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Technical Report 572

F.W. Floyd

Space Data Relay Networks

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3 December 1981

Prepared for the Department of the Air Force
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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

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FOR THE COMMANDER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

SPACE DATA RELAY NETWORKS

F.W. FLOYD

Group 68

TECHNICAL REPORT 572

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ABSTRACT

A space data relay network for controlling and reading-out military satellites could provide better coverage, more capacity and better survivability than the existing network of ground relay stations.

This report compares two architectural schemes for a space data relay network--"centralized" and "distributed". Past studies have concentrated on centralized architectures which, like NASA's Tracking and Data Relay Satellite System, would have dedicated data relay satellites and large ground control centers. Because military requirements are more stringent than NASA's, the data relay satellites would need to be significantly more capable than TDRS. High costs and technical risks have therefore prevented deployment of a military space data relay network.

As an alternative, this report introduces a distributed architecture in which network assets are dispersed among user spacecraft as add-on data relay packages. The ground control centers are likewise small and widely dispersed. The following advantages over a centralized architecture are expected.

- Network design less sensitive to user requirements
- Phased growth rather than block changes
- Permits continuing evolution of technology
- Adaptable to mission-specific or common-user deployments
- More survivable.

This report presents two design examples to illustrate some essential differences between centralized and distributed networks. First, a typical set of user requirements is examined and generalized into broad classes of service in order to decouple basic architectural issues from detailed user requirements. Some network implementation possibilities are discussed and expected advances in the technologies of laser communications, millimeter waves and on-board signal processing are incorporated.

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1. OVERVIEW

It has long been recognized that the problems of satellite control and data read-out would be well served by some form of space data relay network. Militarily we grow increasingly dependent on our space assets, and almost no effort is spared to make the satellites reliable and survivable. Yet, like other military assets, satellites rely on a supporting C^3 (command, control, communications) structure in accomplishing their missions. Today that C^3 structure is far more vulnerable to disruption, sabotage or direct attack than are the satellites themselves. It also limits the potential usefulness of satellites in terms of the coverage and data transfer rates it can provide.

1.1 CENTRALIZED NETWORKS

Today our space C^3 structure is founded on a ground-based data relay network (Fig. 1.1). Commands and data are relayed to and from satellites via overseas tracking stations. A network of data relay satellites would circumvent many, if not all, of the limitations of the present approach. NASA's Tracking and Data Relay Satellite System (TDRSS) (Fig. 1.2) is a good example. The proposition to establish just such a network for military satellites has come up repeatedly for a decade or more. Upon consideration, the conclusions have always been: military requirements (Fig. 1.3) are significantly more demanding than NASA's, meeting them implies a data relay satellite that stretches the state-of-the-art in several directions (Fig. 1.4), therefore the cost and technical risk have been deemed not justifiable.

Therefore the great majority of military satellites will continue using the ground-based network for the foreseeable future. However, there exist a few special systems with particularly pressing needs for a space data relay capability (Figs. 1.5, 1.6). These have triggered some individual, mission-specific technology developments. We can expect other equally pressing requirements to arise from time to time in the future. Rather than have each new problem trigger another solution, it would be better to have a common approach, i.e., an architectural plan.

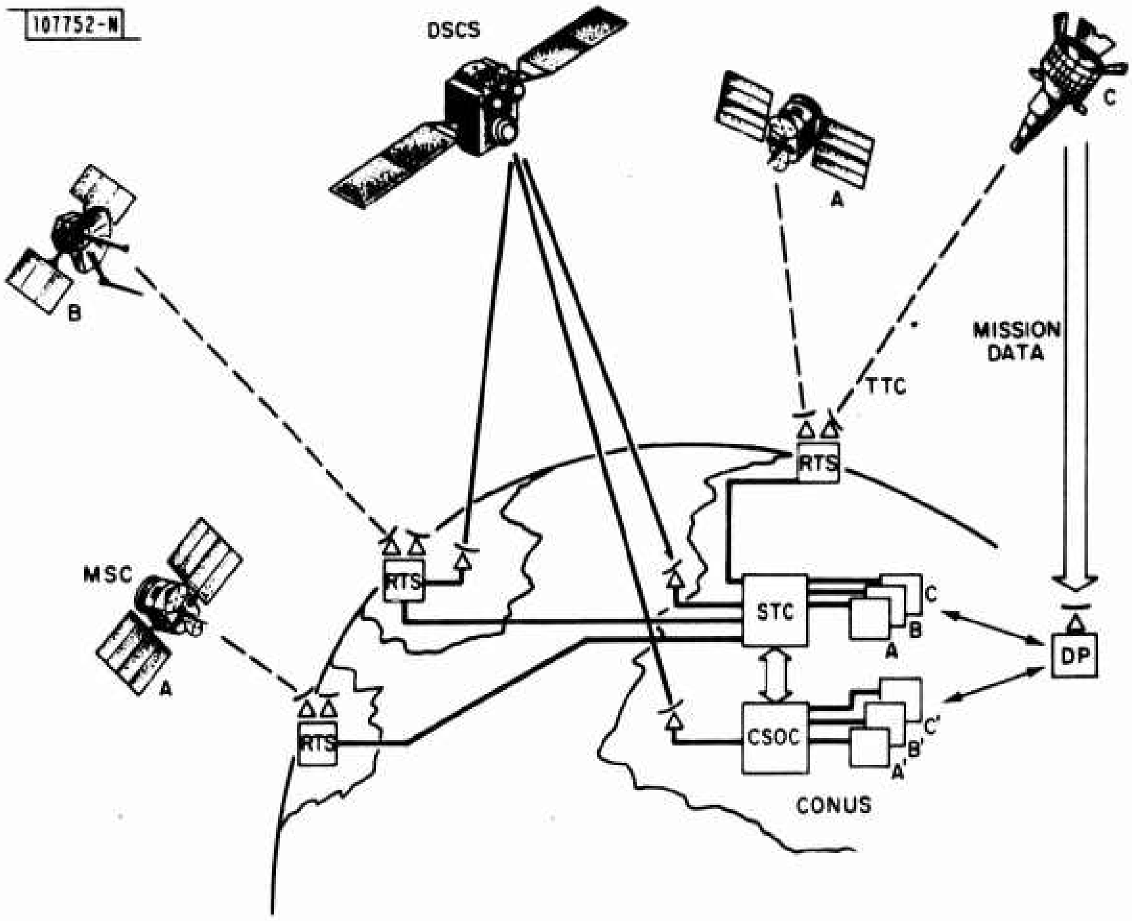

Fig. 1.1. The USAF Satellite Control Facility (SCF), a ground-based data relay network for satellite tracking, telemetry and command (simplified representation).

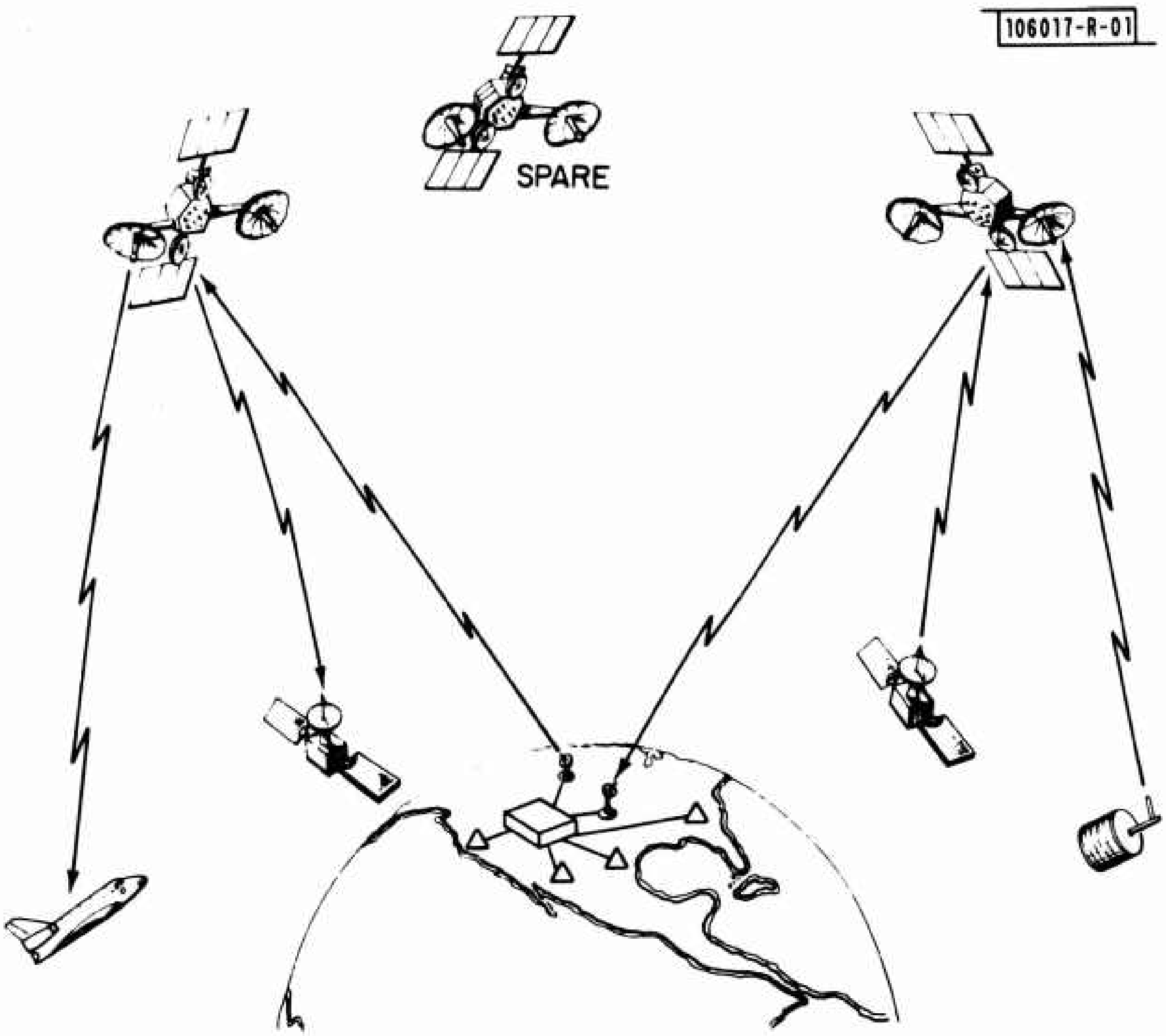

Fig. 1.2. The NASA Tracking and Data Relay Satellite System, a space-based data relay network.

107747-N

FUNCTION	DATA RATE	CHANNELS
COMMAND/TELEMETRY (TTC)	~200 kbps	30
MEDIUM RATE MISSION DATA (MRM)	~10 Mbps	13
HIGH RATE MISSION DATA (HRM)	~1 Gbps	4

Fig. 1.3. Estimated military space data relay requirements for the mid-1990's.

107756-R

ANTENNA SIZES (ft)		SCAN ANGLES (deg) E-W	SCAN ANGLES (deg) N-S
MS ACCESS ANTENNA	8	+80, -35	±25
	3	+80, -35	±30
	3	+80, -35	±30
	3	±30	±30
	2	±80	±30
	2	±20	±20
	2	±20	±20
	4	±80, -35	±25
	4	±35, -80	±25
X-LINK	8	±35	±25
CONUS-MBA	8	0	0

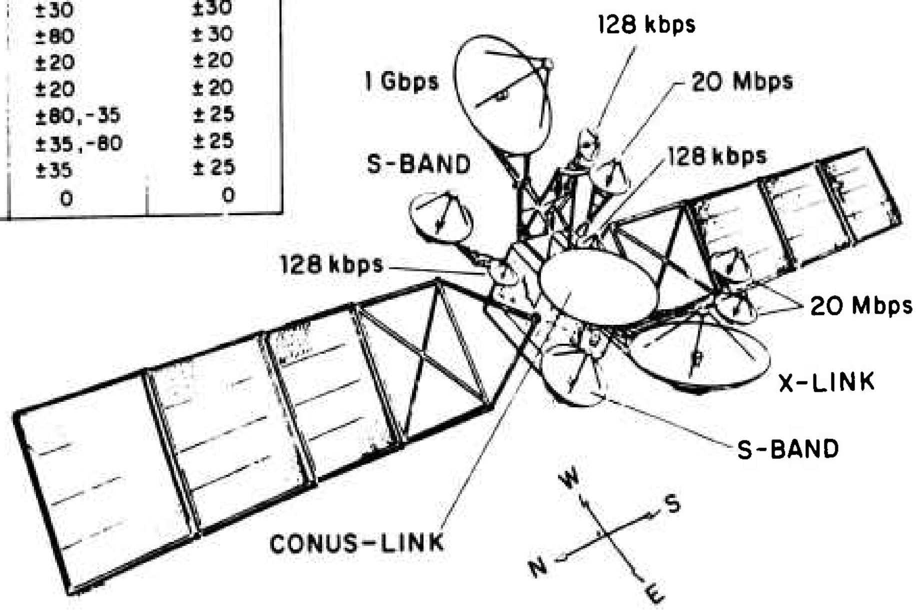

Fig. 1.4. A recently proposed military space data relay satellite.

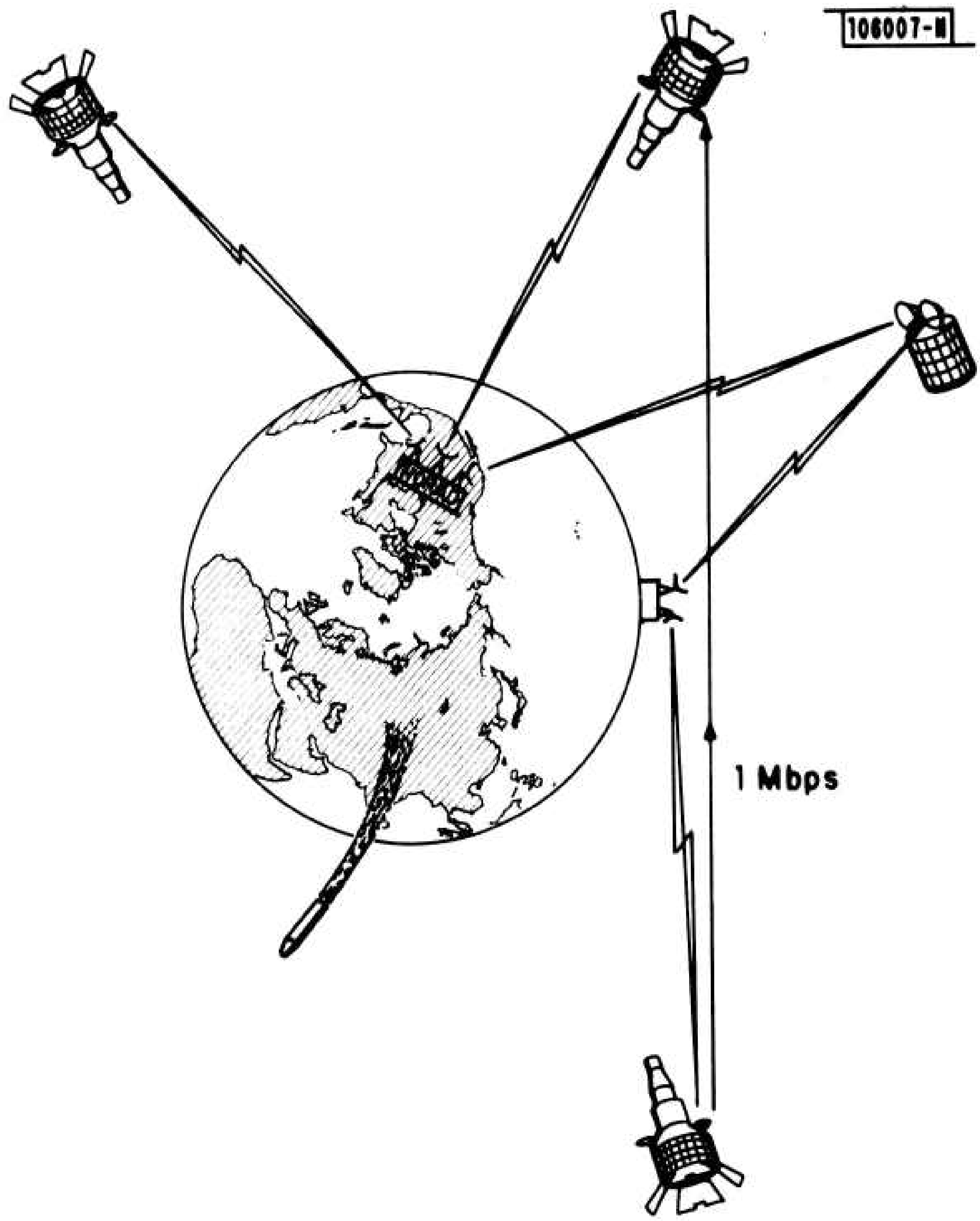

Fig. 1.5. The DSP system. A space data relay link for mission data could improve system survivability.

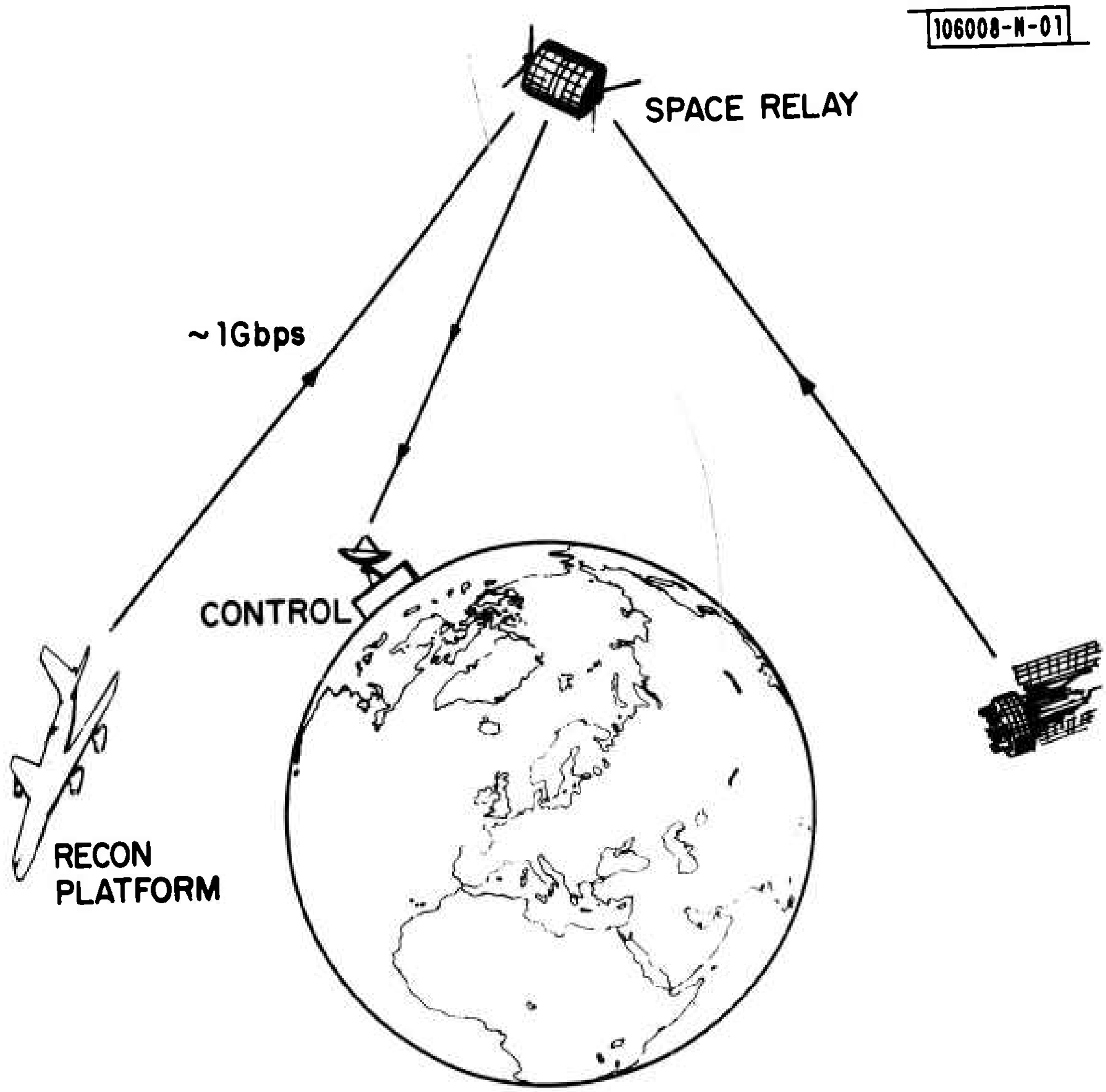

Fig. 1.6. Some near-term requirements for high-rate space data relay links

Recognizing that fiscal considerations alone will preclude TDRSS-like system, this report attempts to lay the ground work for an alternate space data relay architectural plan. It is based on the notion that the C^3 network for our space resources can be distributed among the satellites themselves, rather than being a separate and distinct entity such as the SCF now is or as a TDRSS-like data relay network would also be.

1.2 DISTRIBUTED NETWORKS

This approach is called the "Distributed Network" to distinguish it from the SCF and TDRSS, which are classified as "Centralized Networks". The Distributed Network is based on the prospect that a family of standardized data relay packages (or "Standard Nodes," Fig. 1.7) can be developed to fly as secondary payloads on a variety of high-orbiting satellites. These can provide data relay service to other satellites of the same or other missions. These "Standard Nodes" would be interoperable and have enough built-in flexibility to allow networking them in different ways to meet different situations as they arise: new nodes are added, old ones fail, the coverage requirements change, etc. Such a network could evolve, beginning with high-priority users only, and gradually expanding until all space resources are served. A significant consideration is that the funding of such a network could be spread over many years.

A space C^3 network distributed among user satellites should be inherently more survivable than a network structured around large, dedicated data relay satellites. An equally important consideration is the survivability of mission ground segments. Each mission has, in addition to its satellites, one or more ground control centers or data processing centers. Presently, these centers are mostly clustered in one location (at the site of the master control station of the ground-based network). The distributed network considered here would allow these ground assets to be completely dispersed (even transportable), further enhancing overall mission survivability. Figure 1.8 summarizes the points of comparison between the distributed and centralized networks. These points are expanded upon in the following sections.

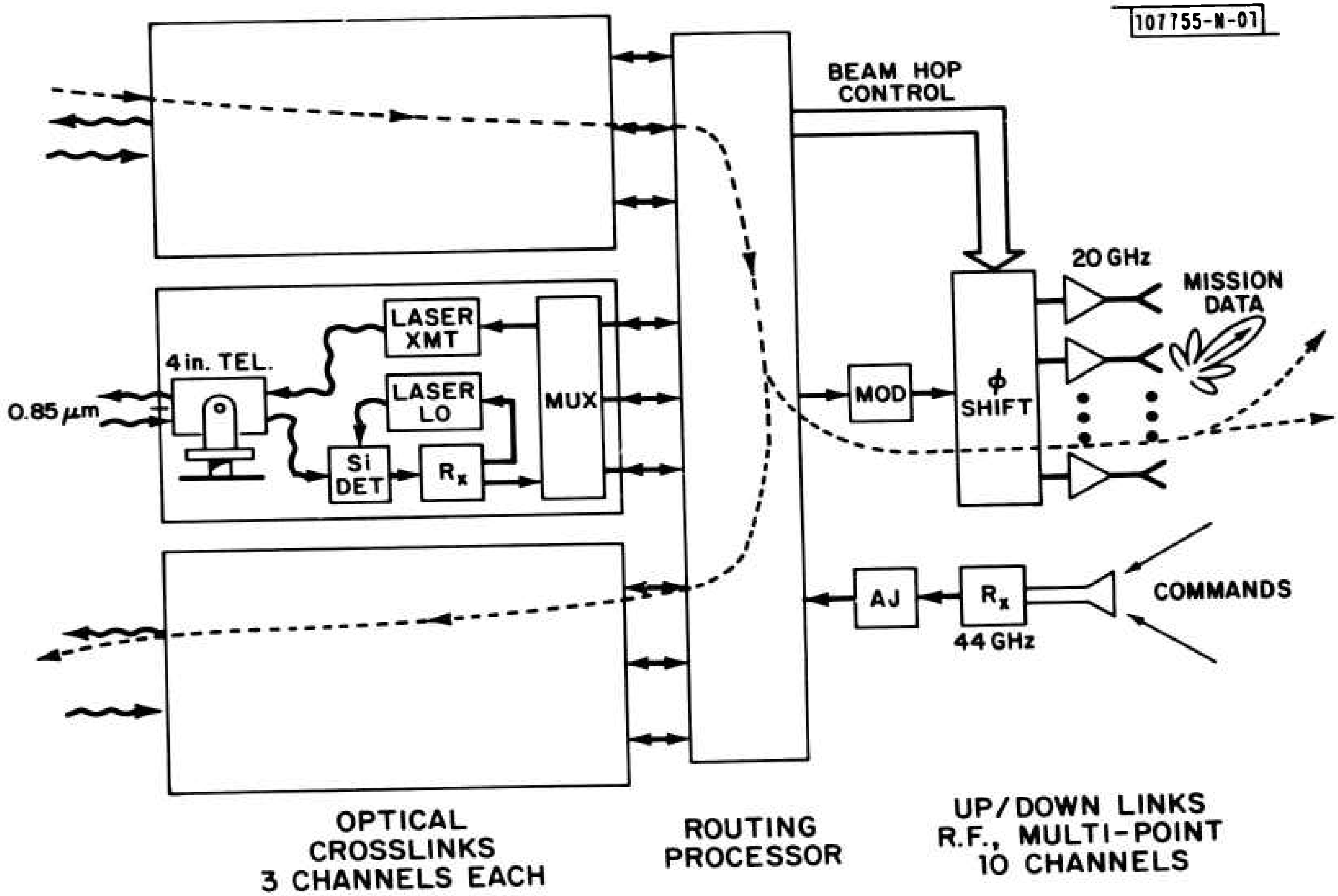

Fig. 1.7. A "Standard Node" for the Medium Rate Mission Data (10 Mbps) class of service.

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	CENTRALIZED	DISTRIBUTED
SPACE SEGMENT	DATA RELAY SATELLITES	PACKAGES ON HOST SATELLITES
GROUND SEGMENT	SEVERAL LARGE NODES	COMPLETELY DISTRIBUTED
GROWTH/TRANSITION	BLOCK CHANGES	EVOLUTIONARY
INITIAL COSTS	HIGH	LOW
ULTIMATE COSTS	HIGH	PROBABLY HIGHER
SURVIVABLE	LESS	MORE
FLEXIBILITY	SENSITIVE TO INITIAL REQUIREMENTS	ADAPTABLE TO CHANGING REQUIREMENTS

Fig. 1.8. Comparing the characteristics of centralized and distributed space data relay networks.

1.3 REPORT SUMMARY

Section 2 discusses the background of the space C^3 problem and defines the terms used in the remainder of the report. Section 3 addresses requirements. It establishes a methodology by which a mass of detailed user requirements can be turned into an overall network specification. This report addresses a particular set of user requirements taken from a recent study sponsored by the ASFC Space Division (Reference 1), however the methods should apply to other reasonable sets of requirements. Section 4 explores a centralized network architecture, which satisfies the example network requirements, and summarizes its characteristics. Section 5 then explores the alternative--a distributed network. An example of such a network is presented and its characteristics are compared with the centralized network. Sections 4 and 5 stress architectural issues. Technology issues are addressed in Section 6. With the continuing maturing of laser communications technology, it appears that a distributed space data relay network will be a technically viable way to fulfill our future military space data relay needs. Political and management issues, which often play a more important role than technology in how future military systems evolve, are outside the scope of this report.

2. BACKGROUND

Space resources have become integral parts of our military force structure and, like any other military force, need a supporting C^3 (command, control and communications) structure to be effective. A data relay network is an important element of the space C^3 structure. This section describes the nature of the space C^3 problem, the functions of a data relay network, and defines the terms used in the remainder of the report.

2.1 A SPACE MISSION

The basic organizational unit of our space forces is the "mission" (or program). The elements of a typical mission are shown in Fig. 2.1. There are usually several mission spacecraft (MSC) per mission. These are divided functionally into "payload" and "bus" (or housekeeping) parts. The mission control center (MCC) on the ground includes both bus and payload control functions. These functional parts may be located together or separately. There may be several separate MCCs for redundancy.

There are three types of communications channel required between MSC and MCCs: mission data, telemetry and command. The latter two are commonly called TTC (telemetry, tracking and command). Mission data rates are typically much higher than TTC rates. Relatively few missions need mission data channels.

Although not indicated in Fig. 2.1, mission data or TTC channels may be "point-to-multi-point" channels to allow more than one MCC site to read out a MSC at one time. These channels may be time-continuous for some missions, although intermittent channels, which allow scheduled contacts with MSC, are sufficient for most missions.

2.2 SPACE C^3 ARCHITECTURE

Since there are many missions, each with several MSC and MCCs, an overall C^3 architecture for space may be represented as in Fig. 2.2. The role of the "data relay network" is to provide the mission data and TTC channels between MSC and MCCs. Although there may exist several distinct sub-networks, the term "data relay network" as used here encompasses the total problem (all channels for all missions).

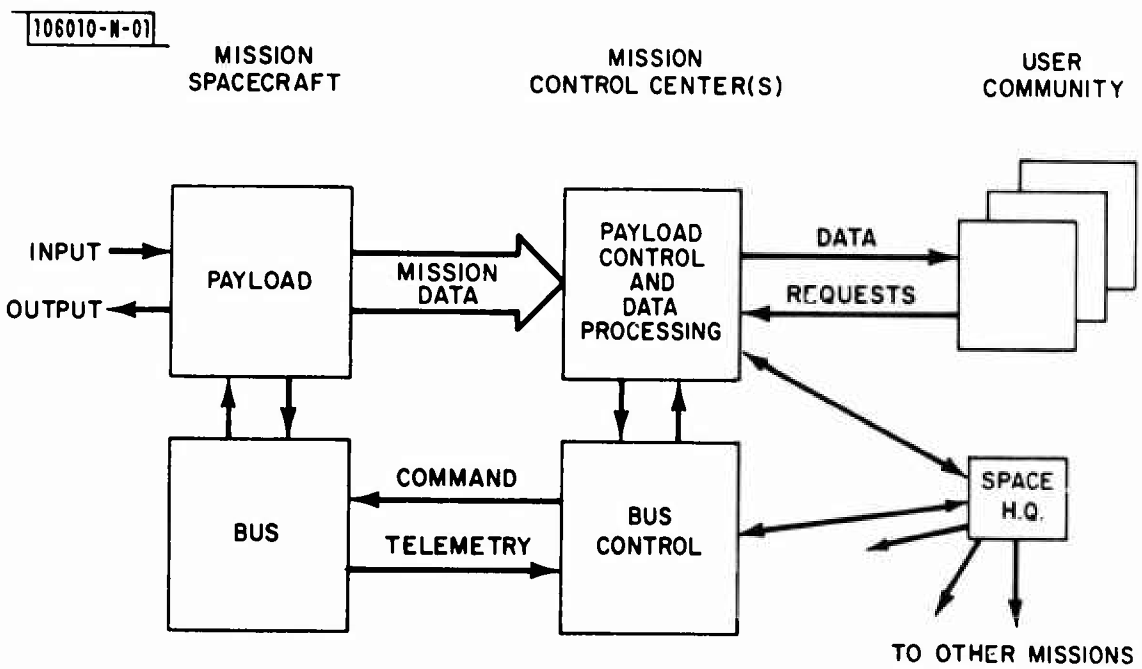


Fig. 2.1. Elements of a typical space mission.

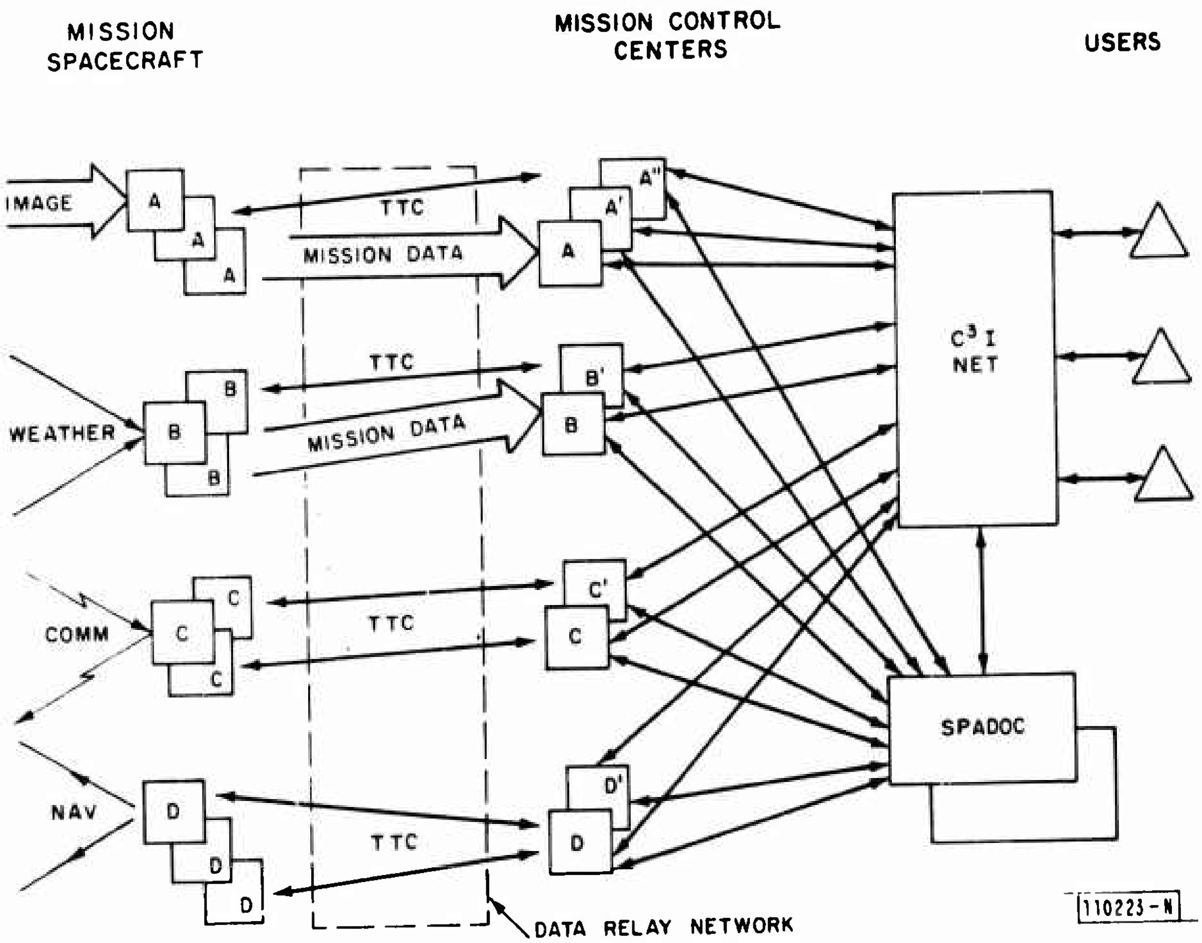


Fig. 2.2. Role of the data relay network in the overall C^3 architecture for space.

The other channels in Fig. 2.2, i.e., those between MCCs and users and SPADOC (Space Defense Operations Center) are not specifically addressed in this report.

Without regard to how the data relay network is implemented, the characteristics listed in Table 2.1 would be highly desirable and are used here as a basis for comparing different network architectures.

2.3 DATA RELAY NETWORKS

As an example of an actual data relay network, Fig. 2.3 shows the USAF Satellite Control Facility (simplified representation), which is a ground-based network. It is presently providing TTC service to virtually all military space missions. (Mission data, where required, is handled by dedicated, special purpose channels.) MSC carry standardized TTC packages for access to the network.

In comparison with the desired characteristics in Table 2.1, the SCF has the following limitations.

Survivability:

- Tracking stations on foreign soil
- Geographic centralization of MCCs.

Responsiveness:

- Limited visibility of low orbits prevents continuous MSC coverage.

Flexibility:

- Terrestrial links cannot handle anticipated mission data rates.

Most of these limitations could be overcome by a network of data relay satellites (a space-based network) as shown conceptually in Fig. 2.4. Some points of comparison of ground and space-based data relay networks are listed in Table 2.2. Figure 2.4 is representative of what will be called a "centralized" space data relay network in this report. In spite of its obvious advantages over the ground-based approach and the fact that NASA has adopted such a network, it has some drawbacks in a military context. These will be explored later in this report and an alternative will be suggested.

TABLE 2.1

DESIRABLE CHARACTERISTICS OF A DATA RELAY NETWORK

1. SURVIVABLE/ENDURING

- Physical:

  Network as survivable as the MSC it supports.

  Permits geographic dispersal of MCCs.

- Electronic:

  Immune to jamming.

2. RESPONSIVE

- Permits Instantaneous MCC/MSC Contact.

  (Example: ASAT attack on one mission detected by another. Warning must be relayed to target MSC via MCCs in near-real time.)

3. FLEXIBLE

- Changing Requirements:

  Can accommodate to unforeseen requirements.

- Changing Technology:

  Can phase-in new technology.

4. AFFORDABLE

- Initial Cost.
- Incremental Growth Cost.
- Total or Ultimate Cost.
- Operating Costs.

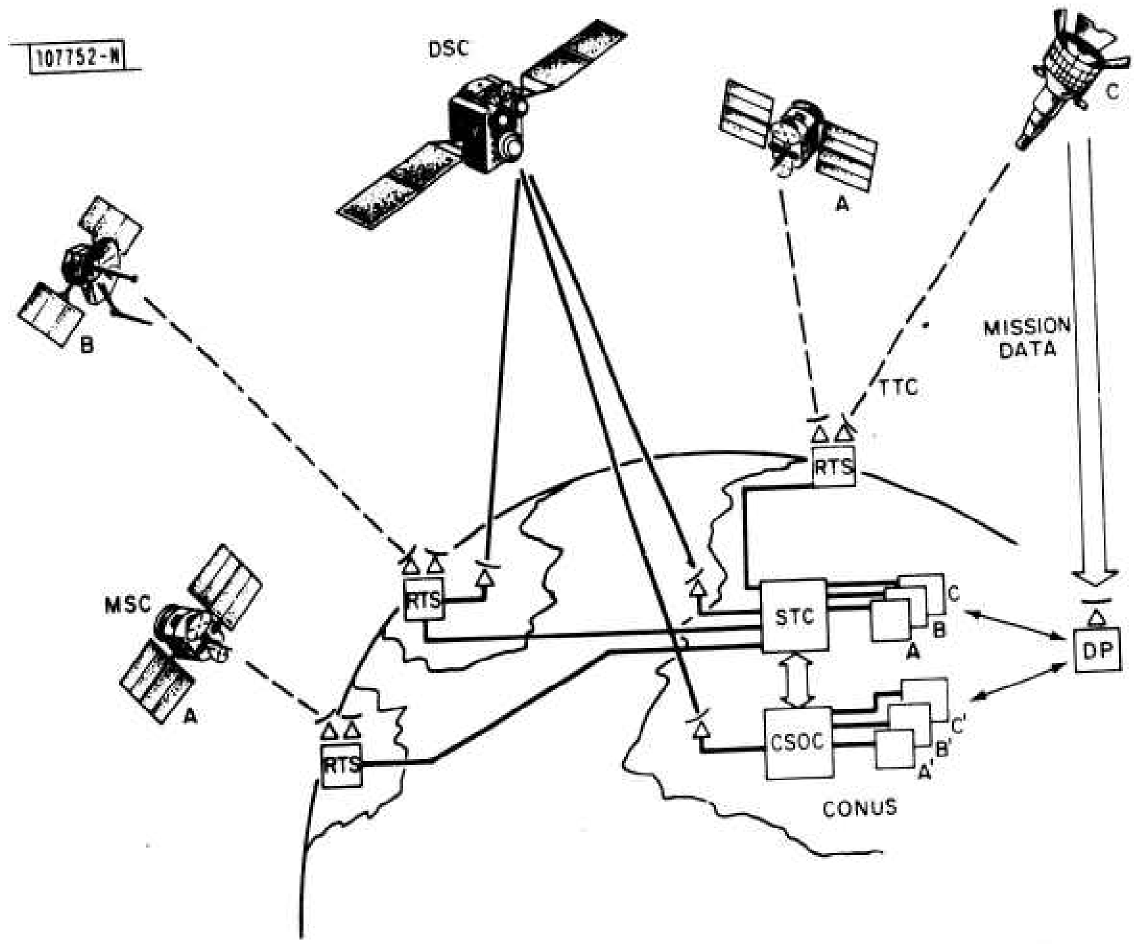


Fig. 2.3. A ground-based data relay network, the USAF Satellite Control Facility (same as Fig. 1.1).

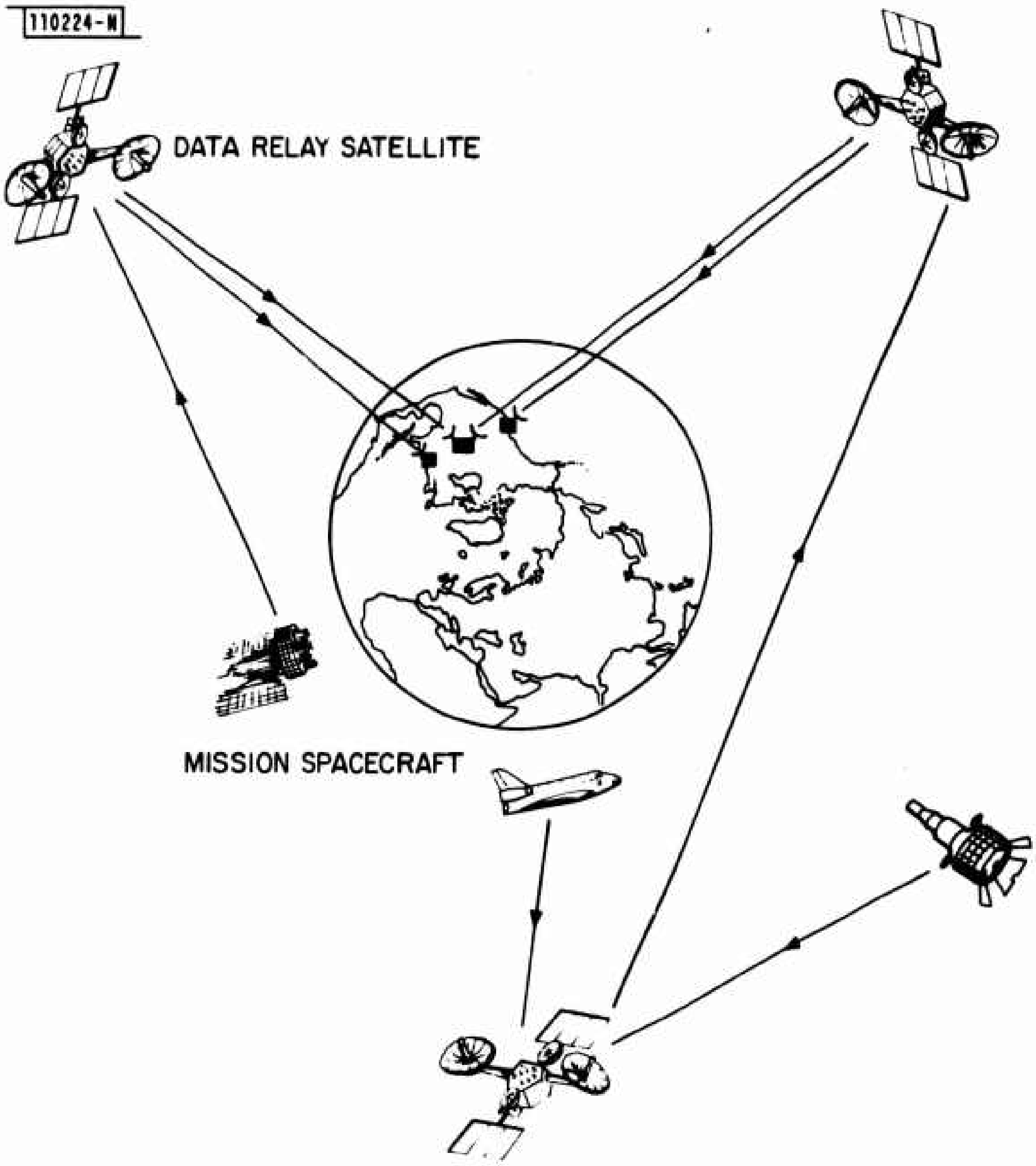


Fig. 2.4. A hypothetical space-based network using dedicated data relay satellites.

TABLE 2.2

COMPARISON OF SPACE-BASED
WITH GROUND-BASED DATA RELAY NETWORKS
(Assume Synch-Orbit Nodes)

- Better Coverage of Low Orbits

  Responsiveness - Real-Time Connectivity

  Survivability - Alternate Paths

- Overseas Sites Not Required

  Survivability

- Allows Distributed Ground Segment

  Survivability - Dispersal

  Responsiveness - MCC Near Users

- Allows Line-of-Sight Connectivity Among Nodes

  Survivability - Alternate Paths

  Adaptability - Reconfiguration

- Anti-Jam Considerations

  Ground-Based Jammers in Main Beams

  Restricts Frequency Choices

- Greater Impact on Mission Spacecraft

  Greater Access Link Range (Typically)

  Smaller Network EIRP and G/T available, therefore

  Larger MSC EIRP and G/T required

  Narrow Beams

  Pointing and Tracking

2.4 NETWORK TERMINOLOGY

Some definitions are needed to expedite the following discussions. We distinguish here between the external and internal descriptions of a network. The external description of a network can be considered as a functional specification for the network and the internal description as the particular realization by which the specification is fulfilled.

External Description: The network is viewed as a "system" (black box) completely described by its inputs and outputs as shown in Fig. 2.5.

1. Access Port: Network input port. The predominant data flow is from MSC to MCC; therefore "input port" refers to the MSC/network interface port. In Fig. 2.3 the tracking station antenna is the access port. In Fig. 2.4 it is the data relay satellite antenna.
2. Access Link: MSC-to-network connection. It would be a downlink in Fig. 2.3 or a crosslink in Fig. 2.4.
3. Exit Port: Network/MCC interface point.
4. Channel: A communications path through the network. Point-to-multi-point channels as shown in Fig. 2.5 are allowed.
5. Contact: An interval of MSC/MCC communication.
6. Network Control: Includes all functions required to establish contacts such as channel switching, spatial acquisition of the access link, etc.

Internal Description: Internally the network is described by a topological diagram (as in Fig. 2.6) consisting of nodes connected by links.

7. Link: A communications medium (microwave, cable, etc.) capable of carrying one or more channels. A link may be an access link, exit link or trunk link as in Fig. 2.6(a). Trunk links are those which do not cross the network boundary.
8. Node: An intersection of two or more links. A channel switching

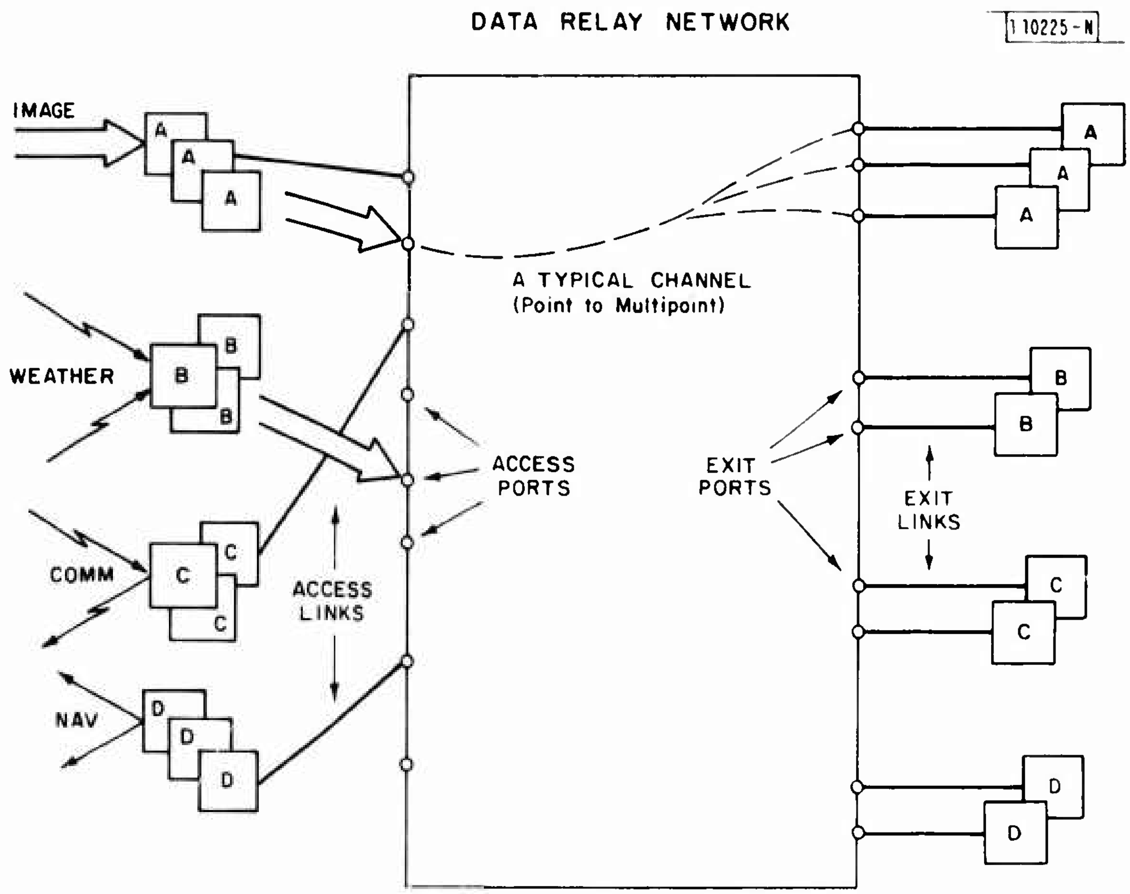


Fig. 2.5. Input/Output description of a data relay network.

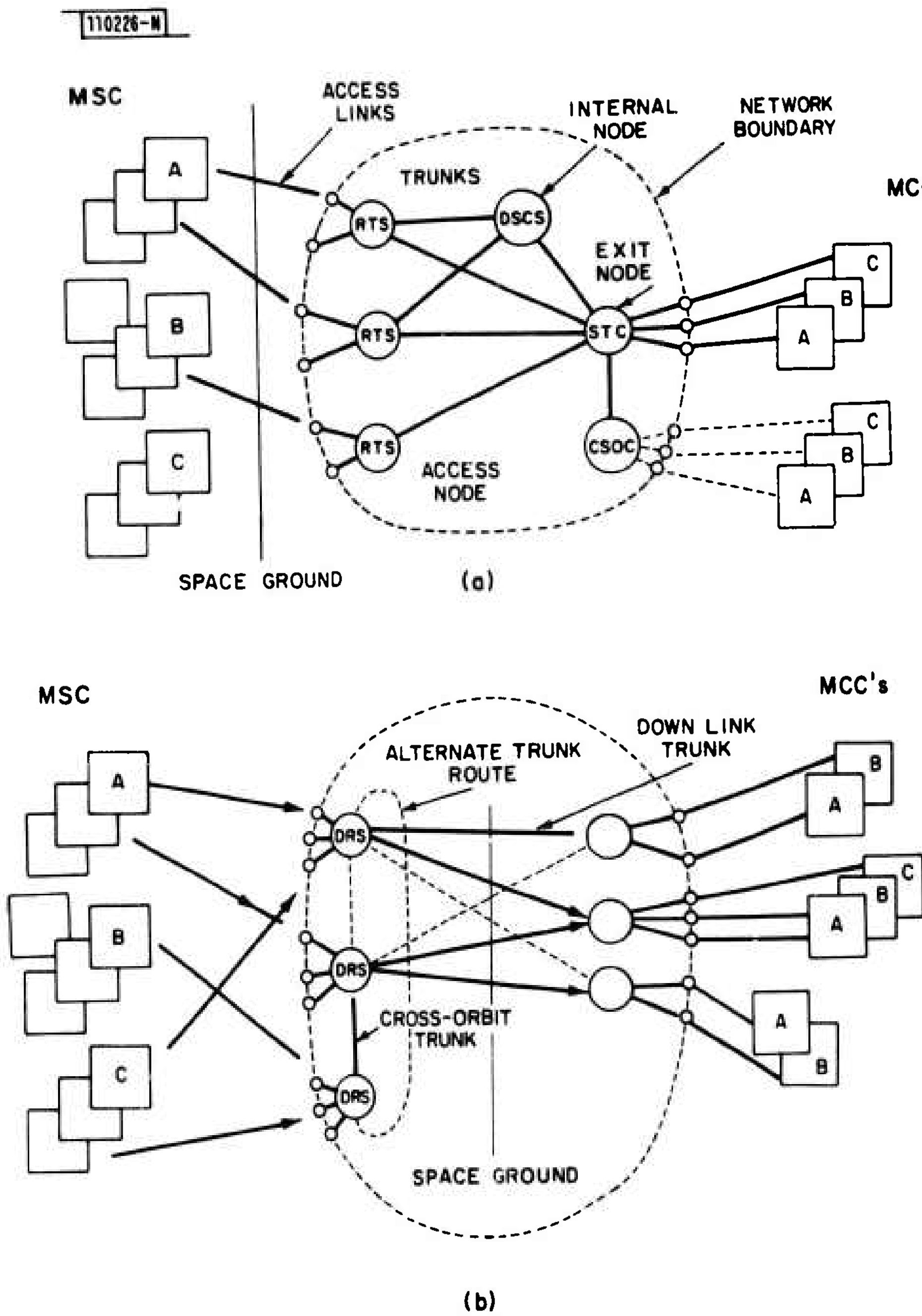


Fig. 2.6. Topological description of data relay networks. (a) The SCF network, (b) The space network of Figure 2.4.

capability is implied. Nodes can be access nodes, exit nodes or internal nodes as in Fig. 2.6(a).

9. Central Node: A node through which all channels pass. There may be more than one central node per network.

2.5 CENTRALIZED AND DISTRIBUTED NETWORKS

Given a desired set of network input/output characteristics (a functional specification), the topology by which the network is realized can range from totally centralized (Fig. 2.7(a)) to totally distributed (Fig. 2.7(b)). Historically, communications networks have tended toward a centralized topology, the incentive being to minimize transmission cost per circuit-mile by multiplexing many circuits together into large trunk links. Generally, one 10 Mbps link is less expensive than ten 1 Mbps links. This approach leads to a topology with a minimum number of nodes similar to Fig. 2.7(a).

At the other extreme, in a totally distributed network, all user terminals would become network nodes, interconnected by direct links carrying one or a few channels each. Fig. 2.7 illustrates two important features of the distributed network relative to the centralized one. First, data may flow across mission boundaries. In the example a spacecraft of mission B is shown relaying data from a mission A spacecraft. Second, the network control strategy is inherently more complex in a totally distributed network. The trunk configuration must be dynamic to accommodate MSC motion, whereas in the centralized network MSC motion is readily accommodated by dynamic access links. The nodes and trunks remain static.

In spite of these apparent disadvantages, a distributed space data relay network may offer some advantages in a military context in terms of greater survivability, lower incremental costs, and an easier evolution or transition from current practices. Later we will examine a distributed network topology that lies between the two extremes of Fig. 2.7 and incorporates some of the advantages of both.

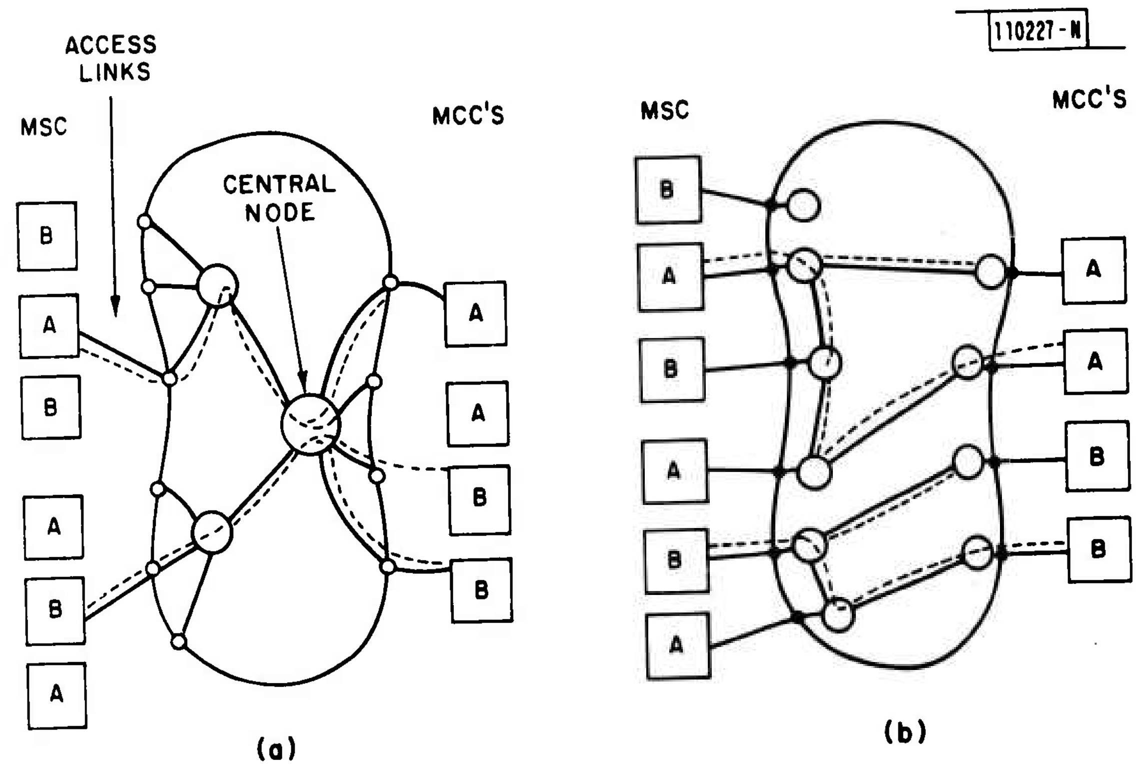


Fig. 2.7. Two classes of network topology (a) centralized (b) distributed. These represent the two extremes of possible network configurations.

2.6 NETWORK ORGANIZATION AND EFFICIENCY

A network can be organized as a single, multi-mission network or as a number of mission-specific sub-networks as shown in Fig. 2.8. In the first case (shared), all access ports are shared among all using MSC. Any MSC can address any port. In the second case access ports and exit ports are assigned to specific missions. A significant difference is that in a shared network every exit port must be able to connect to every access port. In a mission-specific network, exit ports need only connect to access ports of the same mission. This distinction bears on the total number of trunk links required and thus on the cost of the network. It will be a significant consideration in the case of a distributed ground segment (many widely separated MCCs).

Another significant difference is that a shared network may need fewer access ports. This is true when it serves a large population of low duty-cycle user spacecraft. Consider an example where there are 10 missions with 10 MSC each and all MSC require a 20 percent contact duty cycle. The average total data rate is 20 channels; however, to allow for traffic peaks the network must have more than 20 access ports. For example, 99% availability (3σ peaks) could be provided by a shared network with 32 ports (see below). If each mission had its own network, a total of 60 access ports would be needed to give equivalent service. Therefore network sharing effects a 50 percent savings in installed capacity. At the other extreme, if the user MSC are high duty cycle (say 100%), then 100 ports are needed in either case.

Generally speaking, therefore, a shared network for low duty cycle users will have higher efficiency, (therefore lower cost) than mission-specific networks. For high duty-cycle users, there is no efficiency advantage in sharing and mission-specific networks may in fact be cheaper because of the smaller number of downlinks, particularly when multiple distributed MCCs are required.

The above example makes the simplifying assumption of Poisson statistics for network traffic. Under this assumption the contact duty cycle is interpreted as the probability, p, that a particular MSC is communicating at a

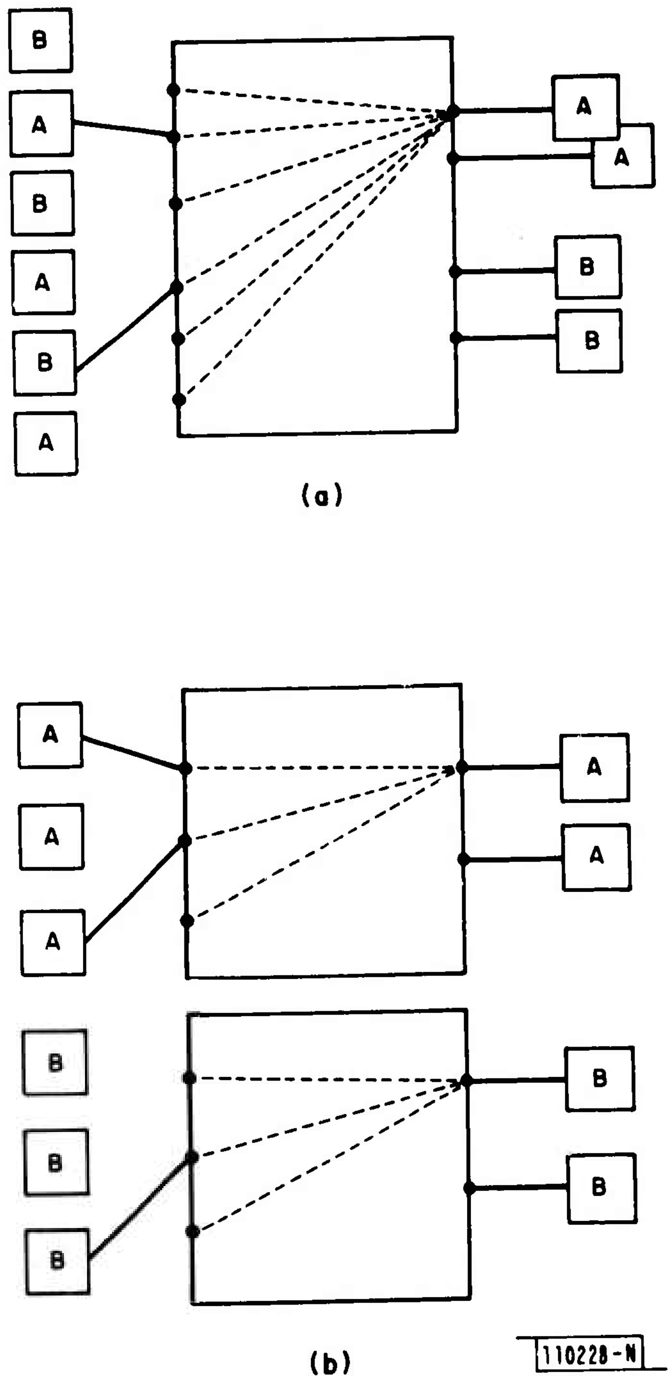


Fig. 2.8. Two forms of network organization, (a) a shared or multi-mission network, (b) seperate mission-specific sub-networks.

particular time. The mean total data rate is Np, where N is the number of MSC. The standard deviation of the total data rate is $\sigma = \sqrt{Np(1-p)}$. For $p = 0.2$ and $N = 100$, $Np = 20$ channels, $3\sigma = 12$ channels, and the network therefore requires 32 channels (or access ports) to accommodate 3σ traffic peaks.

3. NETWORK REQUIREMENTS

In the last chapter we distinguished between external and internal network descriptions. To proceed we now want to adopt a realistic set of specifications (i.e., an external description) for a space data relay network. Then, in the next two sections, we will examine two different internal realizations (topologies) based on the centralized and distributed approaches defined in Section 2.5.

Concerning the baseline "specs" or requirements we will be using for this discussion, they are projected at least 10 years into the future (a typical space program gestation period). Although based on the best information available, they are fuzzy at best, and conclusions that depend strongly on them would be suspect. This is why "flexibility" was identified as a desirable trait in Table 2.1. We are seeking a network realization that depends as little as possible on initial assumptions about requirements.

3.1 THE SCF MISSION MODEL

The input data for this study are provided by Table 3.1 (Ref. 1). Of several requirements models presented in the referenced study, this one was most nearly geared to the mid 1990s.

The mission model lists the missions expected to be on-line, the number of MSC for each, TTC and mission data rates, the number and length of contacts per day, priority and MSC orbits. The column labeled "Mission Data Entry Regions in CONUS" specifies the number and location of MCCs (for some missions). This mission model assumes five large ground stations, each serving a separate CONUS region.

3.2 CLASSIFICATION OF USER REQUIREMENTS

What is needed at this point is a systematic method for extracting an appropriate set of network specifications from the detailed mission model information. A network specification is an "external" description; i.e., the number and location of access ports and exit ports.

TABLE 3.1

SATELLITE CONTROL FACILITY MISSION MODEL
(MODEL 1-C-HI) FROM REF. 1

PROGRAM	Spacecraft/Spares	TLM Data Rate (KBps)	TLM Contacts/Day	TLM Hrs/Contact	TLM Entry Region	CMD Data Rate (KBps)	CMD Contacts/Day	CMD Hrs/Contact	MISSION Data Rate (MBps)	MISSION Contacts/Day	MISSION Hrs/Contact	MISSION Data Entry Regions in Conus	Worldwide BROADCAST Max. Data Rate (Kbps)	Priority	ORBIT Location
S-1	5/2	128	1	24	3,5	1	1	24	1.024	1	24	1,3	--	1	Sync
S-3	8	128	6	0.8	3,5	5	6	0.8	10	6	0.8	3,2	--	1	Med
S-5	4	128	1	24	3,5	10	1	24	10	1	6	3,5	--	1	Low
S-7	4	128	1	24	1,4	2	1	24	10	1	6	1,4	--	2	Low
S-8	1	128	6	0.8	4,5	5	6	0.8	--	-	--	--	--	2	Low
S-9	1	128	6	0.8	4,5	5	6	0.8	--	-	--	--	--	2	Low
S-10	7	128	6	0.8	4,5	5	6	0.8	--	-	--	--	--	1	Med
S-11	4	128	6	0.8	4,5	5	6	0.8	--	-	--	--	--	1	Med
S-12	3	128	1	24	4,5	10	1	24	1000	1	24	5,1	--	1	Sync
S-13	3	128	6	0.8	4,5	10	6	0.8	1000	6	0.8	1,3	--	1	Low
C-1 DSCS	6/3	1	6	0.8	1,5	1	6	0.8	--	-	--	--	--	3	Sync
C-2 FSC	3/2	1	6	0.8	4,5	1	6	0.8	--	-	--	--	--	3	Sync
C-3 SSS	4	1	6	0.8	1,5	1	6	0.8	--	-	--	--	--	3	5X
C-4 NATO	4	1	6	0.8	4,5	1	6	0.8	--	-	--	--	--	3	Sync
N-1 GPS	27/4	4	6	0.8	3,5	3	6	0.8	--	-	--	--	--	3	12-Hr
M-1 DMSP	3/2	10	6	0.8	2,4	1	6	0.8	6	6	0.8	1,2,4	--	1	Low
O-1 STS	1	192	1	24	5	72	1	24	--	-	--	--	--	1	Low
O-2 IUS	1	64	1	24	5	2	1	24	--	-	--	--	--	1	Traj
O-3 STP	2/1	32	6	0.8	4,5	2	6	0.8	20	6	0.8	4	--	3	Low
	3	32	6	0.8	4,5	2	6	0.8	20	6	0.8	4	--	3	Sync
O-4 SDS		1	6	0.8	4,5	5	5	0.8	--	-	--	--	--	2	12-Hr

The first step in this direction is to eliminate unnecessary detail by classifying the information in Table 3.1 by mission into a few broad categories as follows.

1. Channel class: data rates are divided into three broad categories. Each will correspond to a different access port implementation.
2. Space coverage: this refers to the spatial distribution of access ports. Space coverage is determined by a combination of MSC orbit and contact requirements.
3. Capacity: the number of channels (access ports) of each type is determined by the number of MSC and their contact duty cycle.
4. Ground coverage: this specifies the number and location of exit ports and is determined by the desired MCC locations for each mission.

The following sections describe each of these categories in more detail.

3.3 CHANNEL CLASSES

The data rates in Table 3.1 are grouped into three broad categories, each with a designation and nominal data rate as shown in Table 3.2. It is expected that these channel classes will reflect natural technology breakpoints; that is, each class will be realized by a different technique. (See Section 6). For the later architectural discussions, all channel types have been defined as including a 10 kbps "forward" path (MCC to MSC) for spacecraft command and order-wire purposes.

3 4 SPACE COVERAGE

This refers to the spatial distribution of access ports required by a mission. It is determined by MSC orbit and contact duration. The access ports are attached to access nodes. There can be any number of access nodes in a network, but since three is the minimum number that can provide total coverage of all earth orbits, we will classify the space coverage requirement of a

TABLE 3.2

CHANNEL CLASSES

Designation	Forward Data Rate	Return Data Rate
TTC (Telemetry, Tracking & Command)	~ 10 kbps	~ 200 kbps
MRM (Medium Rate Mission Data)	~ 10 kbps	~ 10 Mbps
HRM (High Rate Mission Data)	~ 10 kbps	~ 1 Gbps

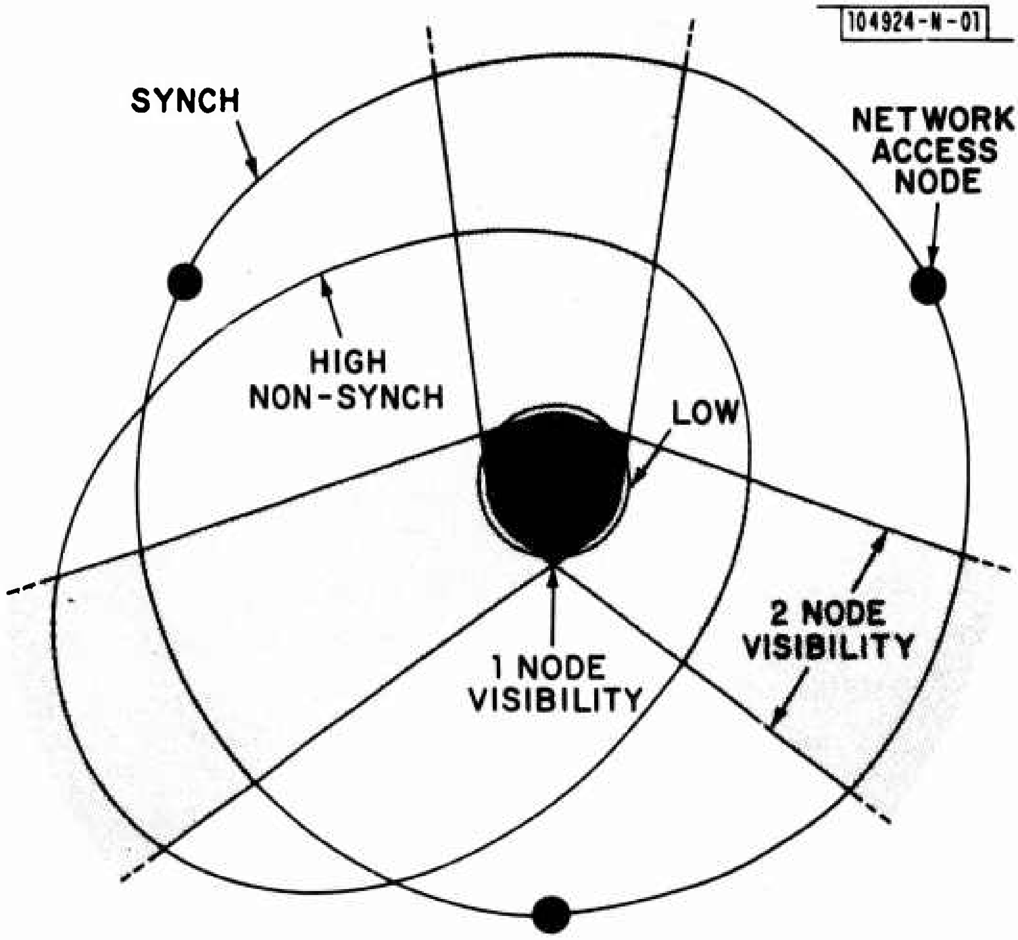
mission as 1-Node, 2-Node or 3-Node. For this study we will assume synchronous-orbit access nodes. (The conclusions of this study can be extended to non-synchronous cases).

3.4.1. ORBIT CLASSES

To proceed, three orbit classes are defined: low, high non-synch, and synch. The distinctions between them are illustrated in Fig. 3.1. Assuming three access nodes separated by 120°, the regions of single-node visibility extend to approximately 2000 nautical miles altitude. Orbits passing through them are defined as "low". "High non-synch" orbits are those which pass through 2-node visibility regions. A "synch orbit" MSC may lie in either a 2-node or a 3-Node visibility region.

3.4.2. CONTACT CLASSIFICATION

The contact durations in the mission model can be classified as either "intermittent" or "continuous". An intermittent contact is one that can be completed via a single access node. For example, a low-orbit MSC has an orbit period of about 90 minutes. It is in view of a particular node for about 50 minutes. A required contact duration of less than 50 minutes would therefore be classified as intermittent. An intermittent contact requirement implies



MINIMUM CONFIGURATION

ORBIT \ DUTY CYCLE	INTERMITTENT	CONTINUOUS
LOW	1 NODE	3 NODE
HIGH, NON-SYNCH	1 NODE	2 NODE
SYNCH	2 NODE	2 NODE

Fig. 3.1. Orbit classification. "Low" orbits pass through 1-Node visibility regions. "High" orbits do not.

the need for only one access port per channel. On the other hand, a continuous contact requirement, in the case of low-orbit MSC, implies that three access ports are needed per channel. (The two unused ports can be utilized for other purposes in a shared network, as we shall see.)

The orbit class and the contact requirement together determine the space coverage requirement as shown in Table 3.3. Again, this is a way of specifying the minimum acceptable number of nodes. A network can have more than three nodes and still be classified as either a 1, 2 or 3-Node network according to the coverage of mission spacecraft it provides.

3.5 CAPACITY

Capacity refers to the total number of network channels required. This in turn determines the number of access ports required. Table 3.4 shows how capacity is estimated from the mission model data. For example, mission S-13 has 3 MSC. It requires 6 TTC and 6 MRM contacts, of 0.8 hour each, per day per MSC. The MSC contact duty cycle is therefore 20 percent. The average data rate per MSC is equivalent to 0.2 TTC channels plus 0.2 MRM channels. The mission average data rate is 0.6 channels each, therefore S-13 is allocated 1 channel of each type in the network capacity determination.

This method of estimating capacity is adequate for the purposes of this study. An actual network design would entail a detailed statistical analysis to determine the number of channels required. As described in Section 2.6, economies can often be realized by sharing a network among as many users as possible.

From Table 3.4, the required total capacity is 45 TTC, 13 MRM and 4 HRM channels. This study will assume that telemetry data are submultiplexed onto MRM and HRM channels wherever possible as shown in Fig. 3.2. The MRM and HRM missions would still have access to the TTC network for backup and initial acquisition, but routine TTC traffic would be off-loaded from the TTC net. By this assumption, the TTC capacity is reduced from 45 to 30 channels as shown in the "Residual TTC" line of Table 3.4.

TABLE 3.3

SPACE COVERAGE REQUIREMENT AS DETERMINED BY
ORBIT CLASS AND CONTACT REQUIREMENT

ORBIT \ CONTACT	INTERMITTENT	CONTINUOUS
Low	1 Node	3 Node
High, Non-Synch	1 Node	2 Node
Synch	2 Node	2 Node

In Table 3.4 missions S-5 and S-7 are peculiar in that each requires 4 TTC channels, but only 1 MRM channel. This may be an error in the mission model, but it will not affect our conclusions.

The number of access ports is closely related to, but not necessarily equal to, the capacity. For example, Figure 3.3(a) shows two mission-specific networks. Mission B has a 1-channel, 3-Node requirement (continuous contact to a low-orbit MSC). This leaves unused access ports which could satisfy mission A's requirement in a shared network as in Fig. 3.3(b). In the latter case the access ports are fully utilized; however, mission A must now tolerate periodic channel interruptions as the mission B channel is handed over from node to node. There is obviously a tradeoff between efficiency and network control complexity in a shared network.

3.6 GROUND COVERAGE

This refers to the number and distribution of exit ports. Ground coverage requirements affect the number and distribution of space nodes, the number of cross orbit trunks needed and the number of downlink trunks.

Four classes of ground coverage are defined as shown below and in Fig. 3.4.

1. Overlap Coverage: All exit ports (MCCs) lie within the mutual visibility region of two synchronous-orbit nodes (Fig. 3.4(a)).

TABLE 3.4

DETERMINATION OF REQUIRED NETWORK CAPACITY

Mission	TTC 200 kbps		MRM 10 Mbps		HRM 1 Gbps		Space Coverage
	Average Data Rate (Channels)	Channels Assigned	Average Data Rate (Channels)	Channels Assigned	Average Data Rate (Channels)	Channels Assigned	
S-12	3.0	3			3.0	3	2
S-13	0.6	1			0.6	1	1
S-1	5.0	5	5.0	5			2
S-3	1.6	3	1.6	3			1
M-1 DMS	0.6	1	0.6	1			1
0-3 STP	0.4	1	0.4	1			1
0-3 STP	0.6	1	0.6	1			2
S-5	4.0	4	1.0	1			3
S-7	4.0	4	1.0	1			3
S-8	0.2	1					1
S-9	0.2	1					1
S-10	1.4	3					1
S-11	0.8	2					1
0-1 STS	1.0	1					3
0-2 IUS	1.0	1					2
0-4 SDS	0.6	1					1
N-1 GPS	5.4	7					1
C-1 DSCS	1.2	2					2
C-3 SSS	0.8	1					1
C-4 NATO	0.8	1					2
C-2 FSC	0.6	1					1
Total	33.8	45	10.2	13	3.6	4	
Residual TTC	22.0	30					

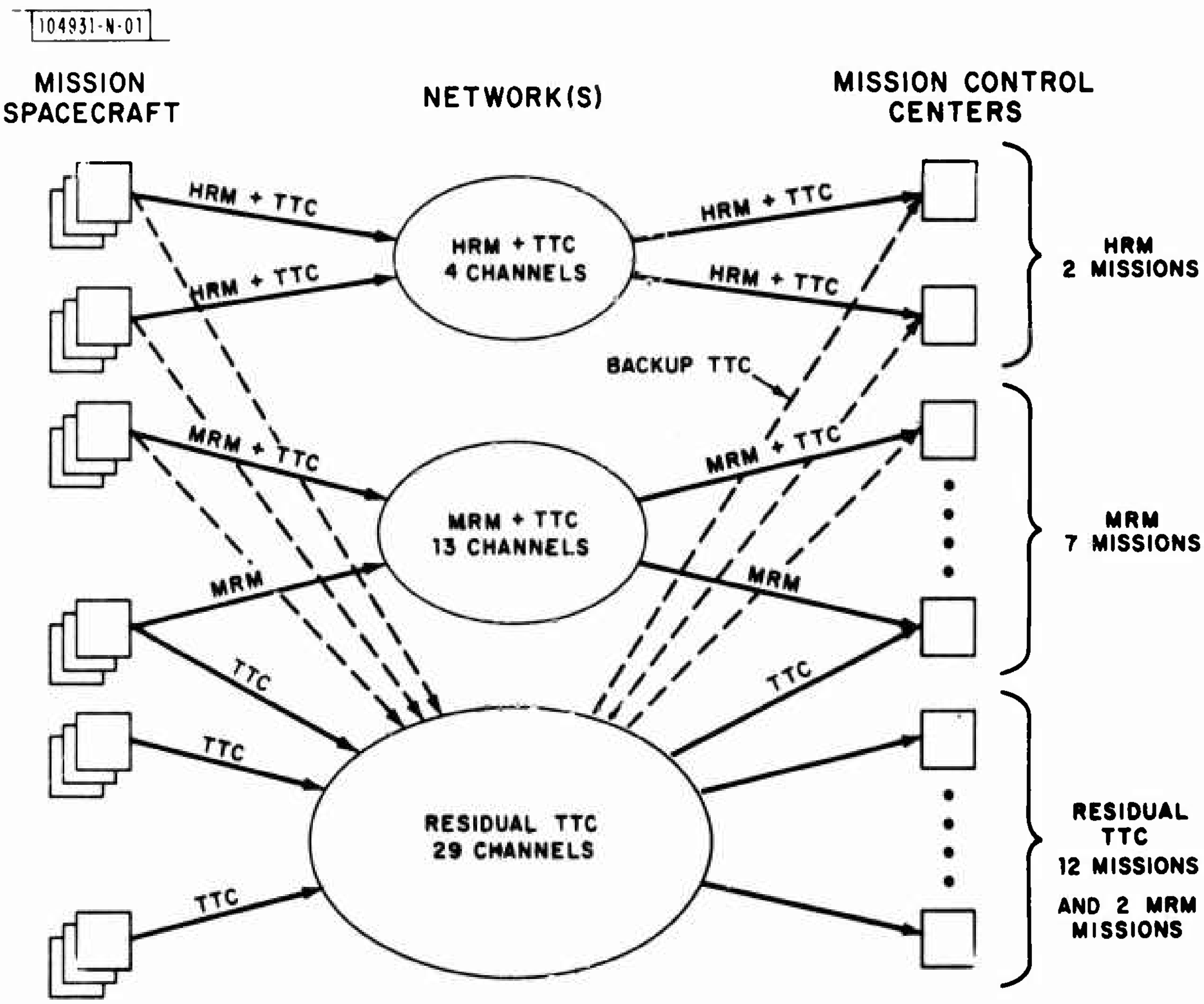


Fig. 3.2. Network capacity requirements and sub-multiplexing of telemetry data.

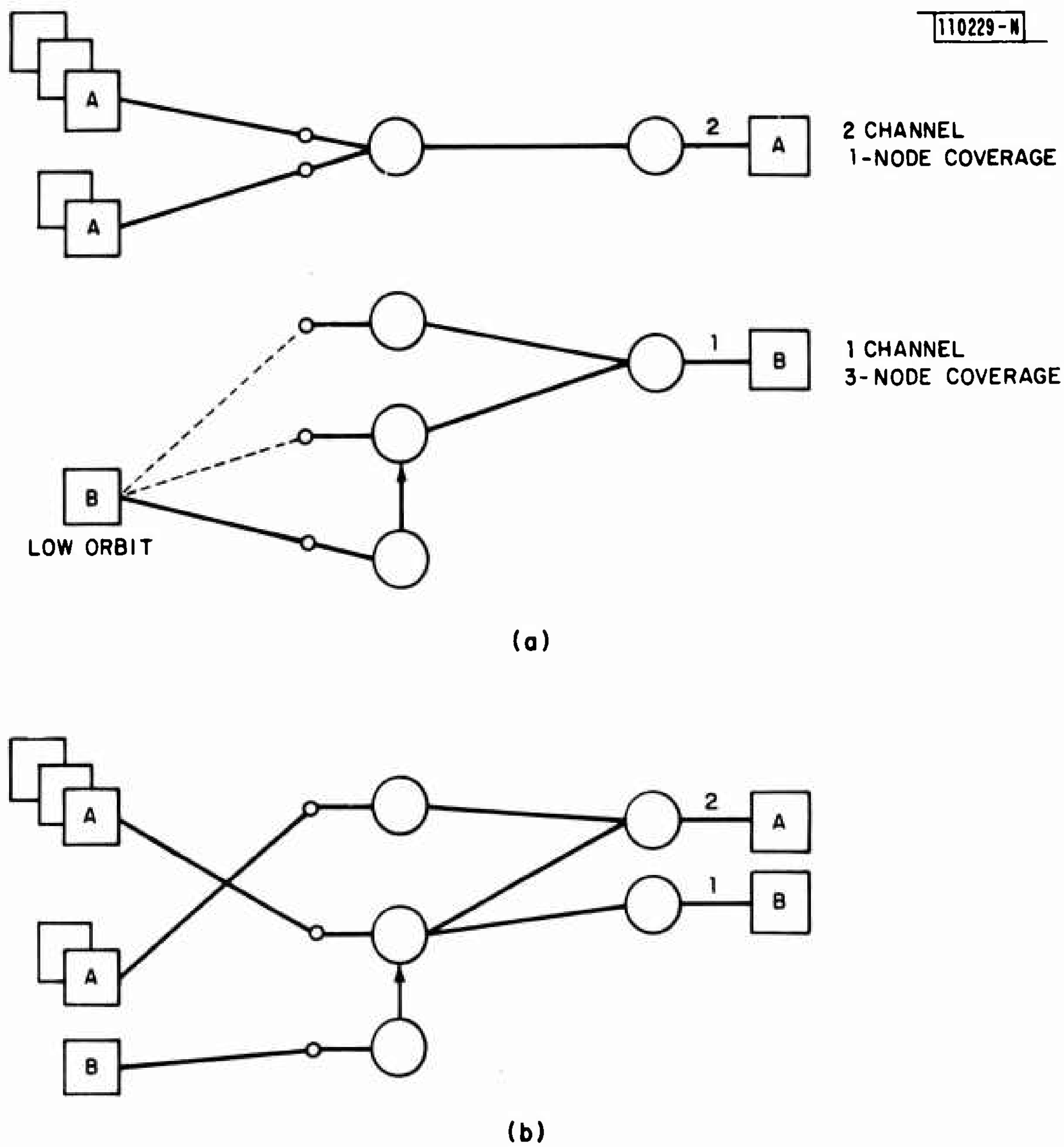


Fig. 3.3. Advantage of a shared network for 3-Node space coverage. The B Channel commutates among three acess ports.

2. 1-Node: The exit nodes extend over the entire visibility region of a synch-orbit node (Fig. 3.4(b)).
3. 2-Node: Even more widely distributed exit ports.
4. 3-Node: Worldwide ground coverage (Fig. 3.4(c)).

In Fig. 3.4 note the trade-off between extended ground coverage and the number of cross-orbit trunk links required.

The mission model used here gives little guidance on ground coverage requirements. It appears to assume that all MCCs are within CONUS, which corresponds to "overlap" ground coverage.

3.7 EXAMPLE NETWORK REQUIREMENT

By the above procedure the mission model data in Table 3.1 can be compressed into the network specification shown in Table 3.5. This will now be used as a baseline to compare two different network realizations (centralized and distributed). Again, these "requirements" represent the most realistic estimates available at the present time. However, they should not be considered firm or fixed.

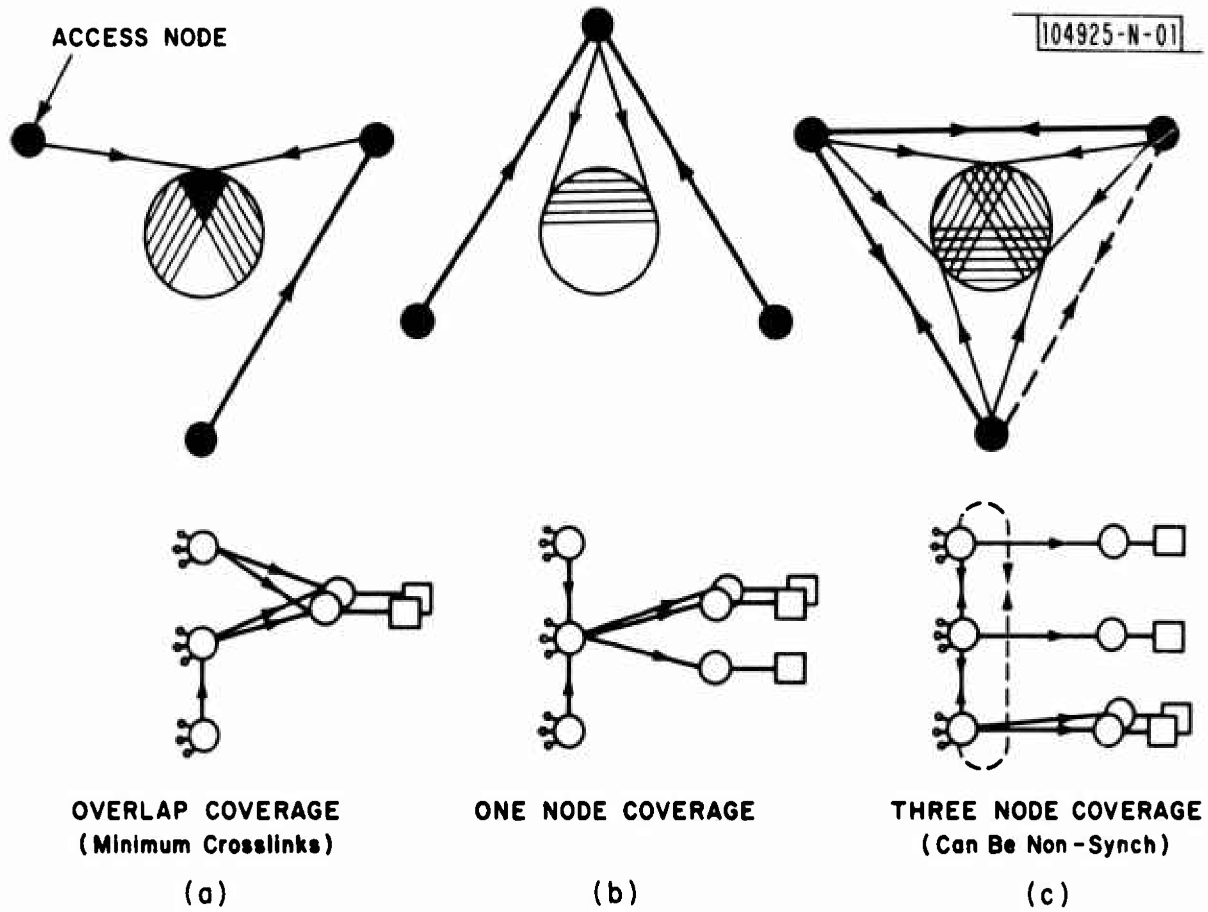


Fig. 3.4. Example of extending the ground coverage pattern of a 3-Node network by adding crosslinks.

TABLE 3.5

NETWORK REQUIREMENT DERIVED FROM SCF MISSION MODEL

SPACE COVERAGE / CHANNEL CLASS	1-NODE	2-NODE	3-NODE	TOTAL CHANNELS
TTC	18	3	9	30
MRM	5	6	2	13
HRM	1	3	0	4

4. NETWORK REALIZATION--CENTRALIZED

The last section addressed the specification, or external description, of a space data relay network. The SCF mission model was used to derive an example set of specifications based on a realistic projection of USAF needs. This section addresses network realization; in this case by the centralized approach. Generally speaking, the centralized approach (Section 2.5) seeks to multiplex individual channels into high-rate trunks to achieve economical transmission and results in a minimum number of nodes. This section covers only the topological aspects of network realization. The technology issues are discussed in Section 6.

4.1 NASA TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

The TDRSS is a good example of a space data relay network that follows the centralized design philosophy. NASA presently operates a ground-based network, the Space Flight Tracking and Data Network (STDN), similar to the SCF. TDRSS is considered a cost effective alternative in that it will supplant most of the STDN stations while providing the higher data rates and extended coverage required by the Shuttle and other new NASA missions. The TDRSS System configuration is shown in Fig. 4.1 and the TDRSS Satellite in Fig. 4.2. A Lincoln Laboratory review recently assessed the suitability of the TDRSS for typical Air Force requirements. Aside from the lack of nuclear hardness and anti-jam capability, a significant mismatch between TDRSS capability and USAF needs was found, as summarized in Fig. 4.3.

4.2 A CENTRALIZED NETWORK FOR USAF REQUIREMENTS

The consideration of TDRSS raises an issue. Given the type of military requirements represented in Table 3.5, is a centralized network similar to TDRSS a viable alternative for the Air Force? To pursue this question, consider Figure 4.4 which shows the topology of one centralized network that would satisfy the requirements in Table 3.5 Since we cannot consider all possible variations, Figure 4.4 attempts to epitomize the whole class of centralized networks in that it has the minimum possible number of nodes and trunks consistent with the requirements.

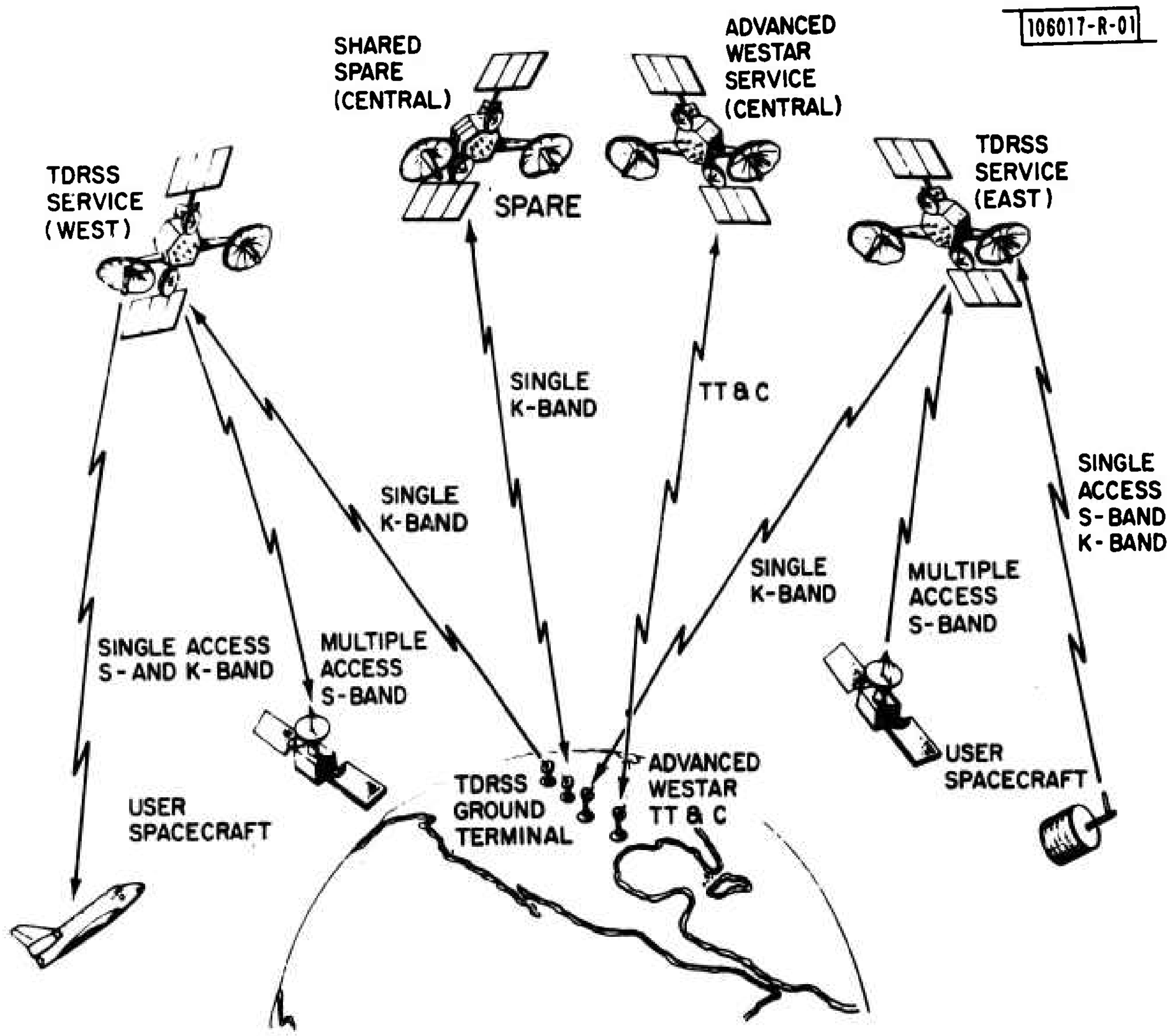


Fig. 4.1. The NASA Tracking and Data Relay Satellite System (TDRSS), an example of a centralized space data relay network.

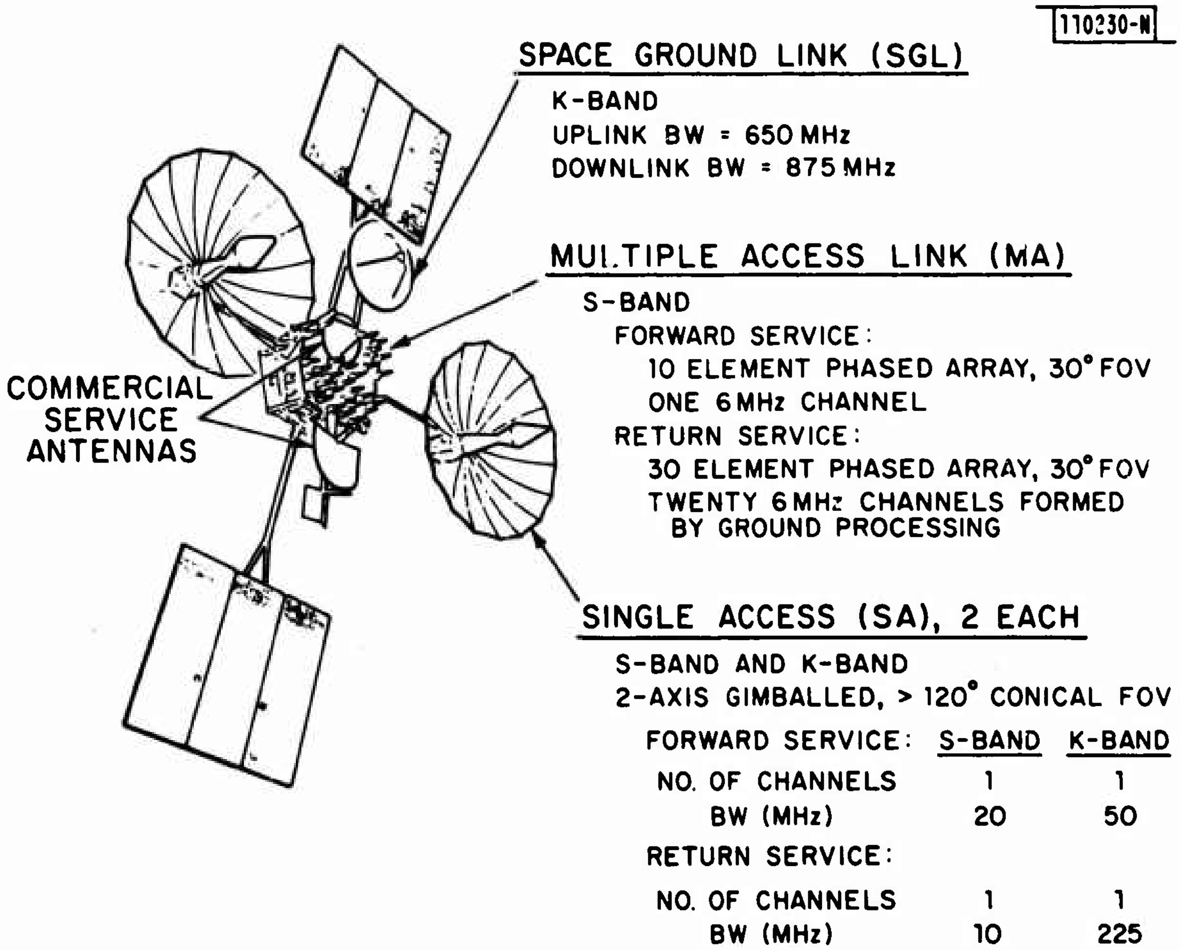


Fig. 4.2. NASA Tracking and Data Relay Satellite. Produced by TRW under contract to Western Union Space Communications Inc. for leased service to NASA.

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REASONS FOR TDRSS/SCF MISMATCH

- DATA RATE OF RETURN LINK MA CHANNELS DOES NOT ACCOMMODATE MAJORITY OF MILITARY USERS

- NUMBER OF FORWARD LINKS IS DEFICIENT

NASA	SCF
20 – 40 USERS LOW EARTH ORBITS MOSTLY LOW RATE DATA	65 – 100 USERS VARIOUS ORBITS MOSTLY MEDIUM/HIGH RATE DATA

Fig. 4.3. Summary of TDRSS capabilities compared to SCF "baseline" mission model (more modest version of Table 3-1).

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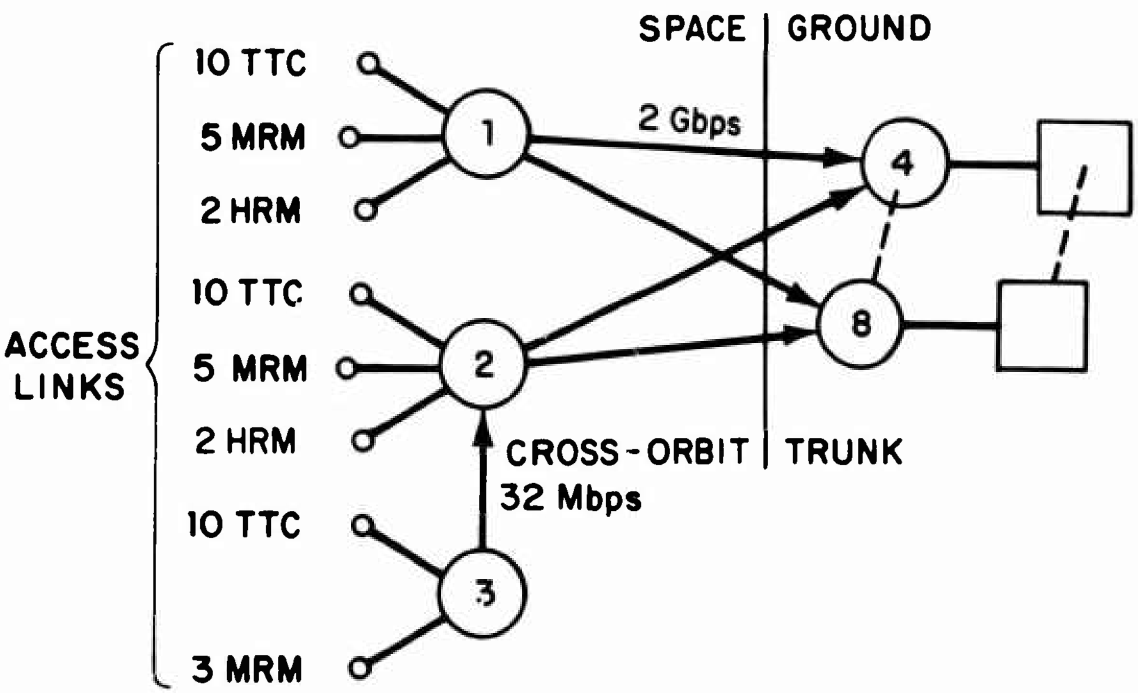
STATED REQUIREMENT:

30 TTC, 13 MRM, 4 HRM
3 NODE SPACE COVERAGE FOR TTC AND MRM
2 NODE SPACE COVERAGE FOR HRM
OVERLAP GROUND COVERAGE (CONUS Only)



MINIMUM NUMBER OF NODES
MINIMUM NUMBER OF TRUNK LINKS
MANY ACCESS PORTS PER NODE
HIGH CAPACITY NODES AND TRUNKS

Fig. 4.4. A centralized space data relay network that would satisfy the example network requirements of Table 3.5.

Figure 4.4 was derived from Table 3.5 as follows.

Access Nodes: Because the mission model includes some missions that need "3-Node" space coverage (Table 3.4), three, equally spaced synchronous nodes are required. Nodes 1 and 2 are CONUS viewing. Node 3 ("blind side") is reached via a cross-orbit trunk.

Access Ports: The following considerations apply in allocating access ports to the 3 nodes. The network is a shared network for maximum efficiency; therefore the number of ports needed is the same as the number of channels (Sec. 3.5). The distribution of ports is arbitrary except that Node 3 must satisfy the "3-Node" requirement in Table 3.5 (9 TTC, 3 MRM). This distribution was chosen because it minimizes the cross-orbit trunk capacity. Note that "10 TTC" represents 10 separate crosslinks. There is a total of 18 crosslinks terminating on Node 2, for example.

Exit Ports: Consistent with the mission model, nodes 4 through 8 represent five exit nodes serving five CONUS regions.

Trunk Links: At each access node the trunk capacity must match the total access port capacity. For example, the cross orbit trunk (32 Mbps) accommodates the 10 TTC ports (200 kbps each) and 3 MRM ports (10 Mbps each) on Node 3. In a shared network all access ports must be capable of connecting to all exit ports of the same channel class (section 2.6). This requirement is satisfied in Fig. 4.4 by making all downlink trunks approximately 2 Gbps in capacity to accommodate multiplexing of the HRM, MRM and TTC channels.

As another example of a centralized network, Figure 4.5 shows a network topology suggested during a recent USAF Space Division study (Ref. 1). This network has a slightly different mix of channel types and has four rather than three access nodes, but otherwise is quite similar to the canonical centralized network model of Fig. 4.4. This example is especially useful because it is accompanied by satellite design studies that give a flavor of physical reality to the topological description. The proposed data relay satellite is shown in Fig. 4.6. It is representative of the class of satellite necessary to fulfill military data relay requirements by a centralized network approach.

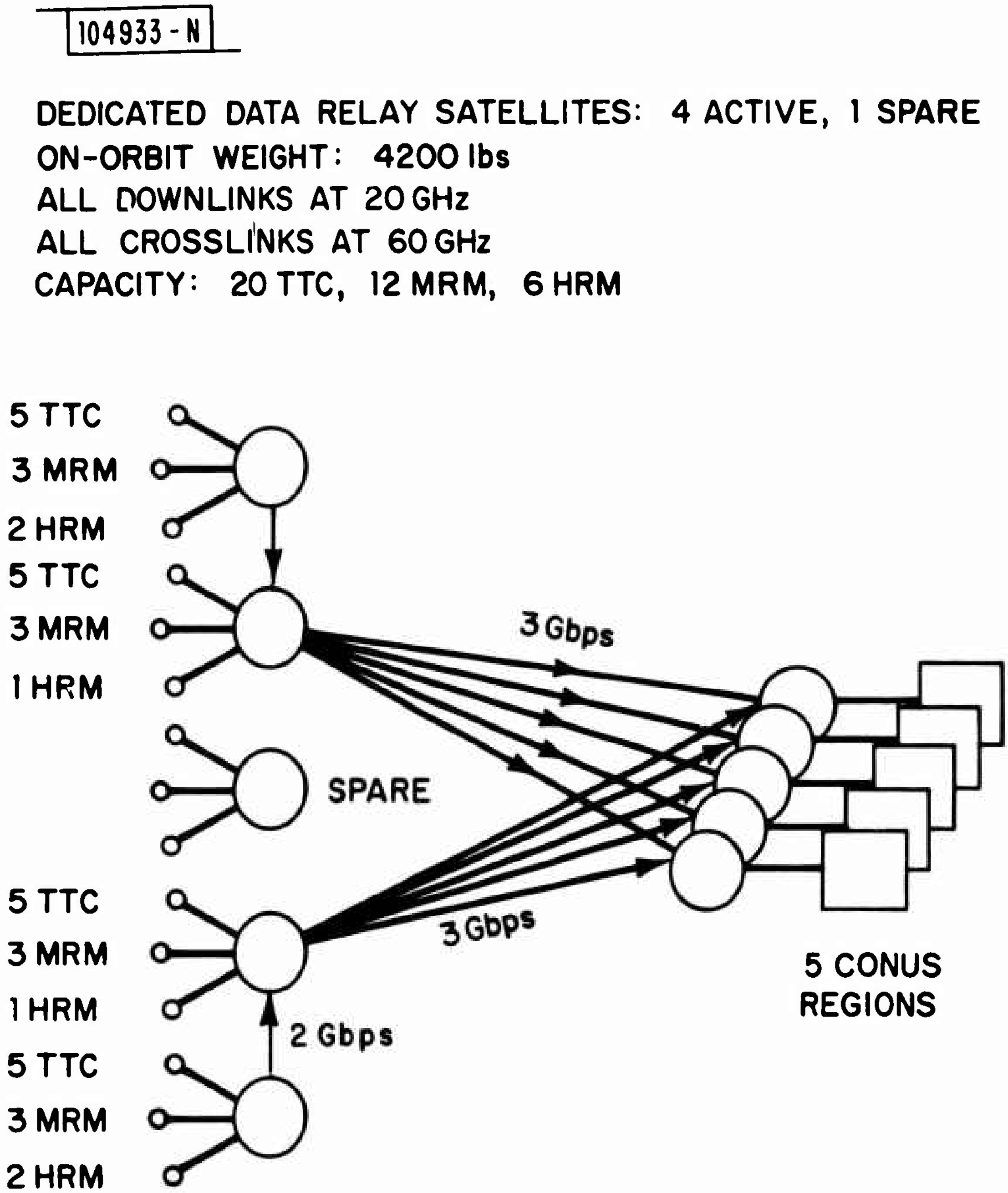


Fig. 4.5. A centralized network proposed in the SCF Upgrade Study (Ref. 1).

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ANTENNA SIZES		SCAN ANGLES (deg)	
(ft)		E–W	N–S
MS ACCESS ANTENNA	8	+80, -35	±25
	3	+80, -35	±30
	3	+80, -35	±30
	3	±30	±30
	2	±80	±30
	2	±20	±20
	2	±20	±20
	4	±80, -35	±25
	4	±35, -80	±25
X-LINK	8	±35	±25
CONUS-MBA	8	0	0

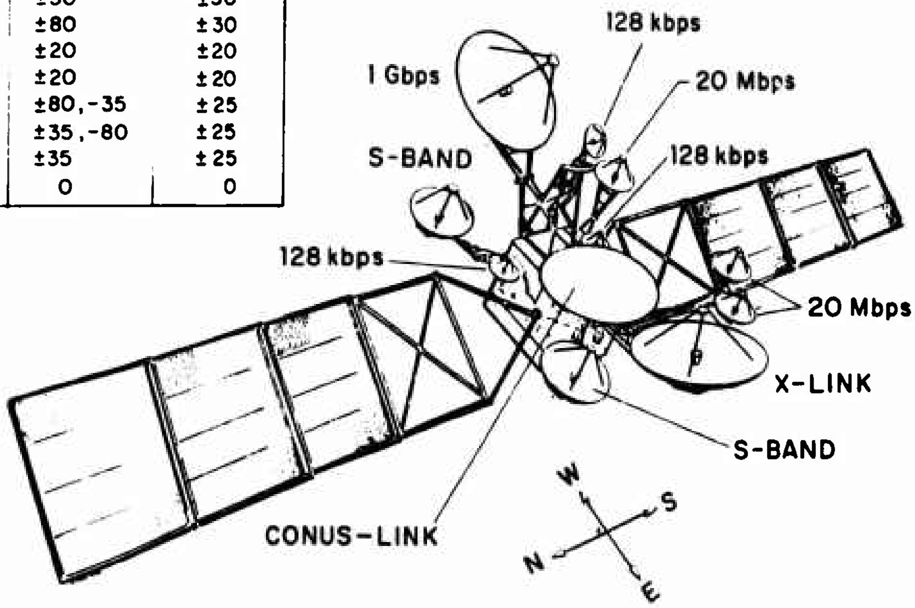


Fig. 4.6. The data relay satellite proposed in the SCF Upgrade Study, based on RF crosslink technology. 4200 lb. (Taken from Ref. 1).

4.3 CHARACTERISTICS OF CENTRALIZED NETWORKS

Of course Fig. 4.6 is just one example of how such a satellite could be realized, but it serves to point out some technical difficulties encountered in matching a centralized network approach to USAF requirements like the ones in Table 3.5.

Such a satellite must have many (10 or more) independently steerable crosslink antennas (or optical apertures in the case of laser communications). The data through-put will be in the multi-gigabit per second class, and several such downlinks must be provided by each data relay satellite.

One can say, independently of design details, that such a satellite would be large and complex by today's standards. Its design would require a detailed specification of user requirements. These requirements would then become essentially frozen early in the program. Typical space systems have a 7 to 10 year gestation period, and the actual user requirements could change substantially before the network became operational. These and other considerations, summarized in Table 4.1, have stymied the acquisition of a space data relay network for military satellites in spite of the obvious limitations of the existing ground-based network.

The next section will explore an alternative approach--a space data relay network based on a distributed architecture.

TABLE 4.1

CHARACTERISTICS OF CENTRALIZED SPACE DATA
RELAY NETWORKS

Topological Characteristics

1. A few large nodes
2. Many access ports per node
3. Few alternate paths

Programmatic Characteristics

1. Dedicated data relay satellites
2. Maximum network efficiency, therefore lowest total cost
3. Large start-up costs
4. Large growth/transition increments
5. Unused capacity in orbit
6. Keyed to a specific set of user requirements
7. Physical survivability of large data relay satellites is an issue

5. NETWORK REALIZATION--DISTRIBUTED

Objections to the centralized network, as applied to typical military requirements, follow mainly from the size and complexity of the data relay satellites. The basic alternatives are: reduce the requirements or divide the data relay satellites into a number of smaller units. A step beyond this second option lies the type of distributed network we will explore in this section. Here the functions of the large data relay satellite will be divided among many small "nodes", of a few channels each. These nodes can be carried as secondary payloads on user spacecraft. Also, the clustering of MCCs near large ground stations will be avoided. Our distributed network will permit the MCC's to be widely distributed over the earth's surface--even transportable.

If it proves feasible, the distributed network would have some distinct advantages over centralized network. Start-up costs would be smaller, growth and transition more gradual, survivability greater, and changes in the user requirements would have less impact on network implementation. In this section the feasibility of a distributed network is explored by the method of working out a specific design example. This example represents only one of many possible variations on the theme; nevertheless, it serves to identify some major issues relating to the whole class of distributed networks. The example is based on the network requirements used in the last section (Table 3.5), except that these are now considered to be ultimate goals toward which the network can gradually evolve rather than fixed "requirements" for initial operation.

Although assumptions and parameter values are stated rather explicitly in this example, they are quoted only for illustrative purposes. They serve to focus the discussion and to help us draw some general conclusions, which will then not depend greatly on the detailed assumptions.

The following sections address topological and architectural issues only. The underlying technology and hardware assumptions and issues are covered in Section 6.

5.1. STANDARD NODES

The distributed network will contain many small nodes carried on host satellites. Standardization and interoperability are therefore important issues. In this example, therefore, our first step is to hypothesize a set of "standard nodes" to serve as basic network building blocks.

For example, Figure 5.1 shows three distinct types of standard node--one for each channel class (Sec. 3.3). (Without going into implementation details, which are reserved for Section 6, it appears that a different technology would be the choice for each channel class.) Nodes of the same type are interoperable. Nodes of different types are not. The nodes are intended to be commensurate in size with being a secondary payload on a host spacecraft. In this example, hosts are assumed to be in synchronous orbit. However, the concept applies as well to Molniya and other high, non-synchronous orbits. Low orbits would not be attractive locations for network nodes. The standard nodes in Fig. 5.1 are discussed in more detail below and in Section 6.3.

5.1.1. HRM NODE

The HRM node in Fig. 5.1 provides one HRM access port and relays that 1 Gbps data stream to two separate ground nodes, arbitrarily located. The choice of one channel per node for this example is based on physical size considerations (Sec. 6.3.3), on the fact that only a few HRM channels are needed, and on the fact that no 3-Node space coverage is needed (Table 3.5). (The latter would require that some HRM nodes support two 1 Gbps crosslinks for cross-orbit trunking.)

The downlink channels to two separate ground sites meet the needs stated in the mission model (Table 3.1). (Each mission has two separate MCCs.) Multiplexing of different 1 Gbps data streams is avoided on grounds that it is not necessary and is technically difficult (but not impossible). Each MCC can have its own exit node arbitrarily located. Large terminals--in the range of 60 feet in diameter--are assumed for the HRM ground nodes.

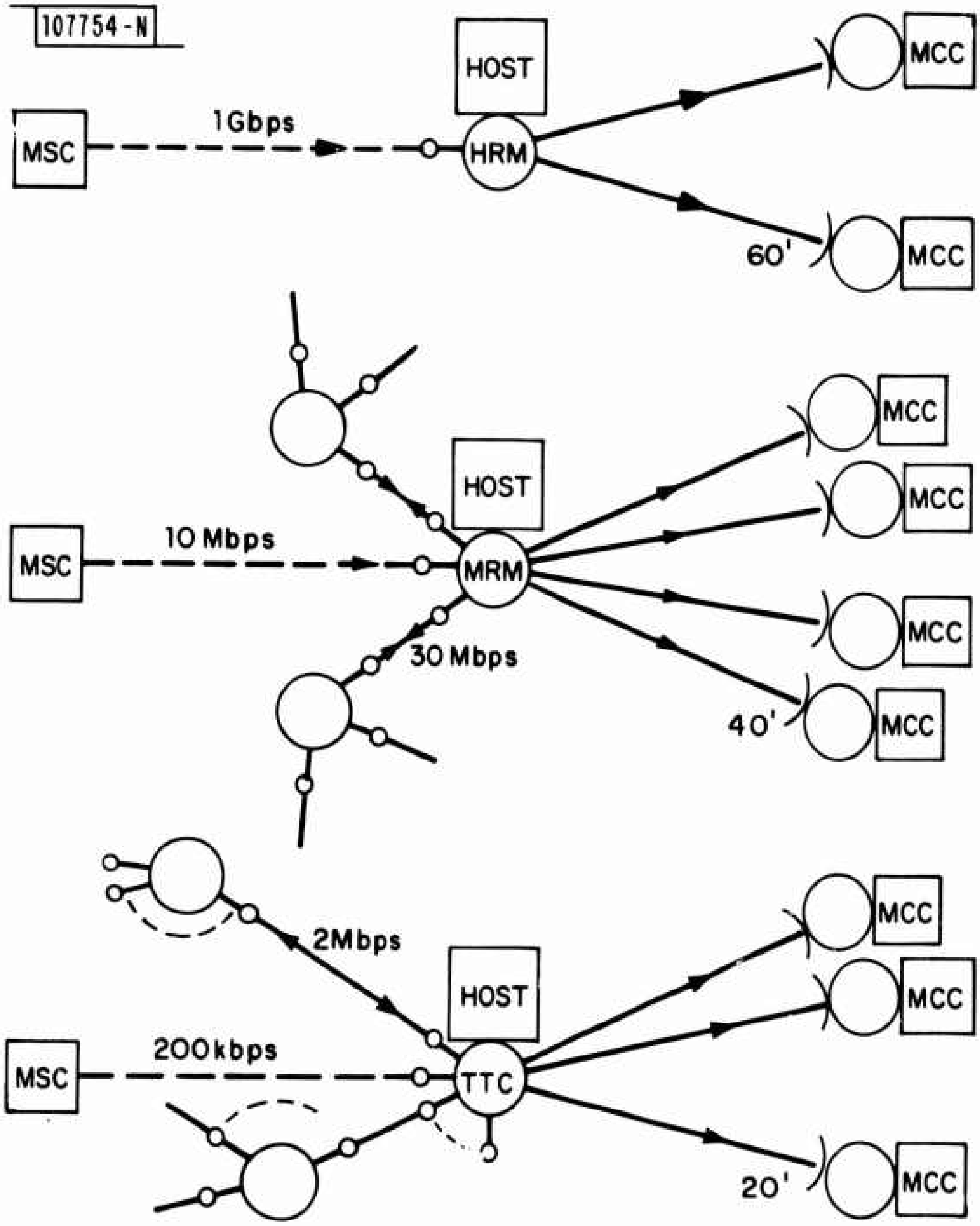


Fig. 5.1. Topological descriptions of the Standard Nodes used in the distributed network design example.

By assumption (Sec. 3.3) every channel includes a 10 kbps "forward link" for spacecraft commands. This capability is implicit in Fig. 5.1. Implementation is covered in Section 6.2.3.

5.1.2. MRM NODE

The MRM standard node contains 3 crosslinks and a "multiple access" downlink, i.e., the downlink can talk to a number of widely separated ground nodes. The crosslinks are bi-directional and multi-channel. They can support up to three MRM channels (10 Mbps each) in either direction. (As before, each MRM channel has a 10 kbps forward link.) The crosslinks can serve either as access ports or as cross-orbit trunks linking to other nodes in the network. These crosslinks allow a network to grow in "tinker-toy" fashion as new nodes are added and crosslinked together with existing ones.

The downlink can support the equivalent of 10 MRM channels (i.e., its aggregate data rate is 100 Mbps). Each channel can be routed to a different location, where "different" means more than one antenna beamwidth apart in angle. Implementation of this type of downlink is discussed in Section 6.2.2. It is similar to one presently being developed for mobile/tactical communications at 20 GHz. MRM ground terminals are assumed to be smaller than HRM terminals. A 40-foot-diameter antenna is used in this example.

5.1.3. TTC NODE

Since there are many TTC users (30 channels required), the TTC node has six crosslinks. Like the MRM crosslinks, each is bidirectional and multichannel. In this case each can support 12 TTC channels (200 kbps each) in either direction (the 10 kbps forward links is again implicit in each channel).

The downlink is again multiple access like the MRM and can support 16 TTC channels (3.2 Mbps) to a distributed set of exit nodes. The TTC ground terminals are assumed to be in the 20-foot-diameter class.

Again, these standard nodes reflect many arbitrary-but-specific choices made for illustrative purposes. They are not necessarily optimal choices.

The following network design example neglects the fact that some or all host satellites are themselves network users; consequently, fewer access ports will be needed than are shown in Table 3.5. The availability and suitability of host spacecraft is not touched on in this study except to say that civilian communications satellites should be included in the list of possibilities.

5.2 CONFIGURATION FLEXIBILITY

With this (or a similar) set of standard nodes, a variety of network configurations can be realized. Fig. 5.2 shows some examples using 2 and 3 MRM nodes connected in different ways. Each configuration has a different capacity, space coverage and ground coverage (Sec. 3). This netting flexibility results from the multi-channel, bi-directional capabilities of the crosslinks.

When more than two or three nodes are present, the interconnection possibilities are so numerous that it helps to think in terms of aggregating some standardized sub-networks of simple geometry as shown in Fig. 5.3.

5.3 EVOLUTIONARY GROWTH

One hoped-for advantage of a distributed architecture is to realize a graceful transition from the ground-based network to a space-based network. By this we mean that the space network can grow in small increments as programs become operational or phase over to its use. An added advantage is that user requirements could change without seriously affecting the basic network architecture. They would only affect how many nodes are needed and in what fashion they are interconnected.

Assume for the moment that the mission model (Table 3.1) represents the ultimate far-term requirement. Fig. 5.4 shows how the MRM network could evolve in phases towards that end. It assumes that the missions become operational in sequence from top to bottom. Each mission has 2 or 3 MCCs which are separate and arbitrarily located. The number of channels required by each mission (from Table 3.4) is indicated next to its MCCs. Growth occurs in six phases--one for each mission added--as shown in Table 5.1. For example, phase 1 is for mission S-1 (DSP), which requires 5 channels and 2-Node space

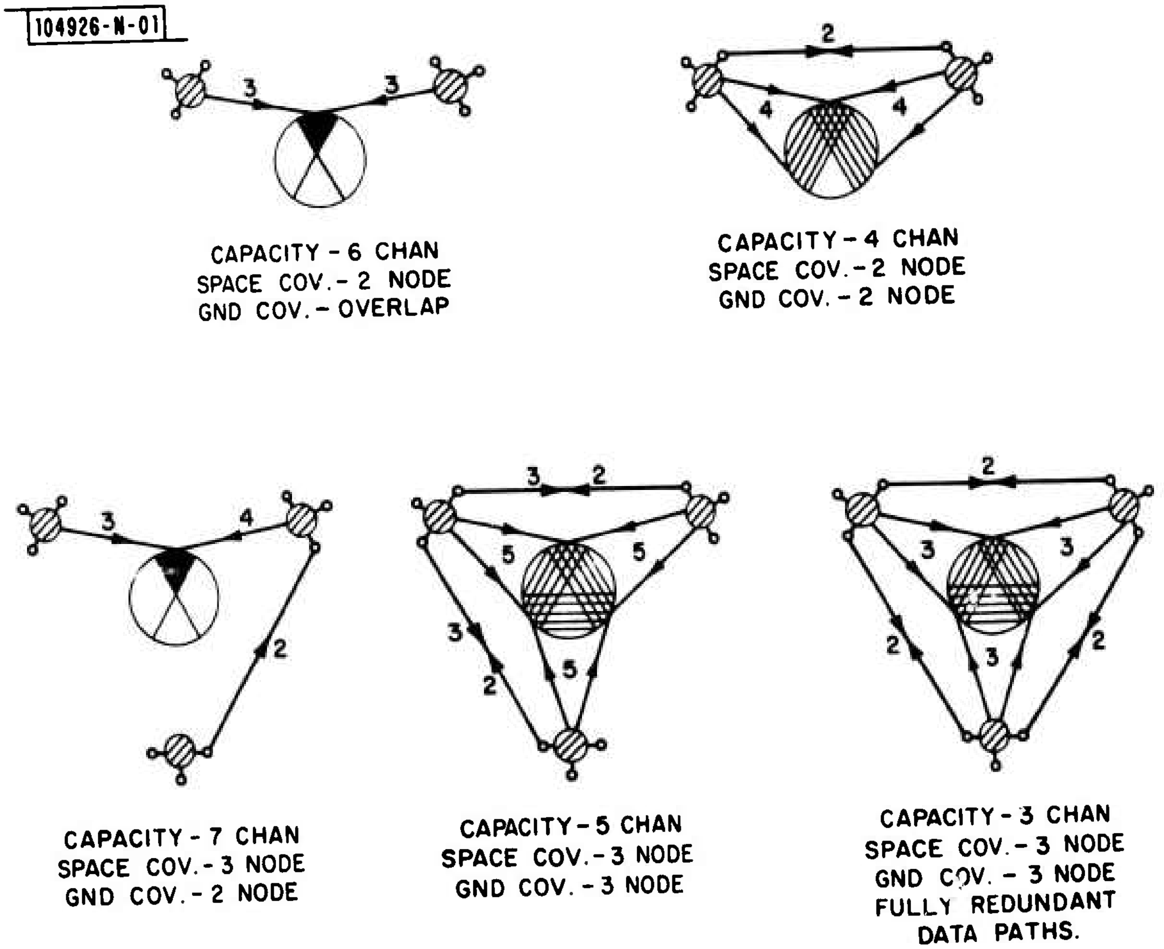


Fig. 5.2. Some examples, using 2 and 3 MRM nodes, of configuration flexibility provided by bi-directional, multi-channel crosslinks.

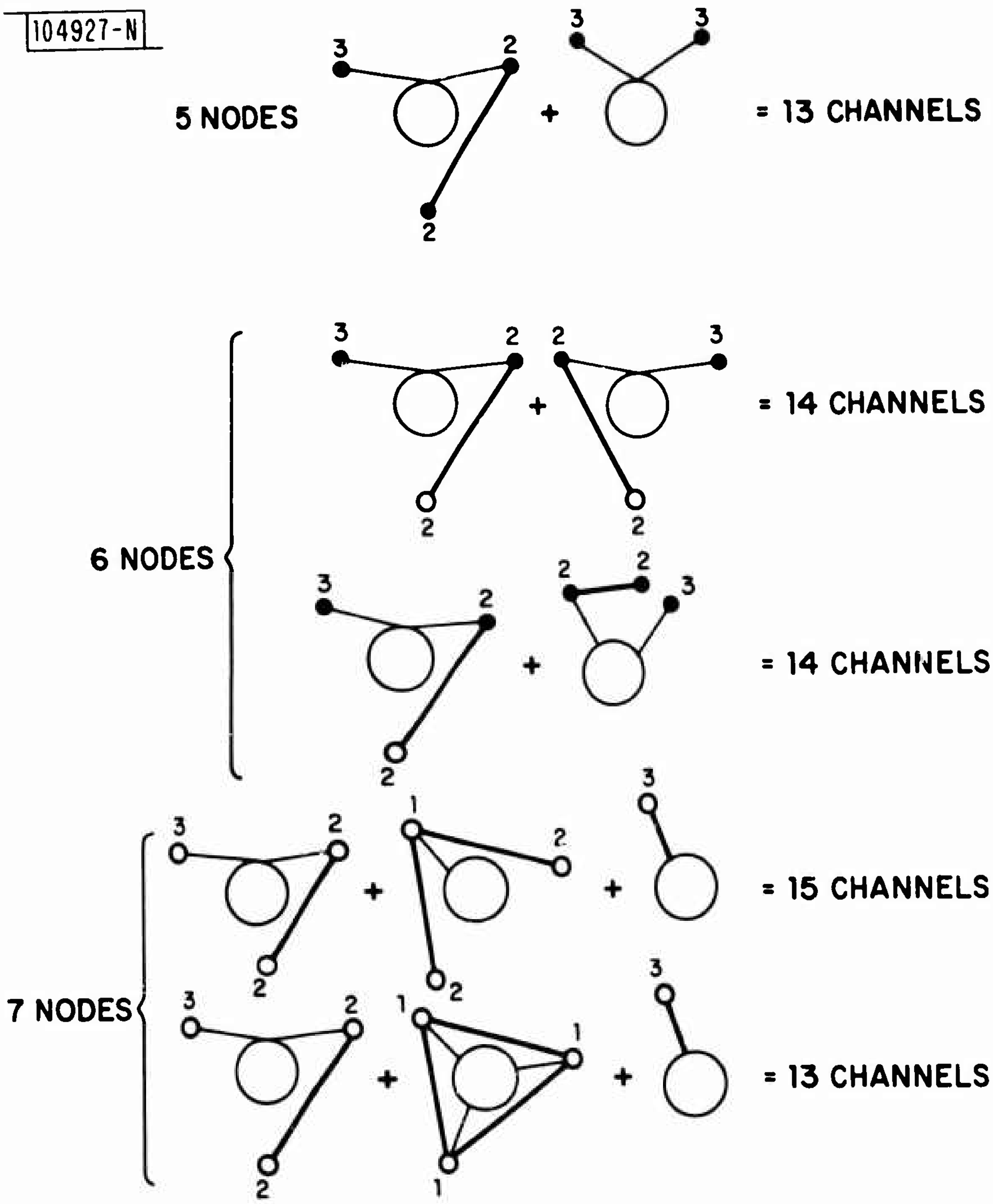


Fig. 5.3. Larger networks can be broken down into some standard sub-network types. MRM nodes are shown. Numbers represent available access ports.

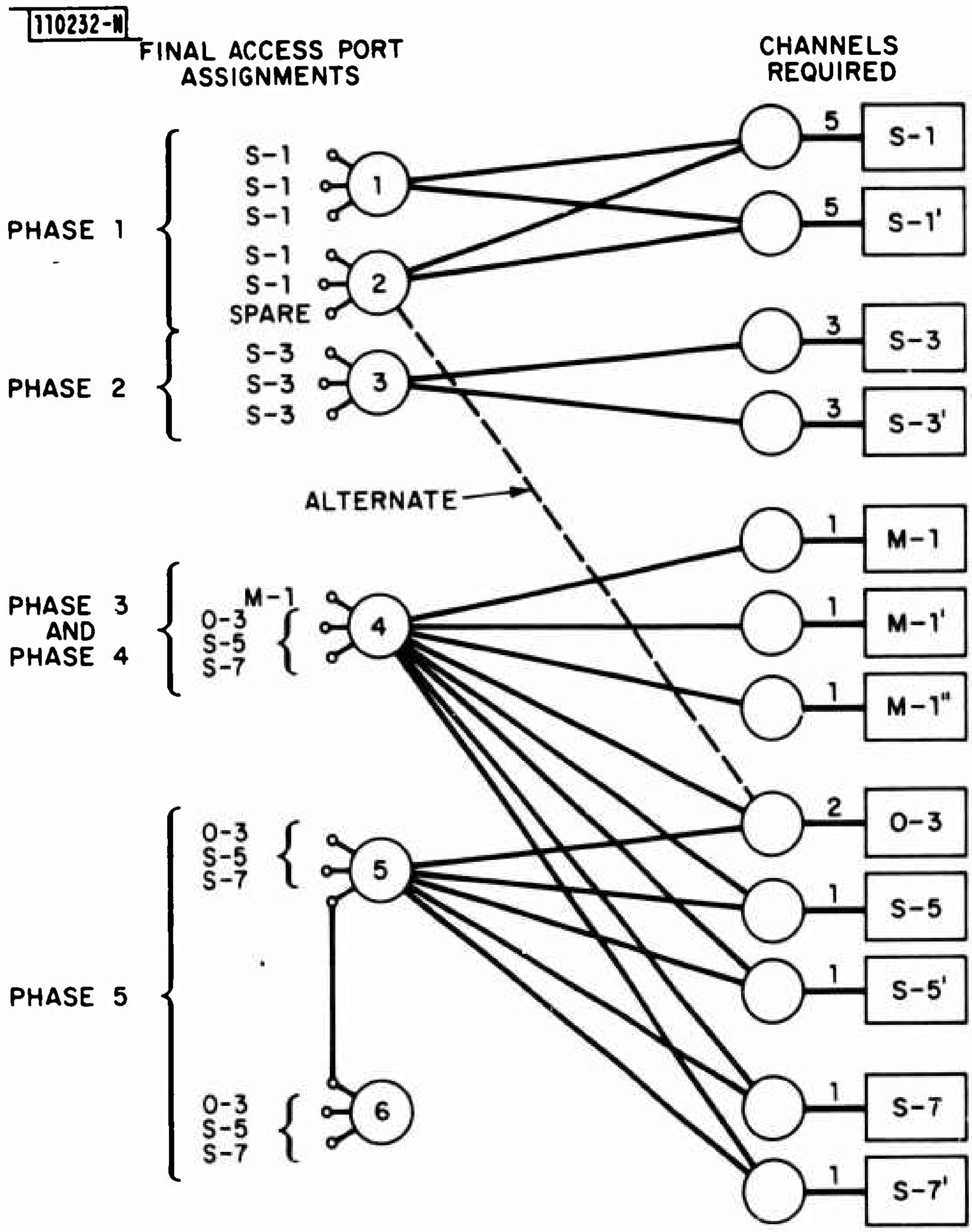


Fig. 5.4. Example of network growth assuming missions become operatial in sequence from top to bottom. Mission requirements from Table 3.1 (mission model). Node utilization at each phase indicated in Table 5.1.

coverage. Nodes 1 and 2 are launched as phase 1 and the ports assigned per Table 5.1 (i.e., Node 2 has two crosslinks and 4 downlink channels in use). The growth proceeds as shown. The final configuration of Fig. 5.4 has 16 access ports available and 13 assigned. There are many other net configurations which could meet the same requirements.

The need for multiple-access downlinks is best pointed out by node 4, which is linked to 8 ground nodes. As the Table indicates, its downlink data rate is equivalent to 5 1/3 channels (53.3 Mbps). However, this is an average figure;

TABLE 5.1

CROSSLINK AND DOWNLINK UTILIZATION OF EACH NODE FOR EACH PHASE OF NETWORK GROWTH. THERE ARE 3 CROSSLINKS AND 10 DOWNLINK CHANNELS AVAILABLE PER NODE

Phase	Mission Added	Node number and (crosslink/downlink) loading) 1	2	3	4	5	6
1	Add S-1	3/6	2/4	—	—	—	—
2	Add S-3	3/6	2/4	3/6	—	—	—
3	Add M-1	3/6	2/4	3/6	1/3	—	—
4	Add O-3	3/6	2/4	3/6	2/4	—	—
5	Change O-3	3/6	2/4	3/6	2/4	2/1	1/0
5	Add S-5	3/6	2/4	3/6	$2\frac{1}{2}/4\frac{2}{3}$	$2\frac{1}{3}/2\frac{1}{3}$	$1\frac{1}{3}/0$
6	Add S-7	3/6	2/4	3/6	$2\frac{2}{3}/5\frac{1}{3}$	$2\frac{2}{3}/3\frac{2}{3}$	$1\frac{2}{3}/0$

the peak data rate can be 80 Mbps. This is why a nominal capability of 10 channels (100 Mbps) was chosen for the MRM standard node downlink.

5.4 NETWORK ORGANIZATION

Figure 5.5 provides an illustration of some different possibilities for network organization and control opened up by the distributed architecture. If organized as a "shared network" (Sec. 2.6), the entire network could be under central control like the SCF. The user MCCs would request and be provided channels via an order wire (not shown) to a network control ground node (also not shown). This control node would have to be capable of communicating with every other network node (both ground and space nodes). There should be redundant control nodes to retain the survivability advantage of the distributed network.

Another possibility is to divide the network into sub-networks for control purposes. In Fig. 5.5 missions S-1 and S-3 could each have its own "mission-specific" network. The network resources (nodes 1, 2 and 3) could be "detached" to the operational control of the using missions in this case. As shown, the remaining missions are sharing a common network under a central control. With either type of organization, alternate paths are available to every mission since all nodes are interoperable and have the built-in flexibility to permit reconfiguring the network in orbit.

5.5 CENTRALIZED/DISTRIBUTED COMPARISON

The MRM standard node was used to illustrate the examples just presented. Similar ideas apply to the TTC and HRM nodes. The characteristics of a network architecture based on the distributed approach are summarized in Table 5.2. A comparison of the features of centralized and distributed architectures is given in Table 5.3. The underlying technical issues and assumptions are covered in the Section 6.

TABLE 5.2

CHARACTERISTICS OF THE DISTRIBUTED NETWORK

Topological Characteristics

- Many Smaller Nodes
- Fewer Access Ports Per Node
- More Trunk Links Required
- Lower Capacity Nodes and Trunks
- More Alternate Paths

Programmatic Characteristics

- Larger Total Investment Than Centralized Approach (To Meet Same Requirement)
- Smaller Initial Investment
- Smaller Growth Increments (Phased Changes)
- Network Matched to Actual Requirements (vs Predicted Requirements)
- Technology Not Frozen
- Network Nodes can be Dedicated Satellites or Packages On Host Vehicles
- Flexible Network Organization (Multi-Mission or Mission-Specific)
- Survivability Through Dispersal of Nodes in Space and on Ground

TABLE 5.3

CENTRALIZED/DISTRIBUTED COMPARISON

	CENTRALIZED	DISTRIBUTED
Space Segment	Data Relay Satellites	Packages on Host Satellites
Ground Segment	Several Large Nodes	Completely Distributed
Growth/Transition	Block Changes	Evolutionary
Initial Costs	High	Lower
Ultimate Costs	High	Probably Higher
Survivable	Less	More
Flexibility	Sensitive to Initial Requirements	Adaptable to Changing Requirements

6. TECHNOLOGY ISSUES AND ASSUMPTIONS

The previous sections dealt with topological and architectural issues. Little was said of technical considerations, although they were implicit throughout the discussions. The purposes of this section are to make explicit those underlying technical assumptions and point out some of the issues raised.

The method used is to give specific examples of one way the various items could be realized. No attempt is made to consider all the ways or to select the optimum one. That would be far beyond the scope of this report. The parameter values are sometimes detailed and explicit for reasons of self-consistency. Again, these are intended as being illustrative and not as firm technical proposals.

6.1 CROSSLINKS

There are two types of crosslinks: access links (MSC to network) and cross-orbit trunks (within network). Data rates range from around 200 kbps to around 1 Gbps. The driving consideration for any of these applications is to minimize aperture size and package weight. Implicit in the foregoing discussions was the assumption that each "access port" represents an independently steered, narrow beam crosslink covering a wide angular field. In the centralized network, the object was to pack many such "ports" onto a few data relay satellites (nodes). The distributed approach strove for small nodes of a few ports each, suitable as secondary payloads on host spacecraft. In either approach the user MSC must not be overburdened by its network interface package. All of these considerations place a high penalty on crosslink size and weight.

6.1.1 MILLIMETER WAVE AND OPTICAL TECHNOLOGIES

Figure 6.1 indicates the range of package weights achieveable (by current estimates) with optical or 60 GHz crosslink frequencies. The 60 GHz weight begins to increase rapidly above 10 Mbps as the RF power requirement escalates. Optical system weights are more affected by overhead items (pointing and tracking, stable platforms, etc.) and are less sensitive to data rate.

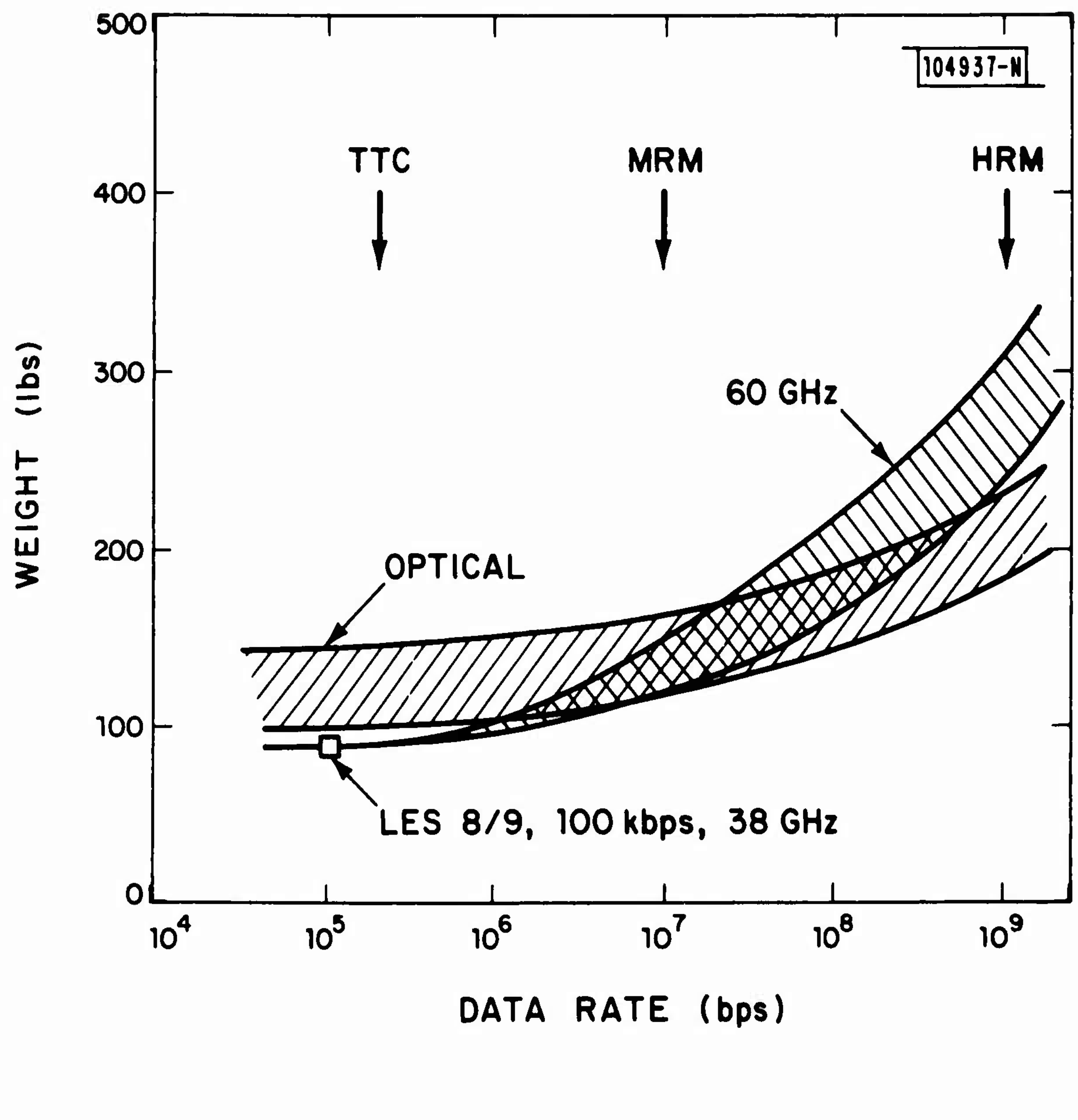


Fig. 6.1. Crosslink package weight estimate for optical and 60 GHz technologies.

Based on weight alone, there is no clear preference for optics over RF except at data rates of a few hundred megabits/sec and above. Aperture diameter comparisons (Fig. 6.2) however make optics appear more attractive over the entire data rate range, but especially so at 10 Mbps and above.

This study therefore assumes an optical implementation for the crosslinks in the MRM (10 to 30 Mbps) and HRM (~ 1 Gbps) data rate regimes. An RF rather than optical implementation is considered to be an appropriate choice for TTC (~ 200 kbps) in spite of the larger aperture diameter. The TTC channels provide spacecraft control functions (Fig. 2.1) and it is recognized that some form of ommi-directional, low data rate capability is needed for launch operations, attitude acquisition, and anomaly recovery situations. This capability is more easily realized at RF than at optical frequencies. The frequency of 60 GHz is chosen for this study because, due to oxygen absorption, the atmosphere would be opaque to ground-based jammers (≈ 100 dB attenuation).

6.1.2 60 GHZ CROSSLINKS

Figure 6.3 provides an indication of the hardware required to realize a 60 GHz crosslink in the TTC data rate regime. On the left is a MSC interface package sending 200 kbps and receiving 10 kbps (spacecraft commands). It has an 18 in. steerable dish, a 2W RF amplifier, and a weight and power of 90 lb and 55 watts. The right-hand package would be on a node of the distributed network. It could serve as an access port, (receiving 200 kbps and sending 10 kbps to MSC) or as a cross-orbit trunk linking up to 12 TTC channels in either direction (2.4 Mbps) to another network node. (All channels include a 10 kbps capability in the "forward" direction MCC to MSC (Section 3.3).) An equivalent package for the centralized architecture (Fig. 4.4) would serve only as an access port and would be slightly less in weight because of the smaller transmitter required (10 kbps only).

A typical link budget is given in Table 6.1 and 4 weight/power budget in Table 6.2. All weights and power numbers are rough estimates.

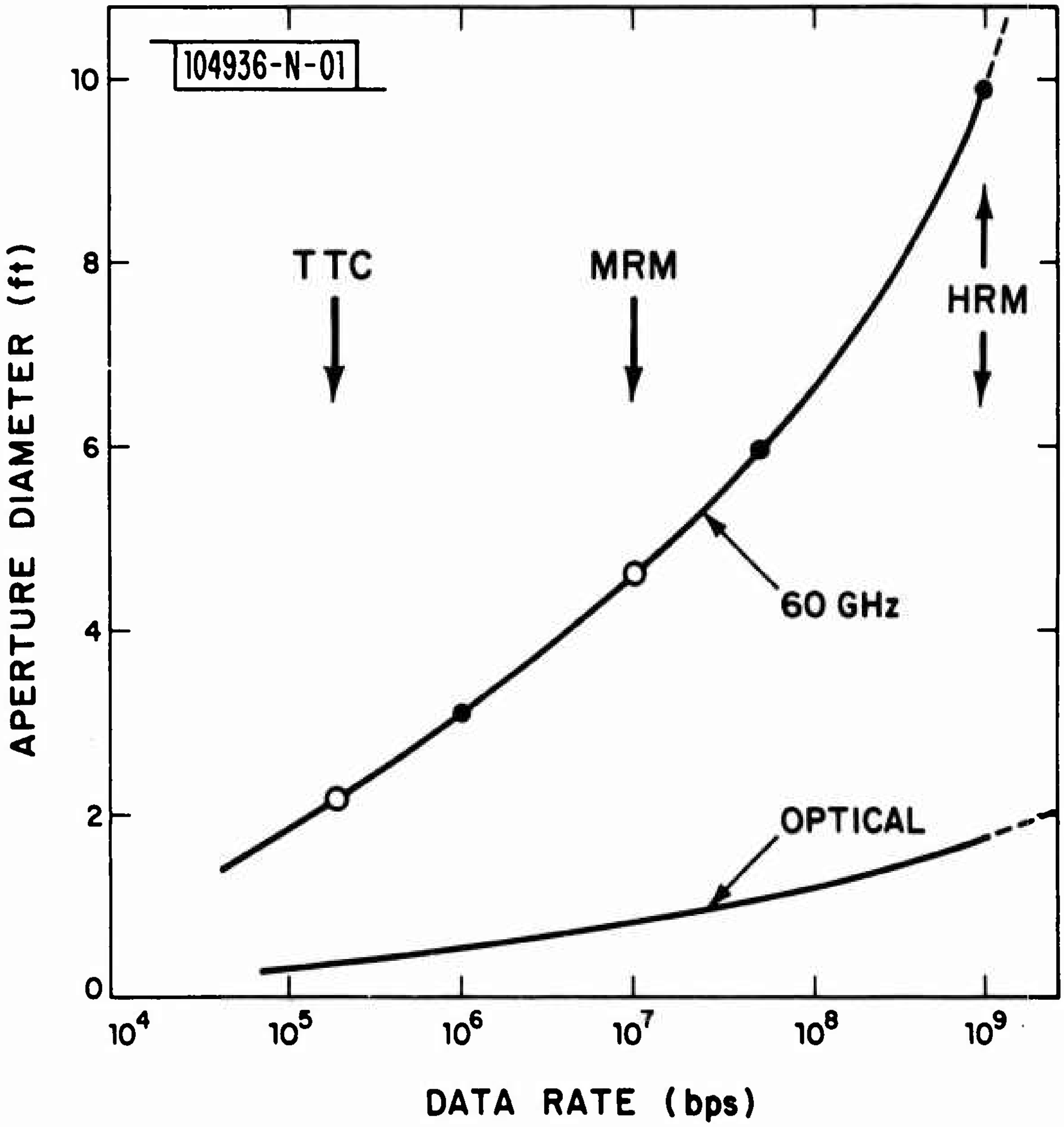
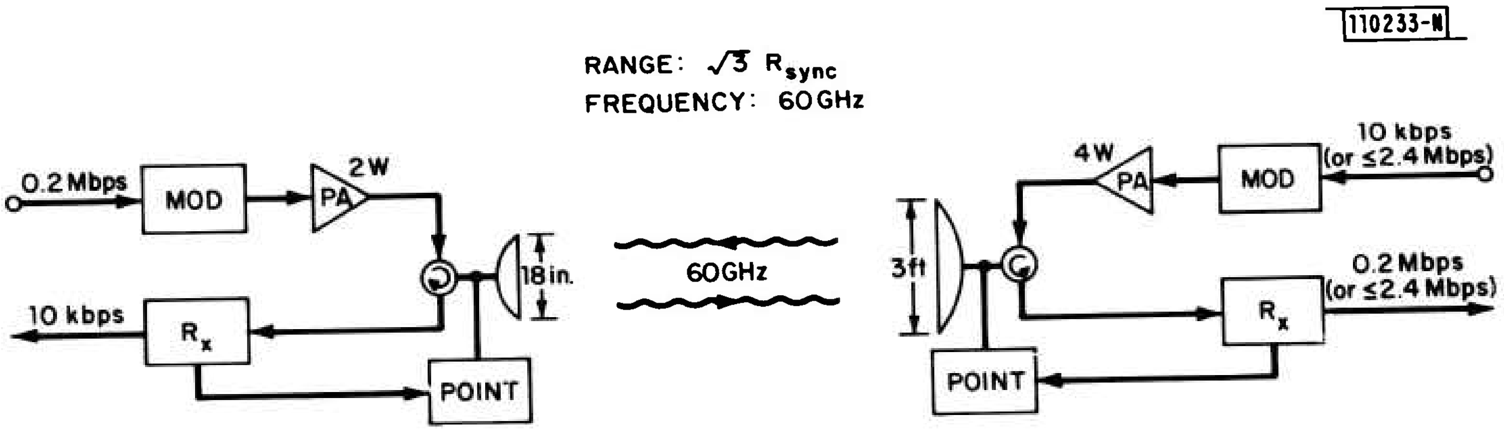


Fig. 6.2. Typical crosslink aperture diameters for optical and 60 GHz technologies. For different receive and transmit apertures, $\sqrt{D_r D_t}$ must fall on curve



MISSION SPACECRAFT PACKAGE

RF POWER: 2 W
SYSTEM NOISE TEMP: 2000 K
E_b/N_o: 10 dB
ANTENNA GAIN: 46 dB (55% eff)
ANTENNA DIAMETER: 18 in. (46 cm)
EIRP: 48 dBW
BEAMWIDTH: 0.8°
PACKAGE WEIGHT: 90 lb
PACKAGE POWER: 55 W

NETWORK NODE PACKAGE

RF POWER: 4 W
SYSTEM NOISE TEMP: 2000 K
E_b/N_o: 10 dB
ANTENNA GAIN: 52.5 dB (55% eff)
ANTENNA DIAMETER: 3 ft (0.91 m)
EIRP: 58.5 dBW
BEAMWIDTH: 0.4°
PACKAGE WEIGHT: 115 lb
PACKAGE POWER: 75 W

Fig. 6.3. Technology assumptions for 60 GHz TTC access link (200 kbps). As a cross-orbit trunk, the network node package can handle 12 TTC channels (2.4 Mbps) bi-directionally.

TABLE 6.1

LINK BUDGET FOR 60 GHZ TTC ACCESS LINK

Trans. RF Power (2W impatt)	3.0 dBW
Trans. Ant. Gain (18 in, 55% eff.)	46.0 dBI
Path Loss ($\sqrt{3}$ Rsynch)	-224.7 dB
Rec. Ant. Gain. (3 ft, 55% eff.)	52.5 dBI
Rec. Signal Power	-123.2 dBW
Data Rate (200 kbps)	- 53.0 dB-Hz
Sys. Noise (2000°K)	+195.6 dBW/Hz
E_b/N_o available	+ 19.4 dB
E_b/N_o required (~ 10^{-5} BER)	10.0 dB
Misc. losses and margin	9.4 dB

TABLE 6.2

60 GHZ CROSSLINK WEIGHT AND DC POWER ESTIMATES

Item	MSC Pkg		Network Node Pkg**	
Mod + R_x	38 lb	26W	38 lb	26W
Impatt PA*	14 lb	15W	22 lb	30W
Antenna + Point	38 lb	14W	55 lb	19W
Total Wt./Pwr.	90 lb	55W	115 lb	75W

*One hot, one cold spare for MSC package. Two hot, one cold spare for Network Package.

**Version for centralized architecture would have a $\leq$ 1 W PA (forward data rate = 10 kbps). Package Wt./Pwr. $\simeq$ 100 lb, 60 W.

6.1.3 LASER DIODE CROSSLINKS

The Medium Rate Mission (MRM) data rates appear to be compatible with emerging CW laser diode technology in the 0.85 micron wavelength range. This is being vigorously pursued by the commercial sector in connection with optical fiber telephone trunks. One attractive prospect offered by this technology is the possibility of optical heterodyne receivers rather than the direct-detection receivers heretofore used in optical links of less than 10 micron wavelength.

The theoretical advantage of heterodyne detection in terms of a higher data rate per milliwatt of available laser power, is illustrated by Fig. 6.4. The approximately 10 dB advantage enjoyed by heterodyne systems arises mainly from the type of optical detector used. Direct detection systems require detectors with internal gain, such as avalanche photodiodes, which have excess noise. In a heterodyne receiver (Fig. 6.5), gain is provided by the local oscillator laser rather than the photodetector, and quantum-limited performance should be attainable with silicon PIN diode detectors.

Realizing this advantage, however, requires significant technical developments in the areas of stable lasers and narrow-beam pointing and tracking. Although far from maturity, this heterodyne technology appears feasible and is therefore adopted to illustrate this study. Figure 6.6 shows an MRM optical crosslink with a 10 milliwatt (-20 dBW) laser diode, and 10 cm (4 inch) optics which, according to Fig. 6.4, should achieve data rates in the 10 to 30 Mbps class with a CW laser power of 10 milliwatts, which is easily available today. Higher power diodes (which are now coming available commercially) or larger optics could extend the achievable data rate to the gigabit per sec range.

At this level of detail we cannot distinguish between the weight and power estimates for a 10 Mbps package and a 30 Mbps package. Both would be in the 100 lb; 100 W class. The 10 Mbps version would be a MSC interface package or an access port of the centralized architecture. The 30 Mbps version pertains to the MRM standard node (Fig. 5.1) of the distributed architecture.

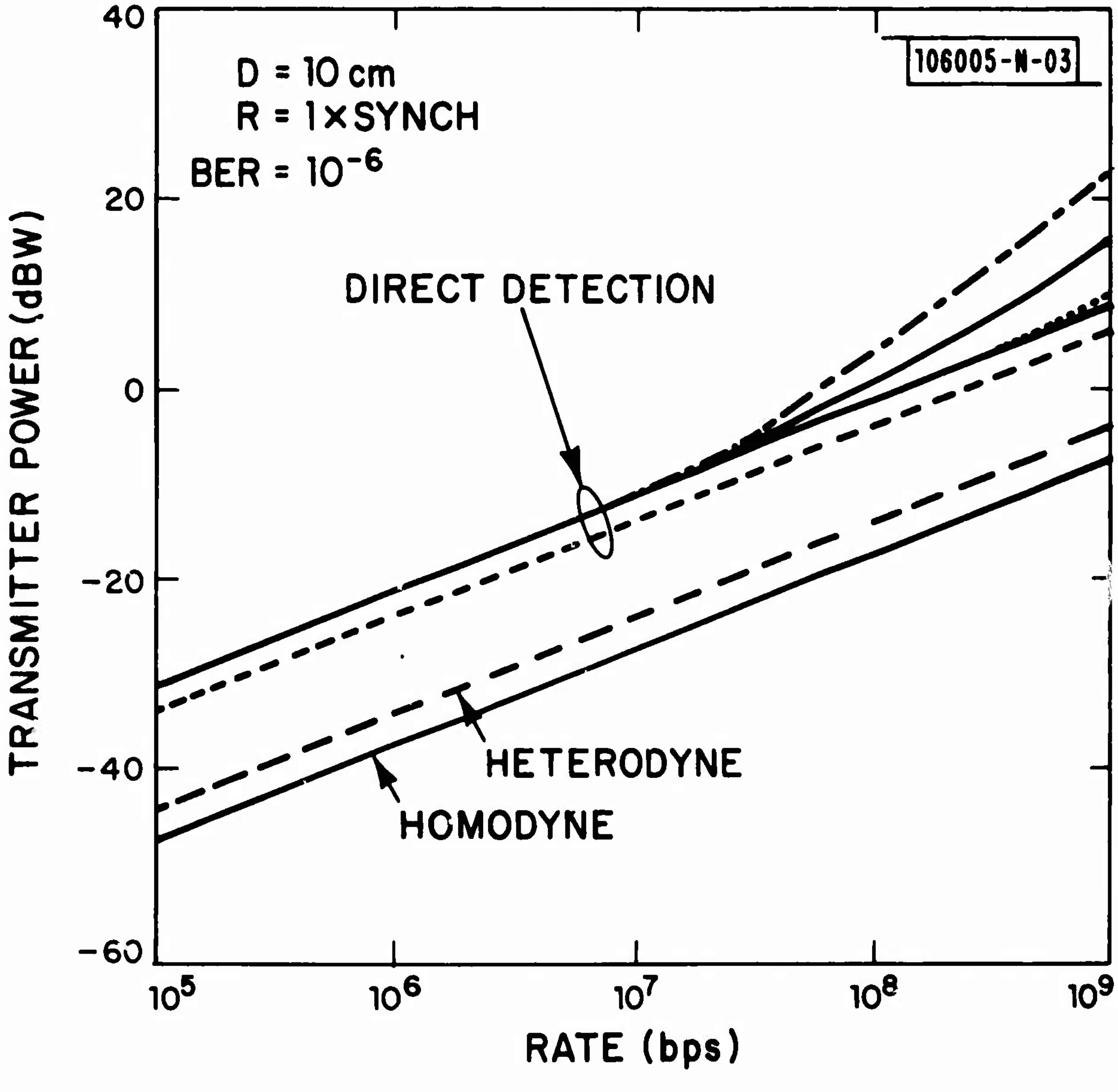


Fig. 6.4. Data rate vs laser transmitter output power for direct detection, heterodyne and homodyne detection techniques.

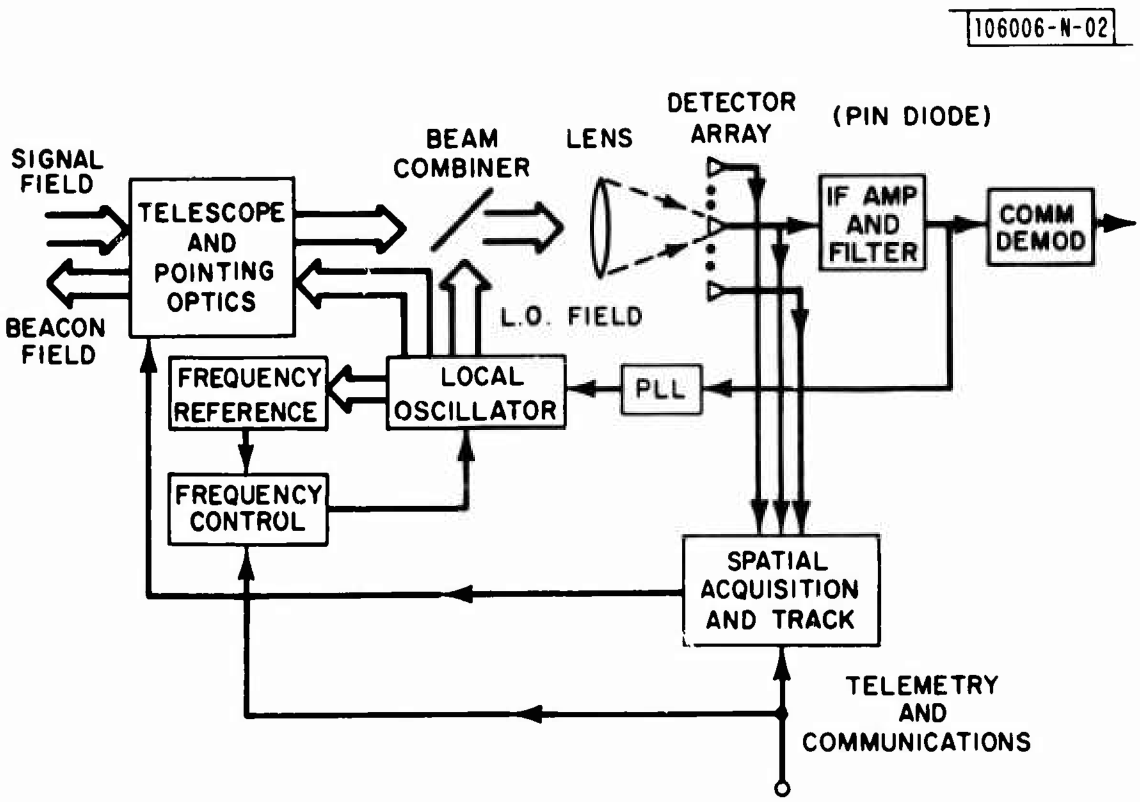


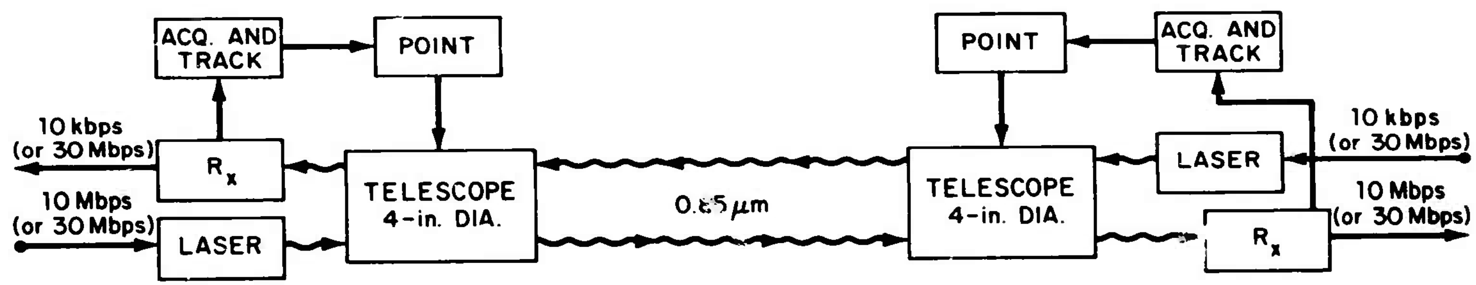
Fig. 6.5. A heterodyne laser communications receiver.

110234-N

RANGE: $\sqrt{3}\ R_{sync}$ (73×10^3 km)

MAX DATA RATE: 30 Mbps, BI-DIRECTIONAL

APPLICATIONS: MRM ACCESS LINK (1, 10 Mbps Channel)
MRM CROSS-ORBIT TRUNK (3, 10 Mbps Channels)



MISSION SPACECRAFT PACKAGE

LASER: GaAlAs DIODE
WAVELENGTH: ~0.85 μm
OPTICAL POWER: ~10 mW
TRANSMITTER BEAMWIDTH: 8.5 μrad
RECEIVER BEAMWIDTH: 25 μrad (Based on 3 × 3 Detecior Array)
TELESCOPE DIAMETER: 10 cm (4 in.)
MODULATION: COHERERENT, PSK OR FSK
PACKAGE WEIGHT: 100 lb
PACKAGE POWER: 100 W

NETWORK NODE PACKAGE

SAME AS MISSION SPACECRAFT PACKAGE

Fig. 6.6. Technology assumptions for optical MRM crosslink (10-30 Mbps). Receive beamwidth based on 3 x 3 detector array.

6.1.4 Nd:YAG LASER CROSSLINKS

The development of direct detection optical crosslinks using Nd:YAG lasers is already well advanced. That work has primarily addressed higher data rate applications (100 Mbps to 1 Gbps), but could be applied to lower data rates as well. For the purpose of this study we have assumed this type of link for the HRM (1 Gbps) class of service. Some typical parameters of such a link are shown in Fig. 6.7. As mentioned in the last section, it is possible that heterodyne diode laser technology could eventually be applied to the HRM as well as the MRM channels; however, that is not assumed in this study.

6.2 UPLINKS AND DOWNLINKS

Both centralized and distributed architectures need multi-channel trunks from the space nodes to the ground nodes. By assumption, all channels have a 10 kbps forward direction capability; therefore, only a modest uplink data rate is needed.

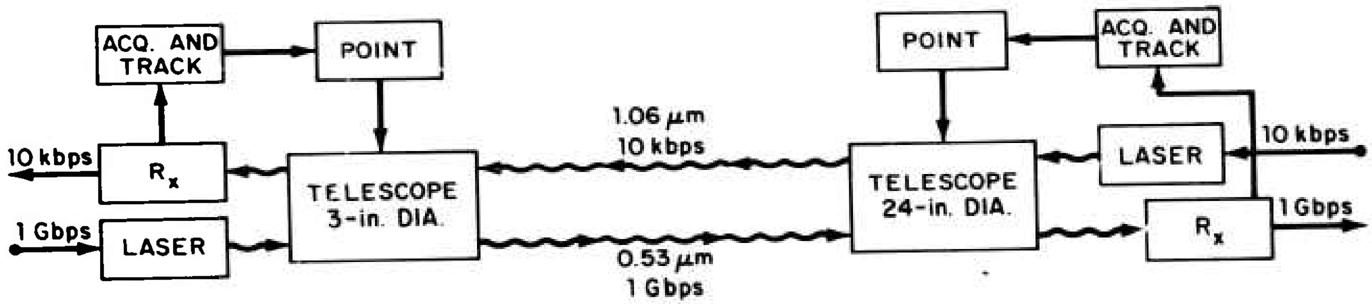
This study assumes that all downlinks are at 20 GHz. This is a presently unoccupied band and requires smaller satellite antennas than the SHF band. Uplinks are assumed to be at 44 GHz. Because the data rates are low and terminal sizes relatively large (20 to 60 feet), jam resistance is inherently high and only a minimal amount of band-spreading would be sufficient protection against any plausible threat.

6.2.1 DOWNLINKS FOR THE CENTRALIZED NETWORK

The centralized architectures (Figs. 4.4 and 4.5) assume five large ground stations (exit nodes) uniformly distributed around CONUS. A particular mission may have MCCs situated at more than one exit node. In Fig. 4.4 the simplifying assumption was made that all channels are downlinked to all exit nodes. This means that all channel switching operations can be done on the ground. Figure 6.8 indicates the downlink hardware required to do this for Node 2 of Fig. 4.4. (Some of the indicated channels arrive by crosslink from Node 3.) The link budget is given in Table 6.3. It assumes a 60 foot, 580°K terminal. The technique of generating five beams by five fixed feeds of a

110235-N

RANGE: $\sqrt{3}\ R_{sync}$ (73×10^3 km)
RETURN DATA RATE: 1 Gbps
FORWARD DATA RATE: 10 kbps



MISSION SPACECRAFT PACKAGE

LASER: Nd:YAG DOUBLED
WAVELENGTH: 0.532 μm
OPTICAL POWER: ~100 mW
TRANSMITTER BEAMWIDTH: ~13 μrad
RECEIVER BEAMWIDTH: ~8 μrad
TELESCOPE DIAMETER: 7.6 cm (3 in.)
MODULATION: INCOHERENT, PULSE POSITION AND POLARIZATION
PACKAGE WEIGHT: 150 lb
PACKAGE POWER: 300 W

NETWORK NODE PACKAGE

LASER: Nd:YAG
WAVELENGTH: 1.06 μm
OPTICAL POWER: ~100 mW
TRANSMITTER BEAMWIDTH: ~100 μrad
RECEIVER BEAMWIDTH: ~1 μrad
TELESCOPE DIAMETER: 61 cm (24 in.)
MODULATION: SAME
PACKAGE WEIGHT: 200 lb
PACKAGE POWER: 200 W

Fig. 6.7. Technology assumptions for optical HRM access link (1 Gbps).

110236-N

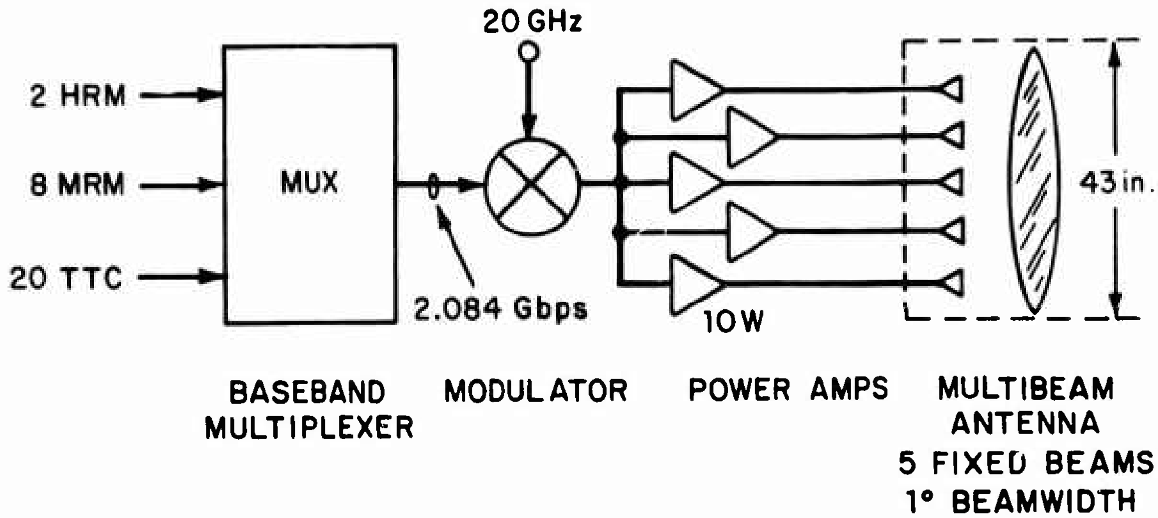


Fig. 6.8. 20 GHz downlink concept for centralized architecture (Node 2, Fig. 4.4). No on-board Channel routing. All 5 ground nodes receive all channels.

multi-beam antenna requires the satellite to remain fixed relative to the five ground stations. A more flexible approach would be desired in an operational system. Also, some savings in RF power (about 3 dB) could be realized by on-board channel switching. With this, channels would be routed only to desired ground stations rather than all stations. These issues were not resolved within the scope of this study as they do not affect architectural conclusions.

TABLE 6.3

20 GHZ DOWNLINK BUDGET FOR CENTRALIZED NETWORK

RF Power per channel (10W per beam)	10 dBW
Antenna gain (1° beam, 43 in, 55% eff.)	44 dBI
Satellite EIRP	54 dBW
Path loss (Rsynch)	-211 dB
Rec. Ant. Gain (60 ft, 55% eff.)	69 dBI
Rec. Signal Power	- 88 dBW
Data Rate (2 Gbps)	- 93 dB-Hz
System Noise (580°K)	+201 dBW/Hz
E_b/N_o available	20 dB
E_b/N_o required	-10 dB
Margin plus misc. losses	10 dB

6.2.2 DOWNLINKS FOR THE DISTRIBUTED NETWORK

It was thought desirable for this study to relax the constraint of having a few large ground nodes with clustered MCCs and allow MCCs to be arbitrarily located instead. (As we will see the technical impact of this is acceptable.) A totally distributed ground segment was therefore adopted as a feature of the distributed architecture (Section 5). (A distributed ground segment in conjunction with a centralized space segment is also possible, but was not considered.)

The basic assumptions governing downlink structure for the distributed network are:

1) The MCC locations are arbitrary
2) Each MCC is an exit node of the network (as opposed to a few large exit nodes with clustered MCCs).
3) Each mission can have several MCCs, therefore.
4) Network channels must have a point-to-multipoint capability (Fig. 2.5).
5) MCCs of the same mission are separated by more than one beamwidth of the downlink antenna.

Under these assumptions, on-board channel routing is a necessity for the distributed architecture. An earth coverage broadcast mode could eliminate the need for switching, but is not feasible because of RF power requirements. The function of the downlink routing processor is then illustrated by Fig. 6.9, which shows two channels being distributed among five separate MCCs (two for mission A, 3 for mission B). One way to realize this function is by means of time-division multiplexing (TDM) with a hopped-beam antenna.

This technique is best visualized with the aid of Fig. 6.10. (The particular parameter values apply to the MRM standard node, Section 6.3.2). Here the input channels (from the same node or from other nodes via cross-orbit trunks) are stored in a buffer memory, then time-division-multiplexed onto an RF carrier at a higher data rate by the digital commutator. An RF switch, synchronized with the commutator, connects the RF carrier to the

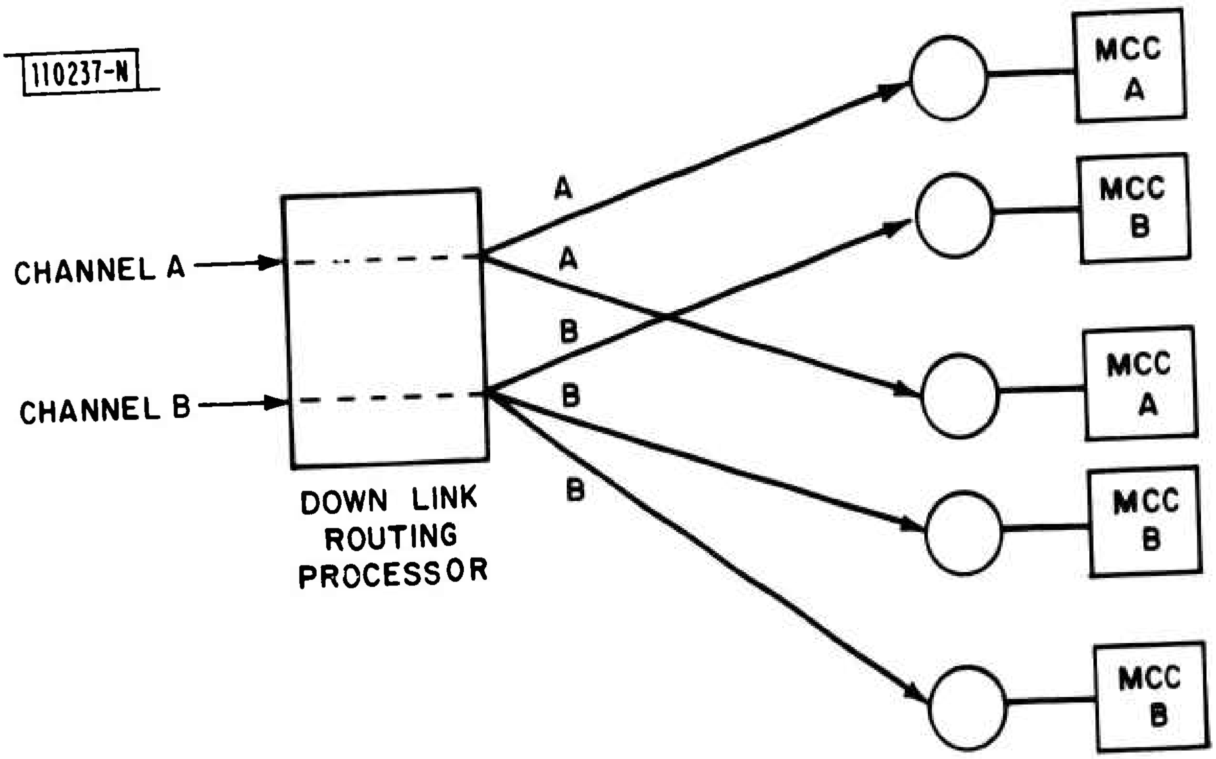


Fig. 6.9. Function of downlink routing processor in the distributed network architecture.

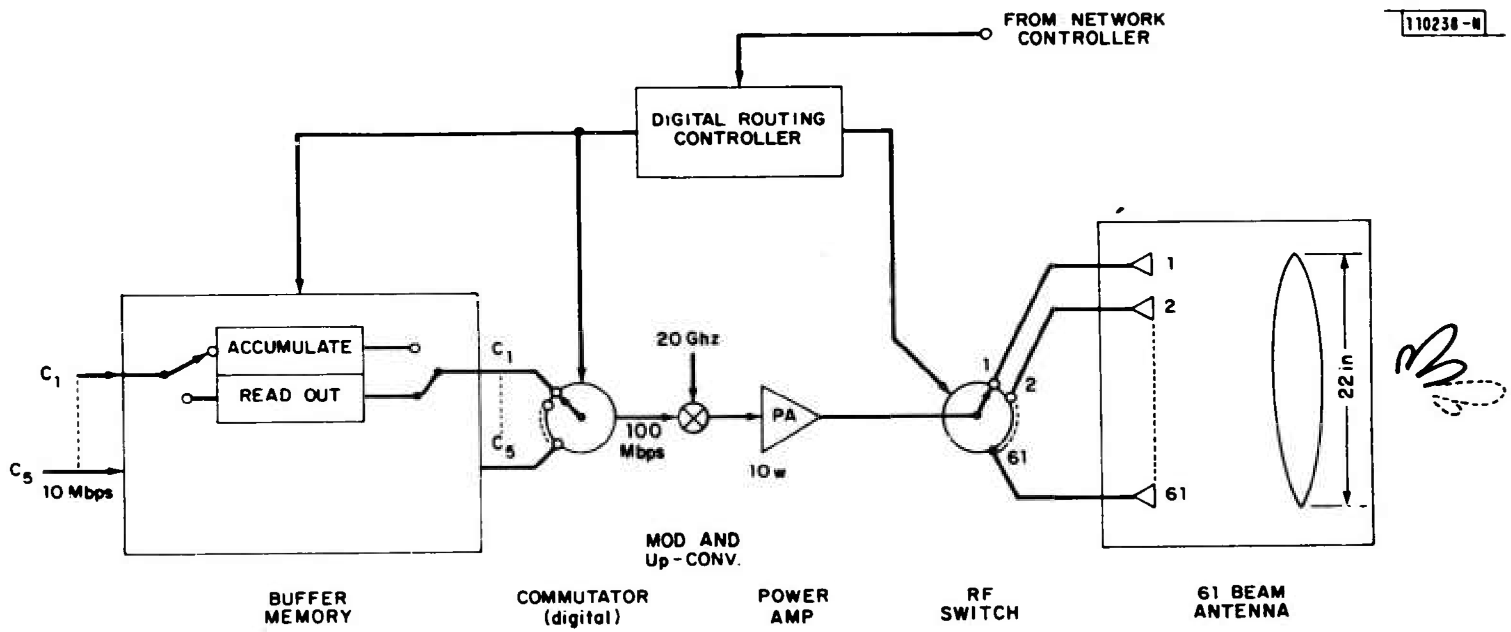


Fig. 6.10. Time-hopped-beam 20 GHz downlink concepts using multiple beam antenna and traveling wave tube amplifier.

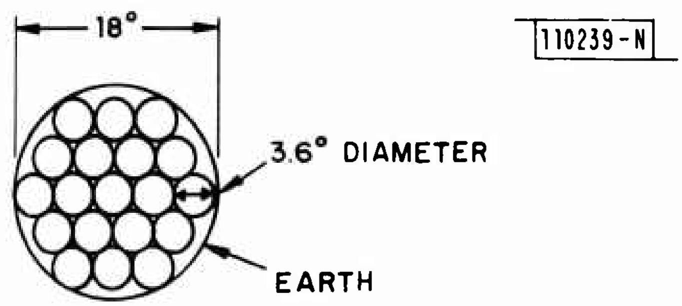
appropriate antenna feed. Each antenna feed represents a spatially distinct downlink beam.

For example, the MRM downlink of Fig. 6.10 has a capacity of 10 10 Mbps channels (some of which may carry the same data, but to separate locations). If a MCC located in beam 3 is receiving one channel, the RF switch will dwell on port 3 for 10 percent of the time. The burst data rate into port 3 is 100 Mbps. The average data rate is 10 Mbps, or one channel.

There is a tradeoff between beamwidth, number of beams (a measure of complexity) and RF power. Figure 6.11 shows the geometrical relationship between beamwidth and number of beams. The 37 and 61 beam geometries were chosen for the TTC and MRM standard nodes respectively (see Sections 6.3.1 and 6.3.2). Typical downlink parameter values are shown in Table 6.4. Note that particular terminal sizes are assumed. (We will return to the HRM downlink shortly.)

Perhaps a better way to implement the TDM time-hopped-beam technique is shown in Fig. 6.12. It is conceptually identical to Fig. 6.10 except that it uses a phased-array antenna with distributed, solid-state power amplifiers rather than a single large PA (which would probably be a TWTA). Such an array antenna (Fig. 6.13) is presently being developed at Lincoln Laboratory for the USAF Space Division as part of the Advanced Space Communications Program for mobile/tactical terminals.

While the TTC and MRM downlinks employ the beam-hopping technique, this study assumes the HRM nodes do not. The reasons are: first, at a 1 Gbps input data rate TDM would be difficult to implement and second, only two downlink channels per node are necessary for HRM according to the mission model used here. A simple scheme using two independently steered dishes is therefore described in Section 6.3.3.



19-BEAM EXAMPLE

NO. BEAMS TO COVER EARTH	HALF PWR BEAMWIDTH	PEAK DIRECTIVITY (dBI)	CIRCULAR ANTENNA DIAMETER (in)
1	18	22.0	2.4
7	6	31.5	7.2
19	3.6	36.0	12
37	2.6	39.0	17
61	2.0	41.0	22
271	1.0	47.0	43

Fig. 6.11. Hexagonal packing of beams to cover earth (18° diameter from synchronous orbit).

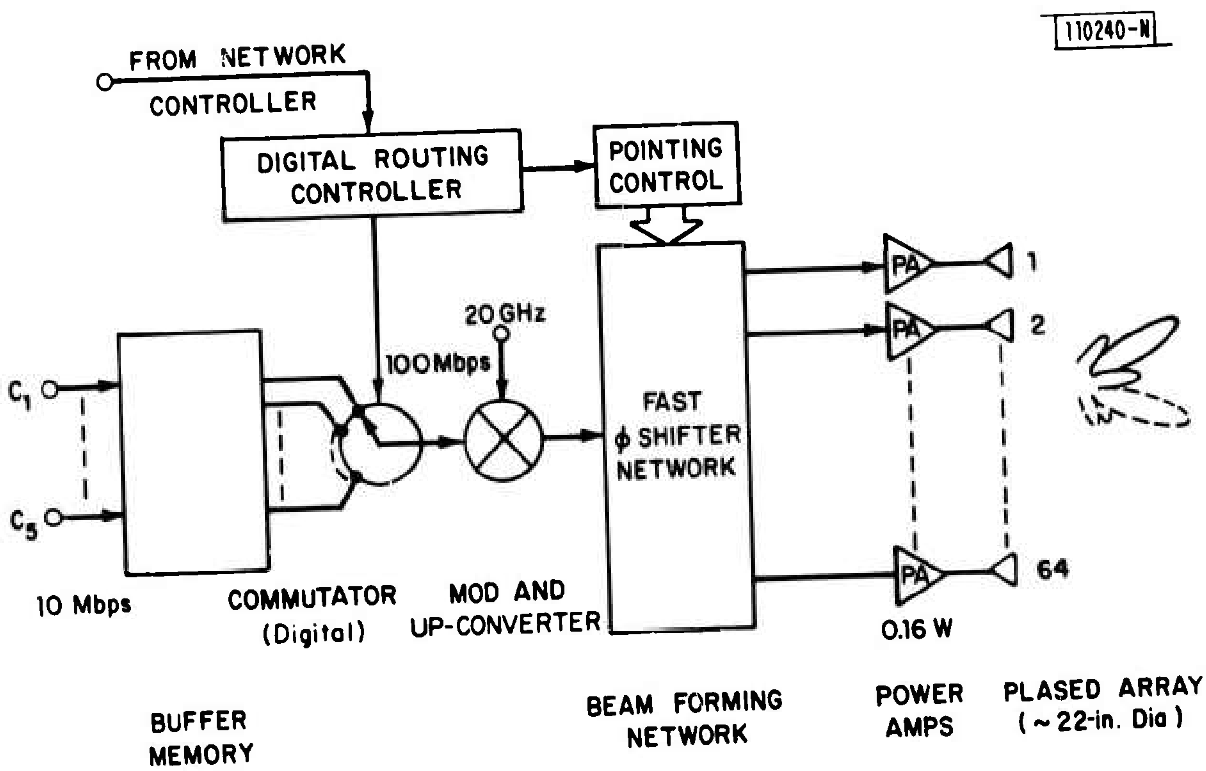


Fig. 6.12. Time-hopped-beam downlink using array antenna with distributed power amplifiers.

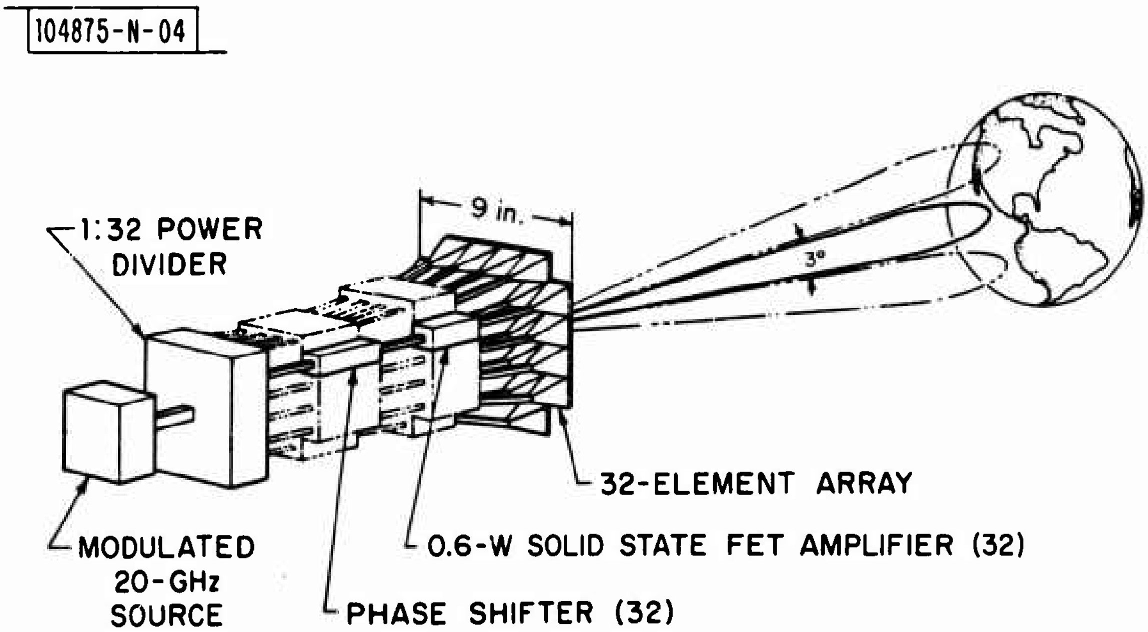


Fig. 6.13. Hopped-beam TDM downlink antenna under development at Lincoln Laboratory.

TABLE 6.4

TECHNOLOGY ASSUMPTIONS FOR THE 20 GHZ DOWNLINKS OF THE DISTRIBUTED NETWORK ARCHITECTURE

Node Type	Ground Terminal Diameter	Number of Downlink Channels	Required EIRP Per Channel	Standard Node Antenna Beamwidth	Standard Node Antenna Diameter	Standard Node Antenna Gain*	Required RF Power
HRM	60 ft	2	51 dBW	1.4°	30 in	41 dB	20W
MRM	40 ft	10	35 dBW	2.0°	22 in	35 dB	10W
TTC	20 ft	16	23.5 dBW	3.6°	12 in	30 dB	4W

*Gain is taken as peak directivity (from Table 6.7) less 6 dB.

6.2.3 UPLINK JAMMING

The 10 kbps forward links on each channel type are used for MSC commands and for a network control orderwire. The only issue is how to protect them against uplink jamming. Table 6.5 shows the link budget for a 250W, 60 ft ground terminal transmitting to an earth coverage horn on the satellite, at a 44 GHz uplink frequency. Table 6.6 shows the levels of jammer EIRP that can be withstood by each terminal with no band-spreading. Band spreading of 100 MHz could provide an additional 40 dB of AJ protection. In short, the network uplinks can be protected against any plausible jamming threat. Uplink multiple access could be implemented by frequency division multiplexing (FDM) techniques.

6.3 STANDARD NODE DESCRIPTIONS

The concept of "standard nodes" was introducted and used in Section 5 with little in the way of supporting physical descriptions. This section provides brief descriptions of the technical assumptions implicit in the distributed architecture discussions.

6.3.1 TTC STANDARD NODE (~ 200 kbps SERVICE)

An example of TTC standard node implementation is shown in Fig. 6.14 with parameter assumptions listed below.

Cross Links (Sec. 6.1.2)

- Frequency: 60 GHz
- Number: 6
- Functions: (a) TTC access port, 200 kbps return, 10 kbps forward
  (b) TTC cross-orbit trunk, up to 12 TTC channels (2.4 Mbps) either direction
- Power Amplifier: 3 impatt diode amplifiers of 2W each, 2 hot, 1 cold spare
- RF Power: 4 W
- Downlink: (Sec. 6.2.2)
  - Frequency: 20 GHz
  - Type: beam-hopped, TDM
  - Capacity: 16 TTC channels (3.2 Mbps)

TABLE 6.5

44 GHZ UPLINK BUDGET (NO SPREADING)

1.	Power Transmitted (250W)	24 dBW
2.	Trans. Ant. Gain (60 ft)	73 dBI
3.	Ground term. EIRP	97 dBW
4.	Path Loss	-218 dB
5.	Rec. Ant. Gain (Earth Cov.)	20 dBI
6.	Rec. Sig. Pwr.	-101 dBW
7.	Data Rate Per Chan (10 kbps)	- 40 dB-Hz
8.	System Noise (1800°K)	+196 dBW/Hz
9.	E_b/N_o Available	55 dB
10.	E_b/N_o Required	- 10 dB
11.	Margin + Loss Allowance	- 10 dB
12.	Excess Margin	35 dB
13.	Jammer EIRP Required (item 3 + 12)	132 dBW

TABLE 6.6

44 GHZ, 10 KBPS UPLINK ANTIJAM CAPABILITY (NO SPREADING)

Channel Type	HRM	MRM	TTC
Uplink Data Rate Per Channel	10 kbps	10 kbps	10 kbps
Terminal Size (ft)	60 ft	40 ft	20 ft
Antenna Gain (dBI)	73	73	67
RF Power (dBW)	250	250	250
Terminal EIRP (dBW)	97	97	91
Excess Margin	35	35	29
Equivalent Jammer EIRP (dBW)	132	132	120

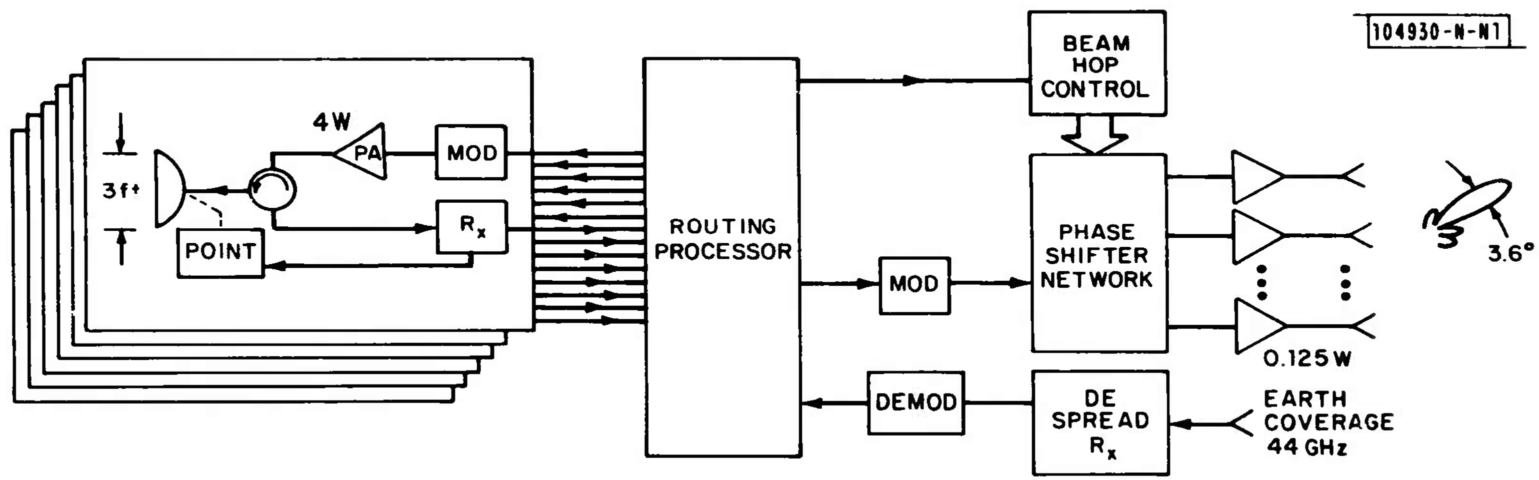


Fig. 6.14. Configuration of TTC standard node.

Antenna: 32 Element phased array, ~ 12 in. diameter

Hopped beamwidth: 3.6°

Operating field of view: earth coverage

Ground Terminal: 20 ft, 580°K

Uplink: (Sec. 6.2.3)

Frequency: 44 GHz

Type: Earth coverage, frequency division multiple access

Capacity: 16 TTC "forward" channels (160 kbps)

Terminal: 20 ft, 250W

Spread bandwidth: < 100 MHz

The routing processor would handle both the downlink routing (Section 6.2.2) and crosslink routing. A control orderwire to the processor from a network controller on the ground is implied.

The TTC standard node, as it is described above, is not particularly plausible as a secondary payload. The six individually steered 3 ft antennas would probably dominate the host vehicle design. Other TTC package configurations should be explored. One option is to reduce the number of crosslinks from six to three per node, in which case it would take more than twice as many standard nodes to meet an equivalent network requirement. Another option would be to develop a 60 GHz version of the multiple-access antenna concept used in TDRSS (See Section 6.4). This would allow several access links to share the same physical aperture. Still another option would be to use optical crosslinks for TTC, but some form of RF link (perhaps at S-band) with an ommi-directional antenna on the MSC would still be required for initial acquisition or emergency operations.

Finally. one should consider architectures in which the ground-based network carries the bulk of low-priority, TTC-only traffic while a distributed space data relay network serves high priority TTC users along with HRM and MRM users.

6.3.2 MRM STANDARD NODE (~ 10 MBPS SERVICE)

The example configuration is shown in Fig. 6.15. Assumed parameters are summarized below:

Optical Cross Links (Sec. 6.1.3)

- Wavelength: ~ 0.85 microns
- Laser: GaAs diode
- Optical Power: ~ 10 mW
- Number of crosslinks per node: 3
- Function: (a) MRM access port, 10 Mbps return, 10 kbps forward
  (b) MRM cross-orbit trunk, up to 3 MRM channels (30 Mbps) either direction

Downlink (Section 6.2.2)

- Frequency: 20 GHz
- Type: beam-hopped, time-division multiplexed
- Capacity: 10 MRM channels (100 Mbps)
- Antenna: 64 element phased array, ~ 22 in. diameter
- Hopped beamwidth: 2°
- Operating field of view: earth coverage
- Ground Terminal: 40 ft, 580°K

Uplink:

- Essentially same as TTC standard node

6.3.3 HRM STANDARD NODE (~ 1 GBPS SERVICE)

Figure 6.16 shows the node configuration. It provides a single HRM channel and can relay it to two ground sites via two individually steered 30 inch antennas. The beam-hopped TDM technique was not considered necessary in this case, considering that implementation at 1 Gbps would be difficult. The parameter assumptions are:

Optical Crosslink (Sec. 6.1.4)

- Wavelength: 0.54 microns
- Laser: Nd:YAG, doubled

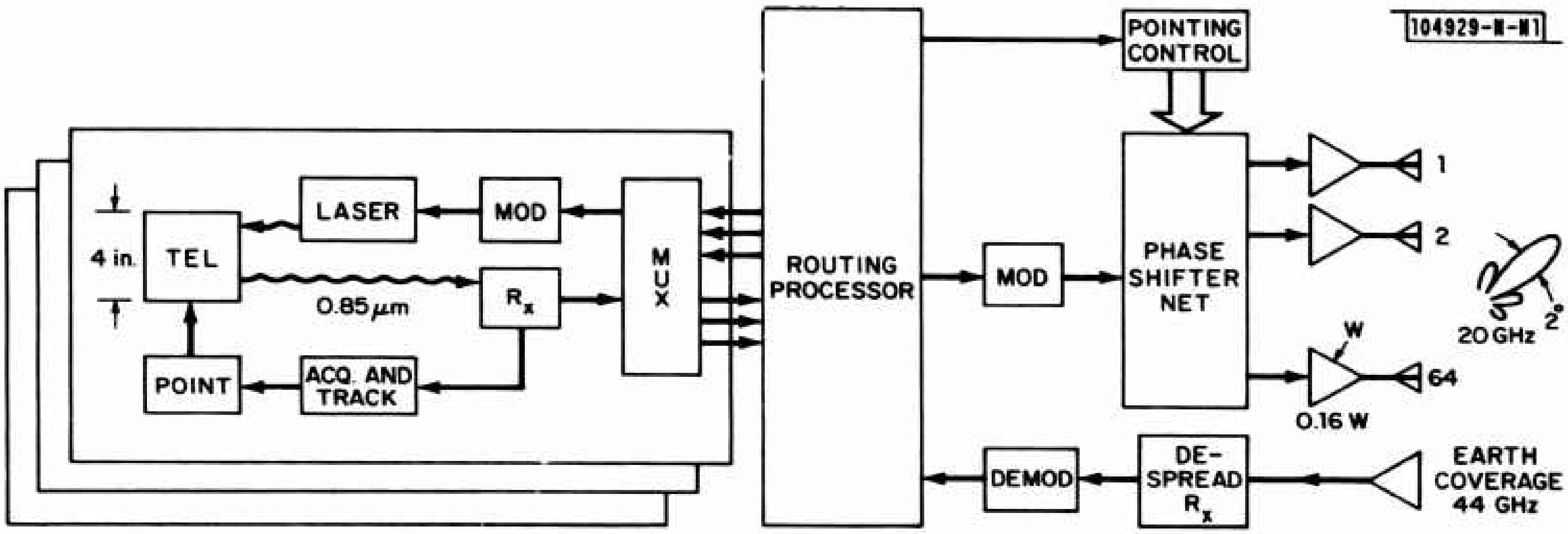


Fig. 6.15. Configuration of MRM standard node.

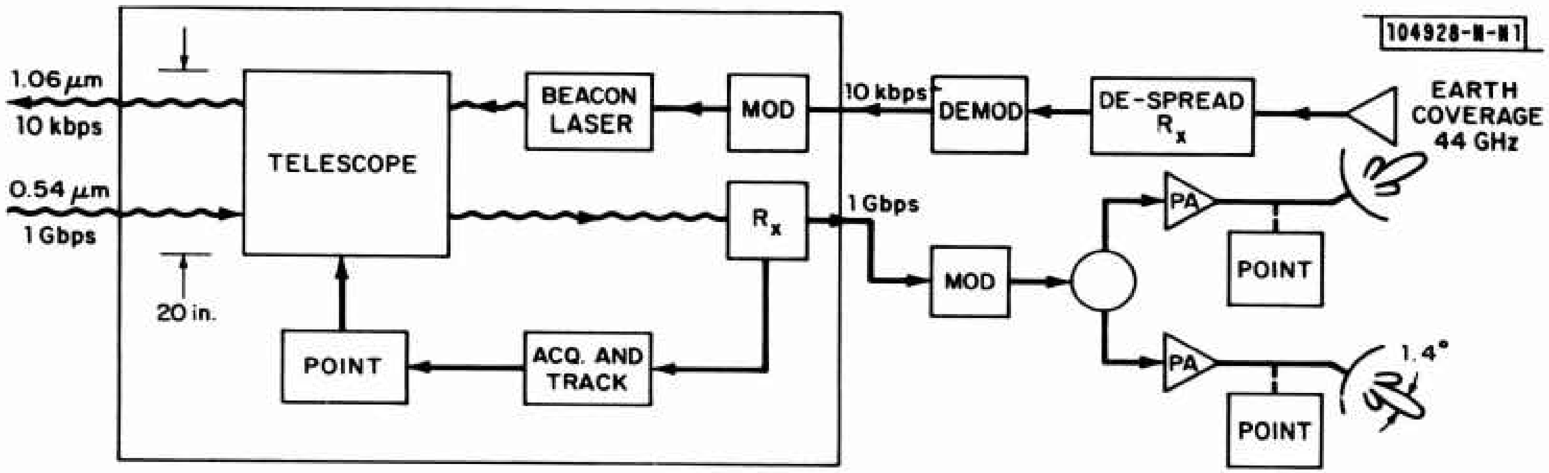


Fig. 6.16. Configuration of HRM standard node.

Number per Node: 1

Function: HRM access port

Downlink

Frequency: 20 GHz

Antennas: 2, 30 in. independently steered

Capacity: 1 HRM Channel (1 Gbps) per beam

Ground Terminal: 60 ft, 580°K

Uplink:

Essentially same as TTC standard node

6.4 MULTIPLE ACCESS ANTENNAS

A problem noted above with the TTC standard node was the number of separate apertures needed. The TDR Satellite avoids a similar problem by its Multiple Access Antenna (Fig. 4.2), for which up to 20 access links share the same physical aperture. There is a technical problem in applying this concept at 60 GHz. The NASA antenna is a 30 element phased array at 2.3 GHz. To maintain roughly the same gain and angular coverage at 60 GHz would imply a 20,000 element antenna. (The number of elements scales as the frequency squared.) A more accurate estimate (Table 6.7) indicates that 4000 elements is about the right number. An equivalent multiple beam implementation of this antenna would require 4000 feed horns. Antennas in this class, that are suitable for satellite applications, do not presently exist.

TABLE 6.7

A 60 GHZ EQUIVALENT TO THE TDRSS S-BAND MULTIPLE ACCESS ANTENNA

1.	Frequency	60 GHz
2.	Wavelength	0.5 cm
3.	Angular coverage (same as TDRSS, orbits below 2000 NM)	28°
4.	Element gain (determined from item 3)	17 dBI
5.	Antenna array gain (from link budget Table 6.1)	53 dBI
6.	Array total diameter ($A = \lambda^2 G/4\pi$)	~ 70 cm
7.	Number of elements (10 log N = item 5-item 4)	~ 4000

REFERENCE

1. Satellite Control System Study; Stanford Telecommunications, Inc. Final Report, on Contract F04701-79-C-0045, Department of Air Force, AFSD. 10 Volumes, (15 December 1979).

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AJ	Anti-jam
AFSC	US Air Force Systems Command
ASAT	Antisatellite
C^3	Command, Control and Communications
C^3I	Command, Control, Communications and Intelligence
CMD	Command
CONUS	Continental United States
CW	Continuous Wave
DSP	Defense Support Program
DC	Direct Current
FDM	Frequency Division Multiplexing
HRM	High Rate Mission Data
IF	Intermediate Frequency
MA	Multiple Access
MCC	Mission Control Center
MRM	Medium Rate Mission Data
MSC	Mission Spacecraft
NASA	National Aeronautics and Space Administration
PA	Power Amplifier
PIN	Positive-Intrinsic-Negative
PLL	Phase Locked Loop
RF	Radio Frequency
RTS	Remote Tracking Station
SD	Space Division of AFSC
SCF	Satellite Control Facility
SCS	Satellite Control Satellite
SPADOC	Space Defense Operations Center
STC	Satellite Test Center
STDN	Space Flight Tracking and Data Network

GLOSSARY OF ACRONYMS AND ABBREVIATIONS (Cont.)

TDM	Time Division Multiplexing
TDRSS	Tracking and Data Relay Satellite System
TTC	Tracking, Telemetry and Command
USAF	United States Air Force

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Today military satellites are controlled through a worldwide network of ground-based tracking stations. A space data relay network, similar to NASA's Tracking and Data Relay Satellite System (TDRSS), could have substantially greater coverage, data throughput and survivability. However, stated military requirements demand large and complex data relay satellite designs. The high cost and technical risk have therefore inhibited the development of a military space data relay network. An alternative space data relay network architecture is introduced in this report. It distributes network assets among the user spacecraft rather than centralizing them in the form of large data relay satellites. The expected requirements are reviewed and two system design examples are presented to illustrate the essential differences between the centralized and distributed architectures. Also discussed are the technologies needed to implement a distributed network, which include advances in laser communications, millimeter wave techniques and on-board signal processing.

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