to determine a network that satisfies the given demand and all the restrictive conditions; its cost should be as close as possible to that of the optimum network in order to save computer running time. A feasible solution is determined for a network with the minimum number of switching centers specified by the user, each center being located at an initial location specified in the input data. Therefore, the process consists of firstly determining the service area for each center, and secondly making a calculation of the equipment required. The service areas are determined by assigning points which have been pre-assigned by the program user.

2.5.2 RELOCATION OF THE SWITCHING CENTERS

Starting from the previous solution and keeping the service areas constant, the aim of this optimization step is to find the most economic switching center locations. This is carried out by moving the centers (except those specified by the user as fixed locations) one by one. Each center is moved until the minimum network cost is reached. After considering all the centers, the process restarts until
the result showing minimum cost is obtained.

2.5.3 REASSIGNMENT OF THE SUBSCRIBERS

Starting from the previous solution and keeping the locations of the switching centers constant, this optimization step determines the lowest cost switching centers’ service areas. For each exchange, the distribution points limiting its service area are considered one by one. A calculation is made of the economic advantage in maintaining its assignment or in assigning it to contiguous exchanges. A reassignment is actually made when the latter alternative is more economical. All the exchanges boundaries are studied, one by one, after which, the process is repeated until the minimum cost is reached. The predefined subscriber assignments, if so specified by the program user, are respected in this step.

2.5.4 OPTIMIZATION OF CARRIER SYSTEM INSTALLATIONS

The aim of this process is to reduce the network cost by installing carrier systems in the subscriber and/or junction plants, instead of using VF. The process is carried out on any feasible network, keeping the exchange locations and service areas constant. Each junction group and subscriber distribution point is analysed one by one. The process is repeated until the minimum cost is reached. Carrier systems are installed when shown to be more economical.

2.5.5 OPTIMIZATION OF SATELLITE EXCHANGE INSTALLATIONS

The concept of satellite exchange is used, in this program, to cover three general types of switching centers homing on other ones, called parent exchanges, in the dialling process. These types, in increasing order of intelligence, are:
- Line concentrator (3)
- Satellites using the "trombone" method (4)
- Satellites using the "discriminating selector repeater" method (4)

The aim of this optimization process is to decrease the network cost by the use of these satellite exchanges instead of rural exchanges. The process applies to any feasible network. By keeping all other conditions in the network constant, this process consists of two steps:
- Each rural center is tentatively converted to the most economic type of satellite exchange satisfying the demand of the rural center service area, assuming that the satellite homes on the nearest rural center. If found economical, the rural center is converted to a satellite; for each satellite exchange of the network, its most economic homing is determined, among the rural centers surrounding the considered satellite.

This process is repeated until the minimum cost network has been obtained.

2.5.6 TELEPHONE EQUIPMENT CALCULATION PROCESS

During the execution of the optimization process steps, decisions are taken based on the total cost of the telephone equipment requirements for each alternative.

Switching Equipment Calculation

Switching equipment requirements for a center are based on the number of lines to be served, the number of junctions to the center it homes on, and the number of junctions from the centers homing on it.

In case equipment is already installed at the point where switching equipment is required, it will be used at its installed capacity or extended, if needed, up to a pre-established limit. If the requirements cannot be met, or if there is no installed equipment, new equipment will be installed to satisfy the total requirements.

Switching equipment costs are calculated by means of a linear function of the number of lines and junctions, for given ranges of these variables.

Transmission Equipment Calculation

The VF transmission equipment requirements are based on the input data VF design rules. These express the distances covered by different gauges (or gauge combinations), in the subscriber loop as well as in the junctions. Carrier equipment requirements are based on the following factors: the equipment is needed because distances are too long to be covered in VF; or a carrier solution is shown to be more economical than the VF solution (paragraph 2.5.4).

The requirements are met by first trying to make maximum use of the existing cables. When new cables are needed, the number of cables to be installed depends on economic criteria pre-established by the user.

Cable costs per length unit are calculated as a linear function of the number of pairs for each gauge. Carrier system terminal costs are computed proportional to the number of systems and channels. Carrier system repeater costs are proportional to the number of systems. The cost of other transmission equipment items, such as VF repeaters, loading coils, etc. are calculated by using linear functions.

Structure Calculation

Structure requirements are based on the number of pairs to be supported on the structure.

In case a structure is already installed, it will be used at its installed capacity or extended, if needed, up to a pre-defined limit. If the requirements are not yet satisfied, a new structure will be installed to satisfy the remaining requirements.

Structure costs are calculated as a linear function of the length.

Cost Considerations for the Existing Plant

Three cost items are associated with the existing telephone equipment: cost, net value (recovery value) and extension cost. They serve to evaluate the extent to which the existing plant should be used, as a result of any of the alternative solutions studied in the optimization process steps. When the installed equipment is suitable to satisfy the demand, it is used and its cost is taken into account (plus the cost due to extension, if needed). Otherwise, new equipment is installed and the total cost for the installation is the new equipment cost minus the existing equipment net value.

2.6 PROGRAMMING NOTES

The program has a modular structure to permit changes or extensions with minimum reprogramming effort.

The programming logic is independent of the number and dimensions of the considered variables.

The program is written in PL/I. Two versions have been prepared for IBM's OS (level F compiler) and D.O.S. (level D compiler). An overlay structure is used; its largest phase, which depends on the input data requirements (network size is the most influential factor) is of the order of 350 kbytes for a network of 40 points and 50 sections. The CPU running time for such a network size is about 3 minutes for each solution corresponding to a given number of exchanges.

Reader, printer and disk unit are required as computer peripheral devices.

3. PLANNING PROJECT

As already mentioned, NTA has acquired considerable knowledge in the field of computer aided planning of rural telephone networks. To serve a mutual purpose, an agreement was reached between NTA, STK and ITTLS to perform a real life test of the new ITTLS program by planning the area of Valdres in Norway.
At the writing of this paper, the planning project has not yet been completed. However, it is in a sufficiently advanced stage to justify the description of the experience gained by running this project and to extract some conclusions.

3.1 THE VALDRES AREA

The Valdres area (4983 km²), located some 200 km northwest of Oslo, is a typical rural area, consisting of five local communities spread along a valley which divides into two at the commercial center of the area. This point (Fagernes) is assumed to accommodate the primary switching center in the future. The economy of this choice will be established in this project.

The population (16950 in 1976 and estimated to be 18800 in 1995) is dispersed mainly along the valleys, forming long strings of subscribers with some cross connections and tentacles into minor valleys.

Farming is the backbone of the economy in the area, but lately tourism has been increasing in importance since several new hotels have been erected in the more mountainous parts of this area.

Significant for the area is also the large number of holiday houses. At present these are outnumbering the ordinary houses and flats, and the growth rate for holiday houses shows that this tendency will be even marked in the future. This creates a very uncertain situation with respect to subscriber forecast since the demand for telephones in the holiday houses until now is an unknown factor. The total number of subscribers in 1976 is 2775, estimated to increase to about 6500 in 1995.

In general, the present network is manual, but some small automatic exchanges are in operation in certain locations. Large investments have also been made in the cable plant, both subscriber and junction, during the last few years.

The area is to be converted to automatic working in the near future, and therefore NTA wants a complete development plan with the minimum PVC costs, considering existing plant.

3.2 DATA COLLECTION

Data collection in this context means the gathering of all the relevant information necessary to carry out the computer run to evaluate the chosen solutions. Obviously the actual network planning needs to be within the frame of the fundamental plans of the Administration; however, the points which will be referred to in this section are those intrinsic to the network planning study: description of the area (telephone demand forecasts and existing plant evaluation) and cost data preparation.

Description of the area is the most important and also the most time consuming part of the data collection process. It is advisable to mention here two important characteristics of the NTA data gathering process: persons responsible for this function have a strong knowledge of the area, and are fully aware of the form in which the data are going to be used. The description of the area comprises the following functions: determining the subscriber locations, and hence the distribution of subscribers in distribution points; determining the subscriber evolution and traffic characteristics per distribution point; determining the cable routes and hence the distance between distribution points; and making a record of existing plant and assessing its cost figures.

The number and placement of distribution points is a compromise between the desired degree of resolution of the area, on one hand, and the more practical needs of having a certain minimum distance between the points and also keeping the number of points within a reasonable bound, on the other.

The subscriber forecast is based on "house equivalents" (i.e., houses, flats, etc.) assuming certain number of subscribers per 100 houses equivalents (h.e.). The real forecast that is based on the number of inhabited h.e. and the actual number of subscribers per 100 h.e. in the future. The evolution in terms of h.e. is estimated from information given by the planners for each local community.

The present number of h.e. is determined by counting, numbers obtained are cross-confirmed by checking against the post office records and local authorities' registrations. Forecast for business subscribers are worked out on the basis of existing numbers, and the growth estimated by the local authorities.

Present traffic data in the Valdres area are not complete for the purpose of this study. Traffic measurements are only available for the existing automatic centers, giving the internal traffic and traffic to/from Fagernes. An important traffic aspect to be taken into account in this study is that of business subscribers. In the Valdres area, most of the business subscribers are located in the tourist facilities, which, in the tourist seasons, generate very heavy traffic mostly terminating outside the area.

Traffic data are obtained from measured values at the existing automatic exchanges. For areas not covered by automatic exchanges, the traffic is estimated from the known values of other similar areas.

The costs used are the loaded costs for installed equipment as experienced by the Administration. A factor is used to represent the costs in terms of PVC. The PVC factor assumes replacement of worn out equipment by equipment of the same type. The next section contains some examples of the way telephone element costs are prepared and defined for the program. Cost will be expressed in relative monetary units (m.u.).

3.3 PREPARING INPUT DATA

Some input data, as for instance subscriber and traffic demand, are usually prepared in such a way that no further manipulation is required to present them in a form satisfying the program input specifications. For other data, however, a previous manipulation of the collected data is needed, to adapt them to the input data format of the program; usually this process implies setting up some working hypothesis, which must be taken into account in the result analysis process. The following are some examples of the input data preparation for the Valdres area study. They will serve to illustrate the former comments as well as to show how some data are actually defined for the computer program.

Division of the Valdres Area into Sub-areas

The NTA Tariff Plan specifies local calls as those within the same local administrative community. Since the Valdres area consists of five local communities, all subscribers in one community will be connected to exchanges located within their own community. Therefore, the network in each local community may be optimized independently of the others. This is also found to be advantageous because the number of distribution points within the different local communities covers the range from about 40 to 100, giving a total of about 300 for the area. Treating networks of this size in one computer run is not practical, and therefore the local communities are handled individually.

Subscriber Loop Design Rules

Following the NTA Transmission Plan, the subscriber loop is designed for a reference equivalent of 6 dB. The subscriber network is based on the use of 0.6 mm and 0.9 mm cables, and 2 mm open wire (o.w.) lines. For economical reasons, the latter is only used to connect small groups of subscribers (4 or less). The utilization of subscriber carrier systems is not foreseen in this particular study.

The design rules of Fig. 5 are prepared according to the previous considerations. The constraint of only using o.w. for small groups of subscribers has been included. The design rules in Fig. 5 correspond to the limiting factor of 6 dB reference equivalent, without leaving any margin for the part of the loop going from the distribution points to the subscriber premises; this is because the length of that part of the loop is negligible, due to the way the distribution points were defined.
The design limiting factor for junctions is the attenuation, that is specified to be 4.8 dB in the Transmission Plan. As in the subscriber network 0.6 mm and 0.9 mm cables are also used. Cables are loaded in all cases and VF repeaters are utilized. Carrier systems can also be used, if economical. The choice is left to the program.

**Junction Design Rules**

The VF design rules, as given to the program, are shown in Fig. 6.

**Cable Costs**

Cable costs are defined for the program as shown in Fig. 7. These are loaded costs for the cable itself. The costs for structure, cable loading, VF repeaters, etc. are given separately.

**Switching Costs**

The switching cost, C, for rural exchanges, is represented by the function

\[ C = 7.65 + 0.08 \times \text{no. of lines} + 0.34 \times \text{no. of junctions} \]

Power supply and building costs are included in the switching cost function. It is assumed that this function is valid for the range of exchange sizes to be installed in the area. Satellite exchanges have not been considered in this particular study.

**3.4 Running the Program and Analysis of Results**

The following set of runs were planned for each of the sub-areas of the Valdres area:

- Considering the existing plant;
- Without considering the existing plant, to have an additional base for judgement of the results obtained by considering it.
- Sensitivity analysis, by varying the expected telephone demand in the holiday house areas.

Although these were the programmed runs, the experience has revealed that the analysis of the results from preliminary runs usually suggests the need for further runs. In fact, this has happened in the Valdres study. After the analysis of the results of the first runs was made for the communities of Øystre Slidre and Nord Aurdal, it was found that forecasted traffic characteristics were not in accordance with the existing junction network. Further investigation of the traffic flows in the area indicated that the forecasted traffic value was wrong. A new forecast of traffic flows was then made for the whole area by taking into consideration certain factors previously disregarded in the first forecasting.

The Valdres project is now in the program running phase. Consequently, it is too early to draw final conclusions. However, it seems worthwhile to take as an example the community of Vang, in order to comment on the results of a run in which the existing plant was considered.

Distance between carrier system repeaters is 1.4 km as an average for both cable gauges.

**FIG. 7: Cable Costs**

**FIG. 8: Vang Area. Subscriber placement**

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The sub-area of Vang is located at more than 30 km from Fagermeier. 42 distribution points have been defined (Fig. 8). The program has been run to consider 3 to 5 rural exchanges. 3 was selected as the minimum number of exchanges because serving the area with only two exchanges was a priori estimated to be an impractical solution, due to the very long subscriber loops implied using VF transmission. For the cost results obtained (with new installations) for these 3, 4 and 5 exchanges, optimum networks are summarized in Fig. 9. It may be observed that the minimum cost solution is obtained for 3 exchanges. Existing cables, are utilized 85%, 83% and 83% for 3, 4 and 5 exchanges respectively. This partially justifies the cost increases with the number of exchanges. In all the cases carrier systems have been used for the junction network; this is the result expected due to the long junction routes, where a VF solution is anticipated to be uneconomical.

3. To find an initial placement of a new exchange is a problem not yet sufficiently analysed. Further investigations will be carried out in this area.

4. The Valdres planning study as well as previous studies is being carried out by a joint team comprising representatives from NTA, STK and ITTLS. This procedure of appointing a working group has been found to be very efficient for this type of project. All controversial points can be discussed with the relevant people in the working group and resolved quickly without causing unnecessary delays.

ACKNOWLEDGEMENTS

We would like to acknowledge all of our colleagues at NTA, STK and ITTLS who contributed to this effort; particularly Mr. E. Garrido, at ITTLS, for his contribution to the development of the program, and Mr. O.H. Klausen for his work in implementing the program at STK and carrying out computer runs.

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4. GENERAL CONCLUSIONS

From our experience to date with the Valdres project, the following conclusions can be drawn:

1. The capability to make cost analyses and sensitivity studies which the use of a computer offers to the planning engineer are facts confirmed by experience with the first generation programs. However, this experience also revealed that an extensive manual effort is required in many cases to evaluate, in different alternative runs, the influence of existing plant or subscriber traffic characteristics; significant manual effort is also needed to quantify the effect that the use of carrier systems may have in the optimum network. The new program, now producing results as described in this paper, has largely improved the scope of the computer aids. The computer results obtained so far are encouraging; the effort needed in terms of manual calculations to establish an economic optimized network seems to be a minimum. The main tasks left for the planning engineer are to collect and prepare the input data, to establish and analyse the relevant computer runs, and to decide on the network development plan to be recommended.

2. The running time of the program has been found to be higher than expected from previous timing calculations. This fact has warranted the starting of a timing analysis study of the program; after the study the running time is expected to be reduced by: A) restructuring the most time consuming program modules; B) introducing controls on the optimization process, based on heuristic consid-