DOMESTIC LONG-DISTANCE COMMUNICATIONS NETWORK STUDY

Communications Systems Engineering

# A SIMPLIFIED MODEL OF THE CANADIAN TERRESTRIAL TRUNK COMMUNICATIONS NETWORK

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# 1. INTRODUCTION

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A simplified model of the Canadian terrestrial trunk communications network is described in this document. The model has been developed as part of a study to determine the most cost-effective satellite/terrestrial Canadian trunk network in the 1980's. The topology, capacity, and costs of the network are described. The existing common carrier network hierarchy is not included in the model.

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The overall purpose of the study is to conduct "technological and economic studies of the effectiveness of various kinds of satellite and terrestrial subsystems to meet predicted communication requirements" [1]. To do this it is necessary to develop a model of the Canadian trunk communication network. One such model that was developed for network optimization studies is the model used in the Hermes Project [2,3]. However, a model of that type was considered to be too detailed and complex, too inflexible, and too tied to the existing common-carrier routing hierarchy to be used in the present study. Rather, the model should have the following characteristics:

1. It must be simple enough, i.e. have few enough nodes and links, that a network optimization program can be used quickly and at reasonable cost. This is necessary because it is expected that the optimization will be done hundreds of times for different satellite costs, terrestrial costs, traffic intensities, etc.

2. It must be flexible enough that existing links such as the TD and TH microwave radio systems and new systems such as the LD-4 digital coaxial cable, digital radio, optic fibre, and millimetre waveguide systems can be included if required, taking into account the traffic requirements and the time within the 1973 to 1990 interval.

3. It must be complete enough to describe the network's capabilities and costs in handling long-haul interprovincial telephone, television, and leased-line services. To do this, heavy-route intraprovincial circuits that use the same system as the interprovincial circuits must be included in the model. Conversely, short-haul circuits, either interprovincial or intraprovincial, that use different radio frequencies, different cable systems, etc. are not included in the model.

4. Any node that is a potential location for a satellite Earth Station for heavy-route telephony or television distribution should be included in the network model. (This excludes Arctic television distribution centres that are far from any existing microwave system.)

The network which the authors consider best meets the above requirements for the DLDCN study is shown in Fig. 1.1. The network contains 21 nodes and 26 links. Several of the links contain several systems in parallel. As the study progresses new nodes and links may be added if necessary to model new systems, or nodes and links may be removed to simplify the model if it becomes obvious that their removal will not appreciably change either the satellite circuit requirements or the long-haul terrestrial circuit requirements in other parts of the network.

The network will be described in detail in the remainder of the report. In Section 2 the major decisions made in arriving at the model shown, and the reasons for making these

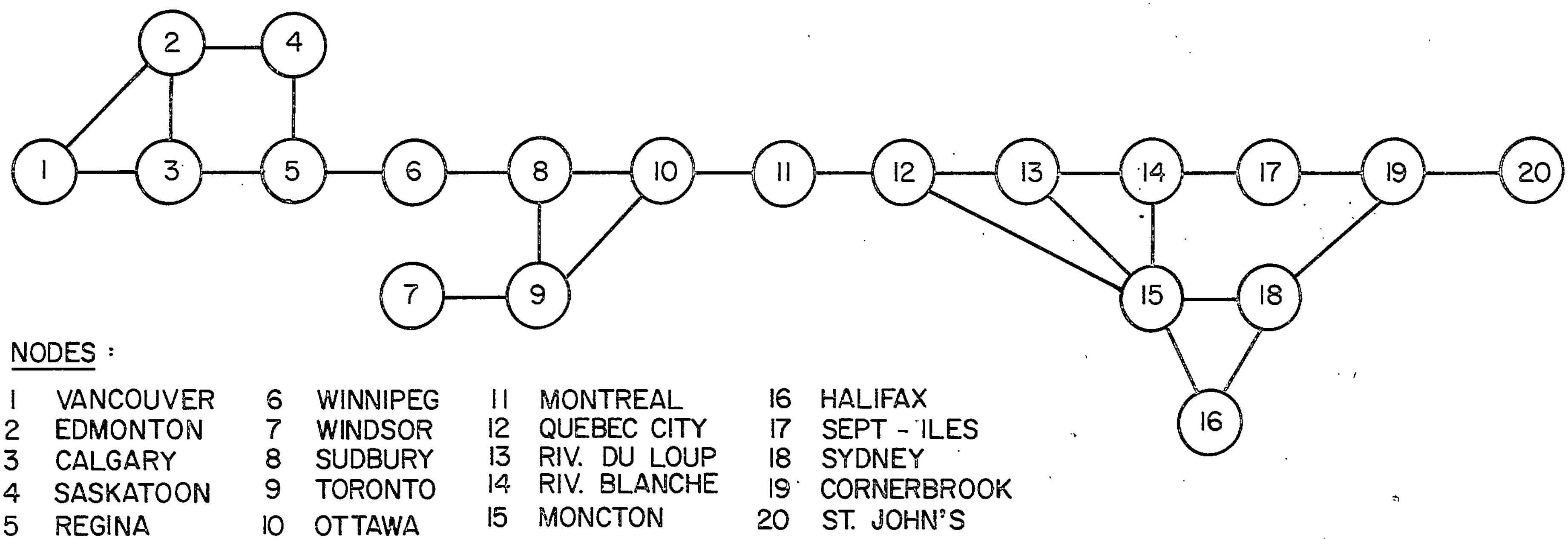


FIGURE 1.1

SIMPLIFIED CANADIAN LONG-HAUL TERRESTRIAL NETWORK decisions, are described. In Section 3 the methods used in modelling a given link, and in reducing a complex metropolitan area to a single node, are described. The costs of the different links are described in Section 4 in terms of the installed system capacity.

## 2. GENERAL CHARACTERISTICS OF THE MODEL

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The factors and decisions on which the terrestrial system model are based are discussed in this section. These include the purpose of the model, the time-frame over which it is to be applicable, the presence of two distinct trans-Canada trunk networks at the present time, the present utilization of the networks, and the means by which the combined satellite-terrestrial network is to be optimized.

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The terrestrial trunk communication network is modelled as an aid in carrying out the domestic long-distance communication network study. Certain assumptions, simplifications, and omissions were made in order to produce a model which is sufficient for its intended purpose and yet is sufficiently simple to be tractable. The model is not necessarily adequate for any other purpose, and should be considered in that light. The factors and decisions which influenced the design of the model are discussed here in sufficient detail that its capabilities and limitations may be appreciated.

The following factors influenced the synthesis of the model:

1. the use to be made of the model,
2. the time-frame over which the model is to be applicable,

3. the presence of two distinct common-carrier trunk networks,

4. the hierarchial structure of the present networks, and the type of traffic carried,

5. the techniques to be used in carrying out the study on the basis of the model,

6. the nature of the traffic forecasts.

The dependence of the network model on these factors is discussed below in Sections 2.1 to 2.5.

## 2.1 THE INTENDED USE OF THE MODEL AND RESULTANT SELECTION OF NETWORK NODES

The network model has been synthesized as an aid in carrying out the domestic long-distance communications network study. For this region all large Canadian population centres and other potential satellite earth stations in Southern Canada have been included as network nodes. Whether such a model can be used in other studies has not been investigated.

The purpose of the DLDCN study is to determine what long-haul trunk communication systems will be required in Canada in the 1980's. More specifically, the question being addressed is what satellite or satellites should replace Anik in the 1980's and how may it best be integrated with the terrestrial network.

The problem is being attacked by first making estimates of television and telephone circuit requirements throughout the 1980's, and then determining how to meet these requirements such that the complete satellite-terrestrial network has minimum cost.

There will be several satellite earth stations in the Arctic for television distribution and thin-route telephony services. These northern communities are located at points which cannot be served by terrestrial means. For the purposes of network optimization they can therefore all be represented by a single node, to which all the required traffic is routed via the satellite. The satellite itself constitutes a node of the network.

In southern Canada the situation is much more complicated, since it is here that division of traffic between terrestrial and satellite systems must be optimized. A location must be included in the network as a node if it meets one or more of the following criteria:

i) it is a major population centre for which traffic forecasts have been made,

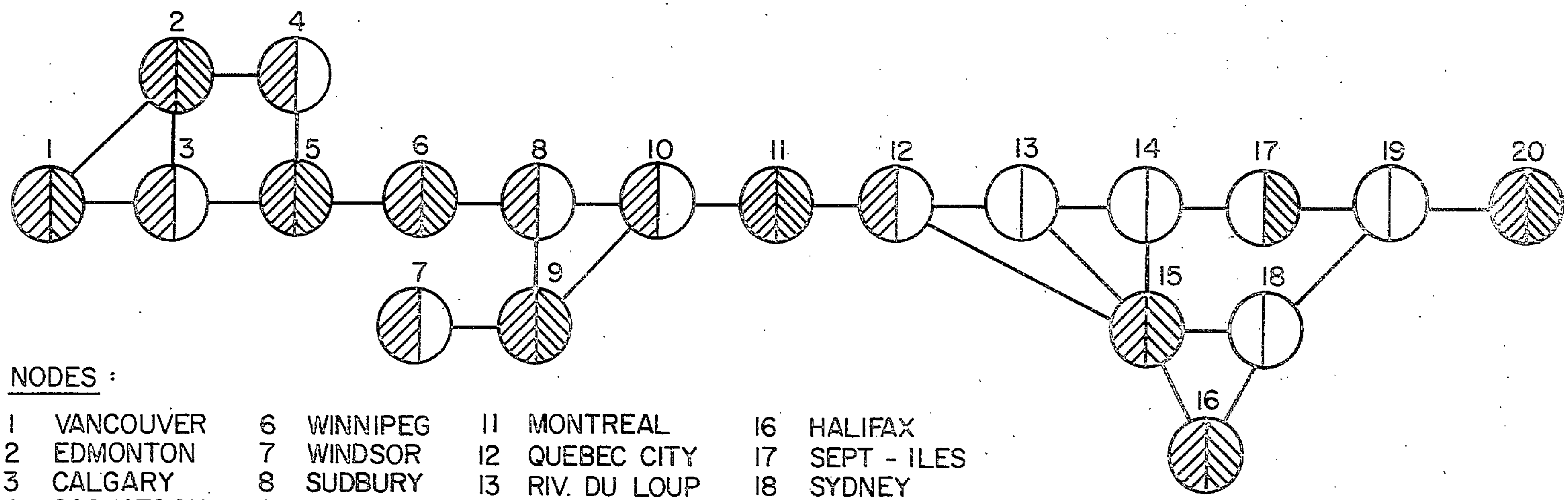
ii) it is a CBC regional centre,

iii) it represents a major junction of terrestrial long-haul facilities.

The network nodes in southern Canada, with the types of traffic generated in each node indicated, are shown in Fig. 2.1.

Certain nodes have been selected as potential locations for satellite earth stations, because they are either significant sources of telephone traffic or are CBC regional centres. These nodes are:

Vancouver
Edmonton (or Calgary)
Regina
Winnipeg
Toronto
Montreal
Halifax
St. John's




NODES :

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| 1 | VANCOUVER | 6 | WINNIPEG | 11 | MONTREAL | 16 | HALIFAX |
| 2 | EDMONTON | 7 | WINDSOR | 12 | QUEBEC CITY | 17 | SEPT - ILES |
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| 4 | SASKATOON | 9 | TORONTO | 14 | RIV. BLANCHE | 19 | CORNERBROOK |
| 5 | REGINA | 10 | OTTAWA | 15 | MONCTON | 20 | ST. JOHN'S |

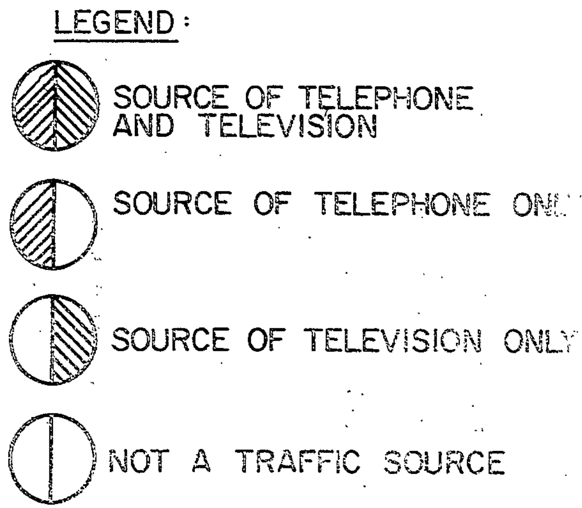


FIGURE 2.1

SOURCES OF TRAFFIC IN THE SIMPLIFIED NETWORK

Each of these nodes is connected in the network model to an associated node representing an earth station, as described in DLDCNS Report No. 8 [18]. Other sources of telephone traffic are sufficiently close to much larger centres that they are not considered as candidates for separate earth stations. A simplified diagram of the complete network including all nodes of Fig. 2.1, several earth stations, the satellite, and a special node to carry the Arctic traffic (node 21) are shown in Fig. 2.2.

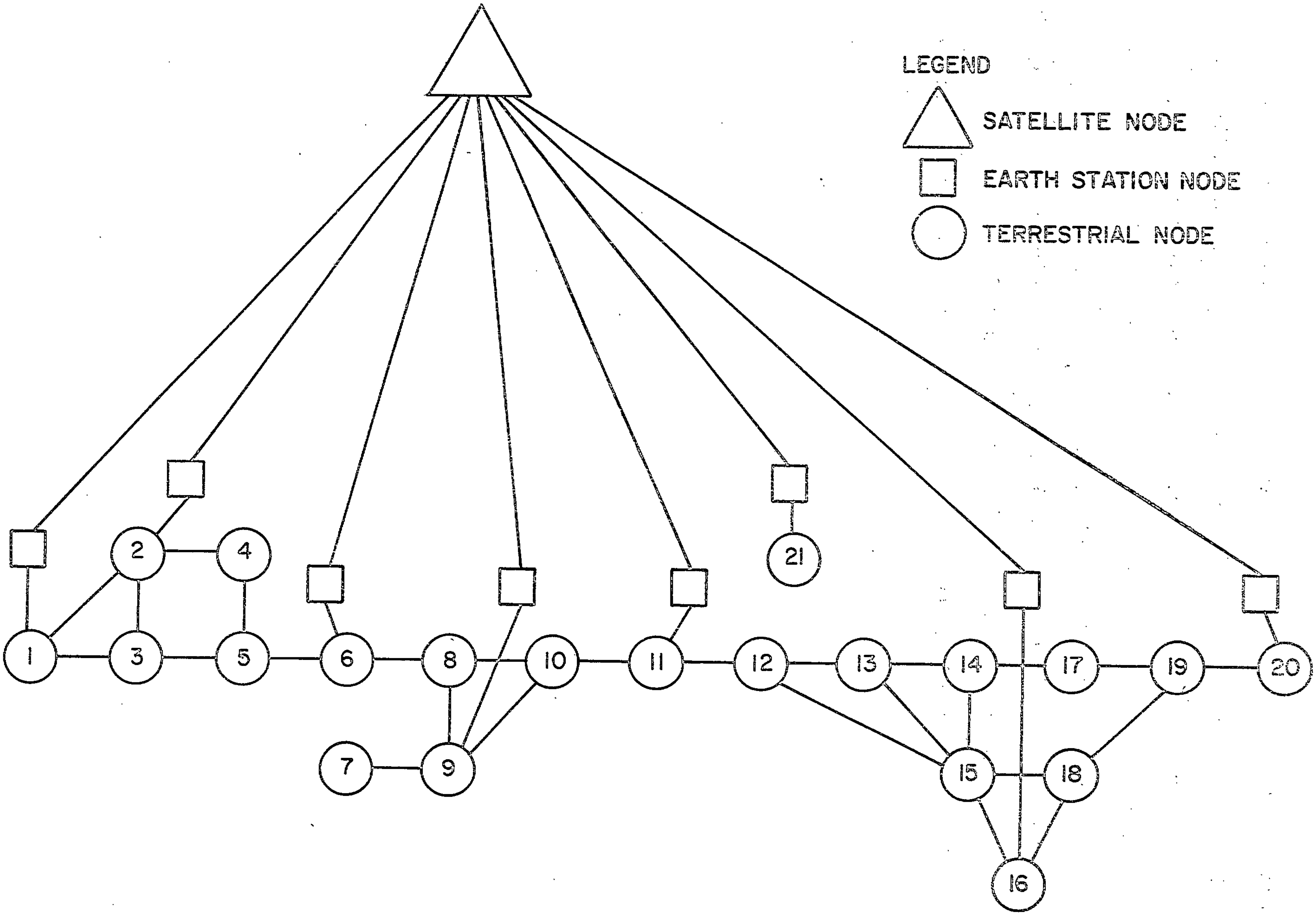


FIGURE 2.2

THE COMPLETE NETWORK MODEL

## 2.2 TIME-FRAME OF THE NETWORK MODEL

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The network model should be applicable from 1973 to 1990 to meet the needs of the project.

---

The time-frame over which the model should represent the long distance network is of course determined by the time-frame that needs to be considered to determine the next satellite system.

The minimum time-frame that need be considered is the operational period of the satellite system being considered. The lifetime of most operational and planned satellites is seven years. If one assumes that the next satellite or satellites will not be launched until about 1980, the end of the Anik satellite's lifetime, then the minimum time-frame that must be considered is from 1980 to 1987.

The 1980 to 1987 time-frame must be extended both forward and backward. The interval 1973 to 1980 must be included so that expansions of the terrestrial network during the lifetime of Anik can be estimated. It is this expanded network that is in competition with the second-generation satellite for television and telephone traffic in the early 1980's.

As well, it is necessary to consider the time-frame beyond 1987, because of the economic dependence between the second-generation and third-generation satellite systems through their partially common Earth Station subsystems. As an example of this dependence, if the shuttle and tug satellite-launch technology in the U.S. made satellite communication very economical in the late 1980's, it might be to the nation's long-term economic advantage to overbuild satellite earth stations in the early 1980's. In contrast, the possible development of long-haul millimetre waveguide and optic fibre systems in the late 1980's may make large satellite systems in that time-frame uneconomical, in which case earth station overbuilding would be very wasteful. The direction of long-haul transmission development in the late 1980's will not be considered further here, other than to show that its direction will influence what systems should be chosen for the early 1980's.

The length of time-frame that can be considered is severely limited by both the inability to forecast traffic requirements accurately beyond the early 1980's and the inability to determine the costs of new transmission media in the same interval. Thus the terrestrial system model should be representative of the long-haul system from 1973 to 1990.

## 2.3 TWO DISTINCT TERRESTRIAL NETWORKS IN ONE MODEL

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At present there are two distinct long-haul trunk networks in Canada, the TCTS network and the CN/CP network. The facilities of these two networks are kept separate in the network model, except for potential inter-network links at major nodes.

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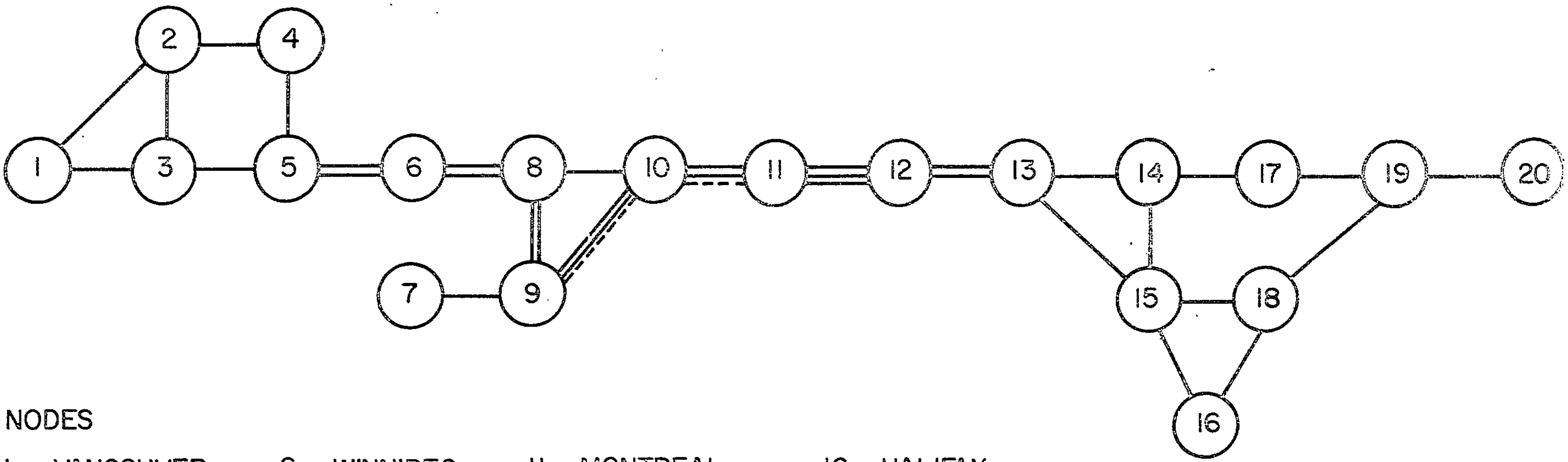
At the present time there are two distinct and largely unconnected networks in Canada, the TCTS network shown in Fig. 2.3 and the CN/CP network shown in Fig. 2.4.

Most of the long-haul heavy-route systems in the TCTS network are 4 GHz analog microwave radio systems. These systems have a capacity of about 12,000 full-duplex voice circuits in the 3.7 to 4.2 GHz band if modern 15 watt transceivers are used, and 16,800 circuits if the 3.5 to 3.7 GHz band is also used. It is expected that by 1980 the capacity of a radio channel could be increased to 1,500 voice circuits, thus increasing the total link capacity in the 3.5 to 4.2 GHz band to 21,000 voice circuits. Based on recent information obtained from the Regulatory Development Branch [6], it will be assumed that all 4 GHz systems can be used over the full 3.5 to 4.2 GHz band if required. There are several other medium-route and heavy-route microwave radio systems in the TCTS network at 2 GHz, 7 GHz, and 11 GHz. However, they are not used for long-haul transmission and so are not included



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LEGEND

——— 4GHz RADIO SYSTEM

- - - - - DIGITAL CABLE SYSTEM

FIGURE 2.3

SIMPLIFIED TCTS LONG-HAUL TRUNK NETWORK

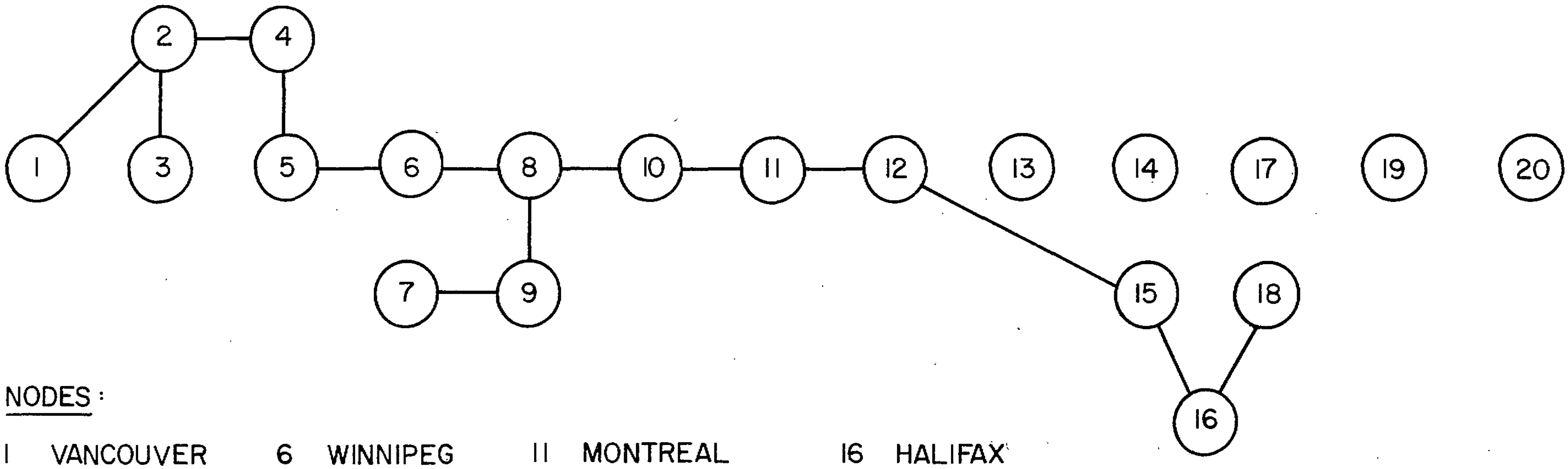


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FIGURE 2.4

SIMPLIFIED CN/CP LONG-HAUL TRUNK NETWORK in the network model. (They do, however, affect the cost of a long-haul 4 GHz system when they use the same repeater and junction sites, as will be described in Section 3.) As well, the TCTS network will include the LD-4 digital coaxial cable system with a capacity of 20,160 voice circuits. Bell Canada has indicated that an LD-4 system will be installed from Montreal through Ottawa to Toronto by about 1976, with possibly later extensions to Quebec City and London, Ontario. The Montreal-Toronto LD-4 system is shown in Fig. 2.3.

The CN/CP network is a single 6 GHz microwave radio system from Vancouver to Sydney, as shown in Fig. 2.4. (The network has recently been extended from Moncton to Sydney [6].) The capacity of a 6 GHz system at present is 10,800 voice circuits, not including two full-duplex radio channels used for route protection, if modern long-haul radio equipment is used throughout the network.

Studies will probably be made both on the basis of two separate networks and on the basis of an integrated network shown in Fig. 2.5. For this reason the total network has been constructed to represent the facilities of TCTS and CN/CP as separate branches and nodes of the network, but includes inter-system links at all the major nodes. If the cost function of these intersystem links is the actual link cost, then a single network is modelled. Alternatively, if the cost of the links are set very high, or if the links are removed, then two separate networks are modelled. In this case separate

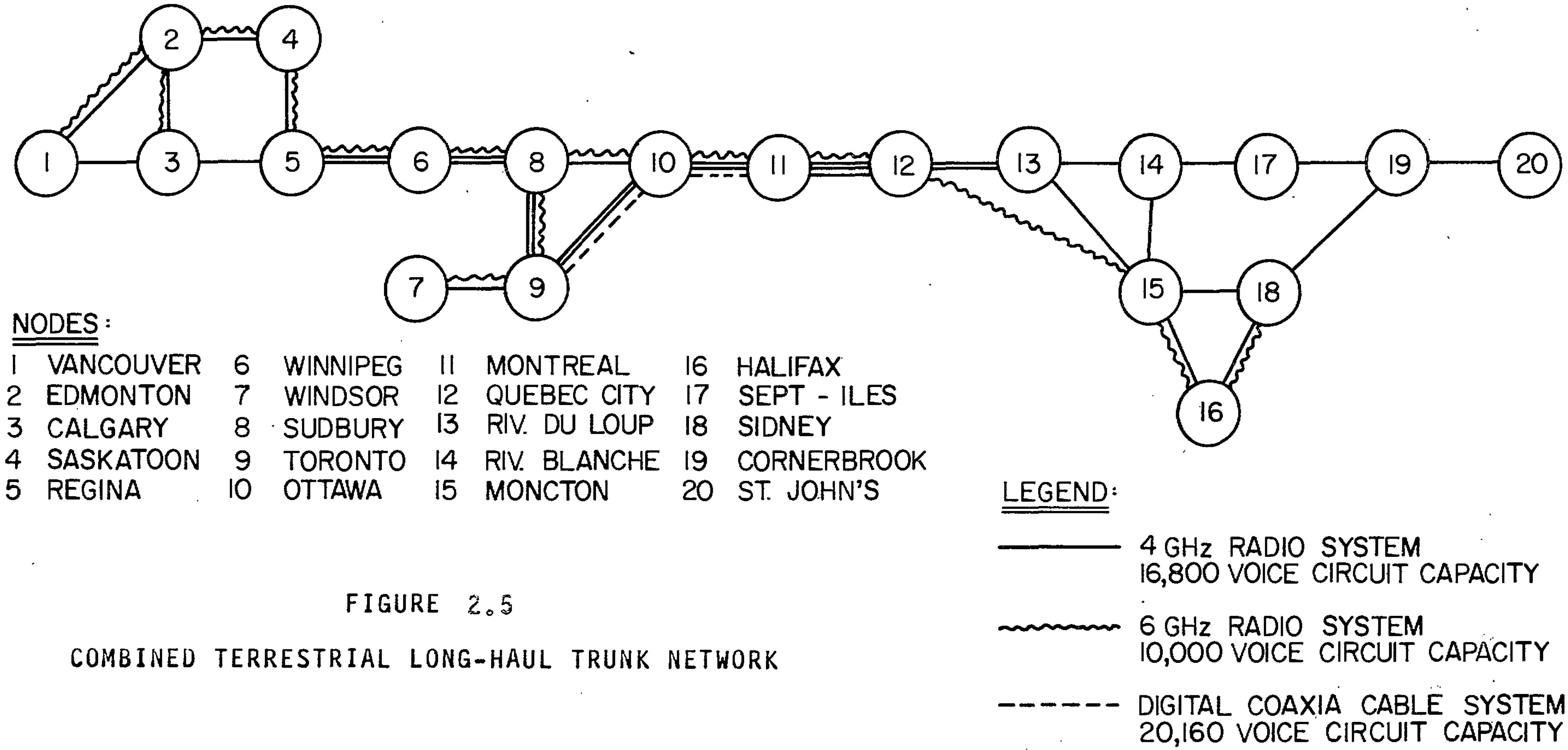


FIGURE 2.5

COMBINED TERRESTRIAL LONG-HAUL TRUNK NETWORK access to the satellite system is provided for each terrestrial network.

## 2.4 LACK OF ROUTING HIERARCHY IN NETWORK MODEL

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The present switching and routing hierarchy of the common carrier is not included in the model of the terrestrial network.

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The present common carrier routing hierarchy was not included in the model because it is expected that the hierarchy will be changed significantly in the next few years. Terreault [8] indicates that the present five-level hierarchial structure will be changed to a three-level structure by the early 1980's. All regional centres and sectional centres, and some primary centres, will become Control Switching Points, the highest of the three levels. All of the sources of telephone traffic shown in Fig. 2.1. will likely be Control Switching Points. Moncton is an exception; it is a major transmission junction point but nearby Saint John will likely be a Control Switching Point.

It is expected that any major new transmission facilities installed by the common carriers would be based on the new three-level hierarchy, not the old five-level one. All telephone traffic sources in the model are expected to be highest level nodes in the new hierarchy, and so the hierarchy can be ignored in developing the simplified network model.

## 2.5 INFLUENCE OF THE OPTIMIZATION ALGORITHM ON THE NETWORK MODEL

Special-purpose computerized network optimization algorithms are being developed to determine the network with minimum total annual cost. The annual cost of each link as a function of link capacity must be specified as input. Since the network optimization will be done many times for different network descriptions and traffic requirements, it is important that the number of network nodes be kept small to minimize the computer execution time and costs per optimization.

The previous four subsections have discussed the relationship between the aims of the project and the terrestrial network model, and how the existing network is modelled to meet those aims. The present section will discuss the relationship between the methods used to meet the aims of the study and the description of the network.

The overall satellite-terrestrial network is optimized, i.e. the network with minimum total annual cost is determined, with the aid of a special-purpose computerized optimization algorithm. (A special-purpose algorithm was developed rather than using a general-purpose integer-programming package because of the large savings in computer time, space, and cost that could be realized with the former. In fact, it is very unlikely that a computer could be found to solve the problem by linear programming, since the number of nodes and links in the network is quite large.) The computer algorithm optimizes the traffic flow for a given set of traffic requirements, terrestrial link costs and capacities, satellite Earth Station capabilities, costs, and locations, and cost of the space portion of the satellite system. Each time any of these parameters are changed the network is re-optimized with the computer program. This is done for several dates throughout the 1973-1990 time-frame, until the minimum-cost satellite-terrestrial network for the complete 1973-1990 interval is determined. In short, the computer algorithm will be used many times, and so the computer time and cost for a given iteration must be kept small. This can be done by careful computer programming, and also by describing the network as simply as possible, i.e. by having as few nodes as possible.

The number of nodes in the network has been minimized by only including major sources of telephone traffic, television regional distribution centres, and major branch points in the transmission system, as described above. At a more detailed level, the nodes and the links have been described and costs have been assigned in such a way that the algorithm can determine the minimum-cost network. The technique used to model major nodes is described below in Section 2.5.1, and the modelling of links with several parallel systems is described in Section 2.5.2.

### 2.5.1 SIMPLIFIED MODEL OF A MAJOR NETWORK NODE

A major node in the network, such as Toronto, is usually developed over thousands of square miles, includes several repeater sites, and costs several million dollars. In the simplified network model such a node is replaced by two star networks, one representing the TCTS system and the other representing the CN/CP system. Each star has a branch connecting the node to each of the other major network nodes that are directly connected to that node.

In metropolitan areas the microwave radio links do not terminate at the switching centres; rather, they terminate at junction repeater points on the outskirts of the metropolitan area. The idealized growth plan for the microwave network of a metropolitan area is shown in Fig. 2.6, taken from Reference [7]. In the figure the circular nodes are junction repeaters and the square node is the central switching and multiplexing point. Most of the traffic going through the node rather than terminating at it is re-routed at the supergroup and mastergroup multiplex levels in the junction repeaters. Only the traffic terminating at the node, and a small amount of through traffic that is de-multiplexed and possibly switched to an alternate route, is transmitted to the central terminal.

The actual Toronto metropolitan network plan is shown in Fig. 2.7. Because of its location there are no microwave links to the south, so the "southern" junction repeater is to the north of the central nodes. The metropolitan network is incomplete in that there are two rather than three microwave links to the north, east, and west. A third difference is that there are three metropolitan switching centres rather than one, as shown, at Roland, Pharmacy, and Adelaide.

The central switching centre or centres are not included in the model, as it is assumed that these costs would be the same whether the traffic was routed terrestrially or by satellite.

The junction repeaters and their costs, however, have to be included as part of the transmission costs of the terrestrial network and of the backhaul systems for satellite Earth terminals. One possible way to do this would be to include each junction repeater as a separate node in the trunk network, and also include the central terminals as traffic sources. However, this approach would result in a much more complex network, and much more computer time and costs to optimize the routing through the network, and so was rejected in favour of a simpler representation.

Three simpler models were considered. In one model the complete metropolitan area was considered to be a single node, and all costs of the system in that area were associated with that single node. This model proved impractical, however,

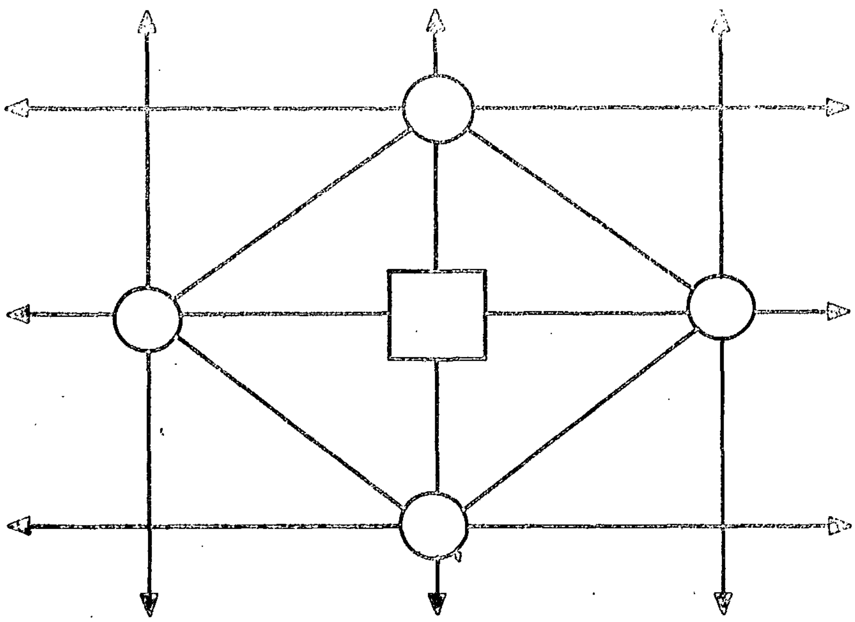

FIGURE 2.6

IDEAL MATURE METROPOLITAN NODE

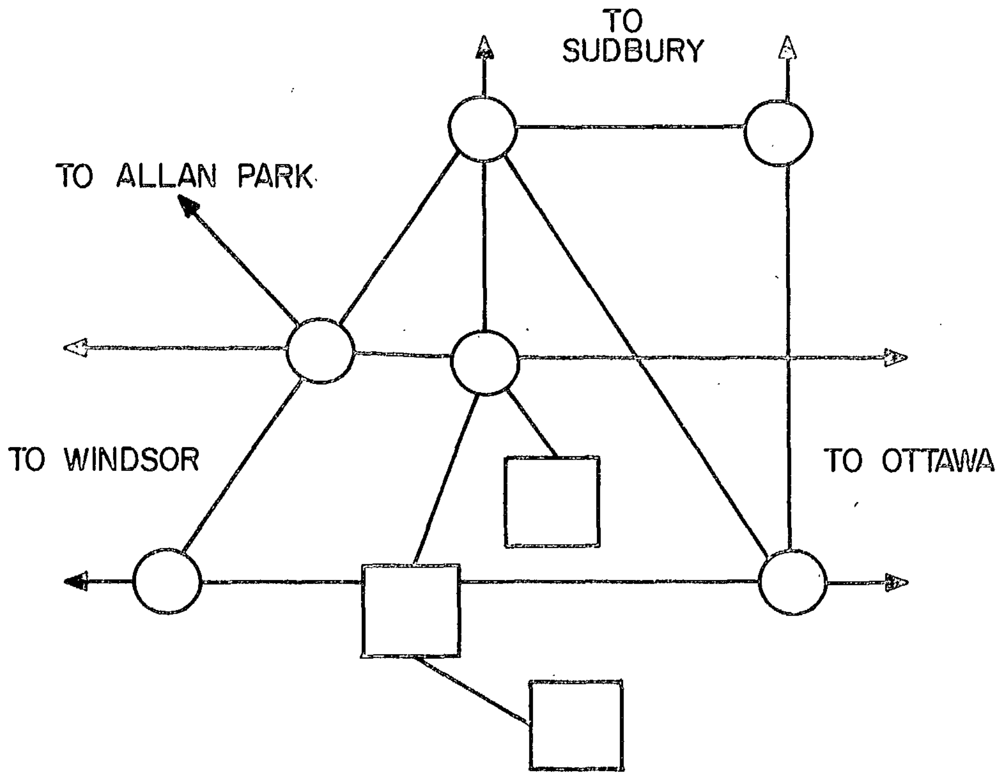


FIGURE 2.7

METROPOLITAN TORONTO NODE, 1973

because the optimization algorithm assumes that all costs are associated with links, not nodes.

A second model that was considered was that of again representing the metropolitan area as a single node, but considering the costs of the junction repeaters, etc. to be part of the costs of the links entering the node, rather than that of the node itself. The total cost of the transmission systems in the metropolitan area was divided among the links entering that node, in proportion to the present installed capacity on each link. Thus the problems associated with assigning costs to nodes were avoided. However, the model proved inflexible in that it was not easy to account for increased metropolitan area costs in an expanded network.

A third model, which retains the concept of all costs being associated with network links rather than nodes, has been adopted. Each metropolitan area is represented by a star network, with a branch of the star for each other node that is connected directly to the node being represented. Separate star networks are used to represent the TCTS and the CN/CP facilities in a given node. The model includes inter-system links between the TCTS and the CN/CP networks at each metropolitan area. The model for the Toronto-Sudbury-Ottawa region is shown in Fig. 2.8.

The cost of a link of the star is assumed to be proportional to the number of installed circuits in the link. The proportionality constant is chosen such that in 1973 the

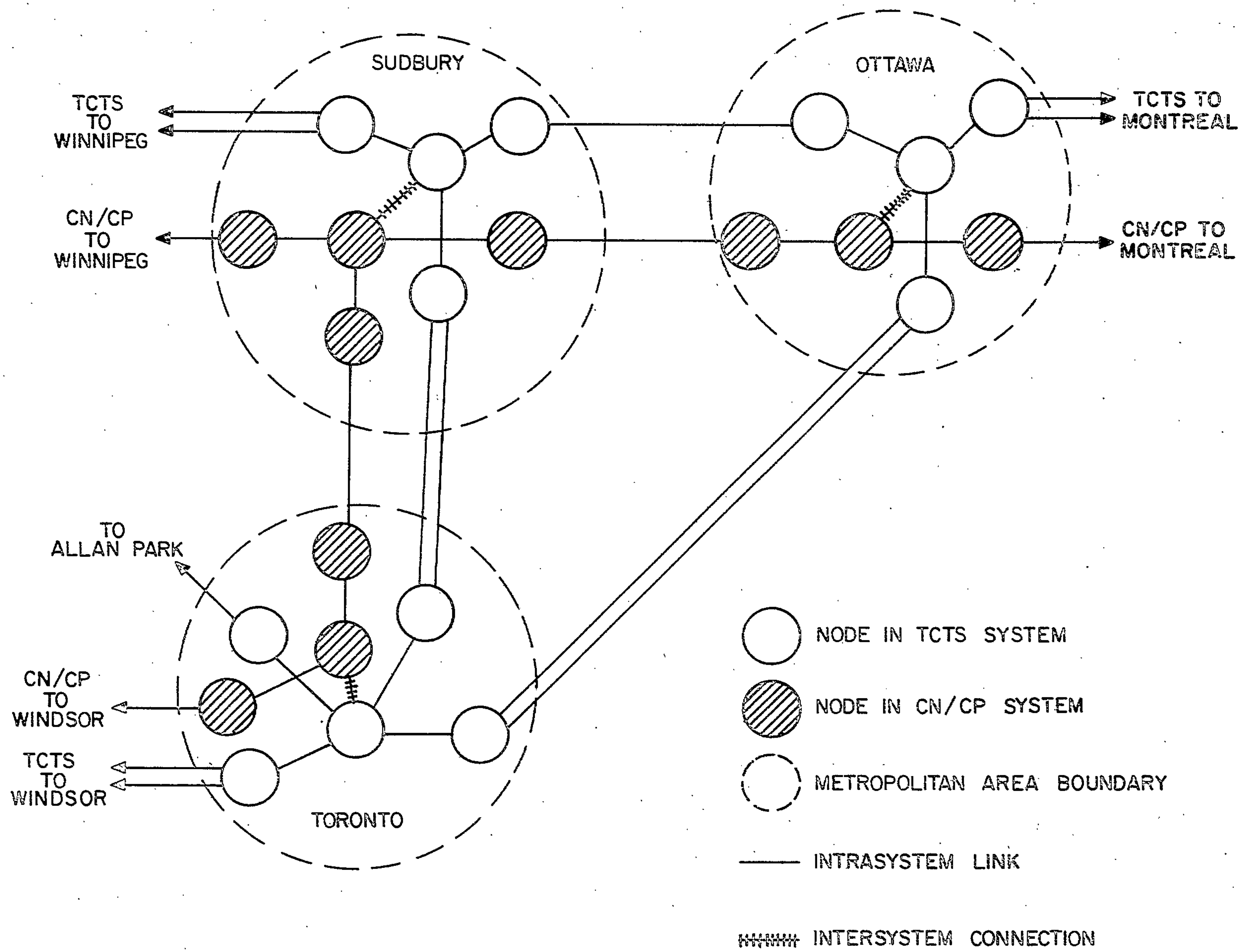
SUDBURY
OTTAWA
TCTS TO WINNIPEG
CN/CP TO WINNIPEG
TCTS TO MONTREAL
CN/CP TO MONTREAL
TO ALLAN PARK
CN/CP TO WINDSOR
TCTS TO WINDSOR
TORONTO
NODE IN TCTS SYSTEM
NODE IN CN/CP SYSTEM
METROPOLITAN AREA BOUNDARY
INTRASYSTEM LINK
INTERSYSTEM CONNECTION

FIGURE 2.8

total cost of each star network is equal to the cost of the actual metropolitan area that it represents. The total metropolitan cost was determined by adding the cost of all the repeaters in the area, with each repeater loaded to its 1973 installed capacity. The costs and installed capacities of different metropolitan areas throughout the network were compared in an attempt to determine a common relationship between metropolitan costs and installed capacity for the whole network. However, no such relationship was found, and so each metropolitan area was independently modelled, and the costs of each link of the star in later years is assumed to remain proportional to the installed capacity in the link with the same proportionality constant as that used for the 1973 network. Economies of scale at each metropolitan repeater site would tend to reduce this proportionality constant with increasing traffic, but the necessity to add more metropolitan links and to go to cable systems in large areas such as Toronto and Montreal would tend to increase the proportionality constant. Since these effects counterbalance each other, and since we are not investigating the expansion of the metropolitan areas in detail, the proportionality constant was kept independent of time and installed capacity.

### 2.5.2 MODELLING OF A MULTI-SYSTEM LINK

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Most links in the network have, or will have, several systems operating in parallel. Dummy nodes are introduced into the network so that each link in the expanded network contains only one system. This modification is made so that a choice between several systems can be made with the optimal routing algorithm.

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As indicated in Fig. 2.5, there are as many as four parallel systems on some of the high-capacity links. It is expected that during the 1980's several new systems will be installed parallel to existing ones. One of the major tasks of the study is to determine what new systems should be introduced, and on what links. The most cost-effective satellite system cannot be determined without also determining the best expansion of the terrestrial network.

The costs of specific systems such as TD and TH microwave radio systems over specific routes, LD-4 cable and digital radio systems, etc. are described in Section 3 below. The form of the system cost function in terms of installed capacity are discussed here without inclusion of numerical information so that the development of the network model can be described. In general, the cost of a system as a function of installed capacity is as shown in Fig. 2.9. There is a large initial cost to install the system, a cost proportional to installed capacity to augment the system, and a maximum capacity beyond which the cost is undefined, and so can be set at infinity in the optimization algorithm.

Suppose now that a link contains several systems in parallel, each with a cost curve of the type shown in Fig. 2.9. Such a link can be thought of as several links in parallel, or as a single complex link. Let us consider first the possibility of representing the multi-system link as a single complex link. In this case it is necessary to specify a single cost function for that link. In determining how this can be done, consider an example in which there are three parallel systems, A,B, and C, in a given link. The cost functions of each of these three systems will be similar to that shown in Fig. 2.9. If the routing strategy on the link of concern is to route traffic through system A until it is full, then use system B until it is full, and finally use system C, then the cost function for the link will be that shown in Fig. 2.10. However, if system C were used before system B the link cost function would be considerably different. The disadvantage of this approach is that it imposes a solution which might not be a minimum cost one. It would be better to let the routing algorithm determine the order in which systems are filled. Thus the use of a single cost function for several parallel systems is not acceptable.

A better approach is to consider each parallel system as a separate network link, as shown in Fig. 2.11. In the figure

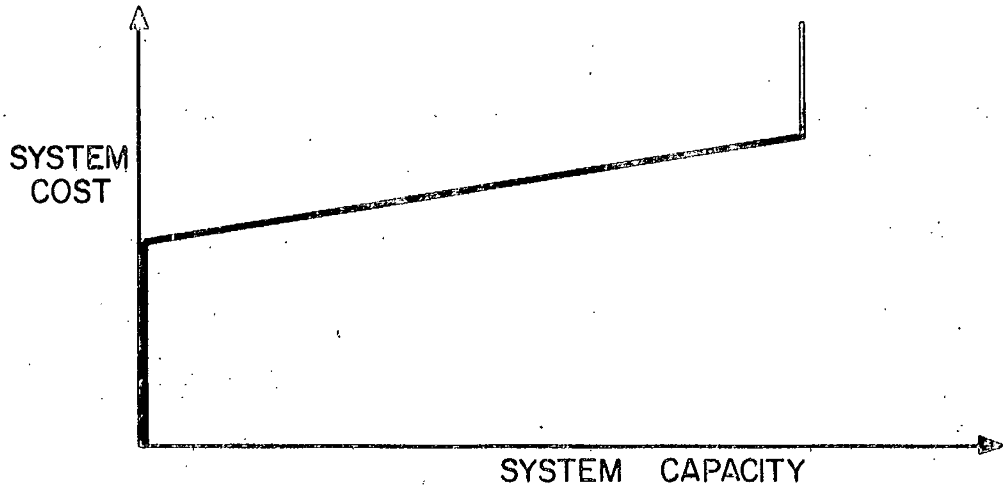


FIGURE 2.9

COST CURVE OF A SINGLE SYSTEM

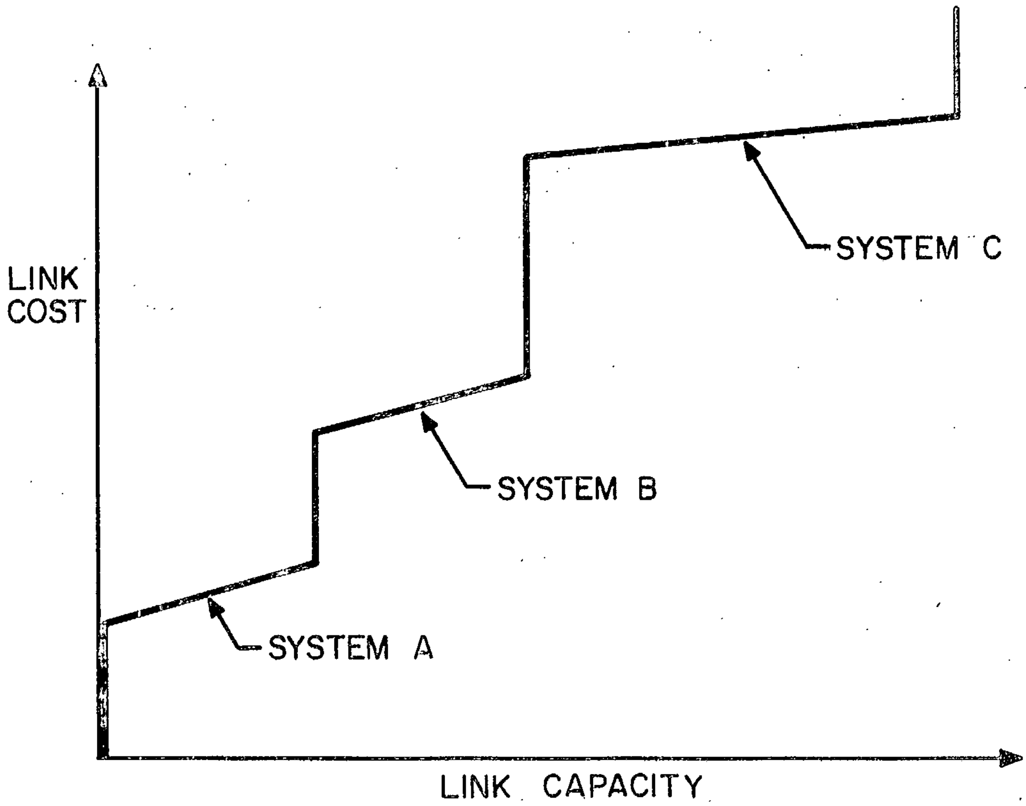


FIGURE 2.10

COST CURVE OF A MULTI-SYSTEM LINK

there are three parallel systems between nodes A and B. Two dummy nodes C and D are created, as shown, so that the total circuit capacity between A and B remains unchanged, and yet no links have either multiple systems in parallel or a composite cost function of the type shown in Fig. 2.10. In the representation of the network shown in Fig. 2.11b, link AB, AC, and AD have cost functions of the type shown in Fig 2.9, and links CB and DB have essentially zero cost.

The advantage of this approach is that the optimization algorithm will automatically choose which of several parallel links to load first. A potential new parallel system is represented by a link with its associated cost function. If it is not economically viable in the network, the routing algorithm so indicates this by not routing any traffic through it.

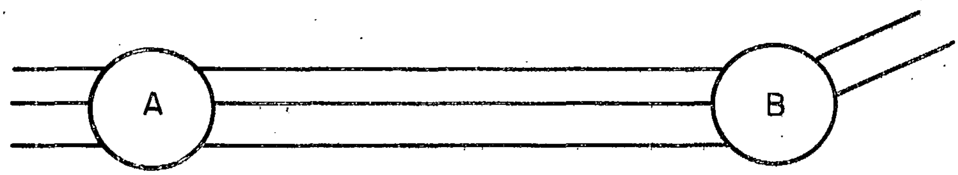


FIGURE 2.11a

MULTI-SYSTEM LINK BETWEEN A AND B

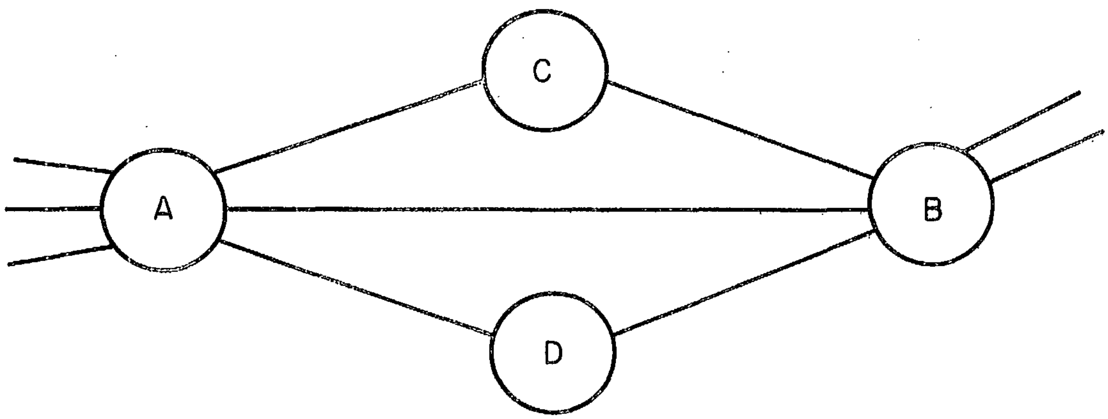


FIGURE 2.11b

INTRODUCTION OF DUMMY NODES

BETWEEN A AND B

# 3. LONG-HAUL HEAVY-ROUTE TERRESTRIAL TRANSMISSION SYSTEMS

At present the Canadian long-haul heavy-route terrestrial network is exclusively 4 GHz and 6 GHz analog radio systems. Analog coaxial cable systems are an available alternative, but are not used in Canada. Heavy-route digital coaxial cable and digital radio systems will be available in the latter part of this decade, followed by digital millimetre waveguide and optic fibre systems in the 1980's.

At the present time the long-haul heavy-route terrestrial communication system in Canada is exclusively 4 GHz and 6 GHz analog microwave radio. TCTS has two trans-Canada systems at 4 GHz, shown in Fig. 2.2, and CNCP has a 6 GHz trans-Canada system shown in Fig. 2.3. The TCTS long-haul system is more complex, in that it has quite extensive metropolitan junctions at the major nodes, and is co-located with short-haul systems at 2 GHz, 6 GHz, 7 GHz, and 11 GHz, which utilize the same buildings, towers, and other civil and electrical facilities.

A second long-haul transmission medium, analog coaxial cable, is available and is extensively used in the United States [9] and Europe, but not in Canada. In the U.S. these systems are known as the L-3, L-4, and L-5 systems.

A system under development at present in Canada is the LD-4 digital coaxial cable system. This system will likely be operational by 1975 or 1976. Digital microwave radio systems at 8 GHz and at 11 GHz or higher are also being developed. The 8 GHz system is an "add-on" to the 4 GHz analog system, in that it will use the same sites and antenna systems. In contrast the 11 GHz system is an entirely new higher capacity system.

In the more distant future digital millimetre waveguide and optic fibre systems will become available. The millimetre waveguide system is a very high capacity one. Bell Telephone Laboratories in the U.S. is developing a system for operation in 1979 or 1980 with a 240,000 voice circuit capacity. In contrast, it is not likely that optic fibre systems will become operational for long-haul use until the mid or late 1980's. At that time it is likely that several optic fibre systems will be available as alternatives to the twisted-pair LD-1 or T-1 system, the LD-4 digital coaxial cable system, and the digital millimetre waveguide system.

The salient features of the above transmission media are described in Section 3.1, as these are the possible systems that may become links in the network described in Section 2. The existing analog radio plant is described in more detail in Section 3.2.

## 3.1 CHARACTERISTICS OF LONG-HAUL TRANSMISSION MEDIA

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The salient features of analog and digital microwave radio, analog and digital coaxial cable, millimetre waveguide, and optic fibre systems are described.

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As stated above, the possible systems that can be used as links in the terrestrial network that was described in Section 2 are analog and digital microwave radio and coaxial cable, and digital millimetre waveguide and optic fibre systems. These systems must be understood well enough to be able to:

i) determine the capital cost vs. installed system capacity curve for the system, as shown in Fig. 2.9;

ii) determine when such a system is likely to be available, if it is not yet being produced;

iii) determine such parameters as system lifetime and maintenance costs for the system so that capital costs can be converted to annual costs.

Each of the above types of transmission media will be described in this way below.

### 3.1.1 ANALOG MICROWAVE RADIO SYSTEMS AT 4 GHz AND 6 GHz

The salient technical features of analog microwave radio systems at 4 GHz and 6 GHz are described. The types of repeaters used in a long haul system are discussed, and the capital costs of equipment in these sites are indicated.

Analog microwave radio is the oldest of the transmission media being considered. It was developed about 25 years ago at 4 GHz, and the first such system was installed in Canada almost 20 years ago. The two 4 GHz systems of TCTS and the 6 GHz system of CNCP are still the only long-haul heavy-route terrestrial systems being used in Canada at present.

The 4 GHz system was originally put into operation as a system with 5 operating and 1 standby full duplex radio channels, each carrying 480 voice circuits or one TV program with audio. The number of voice circuits per 20 MHz wide radio circuit has increased to 600, 960, and now 1,200. It is expected that this will soon be increased to 1,500 voice circuits by using high power low noise transceivers on existing routes. As well as increasing the number of voice channels per radio channel, the number of radio channels has been increased from 6 to 12 in the 3.7 to 4.2 GHz band, and to 16 in Canada by using the wider 3.5 to 4.2 GHz band. (In the U.S. the 3.5 to 3.7 GHz band is used for radio location, and so is not usable for trunk communications.) It is normal practice to use 14 of the 16 radio circuits for operational use and 2 for standby. Thus the present capacity limit of a 4 GHz system in Canada is 16,800 voice circuits at the present time, and will likely be 21,000 voice circuits within a few years.

The 6 GHz system was installed by CNCP in the 1960's. The 6 GHz frequency plan specifies that the system has 8 full-duplex radio channels 29.65 MHz apart. It is normal to use 6 of the 8 channels to carry traffic and 2 for route protection. The system has been equipped to carry 960 voice circuits per pair of radio channels. However, new equipment for use at 6 GHz permits loading of each radio channel to 1,800 voice channels; it is expected that equipment will soon be available that will allow 2,100 voice channels to be carried on a radio channel. Thus the present capacity of the 6 GHz system is 10,800 voice circuits, and it is likely to be increased to 12,600 voice circuits.

In both the 4 GHz system and the 6 GHz system a complete radio channel is used to transmit a network quality TV signal with audio subcarriers. The frequency plans of both the 4 GHz and the 6 GHz systems are very rigid to avoid interference problems as much as possible. As a result, the use of a simplex radio channel for TV transmission in one direction on the route prevents the corresponding radio channel in the opposite direction being used, unless it can be used for TV transmission in the opposite direction. Thus it is assumed that a TV program requires one sixth of the capacity of a 6 GHz system and one fourteenth of the capacity of a 4 GHz system, whether the television requirements are for a simplex or a duplex channel.

Analog radio transmission systems consist of a sequence of radio repeaters along the route, spaced 25 to 30 miles apart. The repeaters are usually located near a main road for easy access. The repeater site consists of an antenna tower some 200 to 300 feet in height, several parabolic dishes or horn antennas on the tower, and a building that shelters the electronic equipment. The prime power supply is the local power grid, with a diesel motor and generator as backup. The site is usually a few hundred yards from the main road, and requires a private all-season road and power line from the main road.

In the microwave repeater, the 4 GHz or 6 GHz microwave radio signal is heterodyned to 70 MHz, amplified, heterodyned up to another carrier in the original band, and transmitted. Systems that detect the video signal, amplify it, and remodulate it on another carrier are less expensive but noisier, and so are only used on short-haul systems. As well as the transceivers, one for each radio channel, each site must have alarm and order-wire equipment, and about one in every six repeater sites has protection switching equipment to enable the use of a standby radio channel when an operating channel fails. At major network junction points the composite video signal is detected, demultiplexed to the mastergroup or supergroup level, and remultiplexed and modulated in different combinations for transmission over the outgoing links.

The major difference between the sites of the 4 GHz TCTS system and the 6 GHz CNCP system is that the former use circular waveguide on the antenna towers, and horn antennas, whereas the latter use less expensive rectangular waveguide and parabolic reflectors. TCTS use the more expensive antenna system so that signals at 4 GHz, 6 GHz, 8 GHz, and 11 GHz can all be radiated through the same antenna system.

There are five types of repeater sites in a typical analog radio system. These are:

i) a regular repeater,
ii) a drop repeater,
iii) a junction repeater,
iv) a junction-terminal repeater,
v) a terminal.

The regular repeater was described above.

A drop repeater is similar to a regular repeater, except that one or more radio channels are re-routed onto a local spur route. At such a repeater, radio channels carrying voice traffic destined for the spur route are demodulated, spur traffic at the supergroup (or mastergroup) level is removed or added as appropriate, and the new composite signal is remodulated on a radio carrier.

A junction repeater is very similar to a drop repeater, except that it is located at a metropolitan junction point. Long-haul signals are radiated in several directions from a junction repeater.

A junction-terminal repeater is located at the central office within a node. Some radio channels at such a site are demodulated and demultiplexed to individual voice circuits, and others are simply re-transmitted. Note that the final demultiplexing to voice-band is not included as part of the transmission system costs.

In a terminal at a central office all radio channels are passed through a frequency modulator-demodulator. Voice signals are multiplexed to or from the voice baseband, and TV signals are re-transmitted over either a local-transmission radio system or an analog coaxial cable system.

The number of video modems and supergroup multiplexers at a repeater site varies from one site to another. Rather than examine each site in detail, the average amount of such equipment was determined and then assumed to exist at each site. These amounts are shown in Table 3.1. As well, the cost of protection equipment was allowed for by allocating one-sixth of its cost to every repeater, rather than by determining which particular repeaters in a sequence contained the equipment.

The capital cost of equipment used by TCTS at these repeater sites, and the cost of the site itself, is given in

TABLE 3.1

Average Amount of Modem and Multiplex Equipment Per Repeater

| Repeater Type | With ≤ 5 Working Channels | | With ≤ 6 Working Channel | |
|---|---|---|---|---|
| | Number of Modems | Number of Multiplexers | Number of Modems | Number of Multiplexers |
| Drop Repeater | 2 | 2 | 4 | 4 |
| Junction Repeater | 1 | 1 | 2 | 2 |
| Junction-Terminal | 1 per direction | 0 | 2 per direction | 0 |
| Terminal | 1 per radio channel | 0 | 1 per radio channel | 0 |

Table 3.2. The installation mark-up ratios are again an average over the whole network, and account for transportation, installation, and testing of the equipment. The installed capital costs of the five types of repeaters are given in Table 3.3 to 3.7. The figures used in these tables are taken from Table 3.2. Costs shown in any line of these tables are incremental costs over those to install a system with the capacity indicated on the previous line. It is assumed that horn antennae are used, and that each antenna requires a feed system consisting of 250' of circular waveguide and 150' of rectangular waveguide. This is an average requirement over all repeater sites in the network. Note also that "initial costs" in these tables includes the site costs, antenna costs, and cost of the alarm and order-wire system. Similarly, the "R.F. connections" cost includes the cost of the rectangular and circular waveguide, the R.F. branching equipment, and the mode filters. On the average, 250 feet of circular waveguide and 150 feet of rectangular waveguide are used to feed each horn antenna. Four antennas are installed on each regular and drop repeater for long-haul use, and two antennae on each junction repeater, junction terminal, and terminal are allocated to a given route. The R.F. connection, power, transceiver, and modem costs in the tables for the junction repeater and junction terminal are less than similar costs for the regular and drop repeaters, because they are attributed to only a single path out of the junction. Stated another way, the total

TABLE 3.2

Capital Costs of Components of Radio Repeaters

| Item | Factory Cost | Installation Mark-up | Installed Cost |
|---|---|---|---|
| Site, including land, buildings, road, prime power, and tower | 75,000 | 1.0* | 75,000 |
| Antenna,horn | 8,000 | 1.4 | 11,200 |
| Antenna,paraboloid | 6,000 | 1.4 | 8,400 |
| Waveguide, circular/ft | 33 | 1.4 | 46 |
| Waveguide, rectangular/ft | 10 | 1.4 | 14 |
| Mode Filter | 1,500 | 1.4 | 2,100 |
| R.F. Branching Eqpt. | 2,000 | 1.4 | 2,800 |
| Alarm and order wire eqpt. | | | |
| -in regular repeaters | 9,500 | 1.87 | 17,750 |
| -in terminals | 13,500 | 1.87 | 25,520 |
| Protection Switching Eqpt./Site | | | |
| -initial cost | 7,500 | 1.87 | 14,025 |
| -incremental cost/channel | 1,500 | 1.87 | 2,805 |
| -increase to double protection | 7,000 | 1.87 | 13,090 |
| Power System | | | |
| -Initial in reg. repeater | 60,000 | 1.0* | 60,000 |
| -Initial in drop repeater | 67,320 | 1.0* | 67,320 |
| and in terminals | | | |
| -To introduce 6th channel | 9,350 | 1.0* | 9,350 |
| -To introduce 11th channel | 9,350 | 1.0* | 9,350 |
| F.M. Modem | 5,500 | 1.87 | 10,285 |
| Transceiver | 14,000 | 1.87 | 26,180 |

*The mark-up is 1.5 in remote sites.

TABLE 3.3

Regular Repeater Installed Capital Costs*, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modems & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 137,750 | 58,400 | 14,025 | 60,000 | 104,720 | 0 | 374,895 |
| 2 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 3 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 4 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 5 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 6 | 2 | | 14,000 | 13,090 | 9,350 | 104,720 | | 141,160 |
| 7 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 8 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 9 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 10 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 11 | 2 | | 5,600 | 2,805 | 9,350 | 52,360 | | 70,115 |
| 12 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 13 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 14 | 2 | | | 2,805 | | 52,360 | | 55,165 |

*Costs shown on any line are incremental costs over the costs to install system with capacity of preceeding line.

TABLE 3.4

Drop Repeater Installed Capital Costs, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modems & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 137,750 | 58,400 | 14,025 | 67,320 | 104,720 | 55,570 | 437,785 |
| 2 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 3 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 4 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 5 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 6 | 2 | | 14,000 | 13,090 | 9,350 | 104,720 | 55,570 | 196,730 |
| 7 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 8 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 9 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 10 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 11 | 2 | | 5,600 | 2,805 | 9,350 | 52,360 | | 70,115 |
| 12 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 13 | 2 | | | 2,805 | | 52,360 | | 55,165 |
| 14 | 2 | | | 2,805 | | 52,360 | | 55,165 |

TABLE 3.5

Junction Repeater Installed Capital Costs, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modem & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 106,375 | 29,200 | 11,220 | 67,320 | 52,360 | 27,785 | 294,260 |
| 2 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 3 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 4 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 5 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 6 | 2 | | 7,000 | 9,350 | 4,675 | 52,360 | 27,785 | 101,170 |
| 7 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 8 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 9 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 10 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 11 | 2 | | 2,800 | 2,805 | 4,675 | 26,180 | | 36,460 |
| 12 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 13 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 14 | 2 | | | 2,805 | | 26,180 | | 28,985 |

TABLE 3.6

Junction Terminal Installed Capital Costs, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modem & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 106,375 | 29,200 | 11,220 | 67,320 | 52,360 | 10,285 | 276,760 |
| 2 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 3 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 4 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 5 | 1 | | | 2,805 | | 26,180 | | 28,985 |
| 6 | 2 | | 7,000 | 9,350 | 4,675 | 52,360 | 10,285 | 83,670 |
| 7 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 8 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 9 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 10 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 11 | 2 | | 2,800 | 2,805 | 4,675 | 26,180 | | 36,460 |
| 12 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 13 | 2 | | | 2,805 | | 26,180 | | 28,985 |
| 14 | 2 | | | 2,805 | | 26,180 | | 28,985 |

TABLE 3.7

Terminal Installed Capital Costs, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modems & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 122,745 | 29,200 | 14,025 | 67,320 | 52,360 | 20,570 | 306,220 |
| 2 | 1 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 3 | 1 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 4 | 1 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 5 | 1 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 6 | 2 | | 7,000 | 13,090 | 9,350 | 52,360 | 20,570 | 102,370 |
| 7 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 8 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 9 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 10 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 11 | 2 | | 2,800 | 2,805 | 9,350 | 26,180 | 10,285 | 51,420 |
| 12 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 13 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |
| 14 | 2 | | | 2,805 | | 26,180 | 10,285 | 39,270 |

costs of a junction repeater are divided among the branches for which it acts as a common node, and the costs shown in Tables 3.5 and 3.6 are only those costs attributable to one such branch.

The cost information presented in Tables 3.2 to 3.7 is summarized in Table 3.8. In this table the site costs and the initial power system costs are kept separate, so that they can be shared between different systems (in different frequency bands) using the site in proportion to the installed number of radio channels in each system. (See Section 4.1.). The "other first-channel costs" are all those costs contributing to the "total costs" figure for the repeater with 1 working and 1 standby channel, as shown in Tables 3.3 to 3.7. The figures in the last three columns of Table 3.8 are self-explanatory, and are taken directly from the last columns of Tables 3.3 to 3.7. Calculation of microwave radio link costs and metropolitan junction costs from the information shown in Table 3.8 is described in Sections 3.2 and 4.

The above costs are those for the TCTS 4 GHz system. The CNCP 6 GHz system is very similar, and is assumed to have similar costs, except for two differences. The CNCP system uses less expensive parabolic antennas rather than horn antennas, and uses rectangular waveguide to feed the antennas rather than circular waveguide. The reason for this different repeater design is that the CNCP system only uses the 6 GHz band, and so can use single band equipment, whereas the total

TABLE 3.8

Summary of Installed Capital Costs of Different Repeater Types, 1973 Dollars

| Repeater Type | Site Cost | Initial Power Cost | Other First-Channel Costs | Costs to Introduce 6th Channel | Costs to Introduce 11th Channel | Costs to Introduce Other Channels |
|---|---|---|---|---|---|---|
| Regular | 75,000 | 60,000 | 239,895 | 141,160 | 70,115 | 55,165 |
| Drop | 75,000 | 67,320 | 295,465 | 196,730 | 70,115 | 55,165 |
| Junction | 75,000 | 67,320 | 151,940 | 101,170 | 36,460 | 28,985 |
| Junction-Terminal | 75,000 | 67,320 | 134,440 | 83,670 | 36,460 | 28,985 |
| Terminal | 75,000 | 67,320 | 163,990 | 102,370 | 51,420 | 39,270 |

TCTS system uses the 4 GHz, 6 GHz, 8 GHz, and 11 GHz bands, and so has chosen to use an antenna system that can be used to propagate signals simultaneously in all these bands, i.e. the horn antenna with a circular waveguide feed.

Because of these differences, the "other first-channel costs" of CNCP repeaters are smaller than those shown in Table 3.8. The "other first-channel costs" for CNCP repeaters are given in Table 3.9 for repeaters with an average 200 foot tower, the height assumed for TCTS repeaters. The other columns of Table 3.8 apply without change, except of course that the cost of the eleventh channel is not applicable. The total long-haul system costs of the CNCP system are not necessarily lower than the corresponding costs of the TCTS system by the amount indicated in Table 3.9, however, because the site costs and initial power costs are shared with the short-haul systems in the TCTS network, and they are not in the CNCP network.

A third long-haul analog microwave radio system which should be considered, but which is not yet used in Canada, is a 6 GHz long-haul system addition to the existing 4 GHz system. The TH 6 GHz system [10] was developed in the U.S. in the late 1950's and early 1960's for use as an add-on to the TD 4 GHz system. Such a system could be used to augment the 4 GHz systems of TCTS if radio interference with the CNCP system is avoided and if TCTS short-haul systems at 6 GHz are re-allocated to 2 GHz, 7 GHz, 8 GHz, or 11 GHz.

TABLE 3.9

First-Channel Installed Capital Costs of Single-Band (CNCP) Repeater Sites, Not Including Site and Power Costs

| Type of Repeater | Reduction in Antenna Costs | Reduction in Waveguide Costs | Total Other First Channel Costs |
|---|---|---|---|
| Regular | 11,200 | 25,800 | 202,900 |
| Drop | 11,200 | 25,800 | 258,500 |
| Junction | 5,600 | 12,900 | 133,500 |
| Junction-Terminal | 5,600 | 12,900 | 115,900 |
| Terminal | 5,600 | 12,900 | 145,500 |

The capacity and frequency plan of this add-on system is the same as that of the independent 6 GHz system, which was described above. The cost of such a system can be determined by determining the cost at each repeater, in much the same way that the 4 GHz system was costed above. In making these cost estimates it is assumed that:

a) the site, antenna, antenna feed, and prime power system are available for the 4 GHz system, so only the marginal costs of the 6 GHz equipment need be considered;

b) the cost of transceivers, protection equipment, and modems, are the same per radio channel as the cost for similar 4 GHz equipment;

c) multiplex costs are higher in proportion to the number of voice circuits on a radio channel;

d) the amount of modem and multiplex equipment used in the 6 GHz add-on is given in Table 3.1, i.e. is the same as that used in the 4 GHz system;

e) the 6 GHz system uses a completely separate alarm, order-wire, and protection switching system;

f) the costs of the power supply system for the 6 GHz system are the same as the incremental costs of the power system for the 4 GHz system.

Based on these assumptions, the cost of a regular repeater for the 6 GHz add-on system is shown in Table 3.10 as a function of the number of working channels. A similar table could be specified for the other types of repeaters, as was done above for the 4 GHz system in Tables 3.3 to 3.7. Instead, these results are summarized in Table 3.11. The capital cost of installing the system, channel by channel, are shown in this

TABLE 3.10

6 GHz Add-On Regular Repeater Installed Capital Costs, 1973 Dollars

| Radio Channels Installed | | Initial Costs | R.F. Connections | Protection Switching | Power | Transceivers | Modems & Mux | Total |
|---|---|---|---|---|---|---|---|---|
| Working | Standby | | | | | | | |
| 1 | 1 | 17,750 | 22,400 | 14,025 | 9,350 | 104,720 | 0 | 168,245 |
| 2 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 3 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 4 | 1 | | 14,200 | 2,805 | | 52,360 | | 69,365 |
| 5 | 1 | | | 2,805 | | 52,360 | | 55,165 |
| 6 | 2 | | | 13,090 | 9,350 | 104,720 | | 127,160 |
| 6 | 1 | | | 2,805 | 9,350 | 52,360 | | 64,515 |
| 7 | 1 | | | 2,805 | | 52,360 | | 55,165 |

TABLE 3.11

Summary of Installed Capital Costs of Different Repeater Types in 1973 Dollars for a TH Add-On to a TD System

11.a Six working and two standby channels at full utilization:

| Repeater Type | First Channel | Fourth Channel | Sixth Channel | Second, Third and Fifth |
|---|---|---|---|---|
| Regular | 168,200 | 69,400 | 127,200 | 55,200 |
| Drop | 241,300 | 69,400 | 200,200 | 55,200 |
| Junction | 124,850 | 36,000 | 102,950 | 29,000 |
| Junction-Terminal | 98,600 | 36,000 | 76,700 | 29,000 |
| Terminal | 132,800 | 46,300 | 95,400 | 39,300 |

11.b Seven working and one standby channel at full utilization

| Repeater Type | First Channel | Fourth Channel | Sixth Channel | Second, Third Fifth and Seventh |
|---|---|---|---|---|
| Regular | 168,200 | 69,400 | 64,500 | 55,200 |
| Drop | 241,300 | 69,400 | 137,600 | 55,200 |
| Junction | 124,850 | 36,000 | 70,150 | 29,000 |
| Junction-Terminal | 98,600 | 36,000 | 44,000 | 29,000 |
| Terminal | 132,800 | 46,300 | 48,700 | 39,300 |

table. Note that none of these costs are "shared" with any short-haul systems, since the costing is done on a marginal cost basis.

There are two ways of using the 8 full-duplex radio channels in the 5.9 to 6.4 GHz band. In one plan a single standby channel is used until five channels are used for customer traffic, and then one more working channel and one more standby channel are introduced. The cost of the system when this plan is used is shown in Table 11a. The other way to use the same band is to have one standby channel throughout, with as many as seven channels for customer traffic. The cost of implementing this system are shown in Table 11b. In this scheme 17% more traffic can be carried at 1% to 2% less total cost, but the protection against fading and failure of electronic equipment is less. It is likely that by the late 1970's 10 to 20 watt solid state amplifiers will be available at 6 GHz with 30 MHz bandwidth, which would allow the carriers to adopt the less expensive strategy.

In summary, the three analog microwave radio systems that are being or may be used in Canada for long-haul transmission are the 4 GHz systems of TCTS, the 6 GHz system of CNCP, and the potential 6 GHz add-on to the 4 GHz system. The salient features of these systems have been described from a communications viewpoint, and the capital costs of repeater sites have been determined in detail. The capital and annual costs of complete microwave systems are described in Section 4.

### 3.1.2 DIGITAL MICROWAVE RADIO SYSTEMS AT 8 GHz AND 12 GHz

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Two digital microwave radio systems will likely be available in the late 1970's or early 1980's. One is a medium-capacity long-haul system at 8 GHz for digital transmission. The capacity of this system is in the 4,032 to 13,440 voice circuit range. Another, higher capacity system will likely become available later at 12 GHz or above, with a 32,256 voice circuit capacity.

---

Two new digital microwave systems are being developed. One is an 8 GHz system that can be added to an existing 4 GHz analog system in the same way that the analog 6 GHz system is added. The other is a completely new system at 12 GHz.

Let us first consider the 8 GHz system, known within TCTS as the RD-2A system. It uses the 7.725 to 8.275 GHz band. The existing frequency plan for this band has eight full-duplex radio channels, each 29.65 MHz wide. A 50 MHz channel in the centre of the band, between 7.975 and 8.025 GHz, is reserved for satellite use. The 8 GHz digital radio system is being designed on the assumption that this use of the band will be changed to six full-duplex radio channels, each 40 MHz wide.

In the RD-2A system digital information is transmitted at T3 rate (46 Mb/s, the equivalent of 672 voice circuits) over the 40 MHz wide radio channels. It is expected that quaternary symbols will be transmitted over such a channel, either by 4 phase PSK or by FSK. The RD-2A1 system uses six operating channels, with no reserve for hot standby. If only one polarization is used on a given radio frequency, the system capacity is 4,032 voice circuits or 225.8 Mb/s of data at 56 Kb/s per voice channel. Full space-diversity is used over each hop to combat fading, because of the lack of available spectrum for frequency diversity. The RD-2A2 system has a total of ten operating 40 MHz channels, each transmitting 672 voice circuits or 37.63 Mb/s of data, for a total of 6,720 voice circuits or 376 Mb/s of data. Both polarizations of each frequency band are used, for a total of ten operational and two hot-standby channels. A further modification to the RD-2A system is the use of partial response encoding to increase the transmission rate to 92 Mb/s on each 40 MHz channel, thereby increasing the total system capacity to 13,440 voice circuits or 3,760 Mb/s of data over full-duplex channels.

The initial costs to install a RD-2A2 system on an existing 4 GHz route are quite small. Other than for the transceivers for the operating and standby channels, the major costs are for the protection system, the alarm and order-wire system, the R.F. connections between the transceivers and the circular waveguide, and the augmentation of the prime power system. The RD-2A1 system would require a large expenditure in addition to this to provide for the space diversity system, since there is no space diversity on the TD system. Since the RD-2A2 system is less expensive for this reason, and since it has a higher capacity, than the RD-2A1, it is likely that it will be implemented rather than the RD-2A1.

Indications are that the RD-2A could be available by 1976 or 1977. The major technical problems appear to be the use of both polarizations and the use of partial response encoding to double the transmission rate. From a network viewpoint, whether it is installed this early will likely depend on how soon the digital-under-voice and/or digital-over-voice systems to carry data on the analog 4 GHz system becomes saturated, i.e. on the growth rate of data communications requirements.

The higher capacity system at 12 and 15 GHz is at an earlier stage of development. Tentative plans indicate that this system will have an overall bandwidth of approximately 2 GHz, with one GHz between 12.2 GHz and 13.25 GHz, and one GHz in the 14.4 GHz and 15.35 GHz. It is expected that each of these bands would be divided into two equal bands approximately 500 MHz wide and that in each 500 MHz wide radio channel quaternary symbols are sent at twice the T-4 rate, i.e. at about 560 Mb/s. Each band is to use both polarizations simultaneously. If no radio channels are reserved for standby, the system capacity is 32,256 full-duplex voice circuits. Such a system may be developed without using standby channels, because the system will be all solid state, highly redundant and therefore very reliable, and because the fading difficulties of the system are due to rainfall and so are not frequency dependent.

It is unlikely that a 12 and 15 GHz radio system of this capacity will be available before the late 1970's or early 1980's. Our present best information is that such a system will not be developed and produced by a Canadian manufacturer. However, it is expected that similar equipment will be produced by other manufacturers, likely foreign, by 1980. For instance Nippon Telegraph and Telephone has a digital radio system under development to transmit 400 Mb/s or 5,760 voice channels per radio channel in the 20 GHz band.

### 3.1.3 ANALOG COAXIAL CABLE SYSTEMS

---

Analog coaxial cable systems form a significant part of the common carrier networks in the U.S. and in Europe although they are not used in the Canadian long-haul network. Systems have been developed to carry 960, 2700, 3600, and 10,800 full-duplex voice circuits per coaxial tube pair, and may use as many as 22 coaxial tubes.

---

Analog coaxial cable systems are widely used for long-haul transmission in both Europe and the U.S. but have not been used in Canada. In the U.S. the use of coaxial cable began in the 1960's with the introduction of the L-3 and later the L-4 system [9]. These systems were introduced to provide a system more protected from natural disasters and from nuclear blasts, and to provide new systems in highly populated areas where there was no more 4 GHz and 6 GHz spectrum available. In contrast, analog coaxial cable systems were introduced in Europe about 1950, a decade before microwave radio systems were used there [11]. They were never used extensively in Canada because TCTS used the 4 GHz TD microwave radio system for major expansion in the early 1950's, rather than the more expensive coaxial cable systems that the Europeans were using exclusively at that time. Further, there are no population densities in Canada such as those in the Boston-to-Washington area, and so no need to go to cable because of saturation of the microwave spectrum.

It is unlikely that large long-haul analog coaxial cable systems will become a significant part of the Canadian network unless the current trend toward digital systems is reversed. However, if the network did remain essentially analog into the 1980's, it would likely include systems such as the L-4 and the L-5.

The analog coaxial cable systems introduced in the U.S. were first the L-3, then the L-4, and more recently the L-5 [12]. The salient features of these systems are given in Table 3.12. Similar systems in Europe have 960, 2700, and 10,800 voice circuits per coaxial tube pair, and up to 22 tubes per cable.

These systems are ploughed or trenched along a purchased right-of-way, usually about four feet below the surface. Dependent repeaters (small, buried, remotely-powered repeaters without route protection equipment, etc.) are placed at one to four mile intervals along the route, with major repeater sites with power equipment and possibly multiplex equipment every fifty to one hundred miles.

An important difference between cable systems such as the L-4 and microwave radio systems such as the TD and TH systems is that the standby channels in the former are used only to protect against equipment failure, whereas in the radio systems the standby channels also protect against

TABLE 3.12

Characteristics of Bell System (US) Coaxial Cable Systems

| System Type | L-3 | L-4 | L-5 |
|---|---|---|---|
| First Commercial Service | 1953 | 1967 | 1974 |
| Simplex Voice Channels per coaxial tube | 1860 | 3600 | 10,800 |
| Nominal repeater spacing (miles) | 4 | 2 | 1 |
| Total route capacity per cable | | | |
| Number of coaxial tubes | 20 | 20 | 22 |
| Number of working pairs | 9 | 9 | 10 |
| Total full-duplex voice circuits | 16,740 | 32,400 | 108,000 |

frequency-selective fading caused by multipath phenomena. As a result, two protective standby channels are used on radio systems when six or more operational channels are used, whereas cable systems with up to ten operational channels use only one protective channel.

Available cost information on these systems is presented in Section 4, although this information does not include system installation in the Canadian environment.

### 3.1.4 DIGITAL CABLE SYSTEMS

---

Digital cable systems which are used in or soon will be used in the Canadian network are the T-1 system and the LD-4 system. Similar systems are being developed in the U.S., the U.K., France and Japan.

---

The only digital cable systems in commercial use at the present time are the T-1 and T-2 twisted pair digital systems. The LD-1, the Canadian T-1 line, is used for interoffice connections as long as 200 miles. Digital transmission on these systems is at 1.544 mb/s. The T-2 line operates at four times this rate, 6.3 Mb/s, and can be used over links as long as 500 miles. However, neither of these systems were designed to carry long-haul traffic, nor could they do so economically.

The first long-haul heavy-route digital system to be introduced in Canada, and perhaps anywhere, is the LD-4 coaxial cable system. Binary transmission over this system is at 4,032 voice circuits or 226 Mb/s of data per tube pair (transmission rate is 273 Mb/s). Present TCTS plans are to use a twelve tube cable for this system, with five operational and one spare tube in each direction. This system will have a capacity of 1,365 Mb/s or 20,160 full-duplex voice circuits. Such a system will be operational by 1976. A larger system with 22 tubes, 10 operational and one spare in each direction, could be developed for use in the late 1970's. Such a system would have a 40,320 voice circuit capacity.

A system such as the LD-4 is the same in many respects as the analog L-5 system. The cable itself is very similar, and the method of cable installation is identical. The repeater site design and repeater spacing is also the same. The major difference is the electronic design of the repeaters themselves.

Systems similar to the LD-4 are being developed in the U.S., the U.K., France and Japan. The T-4 and the T-5 digital coaxial cable systems are being developed in the U.S., primarily as feeder systems for the digital millimetre waveguide system. It is not clear whether the T-4 or the T-5, or both, will become operational. The T-4 has the same salient features as the LD-4, and the T-5 is similar except that it operates at twice the data rate, 550 Mb/s. Systems are being developed at 120 Mb/s in the U.K., and at approximately 100 Mb/s and 400 Mb/s in France and Japan. However, these systems are being developed for networks with a different digital hierarchy, and so are uncompatible and will not be considered further.

The digital cable systems that will be considered in the DLDCN study, then, are the 12 tube and the 22 tube LD-4 systems, and possibly the T-5 system. Available cost information on these systems is presented in Section 4.

### 3.1.5 DIGITAL MILLIMETRE WAVEGUIDE SYSTEMS

---

Sixty millimetre circular waveguide systems are being developed for transmission in the $TE_{10}$ mode between 40 and 110 GHz. The systems are digital with 273 Mb/s loading per carrier. Maximum system capacity is sixty such carriers in each direction, a total of 240,000 full-duplex voice circuits.

---

Digital millimetre waveguide systems are being developed in the U.S., in the U.K., and in France. These systems are expected to have full-load capacities in the order of 250,000 voice circuits, 2,600 picture phone circuits, 180 full-duplex network-quality television circuits, or some combination of this loading. This is over ten times the capacity of the TD microwave radio systems or the LD-4 cable system in operation now or in the next few years.

The most precise description in the open literature of such a system is that provided by P. Hutchison [13] of the system being developed at Bell Labs for A.T.&T. This system is to use 60 mm dielectric waveguide with helical waveguide at regular intervals and at all bends, to act as a mode filter. The transmission mode is $TE_{10}$, the only mode in which the ohmic loss in the waveguide wall decreases with increasing frequency. The system is to use the 40 GHz to 110 GHz frequency band. Below 40 GHz the ohmic losses are too high, and above 110 GHz the mode conversion losses are too high. The band 40 GHz to 75 GHz is used in one direction, and the 75 to 110 GHz band in the opposite direction. Sixty carriers are used in each direction, each carrier being binary modulated at the T-4 rate of 274 Mb/s. Higher modulation rates were not chosen because of increasing difficulties in design of the baseband equipment with higher modulation rates, and because of the dispersive nature of the guide.

The dielectric and helical copper waveguide is inserted in a steel sheeth, and this in turn is placed in a steel duct. The duct is placed in a gravel-bottom trench. The repeater sites for this system are expected to be at 20 to 25 mile intervals. Ten miles of this system have been installed by Bell Labs and another ten miles will be installed in 1974. It is expected to be placed in service in the U.S. Bell system by 1979 or 1980, even if picturephone does not require significant amounts of intercity transmission capacity. The waveguide is being thought of as the next major system to be introduced after the L-5 system.

In conclusion, it is expected that a millimetre waveguide system could be imported by early 1980's if required.

### 3.1.6 DIGITAL OPTIC FIBRE SYSTEMS

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Optic fibre systems will likely be competitive with radio and copper systems over wide capacity ranges. However, these systems are not likely to be available for long-haul use before the late 1980's.

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Optic fibre systems are at a much earlier stage of their development than even the millimetre waveguide system [14]. Items such as repeater spacing, fibre capacity, modulation technique, etc. have not yet been determined. Even the transmission medium itself has not yet been determined, in that multi-mode fibres, single-mode solid fibres, liquid-core fibres, and graduated-refractive-index fibres are all being considered. The attenuation of such fibres is 20 dB/km in commercially available quantities, although attenuation less than 10 dB/km has been achieved with laboratory specimens. In addition, research work is being carried out in design of longer lifetime sources, coupling from the light source to the fibre, and bonding of the fibres in the field. These problems have not been solved, but are expected to be in time.

Short-haul optic fibre systems operating at 6.3 Mb/s and 46 Mb/s using multi-mode fibres and light-emitting diodes as sources will likely find intracity use within the next 5 years. However, the use of optic fibre systems for long-haul high capacity use is expected to take considerably longer, likely 10 to 15 years.

### 3.1.7 SUMMARY OF AVAILABLE LONG-HAUL TRANSMISSION MEDIA

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The options in transmission media for the Canadian long-haul system are summarized.

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In the 1980's several transmission media, both analog and digital, will be available, although it is unlikely that all will be used. The important characteristics of these media are summarized in Table 3.13. Link cost information is presented in Section 4 below.

TABLE 3.13

Possible Terrestrial Transmission Media
for the Canadian Long-Haul Network

| Type | Modulation Technique | Capacity, Voice Circuits | Availability Date Estimates |
|---|---|---|---|
| 4 GHz radio | analog | 21,000 | now |
| 6 GHz radio | analog | 12,600 | now |
| 8 GHz radio | digital | 13,440 | 1976 |
| 12 GHz radio | digital | 32,256 | 1980 |
| coaxial cable | analog | 32,400 | now |
| coaxial cable | analog | 108,000 | 1975 |
| coaxial cable | digital | 20,160 | 1976 |
| coaxial cable | digital | 40,320 | 1978 |
| millimetre waveguide | digital | 250,000 | 1981 |
| optic fibre | digital | ? | 1988 |

## 3.2 EXISTING LONG-HAUL TRANSMISSION SYSTEMS

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The existing TCTS and CNCP long-haul terrestrial systems are described in detail.

---

The existing terrestrial Canadian long-haul transmission facilities consist of two 4 GHz radio systems owned by TCTS, and one 6 GHz radio system owned by CNCP. Recently the Anik satellite system has increased the total long-haul transmission capability; the satellite system will be discussed in another report.

Between nodes, the microwave systems consist of a sequence of repeaters at 20 to 30 mile intervals. Most repeaters outside of the nodal regions are regular or drop repeaters (see Section 3.1.1). As described in Section 2.5.1, a major node in the network is not a single point, but rather includes several repeaters. These repeaters may be any of the five types described in Section 3.1.1. These nodal regions are modelled as a star network, with the cost of a branch of the star proportional to the traffic through that branch and the total cost of the star equal to the total cost of the repeaters in the nodal region. This technique was discussed in more detail in Section 2.5.1.

The metropolitan junction plans of each TCTS node in the terrestrial network (Fig. 2.2) are shown in Figures 3.1 to 3.22. Also shown are the nodes at Thunder Bay and at St. John, since they are major TCTS nodes although they are not in the terrestrial network model of the present study. By drawing the nodal maps as close as possible to the generalized form shown in Fig. 2.6, consideration of possible new systems to be added to the terrestrial network (as required in the network synthesis phase of the study) is facilitated.

The CNCP network is much simpler than the TCTS network. The CNCP nodes of Fig. 2.4 are either drop repeaters or are single-hop spur links similar to the TCTS node at Sept Iles, shown in Fig 3.20. The reason for this difference is that the CNCP network is a single tree structure, whereas in the TCTS network there are cross connections between the two long-haul systems converging at most major nodes, and interconnections between the long-haul network and the local network at every node.

The method by which these metropolitan junctions are incorporated into the model of the terrestrial network was described in Section 2.5.1. The costs of these junctions will be discussed in Section 4.1.4.

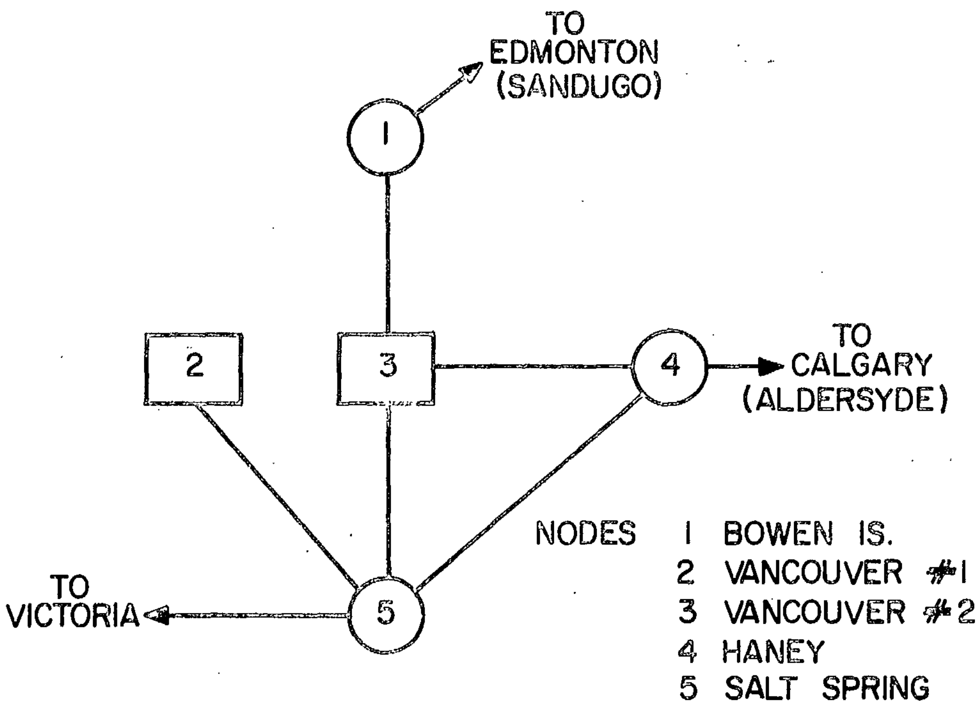



FIGURE 3.1

VANCOUVER METROPOLITAN JUNCTION PLAN

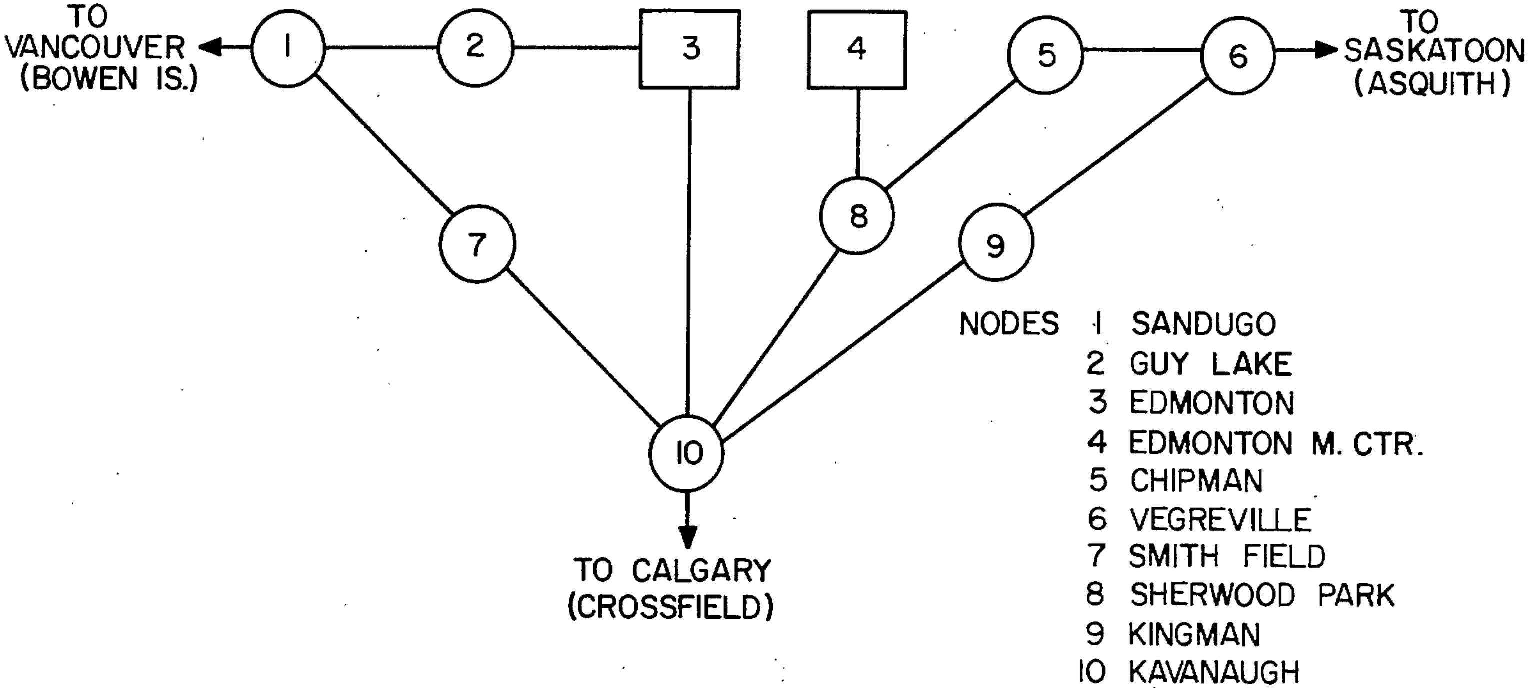



FIGURE 3.2

EDMONTON METROPOLITAN JUNCTION PLAN

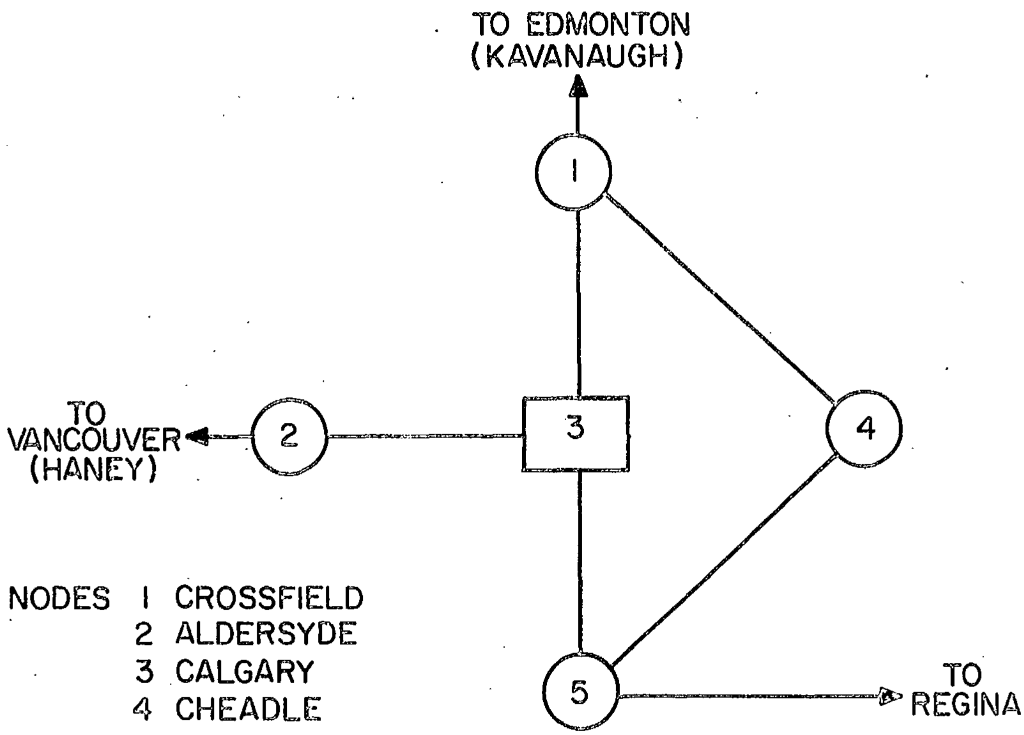



FIGURE 3.3

CALGARY METROPOLITAN JUNCTION PLAN

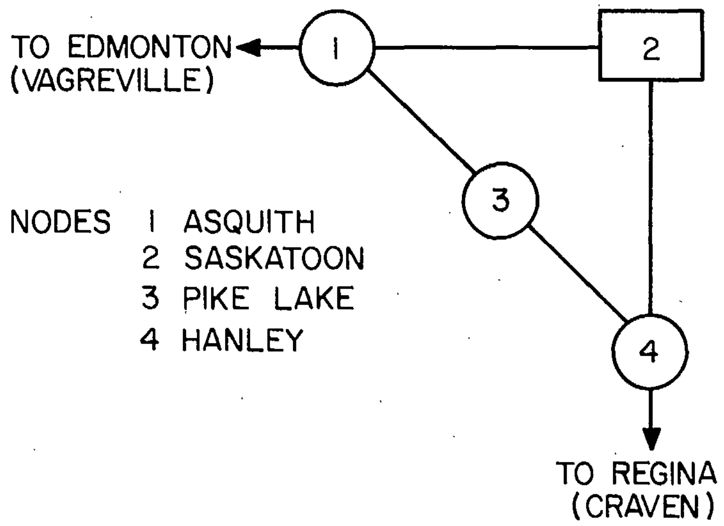
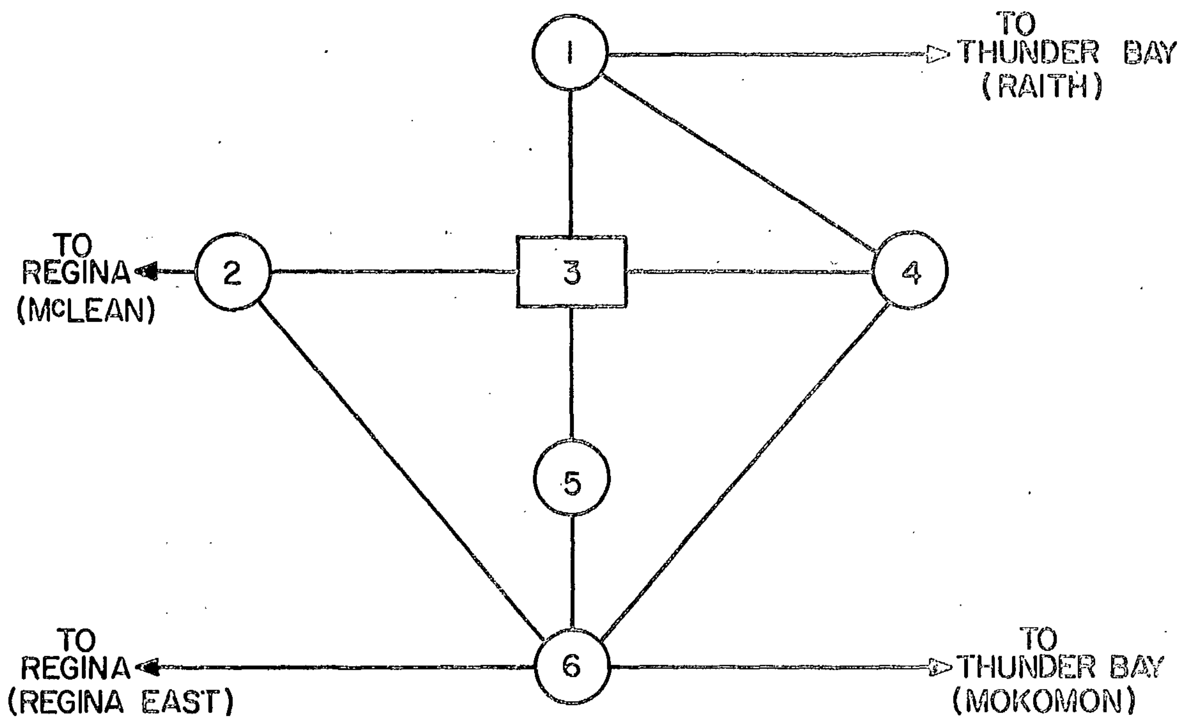



FIGURE 3.4

SASKATOON METROPOLITAN JUNCTION PLAN




NODES

1 QUEEN'S VALLEY
2 QUEEN'S VALLEY
3 WINNIPEG
4 STEINBACH
5 NIVERVILLE
6 MORRIS

FIGURE 3.5

WINNIPEG METROPOLITAN JUNCTION PLAN

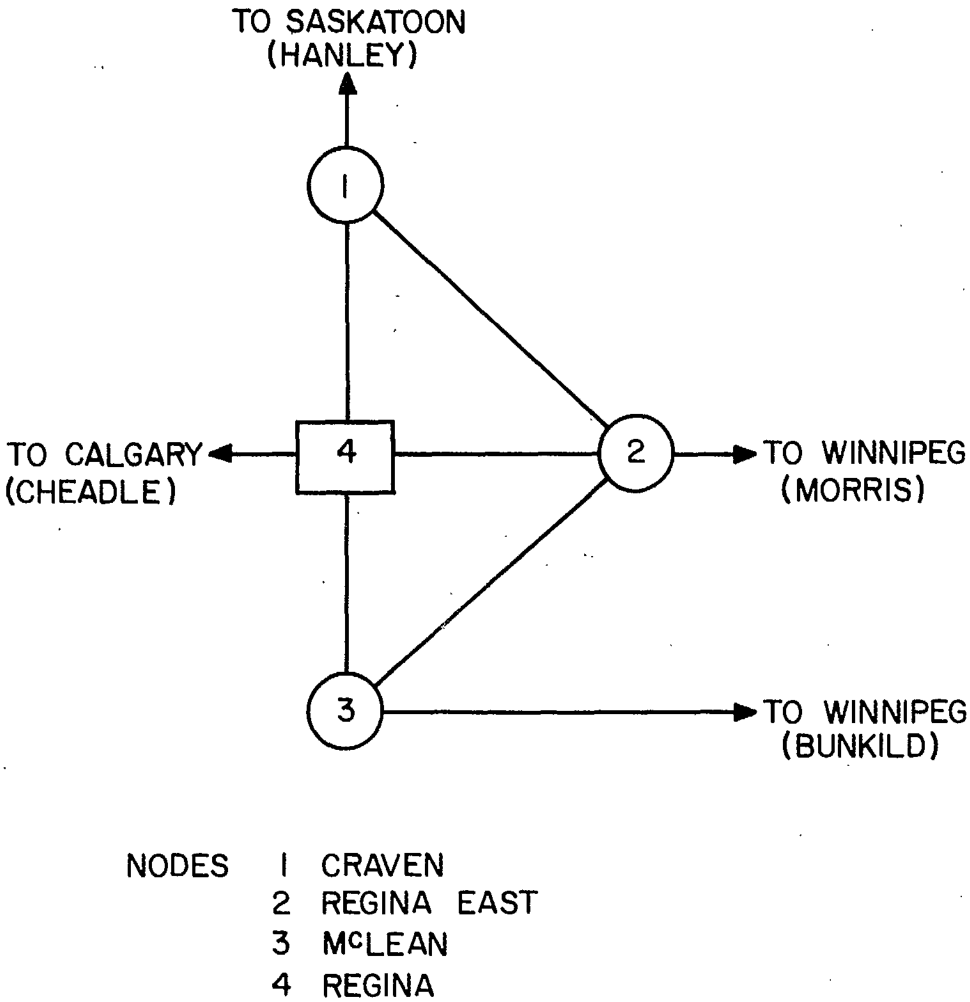
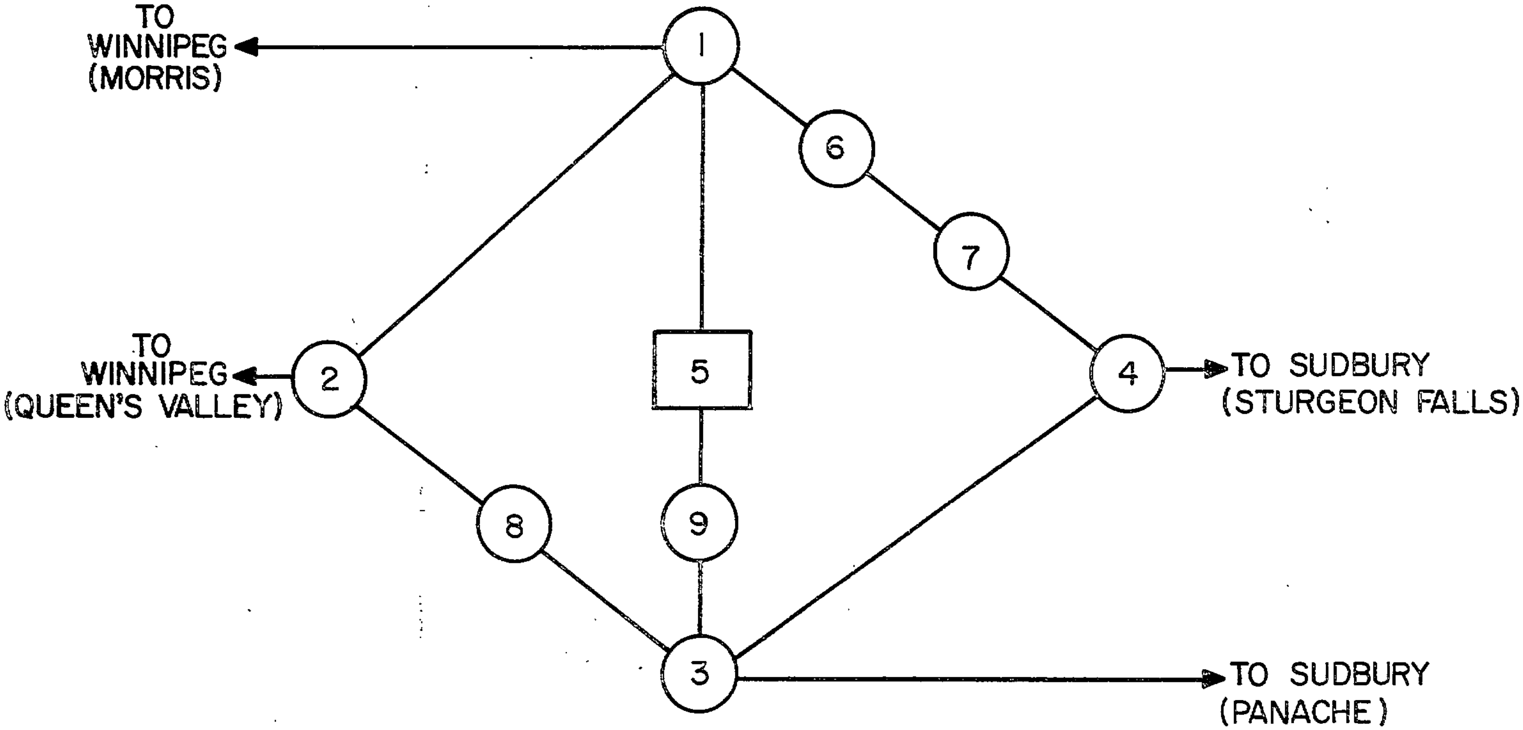



FIGURE 3.6

REGINA METROPOLITAN JUNCTION PLAN




| | | | |
|---|---|---|---|
| NODES 1 | MOKOMON | 6 | LASSETER |
| 2 | RAITH | 7 | CAMERON FALLS |
| 3 | NIPIGON | 8 | EDMONSON LAKE |
| 4 | ORIENT BAY | 9 | LOON |
| 5 | FORT WILLIAM | | |

FIGURE 3.7

THUNDER BAY METROPOLITAN JUNCTION PLAN

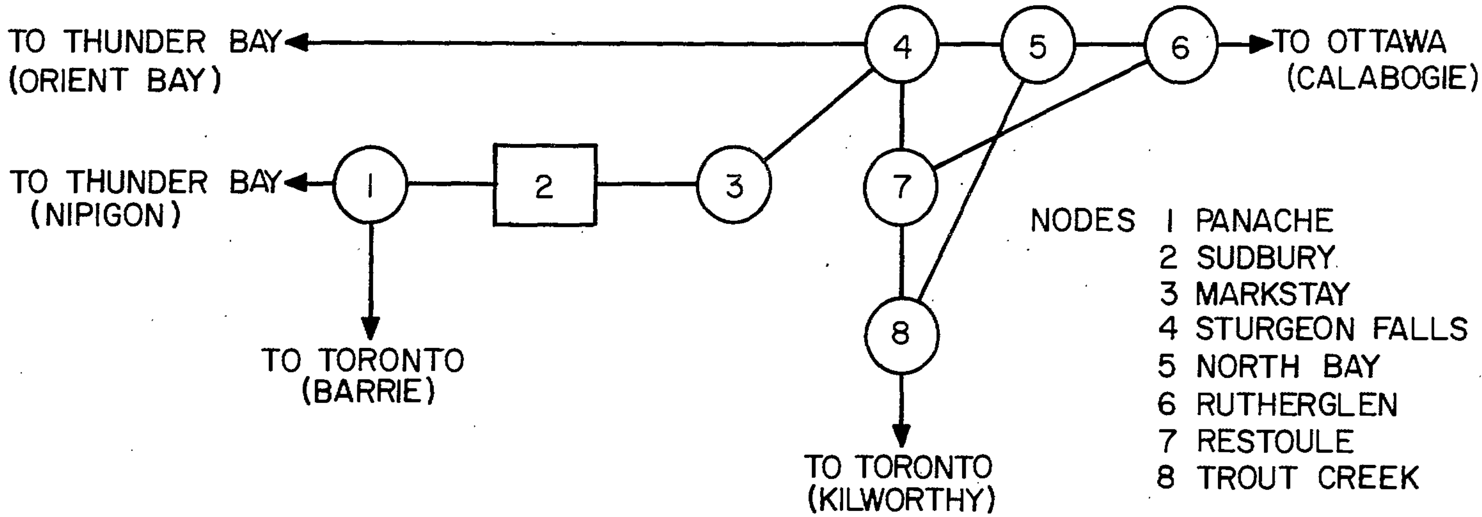
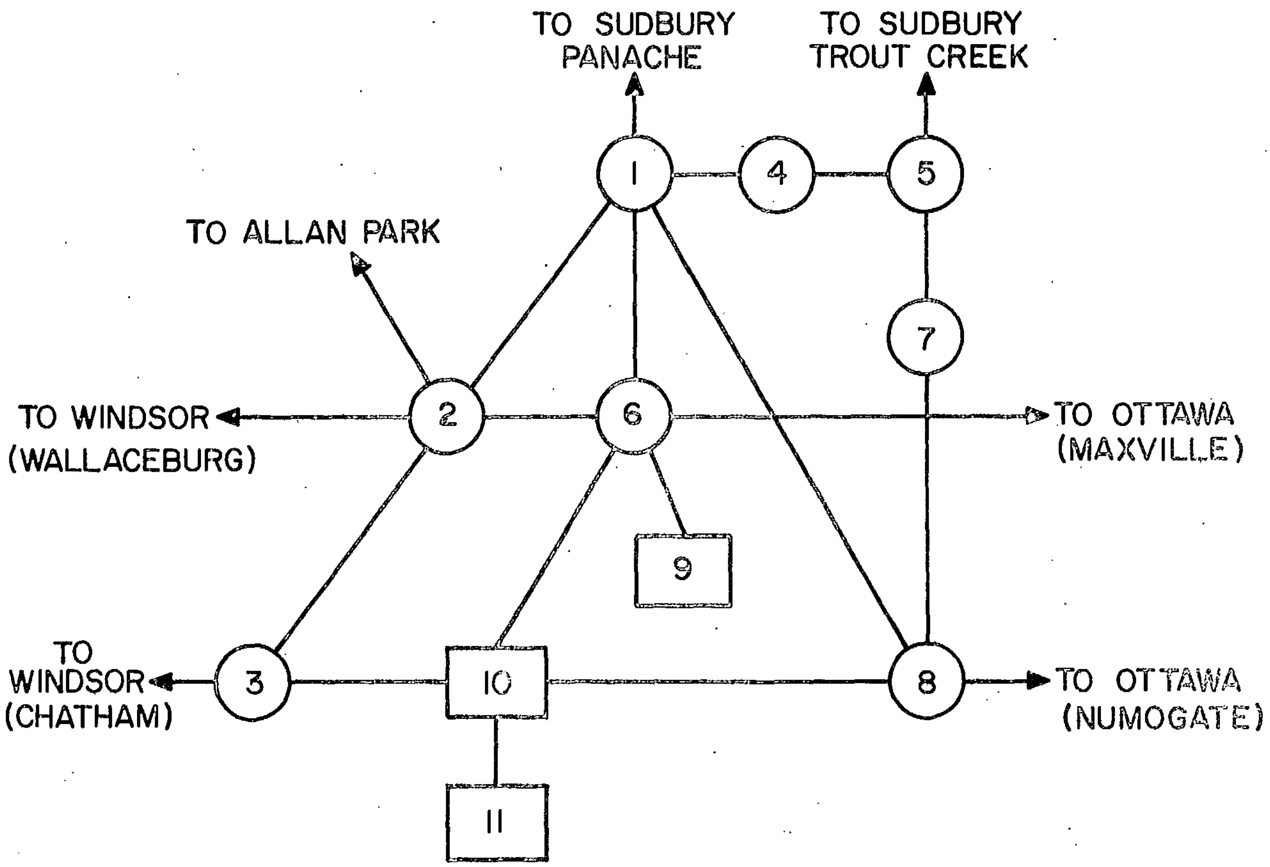



FIGURE 3.8

SUDBURY METROPOLITAN JUNCTION PLAN




NODES
1. BARRIE
2. SHELBOURNE
3. ACTON
4. ORILLIA
5. KILWORTHY
6. AURORA
7. LOGAN HILL
8. UXBRIDE
9. PHARMACY
10. ROLAND
11. ADELAIDE

FIGURE 3.9

TORONTO METROPOLITAN JUNCTION PLAN

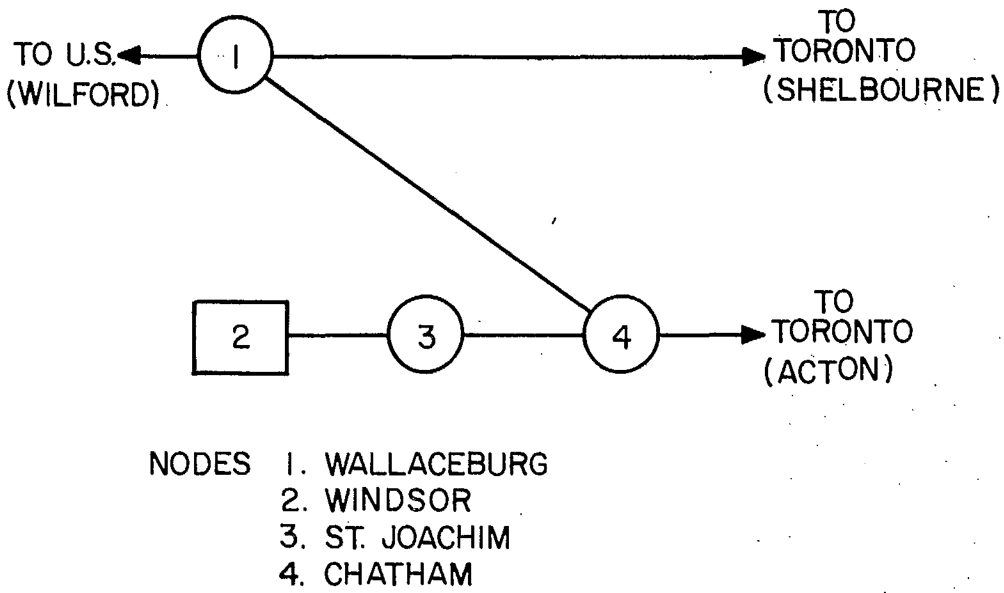
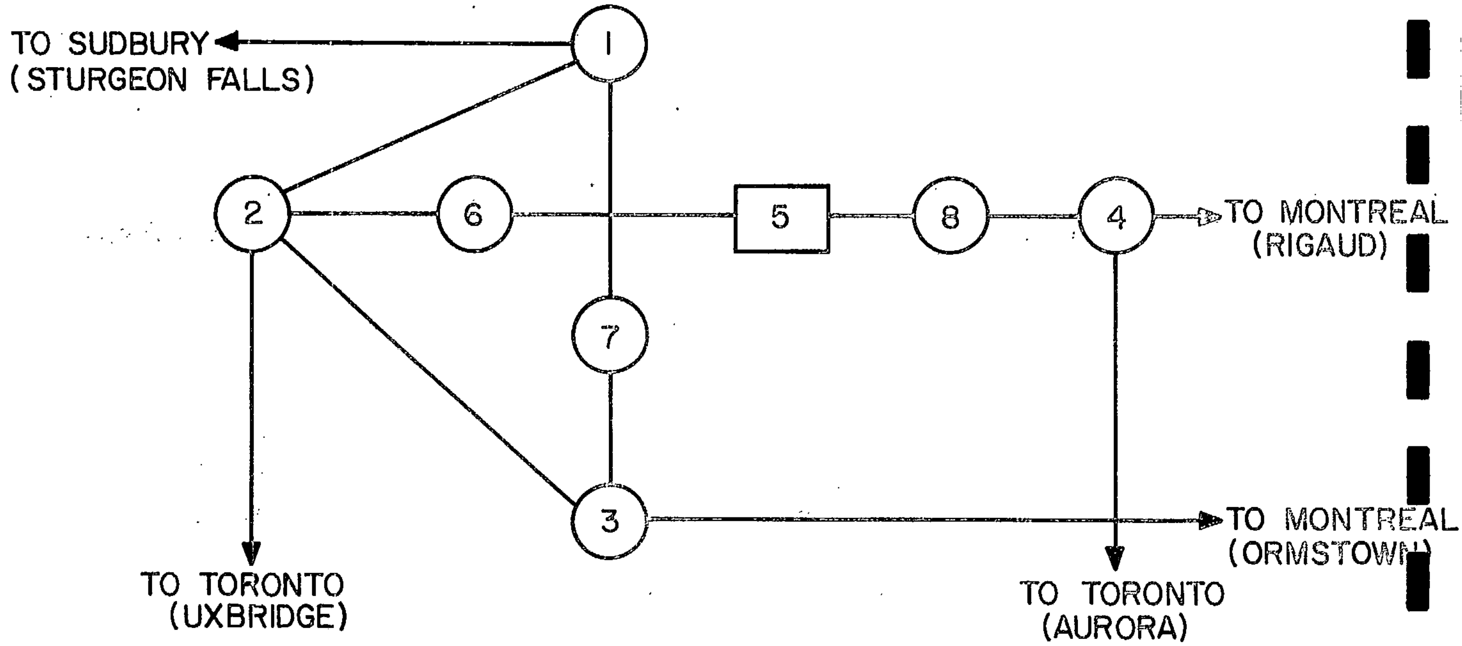



FIGURE 3.10

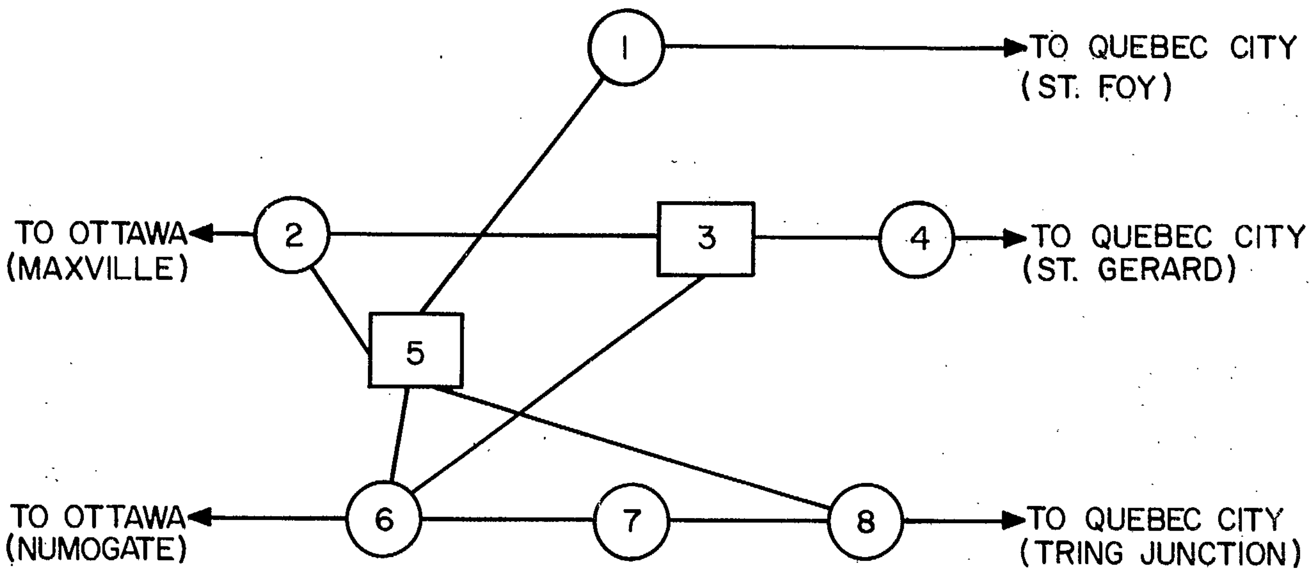
WINDSOR METROPOLITAN JUNCTION PLAN




NODES
1. CALABOGIE
2. NUMOGATE
3. KEMPTVILLE
4. MAXVILLE
5. OTTAWA
6. STANLEY CORNERS
7. BLACK CORNERS
8. LEONARD

FIGURE 3.11

OTTAWA METROPOLITAN JUNCTION PLAN




NODES
1. LAC ECHO
2. RIGAUD
3. MOUNT ROYAL
4. ROUGEMOUNT
5. UPPER LACHINE ROAD
6. ORMSTOWN
7. COVEY HILL
8. ST. ALEXANDRE

FIGURE 3.12

MONTREAL METROPOLITAN JUNCTION PLAN

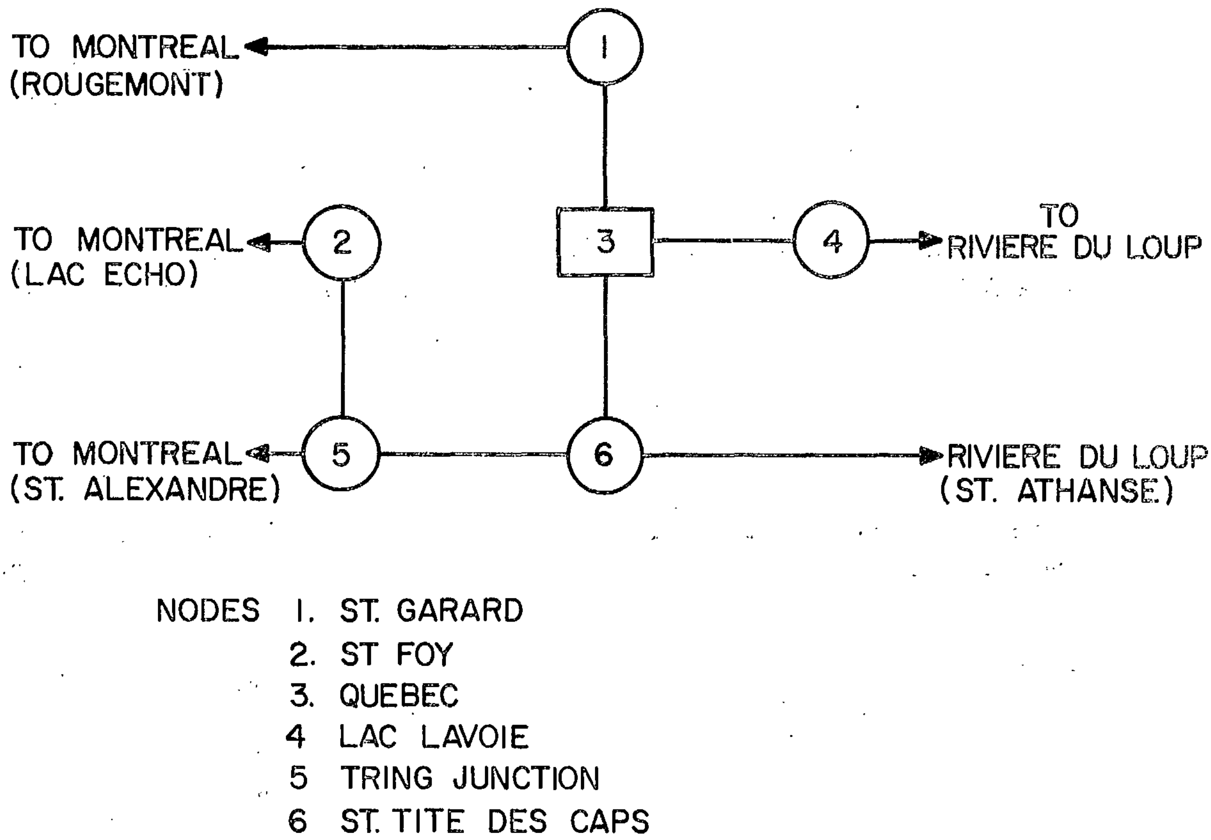



FIGURE 3.13

QUEBEC CITY METROPOLITAN JUNCTION PLAN

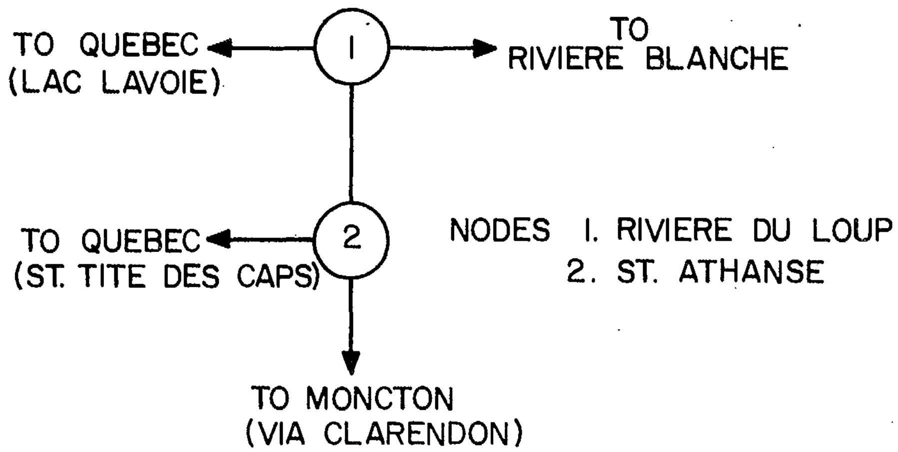



FIGURE 3.14

RIVIERE DU LOUP NODE

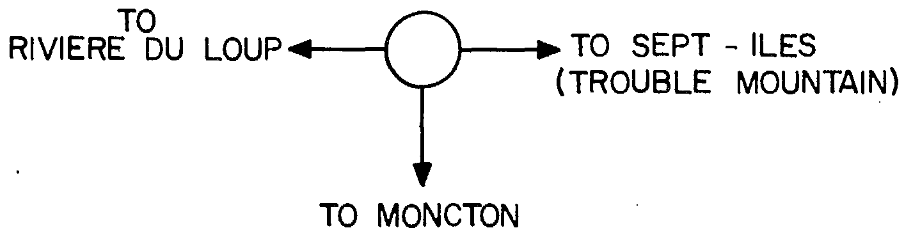



FIGURE 3.15

RIVIERE BLANCHE NODE

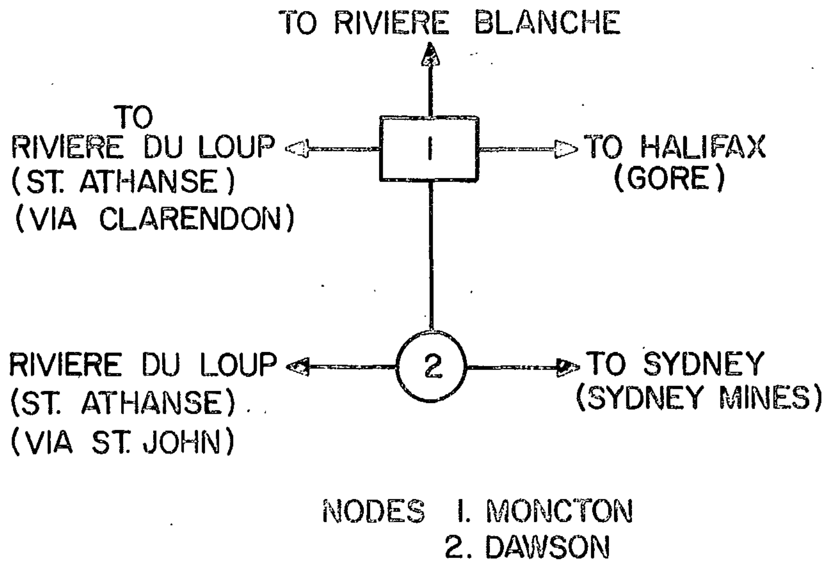



FIGURE 3.16

MONCTON NODE

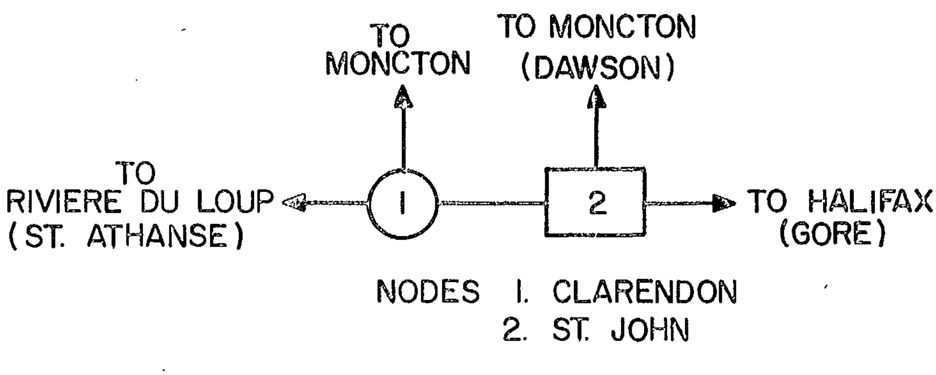



FIGURE 3.17

ST. JOHN NODE

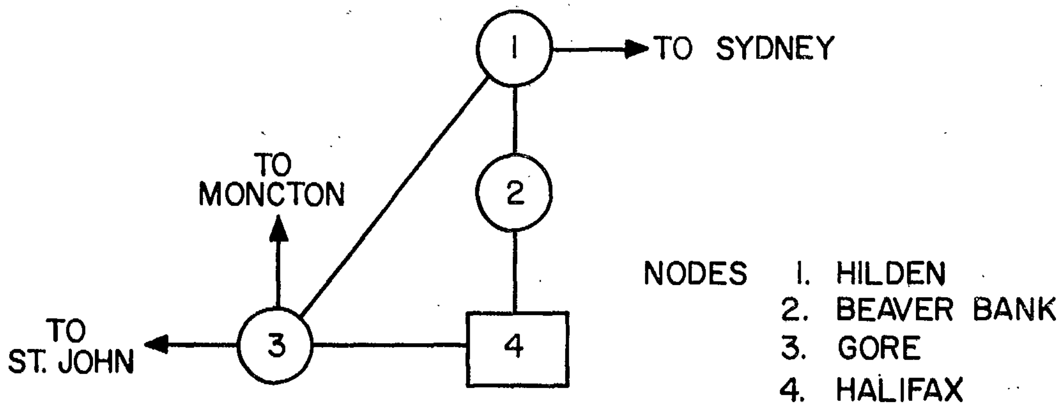



FIGURE 3.18

HALIFAX METROPOLITAN JUNCTION PLAN

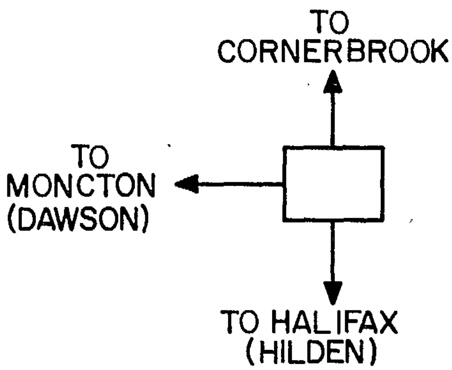



FIGURE 3.19

SYDNEY NODE

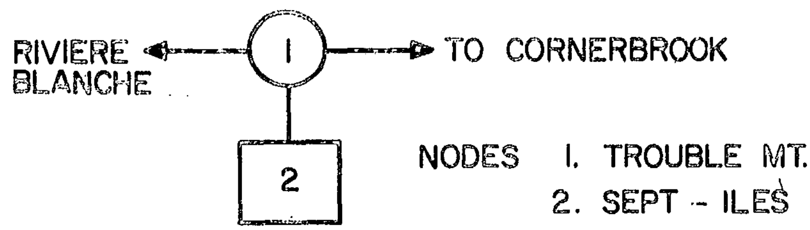



FIGURE 3.20

SEPT ISLES NODE

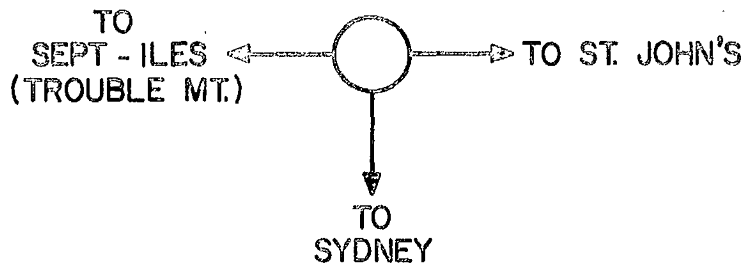



FIGURE 3.21

CORNERBROOK NODE


FIGURE 3.22

ST. JOHN'S NODE

# 4. COST OF LONG-HAUL TERRESTRIAL COMMUNICATION SYSTEMS

The capital costs of existing microwave links and metropolitan junctions, and the capital cost per mile of potential systems, are described in this section.

The nodel of the long-haul heavy-route Canadian terrestrial network that is being used in the DLDCNS was described in Section 2. The salient technical characteristics of the existing and potential links of that network were discussed in Section 3. The capital cost of existing systems and capital costs per mile of potential systems are described in this section. The method for conversion from capital to annual costs for use in the DLDCNS is described by Bowen et al [18]. Those annual costs as used in the network optimization routines are calculated below.

The costs of existing links and metropolitan junctions are described in Section 4.1. Costs per mile of new systems, including 4 and 6 GHz radio systems, are described in Section 4.2. Both the link costs and system costs per mile as a function of installed system capacity is as shown in Fig. 4.1. The solid series of step functions is the actual system cost. The step increases in cost are those incurred in introducing another wideband channel. Costs are especially high when another protection channel or auxiliary equipment must be

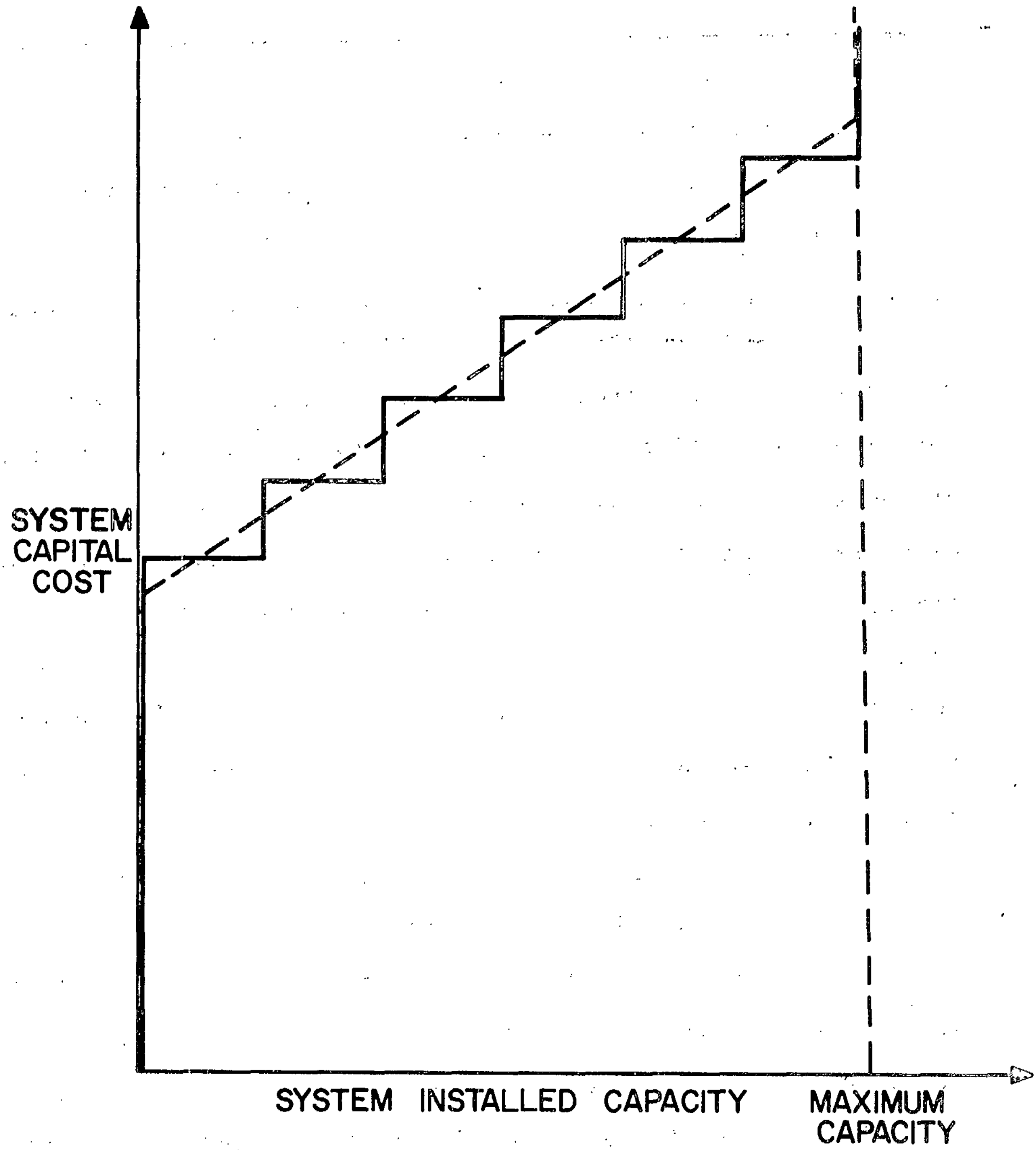



FIGURE 4.1

COMMUNICATION SYSTEM COST CURVE

introduced. The dotted curve is the simpler approximate cost curve used in the initial stages of the network optimization studies.

## 4.1 COST OF EXISTING TERRESTRIAL SYSTEMS

---

The cost of existing microwave radio systems is determined. Existing 4 GHz microwave radio systems, 6 GHz systems, 6 GHz additions to 4 GHz systems, and existing metropolitan junctions are evaluated. The system costs are based on the costs of individual repeater sites, which were determined in the previous section.

---

The capital costs of existing 4 GHz and 6 GHz microwave radio links, 6 GHz additions to existing 4 GHz links, and existing metropolitan junctions are determined. These costs are based on the capital costs of installed individual repeater sites, which are specified above in Section 3.1.1. A portion of these site costs is modified because not all the traffic carried through the site is long-haul traffic, and is also modified because of the relative difficulty of installing the site at the required location.

### 4.1.1 TCTS 4 GHZ Microwave Radio Links

The link capital cost of the first full-duplex radio channel is

$$C_1 = \Sigma_{j=1}^{5} \Sigma_{i=1}^{N_j} (\alpha_{ij} d_{ij} C_{1j} + C_{2j}) \qquad (4.1)$$

where $N_j$ is the number of repeaters of type j on the link, where $1 \leq j \leq 5$, (the five types of repeaters were discussed in Section 3.1.1),

$C_{1j}$ is the site costs plus initial power costs for a type j repeater (see Table 3.8),

$C_{2j}$ is the other first channel costs for a type j repeater (see Table 3.8),

$d_{i,j}$ is the "difficulty factor" for the $i^{th}$ repeater of the $j^{th}$ type, (It is set at 1.0 for accessible locations and 1.5 for remote locations.),

$\alpha_{ij}$ is the fraction of the total traffic through the $i^{th}$ repeater of type j that is long-haul traffic.

The link capital costs of the $m^{th}$ full-duplex radio channel, where $2 \leq m \leq 14$, is

$$\Sigma_{j=1}^{5} N_j C_{m,j} \qquad (4,2)$$

where $N_j$ is again the number of repeaters of type j, and $C_{m,j}$ is the site cost to add to the $m^{th}$ radio channel in a repeater of type j, taken from Tables 3.3 to 3.8.

As shown in Fig. 4.1, the actual cost curve, a series of steps, is approximated by an initial step and a ramp. The initial cost of a link in this approximation is

$$C_I = C_1 - 0.5\ C_N \qquad (4.3)$$

where $C_1$ is the actual link capital cost of the first channel, and

$C_N$ is the incremental capital cost of each other channel except the sixth and eleventh channels.

The cost of a fully implemented link when this step-ramp approximation is used is

$$C_F = C_1 + C_6 + C_{11} + 11.5\ C_N \qquad (4.4)$$

where $C_6$ is the link cost to introduce the sixth channel, and

$C_{11}$ is the link cost to introduce the eleventh channel.

The capital costs of the TCTS links, calculated by using Equations (4.1) to (4.4), are given in Table 4.1. The links are denoted by the major centres and by the repeater sites at their end points, as shown in Figures 3.1 to 3.22. The links between Sept Iles and Cornerbrook and between Moncton and Halifax are not 4 GHz systems, and so special calculations had to be done for these links. The Moncton to Halifax link was evaluated in the same way as the CNCP 6 GHz systems, as described below in Section 4.1.2. The Sept Iles to Cornerbrook link was evaluated as though it were a 6 GHz link with a maximum capacity of five operational and one standby radio channel.

TABLE 4.1

TCTS 4 GHz Link Capital Costs, Millions of 1973 Dollars

| LINK | $C_1$ | $C_6$ | $C_{11}$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Vancouver (Bowen I.) to Edmonton (Sandugo) | 8.876 | 2.966 | 1.335 | 1.051 | 8.351 | 25.26 |
| Vancouver (Haney) to Calgary (Aldersyde) | 7.114 | 2.673 | 1.213 | 0.954 | 6.637 | 21.97 |
| Edmonton (Kavanaugh) to Calgary (Crossfield) | 1.521 | 0.626 | 0.283 | 0.224 | 1.409 | 5.00 |
| Edmonton (Vegreville) to Saskatoon (Asquith) | 3.186 | 1.332 | 0.634 | 0.499 | 2.936 | 10.89 |
| Calgary (Cheadle) to Regina | 5.266 | 2.216 | 1.055 | 0.830 | 4.851 | 18.09 |
| Saskatoon (Hanley) to Regina (Craven) | 1.703 | 0.710 | 0.320 | 0.254 | 1.577 | 5.635 |
| Regina (Regina East) to Winnipeg (Morris) | 5.188 | 2.289 | 1.055 | 0.830 | 4.773 | 18.08 |
| Regina (McLean) to Winnipeg (Bunkild) | 4.067 | 1.670 | 0.774 | 0.610 | 3.762 | 13.52 |
| Winnipeg (Queens U.) to Thunder Bay (Raith) | 5.585 | 1.952 | 0.914 | 0.720 | 5.225 | 16.73 |
| Winnipeg (Morris) to Thunder Bay (Mokomon) | 5.268 | 1.896 | 0.914 | 0.720 | 4.908 | 1636 |
| Thunder Bay (Orient B.) to Sudbury (Sturgeon F.) | 6.830 | 2.713 | 1.265 | 0.996 | 6.332 | 22.26 |
| Thunder Bay (Nipigon) to Sudbury (Panache) | 5.849 | 2.517 | 1.195 | 0.941 | 5.379 | 20.38 |
| Sudbury (Panache) to Toronto (Barrie) | 2.187 | 0.908 | 0.423 | 0.334 | 2.020 | 7.357 |
| Sudbury (Trout Cr.) to Toronto (Kilworthy) | 1.180 | 0.485 | 0.213 | 0.168 | 1.096 | 3.814 |
| Sudbury (Rutherglen) to Ottawa (Calabogie) | 2.225 | 0.908 | 0.423 | 0.334 | 2.058 | 7.395 |

TABLE 4.1 (continued)

TCTS 4 GHz Link Capital Costs, Millions of 1973 Dollars

| LINK | $C_1$ | $C_6$ | $C_{11}$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Windsor (Wallaceburg) to Toronto (Shelbourne) | 1.732 | 0.767 | 0.353 | 0.279 | 1.593 | 6.057 |
| Windsor (Chatham) to Toronto (Acton) | 1.881 | 0.767 | 0.353 | 0.279 | 1.742 | 6.206 |
| Toronto (Uxbridge) to Ottawa (Numogate) | 2.334 | 1.019 | 0.423 | 0.334 | 2.167 | 7.615 |
| Toronto (Aurora) to Ottawa (Maxville) | 4.399 | 1.811 | 0.844 | 0.665 | 4.067 | 14.70 |
| Ottawa (Maxville) to Montreal (Rigaud) | 0.433 | 0.202 | 0.073 | 0.058 | 0.404 | 1.375 |
| Ottawa (Kemptville) to Montreal (Ormstown) | 1.157 | 0.485 | 0.213 | 0.168 | 1.073 | 3.791 |
| Montreal (Lac Echo) to Quebec (St. Foy) | 2.516 | 1.105 | 0.494 | 0.389 | 2.322 | 8.588 |
| Montreal (Rougemont) to Quebec (St. Gerard) | 1.530 | 0.626 | 0.283 | 0.224 | 1.418 | 5.009 |
| Montreal (St. Alexandre) to Quebec (Tring J.) | 1.366 | 0.626 | 0.283 | 0.224 | 1.254 | 4.845 |
| Quebec (L. Lavoie) to Riv. du Loup | 0.688 | 0.326 | 0.143 | 0.113 | 0.632 | 2.458 |
| Quebec (St. Tite) to Riv. du Loup (St. Athanse) | 0.796 | 0.343 | 0.143 | 0.113 | 0.739 | 2.583 |
| Riv. du Loup (St. Athanse) to St. John (Clarendon) | 2.809 | 1.229 | 0.564 | 0.444 | 2.587 | 9.709 |
| St. John (Clarendon) to Moncton | 1.000 | 0.467 | 0.213 | 0.168 | 0.916 | 3.616 |
| St. John to Moncton (Dawson) | 1.468 | 0.608 | 0.283 | 0.224 | 1.356 | 4.929 |
| Riv du Loup to Riv. Blanche | 2.724 | 1.230 | 0.578 | 0.454 | 2.497 | 9.758 |

TABLE 4.1 (continued)

TCTS 4 GHz Link Capital Costs, Millions of 1973 Dollars

| LINK | $C_1$ | $C_6$ | $C_{11}$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Riv. Blanche to Moncton | 4.269 | 1.887 | 0.844 | 0.665 | 0.394 | 14.65 |
| Riv. Blanche to Sept. Isles (Trouble Mtn.) | 1.314 | 0.608 | 0.283 | 0.224 | 1.202 | 4.775 |
| Sept. Isles (Trouble Mtn.) to Cornerbrook* | 8.118 | - | - | 1.161 | 7.537 | 13.34 |
| Cornerbrook to St. John's | 5.349 | 1.739 | 0.859 | 0.675 | 5.012 | 15.71 |
| Cornerbrook to Sydney | 3.336 | 1.155 | 0.564 | 0.444 | 3.114 | 10.16 |
| Moncton (Dawson) to Sydney | 3.232 | 1.286 | 0.597 | 0.470 | 2.997 | 10.52 |
| Moncton to Halifax (Gore)** | 1.035 | 0.337 | - | 0.168 | 0.951 | 2.129 |
| Halifax (Hilden) to Sydney | 2.668 | 1.106 | 0.509 | 0.399 | 2.468 | 8.873 |

*The Sept. Isles to Cornerbrook link is a 2 GHz system. Full capacity is five operational channels and one spare. Each radio channel is 29 MHz wide.

**The Moncton to Halifax link is a TH 6 GHz system.

### 4.1.2 CNCP 6 GHz Microwave Radio Links

The major differences between this system and the TCTS 4 GHz system are:

i) There is no "local" traffic on the system, so $\alpha_{ij}$ of Equation (4.1) is unity for all repeaters.

ii) The metropolitan junction plans are much simpler. The metropolitan junction is usually a junction repeater and a terminal, or it may be simply a junction terminal.

iii) Full-load system capacity is six operational channels rather than fourteen.

iv) First-channel costs are lower as indicated in Table 3.9 because rectangular waveguide and parabolic antennas are used.

v) Supergroup multiplex equipment costs are approximately 1.5 times that used in the 4 GHz system, because of the higher capacity of a TH radio channel.

Equation (4.1) can be used to determine the link cost of the first channel, with all $\alpha_{ij}$ set at unity, and Equation (4.2) can be used for channels 2 to 6. Equation (4.3) is used to determine $C_I$, but $C_F$ is given by the expression

$$C_F = C_1 + C_6 + 4.5\ C_N \qquad (4.5)$$

The capital cost parameters of the CNCP links are given in Table 4.2. All links in the CNCP network are 6 GHz systems except the links between Montreal and Quebec City, and between Quebec City and Moncton. The former is a 4 GHz system. The latter consists of eight 4 GHz hops and eleven 2 GHz hops. Each system is costed as though it were a 4 GHz system with parabolic antennas and limited to five operational channels and one spare channel. The 4 GHz system capacity could be increased by using the interstitial bands, and the hybrid system by doing this and by installing supergroup multiplex equipment at the 2 GHz to 4 GHz junction, but this potential expansion is not taken into account in Table 4.2.

### 4.1.3 6 GHz TH "Add-on" to TCTS 4 GHz links

The third system in which link capital costs can be determined is a 6 GHz TH "add-on" to a TCTS 4 GHz system. Such a system has not yet been installed in Canada, although it has been in the U.S. If it were installed, it would use the same repeater sites as the 4 GHz system. The cost of individual add-on TH repeaters is given in Table 3.11 for a system with six channels operational at full load and with seven at full load. The assumption is made in the cost calculations below that the more efficient system with seven operational and one standby channel would be used. This assumption was made because:

i) It is expected that by the late 1970's, when such a system may be installed, transceiver reliability will be improved.

ii) Multi-path fading is less on a given installed system at 6 GHz than at 4 GHz. (The necessary path clearance is proportional to the square root of radio wavelength.)

TABLE 4.2

CNCP 6 GHz Link Capital Costs, Millions of 1973 Dollars

| LINK | $C_1$ | $C_6$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|
| Vancouver to Edmonton | 8.971 | 2.433 | 1.217 | 8.363 | 16.88 |
| Calgary to Edmonton | 2.067 | 0.668 | 0.334 | 1.900 | 4.237 |
| Edmonton to Saskatoon | 4.431 | 1.440 | 0.720 | 4.071 | 9.111 |
| Saskatoon to Regina | 2.403 | 0.778 | 0.389 | 2.209 | 4.932 |
| Regina to Winnipeg | 4.148 | 1.330 | 0.665 | 3.816 | 8.470 |
| Winnipeg to Thunder Bay | 6.094 | 1.661 | 0.830 | 5.679 | 11.49 |
| Thunder Bay to Sudbury | 7.206 | 2.322 | 1.161 | 6.625 | 14.75 |
| Sudbury to Toronto | 1.852 | 0.610 | 0.305 | 1.700 | 3.834 |
| Toronto to Windsor | 2.852 | 0.915 | 0.457 | 2.624 | 5.824 |
| Sudbury to Ottawa | 4.174 | 1.330 | 0.665 | 3.842 | 8.495 |
| Ottawa to Montreal | 1.387 | 0.447 | 0.224 | 1.275 | 2.840 |
| Montreal to Quebec** | 2.152 | - | 0.334 | 1.985 | 3.651 |
| Quebec to Moncton* | 6.535 | - | 1.051 | 6.010 | 11.256 |
| Moncton to Halifax | 1.365 | 0.447 | 0.223 | 1.253 | 2.818 |
| Halifax to Sydney | 2.373 | 0.778 | 0.389 | 2.179 | 4.901 |

*This link is partly a 4 GHz system and partly a 2 GHz system. The costs are for a system with five operational and one standby radio channel, with 20 MHz r.f. bandwidth per radio channel and use of parabolic antennas.

**This is a 4 GHz link. It is costed the same way as the Quebec to Moncton link.

iii) Seven operating and one standby channel are already being used by some common carriers when most traffic through the system is television.

The link costs are calculated in the same way as the costs for the previous two systems, except that

$$C_F = C_1 + C_4 + C_6 + 4.5\ C_N \qquad (4.6)$$

The capital cost parameters for all applicable TCTS links is given in Table 4.3. This does not include the Sept Iles to Cornerbrook link nor the Moncton to Halifax link, for reasons given below Table 4.1.

### 4.1.4 Metropolitan Junctions

The cost of the existing network metropolitan junctions can be determined in much the same way as the 4 GHz and 6 GHz links were evaluated, since they are composed of the same five types of repeaters. As described in Section 2.5.1, a metropolitan junction is modelled as a star network. The cost of each branch of the star is assumed to be proportional to the installed capacity in that branch, i.e. there is no initial cost associated with the branches of a star. The cost per voice circuit on all branches of a given star are assumed to be identical, but no relationship was found between the costs of branches of different stars and so none was imposed. The cost per voice circuit into a given star is determined by specifying

TABLE 4.3

Capital Costs of a Possible TCTS 6 GHz Add-On System, Millions of 1973 Dollars

| LINK | $C_1$ | $C_4$ | $C_6$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Vancouver (Bowen I.) to Edmonton (Sandugo) | 3.570 | 1.321 | 1.594 | 1.052 | 3.044 | 11.217 |
| Vancouver (Haney) to Calgary (Aldersyde) | 3.223 | 1.195 | 1.420 | 0.954 | 2.746 | 10.133 |
| Edmonton (Kavanaugh) to Calgary (Crossfield) | 0.754 | 0.280 | 0.334 | 0.224 | 0.643 | 2.375 |
| Edmonton (Vegreville) to Saskatoon (Asquith) | 1.595 | 0.627 | 0.656 | 0.500 | 1.346 | 5.127 |
| Calgary (Cheadle) to Regina | 2.651 | 1.044 | 1.090 | 0.831 | 2.236 | 8.524 |
| Saskatoon (Hanley) to Regina (Craven) | 0.853 | 0.316 | 0.378 | 0.253 | 0.727 | 2.684 |
| Regina (Regina East) to Winnipeg (Morris) | 2.751 | 1.044 | 1.190 | 0.831 | 2.335 | 8.722 |
| Regina (McLean) to Winnipeg (Bunkild) | 2.005 | 0.766 | 0.858 | 0.610 | 1.700 | 6.374 |
| Winnipeg (Queen's V.) to Thunder Bay (Raith) | 2.341 | 0.905 | 0.987 | 0.720 | 1.981 | 7.475 |
| Winnipeg (Morris) to Thunder Bay (Mokomon) | 2.268 | 0.905 | 0.914 | 0.720 | 1.908 | 7.329 |
| Thunder Bay (Orient B.) to Sudbury (Sturgeon F.) | 3.255 | 1.252 | 1.383 | 0.996 | 2.757 | 10.374 |
| Thunder Bay (Nipigon) to Sudbury (Panache) | 3.014 | 1.182 | 1.245 | 0.941 | 2.543 | 9.677 |
| Sudbury (Panache) to Toronto (Barrie) | 1.091 | 0.419 | 0.463 | 0.334 | 0.924 | 3.476 |
| Sudbury (Trout Cr.) to Toronto (Kilworthy) | 0.586 | 0.211 | 0.269 | 0.168 | 0.502 | 1.824 |
| Sudbury (Rutherglen) to Ottawa (Calabogie) | 1.091 | 0.419 | 0.463 | 0.334 | 0.924 | 3.476 |

TABLE 4.3 (continued)

Capital Costs of a Possible TCTS 6 GHz Add-On System,
Millions of 1973 Dollars

| LINK | $C_1$ | $C_4$ | $C_6$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Windsor (Wallaceburg) to Toronto (Shelbourne) | 0.923 | 0.350 | 0.398 | 0.279 | 0.783 | 2.925 |
| Windsor (Chatham) to Toronto (Acton) | 0.923 | 0.350 | 0.398 | 0.279 | 0.783 | 2.925 |
| Toronto (Uxbridge) to Ottawa (Numogate) | 1.237 | 0.419 | 0.609 | 0.334 | 1.070 | 3.768 |
| Toronto (Aurora) to Ottawa (Maxville) | 2.173 | 0.835 | 0.923 | 0.665 | 1.840 | 6.925 |
| Ottawa (Maxville) to Montreal (Rigaud) | 0.250 | 0.072 | 0.140 | 0.058 | 0.221 | 0.723 |
| Ottawa (Kemptville) to Montreal (Ormstown) | 0.586 | 0.211 | 0.269 | 0.168 | 0.502 | 1.824 |
| Montreal (Lac Echo) to Quebec (St. Foy) | 1.332 | 0.488 | 0.600 | 0.389 | 1.137 | 4.172 |
| Montreal (Rougemont) to Quebec (St. Gerard) | 0.754 | 0.280 | 0.334 | 0.224 | 0.643 | 2.375 |
| Montreal (St. Alexandre) to Quebec (Tring J.) | 0.754 | 0.280 | 0.334 | 0.224 | 0.643 | 2.375 |
| Quebec (L. Lavoie) to Riv. du Loup | 0.392 | 0.141 | 0.179 | 0.113 | 0.335 | 1.221 |
| Quebec (St. Tite) to Riv. du Loup (St. Athanse) | 0.418 | 0.141 | 0.205 | 0.113 | 0.361 | 1.274 |
| Riv. du Loup (St. Athanse) to St. John (Clarendon) | 1.474 | 0.558 | 0.639 | 0.444 | 1.252 | 4.670 |
| St. John (Clarendon) to Moncton | 0.560 | 0.211 | 0.243 | 0.168 | 0.476 | 1.772 |
| St. John to Moncton (Dawson) | 0.728 | 0.280 | 0.308 | 0.224 | 0.616 | 2.322 |
| Riv. du Loup to Riv. Blanche | 1.482 | 0.568 | 0.617 | 0.455 | 1.255 | 4.714 |

TABLE 4.3 (continued)

Capital Costs of a Possible TCTS 6 GHz Add-On System, Millions of 1973 Dollars

| LINK | $C_1$ | $C_4$ | $C_6$ | $C_N$ | $C_I$ | $C_F$ |
|---|---|---|---|---|---|---|
| Riv. Blanche to Moncton | 2.267 | 0.835 | 1.017 | 0.665 | 1.934 | 7.112 |
| Riv. Blanche to Sept Isles (Trouble Mtn.) | 0.728 | 0.280 | 0.308 | 0.224 | 0.616 | 2.322 |
| Cornerbrook to St. John's | 2.082 | 0.846 | 0.802 | 0.676 | 1.744 | 6.769 |
| Cornerbrook to Sydney | 1.375 | 0.558 | 0.540 | 0.444 | 1.152 | 4.472 |
| Moncton (Dawson) to Sydney | 1.544 | 0.591 | 0.659 | 0.471 | 1.308 | 4.912 |
| Halifax (Hilden) to Sydney | 1.340 | 0.499 | 0.579 | 0.400 | 1.140 | 4.215 |

that the total cost of the star model is equal to the actual metropolitan junction costs when each carry the same 1973 traffic. The cost per voice circuit of a given star model is assumed to remain fixed as the traffic into and through the metropolitan junction increases throughout the 1973 to 1990 period. Note that with this model traffic going through a metropolitan junction pays twice the cost of traffic terminating at that junction.

The total number of installed voice circuits, total capital cost, and capital cost per voice circuit of all complex nodes in the TCTS and CNCP networks are listed in Table 4.4. Nodes not listed in Table 4.4 are single junction repeaters, junction terminals, or terminals, which are costed as part of the internodal link costs. This is the case for the Riv. Blanche, Sydney, Cornerbrook, and St. John's nodes of the TCTS network, and most nodes of the CNCP network.

TABLE 4.4

Capital Costs of Metropolitan Junction Systems, 1973 Dollars

| Junction | Total Traffic, Voice Circuits | Total Cost Millions of Dollars | Cost/Voice Cct. |
|---|---|---|---|
| Vancouver, TCTS | 7,920 | 2.209 | 278.9 |
| Edmonton, TCTS | 16,320 | 4.563 | 279.6 |
| Calgary, TCTS | 23,520 | 3.135 | 133.3 |
| Saskatoon, TCTS | 9,360 | 1.937 | 207.0 |
| Regina, TCTS | 19,680 | 2.249 | 114.3 |
| Winnipeg, TCTS | 16,800 | 3.498 | 208.2 |
| Thunder Bay, TCTS | 12,120 | 5.109 | 421.5 |
| Sudbury, TCTS | 23,040 | 4.161 | 180.6 |
| Toronto, TCTS | 34,320 | 7.798 | 227.2 |
| Windsor, TCTS | 9,600 | 1.706 | 177.7 |
| Ottawa, TCTS | 27,020 | 6.261 | 231.7 |
| Montreal, TCTS | 26,640 | 4.507 | 169.2 |
| Quebec, TCTS | 17,760 | 2.570 | 144.7 |
| R. du Loup, TCTS | 16,560 | 0.359 | 21.7 |
| St. John, TCTS | 12,000 | 1.213 | 101.1 |
| Moncton, TCTS | 8,640 | 0.341 | 39.5 |
| Halifax, TCTS | 12,240 | 2.023 | 165.3 |
| Sept. Isles, TCTS | 3,360 | 0.361 | 107.4 |
| Edmonton, CNCP | 5,760 | 0.745 | 129.3 |
| Regina, CNCP | 3,840 | 1.268 | 330.3 |
| Winnipeg, CNCP | 3,840 | 0.809 | 231.8 |
| Thunder Bay, CNCP | 3,840 | 0.505 | 131.5 |
| Sudbury, CNCP | 5,760 | 0.361 | 62.6 |

## 4.2 COST PER MILE OF NEW TERRESTRIAL SYSTEMS

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The cost per mile and cost per circuit mile of new analog microwave radio, digital radio, analog and digital coaxial cable, millimetre waveguide, and optic fibre systems are estimated.

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New systems, using "off-the-shelf" hardware or equipment being developed, cannot be costed in the same way that the microwave radio systems were costed in the previous section. As an alternative, average costs per route mile and cost per circuit route mile can be obtained, these costs can be converted to costs per airline mile and cost per circuit airline mile, and route distances determined from maps to convert these costs to link costs as a function of installed capacity. A ratio of 1.1 was assumed between route miles and airline miles between two nodes, the equivalent of a $25^0$ route slew angle. The metropolitan junction plans in Figures 3.1 to 3.22 can be used to determine the probable end points of possible new links; the new link would terminate at a metroplitan junction point such as Numogate rather than at a city centre.

## 4.2.1 COST PER MILE OF ANALOG MICROWAVE RADIO SYSTEMS

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The cost per mile of new analog microwave radio systems are calculated from the cost information in Section 4.1 and the airline distances between metropolitan areas.

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The capital costs of existing analog microwave radio systems are given in Section 4.1. New systems of a similar type may be introduced in parallel with these systems to provide a higher link capacity and/or reliability, or possibly new links will be added. An estimate of the cost of such a new system can be made by averaging the costs of existing systems. This was done for 4 GHz, 6 GHz, and 6 GHz "add-on" systems by dividing the total cost of a given type of system by the total number of airline miles covered by that system.

The average cost of 4 GHz microwave systems was determined by averaging all TCTS systems west of R. du Loup except the Vancouver to Edmonton link. As well, the TCTS 4 GHz systems in New Brunswick and Nova Scotia were included, but not the TCTS systems at other frequencies. The Vancouver to Edmonton link was not included because it follows a very indirect route to serve several communities in Alberta and B.C. A total of 5,500 route miles was used in the calculation. Average costs per airline mile are given in Table 4.5.

Similarly, the average cost of 6 GHz microwave radio systems was determined by averaging all 6 GHz CNCP systems. Included were approximately 3,300 route miles. The average costs of this system are given in Table 4.6. Note that these costs are the costs per airline mile between two desired end points.

The average costs of a 6 GHz add-on to a 4 GHz TCTS system can be determined in a similar fashion. The same links were used for this calculation as were used to determine the 4 GHz system's average costs. The 6 GHz add-on costs are shown in Table 4.7. As in Section 4.1, it is assumed that the 6 GHz add-on system would use seven operating channels and one standby channel.

As can be seen from Tables 4.5 to 4.7, the 6 GHz add-on system is the most economical on a per-circuit basis, and the 4 GHz system is the most expensive. The 4 GHz system is the most expensive because of its smaller voice capacity per radio circuit, and the 6 GHz add-on system is least expensive because of its low initial cost.

TABLE 4.5

Capital Cost Per Airline Mile of
4 GHz Analog Radio Systems, 1973 Dollars

| Item | Amount |
|---|---|
| First channel cost per mile | $14,780 |
| Sixth channel cost per mile | 6,030 |
| Eleventh channel cost per mile | 2,880 |
| Other channel cost per mile | 2,360 |
| Initial cost per mile, $C_I$ | 13,600 |
| Full-load cost per mile, $C_F$ | 50,850 |
| Average cost per mile at full load: | |
| -16,800 voice circuit loading | 3.03 |
| -21,000 voice circuit loading | 2.42 |
| Incremental cost per mile: | |
| -16,800 voice circuit loading | 2.22 |
| -21,000 voice circuit loading | 1.77 |

TABLE 4.6

Capital Cost Per Airline Mile of
6 GHz Analog Radio Systems, 1973 Dollars

| Item | Amount |
|---|---|
| First Channel Cost per Mile | $14,870 |
| Sixth Channel Cost per Mile | 4,570 |
| Other Channels Cost per Mile | 2,280 |
| Initial Cost Per Mile, $C_I$ | 13,730 |
| Full-load Cost per Mile, $C_F$ | 29,698 |
| Average Cost Per Mile at full load: | |
| -10,800 voice circuit loading | 2.75 |
| -12,600 voice circuit loading | 2.35 |
| Incremental Cost per Mile: | |
| -10,800 voice circuit loading | 1.48 |
| -12,600 voice circuit loading | 1.27 |

TABLE 4.7

Capital Cost Per Mile of
6 GHz "Add-On" Analog Radio Systems, 1973 Dollars

| Item | Amount |
|---|---|
| First Channel Cost per Mile | $ 7,490 |
| Fourth Channel Cost per Mile | 2,840 |
| Sixth Channel Cost per Mile | 3,230 |
| Other Channels Cost per Mile | 2,270 |
| Initial Cost per mile, $C_I$ | 6,360 |
| Full-load Cost per Mile, $C_F$ | 23,780 |
| Average cost per mile at full load: | |
| -12,600 voice-circuit loading | 1.89 |
| -14,700 voice-circuit loading | 1.62 |
| Incremental cost per mile: | |
| -12,600 voice-circuit loading | 1.38 |
| -14,700 voice-circuit loading | 1.19 |

## 4.2.2 COST PER MILE OF DIGITAL RADIO SYSTEMS

The cost per mile of 8 GHz and 12 GHz digital radio systems is described and compared with existing analog radio systems.

As discussed in Section 3.1.2, medium capacity 8 GHz and high capacity 12 GHz digital radio systems may become part of the long-haul network in the next decade. The 8 GHz system is an "add-on" to the existing analog 4 GHz TCTS system, whereas the 12 GHz system is a completely new one.

The 8 GHz system has a low initial cost and a high incremental cost. The RD-2A1 cost is approximately $6,500 per route mile for the first channel, and $4,500 per route mile for each of the additional five channels. The average cost is approximately $7.20 per voice circuit or per 56 Kb/s of data per route mile at full load, and the incremental cost is approximately $6.70. The RD-2A2 is a similar but higher capacity system at lower cost. Its cost is approximately $4,700 per route mile for the first radio channel, $3,600 for the sixth channel, and $1,700 for each of the other eight channels. Capacity on each of the ten operational channels is 672 voice circuits without the use of partial response encoding, and 1344 voice circuits with the encoding. (It will be assumed that encoding is used.) Thus the RD-2A2 has an average cost of $1.64 per voice circuit route mile at full load, and an incremental cost of $1.40 per voice circuit mile. These costs are converted to cost per airline mile in Table 4.8 by multiplying all costs by 1.1.

The higher capacity 12 GHz system has four operational radio channels, each with a capacity of 8,064 voice circuits. As in the 8 GHz system, a voice circuit can be replaced by 56 Kb/s of data. The cost of the first operational radio channel for this system is approximately $33,000 per route mile. The cost of each of the three additional channels is approximately $12,000 per route mile. Again, these costs are multiplied by 1.1 to determine the cost per airline mile in Table 4.8.

Certain conclusions can be made by comparing the cost parameters in Table 4.8 with those in Tables 4.5 to 4.7. The RD-2D1 system is quite expensive and could not compete with 4 GHz analog radio except for data transmission. However, both the RD-2A2 and the higher capacity 12 GHz system are less expensive than a new 4 GHz radio system. Both are more expensive than the TH analog radio add-on to the 4 GHz system when voice transmission only is considered. However, the higher efficiency of the digital systems for data transmission, and the overall network conversion to digital, may offset the gain of the TH system.

TABLE 4.8

Capital Costs per Airline Mile of Digital Radio Systems, 1973 Dollars

| System | Voice Circuit Capacity | | Radio Channel Cost | | | Cost per Voice Circuit | |
|---|---|---|---|---|---|---|---|
| | per Radio Channel | System Total | 1st | 6th | Other | Full-load Average | Incremental |
| 8 GHz RD-2A1 | 672 | 4,032 | 7,150 | - | 4,950 | 7.90 | 7.35 |
| 8 GHz RD-2A2 | 1,344 | 13,440 | 5,200 | 4,000 | 1,900 | 1.80 | 1.55 |
| 12 GHz | 8,064 | 32,256 | 36,300 | - | 13,000 | 2.35 | 1.65 |

### 4.2.3 COSTS PER MILE OF ANALOG COAXIAL CABLE SYSTEMS

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Capital costs of three analog coaxial cable systems are presented. These systems are used in Europe and in the U.S.

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Capital costs of the L-4 and L-5 systems of the AT&T were obtained from the FCC. As well, the cost information of a V2700 system sold by Lenkurt Electric is available. The costs per route mile that were obtained are again multiplied by 1.1 to convert them to costs per airline mile. The capital costs per airline mile are given in Table 4.9. Note that these are average costs in the U.S.; it is likely that the initial costs would be much higher in the pre-Cambrian and mountainous areas of Canada.

The coaxial cable systems are characterized by a much higher ratio of initial costs to incremental costs than a microwave radio system of similar capacity. The V2700 and the L-4 systems have a significantly higher average cost than any of the microwave radio systems, but a lower incremental cost than most. Thus it is unlikely that such systems would be installed in competition with radio systems, but if a system were installed it would be rapidly filled because of its low incremental costs.

TABLE 4.9

Capital Costs Per Airline Mile of
Analog Coaxial Cable Systems, 1971 Dollars.

| System | Lenkurt V2700 | AT&T L-4 | AT&T L-4 | AT&T L-5 | AT&T L-5 |
|---|---|---|---|---|---|
| Capacity per pair | 2,700 | 3,600 | 3,600 | 10,800 | 10,800 |
| No. of coax pairs | 7+1 | 5+1 | 9+1 | 5+1 | 10+1 |
| Full-load capacity | 18,900 | 18,000 | 32,400 | 54,000 | 108,000 |
| First coax pair cost | 37,000 | 90,600 | 93,700 | 99,000 | 118,000 |
| Additional pair cost | 4,200 | 4,100 | 2,300 | 34,000 | 2,860 |
| Cost per voice cct.: | | | | | |
| -Full-load average | 3.30 | 5.95 | 3.50 | 2.10 | 1.33 |
| -Incremental | 1.55 | 1.14 | 0.64 | 0.32 | 0.26 |

### 4.2.4 COSTS PER MILE OF DIGITAL COAXIAL CABLE SYSTEMS

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The latest available estimate of the LD-4 digital coaxial cable system is discussed.

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The LD-4 is being implemented as a 12 coaxial tube system, although systems with as many as 22 tubes are being considered. The most recent available cost estimates for such a system are that the capital installed cost per airline mile is

$$C(n,m) = 46{,}500 + 1260n + 7{,}200m$$

where $n$ is the number of coaxial tubes in the cable,

$m$ is the number of operational coaxial tube pairs, not counting the single standby pair in all systems.

Note that m can be increased from unity to (n-2)/2 during the lifetime of the system, but that n must remain fixed. The above is the best available estimate for costs in Southern Ontario and the St. Lawrence valley, but would likely be considerably higher in pre-Cambrian and mountainous regions of Canada.

The capacity of a coaxial pair is 4,032 voice circuits or 225.7 Mb/s, or some combination of these. (The actual binary transmission rate on the cable is 273 Mb/s.) The fully-loaded system's average cost per voice circuit mile is $4.85 for the 12 tube system being implemented, and $3.60 for the 22 tube system. In all cases the incremental costs to increase the capacity of an installed system is $1.80 per voice circuit airline mile. A ratio of 1.1 has been assumed for route miles to airline miles, the same as that assumed in costing other systems.

### 4.2.5 COST PER MILE OF DIGITAL MILLIMETRE WAVEGUIDE SYSTEMS

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Available cost estimates of millimetre waveguide systems vary by as much as four to one.

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Digital millimetre waveguide systems are being developed in the U.S., in the U.K., and in France. The U.S. system is being developed for operation by 1980, but no direct cost information on this system is available. Cost information was obtained from references [15], [16], and [17].

The TCTS estimate, [15], is that the initial cost of the system would be about $77,000 per mile, and the full-load cost at 240,000 voice circuit loading would be $135,000 per mile. Thus the full-load average cost per circuit mile is $0.56, and the incremental cost is $0.23. This cost seems quite low; the initial cost is less than that of an L-5 coaxial cable system (see Table 4.9).

Cost estimates from the other references are considerably higher. No absolute cost information is available from reference [16], only relative costs. However, by making assumptions of the cost of more conventional coaxial cable systems, the cost estimate of about $200,000 per mile for a system loaded to 150,000 voice circuits was made. An early estimate in reference [17] is even higher, $150,000 to $1M per mile for a system loaded to 100,000 voice circuits.

In conclusion, the cost information on millimetre waveguide systems is too imprecise to be of value in the network study. Moreover, both the costs and the traffic-handling capabilities of the medium seem too high for the Canadian long-haul network in the late 1970's and early 1980's.

### 4.2.6 COST PER MILE OF OPTIC FIBRE SYSTEMS

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Accurate costs of optic fibre long-haul transmission systems are not available.

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As discussed in Section 3, the development of long-haul optic fibre systems is at a much earlier stage than even the millimetre waveguide system. Even the capabilities, and the costs, of the fibres themselves have changed significantly over the past year or two. It is not expected that optic fibre systems will be operational until the mid or late 1980's. In any case, cost information that is available at the present time is not based on firm system designs, and is not considered to be accurate and reliable enough to be used for network planning.

## 4.3 COST OF WIRE-LINE ENTRANCE LINKS AND INTER-NETWORK CONNECTIONS

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An empirical formula for the cost of a coaxial cable inter-network connection is derived, based on costs of wire-line entrance links.

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Short-haul high capacity coaxial cable systems are used by the common carriers to connect microwave radio terminals and junction repeaters to their multiplex and switching equipment. Such equipment could be used to provide interconnection between the CNCP and the TCTS networks, as shown in Fig. 2.7.

These coaxial cable systems seem to be similar in capacity to the L-3 system of A.T.&T. A coaxial pair is assumed to have a capacity equal to any 4 GHz or 6 GHz radio channel. The cost of such a system is approximately

$$C = 16{,}000 + 2{,}400m + (15{,}000 + 5{,}000n + 400m)d$$

where
- d is the system length in miles,
- n is the number of cable pairs in the installed cable,
- m is the number of coaxial pairs for which the electronics has been installed.

As well as the above transmission costs, there are considerable multiplexing costs because the capacity per radio channel of the two networks is different. As stated in Section

3.1.1, the installed cost of supergroup multiplex equipment is approximately $17,000 per radio channel. If we let m = n = 6 in the above equation, with one spare coaxial cable pair, and install five supergroup multiplexers at one end of the cable, then the total multiplex cost per inter-network connection would be $85,000. (Five radio channnels would be all that would be transferred between networks, since the CNCP network cannot carry more than seven operational channels.) If we now assume an average interconnect cable length equal to five miles, the transmission cost becomes approximately $270,000, and the total interconnect cost is approximately $350,000 per interconnect point.

If we now assume that there are interconnect points at Vancouver, Edmonton, Regina, Winnipeg, Sudbury, Toronto, Windsor, Ottawa, Montreal, and Halifax, the total cost of interconnecting the TCTS and CNCP networks is approximately $3.5 million.

# 5. ANNUAL COSTS OF TRANSMISSION LINKS

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Link annual costs can be determined from the capital cost information in Section 4 and the formulae of DLDCNS Report No. 8 which describe the necessary conversion from capital to annual costs.

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The existing simplified network model is shown in Fig. 2.4. The link capital costs of each link in the existing network are given in Section 4.1. In the 1974 to 1990 interval new links may be added to this network, either in parallel with existing links or between two nodes of Fig. 2.4 that are not presently connected directly. Detailed plans of the metropolitan junction plans of each of the twenty nodes were presented in Section 3.2, so the capital costs of possible new links can be determined from the system capital costs per mile and the available distances between end points.

Capital costs are not used directly in the network optimization calculations. Rather, annual costs are used for this purpose. The conversion from capital costs to annual costs is made with the formulae in DLDCNS Report No. 8 [18].

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---A SIMPLIFIED MODEL OF THE CANADIAN TERRESTRIAL TRUNK COMMUNICATIONS NETWORK.