

DOMESTIC LONG-DISTANCE COMMUNICATIONS NETWORK STUDY
COMMUNICATIONS SYSTEMS ENGINEERING

THE NETWORK OPTIMIZATION TECHNIQUE USED IN THE
DOMESTIC LONG-DISTANCE COMMUNICATIONS NETWORK STUDY

by

R.R. Bowen, G.A. Neufeld, A.R. Kaye
Systems Modelling & Analysis Group

January 1974

HE
7814
D665
1974
#08

HE
7814
D665
1974
#08

DOMESTIC LONG-DISTANCE COMMUNICATIONS NETWORK STUDY

Communications Systems Engineering

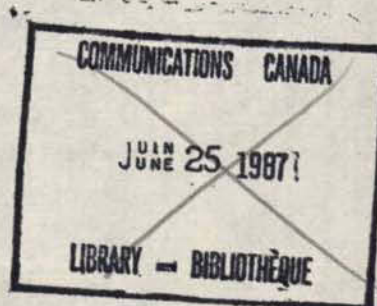
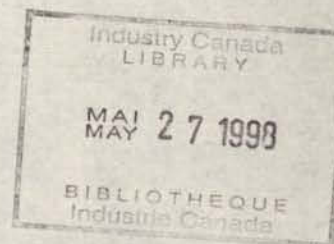
25 THE NETWORK OPTIMIZATION TECHNIQUE USED IN THE
DOMESTIC LONG-DISTANCE COMMUNICATIONS NETWORK STUDY

by

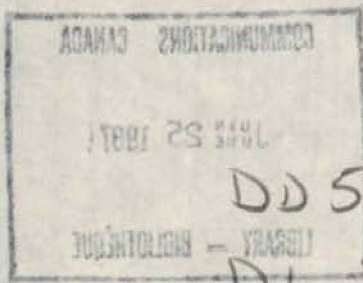
1. [R.R. Bowen, G.A. Neufeld, A.R. Kaye
Systems Modelling & Analysis Group

CRC PROGRAM MANAGER: W.L. Hatton
PROJECT LEADER: A.R. Kaye

DLDCNS Report No: 8
Date of Issue: January 1974



HE
7814
DL65
1974
#08



DD 5300190

DL 5300223

TABLE OF CONTENTS

	PAGE
1. INTRODUCTION	1
2. AN OVERVIEW OF THE SYNTHESIS TECHNIQUE USED	2
3. THE MEASURE USED TO COMPARE FEASIBLE NETWORKS	4
4. PREDICTED END-TO-END CIRCUIT REQUIREMENTS ON THE LONG-HAUL NETWORK	7
5. MODEL OF THE LONG-HAUL COMMUNICATION NETWORK	8
6. COMMUNICATION LINKS AND THEIR COSTS	15
6.1 EXISTING TERRESTRIAL SYSTEMS	16
6.2 NEW TERRESTRIAL SYSTEMS	22
6.3 SATELLITE GROUND STATION COSTS	26
6.4 SATELLITE SPACE SEGMENT COSTS	29
7. THE OPTIMAL ROUTING ALGORITHM	32
8. THE DEMAND-COST STRATEGY	34
9. CHOICE OF SATELLITE SYSTEM PARAMETERS	43
10. OPTIMIZATION OVER THE 1980-1985 INTERVAL	44
REFERENCES	46

i. INTRODUCTION

This report provides a description of the network optimization technique used in the DLDCNS. Previous memoranda on the subject are combined, summarized and corrected.

This report is written as an interim record of the optimization methodology used in the Domestic Long-Distance Communications Network Study (DLDCNS). The methodology has been continuously improved over the past year or more. Because of this continuous improvement many of the references 1 to 7 are not accurate statements of the method now being used for network optimization. The purpose of this report is to indicate how the techniques described previously have been combined and modified to form the present network synthesis technique.

2. AN OVERVIEW OF THE SYNTHESIS TECHNIQUE USED

The steps taken in optimizing the satellite/terrestrial network are summarized. Each of these steps are described in detail in later sections of the report.

In order to synthesize a cost-effective Canadian satellite/terrestrial network for the 1980's, the following steps have been and are being taken:

- i) A description of what is meant by an optimum network is specified. This description must be or lead to a quantitative measure by which networks can be compared.
- ii) A description of the existing network is determined. This description must:
 - a) describe the network as it is in 1973,
 - b) be "expandable" as far as 1990, in that subsystems that may be introduced into the network in the 1980's can become part of the model.
 - c) specify the capabilities and the relevant costs of each system in the network,
 - d) be complex enough to accurately model the essential features of the network, and yet simple enough that different expansion options may be easily chosen and evaluated.
- iii) A description of the most likely traffic loads on the network, and the upper and lower bounds on that traffic estimate, must be made. This traffic includes:
 - a) heavy-route long-haul voice, data, and leased-line requirements in southern Canada, both of the interprovincial and intraprovincial type.

- b) television distribution by the networks such as CBC, CTV and Global TV, and by the cable TV companies and education departments of the provincial governments.
- c) thin-route telephone and data service to remote communities.
- iv) A synthesis procedure for network expansion must be developed. A necessary part of this procedure is an algorithm for routing traffic through a constrained network at minimum cost. As well, however, it is necessary to develop strategies to determine what network options to investigate, and to consider the large number of possible satellite systems in an organized way.

Each of these four areas of activity are discussed in detail below.

3. THE MEASURE USED TO COMPARE FEASIBLE NETWORKS

The optimum network is defined to be the one with minimum cost over the 1973 to 1985 interval, taking into account maintenance, operation, and major refurbishment of existing systems, and maintenance, operation and amortization of new systems.

The basic objective of the DLDCS is to determine the expansion of the long-distance network which would be of greatest national benefit in the long term. This is interpreted to mean expansion of the network to meet predicted traffic requirements in the 1980-1985 time-frame at minimum cost to the nation, with perhaps some consideration of how the network might expand in the post-1985 time-frame.

The approach described in reference [3] is being used. Essentially, that approach is to

- i) ignore all costs that were incurred prior to 1973, since these costs cannot be recovered by changing the network. (Salvage of large microwave systems for sale elsewhere has never been done to date in North America to the author's knowledge. DND has sold mid-Canada system communication links to TCTS, but they are used in place.)
- ii) of the costs after 1973, consider only amortization, refurbishment, maintenance, and operations costs, and ignore corporation profit and income tax "costs".

The costs considered are only those real costs that may change by a re-design of the network. Further, the costs are only costs to the nation as a whole. Items such as profit and taxes are simply a redistribution of wealth within the country.

It has been commented that such a costing procedure is not "realistic", in that it is not the same as that used by the common carriers. It is true that the network may be different if outstanding debt of old systems was included and costs such as profit and tax were included. However, neither system would likely be the same as that which is designed to return maximum profit to a particular common carrier, be it TCTS, CN/CP, or Telesat.

Having specified what costs are to be considered, the next step is to determine in general terms the method used to determine the optimum system. The "optimum" system is that which meets the traffic requirements, fidelity requirements, and network protection requirements at minimum cost. The cost that will be minimized is the present value (in 1980) of the amortization, refurbishment, maintenance, and operations costs in the 1980-1985 time-frame. Consideration will also be given to making this system compatible with the network in the 1973-1980 time-frame and the post-1985 period. This will be done in the following way:

- Step 1: Determine the annual costs of existing and new radio, cable, waveguide, and satellite systems as a function of installed circuit capacity. (This will be discussed in more detail below.)
- Step 2: Determine the minimum cost network for each of the "spot" times 1980, 1985, and 1990. (This will be done with the optimum routing algorithm and the demand-cost strategy, as explained below.)
- Step 3: If these three "spot optimum" networks are not compatible, in that major systems are in an earlier network and not in a later one, or if the satellites in the different networks are not the same, then the "spot optimum" networks will have to be modified so that they are compatible and the present value in 1980 of their costs is minimized.

4. PREDICTED END-TO-END CIRCUIT REQUIREMENTS ON THE LONG-HAUL NETWORK

The network is designed to meet the voice, data, and video requirements of the 1980's. Forecasts of these requirements have been made from available data, and are given in detail in other DLDCNS serial documents.

The raw information on which network requirements in the 1980's must be based are voice and data requirements prior to 1973, population growth and economic growth forecasts for the 1973-1990 interval, predictions of the end-to-end circuit requirements of the common carriers for the 1973 to 1980 interval, and stated requirements of the television networks in the 1980's. Interprovincial and intraprovincial public switched voice and total voice circuit end-to-end requirements have been determined by Keefer [9,10,11]. The CBC requirements are taken from reference 12; requirements of the other television networks are not known, so the estimates stated in reference [7], based on zero data, are used until data becomes available.

It is assumed that these requirements are exogenous variables, i.e. they are independent of transmission costs. One reason for making this assumption is that long-haul transmission rates are determined by many factors, only one of which is transmission costs.

5. MODEL OF THE LONG-HAUL COMMUNICATION NETWORK

A model of the Canadian terrestrial long-haul transmission system is described. The model is complex enough to include all large concentrations of television and telephone traffic, and yet simple enough to be analyzed. The model allows for expansion throughout the 1980's, and includes potential satellite ground stations.

At present, the long-haul heavy-route communication network in Canada consists of two 4 GHz radio systems owned by the members of TCTS, a 6 GHz radio system owned by CN/CP, and the Anik 4/6 GHz satellite system owned by Telesat Canada. In almost all cases these systems are operating far below their ultimate capacity of 16,800 full-duplex voice circuits on the 4 GHz systems and 10,800 voice circuits on the 6 GHz system.

The terrestrial systems include hundreds of radio repeater sites. Rather than include each of these locations as nodes in the long-haul network model, only nodes which are one or more of:

- i) major population centres and so a source of significant long-haul telephone traffic,
- ii) a regional distribution centre for CBC television programs, or
- iii) an important network branch point,

are included. The simplified network includes 20 nodes and 26

connecting links, as shown in Figs. 1 and 2. The reason for including the nodes in the network are shown in Fig. 1. Four nodes in Quebec and the maritimes are not traffic sources, but are included because they are major branch points. Several of the links of Fig. 1 have several systems in parallel, as shown in Fig. 2.

The nodes shown in Figure 1 and 2 are not single repeater sites; some metropolitan nodes cover hundreds of square miles and include as many as ten junction repeaters and switching centres. These complex nodes have been replaced by star nodes, with one branch of the star going to each other major node that is directly connected to the node being represented. Separate star representations are used to model the TCTS and the CN/CP networks. The now rather artificial network is partly shown in Fig. 3. This network model is developed to allow various network expansion options to be investigated, rather than to accurately represent the network in the field node by node.

The ground stations of the satellite system are modelled as extensions of the network shown in Figures 1 to 3. Satellite ground terminals in southern Canada will carry one or more of the following kinds of traffic:

- i) television transmit and receive,
- ii) television receive only,
- iii) multiple-access voice, likely TDMA,
- iv) dedicated use of two satellite transponders between two ground stations.

FIGURE-1

SIMPLIFIED NETWORK MODEL WITH 20 NODES AND 26 LINKS

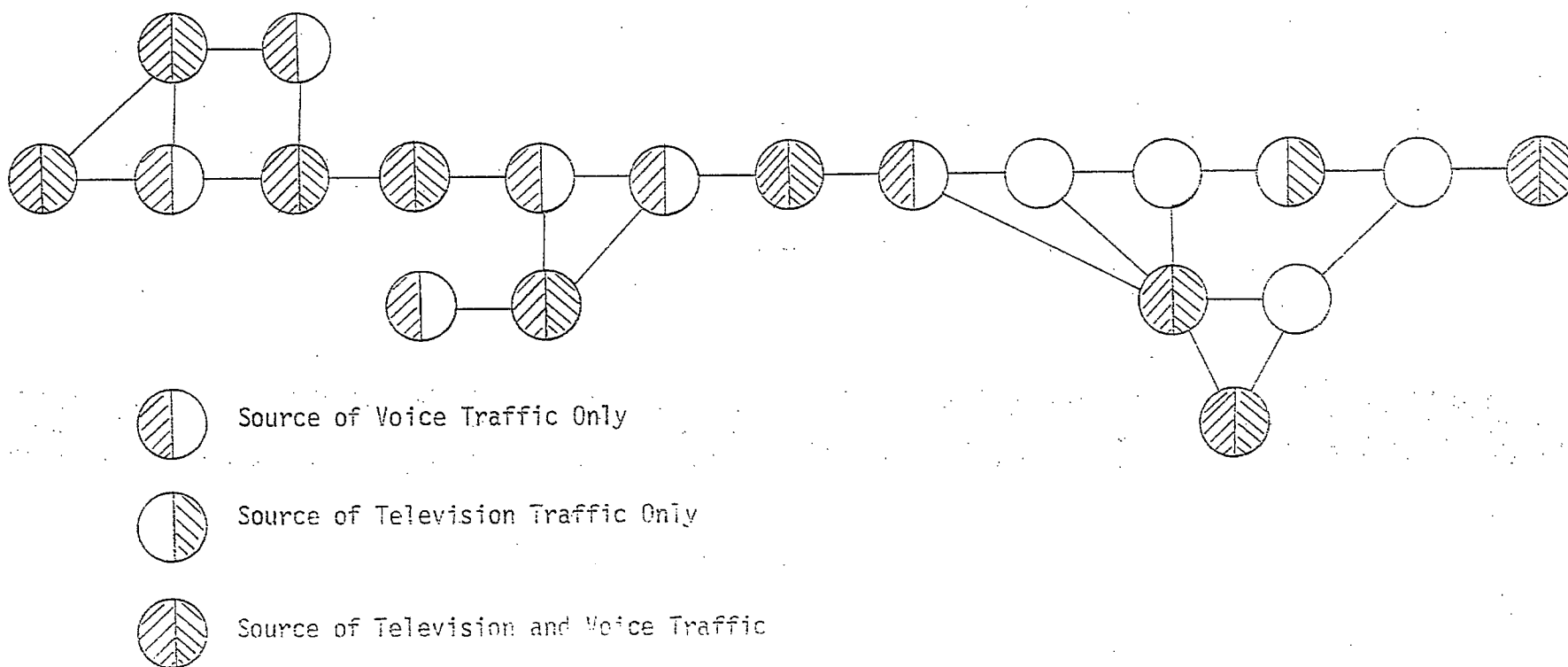
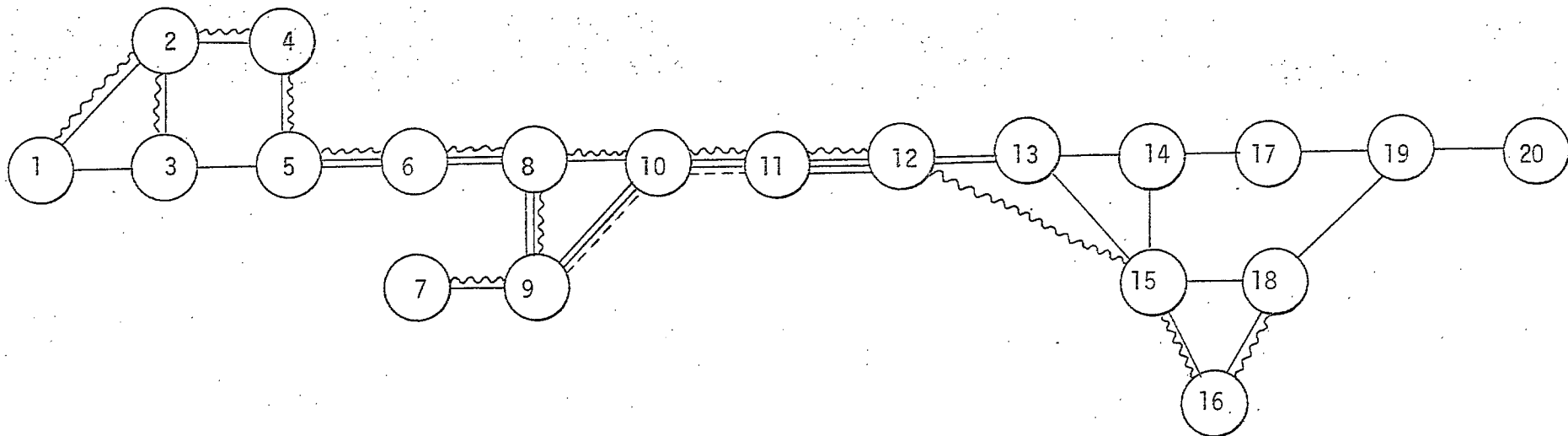


FIGURE 2

EXISTING TERRESTRIAL CAPACITY OF THE LONG-HAUL NETWORK



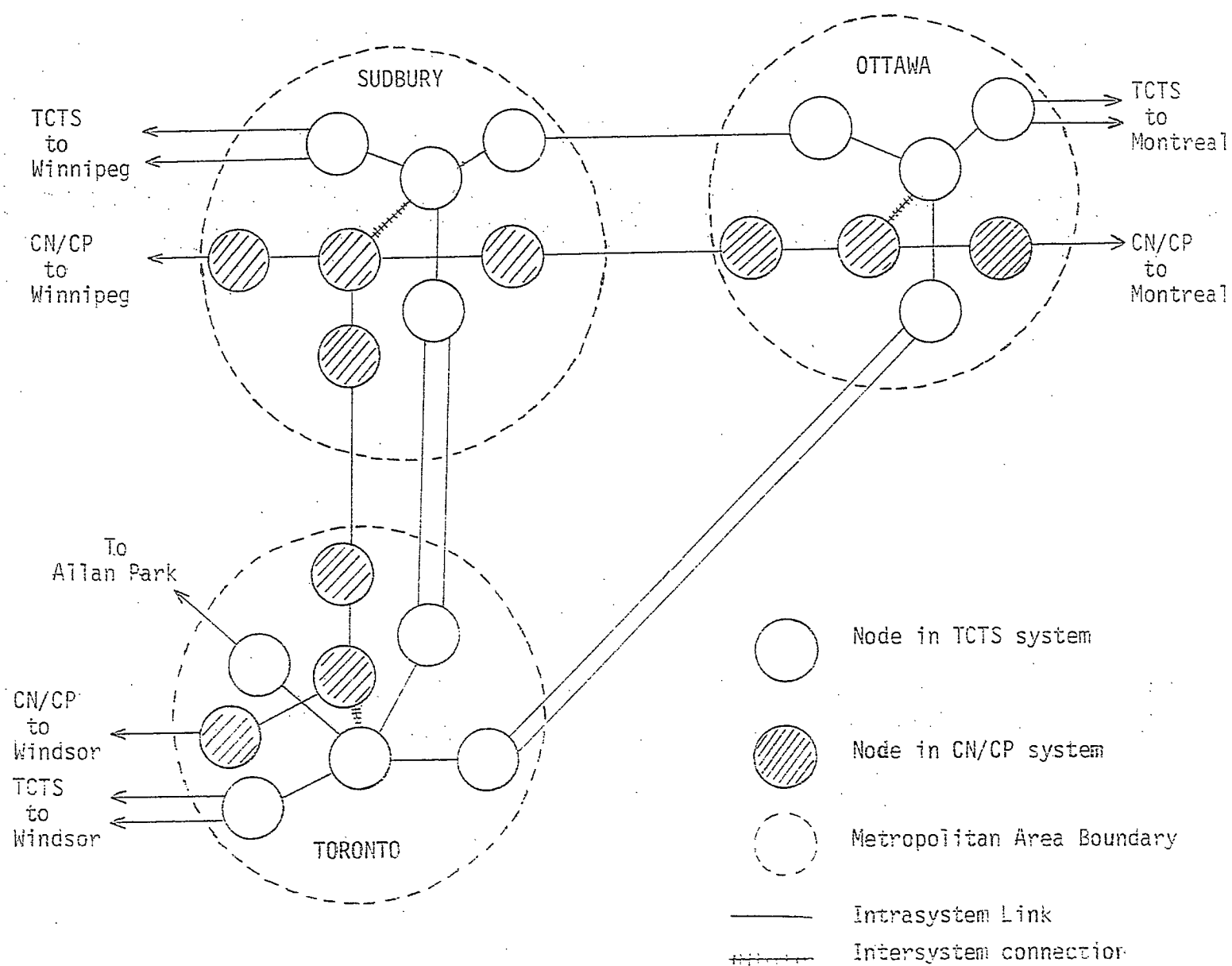
NODES:

- | | | | |
|--------------|-------------|------------------|-----------------|
| 1. Vancouver | 6. Winnipeg | 11. Montreal | 16. Halifax |
| 2. Edmonton | 7. Windsor | 12. Quebec City | 17. Sept Isles |
| 3. Calgary | 8. Sudbury | 13. Riv. du Loup | 18. Sydney |
| 4. Saskatoon | 9. Toronto | 14. Riv. Blanche | 19. Cornerbrook |
| 5. Regina | 10. Ottawa | 15. Moncton | 20. St. John's |

LEGEND:

- | | |
|-------|-------------------------------|
| ————— | 4 GHz Radio System |
| | 16,800 voice circuit capacity |
| ~~~~~ | 6 GHz Radio System |
| | 10,800 voice circuit capacity |
| ----- | Digital Coaxial Cable System |
| | 20,160 voice circuit capacity |

FIGURE 3



The cost of ground station equipment varies widely among that required for the four types of traffic. For instance, television receive-only is much less costly than television transmit and receive. Because of this, a satellite ground station and the terrestrial backhaul system to the terrestrial long-haul network is modelled as shown in Figure 4. Branches of the network representing the ground station are labelled a to e, and nodes are labelled A to F. Television receive-only traffic is carried on branch a, television transmit-and-receive on branch b, multiple-access voice on branch c, and dedicated-transponder voice on branch d. All traffic to the satellite is carried on branch e. Node F is identical to the node at the metropolitan junction to which the ground terminal is associated.

The satellite is represented by a separate node in the network. Nodes A, B, C, and D of each ground station (see Fig. 4) are connected to the satellite.

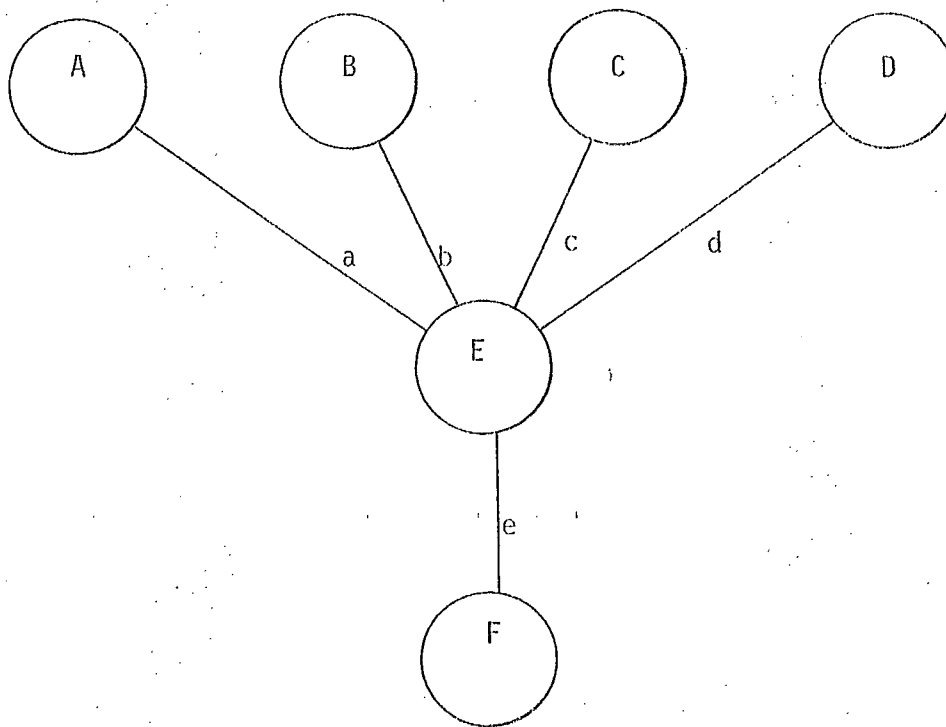


FIGURE 4

NETWORK MODEL OF A SATELLITE EARTH STATION

6. COMMUNICATION LINKS AND THEIR COSTS

The salient characteristics and costs of systems that may become part of the long-haul transmission network in the 1980's are described. Relationships between capital costs and annual costs of these systems are developed.

The network model is such that all costs can be associated with a link of the network, and ownership of each link in the network except the intersystem connections of Fig. 3 can be specified. The long-distance links are assumed to be one of the following:

- i) analog microwave radio links existing in 1973,
- ii) new analog microwave radio links,
- iii) new digital radio links,
- iv) new digital coaxial cable links,
- v) new digital millimetre waveguide links.

The numerical values of the costs of these systems, and the technique used to determine those costs from available data is described below.

6.1 EXISTING TERRESTRIAL SYSTEMS

Existing terrestrial long-haul transmission systems are 4 GHz and 6 GHz analog radio systems operated by TCTS and CN/CP respectively. Determination of the annual costs of these systems takes into account the fact that these systems are already in the field and have negligible net salvage value.

Let us first consider existing analog microwave radio systems, owned by either TCTS or by CN/CP. Information is available giving the location of each repeater site in these systems, the frequencies used, and installed equipment at each frequency band. In the TCTS systems 4 GHz is used for long-haul traffic, and 2 GHz, 6 GHz, 7 GHz, and 8 GHz are used for local traffic. The first step in determining the annual cost of such a system is to determine the capital cost of each repeater site if it were built in 1973. The cost of the building, tower, roads, etc. are divided between long-haul and local systems in proportion to the number of radio channels used by each. This information can be used to determine the equivalent new capital cost of the long-haul portion of the links shown in Figures 1 to 3, as a function of installed capacity on that link. It is assumed that each 4 GHz radio channel can be loaded with 1,200 voice channels or a TV program with several audio channels, and that each low 6 GHz radio channel can carry 1,800 voice channels

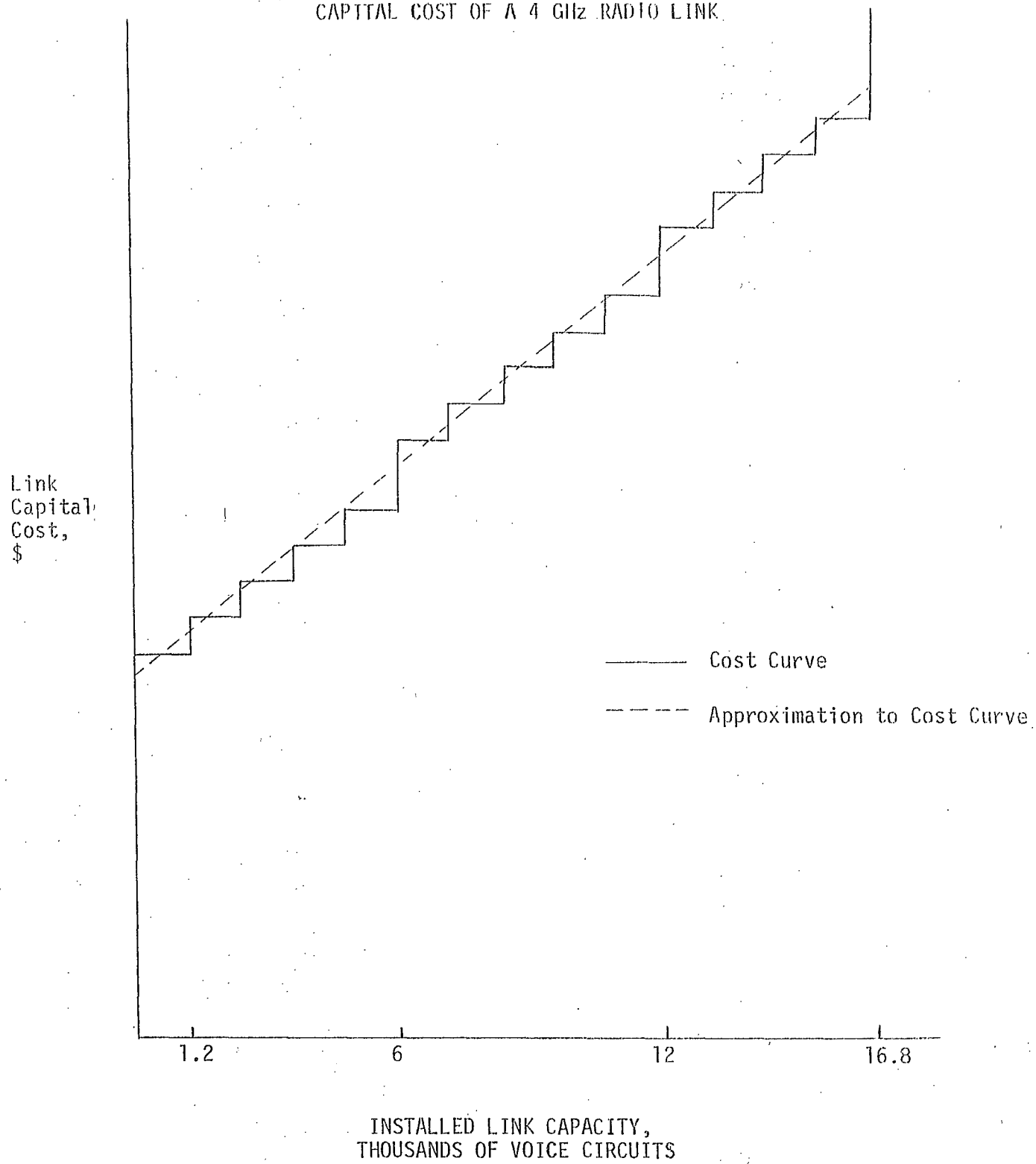
or a TV program with audio. This loading is possible with modern transceivers with TWT output amplifiers, in contrast with the 480 channel and 960 channel loading of older transceivers.

The capital cost of a 4 GHz radio link as a function of installed link capacity is the step-function shown in Fig. 5. Larger costs are incurred when introducing the sixth and the eleventh operating channel. The step-function cost curve is approximated by the ramp, also shown in Fig. 5.

The next step is to convert this capital cost function to an annual cost function, again in terms of installed link capacity. If the amount of traffic carried on the link as a function of time over its complete lifetime were known, then the technique discussed in reference 2 could be used. However, that information is not known a priori; for the time interval between when the system is installed and the present time, this information is known by the carriers (if they have in fact kept these records) but not by CSE, and for the future the traffic carried on an individual route as a function of time is a result of the study, rather than an input. Thus a simpler method of determining annual costs must be determined. Such a method, used in this study, is described in reference 3. This method is to assume that amortization costs, refurbishment costs, and maintenance and operations costs, which together form the system annual costs, are together a fixed percentage of the system capital costs. The result is a system annual cost function in terms of installed system capacity. This function for each link

FIGURE 5

CAPITAL COST OF A 4 GHz RADIO LINK



in the network, together with a description of the network topology, and the end-to-end traffic requirements of the network, forms the input data for the optimal routing algorithm.

Let us now consider how to determine this annual cost function in detail, bearing in mind that we are only going to consider future costs of the network. Consider first the initial step in the capital cost curve. This is the cost of the building, roads, prime power, tower, antenna, etc. For an existing system it is only necessary to consider M&O costs of these items. M&O costs are assumed to be a fixed percentage, α , of the capital costs of the system. (No information is available on different values of α for roads, buildings, antenna systems, and electronic equipment; an overall value of 13% is assumed.)

Consider next the annual costs of electronic equipment that is already installed. It is not necessary to pay complete amortization costs of this equipment, because its purchase was in the past, and past costs are not considered. However, it is necessary to refurbish this equipment at some future date because of obsolescence. These refurbishment costs are

$$A_R = \frac{C \cdot i \cdot (1+i)^{-N_1}}{\{1 - (1+i)^{-(N_1 + N_2)}\}} \quad (1)$$

where C is the refurbishment capital cost.

i is the interest rate or opportunity cost of money,

N_1 is the number of years before refurbishment is necessary,

and N_2 is the lifetime of the new electronic equipment.

The values chosen for N_1 and N_2 are averages over all existing systems. It is tentatively assumed that N_1 is seven years, N_2 is fifteen years, and i is 8%. The effect of inflation on A_R is not included in (1). Using these values of the parameters in (1), A_R/C is 5.7%. If this cost is added to the maintenance and operations cost, the total cost of presently installed electronic equipment is 18.7% of its capital cost.

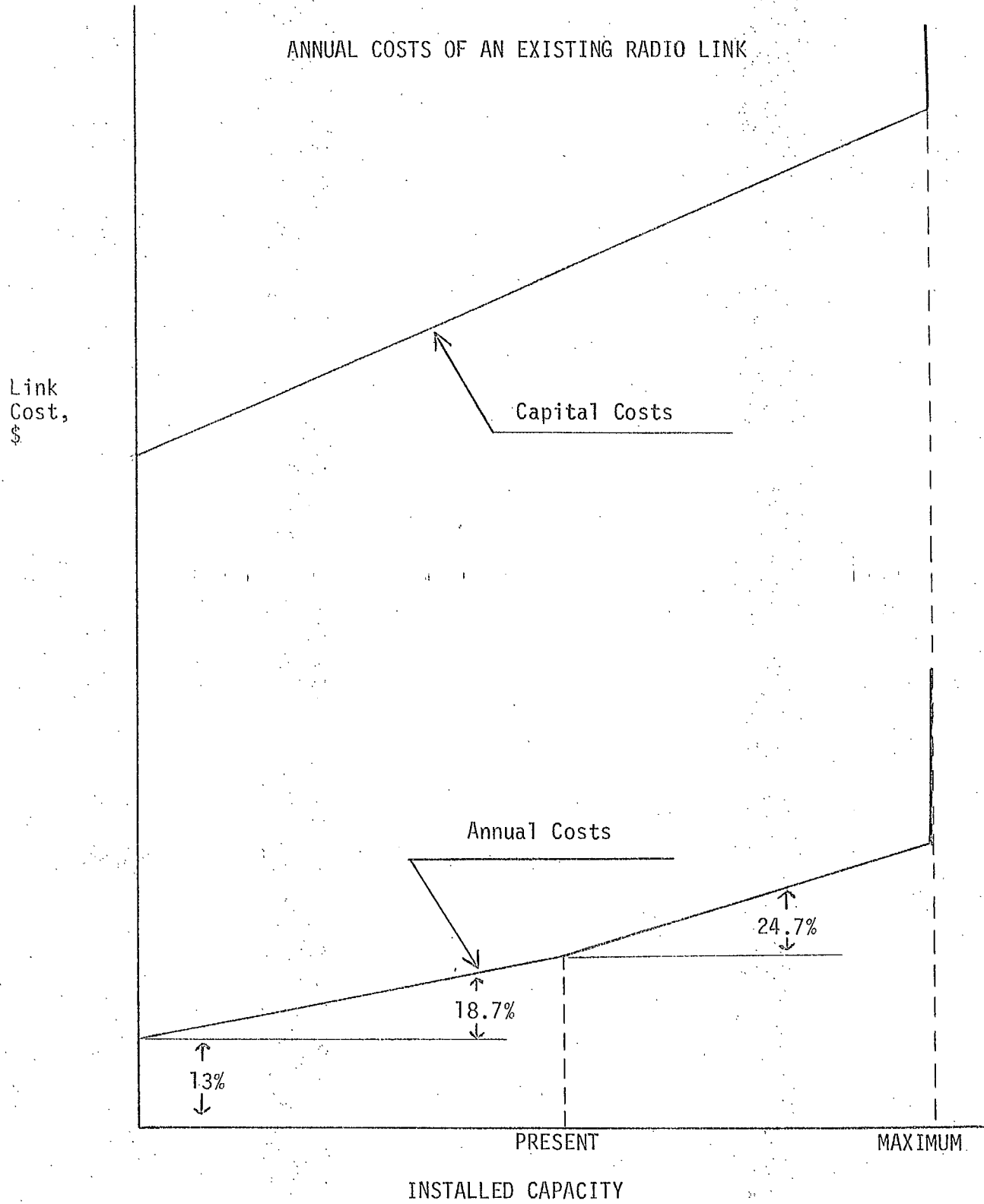
The last item to consider is the cost of new electronic equipment to increase the capacity of the link. The annual cost of this equipment is the full amortization cost plus the M&O costs, a total of

$$C \left\{ .13 + \frac{i}{\{1 - (1+i)^{-N_2}\}} \right\} \quad (2)$$

Again the effects of inflation are not included. With $i = .08$ and $N_2 = 15$ years as in (1), these total annual costs are 24.7% of capital costs.

The relationship between the simplified cost curve and the annual cost curve as functions of installed capacity are shown in Fig. 6.

FIGURE 6



6.2 NEW TERRESTRIAL SYSTEMS

Potential new terrestrial long-haul transmission systems include 4 GHz and 6 GHz analog radio systems, digital radio, coaxial cable, and millimetre waveguide systems. The capital and annual costs of these systems per route mile as a function of installed capacity are described.

New terrestrial systems are those for which the detailed route has not been determined, no microwave sites have been installed, no cables laid for coaxial systems, etc. In that case the procedure is to determine a capital cost and then an annual cost per mile, and multiply the cost per mile by the airline distance between end terminals, times a factor of 1.2 to take into account detours in the actual route.

The cost per mile of any new long-haul system is assumed to be of the form

$$C(m) = C_0 + C_1 m, m \leq M \quad (3)$$

$$+ \infty, m > M$$

where m is the number of installed full-duplex voice circuits, and M is the maximum capacity of the system. Similarly, the annual cost per mile of a long haul system can be written in the form

$$A(m) = A_0 + A_1 m, \quad m \leq M \quad (4)$$

$$\rightarrow \infty, \quad m > M$$

$$\text{where } A_0 = C_0 \left\{ \alpha + \frac{i}{(1 - (1+i)^{-N_3})} \right\} \quad (5)$$

$$A_1 = C_1 \left\{ \alpha + \frac{i}{(1 - (1+i)^{-N_4})} \right\} \quad (6)$$

where α is the ratio of maintenance and operations cost per year to capital costs,

i is the interest rate or opportunity cost of money,

N_3 is the lifetime in years of the initial portions of the system such as the buildings, roads, cables, antennas, etc.

N_4 is the lifetime in years of the electronics of the system, perhaps determined by obsolescence of the equipment.

Different transmission media can be modelled by specifying the values of the parameters C_0 , C_1 , α , M , N_3 , and N_4 for that medium. Media modelled in this way include TD 4 GHz radio, TH 6 GHz radio, 11 GHz digital radio, LD-4 digital coaxial cable, and millimetre digital waveguide systems. In each case it is assumed that N_3 is 25 years and N_4 is 15 years. Estimates of the other parameters are given in Table 1.

TABLE 1
Parameters of Heavy-Route Transmission Media

Medium	C_0	C_1	α	M
4 GHz Radio	\$17k	\$1.10	0.13	16,800
6 GHz Radio	\$17k	\$1.10	0.13	10,800
11 GHz Digital Radio	\$18k	\$1.25	0.13	32,256
LD-4 Coaxial Cable	\$51k	\$1.12	0.10	20,160
Millimetre Waveguide	\$74k	\$0.23	0.10	240,000

The M&O costs are assumed to be 10% for cable and waveguide systems, and 13% for radio systems. The latter are more exposed, and use TWT amplifiers rather than solid state amplifiers. Both of these differences contribute to a higher M&O cost. Based on the information in Table 1, and assuming that the cost of money is 8%, the annual costs of the five media in Table 1 are given in Table 2.

TABLE 2

Annual Costs per Mile of Heavy-Route Transmission Media

Medium	A(o)	M	A(M)
4 GHz Analog Radio	\$ 3,800	16,800	\$ 8,400
6 GHz Analog Radio	3,800	10,800	\$ 6,700
11 GHz Digital Radio	4,000	32,256	\$14,000
LD-4 Digital Cable	\$ 9.9k	20,160	\$14,800
Millimetre Waveguide	\$14.3k	240,000	\$26,300

6.3 SATELLITE GROUND STATION COSTS

Potential satellite ground stations are modelled as part of the terrestrial network. The cost model for these ground station is described. Both existing and new ground stations, including the necessary backhaul facilities, are included.

The network model of a satellite ground station was described in Section 5 and shown in Fig. 4. Links a, b, c, and d represent the electronic equipment to transmit and receive the traffic through the satellite. Link e represents the antenna, the building, access road, prime power system, and backhaul system. The capital cost and technical description of these links has been specified in references [13] and [14]. The conversion from capital costs to annual costs is described below.

There are two possible frequency bands that could be used in a given ground station, the 4 GHz and 6 GHz band or the 12 GHz and 14 GHz band. If 12 and 14 GHz is used the ground station can be located anywhere without interfering with the terrestrial microwave system. However, completely new ground stations would be required. In contrast, if 4 and 6 GHz were used long terrestrial backhaul links are required, but many of these backhaul links and ground stations have already been built for the Anik system.

Consider first a new ground station designed to operate in either band. From references [13] and [14] a capital cost function $C(m)$, a function of the number of voice circuits or television channels flowing through the link, can be determined. The annual cost functions for these links are

$$A(m) = C(m) \left\{ \alpha + \frac{i}{1 - (1+i)^{-N_5}} \right\} \quad (7)$$

where α is the M&O rate, i is the interest rate, and N_5 is the system lifetime for cost purposes. Again, inflation is not accounted for. The values chosen for these parameters are $\alpha = 0.13$, the same as that for terrestrial radio systems, $i = 8\%$ as before, and $N_5 = 7$ years. N_5 is set at 7 years because that is the likely lifetime of the satellite, not because the system would have to be replaced after 7 years. With these values on the parameters, $A(m) = 0.32 C(m)$.

The alternative is to use an existing ground station and backhaul system. In this case it may be necessary to improve the existing site by improving the antenna, increasing the capacity of the backhaul link, adding new transmitters, etc. Let $C_1(m)$ be the capital cost function of the existing equipment as a function of m , the number of circuits through the link, and $C_2(m)$ be the corresponding cost function of the new equipment. The annual cost function of the link is then

$$A(m) = \alpha [C_1(m) + C_2(m)] + i \frac{C_2(m)}{1 - (1+i)^{-N_5}} \quad (8)$$

No amortization costs are associated with existing equipment from the Anik system because these costs have already been incurred and are not recoverable by removing the facilities. If we use the same parameters as were used for a new ground station, (8) becomes

$$A(m) = 0.13 C_1(m) + 0.32 C_2(m) \quad (9)$$

If the amortization time for new ground stations were increased from 7 years to 14 years, the time-frame for two satellite systems, then equations (7) and (8) become

$$A(m) = 0.25 C(m) \quad (10)$$

for an entirely new ground station, and

$$A(m) = 0.13 C_1(m) + 0.25 C_2(m) \quad (11)$$

for an existing ground station.

6.4 SATELLITE SPACE SEGMENT COSTS

The cost model for the space portion of a communication satellite system is described. The costs of the T.T.&C. station and the satellite system control centre are included as part of the space portion costs, as such systems do not carry network traffic and so can most easily be costed as part of the space segment of the system.

The space segment of the satellite system includes the satellite or satellites themselves, and the terrestrial facilities to control the system, i.e. any part of the system not directly associated with a ground station which carries network traffic.

The satellite space segment is a well defined system with a specified lifetime for the actual satellite. Thus the techniques developed in reference [2] can be used to determine the annual costs of the satellite space segment. The annual cost is fixed, and not a function of traffic through the satellite, because there is no opportunity to modify a satellite during its lifetime.

Consider first the cost of the satellites themselves, in orbit. The present value of this portion of the system is

$$P_S = C_D + \sum_{j=1}^N (C_S + C_I + C_L) (1+i)^{-D_j} (1+\gamma) + C_S (1+i)^{-D_{H+1}} \quad (12)$$

where C_D is the portion of the satellite development costs that the manufacturer charges to the system in question,

C_S is the cost of producing another satellite of the same type, and of transporting that satellite to the launch site,

C_I is the incentive charge by the manufacturer for a satellite operating successfully in orbit,

C_L is the cost of launching the satellite, including cost of the launch vehicle, use of the launch site, payment of launch personnel, etc.,

D_j is the planned time interval between the time for which the present value is calculated and the time that the j th satellite is launched,

i is the interest rate,

and γ is the cost of insuring the launch, as a fraction of the cost of a satellite and its launch.

The annual cost of this portion of the system is

$$A_S = P_S \frac{i}{1 - (1+i)^{-L}} \quad (13)$$

where L is the lifetime of the system. If we set $N = 2$, two satellites in orbit, $D_1 = 0$, $D_2 = 0.5$, $D_3 = 1.0$, $i = 8\%$, $\gamma = 15\%$, twice the expected failure rate of a Thor-Delta launch, and $L = 7$ years, the annual cost of the satellites in orbit is

$$A_S = .19 C_D + .61 C_S + .43 (C_I + C_L) \quad (14)$$

As well as the above, the space segment costs include the amortization and the M&O costs of the T.T.&C. station and the satellite control centre. (In the Anik system the T.T.&C. station is at Allan Park and the control centre is on River Road, Vanier.) The T.T.&C. station can be costed in much the same way as a traffic-carrying ground station, in that only M&O costs of the existing portion of the new T.T.&C. station are charged. In contrast, new portions of the existing station, or a completely new station must be charged both amortization and M&O costs. If this amortization is over 14 years, the lifetime of two successive similar satellite systems, and an M&O rate of 13% is used, the annual costs are

$$A_{TTC} = 0.13 C_O + 0.25 C_N \quad (15)$$

where C_O is the cost of the old portion of the T.T.&C. station and C_N is the cost of the new portion.

The total annual cost of the space segment of the satellite system, then, is

$$A_{SS} = 0.19 C_D + 0.61 C_S + 0.43 (C_I + C_L) + 0.13 C_O + 0.25 C_N + A_{cc} \quad (16)$$

where A_{cc} is the annual cost of the control centre.

7. THE OPTIMAL ROUTING ALGORITHM

The optimal routing algorithm routes the specified voice and television traffic over the constrained network at minimum annual cost. The network is constrained in that potential terrestrial links and satellite ground stations are specified and assigned cost functions.

The optimal routing algorithm routes the traffic through the satellite/terrestrial network at minimum annual cost. The input to the algorithm is:

- i) a complete description of the network topology as outlined in Section 5,
- ii) an end-to-end traffic description, as discussed in Section 4,
- iii) the annual cost of each link in the network as a function of traffic carried over that link, as described in Section 6.

The output of the algorithm is:

- i) a description of how telephone traffic between each pair of end points is routed through the network, and how each television signal is distributed through the network,
- ii) a statement of the amount of traffic carried on each link of the network,
- iii) the annual cost of the complete network.

The algorithm used to produce this output is a heuristic one, rather than one which is based on linear programming. It is an extension of the algorithm described in references [6] and [8], generalized to route television as well as telephone traffic at minimum cost. The heuristic approach rather than the standard L.P. approach was taken because of the much larger amount of computer time used by the L.P. programs available. (In a test run with a network of six nodes and eleven links the heuristic algorithm required only about 1% of the time required by the L.P. program to optimize the network.) The Canadian long-haul network model as described for optimization in the computer has about 60 nodes and 120 links, including 17 traffic-generating nodes. The increase from the 20 nodes and 26 links shown in Fig. 2 is due to inclusion of satellite ground stations, metropolitan models, and dummy links introduced to model several parallel systems. The heuristic algorithm can optimize traffic flow through this network in about one minute of Sigma 7 time. About 10 to 15 minutes of programmer time is required to prepare the input data and to do the initial interpretation of the output data.

8. THE DEMAND-COST STRATEGY

The requirements for voice and video circuits through the satellite can be determined as a function of the annual cost of a voice circuit through the space portion of the satellite system. A graphical description of this information is called the satellite demand curve. As well, the optimum satellite for each satellite traffic requirement can be chosen and costed. The satellite system cost curve is the graphical description of this latter information. The cost curve and demand curve can be combined in such a way that the optimum satellite system, subject to the network constraints imposed, can be determined.

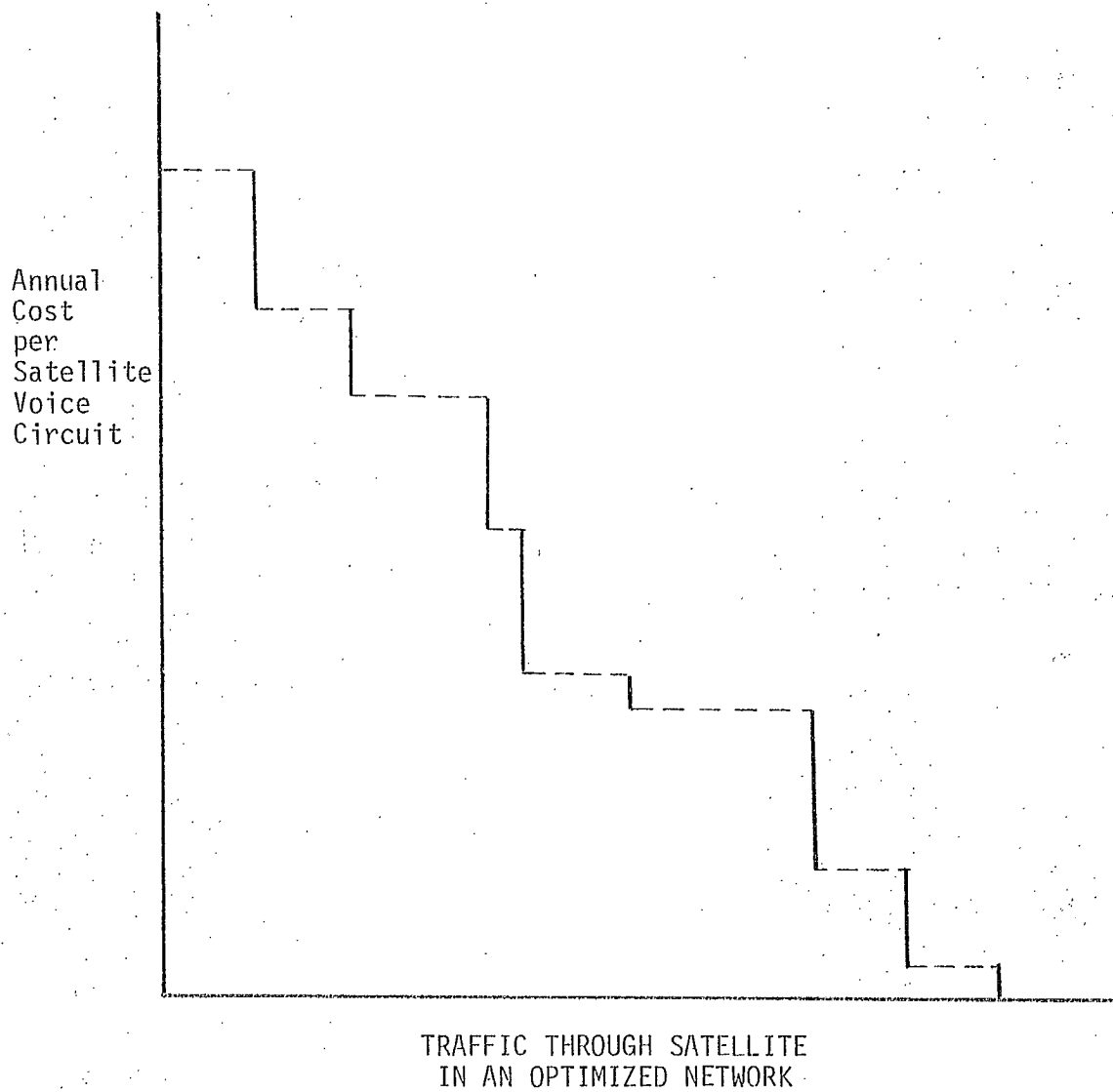
The optimal routing algorithm discussed above specifies how traffic should be routed through the network that has a specified topology and link costs. However, determination of the various satellite options and the associated satellite link costs is a major part of the project; satellite link costs have yet to be determined, and may change significantly as new satellite options are considered. Use of the demand-cost strategy allows for considerable network optimization work to be done without detailed knowledge being available on the satellite system, and prevents the necessity for duplication of effort when considering a different satellite.

Rather than developing a cost function for the satellite links, as was done in Section 6 for the terrestrial links, let us suppose that the cost of transmitting a voice circuit through the satellite is x dollars, with no constraint on the amount of traffic through the satellite. The network can be optimized with the optimal routing algorithm for any specific value of x , and repeated for several values of x . The required number of voice circuits through the satellite in an optimized network can be thought of as a function of x , the "offering price" of a satellite circuit. The graphical representation of this function, plotted with x on the vertical axis and the number of satellite voice circuits on the horizontal axis, is referred to as the satellite demand curve. (The reason for choosing the axes this way will be evident later.) It is expected that such a curve will be similar to that shown in Fig. 7, and will have the following general characteristics:

- i) It is a uniformly decreasing curve, in that only by reducing x can the traffic through the satellite be increased.
- ii) A value X_{MAX} exists such that if the annual cost per voice circuit is greater than X_{MAX} there will be no traffic through the satellite.
- iii) The traffic through the satellite is limited to some finite maximum value even if x is reduced to zero.
- iv) The curve is a series of discrete steps, as shown in Fig. 7. One reason for this is that as soon as a television signal is routed through the satellite the number of equivalent voice circuits is increased by a large amount. The other reason is that as soon as x becomes small enough to attract a voice circuit between a pair of nodes, say between Vancouver and

FIGURE 7

SATELLITE DEMAND CURVE



Halifax, it will either take as much of that traffic as is allowed for network protection reasons, or enough that a link somewhere is no longer required, whichever is smaller.

There will be different demand curves, of course, for different traffic requirements and different terrestrial and ground station link costs.

As well as these demand curves, the actual cost of the space portion of the satellite system can be determined, as described in Section 6.4. There are a number of satellite options, each optimum for a specific amount of satellite traffic, ground station G/T, and modulation scheme. Thus for a given ground segment of the satellite system one can specify the minimum cost of the space segment as a function of satellite traffic, as shown in Fig. 8. For a given satellite the cost curve is constant, and increases in discrete steps as a new more complex satellite becomes necessary. The dotted curves indicate the cost of the larger systems below the capacity at which they are optimum.

If the total annual costs shown in Fig. 8 are divided by the number of circuits through the satellite, the result is an annual cost per satellite voice circuit curve, as shown in Fig. 9. At each value of traffic through the satellite Fig. 9 indicates the minimum possible annual cost of a voice circuit, the cost through a satellite that is optimum for that amount of traffic.

Suppose we now overlay the curves in Figures 8 and 9, as shown in Fig. 10. In this figure the demand curve is the amount that could be charged for a voice circuit at each value of traffic, and the cost curve is the minimum amount that must be charged. From the demand-cost-strategy viewpoint there are three classes of points on the cost curve. These are:

- i) points at which the cost curve is below the demand curve, such as point a;
- ii) points at which the cost curve is above the demand curve, such as point b;
- iii) points at which the cost curve and the demand curve are equal, such as point c.

Points a are feasible points, but at the satellite costs of point a the total network cost could be reduced by increasing the amount of satellite traffic above that indicated by point a.

Points b are not feasible, since no satellite system can meet the costs required by the network. Points c are optimum in that at point c the total network annual cost is minimized. There may be several points c, in that the cost curve and the demand curve may intersect several times. Of this set of locally optimum points, the globally optimum one is that with least satellite voice circuit annual cost. This is also the point with largest satellite capacity, since the demand curve is a decreasing function.

Several network constraints and requirements must be specified before a demand curve and a cost curve can be

FIGURE 8
SATELLITE COST CURVE

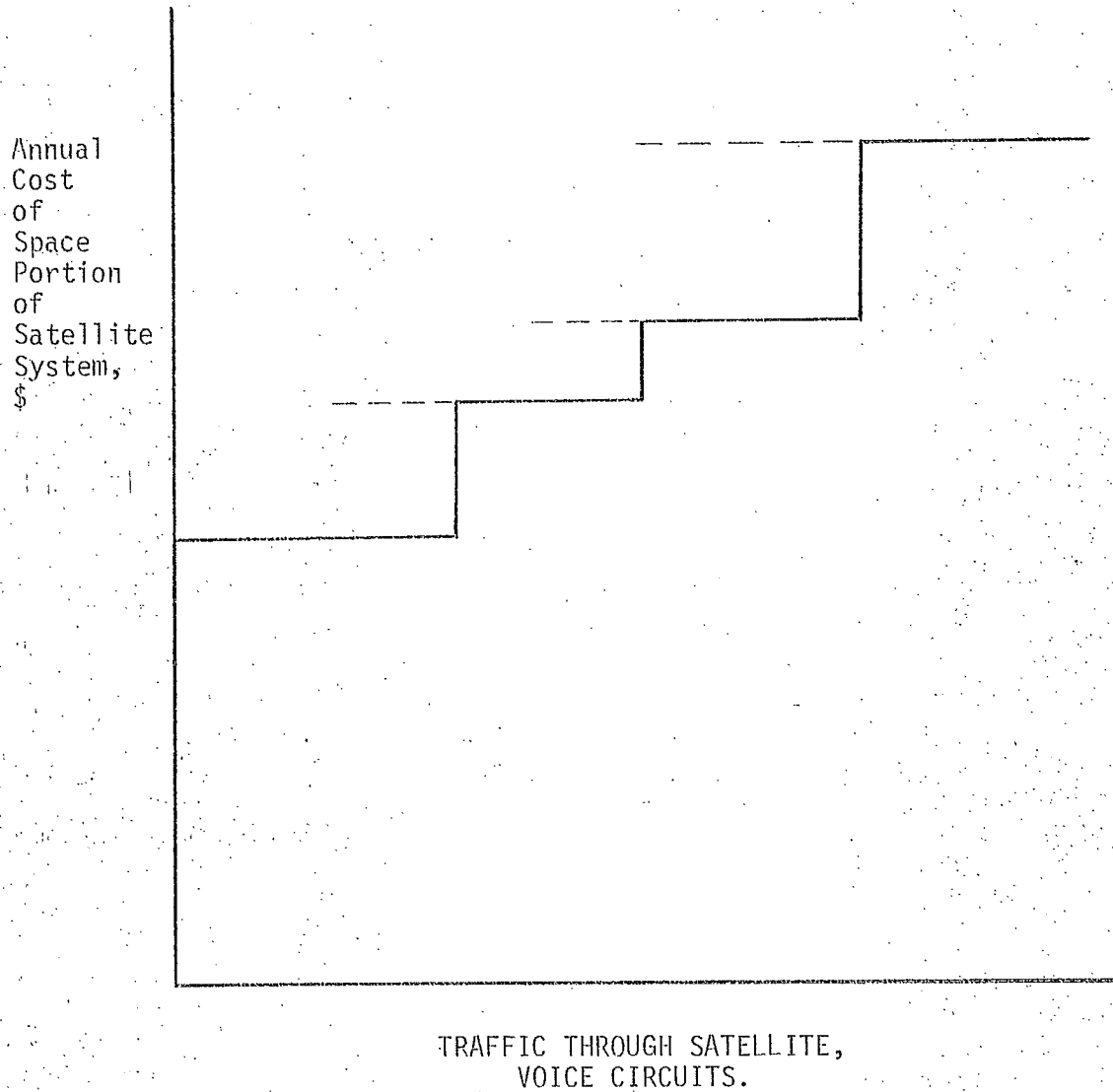


FIGURE 9

SATELLITE COST CURVE

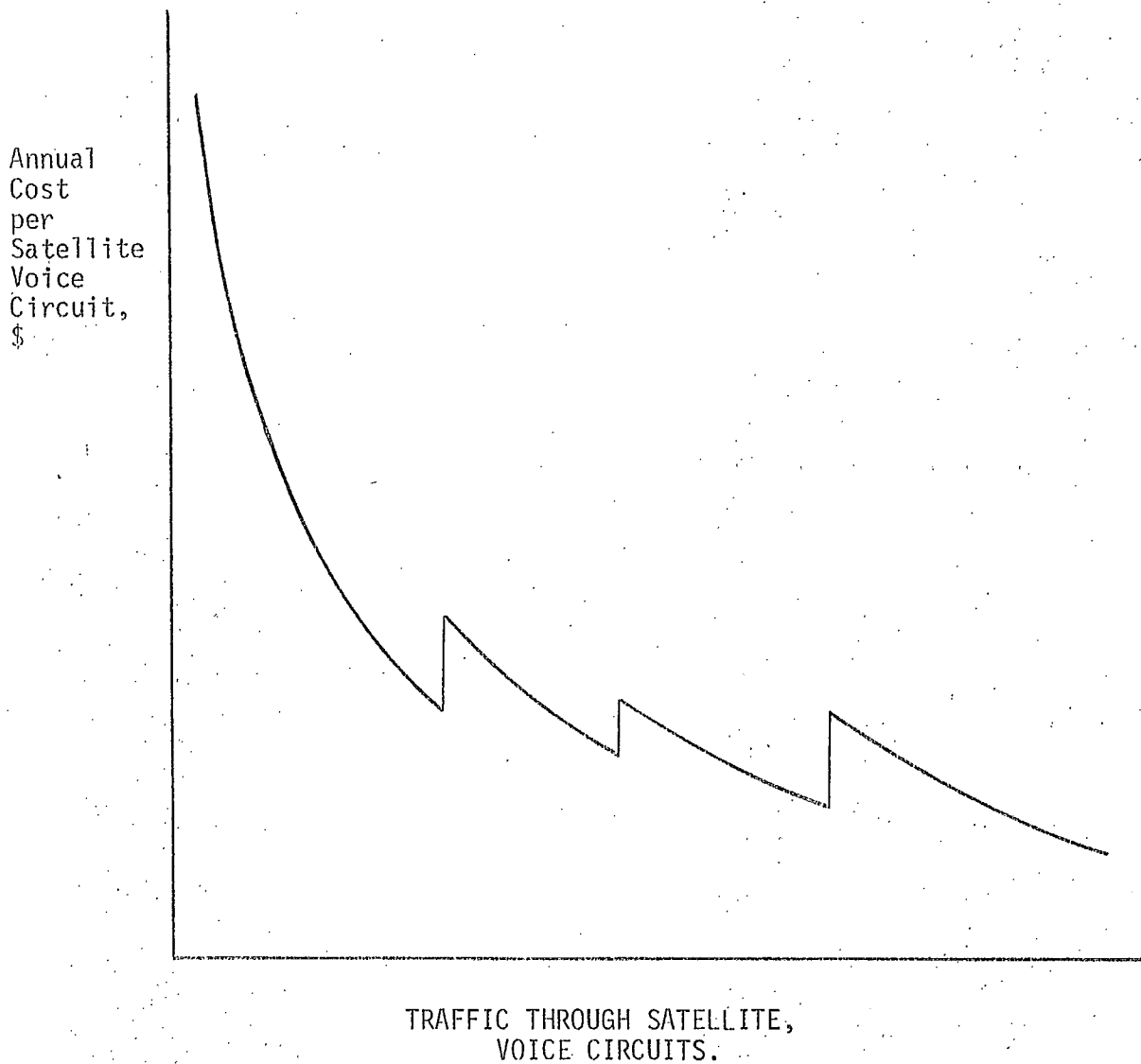
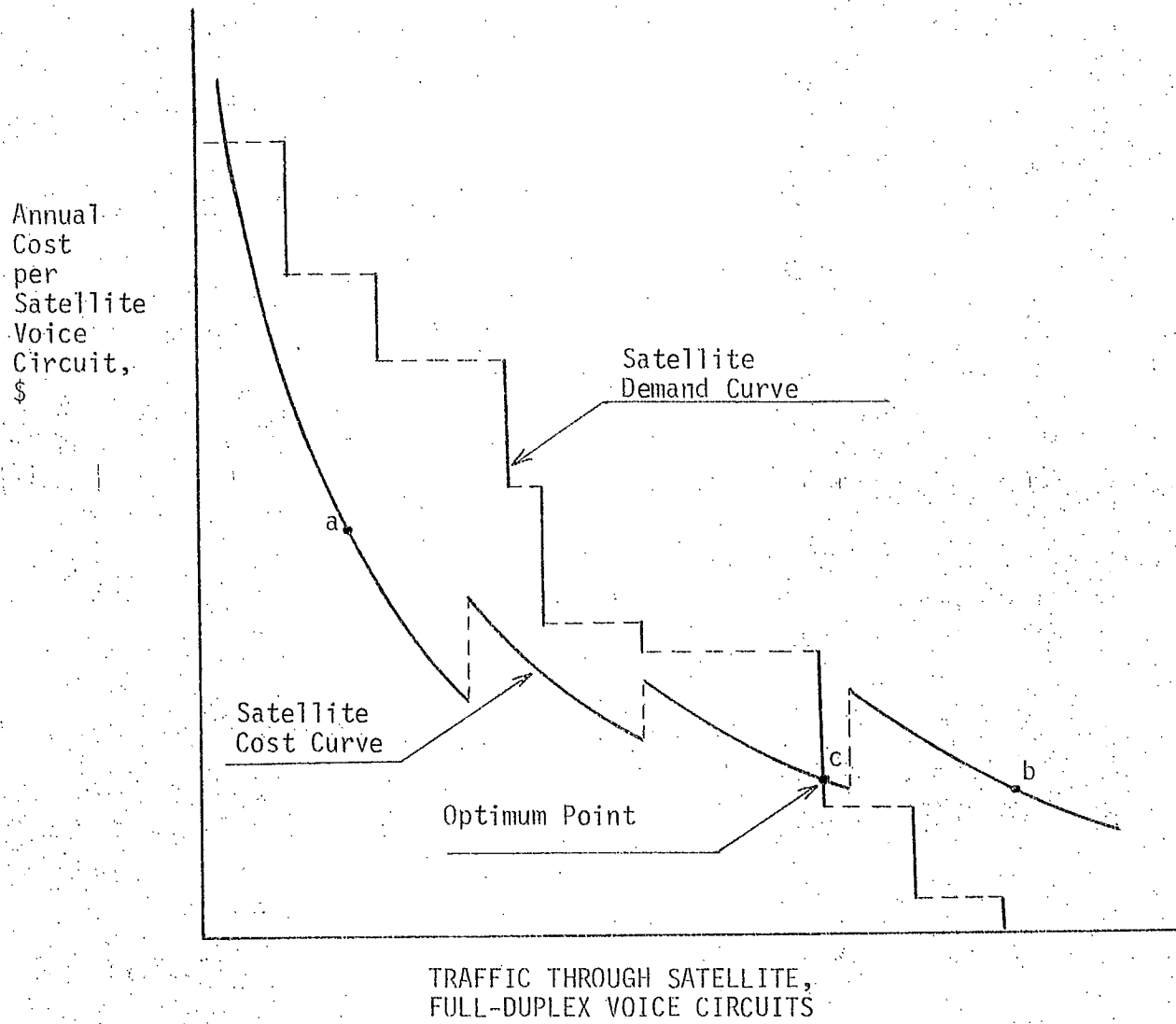


FIGURE 10

OVERLAY OF SATELLITE COST AND DEMAND CURVES



determined. These include the total traffic through the network, the types of system used in the terrestrial network, the amount of network protection imposed, etc. The optimum network, subject to these constraints, is specified once the optimum point c has been determined. Point c on the demand curve can be used to specify the terrestrial network and location of the satellite ground stations. Point c on the cost curve specifies the type of satellite to be used. Cost-demand curves for several networks subject to different constraints and requirements can be obtained, and these results used to determine the globally optimum network and to determine the cost of imposing certain constraints on the network.

9. CHOICE OF SATELLITE SYSTEM PARAMETERS

The demand-cost strategy can be used to optimize the satellite/terrestrial network for which the satellite operating frequency and ground stations have been specified. These constraints can be relaxed by varying the system parameters and re-optimizing the system. The optimum set of system parameters is that set which results in a minimum total system annual cost.

Choice of several basic satellite system parameters such as operating frequency (12 and 14 GHz or 4 and 6 GHz), and ground station antenna diameter, can be determined by using the demand-cost strategy. A satellite system demand-cost curve such as that shown in Fig. 10 is for a specified set of terrestrial link costs, including the costs of the ground station links. As ground-station antenna diameters are decreased, and/or the 12/14 GHz band is used instead of the 4/6 GHz band, it is expected that ground-station costs will decrease and satellite costs will increase. For each frequency band and for various antenna diameters the optimum point c of Fig. 10 can be determined. Associated with each such point is a total network cost. The network with the lowest of these costs is the one chosen. Once this network is determined the optimum satellite frequency band and satellite antenna diameters are known.

10. OPTIMIZATION OVER THE 1980-1985 INTERVAL

The demand-cost strategy can be used to optimize the network to meet a given traffic requirement. Since that requirement is a function of time, the network is only optimum for a single point in time, and yet systems within the network are optimized for intervals as great as 25 years. The optimum solutions for specific time instants must be combined to produce compatible networks over the 1973 to 1990 interval with minimum overall present value.

The network model and links costs described in Sections 5 and 6 are expected to be valid for the complete 1973 to 1985 interval, although they will be updated whenever new information becomes available. However, the optimization of the network, described in Sections 7, 8 and 9, is for a specified traffic input. Since the traffic through the network is expected to increase significantly during the interval of interest (see Section 4 and References 8, 9, and 10), a network optimized for one point in time may not be the same as the network that is best for that point in time when optimization over the complete 1973 to 1985 interval is considered. For instance, the optimum satellite for 1980 may be smaller than that required in the minimum-cost network for 1985.

The measure used to compare different compatible networks for the 1973 to 1985 interval is minimum present value in 1973. The problem is that a new system introduced in say 1980 may not be in the optimum 1985 network, or the optimum satellites for 1980 and 1985 may be different. The optimization technique is to choose a number of compatible systems that are not optimum at all time-points over time-frame, and of these choose the one with the minimum present value. At present this technique has not been mechanized, nor is it likely to be. It will likely depend for the most part on engineering judgement, based on the optimum solutions for specific traffic requirements.

REFERENCES

1. W.L. Hatton, "A Simplified Analysis of Canadian Trunk Communications 1980, CS/CSE Tech. Memo. No. 16, January 1972.
2. R.R. Bowen, "Calculation of Trunk System Annual Costs", CS/CSE Tech. Memo. No. 33, September 1972.
3. A.R. Kaye, "Costing Communication Systems for Comparative Purposes", CS/CSE Tech. Memo. No. 37, September 1972.
4. R.R. Bowen, "A Demand-Cost Strategy for Optimizing Long-Haul Trunk Networks", CS/CSE Tech. Memo. No. 42, November 1972.
5. R.R. Bowen, "On the Costing of Multi-Purpose and Multi-Beam Satellites for Network Optimization Studies", CS/CSE Tech. Memo 52/73, April 1973.
6. G.A. Neufeld, "Computer Optimization of Trunk Communication Networks - A Telpak Problem", CS/CSE Tech. Memo No. 54, May 1973.
7. R.R. Bowen, "On the Distribution of Television Programs over a Satellite/Terrestrial Trunk Network", CS/CSE Tech. Memo No. 57/73, June 1973.
8. G.A. Neufeld, R.R. Bowen, and A.R. Kaye, "The Planning of Domestic Communication Networks", presented at the 44th National ORSA Conference, San Diego, California, November 1973.
9. T.A.J. Keefer, "Forecasting Total Voice Circuit Requirements", DLDCNS Serial Document No. 3, June 1973.
10. T.A.J. Keefer, "Updated Forecasts of Total Inter-provincial Voice Circuit Requirements", DLDCNS Serial Document No. 4, September 1973.
11. T.A.J. Keefer, "Forecasting Intra-Provincial Voice Circuit Requirements", to be published.
12. "Feasibility Study of a Broadcasting Satellite System for the CBC Post-1978 Requirements", BNR Report to DOC, July 1973.

13. J.H. Thomas, "Traffic Capacities and Costs of Terrestrial Facilities Associated with a Satellite of the Anik Type Using Digital Modulation Techniques", DLDCNS Serial Document No. 5, July 1973.
14. J.H. Thomas, "Earth Segment Costs", to be published.



BOWEN, R.R.

--The network optimization technique
used in the domestic long-distance
communications network study

HE
7814
D665
1974
#08

DUE DATE

JUL 24 1996

201-6503

Printed
in USA

