NASA TM-83430

NASA Technical Memorandum 83430

A Comparison of Frequency Domain Multiple Access (FDMA) and Time Domain Multiple Access (TDMA) Approaches to Satellite Service for Low Data Rate Earth Stations

Grady Stevens
Lewis Research Center
Cleveland, Ohio

June 1983

NASA

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Grady Stevens

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-1721

SUMMARY

A technological and economic assessment is made of providing low data rate service to small earth stations by satellite at Ka-band. The results of contracted studies, sponsored by NASA, are compared and the results of NASA in-house assessments are presented. Several FDMA and TDMA scenarios are critically examined with the objective of establishing the utility of such systems to the end user. Recognizing that many services are now available terrestrially or in other satellite bands, the comparisons are always with respect to the competitive alternatives. The major factor establishing acceptable scenarios (from an economic viewpoint) is the projected cost of the earth stations. Based on current estimates of Ka-band earth station costs in an operational environment, small earth stations (1-2 meters in diameter) do not appear to be economically attractive options. Modest size (3-5 meters) earth stations appear to offer significant advantages over current terrestrial alternatives for data and video as well as (in certain cases) voice. The minimum attractive earth station should be sized to process an average of about 1.5 Mbs to achieve this competitiveness. Obviously, this implies large users. It is conceivable that an aggregation of small users could accomplish the same economies of scale. However, of the network options examined for doing so, none are competitive for voice. Digital Termination Service type aggregation appears to offer an economic means of aggregation for data. Of the space segment accessing methods examined, scanned beam TDMA appears to have the greatest advantage. The payload weight estimates are about one-third those of an equivalent capacity multibeam FDMA system. From a total system viewpoint, this advantage is reduced by the more significant cost of the ground segment which tends to mask space segment differences. However, it is clear that FDMA has no advantage over TDMA for providing low data rate service to small earth stations by satellite at Ka-band.

INTRODUCTION

Recent NASA-sponsored, Ka-band satellite studies explored the utility of this band for conventional and new types of services (refs. 1 to 4). Studies by the Ford Aerospace and Communications Corporation (ref. 1) and the Hughes Aircraft Company (ref. 2) examined the feasibility of using this band to serve two major classes of users.

One class consisted of very large traffic sources (100's of Mbs) as in the case of concentration nodes for major metropolitan areas. Cost and technology considerations indicated that the best choice for interconnecting such nodes was several large earth stations and a relatively small, multibeam spacecraft.

The other class of users consisted of relatively small traffic sources (as small as a single voice channel) and was generally characterized by the presence of the earth station on the user's premises. In this case, cost considerations indicated that the earth station should be small (less than 5 meters in diameter). As a result, the spacecraft tended to be quite large and demanded relatively large amounts of power.

In these studies the interconnection of large metropolitan areas was designated as a trunking application and the interconnection of the smaller users was designated as a direct-to-user service application.

The trunking application seemed a natural for Ka-band. High gain, multibeam spacecraft antennas contributed to rain fade compensation as well as achieving frequency re-use. The availability of 2.5 GHz of basic spectrum allocation coupled with this frequency re-use allowed satellite concepts with 25 Gbs capacity having weight and power requirements not significantly different than conventional satellites. Though the earth stations were large (10 m) and expensive, they were cost effective as long as the traffic volume was sufficiently high.

The utility of the direct-to-user applications was not so clear. Although multibeam spacecraft and frequency re-use were also used in these concepts, the spacecraft power requirements (high EIRP) needed to communicate with the small earth stations (low G/T) neutralized the advantages of the multibeam antennas. Also, the benefits of site diversity for rain fade compensation were not applicable in this case as such techniques would more than double the user earth station costs.

Ford and Hughes dedicated about half their study efforts to the direct-to-user application. Consequently, they were limited in the number of alternatives that could be examined. These studies included both FDMA and TDMA concepts and assumed the use of 5 meter (or larger) earth stations. Given sufficient traffic, these earth stations would be cost effective (to be shown later); however, neither study addressed the utility of servicing single channel users.

TRW (ref. 3) suggested a hybrid concept, including both trunking and direct-to-user service on the same spacecraft. The trunking nodes were serviced by fixed spot beams (as in the Ford and Hughes studies) but the direct-to-user service was via scanned spot beams. Using scanned beams one can offer the small users high EIRP without excessive spacecraft power demands (due to the high gain antenna). Also, one can offer the small users a high G/T spacecraft without an unduly complex antenna (six time-shared beams instead of 100's of equivalent fixed beams). Because of these advantages, TRW was able to consider earth stations as small as 2 meters. This was very encouraging, but there was a question as to whether a scanned beam antenna was in fact less complex than a fixed, multibeam antenna.

A concurrent study by GE (ref. 4) examined a satellite switched FDMA concept whereby the spacecraft concept was intentionally made large and the user earth stations very small (down to 1 m). The underlying hypothesis was that the service cost in a direct-to-user system would be dominated by the earth segment cost (due to the large number of stations involved) and the space segment would not significantly impact the user's cost regardless of its size. However, the economic advantage of such a system hinged on the availability of duplex earth stations having an installed cost under $20 K (ref. 4).

NASA initiated several technology developments as part of its current Advanced Communications Technology Satellite (ACTS) program to address the technical feasibility issues brought forward by these studies. However, for the small user application, there remained questions that would not be resolved by the technology efforts. For example, how does one realize a duplex terminal for $20 K? If this is not possible, how does one economically aggregate users into larger terminals that are more cost effective? Which of the accessing methods (FDMA, TDMA, etc.), has the potential for lowest service cost? Is the best accessing method sensitive to the type of traffic?

To address these questions, NASA initiated additional contracted and in-house studies to re-examine operational Ka-band satellite systems which would provide service directly to the user's premises. These studies were focused on the customer premises service application and included the examination of the use of various "tails" to aggregate users to larger earth stations. They were to build on the results of the previous studies and were to take advantage of market data that were developed by the International Telephone and Telegraph Corporation and the Western Union Telegraph Company under NASA sponsorship (refs. 5 to 8).

In addition, NASA recently initiated two contracted earth terminal design studies to examine, in greater detail, the relative complexity and cost of various terminal sizes and the potential for cost reductions. Detailed designs will be included as part of the study efforts.

This report summarizes the results of the contracted satellite system studies (refs. 9 to 12) as well as the results of applicable NASA in-house studies. From these, conclusions are drawn and recommendations made as to the future direction of NASA's efforts with respect to customer premises service applications. For the purposes of this report, instead of the term, "customer premises service," a more generic label, "Low Data Rate Service" or LDRS, is used since the earth terminal may not, in fact, reside on a particular customer's premises.

At the time of this writing, the NASA earth terminal design studies were just getting underway. Therefore, no discussion or results of these efforts is included in this report.

LOW DATA RATE SERVICE VIA SATELLITE

Definition of LDRS

In the earlier NASA-sponsored studies (refs. 1 to 4), the small user was assumed to have a need for, at most, several voice/data channels. He was deemed to have a need for direct access to the satellite, and it was assumed he could accomplish this with a small, inexpensive terminal on his own premises. For the new studies by TRW and GE (refs. 9 and 10), as well as NASA's in-house assessments, this was too narrow a definition. It was desired to include the possible aggregation of users by use of terrestrial "tails." Therefore, this definition was expanded to include any low rate terminal regardless of actual source of traffic. In other words, it could be a corporate facility with a dedicated earth station serving many parallel voice/data channels or it could be an industrial park with several small companies having access to the same terminal via "tails." It could even be a terminal located on some user's premises which was dedicated to videoconferencing.

Need for LDRS at Ka-Band

The need for direct access of satellites by small users was delineated in a set of NASA-sponsored market studies (refs. 5 to 8). These studies estimated demand for all services without regard to the particular satellite technology used.

Figure 1 shows results of one of these studies (Western Union) which compares their estimates of total demand for satellite service with their estimates of total C-band and Ku-band capacity. Also shown is the Western Union estimate of likely C/Ku-band capture. It is significant to note that (according to these estimates) C/Ku-band technology would fail to satisfy demand shortly beyond 1990 (even if the most optimistic projections for capacity were used). Consequently, by the year 2000, there could be an unsatisfied demand for 1,500 equivalent 36 MHz transponders.

TRW, with the assistance of their subcontractor, Future Systems Incorporated (FSI), made an assessment (ref. 9) of these market data as part of their contribution to the latest NASA-sponsored studies. GE, with the help of their subcontractor, Digital Communications Corporation (DCC), performed a similar assessment (ref. 10). The judgment of TRW/FSI was that a Ka-band system for LDRS (given the reduced availability and restricted access to terrestrial nets) could account for about 1.7 Gbs of traffic in 1990, growing to 5.0 Gbs by 2000. The bulk of this traffic, in their judgment, would be videoconferencing traffic. They also felt this would be demonstrated by dedicated private networks. Once these are established, they felt it would then be possible for other users to obtain access through "tails" at a small marginal cost. Also, by that time, it should be possible to share nearby terminals and increase availability through site diversity. Given these developments, they felt Ka-band would account for 5 Gbs of traffic by 1990 and 15 Gbs by 2000. In the judgment of GE/DCC, the Ka-band share could be even larger, up to 33 Gbs by the year 2000, depending on availability achieved. This latter estimate is consistent with the Western Union estimate of previous figure 1.

Table 1 lists various alternatives available today for LDRS. The first entry shows the major cost items for a subscriber to Satellite Business System's (SBS) services as of October 1982. The designations, NAC, FTU, etc., are described in the Appendix. Accessing the SBS satellite network could cost a minimum of $60 K/month plus installation. At 40 voice channels, this becomes comparable to the other alternatives. However, for less than about 20 voice channels, it would appear the SBS option would not compare favorably. Of course, SBS offers interconnection with several locations while the others do not (except for "800" service).

One can see from these service alternatives that LDRS via satellite can be quite expensive. However, it will be shown later in this report that if the satellite and ground terminal technologies are properly selected and are optimally designed and utilized for LDRS, then satellites do offer a competitive alternative to terrestrial systems. For LDRS via satellite, the technologies currently being developed as part of NASA's ACTS program may offer cost advantages over conventional technology. While these technologies are being developed at Ka-band, they will also be applicable, with some adaptation, to Ku-band and perhaps C-band.

ALTERNATIVE SATELLITE APPROACHES TO LDRS APPLICATIONS

Data Sources

In addition to the TRW/FSI and the GE/DCC efforts, there are other NASA-sponsored studies which provide useful information to this comparative analysis. Motorola has made detailed estimates of the weight and power requirements for a TDMA baseband processor (ref. 11) as well as a processor and satellite concept for SS-FDMA (ref. 12).

Ideally, all these studies would respond to the same general requirements which would simplify later comparisons. However, there is a limit to the restrictions one can place on such studies without stifling innovation. Thus, some latitude was granted to both TRW/FSI and GE/DCC. Motorola, on the other hand, was given very specific requirements since their efforts were aimed at eventual development of hardware. Although there were differences in approach, comparisons can be made and valid conclusions drawn regarding LDRS applications.

Figure 2 illustrates the various types of terminals considered in the studies. With TDMA, the user channels are mutiplexed onto a common digital stream and sent to the satellite in bursts with the spectrum being shared by several terminals. In the FDMA approach, the user channels are combined in a Single Channel Per Carrier (SCPC) format and sent to the satellite in parallel fashion using whatever spectrum is available. A hybrid approach is to use FDMA/SCPC on the uplink and TDMA on the downlink. It seemed this would combine the best of both worlds with no timing requirements on the uplink and saturation of the spacecraft transponders on the downlink.

To provide access to these terminals, various beam coverage plans were considered. Single beam CONUS (Contiguous United States) coverage was ruled out in the beginning for reasons that can be seen by examining the comparison shown in Table 2. A comparison is made of a conventional single-beam CONUS Ku-band system (SBS) with several Ka-band configurations with alternate coverage plans. In each case the earth station is assumed to be 5.0 meters and the data rate is a full Ku-band transponder (48 Mbs). With CONUS coverage, both spacecraft would, of course, have the same gain (approx. 32 dB) so that Ka-band would offer no advantage as indicated in the "gain excess" column. The Ka-band earth station would have a higher gain but this would be neutralized by the greater rain fade at Ka-band. Consequently, the Ka-band spacecraft and earth station HPA's (High Power Amplifiers) require much greater power for the same data throughput as indicated in the last two columns of Table 2. If the Ka-band spacecraft antenna is increased in size to yield 1.5 degree beams (half-power beamwidth), the spacecraft antenna would contribute about 8 dB of extra gain to the links. However, one needs to allow for beam edge losses so that the net excess gain would be about 5 dB. Consequently, the spacecraft and earth station HPA's would still be significantly larger than the equivalent CONUS Ku-band system. At about 0.3 degree beamwidth, sufficient excess gain would be available in the links to more than compensate for the rain fades at Ka-band (14 dB uplink and 6-7 dB downlink for 99.5 percent overall availability). Consequently, the Ka-band spacecraft and earth station HPA's would be equivalent to those used at Ku-band. Of course the spacecraft would be more complex, but it would also have much greater capacity (due to the frequency re-use provided by the smaller beams).

Figure 3 shows a typical contiguous, fixed, multibeam coverage plan using 1.2 degree beams. This approach was considered for configurations having as few as 13 and as many as 178 beams. Both FDMA and TDMA accessing were included in all cases.

Figure 4 illustrates a fixed beam plan where only partial coverage is realized with the major metropolitan areas being of primary interest. This configuration covered up to 277 cities (some beams overlapped several cities) yet required much fewer antenna ports than a contiguous beam plan. The purpose was to minimize antenna complexity and other satellite hardware.

Figure 5 illustrates a hybrid approach to CONUS coverage. A feed array is selected to provide CONUS coverage. A fraction of these feeds are combined to act as spot beams located on major metropolitan areas. These would provide the trunking service. The remaining spots would be scanned in a TDMA mode to provide the remaining coverage. Such techniques were originally intended to reduce the antenna complexity. However, it appears such antennas can be quite complex and heavy, even at Ka-band (up to 225 kg).

Accessing such complex spacecraft requires a unique communication system architecture. A general configuration which allows for interconnection of several beams having various types of traffic is illustrated in figure 6. Traffic is intercepted according to type with the appropriate beams. The wideband traffic would be processed with separate trunking beams and an IF switch. Both wideband and LDRS terminals could be in these beams. A separate set of beams (fixed or scanned) would be dedicated to the LDRS traffic in other areas. A LDRS router would be dedicated to this traffic.

Particular configurations result when the type of processors and accessing methods are specified. Certain configurations might not have a wideband processor at all resulting in a dedicated LDRS system. Some configurations could "skim off" the bulk of the traffic through the wideband router leaving a relatively small LDRS router. The selection depends on the specific traffic models one might be using.

Satellite Switched FDMA Configurations

In the recent NASA-sponsored studies, SS-FDMA satellite configurations were developed by TRW, GE and Motorola (refs. 9, 10, and 12, respectively). Different traffic models were assumed by each of the contractors and this led to significantly different approaches.

Figure 7 illustrates how the generic satellite communications configuration of figure 6 would be peculiarized for SS-FDMA. Motorola used this configuration in their study, which included an IF (Intermediate Frequency) switch to process the trunking traffic in a TDMA mode. Only the LDRS traffic was FDMA. GE also had a separate subsystem for the trunking traffic, but they assumed hardwired, wideband FDM channels. Only TRW assumed a fully SS-FDMA processor. Therefore, the size and weight of the LDRS router in each case depended on the traffic remaining (after subtracting trunk traffic) for LDRS service.

Figure 8 illustrates one configuration used by Motorola in their studies. In response to the traffic model specified by NASA, they assigned 18 fixed beams to intercept wideband and LDRS traffic; 22 beams were dedicated to LDRS traffic in other areas. The LDRS processor interconnected a total of 40 nodes. A total of 10 Gbs was processed by this system with the LDRS processor managing about 3 Gbs of this total.

Full interconnectivity between users can be accomplished without dedicating filters to every user channel. Blocks of spectrum can be assigned between specific beams which users share on a SCPC basis. This approach leads to the use of fewer and relatively wideband filters.

Further simplifications can be made if the beams are grouped into zones and spectrum assignments made on the basis of interconnecting the zones. Figure 9 illustrates such an approach used by Motorola to realize a multibeam SS-FDMA system. The beams were grouped to equalize the traffic in 5 zones which resulted in 8 beams per zone (not necessarily adjacent beams). Traffic from beam 1/zone 1 would be distributed to a set of 5 filter banks. An 8x8 row switch would then direct this traffic to any column of the filter bank. These filters would have various bandwidths which enabled the isolation of the various traffic according to beam destination in zone 1. Similarly, the traffic can be directed to beams in the other four zones.

The GE approach to SS-FDMA is illustrated in figure 10. Like Motorola, they segmented the spectrum into blocks and assigned LDRS users to specific blocks depending on destination. The available blocks were 1, 6, and 40 MHz. Unlike Motorola, GE performed the signal routing at a common IF. The switch would then route a maximum bandwidth of 40 MHz at a center frequency of 70 MHz. Not shown is a significant subsystem for preassigned interconnections between beams. In the GE case, the subsystem processed the bulk of the traffic in a trunking mode.

TRW also segmented the traffic. Their segmentation was according to traffic type (video, voice, data) as well as to destination. Only 20 beams were considered in their analysis. Their transponder configuration is illustrated in figure 11. They were unique in that their system configurations were dedicated to LDRS type applications. Spectrum assignments were accomplished as illustrated in figure 12. In each beam, users were grouped according to type. Within a group, say 1.5 Mbs carriers, users were placed according to destination. Only the destination subgroups were routed--not individual users (also true of the GE and Motorola cases). Consequently, any intelligence aboard the spacecraft concerns itself with only groups of channels rather than individual channels. As in the GE and Motorola cases, this considerably reduces the requirements for hardware and intelligence aboard the spacecraft. The resulting processor is illustrated in figure 13. Twenty spectrum blocks are shown for each user type and each beam for a total of 1600 blocks. This was for a 3 Gbs system. Other configurations were considered with greater traffic capability and proportionately greater numbers of filters and switch nodes (the number of beams was fixed at 20).

Satellite Switched TDMA Configurations

As with the SS-FDMA case, TRW, GE and Motorola (refs. 9, 10 and 11, respectively) contributed to the definition of Ka-band SS-TDMA concepts. GE provided concepts for both fixed beam and scanned beam scenarios. TRW focused on the scanned beam scenario and provided concepts which respond to several traffic models. As part of their technology effort, Motorola provided an assessment of likely power and weight requirements for an operational baseband processor as would be used in a scanned beam SS-TDMA system. In this case, Motorola was not required to develop a total satellite concept.

Again, the contractors were given latitude for innovation which also led to significant differences in approach. As with their SS-FDMA approaches, TRW processed the entire traffic load with a dedicated LDRS system. GE and Motorola, on the other hand, used an IF switched trunking subsystem which "skimmed off" a major portion of the traffic. For the same volume of traffic, this led to smaller LDRS subsystems in the GE and Motorola cases than were hypothesized for the TRW cases.

Various beam coverage plans were considered here also. Figure 14 illustrates a fixed beam coverage plan and how interconnection is provided by an IF switch. As was mentioned before, only GE provided details on this type of concept (Motorola and TRW focused on the scanned beam approach).

In providing access to small earth stations, it is desirable to minimize the burst rate of the earth station. This enables a reduction in earth station EIRP, a factor in controlling earth station costs. Consequently, it is beneficial to have several blocks of spectrum, each of which is shared in a TDMA fashion, and which are tailored to the actual needs of the user classes. This is true regardless of whether the beams are fixed or scanned. Figure 15 illustrates this channelized TDMA approach for a fixed beam case. With fixed beams, the IF switch can become unwieldy when one makes use of contiguous beams in the 0.3 degree beamwidth class. Simplifications can be realized by using fewer, scanned beams. Figure 16 illustrates an approach using six scanned beams. The corresponding baseband processor is illustrated in figure 17. In this case, the traffic is channelized into TDMA streams at 3 classes of burst rates. The baseband processor illustrates the unique capability of changing to a new burst rate for the downlink transmissions. This enables the operation of the spacecraft HPA's at saturation.

COMPARISON OF SPACE SEGMENT RESULTS

Comparison of Assumptions

It is helpful to delineate some of the assumptions used in the various studies before comparing results. This will enable inferences to be made which would otherwise be difficult or totally obscured.

As indicated previously, channelization was used in both the FDMA and TDMA scenarios. It was also noted that, in the FDMA case, channelization was to the subgroup level only--not to the level of individual users. Channelization, in this case, refers to that level of signal separation where signals are dropped and added by filter isolation and combining. All contractors were given latitude in selecting a spectrum quantization approach. Obviously, the greater the bandwidth of the filters, the fewer filters one would have assigned to each beam and the fewer the number of interconnections one needs to contend with. Conversely, if narrowband filters are used and each LDRS user is isolated, the number of filters and switch interconnections would become unmanageable.

Generally, none of the contractors isolated LDRS users at the user level. However, there were significant differences in the relative proportions of narrowband and wideband channels in the various approaches. Figure 18 illustrates the number of switched paths used in the various SS-FDMA scenarios. Motorola provided concepts for two traffic models, each having a 3 Gbs LDRS subsystem throughput. With their approach, 1600 switch paths were required for their traffic model "A" (40 LDRS nodes) and 2304 switch paths were required for their traffic model "B" (48 LDRS nodes). Keep in mind that a switched path can carry many SCPC channels. TRW also had 1600 switch paths for their 3 Gbs traffic assumption. For their 5 Gbs assumption, about 2700 switch paths were required. Note that in the Motorola case, the increase in switch paths from traffic model "A" to traffic model "B" was due to the increase in the number of beams. In the TRW case, the increase in switch paths was due to the increase in traffic. If TRW had chosen to absorb the extra traffic by simply using wider bandwidth filters, there would have been no need to increase the number of switch paths at all.

GE generally assumed wider bandwidth filters (in a switched path) than either Motorola or TRW. Consequently, far fewer switch paths were used in their subsystems which also led to lighter weight processors.

The channelization strategy of GE is illustrated in figure 19. Up to about 3 Gbs LDRS subsystem throughput, the number of switched paths (and filters) in all classes increased proportional to traffic. However, at about 3 Gbs, the number of narrowband filters was fixed by GE. The remaining traffic increase was absorbed in a proportionate increase in the number of 40 MHz filters. Obviously, far fewer filters would be required in such an approach than one would need if the number of filters of all classes were increased. As a consequence, the GE cases tended to be less complex than either the Motorola or TRW cases.

Normalized channelization weight and power estimates are shown in figure 20. These estimates were made by taking the total SS-FDMA processor (channelization and switching) weight and power estimated by each contractor and normalizing with respect to the number of switch paths used.

The first bar set represents estimates obtained from a 136 Mbs subsystem proposed by TRW in the 30/20 GHz Demonstration System Design Study (ref. 13). Their estimates of weight and power for the 3 and 5 Gbs processors (second bar set) are only slightly less, due to modest assumptions for technology improvements (ref. 9). The third and fourth bar sets represent the GE estimates (ref. 10). GE assumed a higher level of LSI integration than TRW, which led them to forecast significant reductions in weight; but the power requirements per channel were comparable to TRW's estimates. Motorola (ref. 12) also assumed a high level of LSI integration and, in agreement with the GE assumptions, also achieved lower specific weight. Furthermore, Motorola assumed the use of CMOS technology which led to power requirements lower than either TRW or GE.

Comparison of LDRS Processors

The weight estimates of various LDRS processors are compared in figure 21. With SS-FDMA, TRW's processor is far heavier than that of either Motorola's or GE's. TRW's and Motorola's FDMA processors were nearly equivalent in terms of complexity (1600-2304 switched paths for Motorola compared with 1600-2700 switched paths for TRW) so that the differences shown are mostly due to the previously mentioned assumptions regarding channelization weight. GE's estimates are lowest by far, but this is due to the use of a relatively simple processor (with the bulk of the traffic controlled with wideband filters).

Also shown are TRW's estimates for a TDMA baseband processor for a 3 and 5 Gbs system. These are lighter than Motorola's estimate for a 6.5 Gbs baseband processor, but seem consistent if the weight increases with traffic.

Lastly, it should be noted that TRW's SS-FDMA subsystem (as well as Motorola's or GE's) could be reconfigured to handle the larger traffic cases without weight penalty by simply using wider bandwidth filters.

The power estimates of various LDRS processors are compared in figure 22. With SS-FDMA, Motorola's power estimates are considerably less than either TRW's or GE's. This is primarily due to Motorola's assumption regarding channelization power requirements mentioned earlier.

With SS-TDMA, the TRW and Motorola estimates are comparable even though the Motorola processor handles a greater traffic load. This may not be inconsistent since TRW shows only a gradual increase in power requirement with increase in traffic throughput. Furthermore, the TRW SS-FDMA processor could have been reconfigured for the 5 Gbs case without power penalty by using wider bandwidth filters.

Comparison of Payload Requirements

Though the weight and power estimates of the processors are useful points of comparison, a more critical point of comparison for different access schemes is the impact on total communications payload weight and power. Such a comparison is illustrated in figures 23 and 24.

For the Motorola SS-FDMA cases, some adjustments were made to the Motorola results to enable comparisons for this report. The Motorola study (ref. 12) was for a 10 Gbs SS-FDMA system which included a major trunking subsystem (see data points at 10 Gbs throughput in figs. 23 and 24). The trunking subsystem was removed to obtain an estimate for a dedicated LDRS subsystem with capacity reduced to 3 Gbs (see "LDRS only" in figs. 23 and 24).

The increase in weight for the two Motorola traffic cases is primarily due to the increase in number of beams and the associated hardware.

For SS-FDMA, the total payload (transponder plus processor) weight estimates of TRW are comparable to those of Motorola. The increase in weight with throughput for the TRW cases is due to the increase in traffic as the number of beams was fixed at 20.

The GE SS-FDMA case is shown with the trunking subsystem included as insufficient details were available to isolate the LDRS subsystem.

TRW made use of a significantly lighter RF transponder (excludes FDMA processor) than Motorola. Motorola, on the other hand, assumed a much lighter FDMA processor. As a result, the total payload weights were comparable, as already mentioned. As an optimistic estimate of SS-FDMA weight, it is useful to combine the TRW RF transponder estimates with the lighter Motorola processor estimates (both TRW's and Motorola's processors had approximately a 3 Gbs throughput). This combination is shown at about 1,100 pounds. Even this compares poorly with the estimates for the TRW scanned beam payload, the latter being about one-third the weight of the optimistic SS-FDMA estimate.

A pessimistic weight estimate for SS-TDMA can be obtained in much the same way. Motorola's SS-TDMA processor was heavier than that assumed by TRW. Combining the TRW SS-TDMA transponder with the Motorola BBP, a slightly heavier payload is obtained as shown at 5 Gbs. Comparing the optimistic SS-FDMA estimates with the pessimistic TDMA estimates, one would conclude SS-TDMA has a significant payload advantage over SS-FDMA (this assumes the pessimistic SS-TDMA estimate would exhibit the same weight trend shown in the TRW case).

The payload power requirements are compared in figure 24. Again, adjustments were made to the Motorola data to enable comparisons. Generally, these data show a significant power advantage for SS-TDMA over SS-FDMA. In the case where the Motorola SS-FDMA processor power requirement is combined with the TRW SS-FDMA transponder power requirement, the advantage of TDMA is reduced. Still, a SS-TDMA payload would require only two-thirds the power needed for a SS-FDMA payload.

Inferences Drawn from Data Comparison

From the data shown in figures 21 and 22, especially the GE results, the SS-FDMA processor weight and power requirements can be significantly reduced by concentrating as much traffic as possible in wideband paths.

For a given volume of traffic, SS-TDMA with scanned beams has significant spacecraft weight and power advantages over SS-FDMA.

IMPACT OF GROUND SEGMENT

LDRS Earth Station Costs

For LDRS via satellite, the number of earth stations tends to be large (100's to 1000's). As a result, the service charge to users will be determined primarily by the costs of the earth stations. Consequently, the economic viability of LDRS via satellite is primarily dependent upon the availability of low cost earth stations.

Table 3 lists typical estimates of costs for various FDMA and TDMA earth stations. The FDMA cases are tabulated for both widebeam (about 1.2 degrees) and narrowbeam (0.3 degree) satellite coverage plans. The bit rates shown are average terminal throughput.

The TDMA cases are for a scanned beam system with burst rates of 8 Mbs for the "mini" terminal, 32 Mbs for the "low" and "medium" terminals, and 128 Mbs for the "high" terminals.

Note that the "low" TDMA terminal is about twice as expensive as the "mini" terminal. However, the "low" terminal has about 22 times the capacity of the "mini" terminal. Note also the very small difference in cost between the "medium" and "low" TDMA terminals. Yet the capacity of the "medium" terminal is abut 4 times that of the "low" terminal. A similar trend can be seen in the FDMA terminals. Consequently, the larger terminals should be more cost effective on a per-channel basis as long as one has the traffic to utilize the capacity.

As mentioned earlier, recent studies of LDRS have included the impact of adding terrestrial "tail" networks to aggregate traffic into the larger earth stations. Presumably, this would make the larger earth stations even more effective with respect to cost/channel to the end user.

Both TRW/FSI and GE/DCC delineated several such options and estimated their cost. Table 4 lists cost estimates of FSI for various network options which include the central node costs as well as the tail cost (fiber, coax, etc.). The digital microwave radio mentioned here is only a point-to-point radio and should not be confused with the new point-to-multipoint Digital Termination Service (DTS) now being installed in various cities.

Table 5 lists cost estimates of DCC for various options which parallel those of FSI. One significant difference is the RAPAC system which is a DTS type system. In this case, the DTS system would be the aggregation point for the local traffic which would then be trunked to the satellite earth station.

A terrestrial network would consist of any modem and radio equipment needed by the end user, the local "tail" medium (fiber, radio, coax, etc.), the central node modem and radio equipment, the central node multiplex equipment, and the trunk between the central node and the earth station.

It is revealing to examine the cost impact of the earth station and the "tail" network separately. First, the prorated charge to the user for the earth station alone will be examined. This is illustrated in figure 25. The earth station costs have been prorated among all users according to usage. The annual charge per duplex channel is shown as a function of terminal peak capacity. These estimates assume 0.25 Erlang users and a 0.4 annualization factor applied to the earth station investment (about 20 percent rate of return). Comparisons are shown for the various cases examined in the aforementioned studies.

Note that FDMA terminals are more cost effective for a peak capacity less than about 18 voice channels (roughly, a 1.5 Mbs class terminal). For higher peak capacity, the TDMA terminals are more cost effective. Note also from Figure 25 that at the crossover point, the annual charge is about $2000 user-circuit annually or about $167/month (previously we had noted in Table 1 that current charges are about $680-$1100/month). Of course, this is only the charge for a single terminal. It does not include the charge for the second terminal required for a complete service link nor does it include satellite charges. Even so, doubling this charge (to account for the second terminal) leaves a significant margin (with respect to current alternatives) to cover the space segment charges. This margin increases as the terminal size increases.

So far, 0.25 Erlang users have been assumed. If dedicated circuits are assumed, the above charges would be multiplied by about 4 so that a dedicated charge for two terminals would be about $1340/month. This is more than current dedicated charges, so that one would infer LDRS terminals should be no smaller than about 18-22 channels for cost competitive LDRS via satellite.

This inference is completely dependent on assumptions regarding installed terminal costs. An earlier study by GE (ref. 4) indicated that "mini" terminals (one to perhaps several voice channels) would have to have installed capital costs of about $20 K to be cost competitive for LDRS. This is consistent with the trends shown here and would require dropping the "mini" terminal costs by a factor of 5 from those currently estimated (Table 3). Obviously, significant breakthroughs in technology, coupled with a significant increase in production will be needed to achieve this kind of cost reduction. At the present time, based on available information and technology/cost projections, it must be concluded that "mini" terminals are economically unattractive for LDRS.

For LDRS via satellite, it is unfair to make comparisons solely on the basis of monthly charges. Most current alternatives (by satellite) offer dedicated circuits between two specific points. Access to other locations involve additional charges. However, with the LDRS scenarios presented thus far, no such limitation on access is implied. In fact, any user can access many locations with no additional charge as long as the desired recipient is on the system. Therefore it is useful and revealing to use an alternate method of comparison.

Returning to the aforementioned 0.25 Erlang user, one can calculate the number of call-hours per month he will utilize. Assuming each earth station provides 1:200 blocking, one can determine how many users can be accommodated. Dividing the earth station annual charge by the number of users, and again by the number of hours per user, the cost per call-hour is obtained. This can then be compared with an equivalent terrestrial service, like the type "800" service of AT&T. Such a comparison is made in figure 26.

At this point, the costs of the terrestrial "tails" are accounted for in the user charge, making use of the data in Tables 4 and 5. Generally, the user charge for "tails" depends on the average distance to the end user and is therefore shown in figure 26 as a function of this distance. Two classes of "tails" are shown for comparison. The fiber optics charge increases proportional to distance for the range shown (no repeaters are necessary). The DTS type "tails" are distance insensitive for the range shown. Though the DTS type "tails" were not intended for voice, the charges shown were estimated for this service. Alternatively, they can be regarded as 56 Kbs data lines, which is within the capability of DTS (on a limited basis).

The charges shown in figure 26 were derived by making use of the earth station costs of Table 3 and the "tail" costs of Table 4, except for DTS. The cost estimates for the RAPAC system in Table 5 were used for the DTS costs. A 0.4 annualization factor was assumed for all capital investments. Annualized costs were prorated among all users assuming a forty-hour work week and a 0.25 activity factor per user (in placing calls) to determine a user charge per call-hour. In this analysis a "user" is regarded as some corporate entity within which a demand for outgoing long distance calls meets the aforementioned activity factor.

In each case shown in figure 26, the intercept of the curves with the user charge axis corresponds to the user charge for the earth station and any charges for node equipment (such as radio equipment and modems). Consequently, the intercept for the DTS "tails" is greater than for fiber "tails" due to the greater cost of the node equipment. However, DTS systems have an advantage over fiber "tails" beyond about 2 km since DTS charges are distance insensitive for the range covered in figure 26.

Note that fibers should be no longer than about 2 km, if one desires cost equivalency with "800" service. Also, the DTS type "tails" are only marginal alternatives to "800" service for voice. However, the DTS lines have 56 Kbs capability whereas the "800" lines do not. On this basis, the DTS "tails" are quite attractive.

Dedicated (Private) Satellite Networks

In the earlier discussion it was mentioned that trunking services at Ka-band are cost competitive whereas LDRS will be competitive only if significant reductions in earth terminal costs occur. In fact, it appears that on the basis of projected costs estimated to date, only earth stations in the 1.5 Mb class will be cost competitive. The question then arises, "Who would use such large terminals and were would the volume come from that would decrease the cost of the smaller stations?"

According to the TRW/FSI scenario, what is needed is a group of users who have relatively large node point traffic for which the larger terminals would be applicable. As this user group becomes pervasive, other users could perhaps be aggregated with them at small marginal charge. A test of the reasonableness of this scenario is to examine the largest communication users and compare their needs with the capability of a Ka-band LDRS satellite system. If applicable, this group could then serve as the kernal about which the LDRS system could develop.

To develop such a scenario, the largest corporations in the U.S. were examined. For simplicity, the analysis was restricted to intra-company communications. Also, each corporate subsidiary was assumed to have a dedicated terminal matched to its needs within the classes of terminals available. Finally, the utility of such a system was based on the benefit to the corporation as a whole rather than on a company or subsidiary basis. That is, a subsidiary was allowed to bear a cost penalty to access the system if there was a net benefit to the corporation as a whole.

In an unreleased study for NASA by the Ford Aerospace and Communications Corporation (FACC), a typical large industrial corporation would have a traffic demand as shown in Table 6. In this network, 20 nodes are shown which represent the 20 largest traffic subsidiaries. Note that the largest node has a demand for nearly 1/2 C-band transponder. The total nationwide demand for this private network would easily fill a C-band transponder.

Examining each node, an appropriate terminal can be selected to meet the stated demand. The resulting terminal distribution is shown in Table 7. Note that, according to the findings discussed earlier, all of these terminals should be cost effective. Assuming a total throughput of 5 Gbs, a $500 M space segment with the costs prorated according to traffic demand, and a 0.4 annualization factor for all hardware, the service charges were determined and are shown in Table 8. The monthly charge per voice circuit ($368) is considerably less than current alternatives for private network service and the charge per call-hour is nearly a tenth of "800" service. This is a direct result of the preponderence of relatively large earth stations in the network.

In the earlier market studies it was noted that communications demand could be correlated with corporate sales. If it is assumed that most large industrial corporations have approximately the same number of traffic nodes and that the traffic distribution is similar to the FACC "typical" large corporation, then the previous traffic data can be scaled among the top industrial corporations and used to evaluate the utility of LDRS systems on a case by case basis.

Table 9 shows a traffic comparison of the FACC "typical" large corporation with the average of the "top 100" and the "second 100" industrial corporations. Again, examining the average of the "top 100" and the "second 100" on a node by node basis, one arrives at the terminal distributions shown in Table 10. Note that the average of the "top 100" corporations would have only 1 "mini" terminal whereas the average of the "second 100" corporations would have 7. Computing service costs as before yields the results shown in Table 11.

The monthly circuit charge for the average of the "top 100" corporations would be about $900 and the charge per call-hour would be nearly $6. This total network would consist of 2000 earth stations with a terrestrial investment of about $500 M and annual space segment charges of about $65 M for a capacity equivalent to 25 C-band transponders.

The monthly circuit charge for the average of the "second 100" corporations would be about $2.5 K and the charge per call-hour would be about $16. On the basis of monthly charge comparisons, this does not appear attractive. However, keep in mind that a user has access to a number of locations (20). The utility of this multipoint capability is better illustrated by the charge per call-hour. Though this may appear only marginally attractive, keep in mind the circuit has 56 Kbs capability.

One could infer from this that the "top 100" corporations would be definite candidates for dedicated private networks. The "second 100" corporations would be marginal candidates. Perhaps between the two classes there would be a market for 3000 earth stations and 26 equivalent C-band transponders.

Some of this market would obviously be captured by C-band and Ku-band satellite systems. However, only large industrial corporations have been considered. The demand from others such as large retailers, institutions, etc., could add to this market.

Shared LDRS Networks

The dedicated networks developed in the previous section assumed that the excess capacity of the satellite was sold to other users. The net traffic in the dedicated networks would be 26x40 Mbs or about 1 Gbs. For the assumed 5 Gbs system, the remaining 4 Gbs would have to be absorbed by other users.

Additional dedicated LDRS systems would likely appear among the other user groups like retailers, etc. However, these are expected to contribute only a small addition to the 1 Gbs or so of dedicated traffic already mentioned.

Aside from a breakthrough in small terminal costs, it is more likely that these small user groups would be aggregated into larger terminals through some form of terrestrial "tail." As noted previously, this is, at best, a marginal approach for voice. However, for data networks, this can be very attractive. Also, for videoconferencing, fiber or coaxial "tails" might be an effective way of sharing the larger terminals among several users.

In the TRW/FSI study, a shared network concept was developed in detail. The baseline system was a 5 Gbs, scanned beam, TDMA system which served a combination of dedicated networks (1.7 Gbs) and shared networks (3.3 Gbs). This traffic was assumed to increase, as shown in figure 27, to about a 15 Gbs total by the year 2000. The alternate traffic scenarios were included to examine sensitivity to traffic volume and to traffic distribution.

For the baseline case, TRW/FSI assumed the bulk of the traffic (84 percent) would be videoconferencing. The Alternate 1 scenario was selected to be a predominantly voice/data traffic (67 percent) scenario. Alternate 2 had the same traffic distribution as the baseline and was simply a scaled version of the baseline.

The approximate costs of the baseline system are shown in Table 12. Note that a substantial investment in ground networking is required. Not shown is an additional annual charge of approximately $500 M for leased telephone lines which enable small users to share large earth stations.

Typical expected cash flows are shown in figure 28 for two values of rate of return. These include the aforementioned leased line charges which grow annually with the voice/data traffic. The revenue required to support these cash flows is about $16 K/Mbs-month. This assumes all users contribute on a pro-rata basis to the amortization of all costs and payment of leased line charges. Obviously this would burden the dedicated and videoconferencing users somewhat. However, this makes the system more attractive to the smaller users, many of whom are customers of the larger users.

Figure 29 shows a comparison of the charges for a call-hour for video users on such a shared network. The costs are shown as a function of rate of return. The video costs for the 3 Gbs case are significantly higher than for the 5 Gbs case. This is primarily due to the greater proportion of voice traffic in the 3 Gbs case and the attendent leased line charges (all contribute a pro-rata share).

These are compared with recently announced AT&T videoconferencing charges. The baseline (5 Gbs) scenario compares favorably with the public room rate between Washington and New York. Also, both the baseline and the alternate case have access to many locations nationwide. Of course, the comparison would be more favorable to video users if the leased line charges were totally paid by the small users. There is a greater number of leased lines in the Alternate 1 scenario than for the baseline case. Hence, one would expect the Alternate 1 charges to be higher.

Figure 30 shows a comparison of voice/data charges per call-hour with the alternative "800" service. Both the baseline 5 Gbs case and the alternate case compare favorably with "800" service. The 3 Gbs case is marginally favorable above 20-25 percent rate of return. Previously it was mentioned that the satellite circuits have 56 Kbs capability. However, in this case with leased lines, the small users would be limited to much less data rate. Small users with DTS "tails" could, of course, enjoy the 56 Kbs feature, but no such systems were included in the analysis.

Consequently, a shared system offers favorable rates to both dedicated and shared network users. A variety of services (multipoint voice, data, video, etc.), could easily be incorporated into the same system, offering versatility as well as favorable costs.

Inferences Drawn from Ground Segment Impact

Aside from a breakthrough in small terminal costs, the most favorable mode of operation is with relatively large, dedicated earth stations ($\sim$1.5 Mbs). The most likely customers of such networks would be the "top 100" industrial corporations with perhaps a portion of the "second 100" corporations. Marginally favorable costs can be realized for small users with leased Telco (telephone company) "tails" to larger, shared terminals provided the cost of these "tails" is shared by all users. Alternatively, DTS "tails" could be used, with the small users paying the total "tail" charge, and very favorable rates can be offered for data service of 56 Kbs. Rates for voice are only marginally attractive (even if technically feasible on a large scale).

CONCLUSIONS AND RECOMMENDATIONS

A number of NASA-sponsored studies (refs. 1 to 12) have examined many satellite system and traffic scenarios for providing service to low data rate terminals. Considerable details for alternative system scenarios are available in these studies. In all cases, the earth station and ground networking costs were the primary contributors to user service charges. The method of accessing or type of satellite coverage had an effect on the final user charges primarily to the extent that they affected the earth station cost.

Recent studies by TRW and GE (refs. 9 and 10) have projected costs for "mini" earth stations (one to perhaps several voice channels) that would preclude their being cost competitive for low data rate service (LDRS). It appears that earth stations with 1.5 Mbs of throughput or larger will be required to be cost competitive for LDRS at Ka-band unless significant cost reductions (factor of 5) can be achieved for "mini" terminals. This is judged to be highly unlikely. It is recommended, therefore, that earth terminal technology development at Ka-band be focused on earth stations in the 1.5 Mbs class or larger.

There appears to be no advantage of SS-FDMA over SS-TDMA from a total system viewpoint. For 1.5 Mbs earth stations or larger, TDMA has a slight cost advantage over FDMA for LDRS. Furthermore, TDMA offers a significant advantage in the space segment, requiring about one-third the payload weight and about two-thirds the power of an equivalent capacity FDMA system. It is recommended, therefore, that satellite communications technology development at Ka-band be focused on SS-TDMA architectures.

APPENDIX - DEFINITION OF TERMS

APD - Avalanche photo diode

Availability - The fraction of time a circuit is available. In general, this would include effects due to hardware failure, circuit blockage, rain outage, etc. With Ka-band systems, the rain outage is a major factor and is usually of most concern. In this text then, availability primarily refers to reliability against rain outage and includes the total circuit, i.e. uplink as well as downlink.

BER - Bit error rate; fraction of bits in error.

DCAU - Digital Channel Access Unit; a component used in the Satellite Business Systems earth stations.

DTS - Digital Termination Service; an acronym applied to a relatively new service of providing community digital communications service by TDMA microwave radio.

EIRP - Effective Isotropic Radiated Power; the product of antenna gain and transmitter power (minus antenna and other coupling losses).

FDMA - Frequency Division Multiple Access; a scheme for sharing use of a transmission facility by using alternate frequency assignments for each user.

FTU - Full-Time Transmission Unit; a Satellite Business Systems acronym, representing 224 Kbps of satellite capacity which is assigned to a user 24 hours per day, 7 days per week.

Gbs - Gigabits/sec

GHz - Gigahertz

G/T - Gain to Temperature ratio of an earth station, a commonly used performance parameter.

LED - Modulated Light Emitting Diode

LID - Modulated Laser Injection Diode

Mbs - Megabits/sec

NAC - Network Access Center; earth station used in accessing the Satellite Business System digital satellite network.

PIN - Solid state diode used as a switch for microwave frequencies.

RAPAC - Digital Communications Corporation acronym for their TDMA, point-multipoint microwave radio.

TDMA - Time Domain Multiple Access; a scheme for sharing a transmission facility by using alternate time slots for each user.

VCAU - Voice Channel Access Unit; a voice post interface device used in the Satellite Business Systems digital earth stations.

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TABLE 1. - TYPICAL ALTERNATIVES FOR LOW RATE SERVICE

System	Cost, dollars
SBS[a]	
NAC	12 500/mo[b]
FTU	2 100/FTU-mo[c]
DCAU	700/56 Kbs[d]
VCAU	110/Ch[d]
WU	
Private line voice	680-1100/mo[e]
ATT	
"800"	20/call-hr[f]

[a]Minimum Requirement - 3 NAC's and 3 FTU's. Installation and Test Extra
[b]Ref. 14
[c]Ref. 15
[d]Ref. 16
[e]Ref. 17
[f]Ref. 18

TABLE 2. - COMPARISON OF Ku CONUS SYSTEM WITH VARIOUS Ka SYSTEMS

[99.5 percent Availability, 10^{-6} BER]

Frequency band, GHz	Ind. beam coverage	Approximate ant. gain, dB	Gain excess, dB	Transponder power, W	E/S HPA power, kW
14/12	CONUS	32	0	23	0.6
30/20	CONUS	32	0	209	4.8
30/20	1.5°	40	5.0[a]	66	1.5
30/20	.3°	53	16.5[b]	4.7	.1

[a]Includes 3 dB loss for beam edge
[b]Includes 3 dB loss for beam edge and 1.5 dB for off-axis scan

TABLE 3. - TYPICAL INSTALLED EARTH STATION COSTS

(1980 $K)

Terminal class	FDMA		TDMA	
	Cost[a]	Relative Capacity	Cost	Relative Capacity
High (32 Mbs)	969/830	238	330	440
Med (6.3 Mbs)	471/359	68	233	88
Low (1.5 Mbs)	329/165	14	208	22
Mini (64 Kbs)	95/85	1	109	1

[a]1.2/0.3 degree spacecraft antenna beamwidth.

TABLE 4. - TRW/FSI COST ESTIMATES FOR TERRESTRIAL "TAIL" EQUIPMENT (1981 $)

Item	Local node unit cost	Central node unit cost
Optical fiber		
Xmitter (LED)	1 600/end	5 200 (LID)
Rcvr (APD)	1 200/end	2 600 (PIN)
Cable (2 fiber)	1.5/m	1.5/m
Cable (install)	7.0/m	7.0/m
Digital MW radio		
XCVR	12 500/end	15 000/end
Repeater	(Not req'd)	27 000/8km
Coaxial cable		
Hardware	3 100/km	3 100/km
Construction	8 700/km	8 700/km
Local concentrator		
Comm equipment		12 000
Multiplex		2 500 +100/56 Kbs ch. +500/6.3 Mbs ch.

TABLE 5. - GE/DCC COST ESTIMATES FOR TERRESTRIAL "TAIL" EQUIPMENT (1981 $)

Item	Local node unit cost	Central node unit cost
Optical fiber		
Xmit	2 500/end	5 000/T2
Rcvr		15 000/end
Repeater	7 500/unit	7 500/unit
Cable	1.5/m	1.5/m
Cable (install)	5.0/m	5.0/m
Digital MW radio		
XCVR	10 250/56 Kb	20 000/end
Repeater	10 250/1.6 Km	20 000/3Km
RAPAC (DTS)		
Equip.	11 500 +1 100/ch	117 500 1 100/ch
Ship & Inst	4 000/suscrib.	15 000
FCC permit & fees		9 000
Coaxial cable		
Xcvr	3 000- 5 000	3 000- 5 000
Cable install.	5 600/km	
Local concentrator Multiplex		12 500 +430/line

TABLE 6. - 1980 VOICE TRAFFIC DEMAND
FOR TYPICAL LARGE INDUSTRIAL CORPORATION

[Total Nationwide Demand, 1296 E
(~1 C-band transponder).]

Site	Demand, E	Site	Demand, E
1	446	11	41
2	94	12	41
3	84	13	41
4	77	14	23
5	71	15	23
6	67	16	20
7	64	17	18
8	64	18	13
9	54	19	7.7
10	46	20	2.6

TABLE 7. - TYPICAL LARGE CORPORATION TERMINAL REQUIREMENTS

[1296 E Serviced With a Peak Capability of 2154 E.]

Terminal class, TDMA	Terminals, number
High (440 Ch)	2
Med (88 Ch)	13
Lo (22 Ch)	5

TABLE 8. - COSTS FOR A TYPICAL LARGE NETWORK (1981 dollars)

Item	Cost
Installed Capital Costs	
Terminals[a]	4729 K
Concentration[a]	955 K
Annualized Costs	
Annual ground segment[a]	2330 K
Annual space segment[a,b]	3400 K
User Charges	
Monthly charge/ckt[c]	368
Charge/call-hr[c]	2.39

[a]0.4 Annualization Factor
[b]$500 M Space Segment Prorated Over Traffic Demand
[c]Assumes 1296 Erlangs

TABLE 9. - COMPARISON OF DIFFERENT SIZE NETWORKS

[TRAFFIC IN ERLANGS]

Node	Large corp.	Average of "top 100"	Average of "2nd 100"
1	446 E	84.8 E	20.8 E
2	94	17.9	4.4
3	84	16.0	3.9
4	77	14.5	3.6
5	71	13.6	3.3
6	67	12.7	3.1
7	64	12.1	3.0
8	64	12.1	3.0
9	54	10.2	2.5
10	46	8.7	2.1
11	41	7.8	1.9
12	41	7.8	1.9
13	41	7.8	1.9
14	23	4.4	1.1
15	23	4.4	1.1
16	20	3.9	0.95
17	18	3.4	0.83
18	13	2.4	0.59
19	7.7	1.5	0.36
20	2.6	0.5	0.12
Total	1296 E	246 E	60.5 E

TABLE 10. - TERMINAL DISTRIBUTIONS FOR DIFFERENT NETWORKS

Terminal class, (TDMA)	Large corp.	Average of "top 100"	Average of "2nd 100"
Hi (440 Ch)	2	0	0
Med (88 Ch)	13	1	0
Lo (22 Ch)	5	18	13
Mini (1 Ch)	0	1	7

TABLE 11. - COSTS FOR VARIOUS NETWORKS
(1981 dollars)

Terminal class	Large corp.	Average of "top 100"	Average of "2nd 100"
Installed Capital Costs			
Terminals	4729 K	4086 K	3467 K
Concentration	955 K	751 K	510 K
Annualized Costs			
Annual Ground Segment	2330 K	1983 K	1631 K
Annual Space Segment	3400 K	646 K	212 K
User Charges			
Monthly Charge/Ckt	368	890	2539
Charge/Call-hr	2.40	5.80	16.50

TABLE 12. - COSTS FOR SHARED NETWORKS

[1981 dollars]

Item	Investment
Earth stations (network + dedicated)	$400 M
Ground network (fiber optics)	400 M
Spacecraft (5)	700 M
Total	1500 M

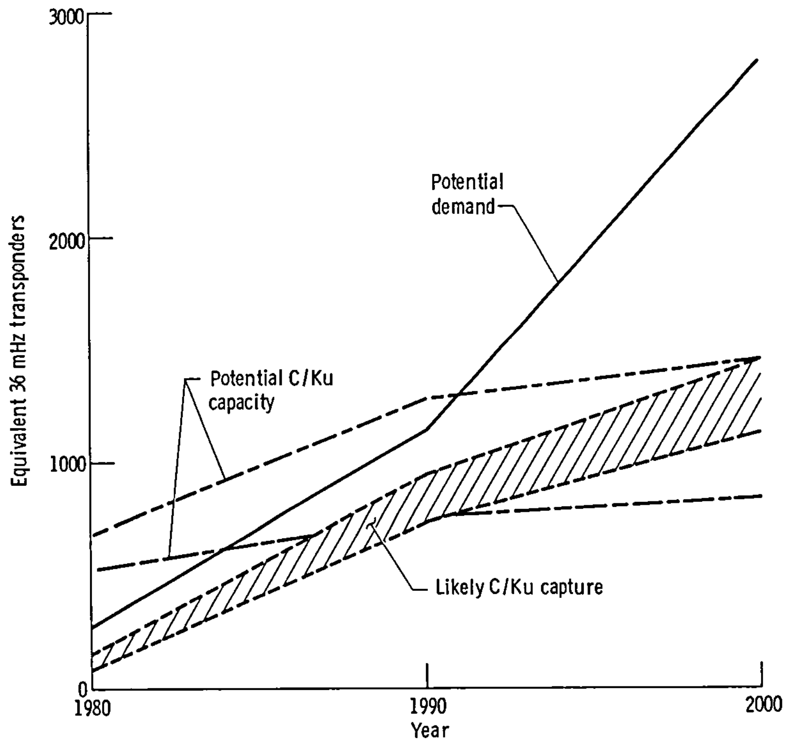

Figure 1. - Comparison of potential satellite demand with potential C-band and Ku-band capacity along with an estimate of likely market capture by C/Ku-band technology.

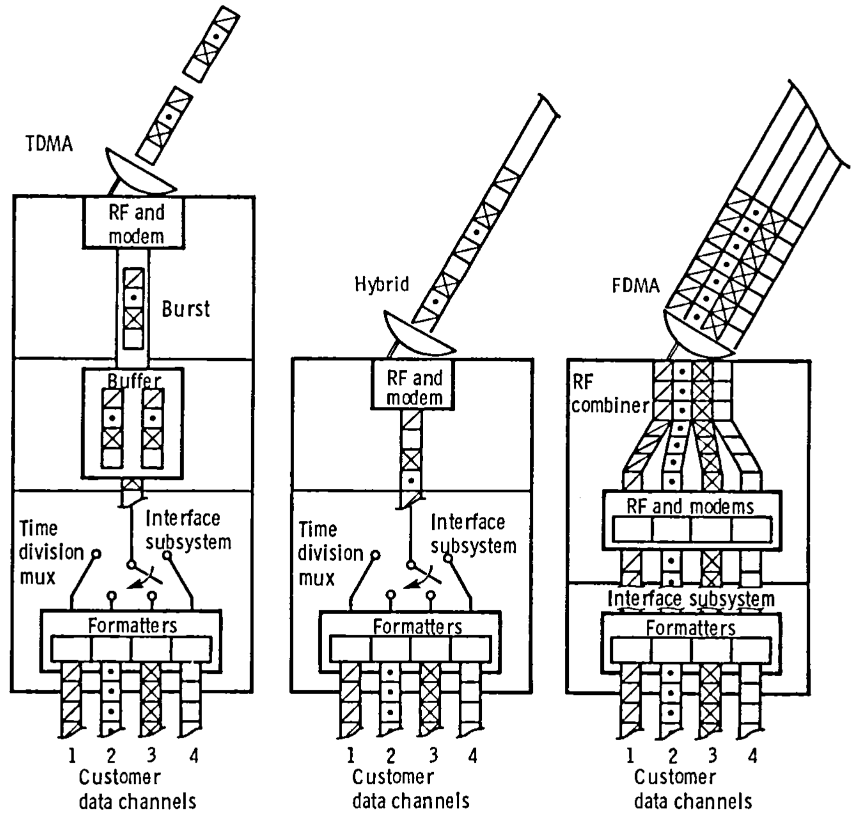

Figure 2. - LDRS multiple access techniques.

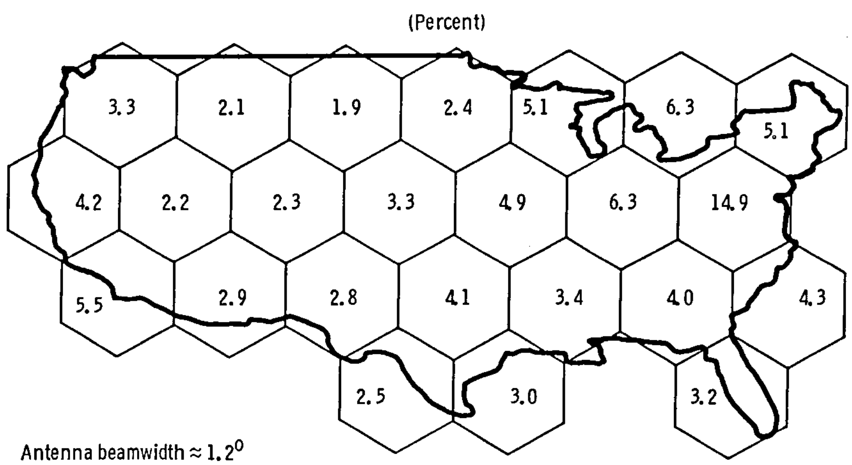

Figure 3. - Typical contiguous beam coverage including apportionment of traffic (percent).

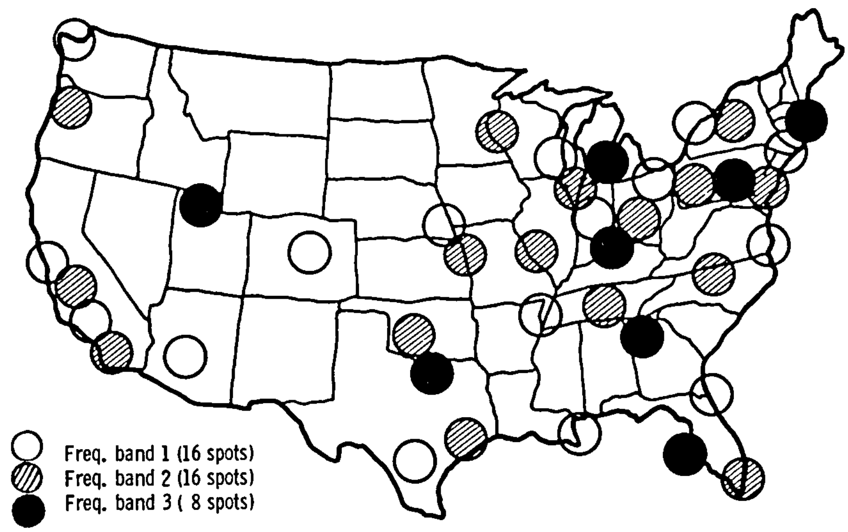

Figure 4. - Alternate fixed coverage with isolated beams.

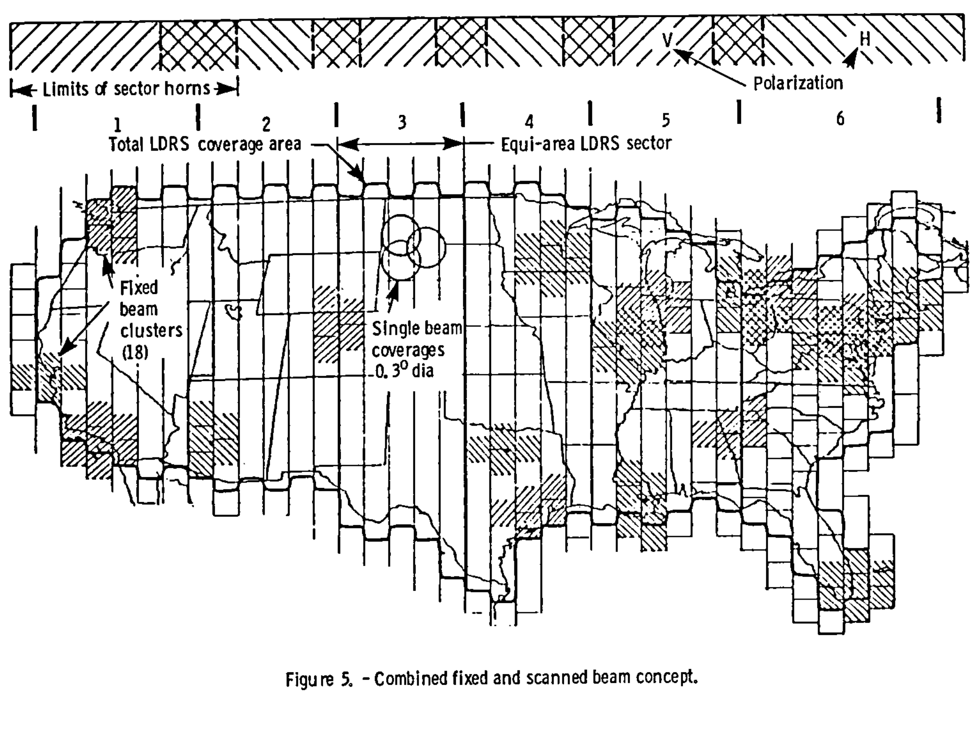

Figure 5. - Combined fixed and scanned beam concept.

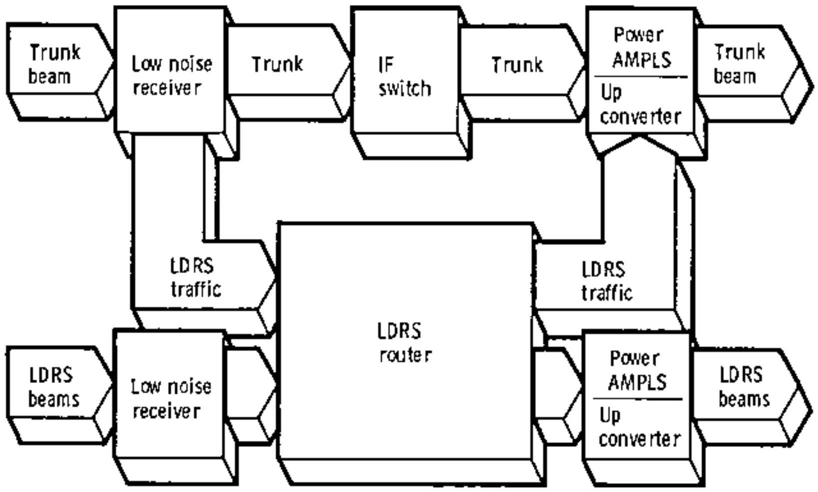

Figure 6. - General communications configuration.

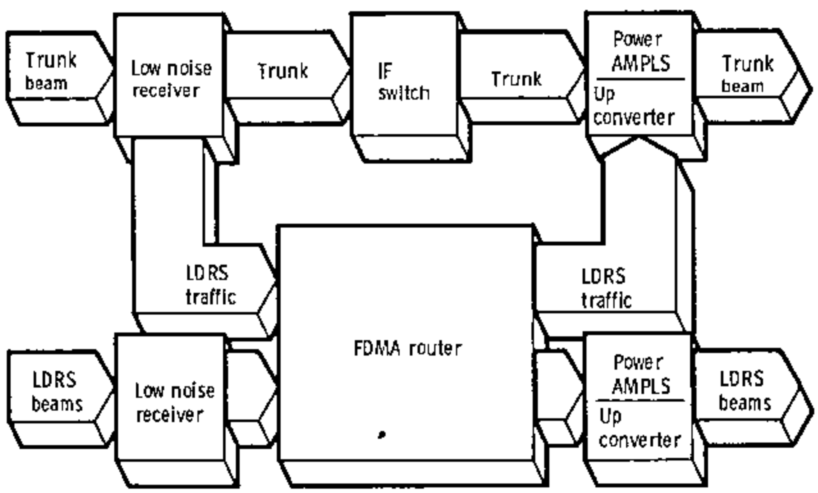

Figure 7. - SS-FDMA communications configuration.

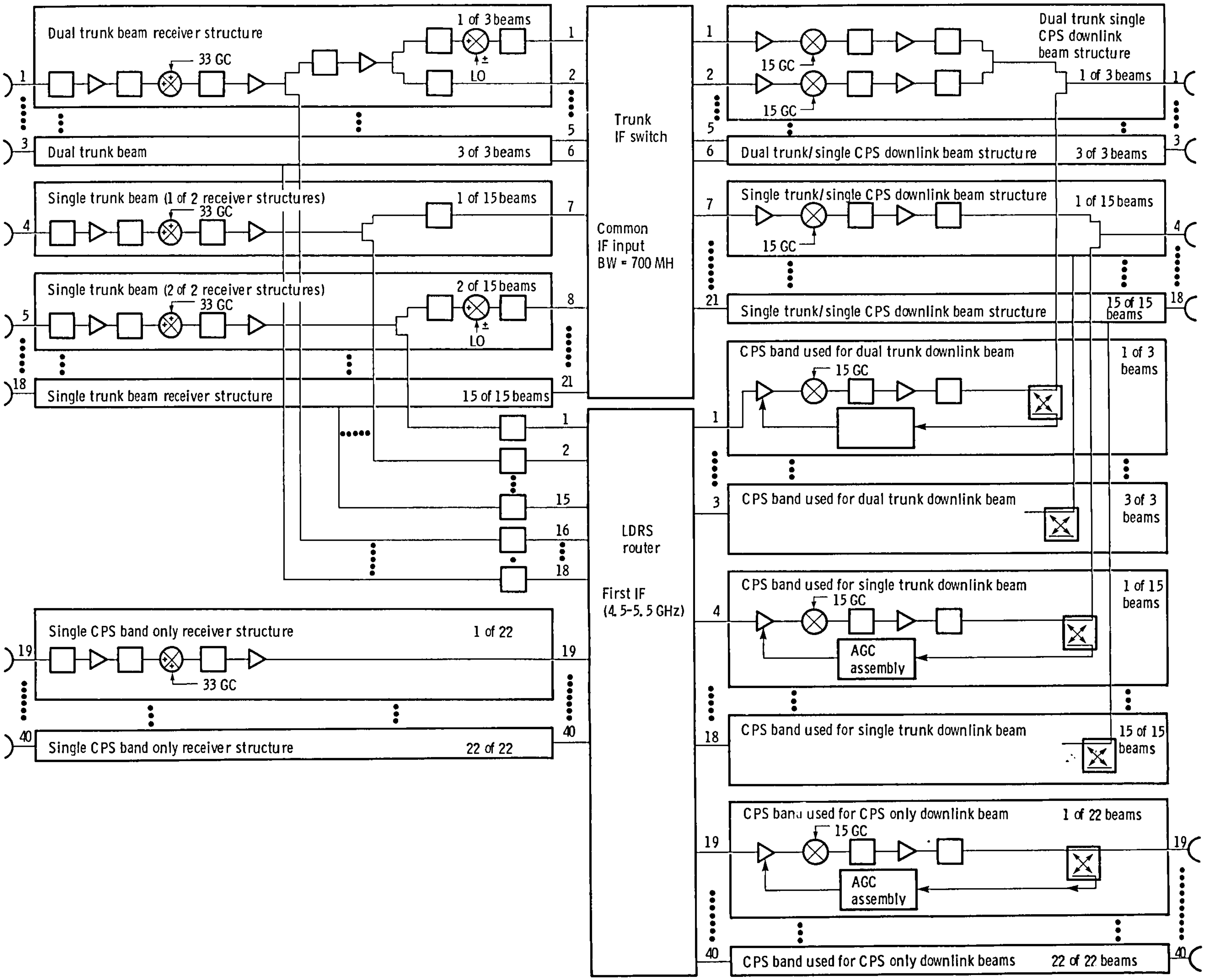

Figure 8. - Motorola transponder configuration.

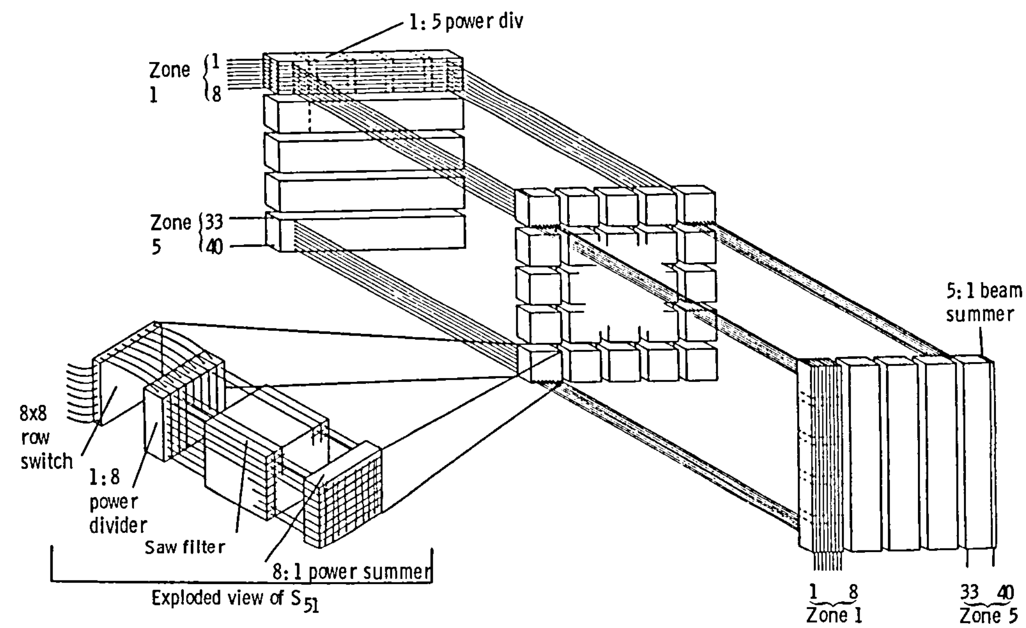

Figure 9. - Motorola router configuration.

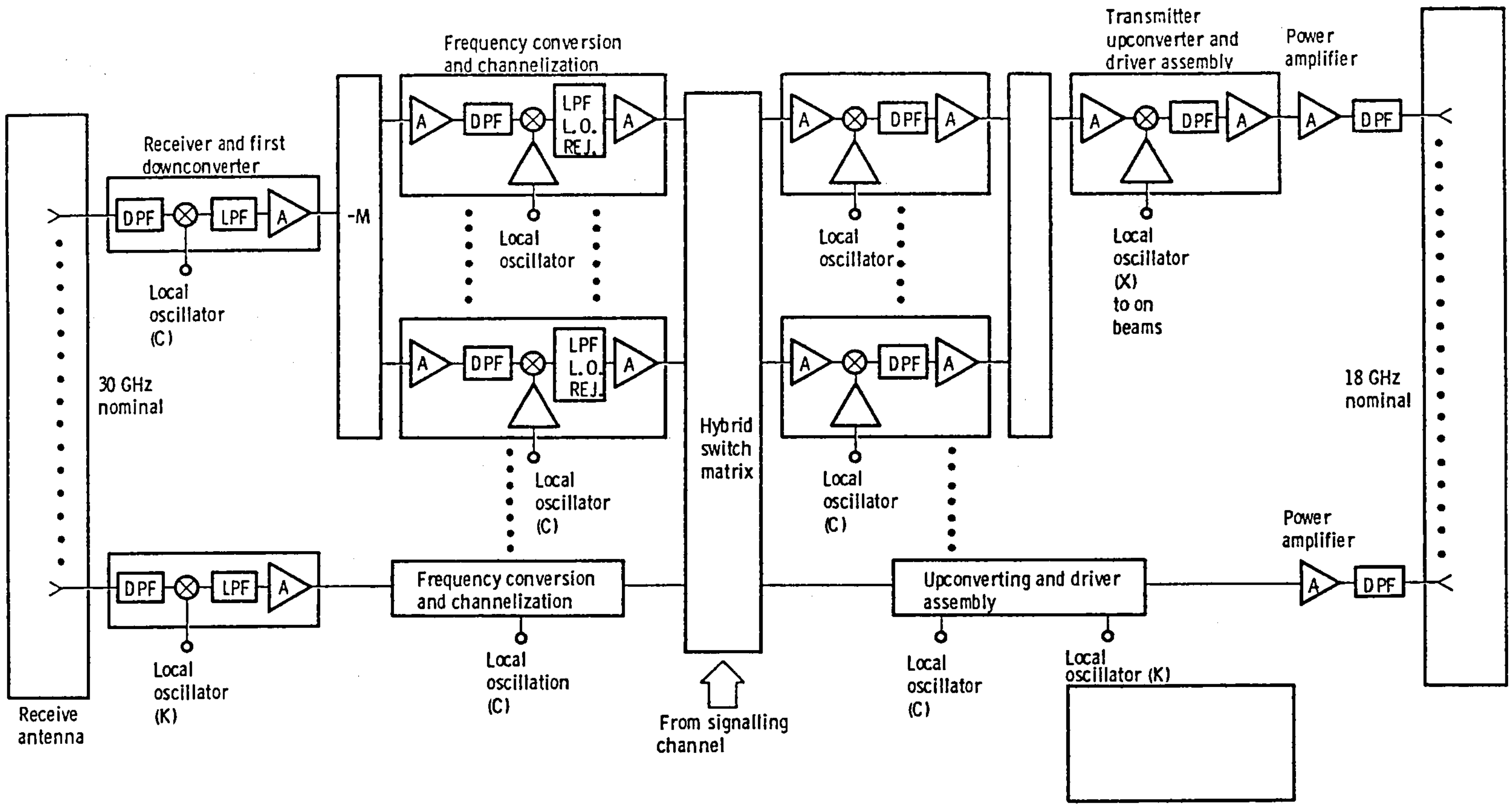

Figure 10. - GE transponder configuration.

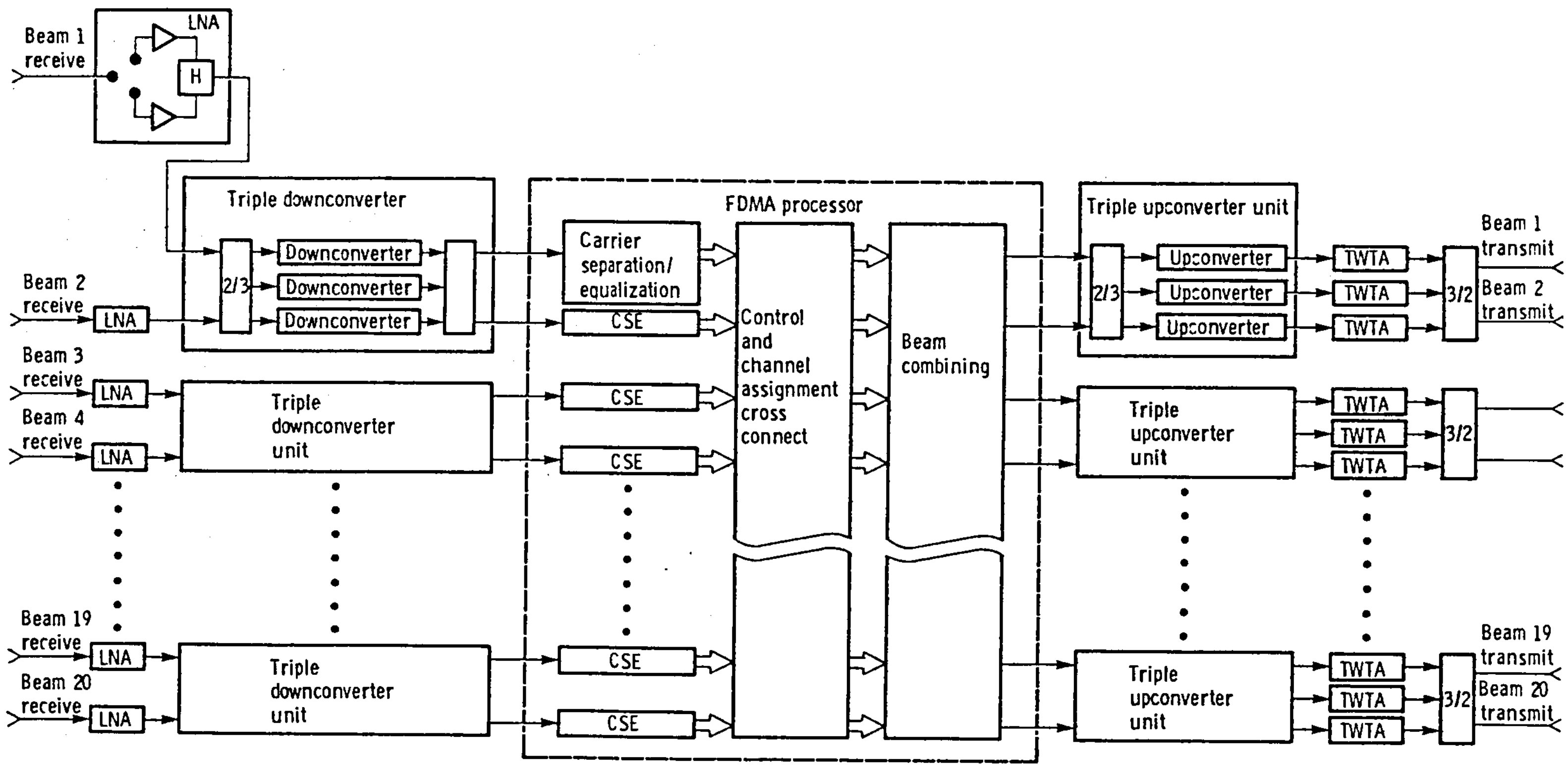

Figure 11. - TRW transponder and FDMA processor configuration.

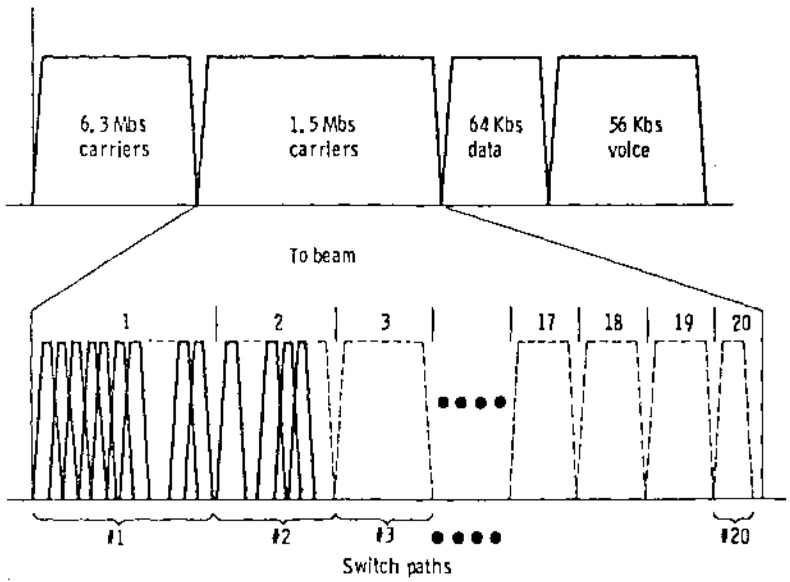

Figure 12. - TRW SS-FDMA channelization.

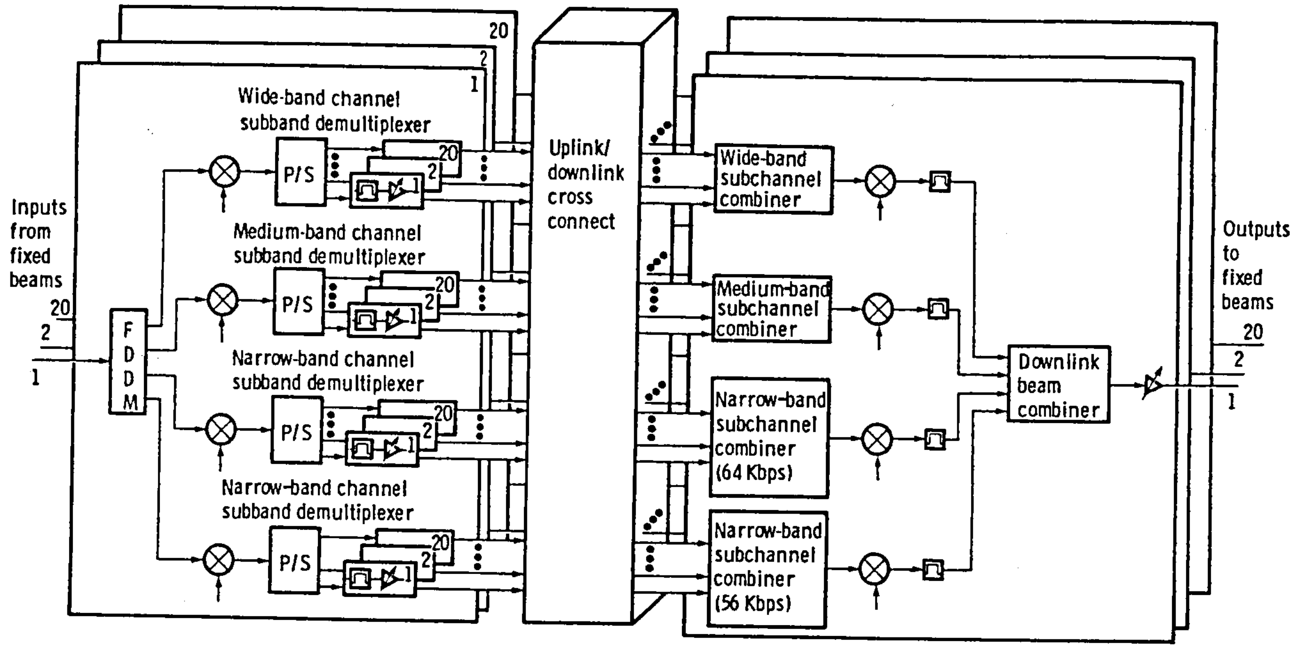

Figure 13. - TRW SS-FDMA processor.

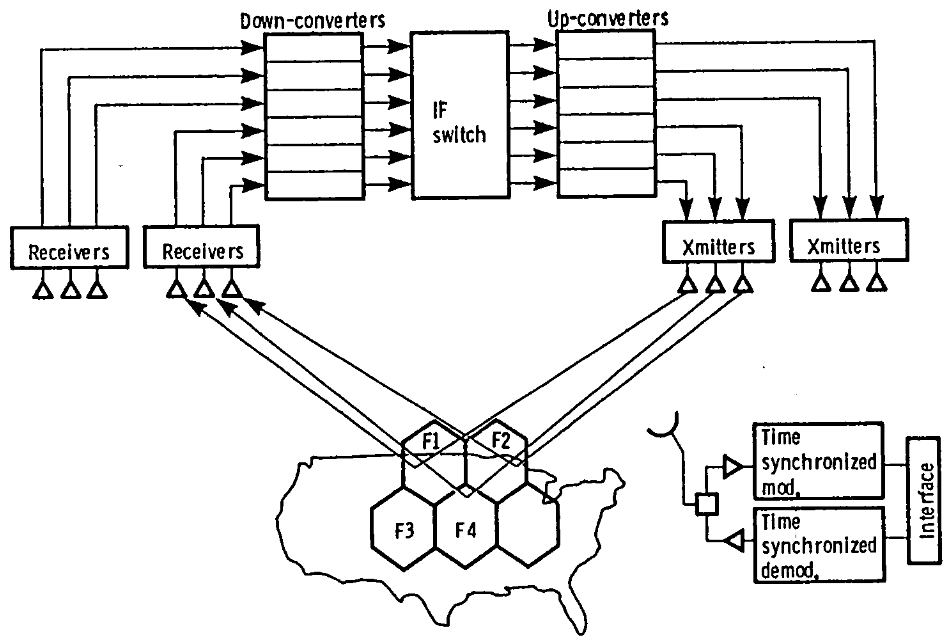

Figure 14. - A fixed beam SS-TDMA configuration.

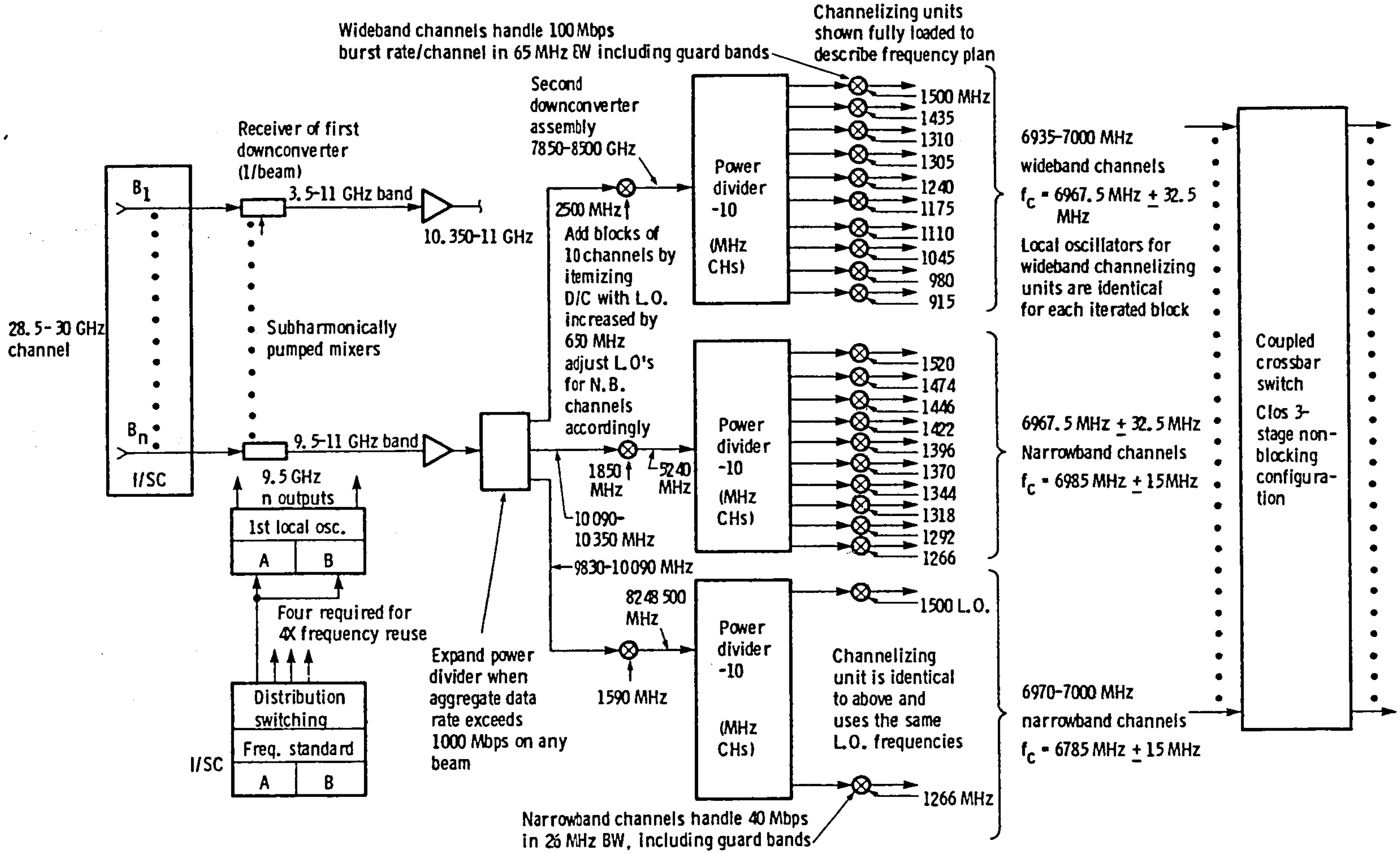

Figure 15. - GE SS-TDMA receiving plan.

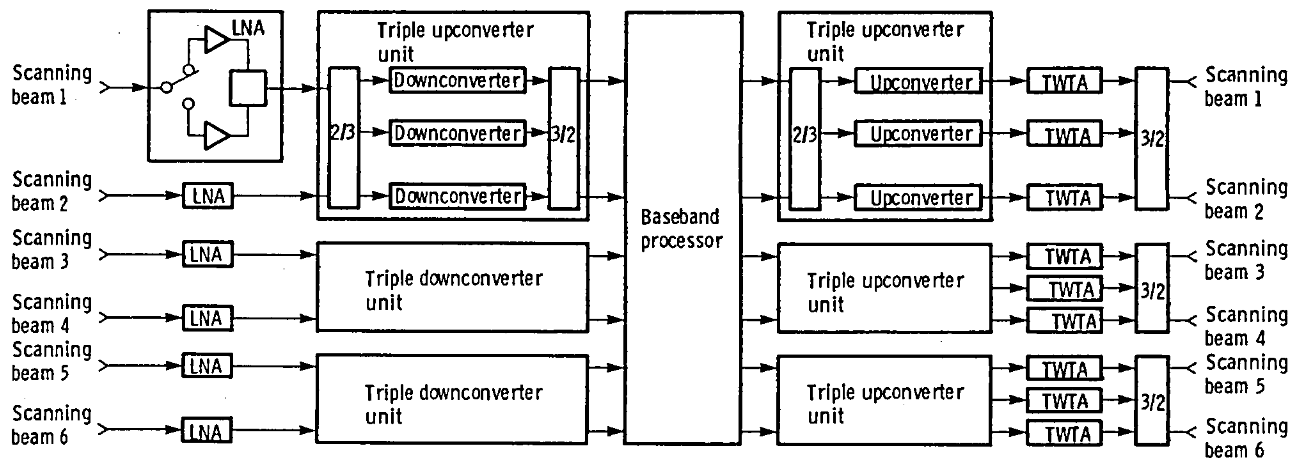

Figure 16. - TRW 3 Gbs scanned beam transponder and processor.

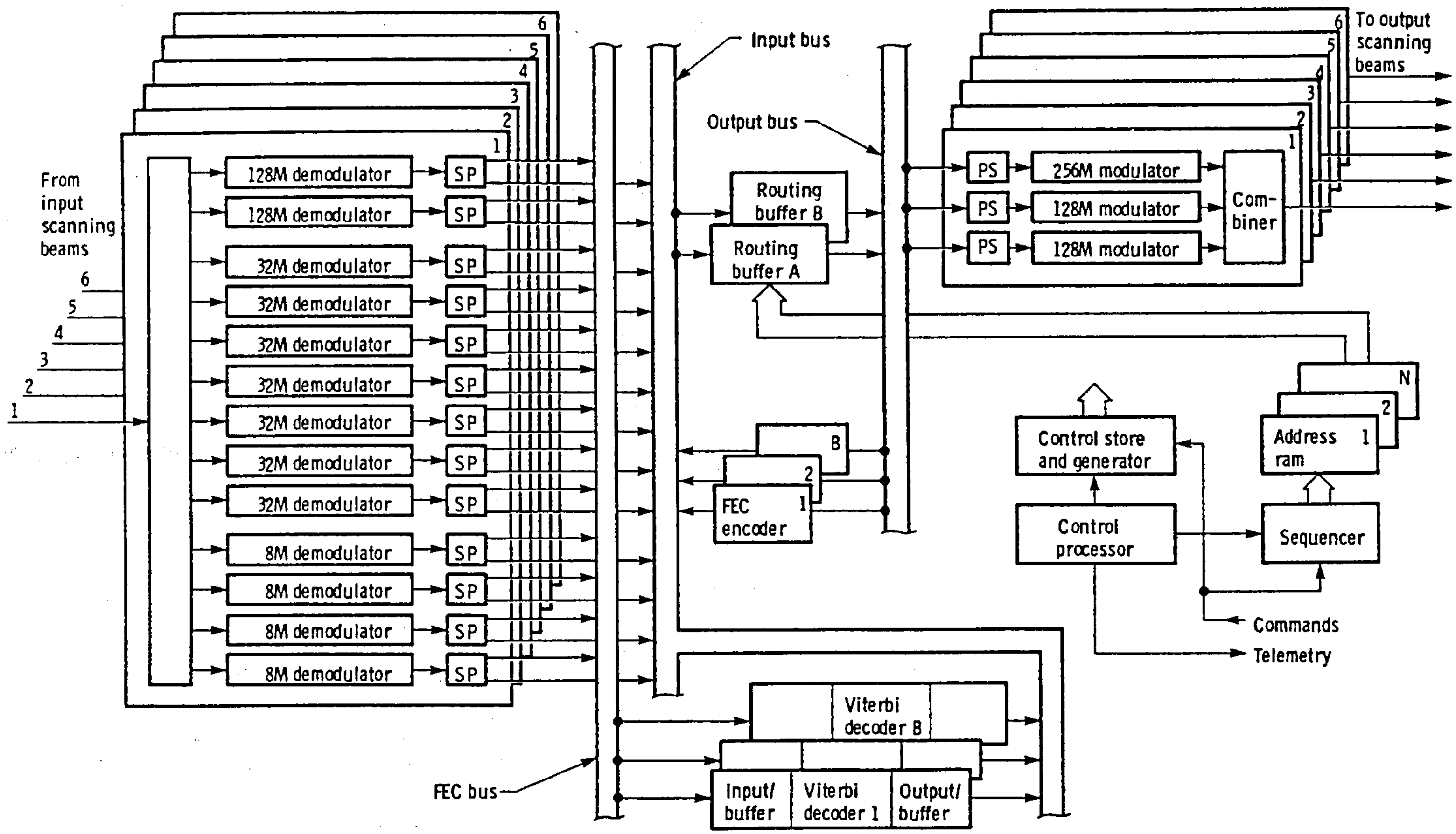

Figure 17. - TRW 3 Gbs baseband processor.

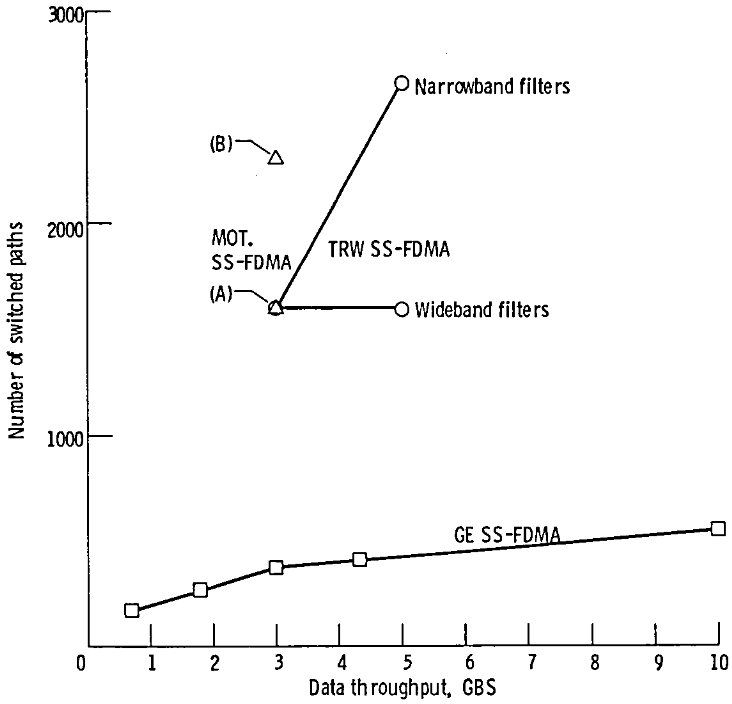

Figure 18. - Comparison of switching complexity.

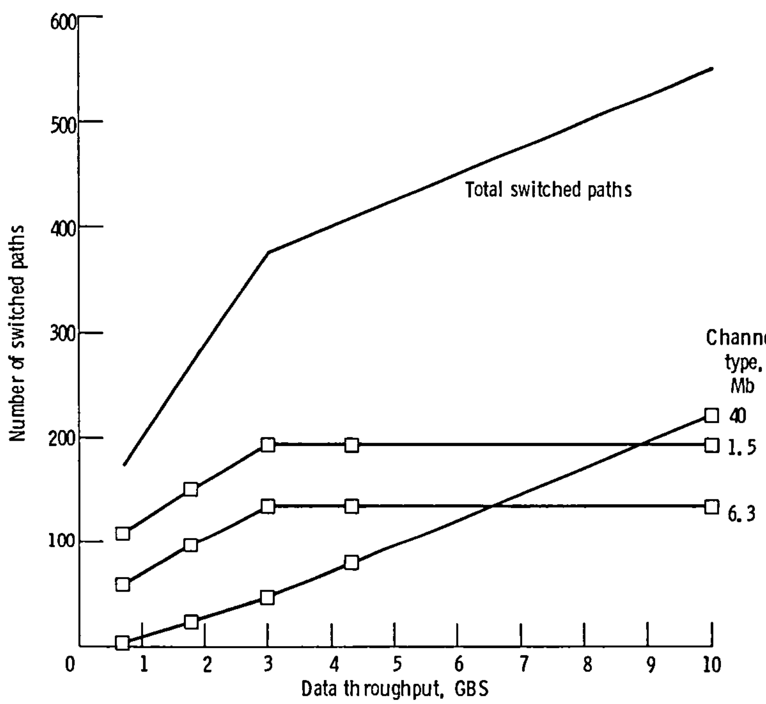

Figure 19. - GE implementation strategy.

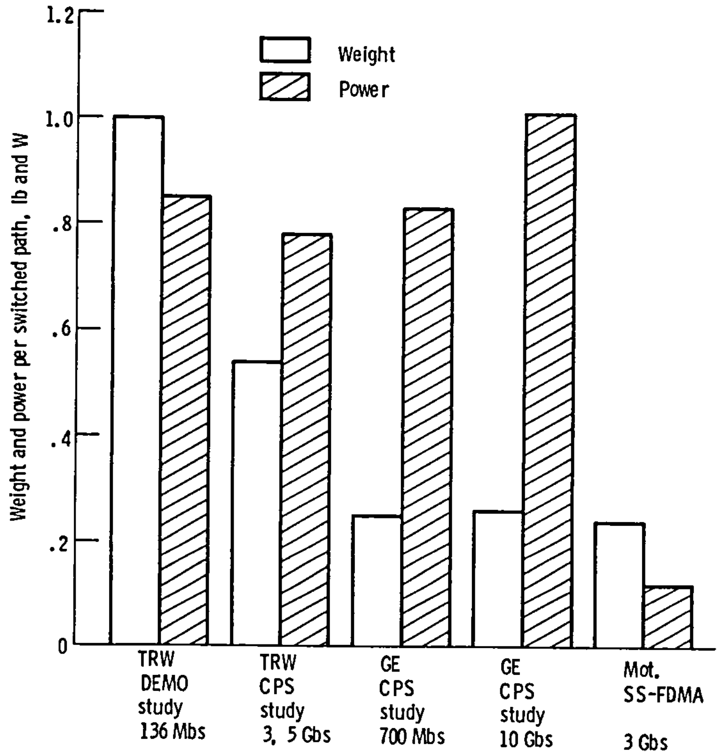

Figure 20. - Comparison of weight/power per switched path.

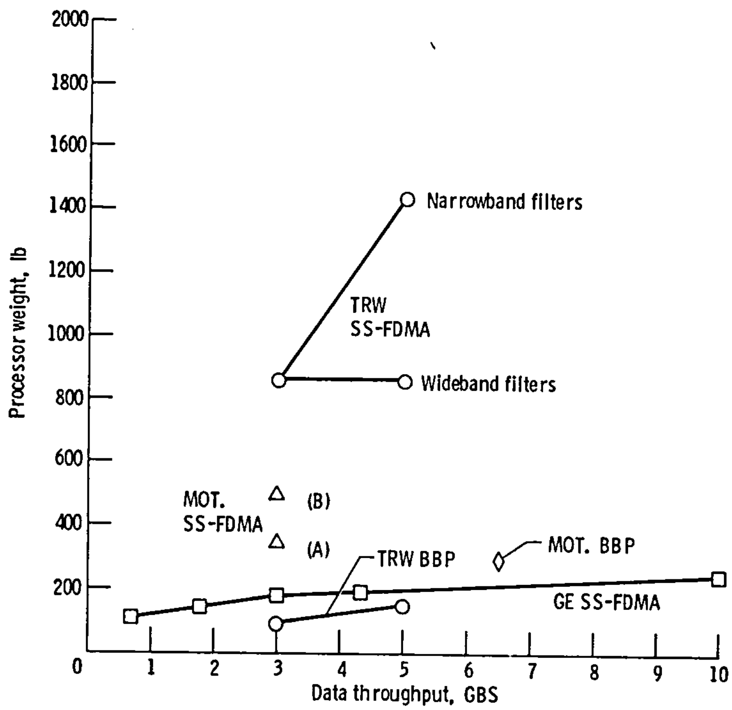

Figure 21. - Comparison of processor weights.

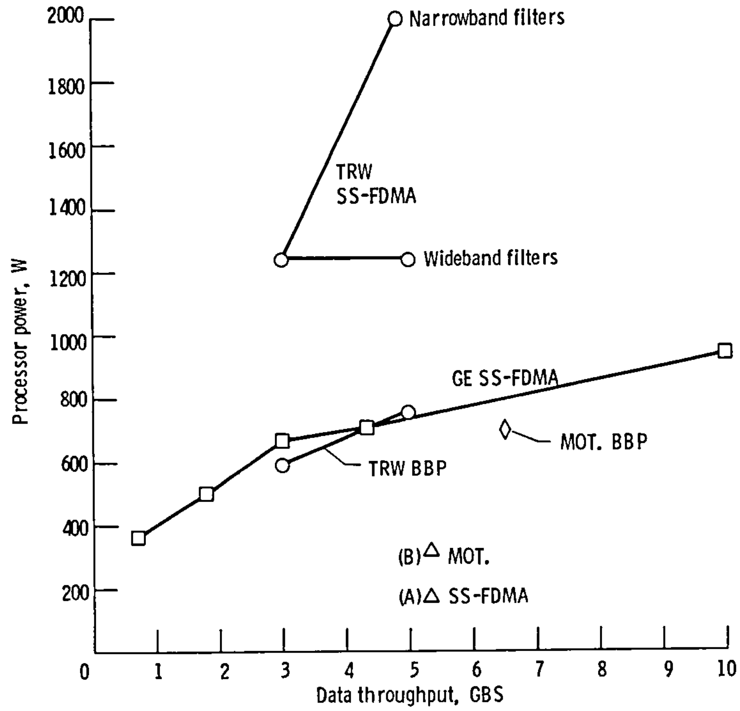

Figure 22. - Comparison of processor power requirements.

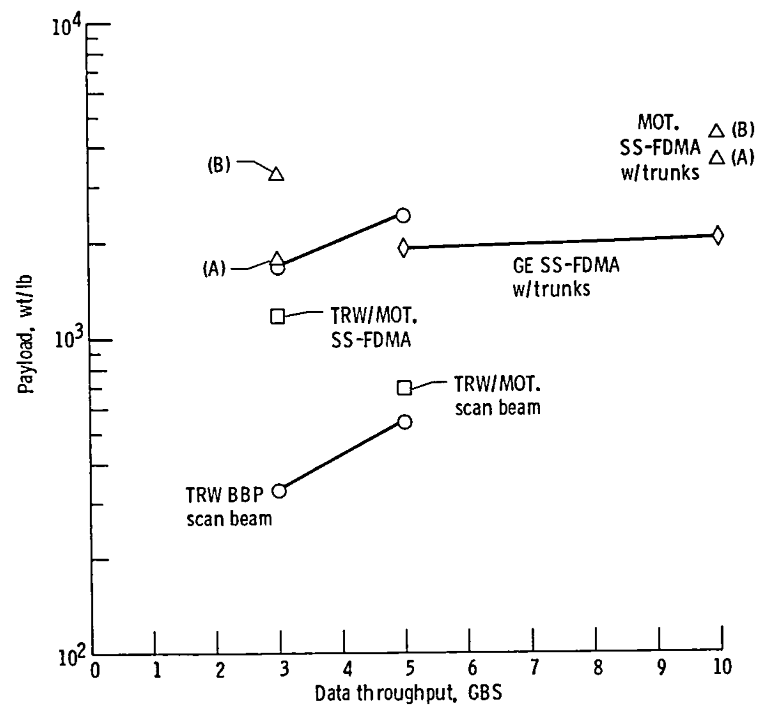

Figure 23. - Comparison of payload weights.

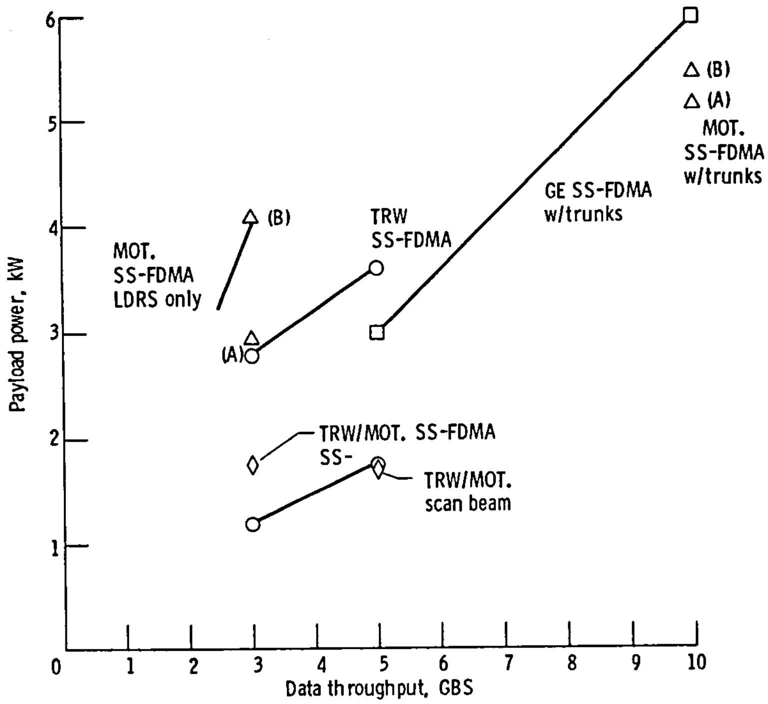

Figure 24. - Comparison of payload power requirements.

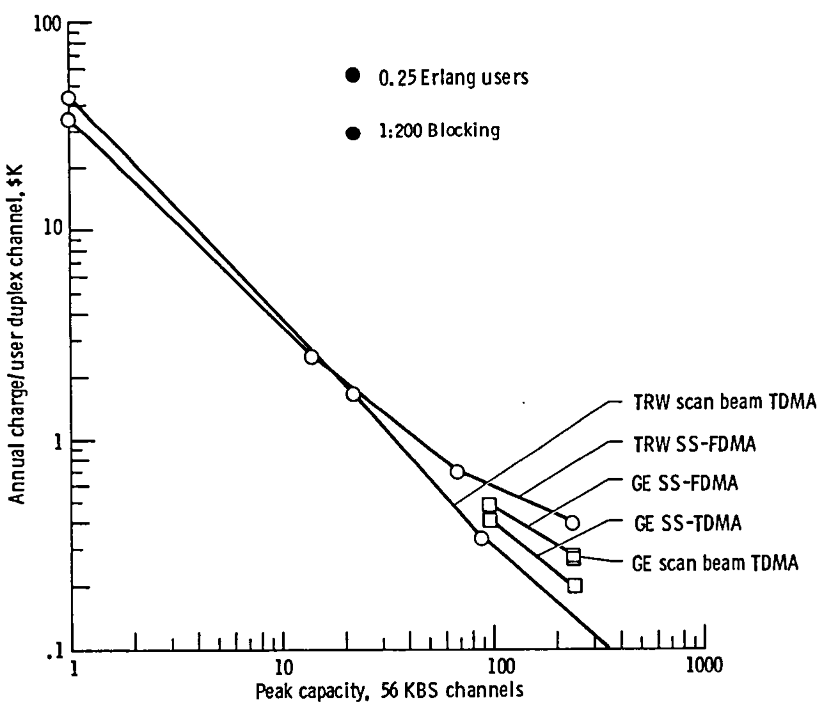

Figure 25. - Comparison of annual terminal costs.

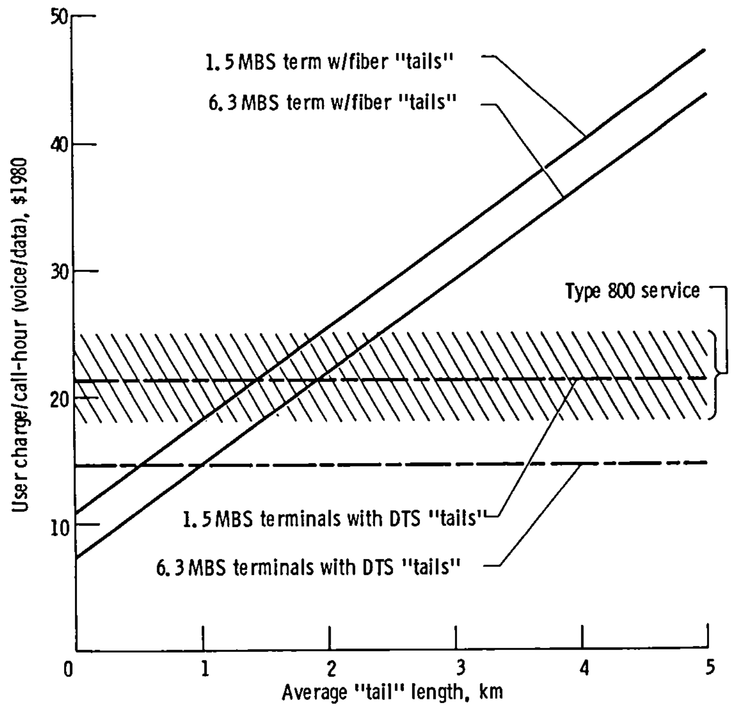

Figure 26. - Some voice/data alternatives

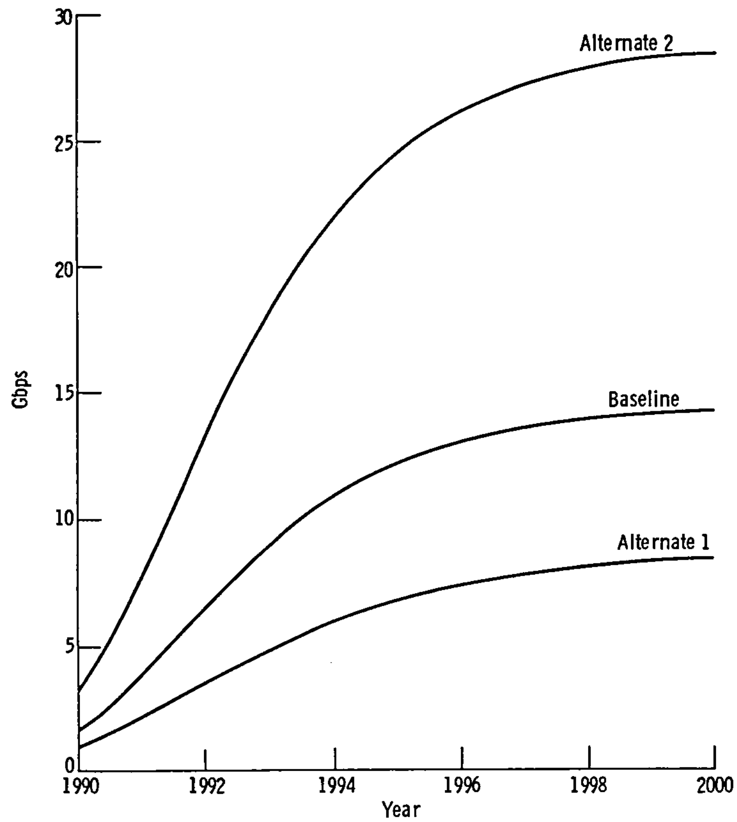

Figure 27. - TRW/FSI market forecast.

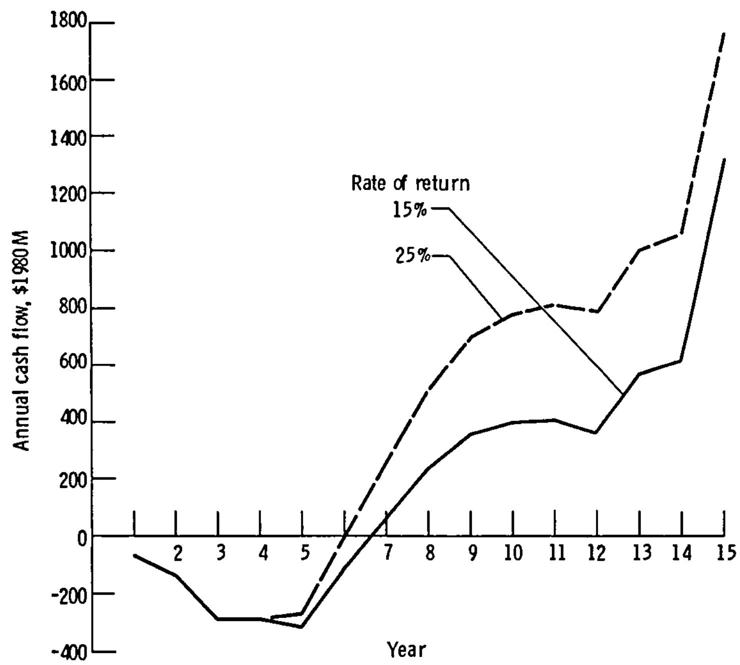

Figure 28. - Typical cash flow analysis.

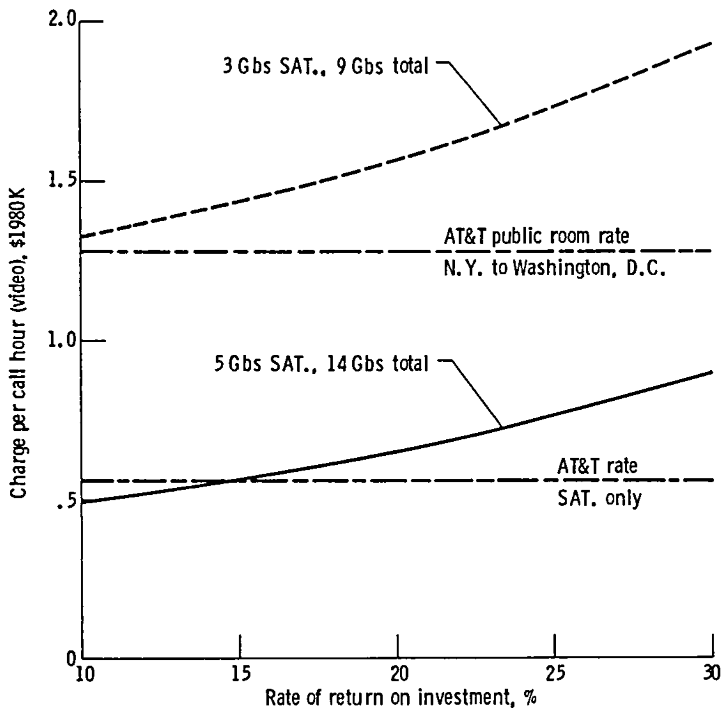

Figure 29. - Alternatives for video in shared network.

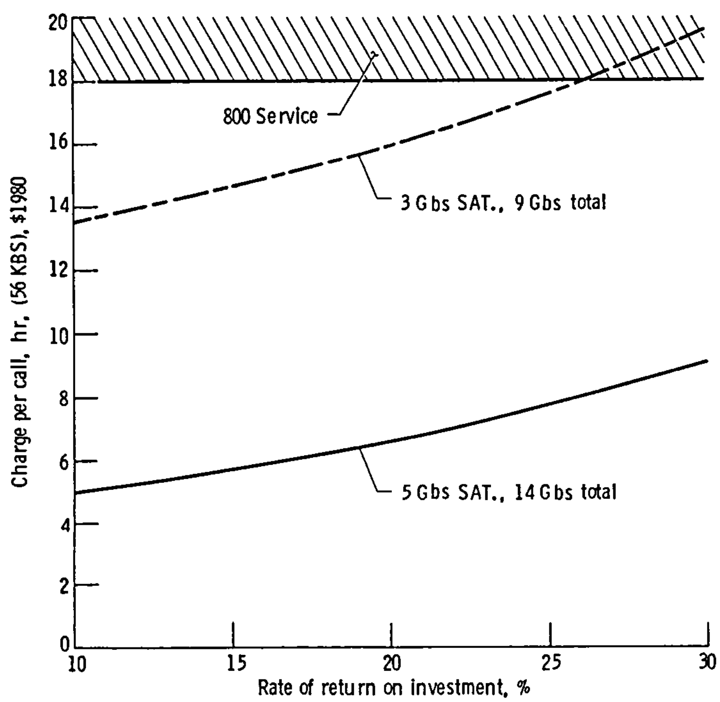

Figure 30. - Alternatives for voice/data in shared network.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83430		
4. Title and Subtitle A Comparison of Frequency Domain Multiple Access (FDMA) and Time Domain Multiple Access (TDMA) Approaches to Satellite Service for Low Data Rate Earth Stations		5. Report Date June 1983 6. Performing Organization Code 650-20-16
7. Author(s) Grady Stevens		8. Performing Organization Report No. E-1721 10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A technological and economic assessment is made of providing low data rate service to small earth stations by satellite at Ka-band. Various FDMA and TDMA scenarios are examined and compared on the basis of cost to the end user. Very small stations (1-2 meters in diameter) are found not to be viable alternatives to available terrestrial services. However, medium size (3-5 meters) earth stations appear to be very competitive if a minimum throughput of about 1.5 Mbs can be maintained. This constrains the use of such terminals to large users and shared use by smaller users. No advantage was found to the use of FDMA. TDMA had a slight advantage from a total system viewpoint and a very significant advantage in the space segment (about 1/3 the required payload weight for an equivalent capacity).

17. Key Words (Suggested by Author(s))	18. Distribution Statement		
Satellites; Communications; Frequency domain multiple access; Time domain multiple access; EHF; Ka-band	Unclassified - unlimited STAR Category 32		
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

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