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AN ILLUSTRATIVE ANALYSIS OF TECHNOLOGICAL ALTERNATIVES FOR SATELLITE COMMUNICATIONS

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ABSTRACT

There are several indications that the demand for satellite communications services in the domestic market will soon exceed the capacity of the satellites currently in place. Two approaches to increasing system capacity are the expansion of service into frequencies presently allocated but not used for satellite communications, and the development of technologies that provide a greater level of service within the currently-used frequency bands. This paper is directed towards the development of economic models and analytic techniques for evaluating capacity expansion alternatives such as these.

The first part of the paper provides a brief overview of the satellite orbit-spectrum problem, and also outlines some suitable analytic approaches. This is followed by an illustrative analysis of domestic communications satellite technology options for providing increased levels of service. The analysis illustrates the use of probabilities and decision trees in analyzing alternatives, and provides insight into the important aspects of the orbit-spectrum problem that would warrant inclusion in a larger-scale analysis. Finally, the application of such analytic methodologies to the examination of satellite R&D decisions such as those faced by NASA is discussed.

Section I

OVERVIEW OF THE APPROACH

1. Introduction

This paper begins the development of economic models and analytic techniques for evaluating NASA communications-satellite R&D decisions. First, a brief overview of the communications satellite orbit-spectrum problem is provided. This overview describes the need for structural economic models that characterize both the systems demand for satellite communications services as well as the supply of such services under a wide range of technology and policy options. The overview also describes the need for methodology to analyze NASA communications satellite R&D alternatives, taking account of considerable market and technology uncertainty.

The second part of the paper provides an illustrative analysis of U.S. domestic communications satellite technology options for providing increased levels of domestic communications services within the constraints of orbit geometry and present frequency spectrum allocation to domestic communications satellites. The analysis illustrates the use of probabilities and decision trees in analyzing technology alternatives and provides insight into the important aspects of the orbit spectrum problem that must be dealt with in a full-scale analysis.

The final section of the report outlines how analyses of the type described in the preceding section can be used to examine satellite R&D decisions such as those faced by NASA.

2. Background

The allocation of geosychronous orbit positions and frequency spectrum to communications satellite use is a complex technical, economic and political problem. The U.S. domestic market will be considered in this discussion as an illustration of these problems.

There are presently three frequency bands allocated to U.S. satellite communications: 4/6 GHz (C band), 12/14 GHz (Ku band), and 20/30 GHz (Ka band). Interference considerations limit the use of the geosynchronous arc, and projections of demand growth indicate that the orbit-spectrum capacity in the C band and Ku band will be fully utilized within a few years. The Ka band is not yet utilized for satellite communications and presents some technical and cost disadvantages relative to the C and Ku bands. One option for expanding domestic satellite communication services is to pursue development of Ka band capability.

In addition to increasing the amount of orbit-spectrum allocated to communications satellites, there are many technical alternatives for providing greater services within a fixed orbit-spectrum. These technical alternatives include changes in satellite and earth station design involving signal processing, antenna design including polarization, demand assignment among a pool of satellites, use of spot and inter-satellite beams and changes in interference design parameters. These technical alternatives offer the possibility of a several-fold increase in communications services for a fixed amount of orbit-spectrum resource.

The demand for domestic communications satellite services has expanded rapidly. In some cases communications satellites have diverted voice and data communications from possible new, more costly terrestrial communications capacity. In other cases, the increasing economic advantage of communications satellites has reduced the costs of long-distance communications, particularly video, and has resulted in the development of new communications services that would otherwise have been uneconomic.

It is very difficult at this time to foresee what balance or imbalance will result between the technical alternatives for expanding orbit-spectrum capacity and the demands for communications services. Moreover, the demand depends on the costs of satellite communications services in relation to the costs of terrestrial communications and the benefits of additional communications. In addition the balance is sensitive to current R&D decisions to develop technology as well as policy decisions to change the allocation or price of the orbit-spectrum.

3. NASA's Role

NASA's role in developing new satellite communications technology is articulated in recent testimony of Associate Administrator Anthony L. Calio before the House Subcommittee on Space Science and Applications.[1] NASA plans to meet the need for improved effectiveness and efficiency in the use of the limited resources of the radio spectrum and geosynchronous orbit positions by:

1) new technologies to expend the capacities of existing bands, and

2) capabilities for functioning in the unused Ka band.

In the first category fall "frequency re-use" methods involving contourable-beam space antennas, onboard switching, signal modulation, and polarization techniques. NASA proposes to take a leadership role in developing these technologies for the Ka band:

> We propose to develope an understanding of Ka-band usage within a multibeam antenna research effort. We believe that a unified R&D effort built around these new technologies and techniques will best advance U.S. leadership in satellite communications and support industry's efforts to increase the capacity of the two lower-frequency commercial bands (C-band and Ku-band). Simultaneously, this activity will provide new information and confidence in equipment for Ka-band use for private commercial purposes. We have widespread, enthusiastic acceptance from the industry on these plans.
>
> A. J. Calio, Testimony of
> February 20, 1979, p. 23

In addition to its role in R&D, NASA provides technical advice to the FCC on spectrum allocation and equipment technical specifications. This role places NASA in a position to participate in a wide range of potential policy decisions on the mechanisms by which frequency usage will be regulated.

Finally, although NASA's role in the regulation of orbit-spectrum usage is limited to technical advice, it is necessary for NASA to take account of the effect of future regulatory policy on the need for new capacity and technology. For example, government policy mandating or encouraging frequency re-use or conservation measures could have a major impact on the need for NASA's R&D on Ka band technology.

4. A Framework for Analysis

Decisions such as those associated with NASA's role in satellite communications are very difficult. While considerable information on the technology and market is available, not all of it is relevant or reliable. Many technology and policy alternatives are possible, but it is very difficult to comprehend the important interactions among the alternatives. And, even if one could project with certainty the outcomes of alternatives, there is still the problem of determining what we want or who is to pay the costs and share in the benefits.

At the beginning we must recognize that no forecasting or other analytic methodology can eliminate uncertainty, make decisions or replace the need for difficult value judgments. Rather, analysis and models are useful in the decision process if they facilitate the decision process in structuring available information and value judgments or preferences in a way that provides insights into the choices among alternatives.

The objective, therefore, is to work towards the development of a process of analysis that is supportive of the NASA decision processes and makes appropriate use of models and analysis.

5. Decision Analysis

Many aspects of communication satellite orbit-spectrum decisions can be captured using readily understood techniques of decision analysis.[2] In particular, the supply and demand for satellite communications services are highly uncertain, as are the technical outcomes of R&D. Early resolution of technical uncertainty through R&D can have an immediate beneficial effect on the market by facilitating good decisions on the design and development of new satellites and the use of the orbit-spectrum resource. The techniques of decision analysis provide a way to put a dollar value on the benefits of resolving uncertainty through R&D, thus allowing the costs of R&D to be rationally compared with the benefits.

Decision analysis is more than an analytical technique for characterizing uncertainty in a decision problem. It is also a process of analysis for bringing policy and technology decisions into a logical relation with the available information, alternatives and preferences.

Typically a decision analysis is carried out with the close involvement of many technical specialists and the responsible executive officials. Through an iterative process of information structuring and alternative generation, a sequence of analyses is performed. The end product is not the analysis but is the insight and communication that is achieved by the participants in the analyses. This process has been successfully demonstrated in many public and private decision settings involving R&D, public regulatory policy, corporate new product decisions, environmental planning and facility capacity expansion.

As a first step towards such an application of decision analysis to communications satellite R&D and policy decisions of interest to NASA, we have developed the illustrative example in Section II of this paper.

6. Structural Modeling

One of the aspects of the decision analysis approach that deserves special attention in the case of satellite communications planning is the complexity of the interactions among the competing satellite and terrestrial communications systems and the demands for communications services. For example, as the cost of communications is reduced by technological advances, new demands for communications services appear. These demands cause the capacity of existing systems to be fully utilized and create a need for new systems that compete for scarce spectrum and orbital positions with existing systems.

Attempts to use simplified models of the communications market are generally not very satisfying. A typical approach is to forecast the magnitude of future communications demand categorized by type of communication, video, data, voice. But in a world where the distinctions between different communication techniques are becoming fuzzy and where the costs of communication, including travel and mail, are changing rapidly, forecasts that extrapolate from past demand data are not very accurate or useful.

A modeling approach that has been applied successfully in many industries is a structural modeling approach. In this approach, the demands for communications are characterized in terms of basic end-use services such as person-to-person and broadcast communications and in terms of the time urgency and content of information to be communicated. Specific end use market segments, such as residential, large business, and small business might be distinguished.

The alternative communications modes, such as voice, video, data, mail, and travel, available to each end-use would be identified and the demands for each derived from the basic end-use data and the prices charged for each service. These prices would be computed with bases of information characterized in the supply side of the model.

Communications services can be provided by a large number of alternative technologies. Each of these technologies has its own unique resource requirements in terms of spectrum resources, capital resources, reliability, and types of communications that can be carried out. The prices of these services are generally determined in part by economic forces and in part by a regulatory policy that allocates scarce public resources and controls prices of some services. These prices and the regulatory policies determine which technologies are developed and utilized to meet demand. The prices charged for the communications services in turn influence demand as described earlier.

In a structural model of the communications market, each generic communications technology would be identified, and the direct capital operating and other costs associated with each unit deployed would be characterized as inputs to the model and would be adjusted within the model to account for inflation and technological learning effects. In addition, the technical information required to compute the amount of spectrum and orbit resources required for a given mix of communications services would be provided.

The model would utilize this and other information to simulate the expansion and operation of an entire communications system including all major forms of communications over a period of twenty or more years. The model calculations would be carried out iteratively because of the simultaneous nature of the interaction between supply, demand and prices.

A structural model of this type would allow investigation of the penetration of different technologies under a variety of assumptions regarding the outcomes of R&D and public communications regulatory policy. Such a model would also be a useful tool for investigating alternative communications satellite regulatory policies.

In this paper we have not attempted any significant structural modeling of the communications market and have instead relied on existing forecasts as a basis for the illustrative decision analysis. This lack of emphasis on a structural model of the communications market should not, however, be taken as an indication of the lack of a need for such modeling. The illustrative example as developed in this paper makes clear the need for better models of the communications market as an aid to communications satellite R&D planning.

Section II

THE ILLUSTRATIVE ANALYSIS

1. Introduction

This section of the paper describes an illustrative application of decision analysis to technology decisions affecting domestic communications satellites. First we examine the likelihood of satellite services demand exceeding the system capacity in the future. Having shown the uncertain need for additional capacity, two options for increasing orbit-spectrum capacity are discussed and compared: the development of conservation and re-use technologies for the frequency bands currently in use, and the introduction of service at a higher frequency band (the Ka or 20 to 30 gigahertz band).

Background information for the analysis is provided by four contractor reports, supplied by NASA. The contractors are Western Union and ITT, whose studies concentrate on the demand for Ka band satellite services, and Hughes and Ford Aerospace, who provided "systems studies" of the technical and cost details of alternative Ka systems.

The first part of the analysis develops a simplified demand model, based largely on the ITT analysis. ITT's forecasts are presented and discussed. Then a probabilistic version of the ITT forecast is developed, based on a set of illustrative estimates by the authors. The next section of the paper examines system capacity. Again the deterministic data from the ITT analysis are used as a base on which to build a probabilistic forecast. The probabilistic forecasts for demand and capacity allow us to examine the question of system saturation in a decision analysis framework.

The next section of the paper considers system expansion through the use of a Ka band service or frequency re-use. A series of scenarios demonstrate how the technologies might be used to meet demand. The comparison of technological alternatives through the use of cost information is discussed and an illustrative cost comparison of Ka service to re-use is presented.

2. Demand

A forecast of the future demand for satellite services is essential to any evaluation of alternative satellite systems. Ideally, the demand model would build a forecast by aggregating over the various types of service. In keeping with a decision analysis approach, the explicit consideration of uncertainty would be desirable.

Below we develop a simple model of demand. We first develop a framework for a general satellite demand model. The model is derived largely from the ITT analysis. ITT's data and results are briefly discussed. In the latter part of the section we develop a probabilistic forecast, using a set of illustrative probability distributions.

The data developed in the Western Union report is in a different form from that used by ITT, and is not used in our demand model. The Western Union data is presented and compared to the ITT data in Appendix A.

Outline of a General Satellite Demand Model. A framework for a satellite demand model is shown in Figure 1. The model estimates satellite traffic in equivalent transponders for a given service (voice, data, or video) in a given year.

We would expect the demand model to be driven by price, which in turn will depend to some degree on the cost of both terrestrial and satellite technologies. The model then determines the total annual demand for long-haul telecommunications traffic. However, of greater interest is the peak level of telecommunications traffic. This will depend on total traffic load, and also on peak hour pricing strategies. The peak demand will determine the capacity requirements.

The next step is to determine the satellite share from the total peak demand. We can think in terms of a "satellite capture ratio," or market share, that determines the percentage of the total demand that goes to satellites. This ratio will vary for different types of service. The major factor in determining this ratio for a given type of service are the relative costs of terrestrial and satellite technologies for a transmission of a given distance. Finally, the average

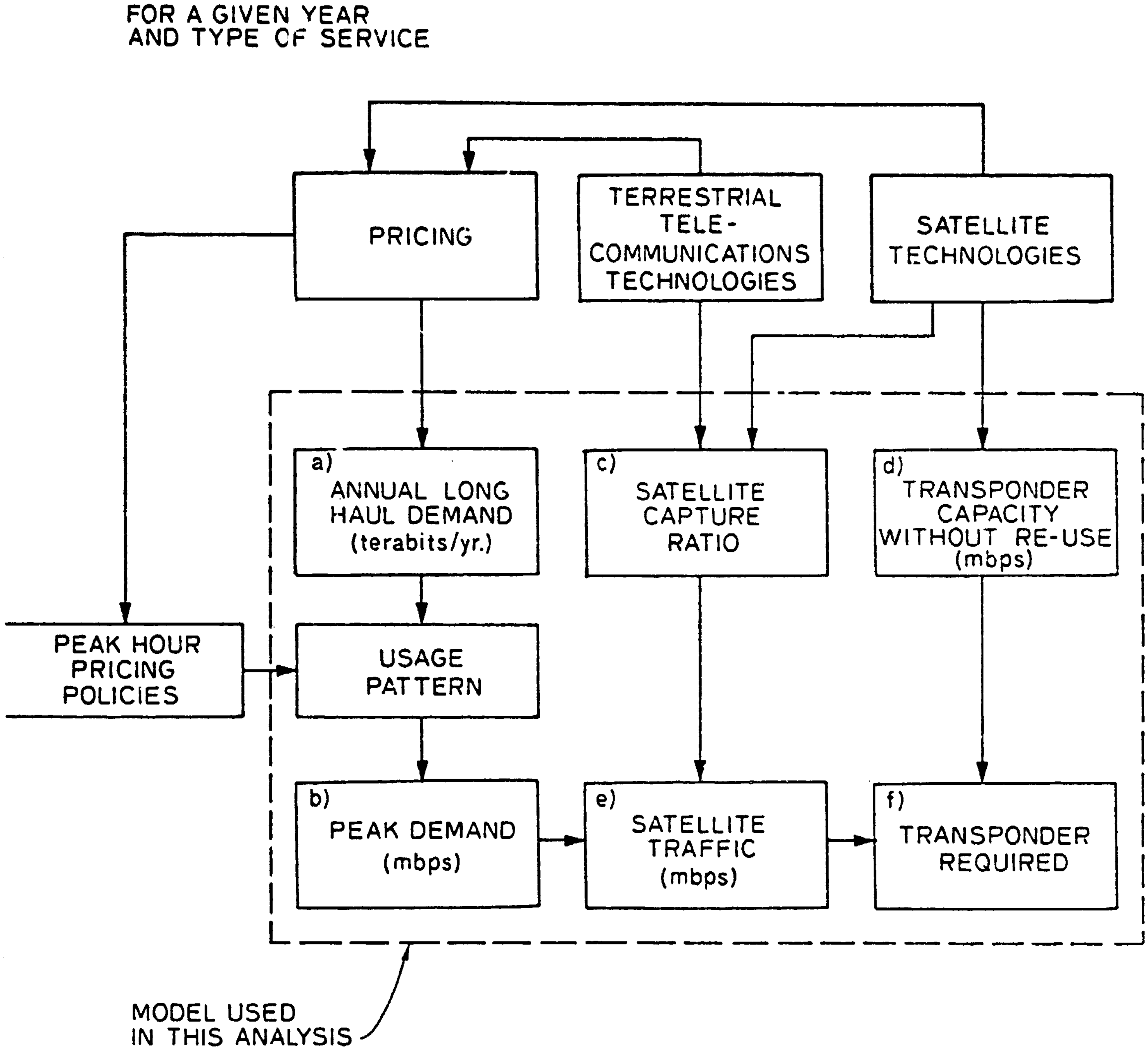


Fig. 1: Framework for Satellite Demand Model

capacity of transponders in use will determine the demand for transponders.

A More Limited Demand Model. The ITT analysis does not explicitly consider price as a factor in demand. Presumably the assumption is that demand is simply not price sensitive, or that price can be determined directly from satellite systems cost estimates and from projections of terrestrial tariffs. This leads us to a simpler demand model, which is shown within the dotted lines in Figure 1. Price and cost characteristics of terrestrial and satellite technologies are considered implicit to the resulting model.

Below we discuss the components of the modified model, and present the relevant data from the ITT report.

a) Yearly Long-Haul Demand. ITT's forecast of yearly demand for the years 1980, 1990, and 2000 is shown in Table 1. It is broken down into three services types: voice, data, and video. Note a common unit, terabits per year, is used for each type of service. The share of the traffic attributed to each type of service is also shown for each year.

b) Peak Demand. Peak demand determines the overall capacity required. Peak demand will depend on the overall traffic level, patterns of usage, and peak period pricing policies.

   Table 2 shows ITT's forecast for peak demand, in millions of bits per second. The available

Table 1: ITT - Forecast of Yearly Demand, in Terabits/yr.

	1980	1990	2000
Voice	559,000 (74%)	1,402,000 (76%)	2,891,000 (77%)
Data	112,000 (15%)	281,000 (15%)	437,000 (12%)
Video	82,500 (11%)	170,700 (9%)	417,300 (11%)
Total	753,500 (100%)	1,853,700 (100%)	3,745,300 (100)

Table 2: ITT - Forecast of Peak Hour Demand (millions of bits per second)

	1980	1990	2000
Voice	43,800 (65%)	108,100 (63%)	204,700 (64%)
Data	20,667 (31%)	50,869 (30%)	78,853 (25%)
Video	2,891 (4%)	13,252 (7%)	37,980 (11%)
Total	67,358 (100%)	172,221 (100%)	321,533 (100%)

Table 3: ITT - Ratio of Peak Hour to Average Demand (Derived)

	1980	1990	2000
Voice	2.5	2.4	2.2
Data	5.8	5.7	5.7
Video	1.1	2.4	2.9

information gives no indication of the methodology used to determine peak traffic. For information purposes, the ratio of peak demand to average demand for each of the services is shown in Table 3.

c) Satellite Capture Ratio. The satellite capture ratio refers to the percentage of long-haul traffic (defined by ITT as traffic transmitted more than 200 miles) that is handled by satellite. This will be different for different types of service.

ITT's capture ratios are presented in Table 4. The report does not state how the ratios were determined. One way of determining capture ratios is presented in the Western Union report. They consider the relative costs of satellite and terrestrial service to split the demand up. They develop a set of terrestrial/satellite crossover curves that determine the relative costs for various distances of transmission. However, the approach may still be simplistic. The ratio can also be different between sets of city pairs the same distance apart, depending on factors including traffic density, geography, etc.

d) Satellite Traffic. Satellite traffic is an intermediate result. It is computed as the product of peak demand and the satellite capture ratio for each type of service.

Table 4: ITT - Satellite Capture Ratio, in percent

	1980	1990	2000
Voice	2	15	25
Data	1	50	60
Video	50	60	60

Table 5: ITT - Unit Transponder Capacity, in MBPS

Year	Capacity
1980	42
1990	72
2000	108

Table 6: ITT - Demand for Transponders (in 36 MHz equivalent transponders)

	1980	1990	2000
Voice	21 (34%)	225 (33%)	474 (42%)
Data	5 (8%)	335 (51%)	436 (39%)
Video	35 (58%)	110 (16%)	211 (19%)
Total	61 (100%)	690 (100%)	1121 (100%)

e) Unit Transponder Capacity without Re-use Technologies. ITT estimates that transponder capacity (in terms of bits received per time period) will increase as time goes on, as shown in Table 5. Because re-use technologies are not explicitly considered in the ITT analysis, we have assumed the capacity increases stem from factors other than the re-use technologies considered later in this report. Thus the data given in Table 5 are taken as base capacities, which can be increased by various re-use technologies.

f) Transponders Required. The resulting number of transponders required can be calculated as the quotient of satellite traffic and transponder capacity. ITT's forecast is shown in Table 6.

Probabilistic Analysis. Below we use the simple model outlined in Figure 1 and a set of illustrative probability distributions on the model components to demonstrate the construction of a probabilistic forecast. The output will be a probability distribution on total transponder demand for a given year.

The equation below determines the demand for a given type of service in a given year:

$$DT_{ij} = \frac{PKD_{ij}}{TC_j} \cdot SCR_{ij} \qquad (1)$$

where: i = type of service: voice, data, or video

j = year

DT = number of transponders required

PKD = peak long-haul demand, in MBPS

TC = unit transponder capacity, in MBPS

SCR = satellite capture ratio

Below we will drop the subscript j . Just one year, 1990, will be considered.

The procedure to be used here will be to assign a probability distribution to each of the state variables. These can be transformed, through the use of equation (1) into a distribution on the number of transponders required for each type of service for 1990. This can further be converted into a distribution on the total number of transponders required.

Probability Distributions on Model Parameters. In general, a continuous or a discrete probability distribution can be assessed by one or more "experts" for each of the state variables. Techniques for the elicitation of distributions are well-established.[3] The distributions we have used here are purely illustrative. In each case a discrete distribution with three branches is used. The value from the ITT report is used as the "nominal" case and is assigned a probability of .5 . "Low" and "high" values, each with a probability of .25 are also assigned. The values assigned are shown in Table 7.

It can be expected that there is probabilistic dependence between certain sets of variables. In the first part of the analysis, where we produce distributions on demand for each of the three types of service, we assume there is no dependence between the peak demand PKD_i , the capture radio SCR_i , and the transponder capacity TC . It would in general be possible to include the dependencies by assessing conditional distributions, or by restructuring the model to include additional variables that explicitly deal with the dependencies, allowing unconditional assessments to be made.

Distribution on Transponders Required for Each Service Type. A probability tree, such as the one shown in Figure 2 for voice, can be constructed for each service. From the tree we can generate a probability distribution on the number of transponders required. The distribution has 27 branches. Because the distributions for voice, data and video traffic are intermediate results in terms of this analysis, they are not presented here; they are shown in Appendix B.

Distribution on Total Number of Transponders Required. It is also possible to use the assigned distributions to produce a distribution on total demand. This requires

Table 7: Probability Distributions for Demand Model for 1990

		Low (prob = .25)	Nominal (prob = .50)	High (prob = .25)
PKD	(Peak Demand)			
	- Voice (mbps)	86,480	108,100	140,530
	- Data (mbps)	25,434	50,869	76,303
	- Video (mbps)	6,626	13,252	33,130
SCR	(Capture Ratio)			
	- Voice	.10	.15	.25
	- Data	.4	.50	.65
	- Video	.45	.60	.7
TC	(Transponder Capacity) (mbps)	54	72	108

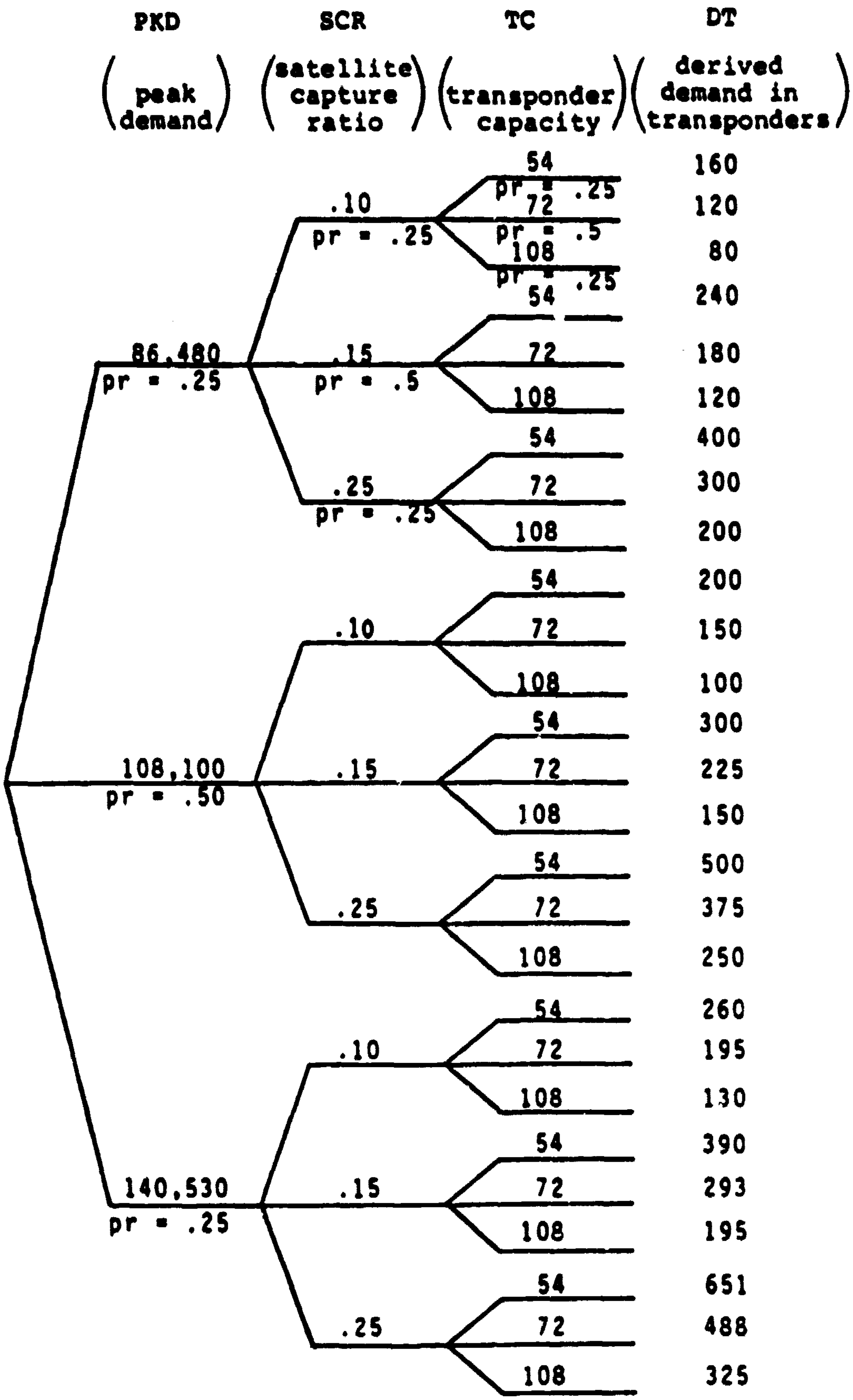


Fig. 2: Probability Tree for Voice Demand

further consideration of the dependencies between the types of service. Two possible approaches for the purposes of the demonstration are: 1) to assume independence between the peak demand for each service and between the capture ratio for each service; or, 2) assume complete dependence between the three peak demand variables, and complete dependence between the three capture ratio variables. The latter approach is used here. This means that if the voice peak demand variable takes on its low value, the data peak demand variable and the video peak demand variable also take on their low values. The same applies to the capture ratio variables. The assumption of complete dependence can be partially justified as follows. There are several common underlying factors that will influence peak demand for all the types of service. These factors include new developments in satellite technology, and general satellite service pricing policies. With respect to capture ratios, the most important underlying factor is the relative costs of satellite and terrestrial technologies; this should affect each of the three service types in a similar way. The fact that these underlying factors will influence the variables in a similar way for each type of service indicates that some dependence between demand for the three service types does exist.

The probability tree is shown in generic form in Figure 3, and the resulting cumulative distribution on total demand is shown in Figure 4. The point estimates from the ITT and WU reports are also shown.

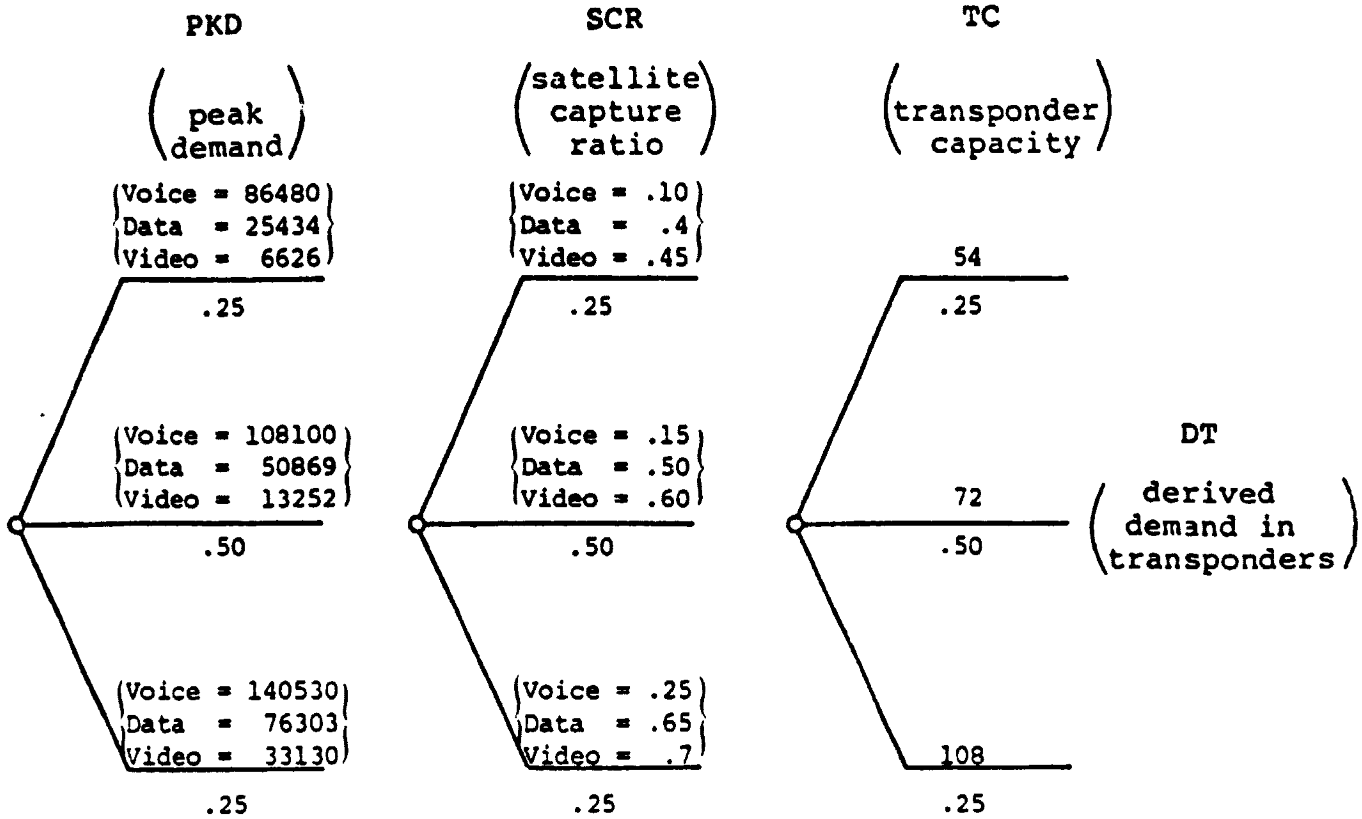


Fig. 3: Probability Tree for Total Demand

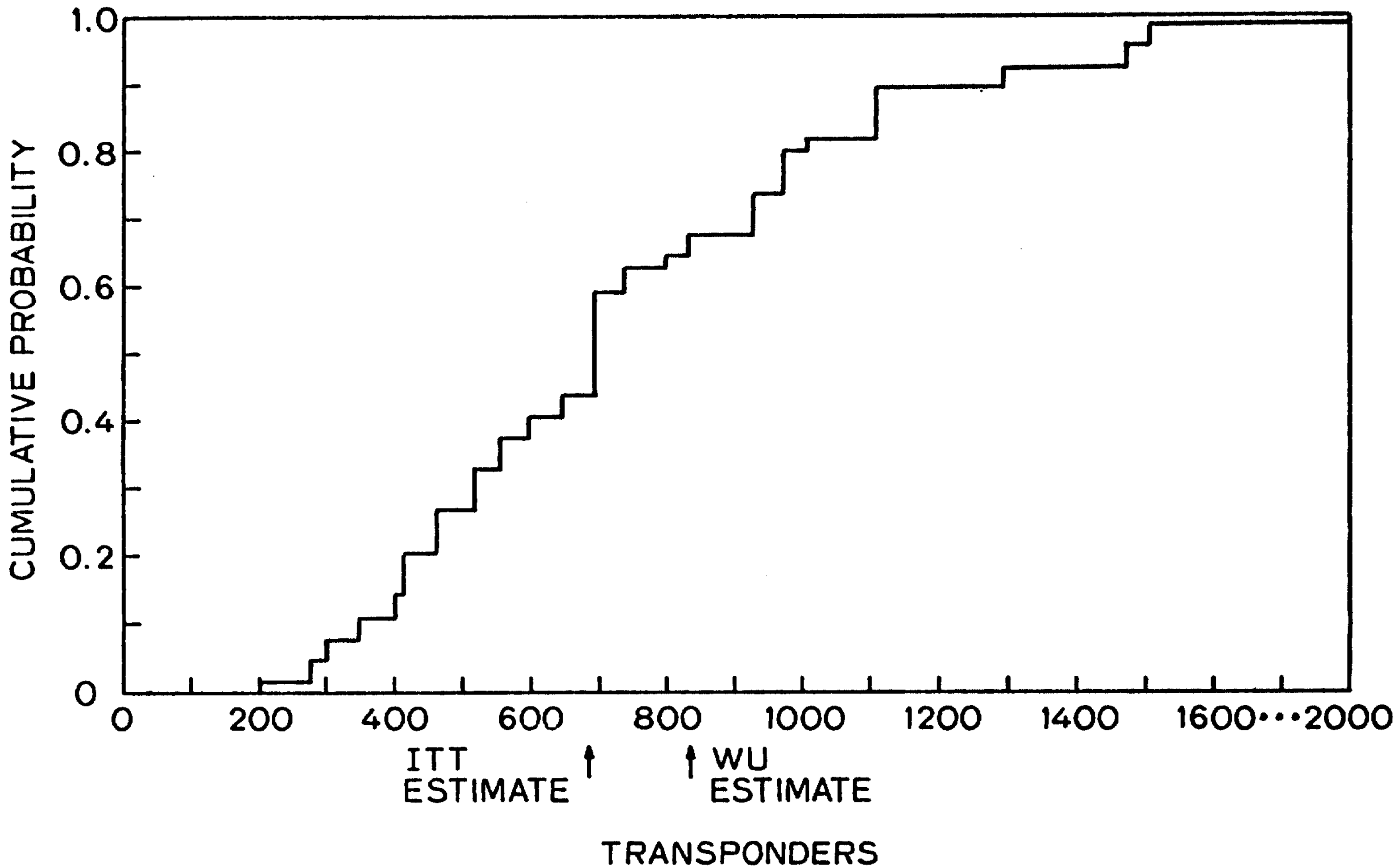


Fig. 4: Cumulative Distribution on Total Demand for Transponders in 1990

3. System Capacity Without Re-Use

In this section we determine the capacity of the domestic orbital arc, in terms of the number of domestic satellites and the resulting number of transponders that can be placed in orbit. The ability of each of the three frequency bands to handle communications traffic is limited by three factors:

- the intersatellite distance required to keep interference to acceptable limits--this determines the number of satellites that can be used;
- the number of transponders per satellite; and
- the fraction of the domestic orbital arc designated for use by the U.S.

The ITT report provides data on the first factor, and presents an estimate of available capacity. We first summarize that data. We then proceed in a manner analogous to that used in the demand section. We present a simple model that determines capacity from information on the three limiting factors listed above. We use the ITT data as a base from which to generate illustrative probability distributions on each of the factors. From these distributions we derive a probability distribution on capacity.

ITT Data

ITT presents three orbital spacing scenarios for the C and Ku bands. They are shown in Table 8. Although it is not explicitly stated, they appear to take 3° as the most likely Ka band spacing.

Table 8: ITT - Satellite Spacing Scenarios

Scenario	C band	Ku band
Minimum Capacity	4.5°	4.5°
Most Probable	4°	3°
Maximum Capacity	3°	3°

Table 9: ITT - Resulting System Capacities (in Transponders)

Scenario	C band only	C and Ku bands combined
Minimum Capacity	216	432
Most Probable	264	648
Maximum Capacity	384	768

The ITT estimates of C and Ku band capacities (in transponders) are shown in Table 9. They present 3 estimates, corresponding to the three spacing scenarios. The method by which the estimates were derived is not currently available. In comparison with our estimates of capacity presented below, the results seem rather high.

Probabilistic Analysis. The following equations can be used to determine maximum capacity, in terms of transponders:

a) combined capacity of C and Ku band:

$$CAP_{ck} = \left(\frac{72}{S_c} \cdot t_c + \frac{72}{S_k} \cdot t_k \right) p$$

b) combined capacity of C , Ku , and Ka band:

$$CAP_{cka} = CAP_{ck} + \frac{72}{S_a} \cdot t_a \cdot p$$

where:

S_c = satellite spacing in C band, in degrees

S_k = satellite spacing in Ku band, in degrees

S_a = satellite spacing in Ka band, in degrees

t_c = average number of transponders per satellite, C band

t_k = average number of transponders per satellite, Ku band

t_a = average number of transponders per satellite, Ka band

72 = the size of the domestic orbital arc, in degrees

p = fraction of the 72° designated for use by the U.S.

A probability distribution on capacity can be produced by assigning probability distributions to the variables in the above model. Again we have assigned illustrative distributions, which are shown in Table 10. The data on spacing is based on the scenarios in the ITT report. It will be assumed there is complete probabilistic dependence between S_c , S_k , and S_a . That is, if S_c takes on its low value, S_k and S_a do also. The three variables relating to satellite transponder capacity, t_c , t_k , and t_a , have been taken as certain for this analysis.

From these distributions, cumulative distributions on capacity without and with the Ka band were derived; the results are shown in Figures 5 and 6. Again, it is pointed out these results assume no re-use technologies are applied. The impact of re-use on capacity will be examined in later sections.

4. The Probability of Saturation

In this section we determine the likelihood of system saturation by 1990 if re-use technologies are not employed. To do this, we compare our probability distribution on total demand, from Figure 4, to the distributions on capacity without and with the Ka band, shown in Figures 5 and 6 respectively. We assume probabilistic independence between the sets of variables making up the demand and the capacity models.

Table 10: Probability Distribution for the Capacity Model

Variable	low value (prob. = .25)	nomimal value (prob. = .5)	high value (prob. = .25)
s_c	4.5°	4°	3°
s_k	4.5°	3°	3°
s_a	4.5°	3°	2°
t_c	-	24	-
t_k	-	12	-
t_a	-	24	-
p	.33	.50	.75

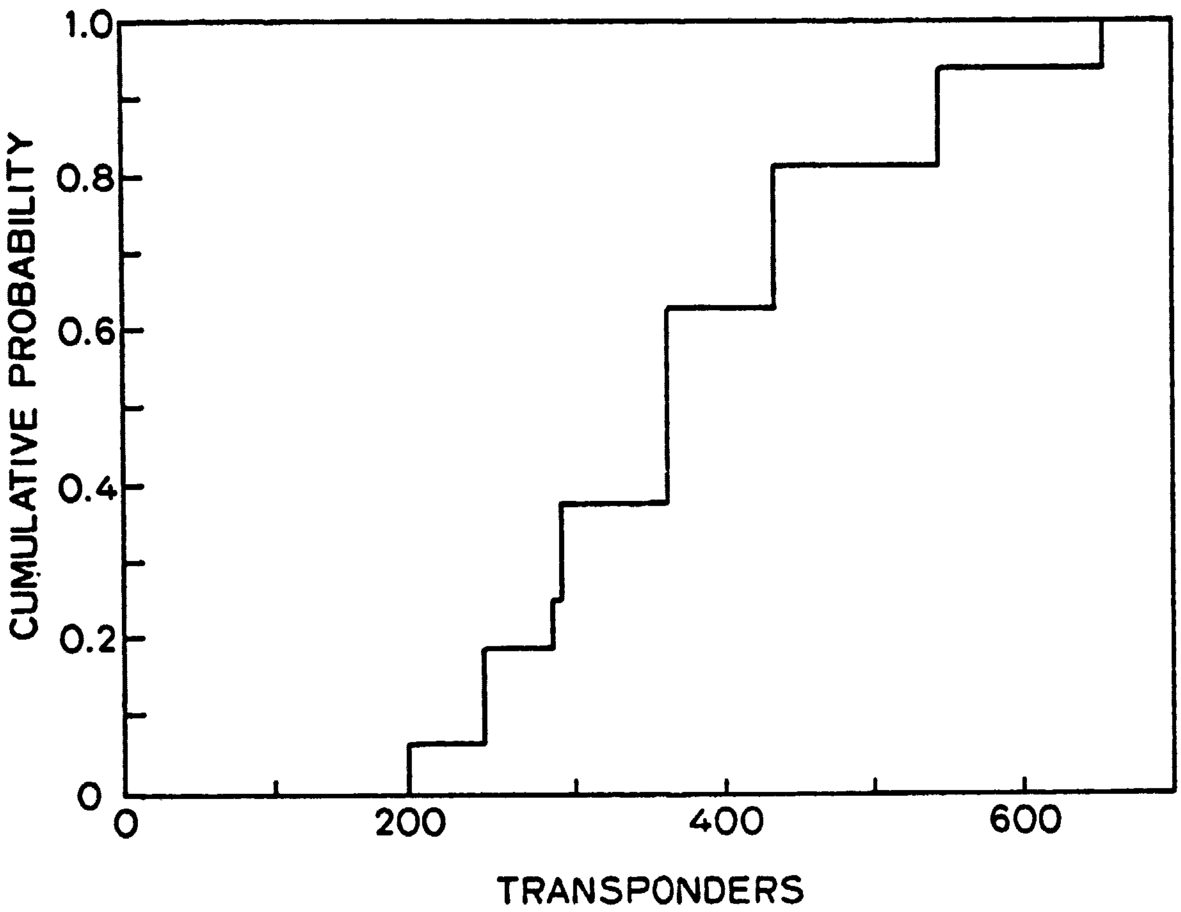


Fig. 5: Distribution on System Capacity without Re-Use and without Ka band

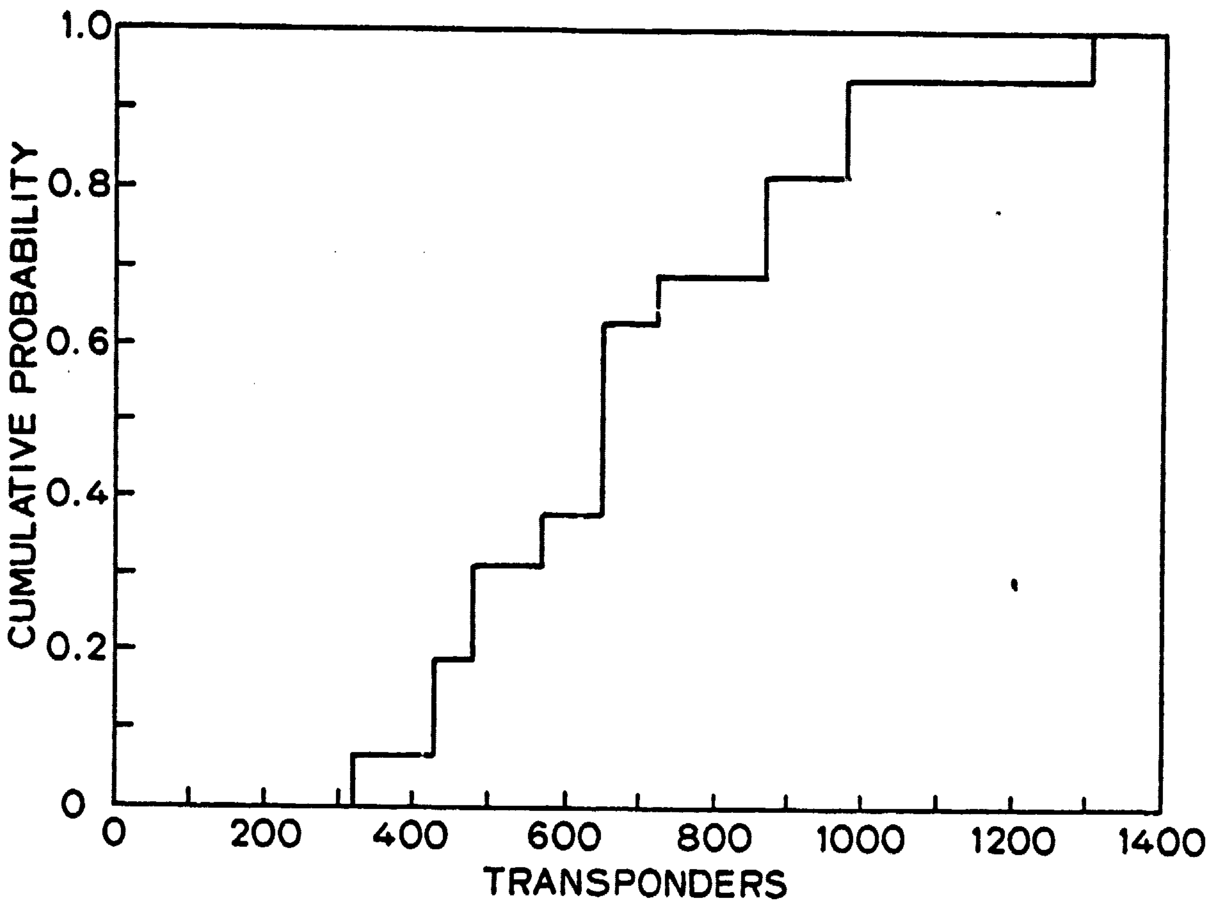


Fig. 6: Distribution on System Capacity without Re-use but with Ka band

We first examine the "most likely" values of the distributions. The median value of demand is 690 transponders; the median capacity without Ka is 360 transponders, and with Ka is 648 transponders. Using the most likely demand and capacity values, we can calculate that without Ka the system can meet only 52% of demand in 1990, while with the Ka band the system can meet 94% of the demand.

Moving away from the "most likely" case, we can use the complete distributions to calculate the overall probability of saturation; i.e., the probability that demand exceeds capacity. The equation used is:

Probability of Saturation =

$$\sum_{q \in Q} \text{Prob}\left(DT > q \mid CAP = q\right) \cdot \text{Prob}\left(CAP = q\right)$$

where Q is the set of all values in the capacity distribution, and DT is the demand for transponders. We have assumed probabilistic independence between demand and capacity.

Therefore:

Probably of Saturation =

$$\sum_{q \in Q} \text{Prob}\left(DT > q\right) \cdot \text{Prob}\left(CAP = q\right)$$

The result of these calculations are:

- without Ka band: .86 probability of saturation
- with Ka band: .54 probability of saturation

Thus without the Ka band and without re-use it is very likely that saturation will occur. Even with the Ka band, the probability of saturation is still greater than .5. This suggests re-use technologies will probably be needed if demand is to be met. In the next section we examine alternative ways of expanding system capacity.

5. Capacity Expansion Alternatives

If demand in 1990 exceeds the capacity of the C and Ku bands (as it appears likely it will), capacity expansion will be required. In this section we discuss how re-use and/or Ka band service might be used to provide additional capacity.

We will avoid consideration of the details of the technological alternatives employed. For example, there are many possible re-use technologies that are or will be available; some of these are coding and modulation techniques, dual polarization, antenna sidelobe suppression, satellite-to-satellite links, and the multiple beam antenna with on-board switching. In the remainder of the paper we assume that one aggregate re-use technology is available. The aggregate technology could include one or more of the above technologies. Presumably the technologies with the lowest marginal costs of use would be selected for use first. The exact configurations of a system would be determined by systems engineering studies. For Ka band service, we ignore attenuation and reliability problems, and assume the service provided is indistinguishable from C and Ku band service.

<u>Analysis of Some Expansion Scenarios</u>. The degree to which expansion will be required depends on the demand level in 1990. From the probability distribution on demand from figure 5 we select three demand scenarios:

- "low" : demand is 415 transponders
- "nominal": " 690 "
- "high" : " 1100 "

In order to keep the analysis simple, we will not use the probability distributions on capacity from Figures 5 and 6. Instead we will take capacity to be certain, and assign the "most likely" values:

C band: capacity is 216 transponders

Ku band: " 144 "

Ka band: " 288 "

Finally, we will consider three technological alternatives, and compare them in terms of their ability to meet demand. They are:

A. Neither Ka band or re-use are available.
B. Ka band is available; re-use is not.
C. Ka band is not available; both the C and Ku bands can be re-used several (3 to 20) times, using an aggregate "package" of technologies.

The alternatives presented are just examples; the list is in no way comprehensive.

The alternatives and the demand scenarios are laid out in tree form in Figure 7. On the right side of the tree the ability of the alternatives to meet each of the three demand levels is described.

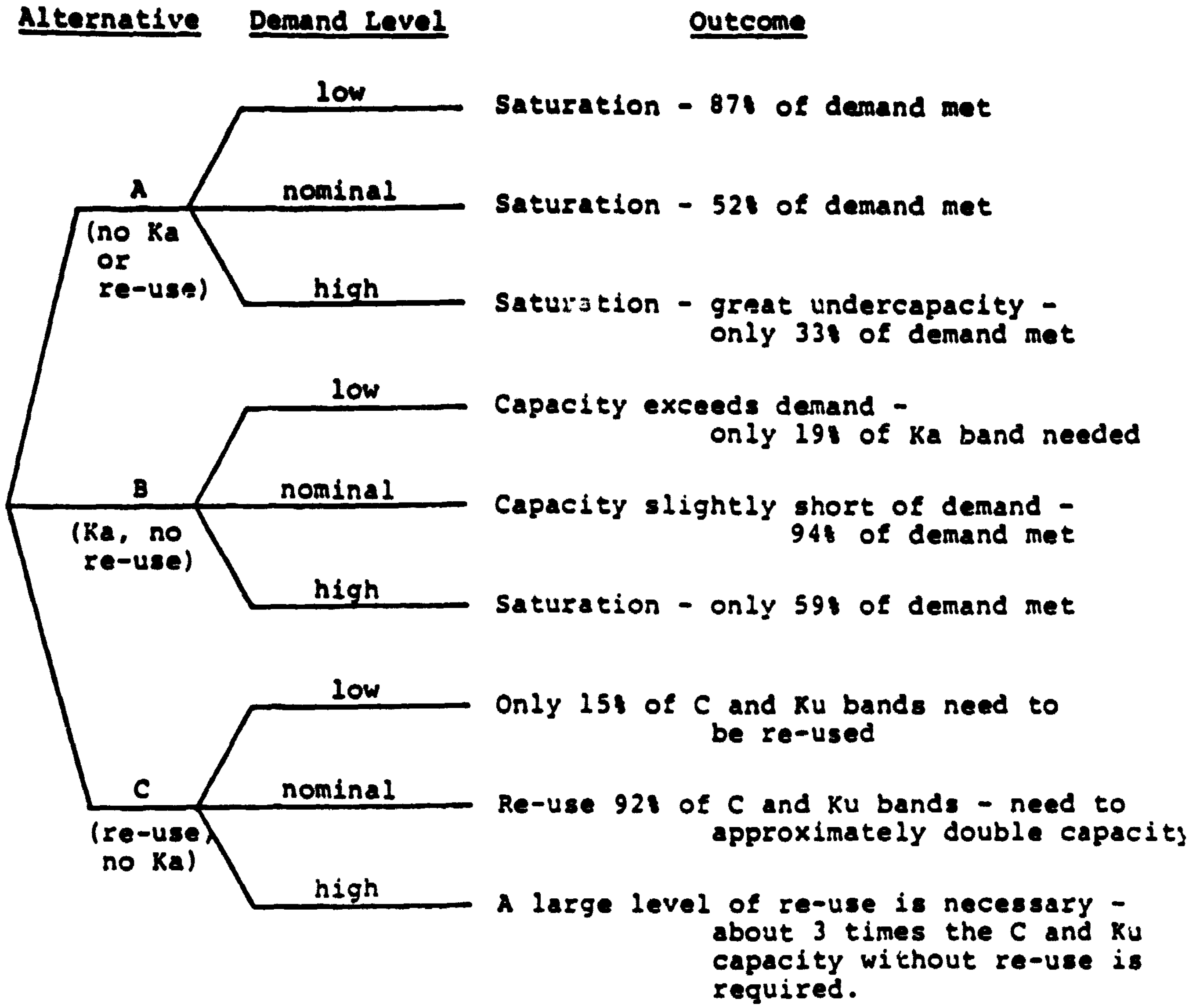


Fig. 7: Scenarios

In Section 4, comparing the full distribution on total demand to the distribution on total capacity led to the conclusion that there is a probability of .86 that demand will exceed capacity if neither re-use or Ka band are available. In the cruder analysis here, we see that in no case can demand be met by just the C and Ku bands without re-use. At the "low" demand level, either a small amount of re-use or a small portion of the Ka band are required to meet demand.

At the nominal demand level, the Ka band on its own falls just short of meeting demand. Under Alternative C, it is necessary to re-use the C and Ku bands so that capacity is approximately doubled. It appears that given a moderate level of success in developing either technology, this level of demand can be met. If a large number of re-use technologies were to become available between now and 1990, there is the potential for a large amount of overcapacity.

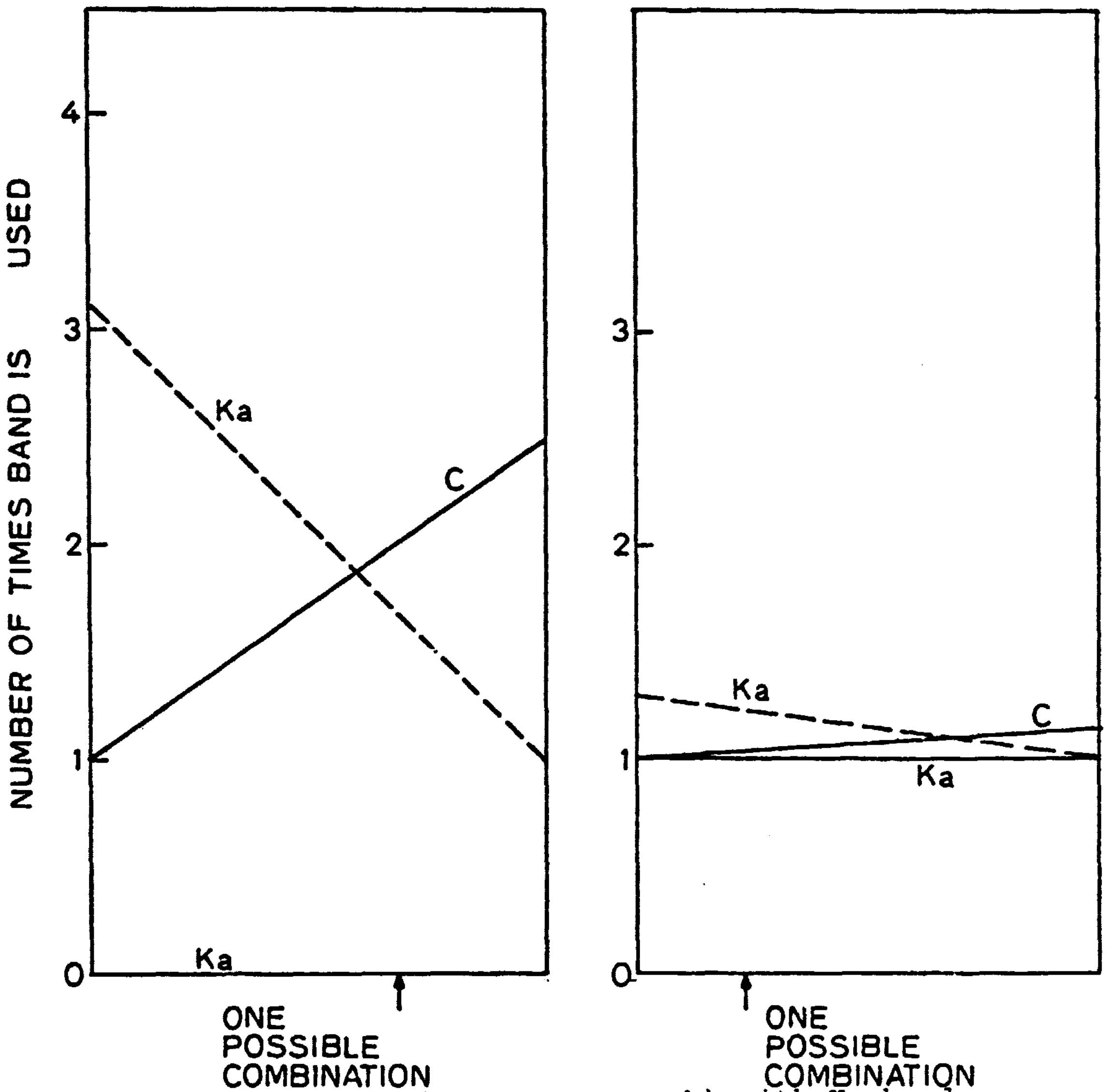
At the high demand level, the addition of the Ka band alone does not come close to meeting demand. Under Alternative C, the C and Ku bands must each be expanded to triple their base capacity in order to meet demand. Therefore unless Ka band and/or re-use are successfully developed by 1990, a large gap between demand and supply could result if the demand level is high.

Combining Ka Band and Re-use Technologies. In general, there are many combinations of C band re-use, Ku band re-use, and Ka service that can be used to meet demand. Examples of combinations that could be used to meet the nominal demand level of 690 transponders are shown in Figure 8. The graph on the left of Figure 8 shows possible combinations if the Ka band is not available; the graph on the right assumes Ka band is available (but cannot be re-used). A vertical line drawn at any point on a graph shows how demand is met: the amount that C band is expanded over its capacity without re-use, the amount that Ku band is expanded over its capacity, and whether or not the Ka band is used.

If the demand for satellite services is taken as insensitive to price, then the optimal choice of satellite technologies corresponds to the problem of finding the system configuration that meets demand at least cost. In the next section we introduce cost data into the analysis.

6. Analysis of the Comparative Costs of Alternatives

By quantifying the uncertainties relating to cost, we can expand the decision analysis framework of the earlier sections of the paper. Unfortunately, the cost data available so far, from the contractor reports and from other sources, is sketchy. Below we present a general outline of how the analysis should proceed. We then present an example of a cost comparison between competing technologies, using illustrative cost data.



a) without Ka band b) with Ka band

Fig. 8: Possible Combinations of C band Re-use, Ku band Re-use, and Ka band to Meet a Demand of 690 Transponders

The General Framework. Figure 9 shows a decision tree, in generic form, that determines the expected cost of meeting demand for a given technological alternative. For example, an alternative might be the use of the Ka band, or the introduction of some combination of re-use technologies. There are four state variables represented in the tree. The first two variables are total demand, and system capacity without re-use for each band. Comparison of the values taken on by these variables determines to what extent frequency expansion is needed. The last two variables are the technical performance of the alternative at the level of service required to meet demand (e.g., amount of re-use attainable), and the resulting cost. In some cases the value of one or both of these variables may be relatively certain. The last two variables provide a general representation; they would appear in different forms for specific analyses. The values at the right side of the tree determine the cost of meeting the resulting demand level. In some cases it may not be possible to meet some high levels of demand with the given technological alternative. "Rolling back" the tree determines the expected cost of using the alternatives.

The cost of terrestrial technologies in direct competition with satellites will also determine the desirability of using the various satellite technologies. The effect of competition from terrestrial service will show up in the satellite capture ratio in the demand model. Since we have even less data on projected terrestrial costs than on satellite

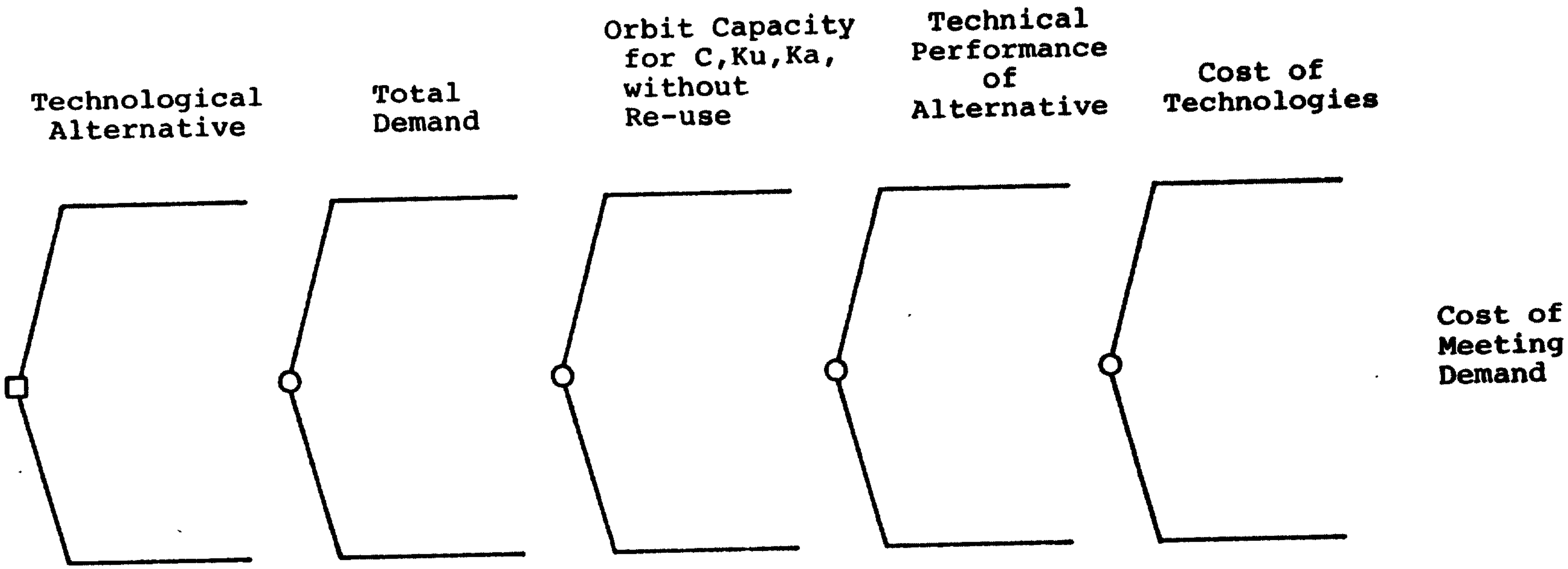


Fig. 9: Tree for Evaluating Competing Technologies

costs, we will assume the contractors' estimates of satellite capture ratios included the possibility of new or improved terrestrial technologies. As noted in Section I, it would be desirable in the future to formulate a structural model that approached the question of terrestrial/satellite tradeoffs in a more comprehensive manner. Pricing policies should certainly be included, as should latent demand--demand not currently observable, but which might appear if the costs were reduced substantially.

An Illustrative Cost Comparison of Ka Service to C Band Re-use in 1990. The following analysis uses illustrative cost data. Its purpose is to show how uncertainty about cost enters into the analysis. A full description of an expanded form of the example appears in Appendix C.

We compare two technological alternatives. The alternatives are simply examples; many other possibilities exist. The alternatives are:

1. C-band re-use. The C band spectrum is re-used through a variety of technologies. The Ku band is used before re-use is employed on the C band. The Ka band cannot be used. For the sake of computational ease, we assume no re-use technologies are used for the Ku band.[4]

2. Ka band. The Ka band can be used. No re-use is possible for the C band or the Ku band. In performing the analysis it was found that the capacity

available from the use of all three bands often fell short of meeting demand. Therefore re-use of the Ka band only is allowed, say through the use of spot beams with on-board switching.[5]

The decision tree for the analysis is shown in Figure 10. There are four state variables: total demand, system capacity, cost of C-band re-use, and Ka system cost.

The total demand distribution from Figure 4 was approximated by a three-branch distribution. In order to reduce the amount of analytic effort required, we again use deterministic values for system capacity. The values used are:

C band: $CAP_c = 216$

Ku band: $CAP_k = 144$

Ka band: $CAP_a = 288$

Uncertainty on system capacity could be added to the analysis with no change in the methodology used.

The basic unit of cost used is dollars per transponder. We are interested only in relative costs. It is assumed the costs for the C and Ku bands are certain, while Ka band cost is uncertain. The following data are used:

Q_c = cost/transponder in C-band = \$1

Q_k = cost/transponder in Ku-band = \$1.50

Q_a = cost/transponder in Ka-band is described by the distribution:

$$\text{Prob}\left(Q_a = \$1.50\right) = .5$$

$$\text{Prob}\left(Q_a = \$5.00\right) = .5$$

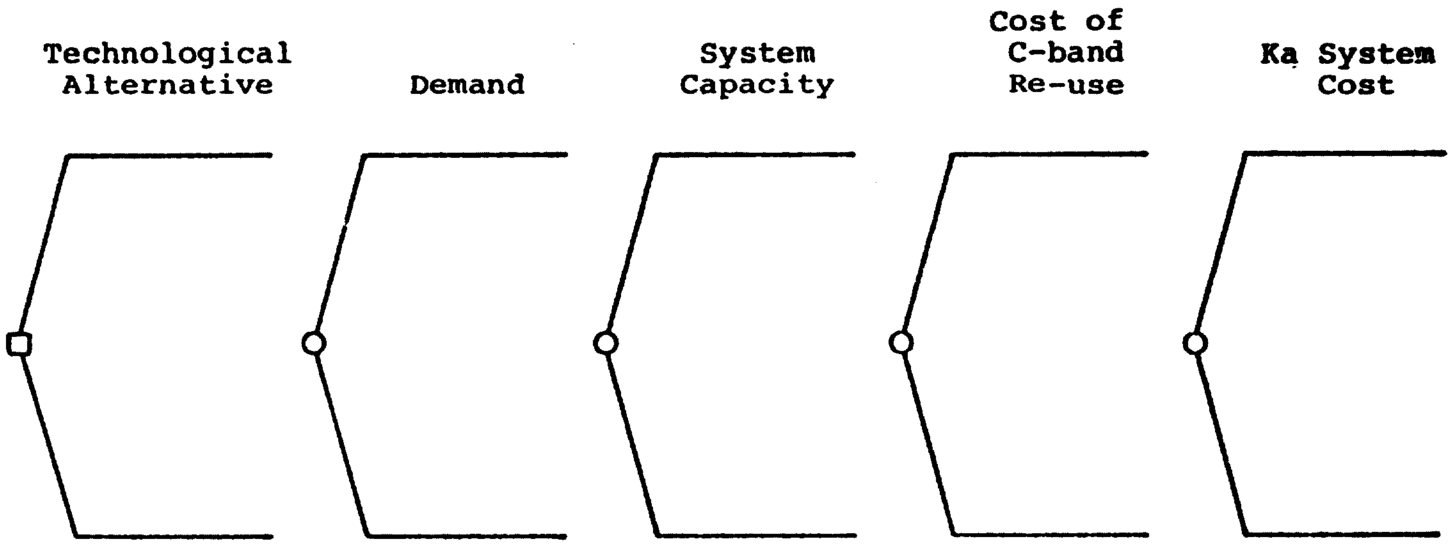


Fig. 10: Tree for C band Re-use vs. Ka band Comparison

A simple model of re-use cost is employed for C band re-use (and for Ka band re-use when required). It is assumed re-use technologies are added one at a time until demand is met. Each technology allows the entire spectrum capacity to be re-used; i.e., it doubles capacity. Cost increases for each re-use, as follows:

$$CRU(n) = Qm^n \qquad (2)$$

where:

$CRU(n)$ = marginal cost per equivalent transponder when the spectrum is being used for the nth time

Q = cost per transponder without re-use

m = a multiplier $(m > 1)$

n = number of times the spectrum is being re-used

This model is used for illustrative purposes. Its form does seem plausible. The acquisition of data on re-use costs would allow this and alternative model forms to be tested with data and compared in terms of suitability.

For Alternative 1, C-band re-use, the multiplier is m_c, and is uncertain:

$$\text{Prob}\left(m_c = 1.2\right) = .5$$
$$\text{Prob}\left(m_c = 2\right) = .5$$

For cases where re-use is required for the Ka band, the multiplier m_a is taken to have the value of 1.2.

Figure 11 shows the full decision tree, with the deterministic capacity variable removed. At the right side of each final node in the tree is the resulting minimum cost for meeting demand. The cost calculations are described in Appendix C.

The tree can be rolled back to yield an expected cost of meeting demand for each alternative. The results are:

Alternative 1, (C-band re-use):
Expected cost = $1621

Alternative 2, (Ka band):
Expected cost = $1802

Because the data used here is illustrative, no definitive statements can be made from the results. However, we can see how the data could be used for decision-making purposes. If Research Programs 1 and 2 were available that led respectively to Alternatives 1 and 2 being available in 1990, then it appears that Program 1 leads to a savings of $181 compared to Program 2. The steps involved in extending the analysis to give explicit consideration to R&D alternatives are discussed in the next section.

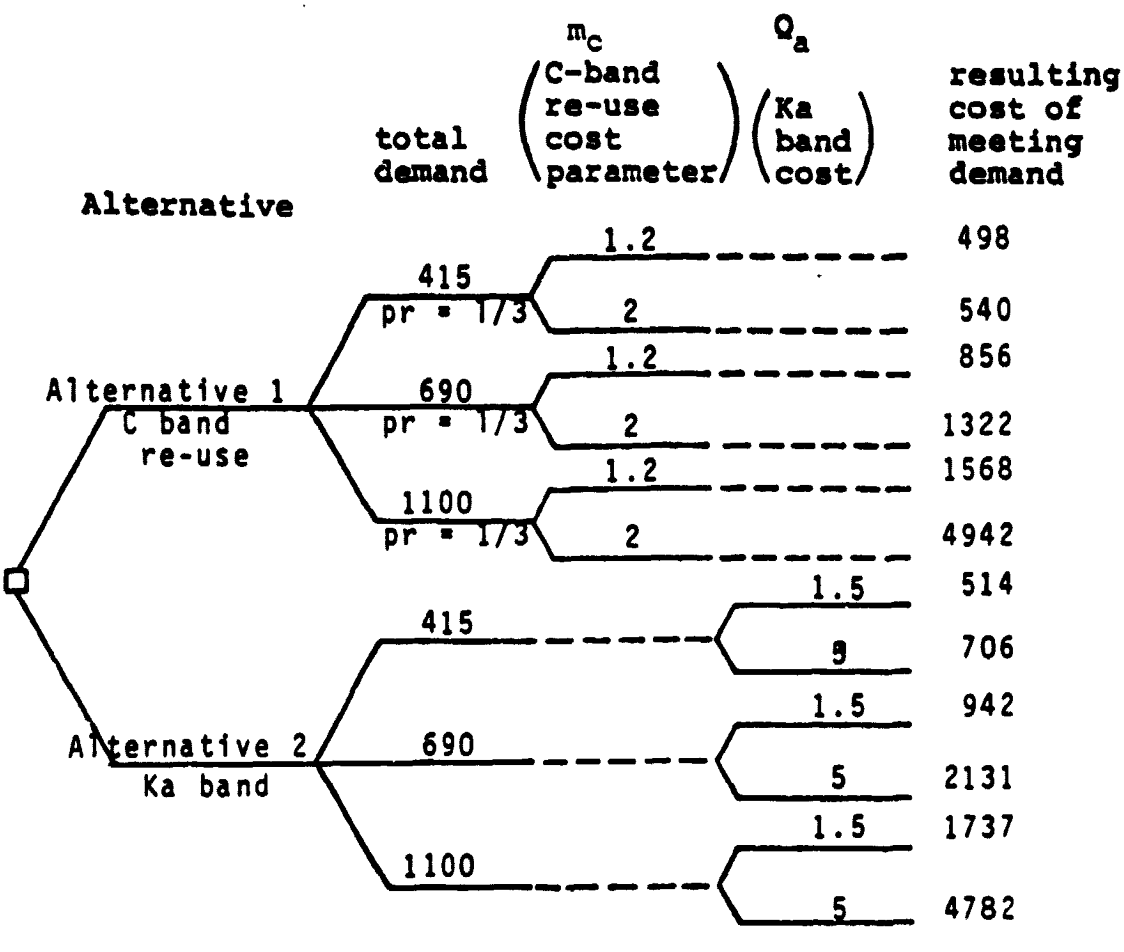


Fig. 11: Decision Tree for Cost Comparison

Section III

APPLICATION OF THE APPROACH TO COMMUNICATIONS SATELLITE R&D DECISIONS

NASA faces a range of decisions in the area of communications satellite policy. The analysis presented here is focused primarily on the choice between Ka band technologies and re-use and conservation alternatives. The discussion here illustrated how a decision analysis approach can be used to address that question.

The analysis, however, intentionally leaves out many issues in order to illustrate analytical techniques. The full approach as outlined in Section I requires consideration of many other issues and much more attention to data, involvement of knowledgeable experts and decision makers, and structural modeling of satellite supply and demand. In addition, to be useful to NASA R&D planning, the focus of an analysis would have to be on the R&D allocation decisions that precede the technology deployment decisions.

Figure 12 illustrates the structure of an R&D decision analysis. This figure shows a two-stage decision tree for the R&D decision problem. In the first stage, R&D allocation decisions and R&D outcomes are represented. In the second stage the deployment decisions and outcomes are represented. The analysis of the second deployment stage would be similar to the analysis presented in the preceding section.

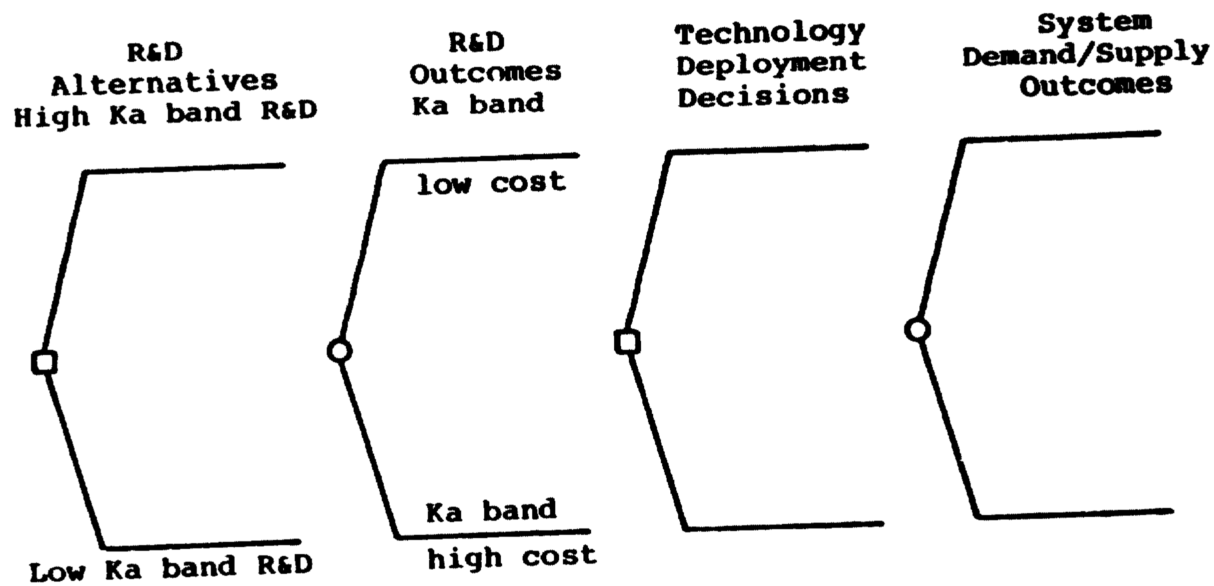


Fig. 12: Two-Stage Decision Tree for R&D Analysis

The analysis of the R&D stage would use the same decision analysis techniques as illustrated in the preceding section. The additional information requirements would include intormation on the cost of each R&D alternative and the probabilitites of various outcomes of the R&D.

Within this structure alternative NASA R&D programs can be represented as alternatives. The value of an R&D program would be characterized in terms of the change in information produced by the program including delineation of new technical alternatives. Numerical values for this information could be imputed from the resulting changes in deployment decisions and reduced costs or increased level of communications services.

We have not carried out the detailed R&D analysis in this paper. Such an analysis should properly be carried out with the close involvement of the relevant technical specialists and NASA officials. This two-stage R&D decision analysis structure when combined with appropriate structural models of communications markets would provide significant insights to NASA R&D planning and could serve as a basis for a rational allocation of NASA communications satellite R&D funds.

Notes

1. Calio, Anthony J. Statement before the Subcommittee on Space Sciences and Applications, Committee on Science and Technology, U.S. House of Representatives, Feb. 20, 1979.

2. For a general introduction to decision analysis, see:
   Howard, R. A., "Decision Analysis: Applied Decision Theory,"
   North, D. W., "A Tutorial Introduction to Decision Analysis,"
   Howard, R.A., "The Foundations of Decision Analysis,"
   all reprinted in Readings in Decision Analysis, SRI International, 2nd ed., 1977.

3. See: Spetzler, C. S., and C. S. Stael von Holstein, "Probability Encoding in Decision Analysis," reprinted in Readings in Decision Analysis, SRI International, 2nd ed., 1977.

4. It may in fact be easier to re-use Ku band than C band, suggesting the alternative of re-using Ku but not C might be more realistic than the one presented here.

5. Re-use of the Ka band will likely use Ku band re-use technology, and therefore should be feasible.

APPENDIX A. Western Union Demand Data and Comparison to the ITT Data

Below we summarize the demand data from the Western Union (WU) report and, where possible, compare it to the ITT data. Western Union's demand model appears to be comprehensive, and fairly complex. It builds up a forecast by aggregating data on a large number of telecommunications services.

Table A-1 shows Western Union's forecast of net long haul traffic for voice, data and video services for 1980, 1990, and 2000. A terrestrial/satellite cost model is then used to split out satellite traffic from the total long haul traffic. The estimate of satellite traffic appears in Table A-2.

The data for the three types of services in the above tables are each stated in different units. This makes comparisons between service types and with the ITT data difficult. The data is eventually all converted into a common unit, equivalent transponders. The process used to make the conversions is not known at this point. There is some indication it is a relatively complex process, and includes consideration of peak hour demand, among other factors.

Western Union's resulting estimates of total long haul traffic and satellite traffic in transponders are shown in Tables A-3 and A-4. In each case we have shown the demand is split between the three types of service. From these data,

Table A-1: WU - Forecast of Annual Long Haul Traffic

	1980	1990	2000
Voice (1/2 circuits)	2,100,000	5,300,000	13,700,000
Data (terabits/year)	1,100	7,000	27,600
Video (widebond channels)	170	290	450

Table A-2: WU - Forecast of Satellite Demand

	1980	1990	2000
Voice (1/2 circuits)	345,000	892,000	2,905,000
Data (terabits/year)	464	3,215	14,533
Video (wideband channels)	79	187	340

Table A-3: WU - Total Long Haul Traffic in Transponders

	1980		1990		2000	
Voice	2100	(92%)	3407	(91%)	8828	(93%)
Data	13	(1%)	75	(2%)	320	(3%)
Video	176	(7%)	253	(7%)	357	(4%)
Total	2289	(100%)	3735	(100%)	9505	(100%)

Table A-4: WU - Satellite Demand in Transponders

	1980		1990		2000	
Voice	346	(80%)	360	(76%)	1862	(80%)
Data	61	(1%)	42	(5%)	201	(9%)
Video	80	(19%)	157	(19%)	258	(11%)
Total	432	(100%)	829	(100%)	2321	(100%)

Table A-5: WU - Satellite Capture Ratio (derived) in percent

	1980	1990	2000
Voice	16	18	21
Data	46	56	63
Video	45	62	72

we are able to derive a satellite capture ratio, which is shown in Table A-5.

It is interesting to compare data from the latter three tables to the ITT data presented in Section 2. In order to facilitate comparison, the relevant pieces of data will be reproduced side-by-side.

Table A-6 compares the contractors' estimates of the way total long haul traffic is split between the three types of service. There is a major discrepancy over the importance of data traffic. Although the difference could be attributable to differing perceptions of what is going to happen with respect to the various technologies, it is also possible the discrepancy stems from the use of different accounting conventions. The fact that the results are so different for 1980, essentially the present, supports the latter view. The discrepancy will hopefully be resolved when the full reports become available.

In Table A-7 the estimates of satellite capture ratio are presented. The results are again very different in 1980, but concur to a large degree in 1990 and 2000.

The estimates of satellite demand in transponders is presented in Table A-8. The forecasts presented in Table A-8 are the product of the full analysis of each of the contractors, and are therefore the most interesting data for comparison. As can be observed, the forecasts are so different that one questions whether they are based on the same set of basic

Table A-6: ITT and WU - Comparison of Split of Total Long Haul Traffic Between Service Types - in percent

Format: (ITT data, WU data)

	1980	1990	2000
Voice	(74, 92)	(76, 91)	(77, 93)
Data	(15, 1)	(15, 2)	(12, 3)
Video	(11, 7)	(9, 7)	(11, 4)

Table A-7: ITT and WU - Satellite Capture Ratio - in percent

Format: (ITT data, WU data)

	1980	1990	2000
Voice	(2, 16)	(15, 18)	(25, 21)
Data	(1, 46)	(50, 56)	(60, 63)
Video	(50, 45)	(60, 62)	(60,72)

assumptions and definitions. Although it is a major task to critique either of the analyses and to improve them, one apparent assumption of the WU analysis is that transponder capacity remains constant at 50 MSPS. If the WU results are recalculated with the increasing transponder capacities used by ITT, the forecast for the total number of transponders, as shown in Table A-9, is much closer to ITT's. This does not mean one analysis is correct and the other is not, but at least it offers one explanation for the discrepancies. We note that there is still a major divergence in terms of the split between voice, data and video traffic.

Table A-8: ITT and WU - Demand for Transponders

Format: (ITT data, WU data)

	1980	1990	2000
Voice	(21, 346)	(225, 630)	(474, 1862)
Data	(5, 6)	(345, 42)	(436, 201)
Video	(35, 80)	(110, 157)	(211, 258)
Total	(61, 432)	(690, 829)	(1121, 2321)

Table A-9: WU - Demand for Transponders, modified to include increasing transponder capacity (in 36 MHz equivalent transponders)

	1980	1990	2000
Voice	412	438	862
Data	7	29	93
Video	95	109	119
Total	514	576	1074

APPENDIX B. The Probability Distributions for Demand for Voice, Data, and Video Services

The distributions are shown on the next three pages.

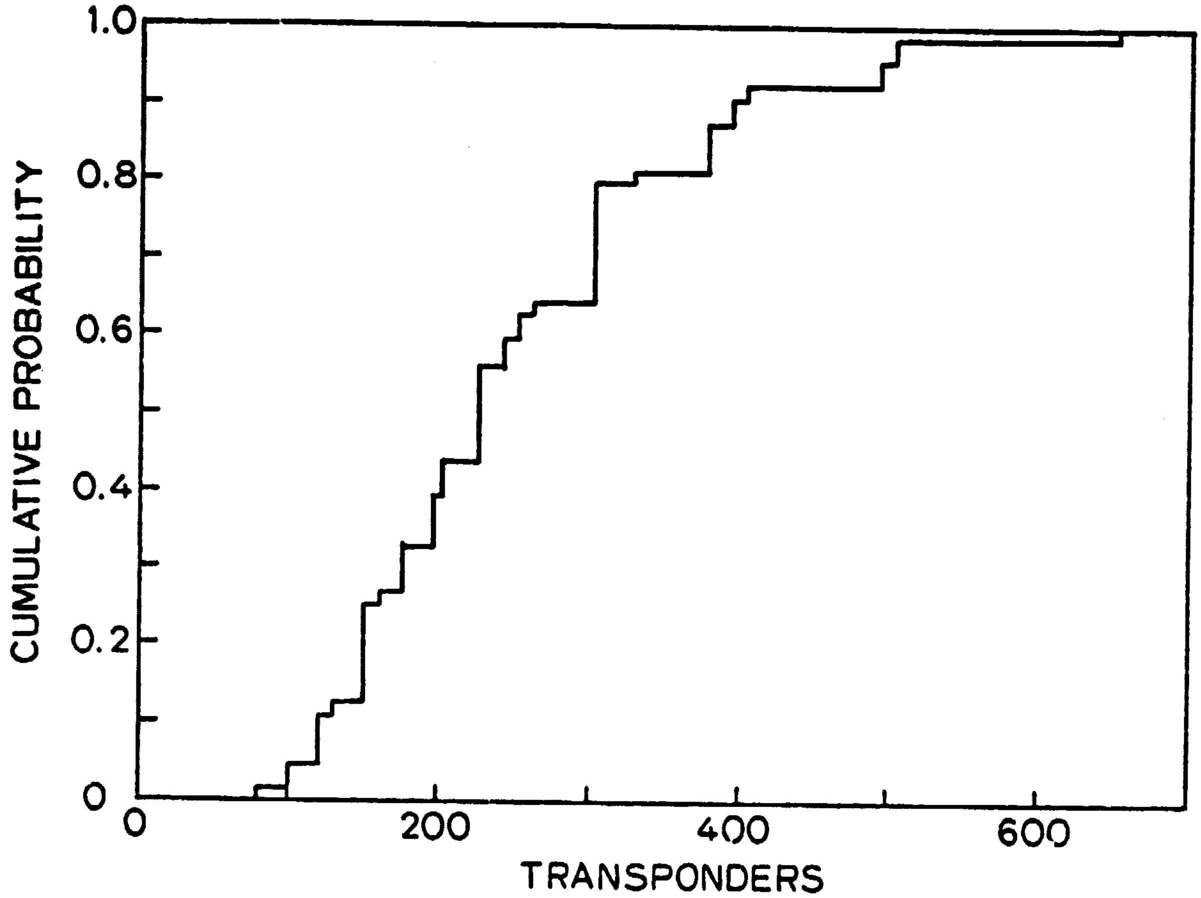


Fig. B-1: Cumulative Distribution on Voice Demand for Transponders

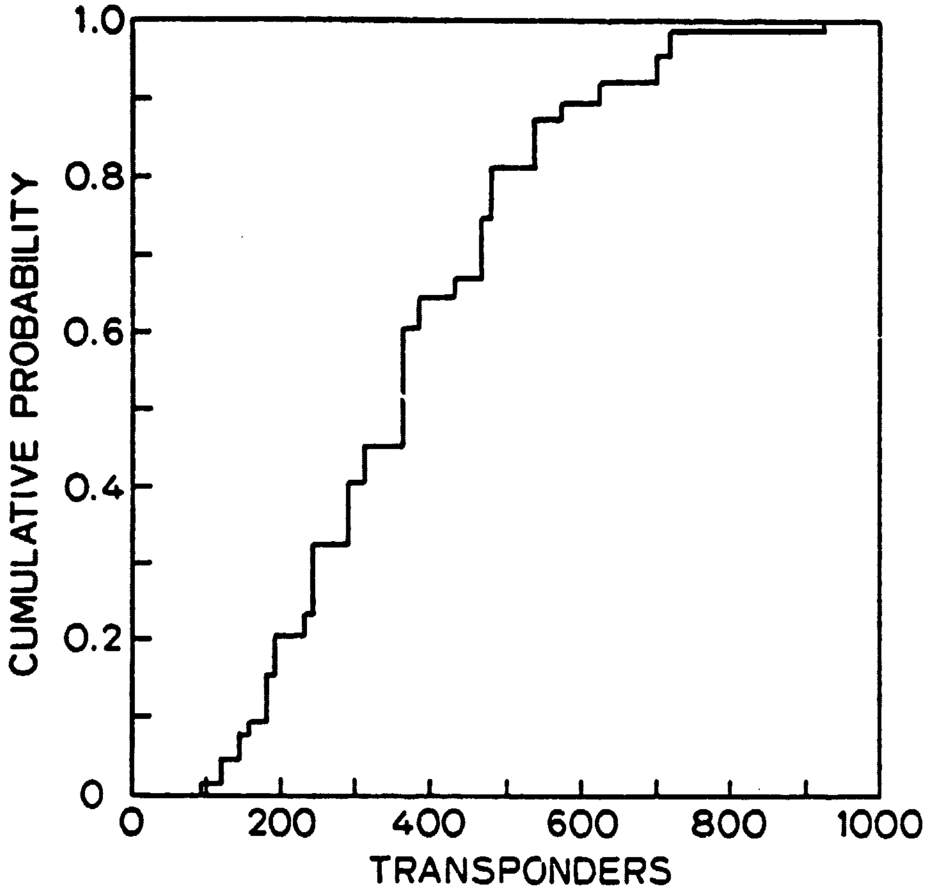


Fig. B-2: Cumulative Distribution on Data Demand for Transponders

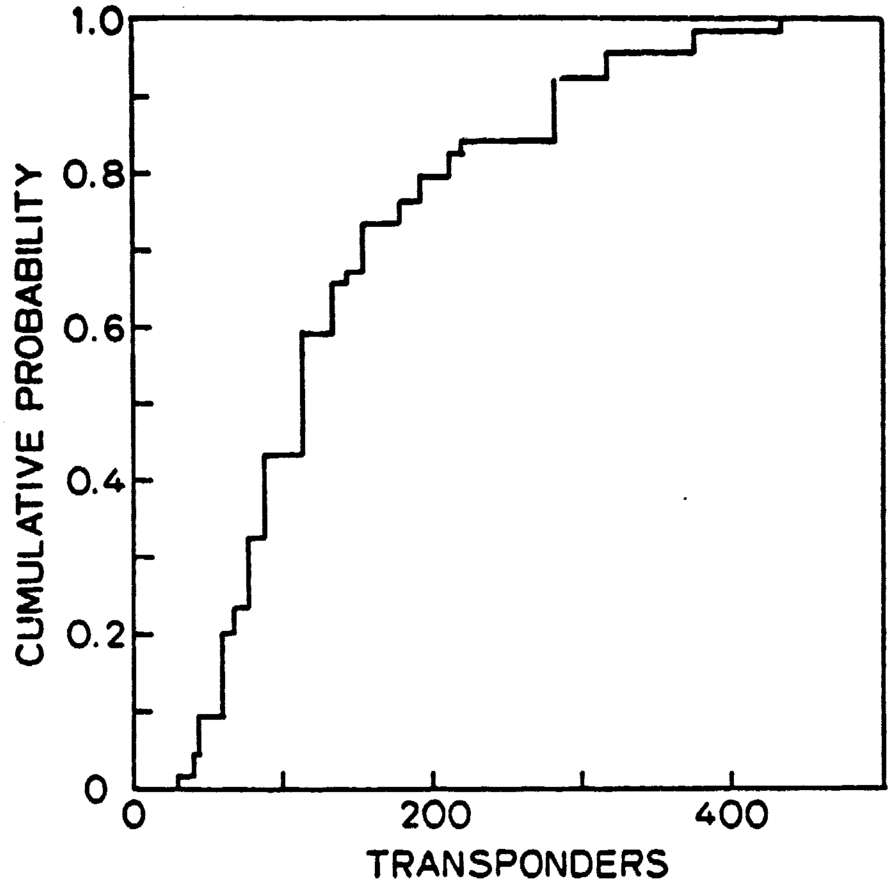


Fig. B-3: Cumulative Distribution on Video Demand for Transponders

APPENDIX C. Expanded Version of the Illustrative Cost Comparison

In Section 6 we presented an illustrative analysis of the costs of Ka band service and C band re-use. This appendix is an expanded version of that analysis: a third technological alternative has been added. A full description of the cost calculations is also presented.

We compare three technological alternatives.

1. C-band re-use. The C band spectrum is re-used through a variety of technologies. The Ku band is used before re-use is employed on the C band. No re-use technologies are available for Ku band. The Ka band cannot be used.

2. Ka band. The Ka band can be used. No re-use is possible for the C band or the Ku band. In performing the analysis it was found that the capacity available from the use of all three bands often fell short of meeting demand. Therefore re-use of the Ka band only is allowed, say through the use of spot beams with on-board switching.

3. Combination. Both of the above are available. The minimum cost combination for each demand level will be used.

The decision tree for the analysis is shown in Figure C-1. There are four state variables: total demand, system capacity, cost of C-band re-use, and Ka system cost.

The total demand distribution from Figure 4 was approximated by three-branch distribution. In order to reduce the amount of analytic effort required, we again use deterministic values for system capacity. The values used are:

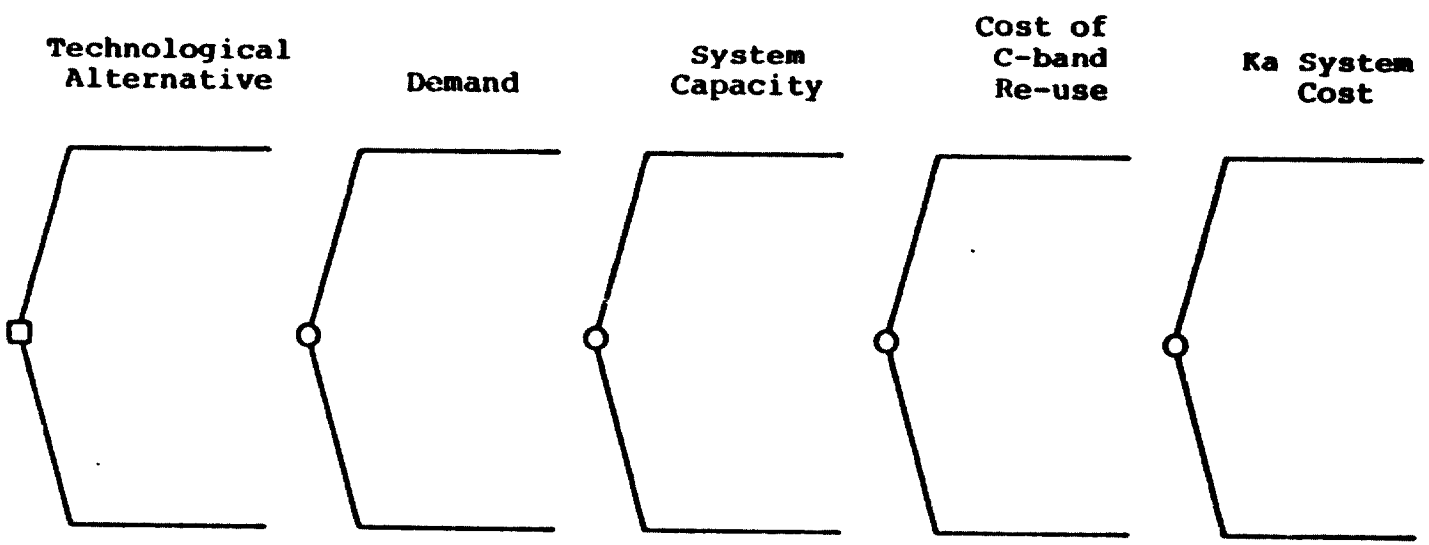


Fig. C-1: Tree for C band Re-use vs. Ka band Comparison

C band: $CAP_c = 216$

Ku band: $CAP_k = 144$

Ka band: $CAP_a = 288$

Uncertainty on system capacity could be added to the analysis with no change in the methodology used.

The basic unit of cost used is dollars per transponder. We are interested only in relative costs. It is assumed the costs for the C and Ku bands are certain, while Ka band cost is uncertain. The following data is used:

Q_c = cost/transponder in C-band = \$1

Q_k = cost/transponder in Ku-band = \$1.50

Q_a = cost/transponder in Ka-band is described by the distribution:

$$\text{Prob}\left(Q_a = \$1.50\right) = .5$$

$$\text{Prob}\left(Q_a = \$5.00\right) = .5$$

A simple model of re-use cost is employed for C band re-use (and for Ka band re-use when required). It is assumed re-use technologies are added one at a time until demand is met. Each technology allows the entire spectrum capacity to be re-used; i.e. it doubles capacity. Cost increases for each re-use, as follows:

$$CRU(n) = Qm^n \quad (2)$$

where:

$CRU(n)$ = marginal cost per equivalent transponder when the spectrum is being used for the nth time

Q = cost per transponder without re-use

m = a multiplier $(m > 1)$

n = number of times the spectrum is being re-used

For Alternative 1, C-band re-use, the multiplier is m_c , and is uncertain:

$$\text{Prob}\left(m_c = 1.2 \right) = .5$$
$$\text{Prob}\left(m_c = 2 \right) = .5$$

For cases where re-use is required for the Ka band, the multiplier m_a is taken to have the value 1.2 .

Figure C-2 shows the full decision tree, with the deterministic capacity variable removed. At the right side of each final node in the tree is a resulting minimum cost for meeting demand. The cost calculations are outlined below.

<u>Cost Calculations - Alternative 1</u>

Demand is met by first using C band, then the Ku band, and then by re-using the C-band as many times (or fraction of a time) as required. For the range of demand values encountered here, the following equation can be used.

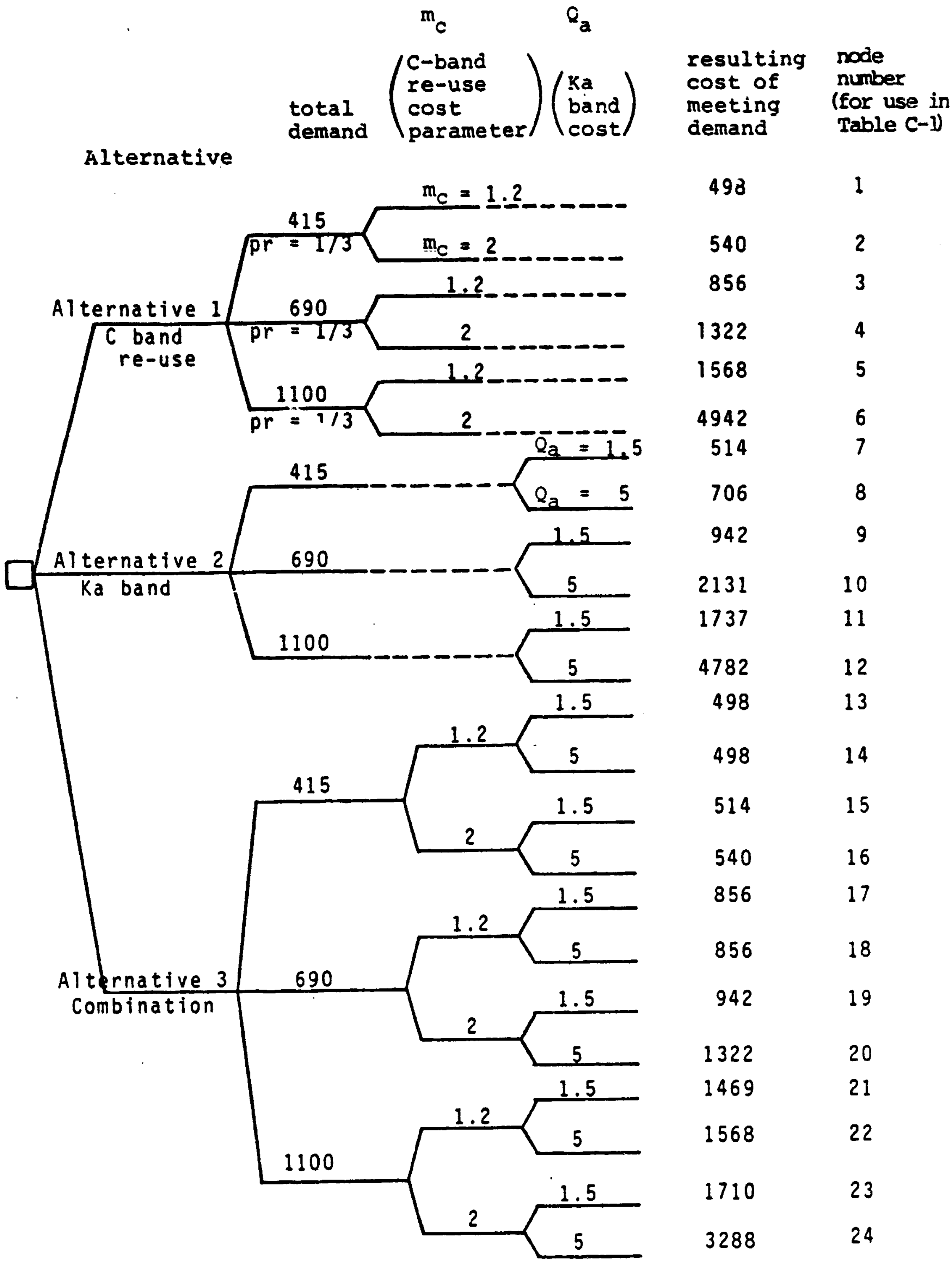


Fig. C-2: Full Decision Tree

Let:

$$R = \frac{DT-CAP_k}{CAP_c}, \quad \text{where DT is demand}$$

$$INT = \text{largest integer less than } R$$

$$i = R - INT$$

Then the total cost is given by:

$$COST = Q_c \cdot CAP_c \left[\sum_{i=o}^{INT-1} m_c^i + fm_c^{INT} \right] + Q_k \cdot CAP_k$$

The amount of re-use required to meet demand for each demand level is described in Table C-1. The resulting costs are shown on the right side of the tree in Figure C-2.

Cost Calculation - Alternative 2

Demand is met by first using the C, then the Ku, and then the Ka band, and then by re-using the Ka band if necessary. For the range of demand values encountered here, we use the following to calculate cost.

Let:

$$R = \frac{DT-CAP_c-CAP_k}{CAP_a}, \quad \text{where DT is demand}$$

$$INT = \text{largest integer less than } R$$

$$f = R - INT$$

Total cost is:

Table C-1: How Demand is Met

Alternative	Node Number from Figure 11	Technologies Used*
1	1	Use 19% of Ka band
	2	Use 19% of Ka band
	3	Use Ka band,then re-use 15% of it
	4	Use Ka band,then re-use 15% of it
	5	Use Ka band,then re-use it once, then re-use 57% of it
	6	Use Ka band,then re-use it once, then re-use 57% of it
2	7	Re-use 25% of C band
	8	Re-use 25% of C band
	9	Re-use C band,then re-use 53% of it
	10	Re-use C band,then re-use 53% of it
	11	Re-use C band three times,then re-use 43% of it
	12	Re-use C band three times,then re-use 43% pf it
3	13	Re-use 25% of C band
	14	Re-use 25% of C band
	15	Use 19% of Ka band
	16	Re-use 25% of C band
	17	Re-use C band, then re-use 53% of it
	18	Re-use C band, then re-use 53% of it
	19	Use Ka band, then re-use 15% of it
	20	Re-use C band, then re-use 53% of it
	21	Re-use C band twice, then use Ka, then re-use 9 % of C
	22	Re-use C three times, then re-use 43% of it
	23	Use Ka, re-use Ka, re-use 76% of C band
	24	Re-use C twice, use Ka, re-use 7% of Ka

*C band and Ku band are always used once before C band re-use or Ka band use.

$$COST = CAP_a \left[\sum_{i=o}^{INT-1} m_k^i + fm_k^{int} \right] + Q_c \cdot CAP_c + Q_k \cdot CAP_k$$

The amount of Ka band use required to meet demand for each demand level is shown in Table C-1. The resulting cost values appear in Figure C-2.

Cost Calculations - Alternative 3

Under Alternative 3, it is assumed demand is first met by using the C and Ku bands once. Additional capacity is added through re-use of the C-band and/or through the use and subsequent re-use of the Ka band. Capacity is added in increasing order of its marginal cost. This generates a supply curve for capacity. Table C-2a shows the increase in marginal cost as the C band is re-used, and as the Ka band is used and subsequently re-used. When the appropriate cost parameters are "plugged in," the supply curve is derived by combining the lists for the two technologies and selecting alternatives in order of increasing marginal cost. Since there are two possible values of Ka system cost and two possible values of C band re-use cost, a total of 4 supply curves were needed in order to calculate the costs at the end of the tree. The development of the supply curve for one set of parameters is shown in Table C-2b the resulting supply curve appears in Figure C-3. For a given demand value, total cost is the area under the supply curve out to

Table C-2a: Marginal Cost of Increased Capacity

C Band Re-use:

Increased Capacity in Transponders	Marginal Cost per Transponder
first 216	$m_c\ Q_c$
next 216	$m_c^2\ Q_c$
next 216	$m_c^3\ Q_c$
next 216	$m_c^4\ Q_c$
⋮	⋮

Ka Band Introduction and Subsequent Re-use:

Increased Capacity in Transponders	Marginal Cost per Transponder
first 288 (introduction)	Q_a
next 288 (first re-use)	$m_a\ Q_a$
next 288	$m_a\ Q_a$
next 288	$m_a^2 Q_a$
next 288	$m_a^3 Q_a$
⋮	⋮

Table C-2b: Development of the Supply Curve for One Set of Cost Parameters

Parameters: $m_c = 1.2$, $Q_a = 1.5$, $m_a = 1.2$

C Band:

Increased Capacity in Transponders	Marginal Cost per Transponder
first 216	1.20
next 216	1.44
next 216	1.73
next 216	2.07
.	.
.	.
.	.

Ka Band:

Increased Capacity in Transponders	Marginal Cost per Transponder
first 288	1.50
next 288	1.80
next 288	2.16
next 288	2.59
.	.
.	.
.	.

Resulting Supply Curve:

Increased Capacity in Transponders	Cumulative Capacity Increase	Marginal Cost Per Transponder
first 216	216	1.20
next 217	432	1.44
next 288	720	1.50
next 216	936	1.73
next 288	1224	1.80
next 216	1440	2.07

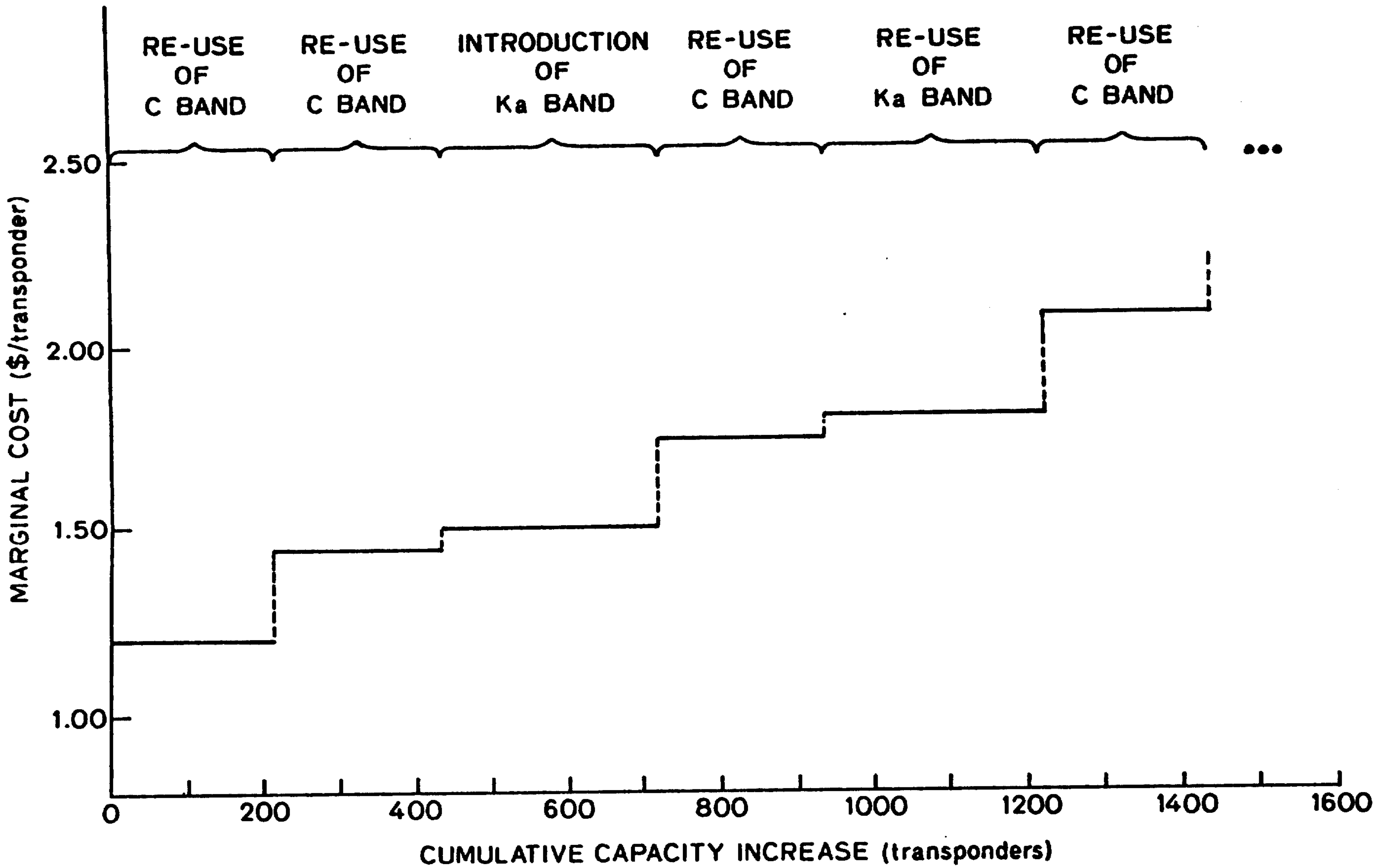


Fig. C-3: Supply Curve Developed in Table C-2b the demand value. Table C-1 shows how demand was met for each of the branches of the decision tree pertaining to Alternative 3.

Results

Because the data used here is illustrative, no definitive statements can be made from the results. However, it is interesting to analyze the tree in Figure C-2 both quantitatively and qualitatively.

The tree can be rolled back to yield an expected cost of meeting demand for each alternative. The results are:

Alternative 1, (C-band re-use): Expected cost = $1621

Alternative 2, (Ka band): Expected Cost = $1802

Alternative 3, (Combination): Expected Cost = $1171

If Research Programs 1, 2, and 3 were available that led respectively to Alternatives 1, 2, and 3 being available in 1990, then it appears that Program 3 leads to a savings of $450 compared to Program 1, and a savings of $631 compared to Program 2. If the costs of the research program were available, the net savings generated could be compared.

In Section II, comparing the full distribution on total demand to the distribution on total capacity led to the conclusion that there is a probability of .86 that demand will exceed capacity if neither re-use or Ka band are available. In the cruder analysis here, we see from

Table C-1 that in no case can demand be met by just the C and Ku bands without re-use. In the case of the lowest demand value, 415 transponders, demand is met either by using 19% of the Ka band or by re-using 25% of the C band. For the higher demand levels of 690 and 1100 transponders, the introduction of the Ka band without re-use is not sufficient to meet demand. It appears likely that re-use will be required by 1990. At the highest demand level, extensive re-use is necessary. We also note that the lowest cost "solutions" involve mixing re-use of the C and Ka bands.