INTERNATIONAL NETWORK OPTIMIZATION METHODS

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ABSTRACT
For the past ten years or more the ITU has been involved in studying the international networks of large regions of the world. In two of these, computers were used extensively for the optimization calculations of the networks. The optimization methods were based on those recommended in CCITT Manual QAS 2 (1) for local networks. These methods had to be adapted for international networks, where the use of cost functions for various transmission systems, terrestrial as well as satellite, pose problems. The effect of the time differences between countries on the traffic distribution over 24 hours has been taken into consideration. A method of calculating the optimum combination of one-way and both-way circuits on international routes has been developed. The importance of diversification on international routes is also discussed.

1. GENERAL
The results and conclusions presented in this paper are based on the experience gained in the preparation of a Master Plan for the international telecommunication network for the Middle East and Mediterranean region. This study, undertaken by the ITU, has directly involved 28 countries of the above mentioned region. Indirectly, however, it concerns the whole world as all traffic streams of an international nature for the 28 countries are included.

The author presented a paper at the ITC-8 (2) on the same subject, giving the basic methods used for international network planning. This paper is therefore an extension of the subject, giving the latest details on the methodologies applied.

In the network optimization program explained in the following paragraph, the program of the regional network has been enlarged to cover terrestrial network routes to all of Europe as well as to some neighbouring countries in Asia and Africa (Iran, Kenya, Senegal). For all other distant destinations the program considers satellite communication means as the transmission media to be used.

It is obvious that for such a large network a rather complicated optimization program has to be defined in which several constraints must be built in, to take into consideration existing or planned international transmission systems (including existing satellite communication means such as Intelsat, Arabsat, etc.).

The optimization program aims at minimizing the annual costs for the international network of the Region. By this method we can evaluate not only the optimum network structure (routing) but also the most likely systems (transmission means) to be used for the various links. As will be seen from the detailed explanation of the network program in paragraph 2, this adds a large number of parameters to the program.

Having thus obtained an optimized network structure (on a fundamentally theoretical basis), the results have to be studied individually to take into consideration in certain cases a more realistic approach to the routing of calls, as the diversification of circuits on several terrestrial or satellite routes cannot be foreseen in a network optimization program which, by its nature, will only indicate one route, the marginally cheapest one. The importance of diversification has been discussed frequently during many meetings held with the countries concerned, and the diversification methods applied in the network configuration proposed is a result of such discussions and understandings with the countries concerned.

2. NETWORK OPTIMIZATION COMPUTER PROGRAM

2.1 General Aspects
The object of the computer program is to find the network configuration representing the minimum annual cost for a given set of data. Obviously, it is quite impossible to construct a program which in all details corresponds to the real network. A mathematical model has to be designed, accurate enough to provide results that can be used for further more detailed planning, but also simplified to such a degree that mathematical analysis becomes a practical possibility. This is especially valid for the cost and traffic structure.

Once the model has been designed, a method has to be developed to arrive at the optimal solution. Again, even for the already simplified model, it would be practically impossible to reach the exact optimum by using standard mathematical approaches; there are too many variables and some of the functions involved are not easy to work with. A reasonable way of solving the problem is sub-optimization, that is dividing the model into a number of manageable parts, each of these parts then being optimized separately under the assumption that all other parts have already been optimized, or at least solved in a near-optimal way. By starting this process at a suitable point, treating each part when the necessary information has been made available, and then repeating the whole process until the system of variables approaches stability, a very good, if not always optimal, solution can usually be achieved with reasonable computational efforts. Fortunately, telephone network optimization shows rapid convergence, provided that the initial assumptions are sufficiently good.

The flowchart (Figure 1) shows in addition to input and output data the four main steps in this iterative process and their interdependence. A short description of each of these steps is attached. Each step is again subdivided into smaller units.

The program is written in Fortran 4 and consists of approximately 4000 statements; it is implemented on the ITU computer in Geneva. Execution time for the network considered here is about 2 hours for each case.

2.2 Optimal Dimensioning of Routes
This part of the network optimization program is concerned with:

- the calculation of initial traffic streams for each pair of countries, and for each one-hour period of the day;
- determination of whether a route should be installed for any such pair, and if so, the number of circuits on that route; in other words, optimally dividing the traffic streams between lower and higher levels of the network hierarchy;
- calculation of the parameters, mean and variance, of the overflow traffic for any route and adding them to the traffic streams offered to the relevant overflow routes.

The traffic streams between any pair of countries are initially calculated by selecting the proper traffic profile, using the time difference between the countries as index, and multiplying this by the total daily traffic volume, thus obtaining the traffic value for each one-hour period of the day.

Starting at the lowest level of the hierarchy the program will then investigate all pairs of countries to determine the type and size of the route. In each case there are three possibilities:

D: Predetermined Low-Loss Route;
The number of circuits on such a route can be calculated directly from the traffic offered and the grade of service stipulated; no overflow traffic to higher levels.

T: Predetermined Non-Existent Route;
Number of circuits zero; all traffic is added to appropriate traffic streams on higher levels.

H: High-Usage Route;
The number of circuits will be optimized and is therefore dependent not only on the traffic offered, but also on the ratio between the cost per circuit on the direct route and on the relevant overflow routes.

Theories and methods for optimization of the number of circuits on H-routes can be found in various papers by Y. Rapp (3) et al.; these are, however, valid only for networks with coincident busy hours. As this is not the case in the network considered here, a special method
had to be developed to take into account the non-coincidence of busy hours.

As mentioned above, cost per circuit for the various routes involved in a traffic case have to be known prior to optimization. As the proper cost calculation will not be made until we reach Steps 4 and 5 of this iterative process, assumptions have to be made at the start of the first iteration. These assumptions are described in Step 4.

When the proper number of circuits has been determined, overflow traffic can be calculated for each hour of the day. These are then added to the traffic streams offered to higher levels, and the process is repeated until all routes have been processed.

2.3 Both-way Circuits

The procedure described in Step 2 dimensions and optimizes all routes as if they were one-way circuits. In reality most routes in a long distance network will usually be both-way circuits or an economic mixture of one-way and both-way circuits (see paragraph 8).

Although it is simple enough to calculate correctly the most economic number of circuits for last choice routes, the optimization of an alternative circuit is converted into a two-way circuit as a problem. To illustrate the problem, consider the configuration shown below:

![Configuration Diagram]

If the traffic A12 and A21 are offered to separate routes, i.e., one-way circuits, the overflow traffic from each of these routes will be statistically independent and we can therefore apply the standard dimensioning methods, e.g., Erlang and Wilkinson, for the calculation of the number of circuits needed for the tandem routes.

If, on the other hand, A12 and A21 are offered to the same route, as is the case with both-way circuits, these methods cannot be applied as the overflow traffic streams are now dependent and calculations of a much more complicated and time-consuming nature have to be used. For a network of this size, this would be quite impractical and as a reasonable compromise, we have therefore adopted the following procedure:

- all routes in the network are optimized and dimensioned as if we were dealing only with one-way circuits;
- taking each pair of exchanges in turn, the number of circuits considered as both-way circuits in such a way that the overflow traffic does not increase, thus avoiding changes in the traffic pattern on the higher levels of the network hierarchy.

This approximative method will result in a much more economic network than the one originally calculated as in Step 2, although there will still be a slight overprovision of circuits.

2.4 Choice of Paths (Way)

The selected path for the route between two countries is mainly on economic and practical considerations. These are sometimes in conflict with each other.

Given the choice of different paths between origin and destination the computer program will always select the most economic solution. This, however, might not be the desired solution for a variety of reasons, e.g., security. There is an option to predetermine any path, or even assign the route to a number of paths (diversification).

To find the optimal path, i.e., the most economic from an overall network point of view, the program assumes that Step 5, choice of the best, i.e., most economic, combination of transmission systems; we now know:

- the total demand of transmission channels (calculated in Step 4);
- the existing transmission systems and their capacities;
- the systems, or combinations of systems, that can be installed on any particular link and the corresponding costs and capacities.

The first step is quite obvious; if the demand for channels is less than the total capacity of the existing systems, no further investigations need be made for that link. The computer program will calculate total costs, and cost per circuit, which will then be used for re-optimization according to Step 2 and 4 in the next iteration.

Should the demand exceed the existing capacity, the excess number of circuits will be used to determine the optimal type and number of new systems. This is done by using a technique known as "Dynamic Programming", which very efficiently investigates all relevant combinations of systems and chooses the cheapest one satisfying the circuit demand. Again, total costs and per circuit costs are calculated for future use.

3. INPUT DATA USED FOR THE NETWORK CALCULATIONS

An extremely large volume of data had been assembled and analysed before obtaining the necessary forecasts to be used in the calculations, made for the base years 1980, 1985 and 1990.

3.1 International Telephone Traffic Forecasts

On the basis of forecasts, traffic is calculated from each of the 28 countries to each of the 75 destinations used to represent all world destinations.

3.2 Diurnal Telephone Traffic Distribution

The use of a fixed concentration factor for calculating the busy hour traffic is usually valid for relations where the time difference in working hours is zero or very small, say a few hours.

In the case of this Region, however, the time-differences within the Region are between 0 and 4 hours. For traffic to countries outside the Region the difference attains ± 12 hours as the destinations concern all the world.

For such networks a fixed concentration factor should not be used, as has been shown in papers presented to the ITC Congresses and also studied by the CCITT Study Groups. The time profiles recommended in CCITT Rec. E.523 have been used in the computer network calculation program.

3.3 Node Numbers and Permissible Routing between Nodes

All existing and potential international arteries are represented by a series of segments, each segment being defined by two nodes.

The nodes are selected at important points in the network, principally where there is a branching point. The network also includes nodes in the arteries through a country that are mainly related to the national network structure of that country, as in the calculations we have also considered the national circuit requirement for those segments that carry both national and international traffic.

3.4 Systems and Systems' Costs

The various types of transmission systems allowed for in the computer calculations cover all important systems known today. They include submarine cables, troposcatter system, radio relay systems with 960 or 1880 ch carriers in stages of 1 + 1 to 6 + 1 carriers, land coaxial cable systems, Intelsat systems (Atlantic Ocean and Indian Ocean) and the regional satellite system ARABSAT for the Arab League countries, planned to be in operation in 1982.

3.5 National Trunk Circuit Forecasts

Most international transmission systems also carry national trunk traffic for parts of their length. To calculate the marginal costs per circuit, both the national and international circuit components must be known. The national trunk circuits required have therefore been evaluated for the base years 1980, 1985 and 1990.

3.6 Permissible and Mandatory Systems

Systems that already exist or have been ordered are considered as mandatory systems. They are thus indicated in the input data, specifying the type of system (see 3.4) with its cost functions, as well as its exact routing pattern, according to the node numbers attributed.

All kinds of systems that can possibly exist between two nodes are called permissible systems. Thus for each segment of the network is indicated which of the specified systems (3.4) could be considered, so that the optimization process will test the maximum possible alternatives in order to come to the best solution. This is also the case for the segments where mandatory systems exist. Once the mandatory system is filled up to its capacity the calculation process
starts looking for an additional system, or extension of existing system which is then specified.

4. ROUTING CONSIDERATIONS

4.1 General

During the period of the study of the Master Plan for the Middle East and Mediterranean Telecommunication Network, over one hundred computer runs have been made in order to define the optimized network structure.

They have included the study of a large number of structural models, based on the CCITT hierarchical network structure CT2 - CT1 - CT1 - CT2 - CT3 as given in CCITT Rec. E.171.

It should, however, be mentioned that since in most of the Project countries at least one satellite communication earth station is available, a decision making part of its international traffic is carried over these to distant countries and by existing transmission links to the neighbouring countries. The part of the international traffic that has to pass one or more transit countries is therefore small, and the back-bone route via several ITSC's is used only in a few cases and basically for the very low traffic destinations and for overflow traffic.

4.2 Satellite Communication Routes

4.2.1 ARABSAT

The decision to establish an Arab Satellite system was taken in 1976. This will introduce a new and efficient means of communication between the countries of the Arab League. It has been included in the network optimization program, based on the cost estimation for such a system.

The ARABSAT system will be used for both TV/Broadcasting and Telecommunication purposes. As these network optimization calculations only use telephone traffic forecasts and therefore only give the required telephone circuits, the costs used for the ARabsat system have been reduced to 75% of total estimated costs.

4.2.2 INTELSAT

Most of the Project countries have access to the INTELSAT System by at least one earth station. Several countries have, or are planning, earth stations to both the Atlantic Ocean Satellite(s) and to the Indian Ocean Satellite.

In the network optimization program for this Master Plan a distinction has been made between the two satellite regions, Atlantic and Indian. For this reason traffic streams that can only be reached by one of these satellites (where there is not an overlap of the coverage area), may have to be routed via an available earth station in a neighbouring country.

4.3 Diversification

Introduction of the diversification aspect in the computer program would imply an estimation in monetary terms of the value of such diversification. This is probably not possible, and therefore the basic computer calculations made in the Master Plan do not give an answer on this point.

Diversification on terrestrial and Intelsat routes have generally been made by allocating an equal number of circuits for each possible route.

Terrestrial routes have also been selected having the lowest possible number of transit countries involved. For the Arab League countries a percentage distribution between circuits using Arabsat and terrestrial routes has been drawn up in consultation with the countries concerned.

The maximum diversification used is division of the circuits into five routes, each carrying 20% of the total number of circuits. Obviously such an extensive diversification can only be used when the circuit requirements are greater and several terrestrial and satellite routes are available. In most cases the diversification applied in the regional study is based on fewer possible routes.

5. MASTER PLAN NETWORK CONFIGURATION, CIRCUIT REQUIREMENTS

On the basis of the above considerations, the final results of the computer calculations are represented in three optimized networks, one for each base year 1980, 1985 and 1990.

As the input data refers only to international telephone traffic, the circuit requirements calculated do not cover the need for telex, telegraph or leased circuits. A limited study of the network has shown that adding about 25% to the calculated circuit requirements for the telephone service will suffice to cover the other abovementioned services.

However, a detailed study of the network configuration and circuit requirements of the telex service of the region is to be undertaken.

6. CHOICE OF TRANSMISSION SYSTEMS

The outcome of the computer calculations with regard to selected transmission systems is given at the end of the calculation printouts.

Studying the results for the years 1980, 1985 and 1990, we find that where there are differences between the years, the choice may have been a coaxial cable system in 1980 "replaced" in 1990 by a microwave system.

Where the systems selected for the base years 1980, 1985 and 1990 are the same, this is an indication that the system appears to be the most economical for the 10-year period considered.

Where the systems selected differ, the matter obviously has to be studied in greater depth to consider circuit requirements for the link during a period of say 10 to 20 years depending on the type of system foreseen.

7. CALCULATION OF THE optimum NUMBER OF ONE-WAY AND BOTH-WAY CIRCUITS FOR AN INTERNATIONAL ROUTE

The computer calculations used for the establishment of this Master Plan are originally based on one-way circuit estimates. These are then transferred to both-way circuits, as explained in paragraph 2.

However, the most economical solution depends on many factors, e.g., the traffic volume in each direction, time difference between the traffic destinations, cost ratio between a one-way and a both-way link, and possible congestion.

The problem has been studied and a separate computer program written which gives the best estimation of one-way and both-way circuits.

Since the possible combinations of variables are practically unlimited, it is impossible to provide a tabular printout. The formulations used for the calculations are given in Figure 2.

The results for the case in which the traffic in both directions is equal and for certain cost ratios (3), have been tabulated.

Figures 3, 4, 5 and 6 were prepared on the basis of these tables. Figure 3 shows how the calculated number of both-way circuits depends on the time difference between the two destinations. This example only refers to the fact that the link carries traffic with one specific time difference. In reality there may be several traffic streams with different time differences over the same link, and these can be calculated from the computer program developed.

The other figures (4, 5 and 6) show that the lower the cost of a one-way link (transmission circuit, multiplex and termination in international switching centres relative to a both-way link, the greater is the saving by using an optimized combination of one-way and both-way links instead of only both-way links. This fact is emphasized by increasing traffic and shows cost savings that may be of the order of 20-30%.

8. CONCLUDING REMARKS

It has been reassuring to note that traffic inputs for the various base years, covering a period of 10 years, result in an almost identical network configuration.

The requirements in circuits is obviously in direct relation to the traffic data input. The fact that the network configuration is not very sensitive has assured us that although we have not yet been able to include in detail the traffic requirements for telex and other services, we may expect to find that this will not change the already established network configuration.

A matter of greater concern is how to develop an optimized reliable international network, considering the introduction of diversification, automatic rerouting, etc., and finding a method of evaluating the value of such diversification and network management in order to design an international network to be technologically optimized to satisfy the customers of today and tomorrow.
9. ACKNOWLEDGEMENT

My acknowledgement are due to LM Ericsson, Stockholm, who have provided the computer program used by ITU for the network planning of the above-mentioned study. I am very grateful to the late Dr. Yngve Rapp who designed these programs and who was always prepared to give his advice and encouragement on work in this field.

I also acknowledge the contribution towards modification of these programs to suit the special needs of the international network planning undertaken by ITU, made by Mr. Thomas Fried who participated on several occasions in the ITU Project in the capacity of ITU expert.

10. REFERENCES

(1) CCITT Handbook on local Telephone Networks, (1968), GAS 2.


FIGURE 1

INPUT
Grade of service
Network hierarchy
Traffic profiles
Diurnal traffic volume
Routing constraints
Geographic lay-out
Transmission systems
Switching costs

OPTIMAL DIMENSIONING OF ROUTES
Traffic distribution
Circuit cost
Efficiency of backbone routes
Number of circuits

Adjustment for both-way circuits

Optimal choice of path for each route

Optimal choice of transmission systems for each link

Adjustment for route diversification

RESULTS
Traffic flow
Number of circuits
Route congestion
Circuit cost
Routing
Route paths
No. of circuits, and costs, per link
Transmission systems per link
Summaries: traffics, circuits, costs

Flow chart for Network Planning Computer Program

FIGURE 2

\[
\begin{align*}
& i \rightarrow j & M_i(t) \rightarrow o \ldots o & m_i(t) & v_i(t) \rightarrow \{ & M_j(t) & V(t) & \cdots \}
\end{align*}
\]

\[
\begin{align*}
& j \rightarrow i & M_j(t) \rightarrow o \ldots o & m_j(t) & v_j(t) \rightarrow \{ & M_i(t) & V(t) & \cdots \}
\end{align*}
\]

OPTIMIZE : \( (N_1 + N_2) \cdot \xi + N_{BW} \)

Explanation of Symbols:

- \( A \) = daily traffic volume in Erlang hours, \( i \rightarrow j \text{ and } j \rightarrow i \)
- \( N_1(t) \) = traffic offered from \( i \rightarrow j \) in time interval \( t \) (from \( A \) and traffic profile)
- \( m_1(t) \) = mean of traffic rejected from \( N_1 \) one-way circuits
- \( v_1(t) \) = variance of traffic rejected from \( N_1 \) one-way circuits
- \( N_2 \) = number of one-way circuits, \( i \rightarrow j \)
- \( N_{BW} \) = number of both-way circuits, \( i \rightarrow j \)
- \( \xi \) = cost ratio between one-way and both-way circuits
- \( B \) = maximum permissible congestion

Formula used:

\[
\begin{align*}
& m_1(t) \{ \text{calculated in the usual way, i.e.} \\
& v_1(t) \{ \text{calculated in the usual way, i.e.} \\
& m_1(t) = H_1(t) \cdot N_2(N_1(t)) \\
& v_1(t) = m_1(t) \cdot \left[ 1 - m_1(t) + \frac{N_1(t)}{N_1 + 1 + m_1(t) - N_1(t)} \right] \\
& K(t) = m_1(t) + m_2(t) \\
& V(t) = v_1(t) + v_2(t) \\
& N_{BW} = f(H(t), V(t), B_{BW}); \text{ according to Wilkinson (4)} \\
& \text{where } B_{BW} = \min\left[ \frac{B_1}{B_2}, \frac{B}{B_{BW}} \right] \\
& \text{and } B_1 = \max\left[ \frac{m_1(t)}{N_1(t)} \right] \\
& B_2 = \max\left[ \frac{m_2(t)}{N_2(t)} \right]
\end{align*}
\]

For cost comparison \( N_{BW} \) has been calculated exact, i.e., as a non-integer value. Before printing table value \( N_{BW} \) has been rounded upwards to the next integer.