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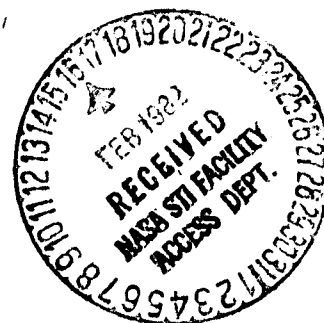# Satellite Applications to Electric-Utility Communications Needs

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December 1, 1981

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ABSTRACT

Significant changes in the Nation's electric power systems are expected to result from the integration of new technology, possibly during the next decade. Digital communications for monitor and control, exclusive of protective relaying, are expected to double or triple current traffic. Estimates of this traffic have been made and a nationwide estimate of 13 Mb/s has been projected. Of this total, 8 Mb/s is attributed to the bulk-power system as it is now being operated (4 Mb/s) and a complex of the larger-sized dispersed storage and generation units (4 Mb/s). This traffic could be accommodated by current communications satellites using 3- to 4.5-m-diameter ground terminals costing $35,000 to $70,000 each. The remaining 5-Mb/s traffic is attributed to new technology concepts integrated into the distribution system. Such traffic is not compatible with current satellite technology because it will require small, low-cost ground terminals. Therefore, a high effective isotropic radiated power satellite, such as the one being planned by NASA for the Land Mobile Satellite Service, will be required. A new frequency allocation for the utility's fixed service may also be desirable. Inclusion of other electric-utility operations-related functions could significantly increase this traffic; nevertheless, a shared service with other users may be desirable to provide an efficient satellite workload.

iii

ACKNOWLEDGMENT

iv

ABBREVIATIONS AND ACRONYMS

ACE	area control error
AGC	automatic generation control
ANSI	American National Standards Institute
ATS	Advanced Technology Satellite
BER	bit error rate
BPS	bulk-power substation
BSS	broadcast-satellite service
CATV	cable television
CCIR	International Radio Consultative Committee
C/I	carrier-to-interference ratio
C/IM	carrier-to-intermodulation ratio
C/N	carrier-to-noise ratio
CONUS	Continental United States
DAC	distribution automation and control
DCS	designated control station
DDC	distribution dispatch center
DOE	Department of Energy
DSG	dispersed storage and generation
ECC	energy control center
EDC	economic dispatch control
EIRP	effective isotropic radiated power
EMS	energy-management system
E_b/N_o	energy per bit-to-noise power density ratio
EPRI	Electric Power Research Institute
FCC	Federal Communications Commission
FDMA	frequency-division multiple access
FDM/FM	frequency-division multiplex/frequency modulation
FSK	frequency-shift-keyed (modulation)
FSS	fixed-satellite service
GOES	Geostationary Orbiting Experimental Satellite
G/T	receive antenna gain/receive-system noise temperature
HPA	high-power amplifier

ABBREVIATIONS AND ACRONYMS (Cont'd)

IEEE	Institute of Electrical and Electronics Engineers
LDC	load-dispatching center
LFC	load frequency center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PAX	private automatic exchange
PFD	power flux density
PLC	power-line carrier
PSK	phase-shift-keyed (modulation)
PURPA	Public Utility Regulatory Policy Act
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SCPC	single channel per carrier
TDMA	time-division multiple access
TWT	traveling wave tube
UHF	ultra-high frequency
VAR	volt-amperes reactive
VHF	very-high frequency
WARC	World Administrative Radio Conference

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

Figures

CONTENTS (Cont'd)

PART ONE

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

SATELLITE APPLICATIONS TO ELECTRIC-UTILITY COMMUNICATIONS NEEDS

This study assesses the applicability of satellites to the communications requirements for monitor and control of electric utilities. The current nationwide bulk-power-system monitor and control traffic is estimated at 4 Mb/s. It is further estimated that by the year 2000 the larger sizes of dispersed storage and generation units will contribute 4 Mb/s of additional traffic. Both of these needs seem amenable to, and can be satisfied by, current communications satellites. In contrast, future monitor and control traffic, estimated at about 5 Mb/s, stemming from integration of new technology into the distribution system is not compatible with current satellite technology. New satellites are required which permit the use of small, low-cost ground terminals. The satellite planned by NASA for the Land Mobile Satellite Service is a good example. Other operations-related functional requirements that seem to be compatible with the current or planned satellite technology, if the Land Mobile Satellite Service is included, are: (1) voice and data communications to various operational sites, mobile units, maintenance/service centers, and engineering/administrative locations, and (2) remote video monitoring and teleconferencing, for which needs are emerging or increasing. These functions would significantly increase the potential satellite traffic assignable to the electric utilities.

Many electric utilities are in the process of upgrading their control systems to provide more comprehensive and automated control of bulk-power-system functions. In addition, control will eventually be extended to the distribution system for operational- and load-management purposes. This development will be accompanied by, and perhaps hastened by, the need for control of dispersed storage and generation (DSG) units located in the distribution system. All of these control processes will involve the development of reliable communication systems of suitable capacity. The purpose of this report is to explore ways in which these communications might be provided by satellite transmission.

A satellite system serving bulk-power-system needs could be established through the lease of capacity on one of the current C-band commercial satellites. It is estimated that the total bulk-power control-system traffic of a large utility (i.e., one supplying 1% of the nation's electrical energy) is about 40 kb/s. With current tariffs, the annual cost of leasing backed-up transponder capacity to accommodate this traffic is about $10,000. Because of the small point-to-point traffic on most bulk-power-system links, each satellite channel would most probably be operated in a time-division-multiple-access (TDMA) mode, with the channel bandwidth chosen to accommodate the total bulk-power-system traffic of a single utility.

The price of a fully redundant, 4.5-meter, TDMA earth station designed for this application is estimated to be $74,000. Incorporation of redundancy into the earth-station design virtually eliminates the possibility of an outage due to component failure in the ground segment. In the event of a transponder failure, the presence of an alternate communications mode makes possible an almost instantaneous switchover to the backup transponder. A significant communications outage, lasting several hours, would occur only as the result of a total satellite failure. In this event, the alternate communications mode would be used until the earth-station antennas could be repointed in the direction of the backup satellite.

1

C-band satellite communications could also be used in the control of DSGs. These renewable sources of energy are expected to contribute between 4% and 10% of the nation's electrical energy supply by the year 2000. C-band transmission is an ideal form of communications for those types of DSGs (e.g., hydroelectric and wind-generation) located in remote areas, where location and/or terrain make other communications alternatives unattractive.

On the other hand, satellite transmission at C-band may be inappropriate for DSGs located in more populous areas, because of the need for coordination with terrestrial services operating in the same frequency band. Satellite transmission at K_u-band would solve this problem; however, current K_u-band satellite systems are designed for wideband operation, rather than the narrow-band TDMA mode necessitated by the low DSG data rates. The latter are about 150 b/s per DSG (for a 2-s scan rate) in both the poll and response directions. A large utility might include 100 DSGs in the 1-MW-plus category and have a combined DSG poll/response data rate of about 40 kb/s (including data generated by smaller DSG units).

A maximum antenna size of 3 m has been postulated for general DSG use, as well as for other specific distribution-system applications. C-band transmission with this size dish has not yet received Federal Communications Commission (FCC) approval. However, it appears from applying a proposed International Radio Consultative Committee (CCIR) Recommendation, that interference into adjacent satellite systems would not be excessive with 3-m antennas. The maximum data rate supported by such a system, based on an earth-station high-power amplifier (HPA) rating of 5 W, varies from 12 to 19 kb/s depending on the sensitivity of the satellite receiver.

The price of a nonredundant, 3-m earth station suitable for DSG operation is estimated at $32,000. Redundancy is not required, because an earth-station failure would produce only a local effect. A transponder failure could be overcome by programing the DSG controller to attempt to communicate over the backup transponder whenever communication has been interrupted for a specified period of time. A total satellite failure would require repointing of earth-station antennas before communication could be resumed.

Most distribution automation and control (DAC) functions could be performed effectively via satellite only through the introduction of earth-terminal equipment which is cost-competitive with equipment needed for other communications alternatives (i.e., hundreds of dollars rather than thousands). Because of the increasing cost of earth-terminal equipment with frequency, the lowest possible frequency should be sought. For this reason, and also because of the need to avoid interfering with other satellite systems, S-band transmission offers the most promise among existing fixed-satellite-service (FSS) frequency allocations. However, the compatibility of such a system with terrestrial services operating at S-band requires further investigation.

The alternative to S-band transmission would be the allocation of a new frequency band, perhaps 1 MHz in width, for the utility application. A lower limit on the range of candidate frequencies would be set by the man-made noise background in urban areas, but would presumably be about 1 GHz.

It is concluded that bulk-power-system communications requirements can be satisfied by using current C-band satellites and relatively inexpensive

2

earth stations. The DSG communications can be provided by current satellites, with even less expensive earth stations, although the need for this type of communications is not expected to fully materialize until the 1990s. DAC communications by satellite, on the other hand, requires the availability of satellite systems which can utilize very small and inexpensive ground terminals, and possibly a new frequency allocation as well. Such satellite systems do not now exist commercially although planning is underway within NASA's Land Mobile Satellite Service program. The cost effectiveness of such a satellite network when applied to, or shared by, the electric utility industry remains to be established. Other potential users having similar requirements might include oil and gas distribution, exploration and production companies, medical data exchange networks, emergency warning networks, etc.

In light of the above, the following near-term actions are recommended.

(1)   Follow-on traffic study to include mobile communications requirements of utilities and requirements of major transmission utilities such as TVA, Bonneville or Western Area Power Administration.

(2)   Follow-on frequency management study to investigate interference, coordination, and assignment issues in greater depth, particularly at S-band and lower.

(3)   Formulate a program for experimentally exploring, in partnership with a utility, the feasibility of key concepts developed in this and the follow-on studies, but using existing C-band satellites. Such a program might include, for example, the establishment of an experiment link for monitor and <u>control</u> of various bulk-power-system units.

(4)   Identify and survey other potential users of a "narrow band" fixed-satellite service system. Identify user requirements and develop an estimate of potential communications traffic.

3

PART TWO

SATELLITE APPLICATIONS TO ELECTRIC-UTILITY
COMMUNICATIONS NEEDS

SECTION I

INTRODUCTION

The communications systems of many electric utilities are undergoing major new developments. In the areas of power generation and transmission (i.e., the bulk-power system), upgrading of existing communications parallels the modernization of utility control systems. This modernization process is aimed toward greater automation, higher reliability, and general streamlining of data gathering and analysis. Reliability considerations demand that each pair of sites exchanging data be connected by a pair of independent communication paths. A satellite link can serve as one such path. Moreover, satellite transmission can readily be established with current communication satellites, since the required earth stations are compatible in size and cost with bulk-power-system installations.

By contrast, communications within the distribution system is in its infancy. Control over customer loads to reduce peak-power requirements has been exercised in the United States only in the last several years. Moreover, automation of operational-management functions, such as feeder-network reconfiguration, is largely in the discussion stage. However, interest in distribution automation and control (DAC) is expected to increase as sources of renewable energy become more prevalent in the distribution system. As these dispersed storage and generation (DSG) units begin to represent a significant portion of the nation's generation capability, it will become increasingly important to integrate them into the utility control system.

At present, various competing technologies are being examined to determine which are best suited to perform the different DAC functions. It is logical to include satellite transmission among the candidate communication modes.

The feasibility of conducting utility-company communications by satellite depends on the number and nature of sites at which earth stations must be deployed. A control-system model presented in Section II provides a framework for discussing the communications topology. Actual control systems vary in structure; consequently, this model should be regarded as merely typical. Moreover, because DAC is virtually nonexistent today, the portion of the model pertaining to distribution-system operation is somewhat hypothetical. Nonetheless, introduction of the model makes possible a categorization of communications links by earth-terminal types, as well as an association of control (and thus communication) functions with the various links.

An assessment of satellite communications must begin with a determination of the traffic requirements. Two different traffic estimates are developed for the bulk-power system in Section III, following a description of the principal monitor and control functions to be performed. The first estimate is based on the control-system requirements of a local utility. This estimate is formed by considering the totality of points that must be monitored and/or controlled, together with the associated scan rates. The second estimate is based on a detailed model utility of comparable size, and was compiled at JPL (Reference 1) based on one of the Electric Power Research Institute (EPRI) synthetic utilities (Reference 2). Systematic examination was made of the

monitor and control requirements of each bulk-power-system installation. The two estimates differ by a factor of about 4. A reconciliation of the two estimates is possible, so that, between them, a reasonably good idea of the bulk-power-system traffic can be obtained.

An estimate of DSG traffic requirements is presented in Section IV, again following a description of associated monitor and control functions. Alternate topologies for the DSG links are described in terms of the control-system model. The basic data requirements are extracted from a recent General Electric Company report (Reference 3); however, the assumed message format is based on recommendations contained in an Institute of Electrical and Electronics Engineers (IEEE) working paper (Reference 4). The DSG traffic, projected to the year 2000, is comparable in magnitude to the bulk-power-system traffic.

Three different distribution-system traffic estimates are presented in Section V. Two are based on studies performed at MITRE Corporation (Reference 5) and Boeing Aerospace Corporation (Reference 6); the third was developed at JPL (see Reference 1). The three estimates are not directly comparable in either functional requirements or message format. Moreover, there is a wide divergence in the magnitudes of the estimates. This is not too surprising, considering that there is little hard evidence on which to base a projection of DAC traffic. Because it is consistent in method of derivation with the bulk-power-system and DSG-traffic estimates, the JPL estimate has been taken as a measure of future distribution-system traffic.

With a description of the functions to be performed and estimates of the data rates required for their performance, it is possible to assess the suitability of satellite communications. This is done in Section VI, which constitutes the heart of this report. As a preview to this rather detailed discussion, some of the major considerations are highlighted in the following paragraphs.

The traffic estimates given in Sections III through V represent the total projected traffic for each segment of the utility system. In the bulk-power system, much of this traffic exists today and is carried by transmission modes other than satellite. The extent to which satellite transmission might be adopted in the future depends on utility-company plans to augment the existing communications capability, either in breadth of activity or in reliability. The former aspect is related primarily to the needs of control-system modernization.

Within the distribution system, the major question concerns the rate at which the projected traffic will materialize. Satellite transmission is at a slight disadvantage as a candidate to support this traffic, since experimental evidence is already being gathered on the suitability of alternate communications modes (Reference 7). More importantly, appropriate satellites for transmission to many distribution sites do not exist today.

Except for transmission to mobile units, utility-company communications via satellite should be conducted at frequencies allocated to the fixed-satellite service (FSS). Many of these bands are shared with the fixed (terrestrial) service, a circumstance that could make frequency coordination of any proposed satellite service difficult in populous areas. Additionally, Federal Communications Commission (FCC) approval of small earth stations

(i.e., <4.5-m antenna diameter) for C-band transmission may not occu.. For
these reasons, transmission via present-day satellites is largely limited to
bulk-power system and, depending on the minimum permissible antenna size, DSG
applications.

The problem of finding a suitable transmission vehicle is compounded by
the low data rates generated throughout the utility system. The total control-
system traffic for a large utility can be measured in tens of kilobits. There-
fore, satellite transmission is most appropriate to satellites that permit
access by narrowband carriers in a shared-transponder mode.

On the other hand, the combination of narrowband transmission and the
need for very low-cost earth terminals makes distribution-system traffic a
natural candidate for inclusion in NASA's Narrowband Communication Program
(Reference 8). The primary application of this program to date has been the
Land Mobile Satellite Service. Technology developments required for
implementation of an operational LMSS system are discussed in a recent paper
by Weber, et al., (Reference 9). Much of the same technology would be
applicable to utility-company communications. However, the latter application
would require a frequency different from the (806-890)-MHz band newly
allocated to the Land Mobile Satellite Service.

With the total traffic generated by a typical large utility being fairly
small, point-to-point data rates are extremely low. For example, the average
data rate on links joining bulk-power-system sites to the energy control
center (ECC) of a large utility typically ranges from 1 to 20 kb/s. On the
other hand, generation plants, and the transmission system as well, have a
number of points that must be monitored as frequently as every 2 s. This
creates the need for a large number of communications links to time-share a
common, narrowband satellite channel.

The subject of transponder multiple-access is discussed in Section VII.
From the standpoint of network control, it is desirable to assign separate
satellite channels to different utilities. This assignment implies a variable
channel bandwidth, with each utility assigned a band commensurate with its
traffic requirements. The ability of modest sized earth stations (i.e., those
with 3-m antennas), operating in conjunction with current C-band satellites,
to support the required data rates is demonstrated in Section VIII.

Timing considerations for a time-division multiple-access (TDMA) system
are also discussed in Section VII. Because a relatively long TDMA frame period
of 2 s suffices in the bulk-power system, timing of transmissions from
different stations can be relatively crude without adversely affecting trans-
mission efficiency. The absence of a need for precise timing has important
implications regarding the complexity of earth-station design.

Because of the possibility of satisfying bulk-power-system and certain
distribution-system communications requirements with current C-band
satellites, a detailed link analysis of such a system is provided in Section
VIII. Both 4.5-m and 3-m earth-station antennas are considered. In the
process, link equations that must be satisfied for satellite transmission at
any frequency are developed.

Trade-off curves are presented, in the 3-m case, for the required earth-station transmitter power as a function of the channel data rate, with satellite receiver sensitivity as a parameter. Limitations on uplink transmitter power (or, equivalently, the channel data rate) imposed by the need to avoid injecting excessive interference into other satellite systems are also considered. In this regard, it is shown that the use of 3-m antennas is consistent with the projected distribution-system data rate of a large utility in the year 2000.

This report is directed at two distinct audiences: those concerned with utility-company communications, for whom satellite transmission is simply one possible communications mode; and communications-satellite engineers, to whom utility-company communications requirements represent another possible area of application. The amount of tutorial material presented in the utility area, and the relative lack of same in the satellite area, largely reflects the association of the writer with the latter group.

Thus, readers with a knowledge of electric-utility operations may find the descriptive material in Sections II through V superfluous. However, this material should be helpful to communications-satellite engineers in understanding the nature of utility-company communications requirements. The latter group, hopefully, will have no problem with the discussion of satellite link design in Section VIII. However, those not versed in satellite communications may wish to consult other sources before attempting this material.

SECTION II

ELECTRIC-UTILITY CONTROL-SYSTEM MODEL

The major elements of a typical present-day electric utility are described and a representative control structure is modeled. As a future projection the control system model is extended to the distribution system, even though virtually no regular communication is carried below the distribution substation today. The traffic estimates used in this report are derived later using the control structure depicted by this model.

The major elements of an electric-utility system include the bulk or central generation plants, transmission system, distribution system, and customer-load system (Figure 2-1). Power produced at bulk sources is stepped-up in voltage for transmission to bulk-power substations (BPSs), at which point the voltage is reduced before further transmission, over subtransmission links, to distribution substations. The combination of central generating plants and transmission lines terminating in BPSs is referred to as the bulk-power system. The transmission system is typically quite complex, with a number of alternate paths (for reliability purposes) connecting each generating plant with the various BPSs. In addition to these connections, transmission links referred to as interties provide connections with the bulk-power systems of other utilities.

A number of different voltage levels can be found within the bulk-power system. Although there are certain voltage levels that commonly appear, there is little uniformity, even within a given utility, in the voltage appearing at the primary or the secondary side of a BPS transformer. In fact, the tendency toward ever-increasing transmission-system voltages has resulted in voltage levels, associated at one time with the bulk-power system, having been pushed downward into the distribution system.

The distribution system begins at the secondary side of the BPS transformer. The role of each principal element of the distribution system is defined in Table 2-1. The distribution system is characterized by a radial network structure, so that at any given time each primary feeder circuit, together with the associated laterals and secondaries, is associated with a particular distribution substation. An elaborate system of switches permits sections of customer load to receive power via alternate paths to the substation, or from a different substation, should a fault occur along the initial path.

Responsibility for ensuring that a reliable supply of electrical power is delivered to the customer at minimum system operating cost rests with the ECC. This term is often used interchangeably with the term energy-management system (EMS). For present purposes, an EMS is defined as a collection of control strategies and operational practices, together with associated hardware and software, needed to accomplish the objectives of energy management (Reference 10). Activities of the EMS include: management of all generation and transmission equipment within its area of control (for frequency and voltage control); control of power exchange to/from external areas; diagnosis and
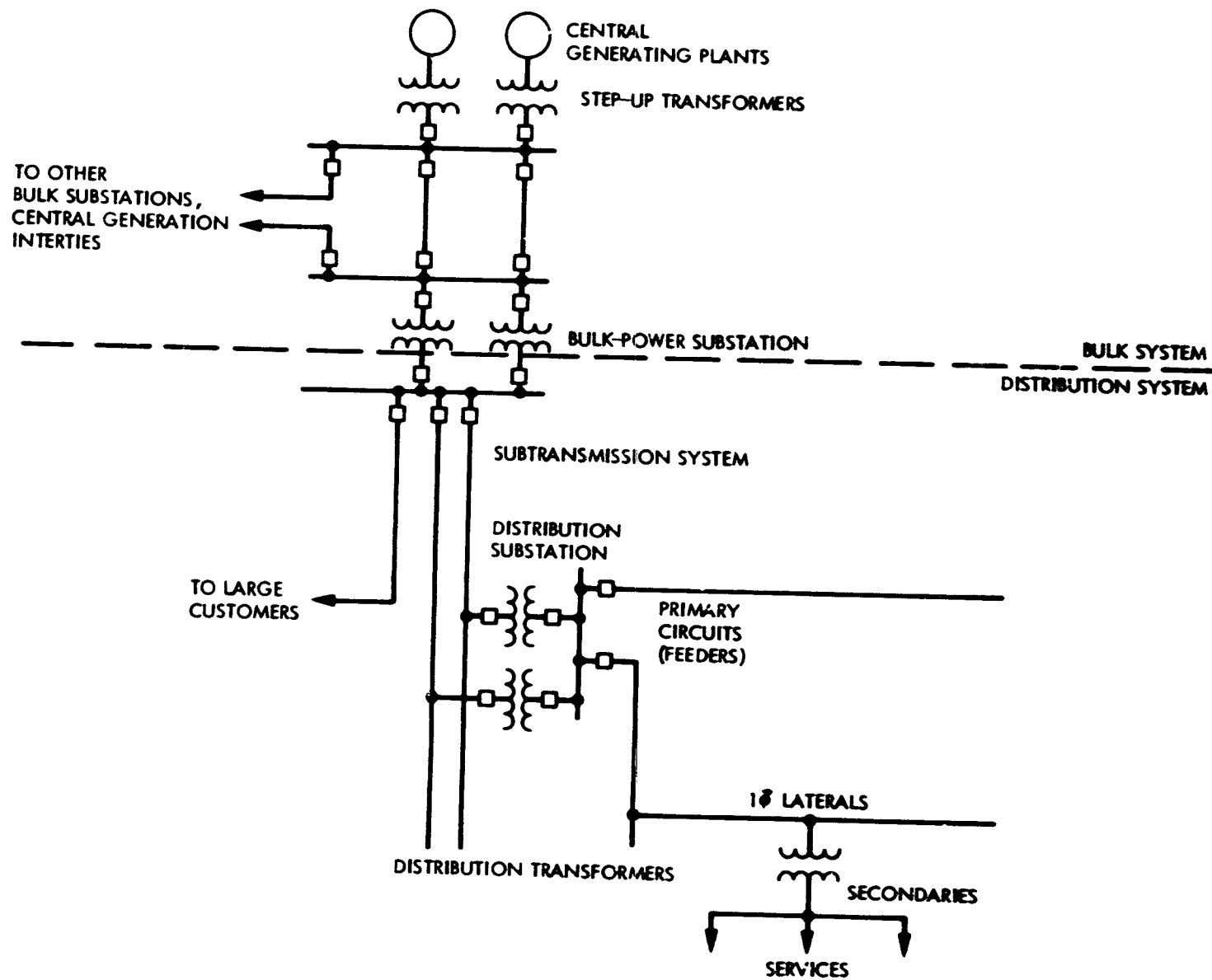
Figure 2-1. Major Components of an Electric Power System

Table 2-1. Functional Classification of Distribution-System Components

Component	Function
Bulk-power-substation secondary	Receives power from the transmission system
Subtransmission system	Circuits that emanate from the bulk-power substation and supply the distribution substations
Distribution substation	Receives power from the subtransmission circuits and transforms it to the primary-feeder voltage
Primary feeder, lateral	Circuits that emanate from the distribution substations and provide path of power flow to the distribution transformers
Distribution transformer	Transforms power from primary feeder voltage to consumer-utilization voltage
Secondaries and services	Circuits that provide path of power flow at secondary or utilization voltage from the distribution transformer to the consumer property

correction of system electrical problems; and recording of data pertinent to system operation, diagnostics, and billing. Thus, EMS is an all-inclusive term that embraces control-system equipment distributed throughout the utility network. By contrast, the ECC is the physical site from which the real-time aspects of EMS operation are directed.

The general form of present utility control systems is shown in Figure 2-2. Direct control is exercised by the ECC over generating plants, transmission lines, and BPSs, i.e., over all bulk-power-system elements. The output required of each generating plant, determined at the ECC, is communicated over a data link to a local controller, which determines how the total power required is to be apportioned among the various generation units. Voice communication is also maintained between the ECC and personnel permanently assigned to the generating plants.

Bulk-power stations may be either manned or unmanned. Unmanned substations are controlled and monitored via supervisory control such as the modern supervisory control and data acquisition (SCADA) systems. Manned substations may also include SCADA remote units.
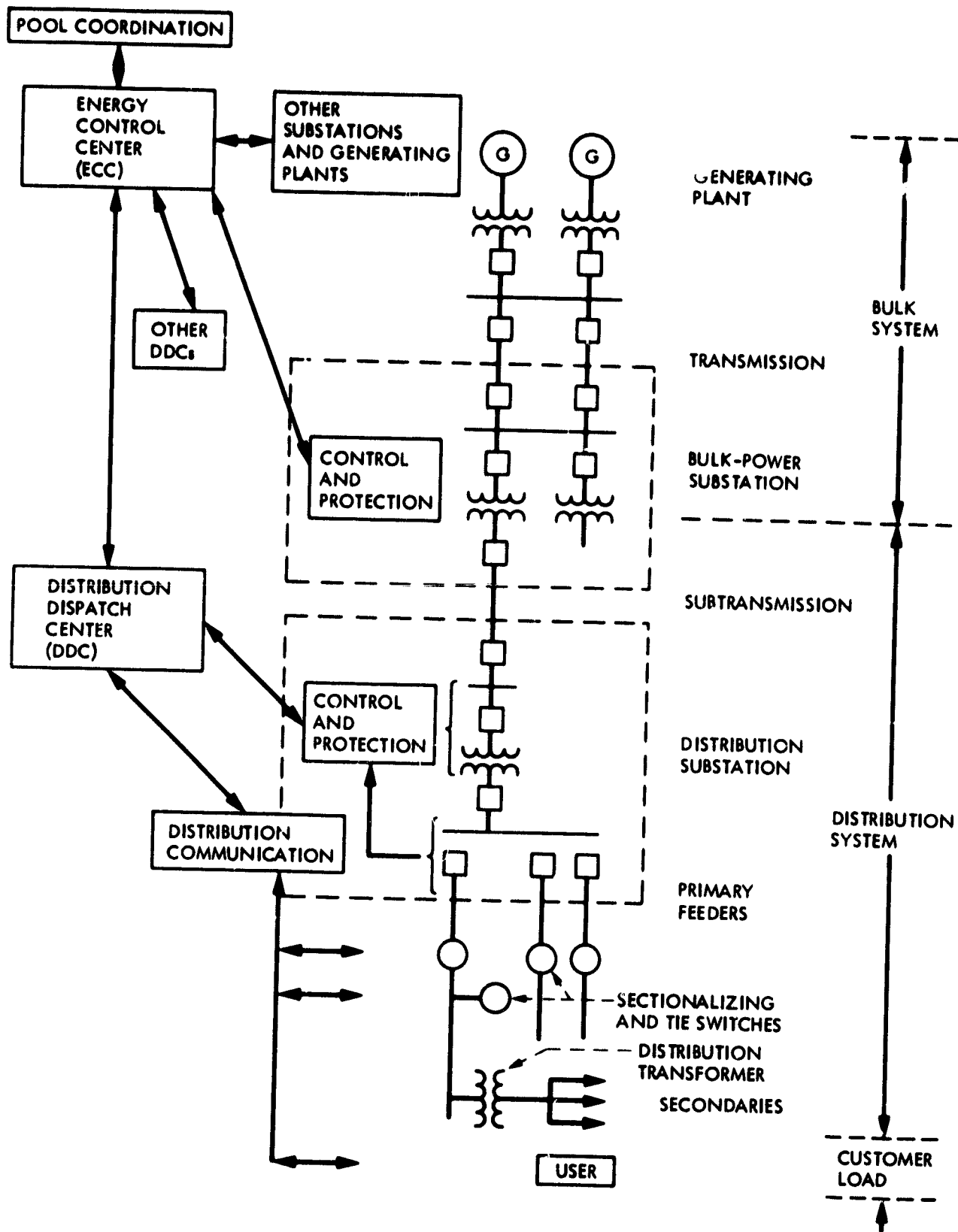
Figure 2-2. Typical Utility Control-System Structure

Distribution-system control is effected through a network of distribution dispatch centers (DDCs). Each DDC has a direct communications link to the ECC, as well as to the distribution substations under its control (which may number as many as 50). Distribution substations have generally been operated unmanned, with separate subsystems for control, protection, and monitoring. SCADA remote units are becoming more prevalent at distribution substations for control and for communication of necessary information back to the DDC.

Virtually no regular communication exists to utility-system sites below the distribution-substation level (except for load management, which is nevertheless in its infancy). Thus, fault detection is left to other means, such as a telephone call to report the loss of service. Reconfiguration of the distribution feeder network, including isolation of faulted feeder sections, is accomplished manually by teams dispatched by the DDC.

The control-system model used in this report, which is intended to be representative of future, modernized control systems, is depicted in Figure 2-3. The major formal distinction between this model and that of Figure 2-2 is the insertion of control points at the distribution-substation level, referred to as DACs. These control points, in one-to-one correspondence with the substations, monitor operation of the feeder networks and issue appropriate commands for feeder-network reconfiguration. The DACs are also responsible for performing load management and remote meter reading, as well as for controlling DSGs assigned to the associated distribution substation.

Apart from the formal distinctions between Figures 2-2 and 2-3, the future control system will incorporate a greater degree of automation and perform functions not done by present-day control systems.
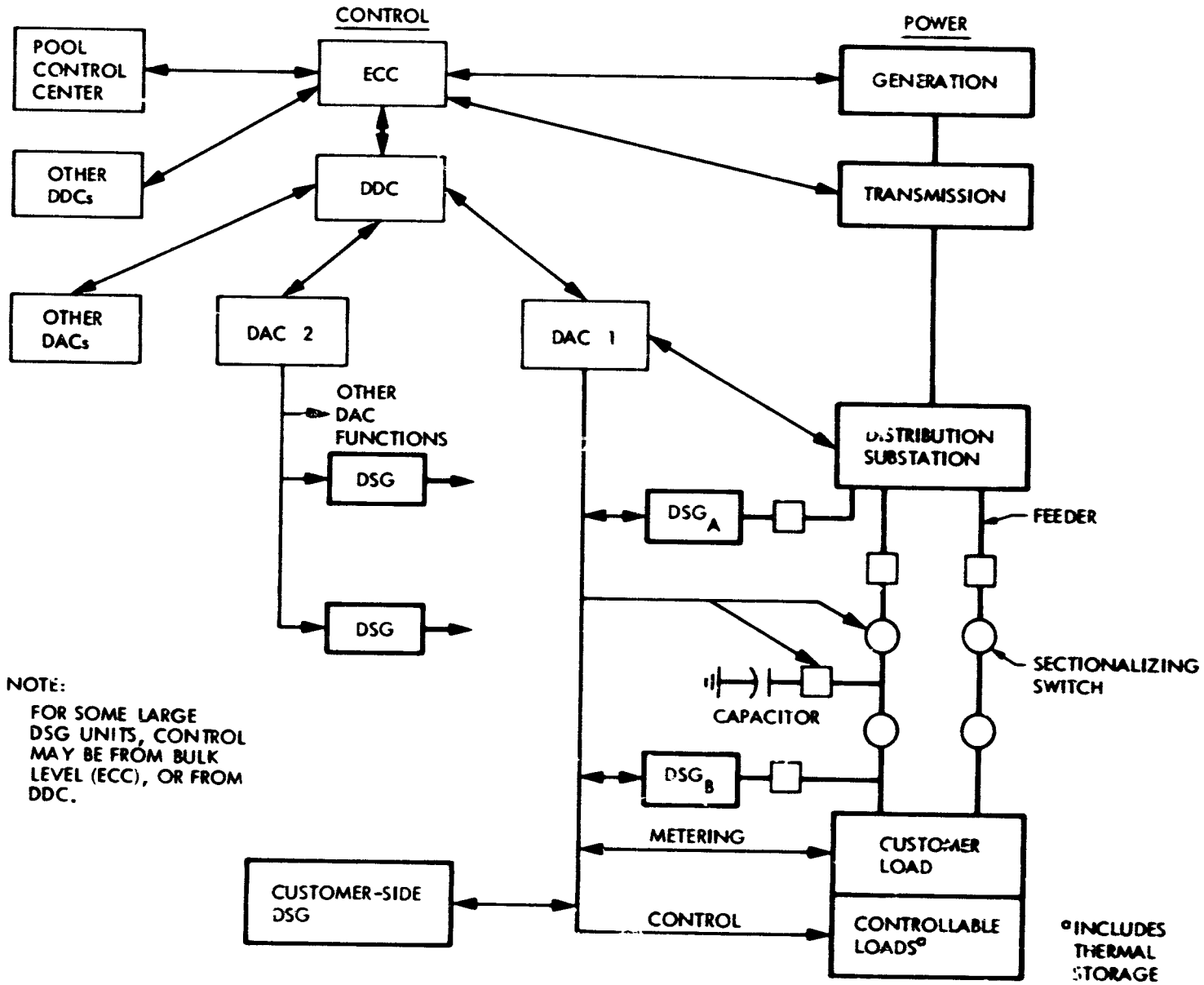
Figure 2-3. Future Control System Incorporating Distribution Automation and Control

SECTION III

BULK-POWER-SYSTEM TRAFFIC REQUIREMENTS

*Traffic requirements for monitor and control of the bulk-power system are developed.
The estimates for a large, local, metropolitan utility have been compared to those
generated for a modeled utility and a composite was gen- --ed. The resulting composite
has been employed in later sections of this report and m-,' be summarized as 40 kb/s for
a representative large utility and 4 Mb/s for the U.S. electric utility industry.*

In the control-system model of Figure 2-3, the ECC exerts direct control
over the bulk-power system and indirectly monitors distribution-system opera-
tion through the DDCs. The major bulk-power-system elements are the central
generating plants, BPSs, transmission lines connecting generating plants with
the BPSs, and interties with other utilities. The latter provide the necessary
connections so that energy can be delivered from one utility to another.

The bulk-power system will often include a number of switching stations,
which provide alternate connections between generation units and BPSs, thereby
improving the reliability of the transmission system. Switching stations gen-
erally collect and redistribute power at a common voltage, i.e., they normally
do not perform a voltage-transformation function. Occasionally, switching
stations will be found in the subtransmission system. Control over the sub-
transmission system, to the extent required, is also performed by the ECC.

Different utilities are in various transitional stages from a control
system that has evolved in a piecemeal fashion to one that is highly automated,
with frequent and comprehensive monitoring of individual generation units and
numerous critical points in the transmission system. Control may be central-
ized or decentralized within the bulk-power system; the model in Figure 2-3
assumes a single control point in the form of the ECC. Redesign and/or up-
grading of the telecommunications system is an integral (and major) part of
control-system modernization.

Following a brief discussion of the monitor and control functions
required in the genei .ion and transmission areas, and a description of the
control system proposed for one local utility, a pair of independent bulk-
power-system traffic estimates are presented. The first, which is relatively
crude, is based on the number of status, alarm, and analog points that must be
reported for the entire local utility bulk-power system. The second estimate
is derived from a utility model developed by JPL (see Reference 1) from one
of the EPRI synthetic utilities (see Reference 2) and represents a top-down
approach to specifying the data requirements. The latter method has also been
used to estimate the distribution-system traffic (see Section V-E).

A. MONITOR AND CONTROL FUNCTIONS

The primary activity of the ECC is to ensure that a reliable supply of
electrical power is delivered to the customer at the minimum system operating

cost. Attainment of minimum operating cost implies that the operating frequency and voltages must be maintained at the proper values. In addition, power flow between areas must be controlled to meet contractual agreements with other systems. To implement these functions, a SCADA system is generally employed. The required analysis of collected data is performed by computer, while subsequent control actions may be either automated or manual.

The ECC is responsible for the control of all bulk-generation sources. The ECC might occasionally exercise direct control over large DSGs, but for the most part these would be under the control of a DDC or DAC. The term automatic generation control (AGC) is used to describe automated regulation of the power output of generators within a prescribed area, to maintain the scheduled system frequency and the established interchange with other areas. The distribution of generation requirements among alternative sources to achieve maximum system economy is referred to as economic dispatch. In selecting a set of generator outputs, consideration is given to incremental costs of power generation, together with the associated transmission losses. Additionally, a balance must be struck between real-time load requirements and the need for periodic maintenance of generation units.

In current utility operations, whenever the power system deviates from scheduled interchange or frequency (usually 60-Hz) values, an area control error (ACE) is generated at the central control point. This error is distributed among the generation plants under control, with each plant directed to raise or lower generation so as to bring the ACE to zero. A controller within each plant further distributes the error among individual generation units to achieve maximum economy.

Generally, when the ACE exceeds a specified amount, economics are overridden and all plants share equally in the ACE to improve generation response. Within each plant, however, the error continues to be distributed according to economics. If the system response to a large ACE is sluggish, the control-center dispatcher telephones plant operators to manually adjust generation and assist in system regulation.

Inability of a utility to control individual generation units from a central control point results in a loss of regulating capability and an associated economic penalty. This problem will be solved, in general, for single-utility-owned generation units once a comprehensive and automated energy-control system has been implemented. The problem will remain, however, of coordinating the output of generation units shared with other utilities.

The local utility studied, for example, has numerous ties with other utilities at the BPS or switching-station level. Moreover, most future major generation sources will be located outside its control area and will assume the form of jointly-owned nuclear or coal-fired units. Current operating agreements do not provide for joint regulation of jointly-owned plants.

The ECC is also responsible for the configuration of the power transmission system, and must ensure its security and safety of operation. The

transmission system is reconfigured through the action of circuit breakers located at various BPSs and switching stations. Automatic voltage/volt-amperes-reactive (VAR) control is the process of maintaining line voltage and VAR flow throughout the transmission system within predetermined limits. Line voltages are most frequently maintained at desired values through the adjustment of load-tap-changing transformers. VAR flow control, which is needed to limit transmission losses, is accomplished through the introduction of reactive compensation at appropriate points.

B.   UTILITY EXAMPLE

The traffic occasioned by the control-system activities studied provides one example of the requirements of a large utility. Before an estimate of this traffic is derived, however, some of the characteristics of the present and planned bulk-power control systems will be described.

1.   Shortcomings of Present Control System

Transmission-system control, which is conducted by the load- dispatching center (LDC), suffers from several deficiencies. Both VAR flow control and transformer load-tap adjustment are accomplished by telephone communications with substation operators, rather than in an automated manner. Post-disturbance analysis is often difficult because of an insufficient number of monitoring points. Frequently, there is also a loss of telemetry data due to lack of alternate metering points, alternate communication routes, or a reliable communications system in some areas.

As presently exercised by the LDC, transmission control extends only as far as the 15 manned BPSs. The balance of the transmission and subtransmission system, which includes 6 unmanned BPSs, 3 switching stations, 94 distribution stations, and 15 industrial stations, is controlled from the 15 manned BPSs. In this network, which is an example of a supervisory control system, each manned BPS controls the circuit breakers and load-tap-changing transformers of, and receives telemetry data from, the substations within its area of control, much as the ECC does for the entire transmission system in the control-system model.

Every master (manned) BPS contains a separate supervisory unit for each remote receiving or switching station, most distribution stations, and some industrial stations under its control. For example, one master station has 14 master sets and 5 station control boards, which keep track of 1,220 control and indication points. This multiplicity of supervisory units leads to very unwieldy operation of the supervisory control system. It is especially diffi-cult to analyze the trouble during emergency and stress conditions, should a number of alarms or line outages occur within a short time interval. Operators do not have sufficient time to log all the sequences of alarms and outages, and therefore must rely on their memory to reconstruct a series of events.

In addition to the present supervisory control system, the utility has a loop supervisory system, with a master station located at the LDC and remote

sites located in manned and unmanned receiving and switching stations. The
loop supervisory system has no control capability; it merely transmits circuit-
breaker, hot-bus, and hot-line indications from the remote stations to the LDC
for display on a system map board.

2.   Future SCADA System

The utility provides a good example of a utility that is making the
transition to a modernized control system. The SCADA system will have
automated primary and alternate digital control systems, a digital backup
system for AGC, and a manual control system for those occasions when all else
fails. Control will be centralized at the newly designated ECC, as the role
of the existing LDC is gradually phased out. The final form of the telecom-
munications (TELECOMM) network topology is shown in Figure 3-1. Although the
distribution substations are physically linked directly to the BPSs, as
before, the latter function only as relay stations as far as data relating to
the substations are concerned.

The data circuits will be a combination of cable, cable carrier, power-
line carrier, and microwave facilities. The network will use utility-owned
facilities if they are either available or cost-effective to install. Remote
terminal units (RTUs) located at the receiving, switching, and distribution
stations will be connected to the ECC either point-to-point on dedicated
channels or multipoint on the same channel, depending on the data load from
each RTU. On multipoint channels, each RTU will have a unique address and
will be polled on a time-shared basis by sequential addressing.

In addition to the data channels, a voice communications system will be
provided to meet load-dispatching requirements. This system will include
private-automatic-exchange (PAX) equipment at the ECC and the receiving sta-
tions. Tie trunks will be provided from the ECC to the receiving, switching,
and generating stations, as well as between other pairs of bulk-power-system
stations. Lines will also be provided to distribution stations. This
configuration will support an internal dial system between the ECC and the
remote stations, thereby eliminating many existing dedicated lines.

3.   Traffic Estimate Based on Bulk-Power-System Requirements

Data regarding the performance of the bulk-power system must be gathered
at regular intervals that depend on the importance of the function being
monitored. From Table 3-1, which states the sampling rates, all AGC-
related data require updating every 2 seconds. The same is true of bulk-
power-system breaker and device status, as we. as high-priority alarms and
indications. Transmission-system analog values, in addition to subtransmission
related quantities, may be sampled at lower rates.

A rough estimate of the volume of data that must be communicated to the
ECC to adequately monitor bulk-power-system performance was made. The equiva-
lent 2-s sampling load for the year 2000 will include 1,850 device-status
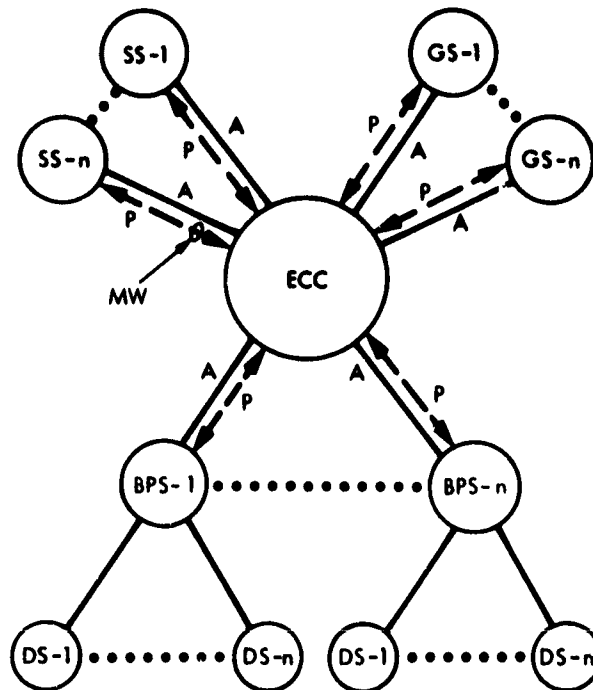
ABBREVIATIONS

ECC	ENERGY CONTROL CENTER
GS-n	nTH GENERATING STATION
SS-n	nTH SWITCHING STATION
BPS-n	nTH BULK-POWER SUBSTATION
DS-n	rTH DISTRIBUTING STATION
MW	MICROWAVE
P	PRIMARY CHANNEL
A	ALTERNATE CHANNEL

NOTES:

1. ALL PRIMARY CHANNELS FROM BPSs TO ECC WILL BE PREDOMINATELY MICROWAVE (WHERE AVAILABLE).

2. ALL ALTERNATE CHANNELS WILL USE ANY FACILITIES AVAILABLE. ALTERNATE PATHS WILL BE SELECTED FROM TELECOMMUNICATION FACILITIES OTHER THAN THOSE USED FOR THE PRIMARY CHANNEL, IF AVAILABLE.

3. PRIMARY CHANNELS REQUIRED FOR RTUs:

   RTUs (AT GS/SS/BPS) - 1 MW CHANNEL PER RTU
   RTUs (AT DS)   - 1 MW CHANNEL PER DS (BPS TO ECC)
   SPARES   - 2 MW CHANNEL PER BPS

4. ALTERNATE CHANNELS REQUIRED FOR RTUs AT GS, SS, BPS:

   1 CHANNEL OR 1-4 WIRE OR 2 PAIRS PER GS, SS, BPS

Figure 3-1. Telecommunications Channel Network

Table 3-1. Polling Rates for Data Acquisition

Function	Polling Interval, s
Bulk-power-system analogs for AGC (tie flows, generation, and frequency)	2
Bulk-power-system breaker and device status	2
High-priority alarms and indications	2
Bulk-power-system internal flows and voltages	10
Subtransmission-system breaker and device status	10
Subtransmission-system flows and voltages	30
Noncritical system data (weather, transformer temperatures, etc.)	30
Low-priority alarms	30
Bulk-power substation power transformer and tie-line energy accumulations	3600

points, 1,729 alarm points, and 770 analog points. This compilation was made
to assess the required computer processing time, rather than to determine a
communication requirement. For the latter purpose, it is necessary to specify
a communication protocol, together with a distribution of the number of sample
points per RTU during each scan.

The protocol for "automatic supervisory and data acquisition systems for
electric generation, power utilization, and power conversion stations" de-
scribed in an IEEE working paper (see Reference 4) will be used to estimate the
bulk-power-system communications requirements. This paper is based, in turn,
on the American National Standards Institute (ANSI)/IEEE standard approved in
1979 (Reference 11). The poll and response message formats are shown in
Figure 3-2. Because the information field of the response message can vary
from 3 to 27 8-bit bytes, the total response message, exclusive of the
preamble, can be as short as 74 bits or as long as 266 bits.

The length of a specific RTU response message depends on the number of
data points of each type to be reported. It is recommended that 12 bits
(including 1 sign bit) be reserved for each analog value (see Reference 4).

POLL MESSAGE

MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION
16 bits	24 bits	34 bits

RESPONSE MESSAGE

MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION
PREAMBLE +16 bits	24-216 bits	34 bits
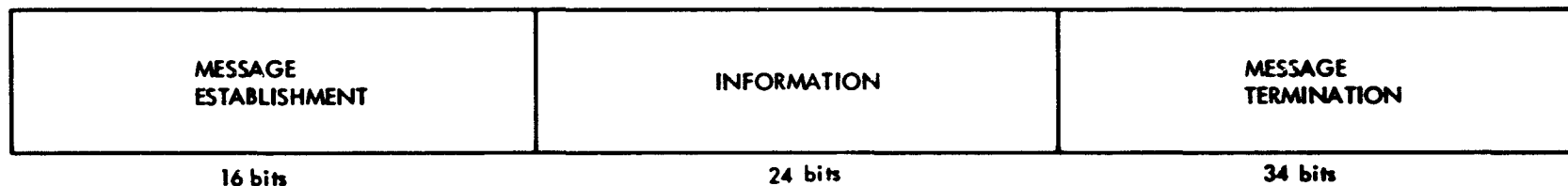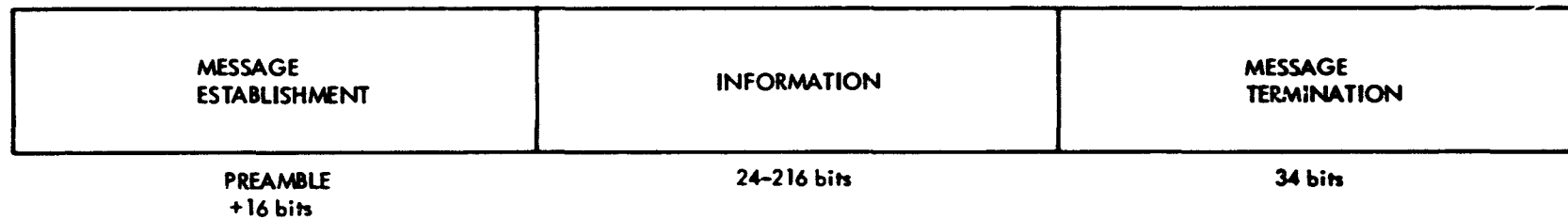
Figure 3-2.   Poll/Response Message Formats

It will initially be assumed that the data for each RTU response is a multiple of 192 bits (24 bytes), or the equivalent of 16 analog values. This is not unreasonable because there are typically more than 100 analog points per BPS (although not necessarily all sampled at 2-s intervals). With an information field of 24 bytes, the message length is 242 bits. The assumption of a near-maximum-length information field for each block of the response message leads to a data-transfer efficiency of $192/242 = 0.79$.

The bit rate corresponding to 770 analog points reported at 2-s intervals is $770 \times 12/2 = 4.62$ kb/s. The 1,850 device-status and 1,729 alarm points require only a single bit per point (although it is suggested that some points may require a second, "memory" bit). If these binary variables are also sampled every 2 s, the total bit rate is 6.4 kb/s. If the data to be reported by each RTU were actually an integer multiple of 192 bits, the composite RTU data-response transmission rate would be given by $6.4/0.79 = 8.1$ kb/s. To account for the fact that the last message block transmitted by an RTU will generally contain fewer than 192 bits, the transmission rate should be rounded up, say to 10 kb/s.

The effect of the preamble on message efficiency has been ignored to this point. The preamble is used for carrier acquisition and bit synchronization. In the response direction, it is assumed that the carrier frequency and bit timing are derived from the corresponding quantities in the poll signal. As a result, carrier-frequenc and bit-timing uncertainty in the signal received at the polling station will be quite small. For this reason, the preamble can be made quite short and should have only a slight effect on message efficiency.

It should be mentioned that, rather than transmit each analog and binary value at the required update interval, data could be reported "by exception." For a binary variable, this means reporting change-of-status only. For an analog variable, only a departure from the previously reported value by more than a specified amount would be communicated. Of course, all data points reported in this manner would require (say 12-bit) identification. (In the previous case, the position of data within the information field identified the point being sampled.) This 12-bit identification would double the number of information bits for each analog value reported; for each binary value, the increase would be from 1 to 13 bits.

It is impossible to assess the transmission efficiency of the reporting-by-exception alternative without knowing the frequency with which different variables require updating. The potential improvement is limited by the lower efficiency of a given protocol with reduced message lengths. Also, any improvement in transmission efficiency would be partially offset by the increased complexity of RTU hardware and master-station software, especially as they relate to analog data values.

The poll-message traffic will be smaller than the response-message traffic, because the information field on each scan need only identify the set of points to be sampled (in addition to specifying any necessary control actions). The number of bits required for this purpose depends on the number of different groupings that must be distinguished.

Because of the large satellite propagation delays, separate channels will be assumed for the poll and response directions (see Section VII-D). This separation of channels allows the ECC, which is the only polling station, exclusive use of one of the channels. The ECC can therefore transmit, in a continuous manner, with no need for preambles at the start of messages. Infrequent transmission segments can be reserved for acquisition purposes, to accommodate new stations in the network or stations that, for one reason or another, have temporarily lost the ECC signal.

For simplicity, equal channel bandwidths will be allocated in the poll and response directions. The total capacity required for this utility, therefore, is 20 kb/s. The bulk-power-system traffic requirement will be extrapolated to a nationwide requirement by considering the fractional number of customers served. If the number of electric meters is taken as a measure of the number of customers, there is a total of 110 million customers served by the nation's 3,100 utilities (see Reference 6). This utility, on the other hand, has a total of about one million customers. It may be concluded that, nationwide, bulk-power systems generate traffic at the combined rate of 2 Mb/s.

C. TRAFFIC ESTIMATE BASED ON JPL ELECTRIC-UTILITY MODEL

R. M. Barnett at JPL has computed the traffic requirements for a synthetic utility representing approximately 1% (i.e., 11,000 MW) of the capacity of all U.S. electric utilities (see Reference 1). This computation was done by making assumptions regarding the number of RTUs at each site, together with the number of devices to be sampled and the corresponding scan rates.

The salient features of the utility analyzed are presented in Table 3-2. This model deviates from the one presented in Figure 2-3 in that distribution substations report directly to the ECC, rather than through a DDC. Some of the data on these links refer to distribution-system activities (in compressed form), and other data relate either to the role of the substation as a terminus of the subtransmission system or to the status of the substation elements. Thus, the substation-to-ECC links carry data relating to both bulk-power-system and distribution-system activities.

To obtain the data requirements for the model utility, it was assumed that a single RTU is adequate for each distinct site, with the exception of generation plants. In this case, a separate RTU was assumed for each class of generation unit (i.e., nuclear, oil, combustion turbine, etc.), with an additional RTU for the associated switchyard.

The assumed sampling rates for different types of monitor points are essentially the same as those shown in Table 3-1. The assumed format for poll and response messages is also the same as that used to derive the previous traffic estimate. The resulting traffic in the poll and response directions is shown for each type of link in Figure 3-3. A data summary according to generation, transmission and subtransmission, and distribution-substation functions is given in Table 3-3. It will be assumed, for simplicity, that all

Table 3-2. Salient Features of Synthetic Utility

Item		Number
Generating plants		6
Bulk-supply substations		35
Industrial substations		40
Switching stations		6
Intertie lines		15
Distribution substations		200
Meters		1.0×10^6
	Large	10
DSG Sites	Intermediate	39
	Small	2500

Table 3-3. Synthetic-Utility Bulk-Power-System Data Requirements, kb/s

Functional Area	Poll	Response
Generation	7.4	21.3
Transmission and Subtransmission	4.3	19.0
ECC to DAC	0.5	4.7
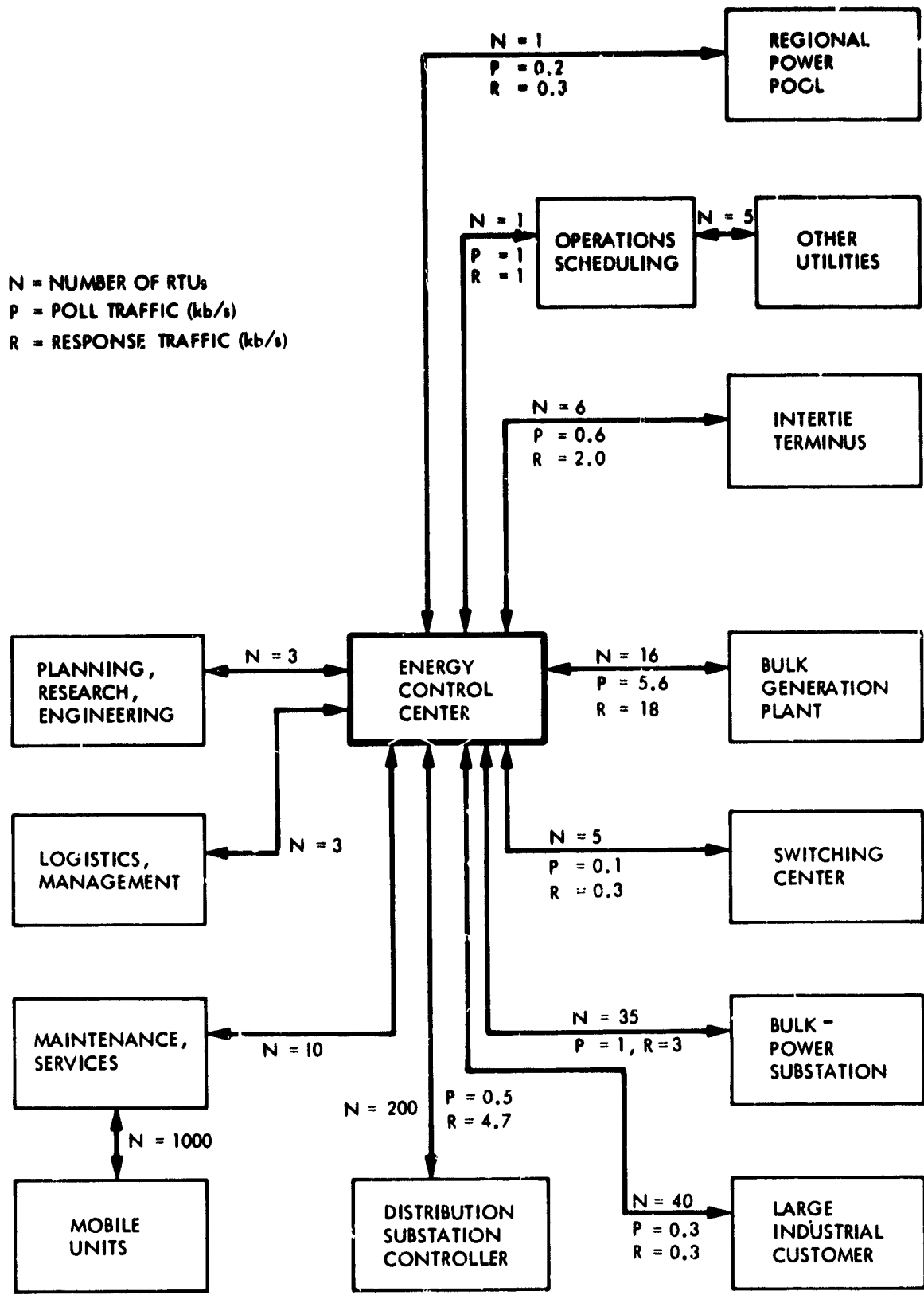
Figure 3-3. Energy Control Center Data-Flow Diagram

ECC-to-DAC traffic is related to bulk-power-system activities. The total bulk-power-system response traffic is then 45 kb/s. With equal channel bandwidths in the poll and response directions, the bulk-power-system channel-capacity requirement is 90 kb/s.

The corresponding traffic for the entire United States is roughly 100 times as great as that for the synthetic utility, or 9 Mb/s. This is 4.5 times the traffic estimate previously obtained. The disparity is accounted for, in part, by the larger number of bulk-power-system installations (e.g., 35 versus 19 BPSs) included in the model utility. In addition, it will be recalled that a data-transfer efficiency of 0.79 resulted from message-length assumptions in the former computation of traffic requirements. This efficiency is near the upper end of the 0.5 to 0.8 efficiency range believed to be typical. For all of these reasons, the composite bulk-power-system data rate for the U.S. electric-utility industry will be taken as 4 Mb/s and that of a single large utility as 40 kb/s.

SECTION IV

DISPERSED STORAGE AND GENERATION SYSTEMS TRAFFIC REQUIREMENTS

A projection is made of future, year 2000, DSG population. New monitor and control functions and communications network topologies are discussed. A representative communications format and protocols are assumed and communications traffic for this new utility element is estimated. A large utility might have 100 DSGs of the 1 to 5 MW class and require 30 kb/s. The national requirement would be about 4 Mb/s, and if small, 3-m ground-station antennas were employed, this would use up 1 transponder on a present-day C-band satellite.

Dispersed storage and generation (DSG) systems will become more prevalent with the passage of time. These devices may be wholly owned by utilities, co-owned by private parties, or completely under private ownership. A privately owned system will normally be designed to serve one or more neighboring energy users. When the energy generated by a DSG unit exceeds the requirements of its intended users, the excess energy may be sold to a utility company. The Public Utility Regulatory Policy Act of 1978 (PURPA) mandates the purchase by utilities of excess energy produced by small facilities (i.e., those under 30 MW), at rates equal to what it would cost the purchasing utility to generate the energy itself. Conversely, when the output of a DSG unit fails to meet user requirements, additional energy may be obtained from standard utility-company sources.

Utility-owned DSGs, on the other hand, represent a source or a sink of energy that must be controlled through the utility's ECC. Depending on the size of the DSG and the structure of the control network, the DSG may be considered either (1) part of the total energy resource available to the system, or (2) an integral part of the load presented to one of the distribution substations. In either case, the activities of the DSG must be remotely controlled and monitored, to an extent determined by the magnitude of its role in the generation and distribution processes.

It has been estimated that, by the year 2000, between 4% and 10% of electric-power generation in the United States will be supplied by DSGs. With an average unit size in the range of 1 to 5 MW, there will be 10,000 or more units that require remote control (see Reference 3). These DSGs may assume various physical forms: solar thermal electric, photovoltaic, wind, fuel cell, storage battery, hydro, or cogeneration (i.e., combined heat and electrical output). A concise description of several renewable forms of energy sources given in Appendix A. Despite the physical dissimilarities, the monitor and control requirements tend to exhibit a commonality that, for the most part, permits the physical distinctions to be ignored in arriving at the communications requirements.

Although bulk sources of electrical power are generally controlled and coordinated directly by the ECC, DSGs will generally be tied into the power system at the distribution level because of their relatively small size. The DSGs may be physically located at the substation, feeder, or customer site. Except for the largest DSGs, the highest level in the control hierarchy that will recognize the existence of an individual DSG is the DDC.

In the remainder of this section, DSG communications and control will be described as envisioned for the DSG population in the year 2000.

A. COMMAND AND CONTROL FUNCTIONS

One of the principal command and control functions is scheduling and mode control of the DSGs. This function involves daily, weekly, and monthly scheduling of DSG service times, as well as appropriate maintenance activities. Mode control refers to the choice of on, off, or standby operation at appropriate times. While DSG scheduling is generally the responsibility of the DDC, the schedules are established in response to the overall power-system-generation scheduling performed by the ECC.

A few of the larger DSGs may be provided with AGC to maintain load frequency control (LFC), generally via the area DDC. This involves adjustment of the DSG output voltage at intervals ranging from 2 to 10 s. In most cases, however, DSG output voltages are simply reported to either the DDC or the local DAC for inclusion in the general AGC process conducted by the ECC.

Economic dispatch control (EDC) incorporates the DSG into a comprehensive plan for ordering the use of available energy sources (including energy purchased from other utilities) to minimize the cost of meeting specific load requirements. Economic dispatch control, with respect to DSGs, involves a periodic determination (e.g., at 5-min intervals) of the power available from those units (e.g., solar, wind) which depend on environmental conditions for their input power.

Distribution volt/VAR control represents another control function assigned to the DDC (or to the DAC). By this means, the voltage and the VAR flow throughout the distribution network are controlled to maintain voltages within an acceptable range and reduce power losses through the system. Normally, desired voltage ratios are maintained through load-tap-changing transformers, while VAR control is exercised by switching capacitors in and out of the system. However, inclusion of certain types of DSG units provides another means of controlling voltage or VAR. For example, if the DSG is a synchronous machine, its reactive capability can be used to affect distribution-system voltages and to supply or absorb VARs.

Load control is normally interpreted as referring to the disconnection of certain customer devices to reduce the collective load on the system to a level consistent with the capability of the bulk-power sources. If the DSGs are regarded as an integral part of the distribution system, an increase in DSG output can be used as an alternative means of reducing the net load on feeder sections or the distribution substation.

A related aspect of load control is the restoration of power following the occurrence of a fault within the distribution system. Once the fault has been isolated, service can be restored, even to feeder sections that have become isolated from the distribution substations, provided one or more DSGs, capable of sufficiently stable stand-alone operation, are connected to the isolated section.

B. DSG COMMUNICATIONS TOPOLOGY

To coordinate activities of DSGs with those of larger power sources, the ECC regards all DSGs directly controlled or coordinated by a specific DDC as a single composite power source. The DDC is responsible for translating ECC commands pertaining to its composite DSG into a consistent set of commands to be communicated to individual DSGs under its control. Conversely. the DDC must combine data collected from the various DSGs to produce a single set of data, for transmission to the ECC, which represents the activity of the composite DSG.

A system in which all DSGs are directly controlled by and report data directly to the DDC has been referred to as a centralized monitor and control system (see Reference 3). In this case, DSG activities are handled separately from other distribution functions. Decentralized monitor and control of DSGs can be effected by combining DSG-related functions with other DAC functions at the substation level. In this type of system, the various DAC centers act as concentration points between the DDC and the DSGs under its control. The role of the DAC with respect to the DSGs has not been sufficiently defined at this point to determine the extent to which decisions affecting DSG operation are made at the DAC level, rather than at the DDC.

One would normally expect a system which includes a large number of DSGs of various sizes to exhibit a hybrid control structure, with some DSGs reporting directly to the regional DDC and others remaining under the control of the subordinate DACs. In general, the smaller the size of the DSGs, the greater the tendency toward decentralized control and the smaller is the need for reported data. In fact, for very small DSGs (i.e., 1.0 MW), there may be only (automatic) local control, based entirely on local conditions. For a DSG of given size, the tendency toward decentralized control would logically increase as the total number of DSGs increases, since it is undesirable to place an undue burden on the DDC from either a communication or a computational standpoint.

Apart from the general tendencies cited above, there are several advantages in using decentralized control. (1) It permits more rapid response to fault conditions; i.e., if the distribution function for the area served is otherwise under the control of a DAC, decentralization eliminates the need for communication with the DDC when dealing with a fault. (2) As additional DSGs are brought on stream, the capacity of the DDC to process and/or communicate the required data could be exceeded. It is generally simpler and less expensive to provide the needed capability in the DAC than it is to upgrade the DDC. (3) the trend toward distributed processing in networks seems to be an all-pervasive one, resulting from the rapid decline in the cost of computation relative to that of communications.

It should be recognized that the degree of centralization is also a function of time. Presently, when there are few DSGs and the control network has only limited capability at the lower levels, greater control is exercised at higher levels than would otherwise be the case. For example, certain DSGs, presently under direct control by the ECC, will later fall under the super-

vision of one of the DDCs. The emphasis in this report is on this later period. Specifically, it assumes the existence of a fully developed control network in which the DSG requirements are integrated with the other DAC functions.

From the foregoing discussion, it is clear that the communications links required to service the DSGs will be primarily of the DAC-to-DSG type, with a smaller number connecting DSGs to DDCs. Additionally, there will be a certain amount of DSG-related traffic on DAC-to-DDC links. However, this traffic will be condensed relative to that on a direct DSG link, to a degree determined by the extent of DSG control exercised at the DAC level. For ease of discussion, it will be assumed that all DSG links are of the DAC-to-DSG type.

C. TRANSMISSION PROTOCOLS

Communication over DAC-to-DSG links will be conducted in a poll/response format, in the same manner as other monitor and control communications. In addition to a request for information relating to status changes, alarm conditions, and different variable values, messages directed at DSGs will contain any necessary control information. There are certain basic control functions common to most DSGs, which were described in Section IV-A. The amount of data required to perform these functions depends on the degree of control to be exercised, and thus on the size of the DSG.

The communications capacity that must be reserved for monitor and control of an individual DSG unit depends on the means of communication as well as on the amount of data to be communicated. For satellite transmission, monitor and control of a number of DSGs can be accomplished quite simply, from a conceptual viewpoint, by the use of TDMA techniques. A general discussion of TDMA transmission as it might apply to utility-company communications can be found in Section VII. The present discussion is intended only to assess DSG traffic requirements. Specifically, other distribution-system messages that might be interleaved with the DSG traffic are ignored.

In the DAC-to-DSG direction, each DAC sharing a given channel (i.e., frequency) is assigned a time slot within the TDMA frame (Figure 4-1). Within each slot, messages are addressed, in sequence, to the various DSGs under control of the DAC. These messages are part of a single transmitted burst by the DAC; consequently, carrier and bit synchronization need be performed only once per TDMA frame for each DAC.

The DSGs polled by DACs transmitting on a given channel respond, over a reverse channel, in the same sequence in which they are polled. Guard bands must be provided between DSG transmissions to ensure that different DSG bursts arrive at the satellite in a nonoverlapping manner. The same is true of DAC bursts in the polling direction. In addition, carrier and bit synchronization must be performed separately on each DSG burst.

As will be discussed in this report, poll and response messages can be of various lengths. If a poll is longer than the response to the preceding poll, it may be transmitted without delay. However, if a poll is shorter than
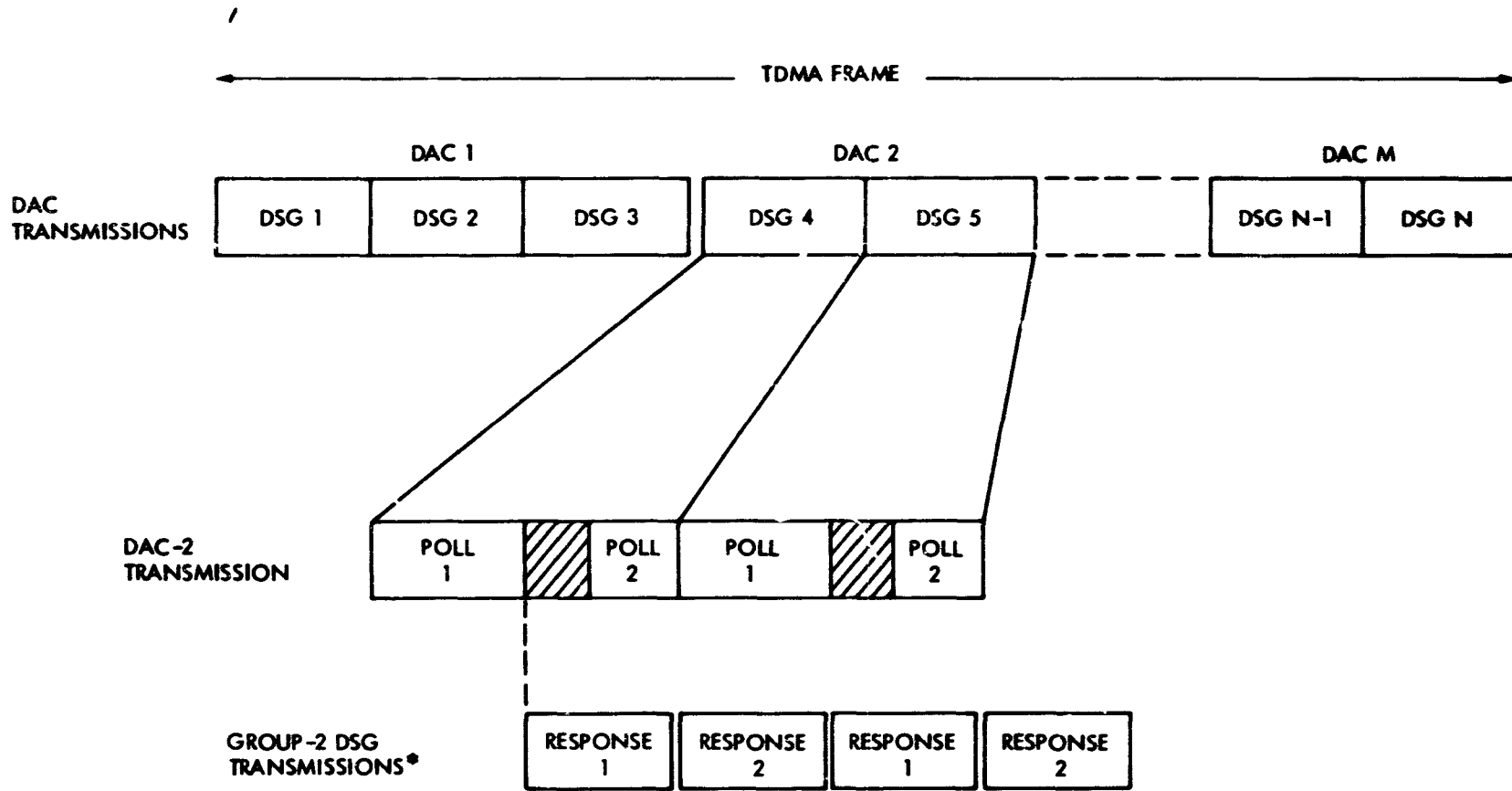
Figure 4-1. Time-Division Multiple-Access Frame Format

the preceding response, the pcll must be delayed so that its own response does not overlap the preceding response. This situation accounts for the cross-hatched gaps between polls by the same DAC in the illustrative message sequence of Figure 4-1. The DAC transmits a predetermined pattern during these gaps, so that burst continuity is maintained.

Although there are many monitor and control functions that need to be performed for DSG operation, the traffic requirements occasioned by these functions are dominated by LFC and SCADA messages. For DSGs in the (1-5)-MW range, an LFC cycle as small as 2 seconds may be required. The SCADA function, in which data are assumed to be reported by exception,[1] is responsible for detecting any abnormal conditions. Depending on the size of the DSG, an update interval of 2 to 10 s may be required. (Note that the round-trip satellite propagation time of approximately a half-second is barely compatible with a 2-s update interval for either function.)

The data requirements associated with an individual DSG depend on the amount of overhead incorporated in each message. As a guide, the message format recommended in the previously cited IEEE working paper (see Reference 4) will be adopted. Although the format is intended for use with any suitable transmission medium, the recommended half-duplex operation is inconvenient, if not inappropriate, for satellite transmission (see Section VII-D). As stated earlier, separate channels (i.e., full-duplex operation) will be employed for the poll and response messages.

The specific message combinations assumed for the LFC and SCADA "transactions" (see Reference 3) are shown in Figure 4-2. The same general message format is used for other monitor and control functions, except that the information field in response messages may vary from 3 to 27 bytes. The two messages transmitted by the DAC as part of the LFC transaction constitute a single poll message in the language of Figure 4-1. The first is of a control nature and either raises or lowers the DSG voltage. The second is a request for data, which are processed in time to determine the contents of the next control message.

The message-establishment field of the IEEE-recommended message format is further divided in Figure 4-3. The preamble is used for carrier and bit synchronization. (The 8-bit sync subfield provides message, as distinct from bit, synchronization.) It 's required, therefore, only once per DAC burst, rather than for each DAC-to DSG message. Similarly, only one sync subfield is required per DAC burst. Each DSG response, on the other hand, must include both a preamble and a sync word.

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[1]This assumption is inconsistent with the manner in which the bulk-power-system traffic was assumed to be reported in Section III. Using an alternative set of assumptions, Barnett (see Reference 1) found the combined poll/response traffic per DSG to be 70% greater than that computed in Section IV-D.

LFC TRANSACTION

CONTROL

M→R	MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION
	PREAMBLE +16 bits	24 bits	34 bits

DATA REQUEST

M→R	MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION

DATA

R→M	MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION

SCADA TRANSACTION

DATA REQUEST

M→R	MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION

DATA

R→M	MESSAGE ESTABLISHMENT	INFORMATION	MESSAGE TERMINATION

M = MASTER STATION
R = REMOTE STATION

Figure 4-2. Message Formats for LFC and SCADA Transactions

PREAMBLE	SYNC	ADDRESS
	8 bits	8 bits
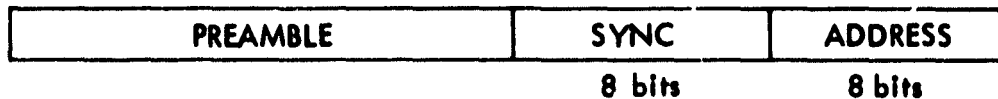
NOTES:

PREAMBLE PROVIDES FOR CARRIER RECOVERY AND BIT SYNCHRONIZATION

SYNC IS AN 8-BIT PATTERN THAT IS USED TO IDENTIFY THE POSITIONS OF ALL SUBSEQUENT MESSAGE ELEMENTS

ADDRESS IDENTIFIES THE CONTROLLED STATION FOR TRANSMISSION IN EITHER DIRECTION

Figure 4-3. Message Establishment Field

The address subfield is intended to identify the remote station (in this instance, the DSG) for either direction of transmission. No provision was made for DAC identification, because the communications process was presumed to be of the point-to-multipoint type. However, since a number of DACs generally share the same channel, each DAC must identify itself once per transmitted burst, immediately following the sync word. This requirement could, in principle, be avoided by providing each DSG polled on a given channel with a unique address. However, this would require a degree of coordination among DACs, possibly including those belonging to different utilities, which is undesirable. Because of the small number of bits involved, this addressing requirement will be ignored.

The preamble in the polling direction is assumed to consist of 130 bits.[2] Because the sync subfield is 8 bits long, the first poll in each burst exceeds the remaining poll messages in length by 138 bits. The carrier frequency and bit timing of each response message are derived from the corresponding poll message. Because there will be very little uncertainty in either of these quantities, the response preamble can be made quite short. This preamble will arbitrarily be taken as 16 bits. The resulting poll and response message lengths, for both LFC and SCADA transactions, are shown in Table 4-1. The first number indicated in the poll column refers to a message that does not require a preamble or a sync word; the number in parentheses gives the message length with the preamble and sync subfields included.

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[2]The number of bits required for carrier recovery and bit synchronization depends on the method chosen to implement these functions. Carrier recovery is normally measured in units of time, and then converted to an equivalent number of bit periods as a matter of convenience.

Table 4-1. Required Message Lengths (bits) for Single Transaction

Transaction Type	Poll	Response
Load frequency control	132 (270)	90
Supervisory control and data acquisition	66 (204)	90

D.   SINGLE-DSG DATA RATE

With a 2-s update interval for both the LFC and SCADA functions, each function is performed once per frame for each DSG. The pair of polls for the first DSG addressed by each DAC requires a total of 474 bits, while subsequent poll pairs consist of only 198 bits. All response pairs comprise 180 bits. If the poll and response channels are designed for equal transmission rates, the bandwidth requirement is set by the magnitude of the poll traffic.

The average poll traffic per DSG depends on the average number of DSGs per DAC. There are about 3,300 electric meters per distribution substation, on the average (according to Table 5-1). Because there are approximately 100 million meters nationwide, the total number of distribution substations is about 30,000. On the other hand, it was previously estimated that there are 10,000 DSGs requiring rapid-update remote control. Thus, there is an average of one-third DSG per distribution substation, or per DAC.

If each DSG were controlled by a separate DAC, there would be only one pair of poll messages per DAC transmission burst. It will be assumed that only one-ninth of the DACs are involved in DSG control, so that, within this group, there is an average of 3 DSGs per DAC. The average poll traffic per DSG in each TDMA frame, therefore, is 290 bits. For a 2-s frame, the average data rate per DSG is 145 b/s.

E.   SINGLE-UTILITY DATA RATE

The total bandwidth requirement for a large utility will now be estimated. There are 3,100 utilities nationwide (see Reference 6). It arbitrarily will be assumed that a large utility controls 1% of the DSGs in use, or about 30 times the average number per utility. Of the 10,000 DSGs in the (1 to 5)-MW range projected for the year 2000, about 100, producing a combined polling data rate of 14.5 kb/s, will be controlled by a large utility. It is presumed that the DSGs in the "large" category (i.e., 5 MW) will not add significantly to this total, because of their relatively small number.

There will likely be a considerably larger number of DSGs below 1 MW under the control of typical large utility. The composite bit rate generated by these DSGs depends on the relationship between the required scan rate and the number of DSGs of given size. It will be assumed that the product of scan rate and number of DSGs decreases rapidly enough with decreasing DSG size to prevent the small DSGs from becoming a dominant factor in the overall bandwidth requirement. More specifically, it will be assumed that the combined scan rate of DSGs under 1 MW is 0.4 times that of DSGs exceeding 1 MW. This leads to a total polling data rate of 20 kb/s for the DSGs under the control of a large utility.

Although there may be some question about the combined data rate of small DSGs, incorporation of a DSG into a satellite-based TDMA system can be considered only if it makes good economic sense. With an estimated cost of $1000/kW, a DSG with a capacity of 1 MW or more requires a capital investment in excess of $1 million. The cost of an earth station designed to service a DSG is estimated at $32,000 (see Section VIII-E), or a maximum of 3.2% of that of the DSG. Thus, the cost of satellite communications is not unreasonable for sufficiently large DSGs.

For DSGs of capacity much less than 1 MW, on the other hand, the economics of satellite communications for an individual DSG is at least questionable. However, several smaller DSGs in close proximity could share a satellite terminal, thereby considerably reducing the cost of communications. In addition, the communication overhead could be reduced to the point where the bandwidth requirement of such a group of DSGs would be only slightly greater than that of a single DSG in the medium or large category. It is not unreasonable, therefore, that the total bandwidth requirement for DSGs communicating via satellite not be much larger than that required for those DSGs with a capacity exceeding 1 MW.

There is a basic relationship among the channel data rate, the frame period, and the number of DSGs addressed on a given channel. This relationship is exhibited in Figure 4-4 under the condition that all DSGs are polled at the same rate. Thus, a 100-DSG utility would require a 15-kb/s polling channel for a frame period of 2 s. A channel of equal bandwidth would be required in the response direction.

The number of DACs accessing each channel would typically be given by the number of DSGs per channel divided by the average number of DSGs per DAC. With the previous assumption of three DSGs per DAC, the number of DACs per channel is one-third the number of DSGs.

F.   SYSTEM TRAFFIC ESTIMATE

The combined transmission rate for the 10,000 DSGs in the (1 to 5)-MW range is 1.45 Mb/s, since each one contributes an average of 145 b/s. With the under-1-MW DSGs assumed to contribute in the same proportion as before, the total transmission rate for all DSGs becomes 2.0 Mb/s. This is the required capacity in both polling and response directions, so the total system capacity requirement is 4.0 Mb/s.
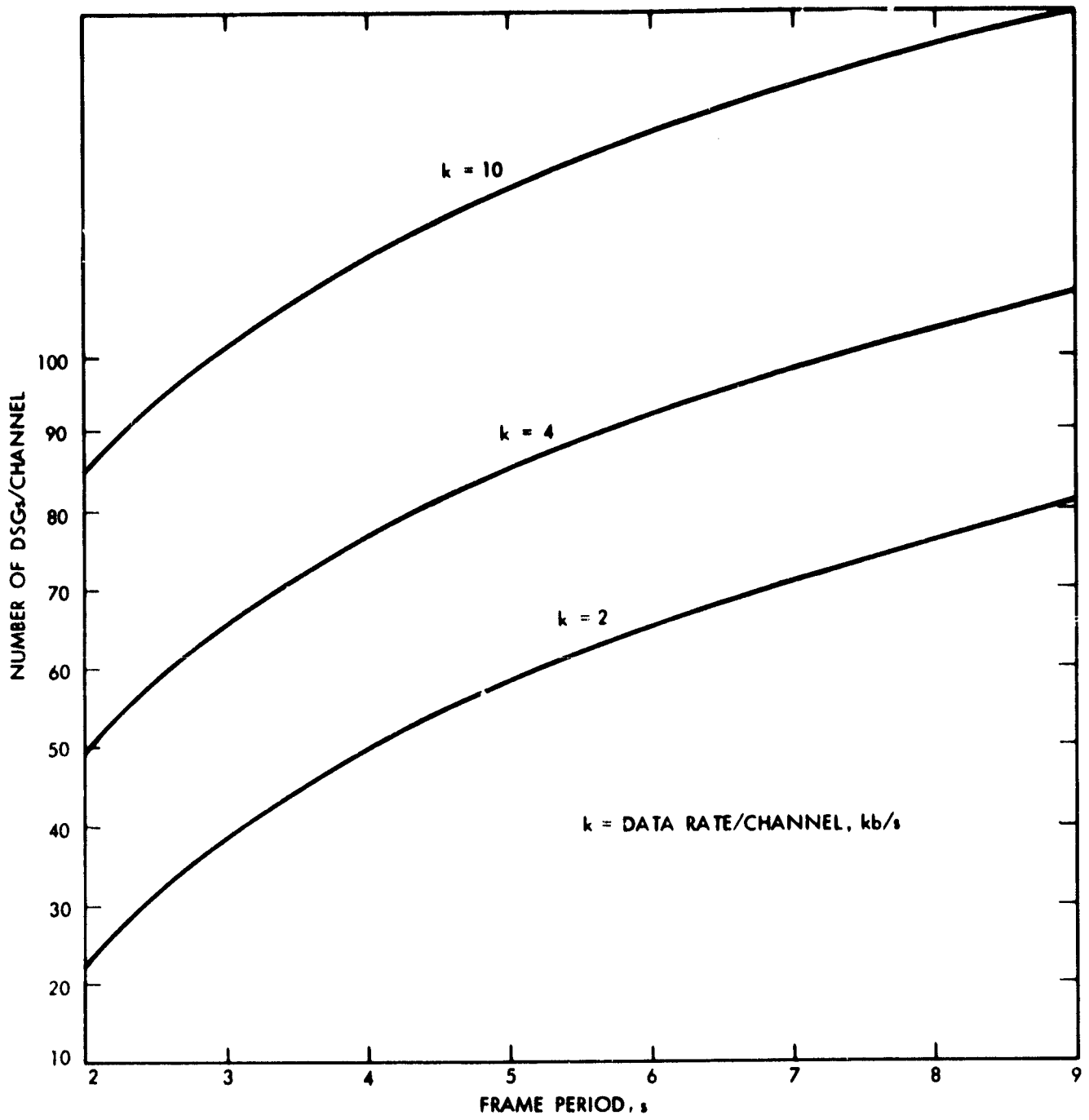
Figure 4-4. Channel Capacity Requirements

The system capacity requirement, when stated as a data rate, is tantamount to a bandwidth requirement. However, DSG transmissions would be severely power-limited with current satellites. The maximum permissible antenna size for an earth station co-located with a DSG is assumed to be 3 m. Link calculations based on this antenna size (see Section VIII) lead to the conclusion that, for present-day C-band satellites, the transponder capacity is about 5 Mb/s. The computed DSG traffic, therefore, would require the resources of nearly a full transponder.

To devote the resources of an entire transponder to DSG transmission is not unreasonable. The annual cost of leasing a backed-up C-band transponder is about $2 million. If the transponder is shared by 10,000 DSGs, the annual cost per DSG is $200. This is less than 1% of the estimated capital requirement for earth-station equipment. It also represents just 0.02% of the cost of a DSG in the 1-MW range.

In one sense, the system capacity requirement of 4.0 Mb/s is conservative, because a SCADA and/or LFC scanning interval several times the assumed value of 2 s may suffice for most DSGs. On the other hand, the amount of electric power that will be supplied in the future by DSGs may have been underestimated in the past. In a "significant change in direction for public utilities and U.S. energy production," Southern California Edison Company recently announced that 30% of its additional generation needs by 1990 will be met by renewable and alternate sources, including wind, geothermal and solar power, fuel cells, hydro-electricity, and cogeneration (References 12 and 13). Just last year, the company stated that only 15% of its new supplies through the year 2000 would come from unconventional sources.

This radical change of plans is largely the result of a reduced rate of increase in the demand for electric power in the United States, coupled with the high cost of financing and long lead times associated with the production of electric power from nuclear sources or coal. These factors have combined to make the construction of a nuclear power plant, typically requiring 10 years, an extremely risky proposition, not to mention the currently hostile regulatory climate. By contrast, renewable energy sources require a much shorter period for development and can be brought on stream in much smaller increments, thereby greatly reducing the financial risk.

Although many of the renewable energy sources constructed in the future will be integrated into the bulk-power system, the increased emphasis on this form of generation should lead to a proliferation of renewable sources tied into the distribution system (i.e., DSGs). The technological advances resulting from this increased emphasis should enhance the economic feasibility of relatively small and dispersed energy sources.

SECTION V

DISTRIBUTION-SYSTEM TRAFFIC REQUIREMENTS

The functions associated with load and distribution-system operational management are discussed. Three independent estimates of communications traffic are examined; at this time there is little real communication carried below the distribution substation level. A Boeing Corporation study, which considered only commanding and remote meter reading, projected 40 kb/s for the nation. A Mitre Corporation study seemed to project a 400 kb/s requirement where some monitoring is included, and a JPL study projected 4 Mb/s based on a more detailed monitor and control analysis and rather frequent (30-s) scanning. This latter estimate has been used as a measure of the possible future distribution system traffic.

The functions that fall under DAC can basically be considered as part of either load management or operational management. Load management deals with the control of loads at customer sites, either to decrease the generating capacity required of a utility or to rapidly reduce the total load under an approaching overload condition. Operational management is a broad term referring to internal utility-company functions designed to maintain an optimal configuration, with respect to efficiency and performance, of power-system elements. Although the term could encompass the generation and transmission functions as well, attention here is restricted to the distribution system.

A. LOAD-MANAGEMENT FUNCTIONS

One means employed to reduce peak loads, and thereby required generating capacity, is discretionary load switching, i.e., provision of an economic incentive to a utility's customers to permit the utility to switch certain loads off during periods of peak loading. The devices affected by this policy may be residential appliances such as air conditioners and electric water heaters, or they may be industrial loads supplied under interruptible service contracts. Such devices generally fall into either of two categories: units which provide substantial thermal storage capacity or units whose immediate use is deemed nonessential.

Reduction of peak load may also be effected indirectly by peak-load metering, i.e., the remote switching of meter registers to increase rates during periods of peak electrical usage. In this approach, control remains with the consumer, rather than with the utility, as in the case of discretionary load switching. This feature may make the procedure more palatable to the customer; however, it is also likely to make it less effective, since many customers will choose not to act in the desired manner (e.g., during periods of extremely high temperatures, they may decide to pay virtually any price for continued use of air conditioners).

A closely related technique is time-of-day metering, in which meter rates are varied in a preprogramed manner based on predictions of load conditions. Meter rates, in this case, would be controlled by a local clock. Although there is less flexibility in this procedure, it does eliminate the need to communicate meter-rate information to the customer site. Since the customer

is aware of the rate schedule in advance, he can make his plans accordingly. With peak-load metering, a change in rates must somehow be brought to the customer's attention for maximum effectiveness.

It should be noted that remote meter reading, as contrasted with control of meter registers (either locally or remotely), is not considered to be a part of load management. Rather, it may be treated as a third category under the general DAC heading.

The rapid reduction of load to avert an overload condition is referred to as load "shedding." Of the two means employed to accomplish this shedding, voltage control is the more frequently used. However, voltage control is also of limited effectiveness, as it is necessary to maintain all customer service entrances at acceptable voltage levels. Application of voltage control for this purpose results in a "brownout" condition.

The action more generally associated with the term "load shedding" is the dropping of large blocks of load by the utility. Rather than being selective as to the appliances affected, the utility will generally cut off all power to a selected set of customers. When different sets of customers are sequentially affected, typically for several hours, a "rolling blackout" results.

B. OPERATIONAL-MANAGEMENT FUNCTIONS

There are many functions of operational management. Although there is no universally accepted set of terms, several of the principal functions are described in the following paragraphs.

Voltage Control. Although also mentioned in connection with load management, voltage control refers here to the broad function of maintaining voltages throughout the distribution system at required levels. The principal means of accomplishing this is through the use of tap-change-under-load transformers. As the load on various feeders changes, the tap positions on distribution-station and secondary-distribution transformers are modified to maintain the voltage at prescribed points on the feeder lines within specified tolerances.

Volt-Amperes-Reactive Control. To minimize transmission losses, it is necessary to eliminate reactive power flow throughout the distribution network. This is done, on a dynamic basis, by switching capacitors in or out of the system at judiciously selected points. VAR control is also important in maintaining the frequency at its nominal 60-Hz value throughout the system.

Load Reconfiguration. This function involves remote control of switches and breakers to permit reconfiguration of circuits for load diversity, maintenance, or new construction.

Feeder-Load Management. This function involves the monitoring of feeder loads and the capability to equalize loads over several feeders from one substation.

Transformer-Load Management. This function requires monitoring distribution-transformer loading and core temperature to prevent overloads and burnouts.

Fault Detection and Isolation. Sensors located throughout the
distribution network can be used to detect abnormal conditions. This
information is used to automatically locate faults, isolate the faulted
segment, and initiate circuit reconfiguration.

C.   MITRE TRAFFIC ESTIMATE

Three different sources have been used to estimate the data requirements
to accomplish the DAC functions described previously. The first two are a
MITRE report written in 1976 (see Reference 5) and a recent Boeing study per-
formed under JPL management (see Reference 6). The third estimate, compiled
at JPL, is based on an enumeration of monitor and control points in the dis-
tribution system.

The MITRE results are based on the requirements of a typical metropolitan
utility with 200 primary distribution feeders, each serving 5,000 meters, so
that there are 1 million meters in all. Bit rates are developed for each dis-
tribution-system function by combining the number of units to be controlled or
monitored, an assumed scan rate, and a message length which is equal to the
number of address bits plus the number of data bits. Thus, the stated bit
rates do not account for any overhead other than addressing.

The MITRE results (see Reference 5, Appendix C) will not be quoted here
in any detail, because the functions examined represent a "wish" list, rather
than a set of requirements. In addition, several control-type message fre-
quencies seem to be unreasonably low, while the monitor-type message volume is
unrealistically high. As an example of the latter, "on-line" monitoring of
line parameters is suggested at intervals of 17 ms (i.e., once per power-line
cycle) to permit real-time control of circuit elements from a central control
point.

After detailing the various monitor and control functions that <u>might</u> be
performed and their associated transmission rates, the MITRE report simply
states that a "200 bit-per-second bidirectional capability will afford sub-
stantial inherent message redundancy along with growth capability" for the
utility under consideration. With a typical message length (i.e., data plus
address bits) of 10 bits, there are 20 messages/s in each direction with
respect to a central control point.

Further discussion of required transmission rates will be restricted to
the case of satellite transmission. A TDMA system similar to that described
for DSG communications will be assumed for the other DAC functions. As with
the DSG response to a poll message, it is assumed that carrier frequency and
bit timing for each RTU response are derived from the corresponding poll trans-
mission. This leads to a response message length, including preamble, of about
100 bits. The effective transmission rate in the response direction, there-
fore, is 2 kb/s.

A longer preamble is required for the first poll message in each DAC
burst. However, because each DAC addresses a number of distribution-system

points, the average number of preamble bits per message in the poll direction should be no larger than that in the response direction. It is reasonable, therefore, to treat the total distribution-system traffic requirement as being twice the response data rate, or 4 kb/s.

By assumption, the utility giving rise to the 4-kb/s transmission rate serves 1 million meters. There are approximately 100 million meters nation-wide, so that, with 100% participation, the capacity requirement would be 400 kb/s.

Although the 200-b/s transmission requirement for a large metropolitan utility, as stated in the MITRE report, is not broken down by function, several comments made with this estimate are worth repeating. First, it is claimed that, were the meter-reading function universally accomplished by electronic means, the average meter-reading data rate would be commensurate with the peak rate generated by the combination of operational-management and load-management functions. Under these conditions, the transmission requirements could be thought of as deriving either from the meter-reading function alone or from the combination of all non-meter-reading functions.

This claim contradicts the findings in the Boeing report. According to Boeing, the peak hourly message traffic from operational- and load-management functions is about four times the average message traffic from all sources, and about seven times that from meter reading alone. It follows that, because meter reading is non-time-critical and can be deferred to relatively inactive periods from the standpoint of operational or load management, it may be ignored in computing the peak traffic requirements. Since the MITRE report is not in disagreement with a computation made in this manner, it will be taken as fact that the peak traffic derives from the combination of operational and load-management functions.

The MITRE report further states that the load-management traffic "is al-most negligible by comparison with" that generated by operational management. The Boeing report is in substantial agreement, with peak message rates in the ratio of 3.5 to 1.

D.   BOEING TRAFFIC ESTIMATE

Before stating the Boeing traffic results, the method used in the study will be described. First, a profile of the utility industry was projected to the year 1995. The number of utilities nationwide was estimated at 3100, with a total of 110 million electric meters. A state-by-state breakdown of these two quantities was also derived. Growth curves were developed for the percentage of residences participating in load management and remote meter reading. Under the assumption of "maximum motivation," these figures are 60% and 30%, respec-tively, in 1995. Similarly, maximum motivation pertaining to utility-company participation in distribution automation was estimated at 40% in 1995.

Load management, for computing traffic rates, was interpreted to mean discretionary load switching. The peak-message computation was based on the predicted number of devices of each type, the number of devices grouped together

for addressing purposes (chosen to be 512), and the rate at which commands are issued (e.g., the number of times per hour an air-conditioner group is switched on or off).

To derive the operational-management traffic, standardizing assumptions were made regarding the number of circuit elements of each type (e.g., substation transformers, sectionalizing switches) on a per-distribution-substation basis. Then, by the additional assumption of 3.3×10^3 electric meters per distribution substation, the standardization was converted to a per-meter basis. The resulting set of distribution-system elements is shown in Table 5-1, while the assumed message frequencies for control purposes are given in Table 5-2. Because operational-management traffic dominates the peak-hour load, the entries in these two tables represent the key ingredients in the traffic-requirements calculation.

Both the monthly traffic and the peak hourly traffic for the major DAC functions are shown in Table 5-3 for the Western region of the United States. It is seen that operational-management messages represent 74% of the peak-hour traffic and, within that category, roughly 60% of the messages are accounted for by feeder management. If the peak transmission rate (in b/s) corresponds to the peak hourly message rate and the average message length is 100 bits, the required capacity for the Western region is 2.5 kb/s. This is interpreted as a combined capability for the poll and response directions, although Boeing's assumed transaction formats are not directly comparable with the previously assumed formats for DSG communications.

Based on the Western-region capacity of 2.5 kb/s, the required capacity for all of Continental United States (CONUS) is approximately 15 kb/s. The previous estimate of 400 kb/s, based on the MITRE report, assumed 100% maximum motivation. Conversion of the traffic estimate based on Boeing data to a 100%-maximum-motivation equivalent results in a data rate of approximately 40 kb/s. This order-of-magnitude disparity between the two estimates may be attributed to the fact that the Boeing estimate seems to be based primarily on control-message traffic rather than the associated monitoring requirements. This supposition is supported by the low message frequencies in Table 5-2.

To obtain a better estimate of the DAC traffic requirements, a comparable analysis is required of the monitoring data needed to perform the operational functions listed in Table 5-3. Such an estimate is presented in the next section.

E.   JPL TRAFFIC ESTIMATE

This traffic estimate was compiled by R.M. Barnett of JPL's Telecommunications Systems Section (see Reference 1), as was the bulk-power-system traffic estimate presented in Section III-D. Because of the radial network structure of the distribution system, the traffic estimate is logically organized according to the requirements associated with an individual distribution substation. The number of elements that require monitoring in the assumed model is given in Table 5-4.

Table 5-1. Distribution-System Element Population

Element	Per Distribution Substation	Per Electric Meter
Distribution substations	1	3×10^{-4}
Distribution-substation transformers	4	12×10^{-4}
Voltage regulators	6	1.7×10^{-3}
Sectionalizing switches	10	3×10^{-3}
Capacitors	10	3×10^{-3}

Table 5-2. Operational-Management Event Frequency

Function	Frequency of Occurrence
Load reconfiguration	6% of feeders/day during worst-case month
Voltage regulation	Twice daily during worst-case month
Transformer management	Every 15 min during peak load, otherwise once per day
Feeder management	10 samples per hour during peak load, otherwise once per day
Capacitor control	Twice daily during worst-case month
Fault detection, location, and isolation	1% of feeders/month
Load studies	10% of substations/year

Table 5-3. Communications Traffic, Western Region: 1995

	Monthly Traffic (messages/month)	Peak Traffic (messages/hour)
Load management	4.2×10^6	19.2×10^3
Air conditioners	2.3×10^6	9.4×10^3
Water heaters	1.5×10^6	8.2×10^3
Miscellaneous	0.4×10^6	1.6×10^3
Real-time operational management	2.8×10^6	66.0×10^3
Load reconfiguration	0.2×10^6	3.4×10^3
Transformer management	1.1×10^6	14.0×10^3
Feeder management	0.6×10^6	40.0×10^3
Voltage regulation	0.8×10^6	8.0×10^3
Capacitor control	0.3×10^6	4.5×10^3
Fault detection, isolation	0.1×10^6	0.6×10^3
Remote meter reading	9.8×10^6	Not applicable
Total consumption	3.7×10^6	
Maximum demand	0.4×10^6	
Time-of-day	5.7×10^6	
Total	16.8×10^6	85.2×10^3

Table 5-4. Distribution-System Monitoring Points

Element	Number
Feeder	6 per distribution substation
Remote capacitor bank	1 per feeder
Remote voltage regulator	1 per feeder
Remote operated switch	4 per feeder
Remote MW/MVAR power-flow sensor	1 per feeder

The data requirements are dominated by monitor, as opposed to control, functions. The assumed poll/response message format is the same as that for the SCADA transaction associated with DSG communications (described in Figures 4-2 and 4-3). It is assumed that the carrier frequency and bit timing of the response message are derived from the corresponding poll signal; therefore, the preamble in the response direction can be made relatively short. In the polling direction, there are 42 remote points to be monitored for each distribution substation. If all 42 remote points are sampled at the same rate, they can be addressed in a common poll burst. Thus, the number of preamble bits per message will be quite small in the poll direction as well. For these reasons, the preamble bits have been ignored.

The data rate associated with distribution-system monitoring functions depends on the required scan rate. There is little guidance in this matter, since regular communications below the substation level for the most part does not exist today. To arrive at an overall data rate, a common 30-s scan rate was assumed for all distribution-system functions. With this assumption, the monitoring functions, on a per-substation basis, require a data rate of 115 b/s in both poll and response directions.

A utility providing 1% of the nation's electrical energy typically includes about 200 distribution substations. The corresponding combined poll/response traffic requirement is 46 kb/s. Countrywide, the total distribution-system traffic would be 4.6 Mb/s.

In the above traffic compilation, the polling site was not explicitly identified. In keeping with the control-system model (see Figure 2-3), however, all remote sites located on feeder lines are monitored from DACs. Composite data relating to distribution-system activities must be communicated from each

DAC to its associated DDC. The estimated data rate for links of this type, on a per-substation basis, is 2.5 b/s in the polling direction and 7.5 b/s for response messages. If equal bandwidths are assumed for the poll and response directions, the combined channel-capacity requirement is 15 b/s. A typical large utility then requires a channel capacity of 3 kb/s, while nationwide the requirement is 300 kb/s.

Estimates have not been made of the data rates associated with either load management or remote meter reading. It was pointed out earlier, however, that operational-management functions dominate the traffic requirements associated with the distribution system.

The nationwide data-rate estimate of 4.6 Mb/s for links controlled by DACs is an order of magnitude greater than the distribution-system traffic estimate by MITRE and two orders of magnitude greater than the Boeing estimate. The JPL estimate has been selected as a measure of distribution-system traffic for two reasons. Firstly, no underlying assumptions for the MITRE estimate are provided, while the Boeing estimate considers only control messages; and secondly, the JPL estimate was compiled in a manner consistent with the bulk-power-system and DSG-traffic estimates presented in Sections III and IV.

As a final point, it should be emphasized that the above data rates are based on the rather arbitrary assumption of a 30-s scan interval. Should a less-rapid scan rate prove adequate, the data rate would be reduced in proportion.

SECTION VI

THE ROLE OF SATELLITES IN UTILITY CONTROL-SYSTEM COMMUNICATIONS

General issues of the satellite role are examined such as frequency allocations, interference, earth-station requirements and costs, and reliability considerations. These are then related to previously established functions and projected future needs to assess viable options for satellite applications. Redundant earth-station costs (about $75K each) and transponder lease (about $10K/year/utility) make present-day C-band links an attractive alternative for bulk-power systems. Small, non-redundant earth station costs (about $35K each) could make C-band links viable for new DSG installations and many distribution substations. The extension of monitor and control automation into the distribution system via present-day satellites seems impractical because of earth-station problems of size, cost, and frequency coordination. These applications must probably await the availability of high G/T satellites such as those being considered in NASA's Land Mobile Satellite Service program. In addition, a new frequency allocation near 1 GHz seems desirable.

Evaluation of the role that satellites might ultimately play in satisfying utility-company communications needs is a multifaceted problem. Among the many questions that must be answered are the following:

(1)   What frequency bands have been allocated, or might be allocated in the future, to the type of communications represented by utility company needs?

(2)   What satellites are currently operational or in the planning stage that use appropriate frequency bands and permit a method of access suitable to utility-company use?

(3)   What operational restrictions must be observed to avoid excessive interference either into or from other satellite and/or terrestrial microwave systems?

(4)   What are the earth-station characteristics required for operation with current or planned satellites?

(5)   Which control-system functions are compatible with these characteristics and the implied earth-station costs?

(6)   To what extent are future communication needs now satisfied by terrestrial facilities which represent sunk costs to the utilities?

(7)   In which applications (if any) is satellite transmission an obviously preferred means of communications?

(8)   How cost-effective is satellite communications compared with other candidate means of communications?

(9)   In situations where satellite transmission might be chosen as the primary means of communications, are there realistic backup measures available in case of transponder or satellite failure?

(10)   Are there control-system applications in which satellite transmission is best suited as a backup to another, primary form of communications?

Questions relating to satellite system design, such as frequency allocation, available satellites, and required earth-station characteristics can be answered in a relatively definitive manner. Identification of control-system functions for which satellite transmission is a viable means of communications can be done in rather general terms by reference to different levels or communication links in the control-system hierarchy.

Comparison of satellite transmission with other means of communications is more difficult, especially since no attempt has been made (here or elsewhere) to specify and cost-out an earth-station design which is specifically tailored to the utility control-system application. The best that can be done at this point is to add to representative costs for the radio frequency (RF) components an estimated cost for the baseband equipment. However, this procedure will tend to overstate the ultimate cost of an earth station designed in an integrated fashion and produced in quantities commensurate with the potential utility-company market.

The extent to which various utilities' future needs are satisfied by facilities now in place or to be installed in the near future is presently unknown and can best be determined by a survey of major utilities. In the absence of such information, specifically as it relates to bulk-power-system requirements, the discussion here will be confined to the suitability of satellite communications.

Of special concern is the question of reliability. The adequacy of satellite transmission as a primary means of communications hinges on a detailed knowledge of operational procedures and an estimate of the time required to restore satellite service following a catastrophic failure. Even then, acceptance of satellite transmission for primary communications is a very subjective matter. Consequently, the aim in this area will be to elaborate on questions already posed, rather than to provide definitive answers to these questions.

A. ALLOCATED FREQUENCY BANDS AND AVAILABLE SATELLITES

Satellite communications to support the control-system functions described in Sections III-V should be performed at frequencies allocated to the fixed-satellite service (FSS). The FSS allocations resulting from the 1979 World Administrative Radio Conference (WARC) are shown in Table 6-1 (Reference 14). Allocations restricted to a specific geographic region are so designated by the symbol R. Of present interest is Region 2, which consists of North and South America and Greenland.

As a result of the 1979 WARC, considerably more bandwidth has been allocated to the FSS in several bands. Of special interest is S-band, where the downlink (space-to-earth) allocation has been expanded, in Region 2, to span the band from 2.5 to 2.69 GHz. Previously, it had comprised the band from 2.5 to 2.535 GHz. A portion of the new band, 2.655 to 2.69 GHz, remains allocated to uplink transmission.

Table 6-1. Fixed-Satellite Service Allocations Below 35 GHz: 1979 WARC

Band	Earth-to-Space[a] (GHz)	Band-width (MHz)	Band	Space-to-Earth (GHz)	Band-width (MHz)
S	2.655-2.690 R2[b],3[b]	35	S	2.5-2.690 R2[b] 2.500-2.535 R3[b]	190 35
6	5.725-7.075 R1 5.85-7.075 R2,3	1350 1225	4	3.4-4.2 4.5-4.8	800 300
8	7.9-8.4	500	7	7.25-7.75	500
12	12.5-13.25 R1 12.7-13.25 R2 12.75-13.25 R3	750 550 500	12	11.7-12.3 R2[b,c] 12.2-12.5 R3[b,d] 12.5-12.75 R1.3	600 300 250
14	14.0-14.5	500	11	10.7-11.7	1000
30	27.0-27.5 R2,3[e] 27.5-31.0	500 3500	20	17.7-21.2	3500

[a]Does not include bands that are limited to BSS feeder links.

[b]Limited to national and sub-regional systems.

[c]Upper band-limit (12.3 GHz) may be replaced by a new value in the range 12.1-12.3 GHz at the 1983 WARC for Region 2.

[d]Footnote allocation.

[e]Intended for use by, but not restricted to, BSS feeder links.

In addition, the S-band power-flux-density[3] (PFD) limit on the FSS has been increased to agree with that for the broadcast-satellite service (BSS), which shares the 2.5 to 2.69 GHz downlink. The PFD limit is now -137 dBW/m^2 in any 4-kHz band, for elevation angles greater than 25 deg.[4] The previous limit had been -144 dBW/m^2 per 4 kHz in the more restricted FSS band. The expressed purpose of increasing the PFD limit is to facilitate the use of small earth stations in FSS applications.

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[3]The downlink PFD is the radiation level at the surface of the earth.

[4]The PFD limit is lower for elevation angles less than 25 deg. However, there is about a 15-deg segment of the geostationary arc that is visible, at elevation angles greater than 25 deg, from all points in CONUS.

The uplink and downlink allocations at both 6/4 GHz (C-band) and 14/12 GHz (K_u-band) have also been expanded. Commercial applications to date have been primarily at C-band. However, because the geostationary arc is severely overcrowded at these frequencies, many future commercial systems will operate at K_u-band. Even at the K_u-band frequencies it is expected that crowding will occur also.

The remaining two bands listed in Table 6-1 are of little interest for the present application. The 8/7-GHz allocation is restricted to government use. The 30/20-GHz band, for which satellite designs are being advanced under NASA sponsorship, will ultimately afford an alternative to the overcrowded 6/4-GHz and 14/11-GHz bands for commercial applications. However, the cost of 30/20-GHz components are expected to be somewhat higher initially than the costs at the lower frequencies. Moreover, signal attenuation due to rain at 30/20 GHz calls for more margin to maintain reliable communications. Because of these factors, the 30/20-GHz band is expected to be used primarily for large-bandwidth, heavy-trunking applications.

It should be noted that there are a number of frequency bands below S-band that have been allocated to satellite applications other than the FSS. Primary among these are the meteorological application and various mobile-satellite services.

Of the frequency bands both allocated to the FSS and suitable for the utility application, only C-band and K_u-band will be represented by commercial satellites in the foreseeable future. It has been seen in Sections III-V that utility control-system data rates are quite low; for example, the traffic generated in the bulk-power system of a large utility can be measured in tens of kilobits. On the other hand, the K_u-band satellite systems presently planned for U.S. domestic use are designed to operate at very high data rates, and with quite complex earth stations. For example, the SBS satellite has 10 transponders, each of 49 MHz bandwidth. The system is designed to operate in a TDMA mode, at data rates from 43 to 48 Mb/s. Advanced Westar has four 225-MHz, K_u-band transponders. Again, the full transponder bandwidth will be allocated to transmission from one earth station at a time. Other common carriers, such as General Telephone and Southern Pacific Communications, plan to operate K_u-band satellites. It remains to be seen whether the design of these satellites and the planned mode of operation is compatible with the utility control-system application.

This discussion is not intended to rule out the possible use of K_u-band satellites, or even a K_u-band payload on a basically C-band satellite. (Advanced Westar and the proposed Southern Pacific Communications satellite combine C-band and K_u-band transmission.) One motivation for providing such a capability is the absence of a fixed-service (i.e., terrestrial) frequency allocation in the (14.0 to 14.4)-GHz portion of the band allocated to satellite uplink transmission. (The uplink allocation comprises two 500-MHz bands, 12.75 to 13.25 GHz and 14.0 to 14.5 GHz). It is possible, therefore, to locate earth stations without concern for possible uplink interference (through earth-station antenna sidelobes) <u>into</u> terrestrial microwave systems. The possibility of downlink interference into other systems is controlled by PFD limits in the band from 10.7 to 11.7 GHz. No PFD limits appears to exist in the (11.7 to 12.2)-GHz allocation, but non-interference remains an application requirement.

It would still be necessary, in operating at K_u-band, to take precautions to avoid interference **from** terrestrial microwave systems, since the fixed and mobile services share the (10.7 to 12.2)-GHz band with .he FSS. However, this reduces the problem to a technical one and avoids the inherent opposition of terrestrial common carriers to satellite applications that are potential sources of interference.

Operation at K_u-band has its disadvantages, however. Component costs are generally higher than they are at lower frequencies. In addition, rain attenuation adds to the margin requirements and generally leads to larger power requirements.

The primary obstacle to utility-company communications at C-band is the shared allocation with terrestrial services throughout the (newly expanded) uplink allocation from 5.85 to 7.075 GHz. (PFD limits govern downlink transmission.) Because of the widespread use of the 6-GHz band by terrestrial common carriers, coordination of satellite transmission at these frequencies can be difficult, especially in metropolitan areas. (C-band earth stations are often located outside densely populated areas, with microwave "tails" extending into the cities.) On the other hand, if there is considerable flexibility in the precise location of an earth station, or if the earth station is to be located in a remote area (as might be the case with several types of DSG), C-band transmission would be a logical choice.

The obvious advantage to C-band communications is that there are a number of satellites currently in use that operate on a frequency-division, shared-transponder basis. It is possible, therefore, to lease a narrowband element of satellite capacity which is commensurate with the low data rates typical of utility control-system functions.

Even in areas where C-band satellite communications might have only limited application because of the terrestrial-interference problem, the availability of C-band satellites, together with an appropriate access method, makes C-band especially attractive for a demonstration or pilot program. Because of the critical role of control-system communications and the predictably conservative approach of utility-company management to radical innovation in this area, it is necessary to demonstrate the technical feasiblity of satellite communications well in advance of any attempt at widespread adoption of this transmission mode.

Accordingly, C-band satellite link designs are developed in Section VIII which show that communications suitable for utility control-system use is possible with earth stations of modest size and cost. For example, a data rate of 12 kb/s can be supported, using current satellites, with a 3-m antenna combined with a 5 W high-power amplifier (HPA). Newer satellite designs, exhibiting greater receiver sensitivity, require less uplink transmitter power to support a given data rate. Although uplink transmission at 6 GHz with antennas smaller than 4.5 m has not yet received FCC approval, the level of interference injected into adjacent satellite systems with the above parameter values is not excessive.

The remaining fixed-satellite frequency allocation which is suitable for utility company needs is at S-band. This band has not been attractive for commercial purposes because the total allocation is quite small in comparison with that at either C-band or K_u-band. Prior to the 1979 WARC, only 35 MHz was available in each of the uplink and downlink directions. Although a total of 190 MHz is now allocated to the downlink, the uplink allocation is unchanged.

One of the attractions of S-band for the utility application is the high performance and low cost of components as compared with those at either C-band or K_u-band. A significant disadvantage, however, is the heavy use of S-band for terrestrial transmission by the common carriers. It could be difficult, therefore, to frequency-coordinate a large number of earth stations within a metropolitan area. The coordination problem does become less severe as the required bandwidth becomes smaller. However, it is highly desirable that control-system of a given utility be operated at the same frequency (see Section VII-A). Therefore, it is necessary that a common frequency band be cleared at all earth-station sites. This makes it less likely that S-band could be used for uplink transmission by a large number of stations within a metropolitan area.

An S-band downlink, on the other hand, is a distinct possibility (although interference from terrestrial carriers would have to be taken into account). Should a satellite be designed to produce a large effective isotropic radiated power (EIRP) per unit bandwidth, to minimize earth-station costs, there would be little problem of potential interference with other satellite systems. (By contrast, at either C-band or K_u-band, the crowded geostationary arc demands relative uniformity of satellite characteristics to avoid interference between adjacent satellite systems.) The problem that arises is the need to couple the S-band downlink with an appropriate uplink frequency. For applications such as load management, where one-way communications may suffice, uplink frequency coordination would be required only at a limited number of controlling earth stations. Therefore, an S-band uplink might be used for this purpose.

The basic problem with this approach is that most utility control-system applications require two-way communications. It might be possible to coordinate the placement of earth stations for bulk-power-system communications with existing terrestrial links at S-band, because of the relatively small number of earth stations involved. However, for widespread distribution-system application, it could prove necessary to choose an uplink frequency not shared with the terrestrial services. Of the frequencies allocated to the FSS, only K_u-band meets this requirement.

The other possibility is an uplink allocation for utility-company use outside the present FSS bands. Based on the data rates previously developed, the potential traffic for distribution systems nationwide is about 5 Mb/s. Because only a relatively small percentage of this traffic is likely to materialize and be carried over satellite links, a 1-MHz allocation should suffice. Should a new uplink allocation be proposed, it would also be reasonable to consider a new downlink allocation, of similar bandwidth. By this means, questions of interference with and by other services could be eliminated.

The foregoing discussion has been concerned, in rather general terms, with available frequency bands and satellites. Little attempt has been made to relate these factors to the requirements of specific control-system links, except to note certain trends based on the number or size of earth stations to be deployed. In the next section, the possible role of satellite communications in control-system operations is considered at different levels of the control-system hierarchy. The availability of suitable frequencies and/or satellites constitutes one aspect of this broader subject.

B.   SUITABILITY OF SATELLITE COMMUNICATIONS

It is clear from the discussion in the last section that the feasibility of satellite transmission for electric-utility communication needs depends on such factors as:

(1)   The number of earth stations to be coordinated with terrestrial links, if the uplink frequency is in a band shared with terrestrial services.

(2)   The repeater characteristics of available or planned satellites.

(3)   Earth-station costs corresponding to the satellite-repeater characteristics, for the selected frequency band.

The first factor will vary depending on the portion of the control system involved. In general, there will be relatively few bulk-power-system earth stations in comparison with the number of earth stations for distribution-system applications. The second and third factors are fixed once the frequency band is specified (except for the possibility of a specially designed satellite payload). However, the implications of these factors can be very different at different levels of the control-system hierarchy. Furthermore, the reliability requirements vary within the control system, generally being higher in the bulk-power system and lower in the distribution system. It is necessary, therefore, to consider the different segments of the control system separately in assessing the suitability of satellite communications.

1.   Bulk-Power System

Because of the major role played by each generating plant, BPS, and switching station, the bulk-power control system must be extremely reliable and constantly available. As a integral part of the control system, the communications links that carry the monitored data to the ECC and the resultant commands in the reverse direction must be equally available and no less reliable. To ensure the desired reliability, there should be a pair of parallel communications systems that are as nearly independent of one another as possible. From the standpoint of independence, a set of satellite links from the ECC to the various bulk-power-system sites would constitute an ideal backup network to an already existing primary communications system.

A backup satellite system would include an appropriately sized frequency band of reserved satellite capacity, which would remain unused (other than for test purposes) except in the event of a failure in the primary communication system. Based on the estimated 40-kb/s required capacity for a large utility (i.e., one providing 1% of the nation's electrical energy), annual transponder lease costs would be about $10,000 with current C-band satellite tariffs.

One problem with C-band transmission, already mentioned, is the need to frequency coordinate each earth station with existing terrestrial common-carrier links. If there is considerable flexibility in locating the earth stations on the properties occupied by the various generating plants and BPSs, this may not be too severe a problem. The alternative is to choose an off-site location for the earth station. This choice would necessitate a secondary link to connect the bulk-power-system site with the earth station. It would also involve the expense of purchasing or leasing an appropriate piece of land for this purpose, if the utility transmission corridor could not be used.

It is estimated (see Section VIII-E) that the price of a 4.5-m, C-band earth station with redundant components, for use at one of the remote (i.e., non-ECC) locations, is $74,000. These figures are based on current component prices, with the exception of the TDMA baseband equipment, where a development effort is required and for which only the recurring equipment cost has been considered.

Satellite transmission can also be used as a _primary_ means of communication within the bulk-power system. The opportunity for using satellite transmission depends on the extent to which various utilities intend to reconfigure their communication systems in the future. Such a reconfiguration may be expected with the development of an ECC to control bulk-power-system operations. From a tabulation by Dy Liacco (Reference 15), it can be seen that 59 U.S. utilities will have placed control centers of this type in service by year-end 1980. An additional 17 utilities plan to have control centers in operation by the end of 1982. These 76 utilities represent about 2.5% of the total number of utilities in the United States. However, they clearly represent a much larger (though undetermined) percentage of the total power generated.

The fact that an ECC is in operation does not necessarily imply that re-configuration of the communication system has been completed. As has been seen for the LADWP, at the end of Stage 1 of the control-system implementation, only the microwave link connecting the ECC with the existing communication network will have been completed. Installation or upgrading of microwave links to the various generation plants and receiving stations will be done subsequently. It is reasonable to assume, therefore, that some of the 17 utilities scheduled to place control centers in service during 1981 or 1982 could use satellite transmission within their bulk-power systems. The same is true of utilities that will introduce control centers in later years. There is less likelihood of widespread (primary) use of satellite transmission among utilities that already have control centers in operation.

If satellite links are to be used in bulk-power-system operations, whether for primary or backup transmission, they must be compatible with the

alternate means of communication between the same pairs of points. For example, the protocol employed by the ECC in polling RTUs includes the choice of a "time-out" interval, following which some action is taken (perhaps a repeat poll) if no response has been received. Other things being equal, the time-out interval would have to be 0.54 s longer for satellite transmission than for terrestrial transmission to allow for the two-way propagation delay. Because it will be necessary to switch between terrestrial and satellite transmission in the event of a communication failure, the protocol selected should be compatible with either transmission mode.

The final question to be considered for bulk-power-system communications is that of reliability. Because there will be two independent means of communications, if satellite transmission is chosen for either the primary or backup mode, infrequent failures can be permitted provided restoration of the failed mode can be accomplished fairly quickly. In the case of satellite transmission, earth-station redundancy with automatic switchover capability will virtually eliminate the possibility of earth-segment failure (barring sabotage or an act of nature). Therefore, only the satellite remains as a significant failure possibility.

Because of the low utility data-rate requirements in comparison with typical transponder capacities, all U.S. bulk-power-system communications could conceivably be served by a single satellite transponder. At the very least, many utilities would likely share a common transponder. Failure of a single transponder, therefore, could eliminate either the primary or the backup means of communications for a large portion of the utility industry, if satellite use were to become widespread.

Fortunately, switchover to a backup transponder in the same satellite can be accomplished in a straightforward manner. Because an alternate means of communication has been assumed for all bulk-power-system links, commands to effect this switchover can readily be sent to all bulk-power-system sites. The transponder to be accessed is determined by choice of a crystal of appropriate resonant frequency in the earth-station up- and down-converters. If "double-conversion" devices are employed to shift from the 70-MHz IF to the RF frequency, and vice versa, a transponder change requires no more than the replacement of a crystal. This process can be automated because, with the backup transponder generally known in advance, the appropriate crystal can be included with the earth-station equipment. The switchover can be accomplished within seconds of the time the transponder failure becomes known at the ECC.

It is worth mentioning that, in the history of C-band satellites such as Anik, Westar, and Intelsat IV, transponder failures have not occurred suddenly. Rather, they have taken place over a period of time as the result of a reduction in gain of the transponder TWT. Consequently, an orderly transition to a backup transponder has always been possible for essential services.

There has not yet been a total failure of an operational commercial satellite. It is necessary, nevertheless, to be prepared for one if satellite transmission is to be used for utility control-system communications. Satellite transmission would not be used as either the primary or the alternate means of communications unless a backup satellite was on-station and operational.

To switch from the primary satellite to the backup satellite, it is necessary to repoint each earth-station antenna in the new direction. This repointing would take some fraction of an hour for a trained technician to accomplish, once he is on-site. The total elapsed time required to repoint all antennas of a utility company's bulk-power system depends on the number of technicians available, as well as on the number and geographic distribution of earth stations.

At least one major utility has been actively considering the possible role of satellites in bulk-power-system communications. Niagara Mohawk Power Corporation recently completed an experiment using NASA's experimental Applications Technology Satellite (ATS-3) and the Geostationary Orbiting Experimental Satellite (GOES) (Reference 16). These satellites are under the control of NASA and the National Oceanic and Atmospheric Administration (NOAA), respectively. Links were established to a BPS and to the Power Control Center through both satellites. The GOES was used solely to relay environmental data, while ATS-3 was also involved in the simulation of a typical SCADA system. Niagara Mohawk is also investigating possible operation through current commercial satellites.

2. Dispersed Storage and Generation

While DSGs are properly considered part of the distribution system, their characteristics and communication requirements are sufficiently distinct from those of other distribution-system elements that they will be considered separately in assessing the merits of satellite transmission. For the most part, the 10,000 DSGs of substantial size (i.e., >1 MW) that are

anticipated by the end of the century do not exist today. Therefore, in conceptualizing a communication system for use in their control, all available media may be considered without prejudice based on already existing means of communication.

There is a great deal of flexibility in choosing the location of certain types of DSGs. For example, photovoltaic cells of significant capacity can be located anywhere there is extensive land area that can be devoted to this purpose. While this requirement may restrict their development in densely populated areas, these devices should eventually be quite prevalent in rural, if not suburban, areas. Because of the relative accessibility of these locations, several means of communication, including telephone (private-line only) and radio, are available for control of the   DSGs.

On the other hand, hydroelectric units must be located at the site of naturally flowing water, hydroelectrically pumped storage systems depend on the existence of a pair of reservoirs at different levels, and wind-generation systems also require the presence of appropriate natural conditions. Moreover, all of these required local conditions are likely to be found in remote areas, where distance and line-of-sight requirements preclude the use of communication media such as telephone and radio. In these cases, satellite transmission may be regarded as a naturally preferred alternative.

For DSGs that are remotely located, any of the fixed-satellite frequency allocations is likely to be a suitable choice. From the standpoint of available satellites with suitable access methods, C-band is the only currently viable candidate. However, if a single choice of frequency is to be compatible with all prospective DSG locations, there would seem to be no alternative to a K_u-band uplink, among existing frequency allocations.

The price of a 3-m, C-band earth station with nonredundant components is estimated at $32,000 (see Section VIII-E), and is therefore compatible with a DSG in the 1-MW-plus category. A K_u-band earth station would be somewhat more costly. A 3-m antenna should be physically compatible with most DSG sites. Furthermore, as is shown in Section VIII-D, an antenna of this size will not cause excessive interference with other satellite systems. Earth-station redundancy is not required because a communication failure involving a single DSG would have at most a local effect. It is only necessary to program the local controller so that, during a communications failure, the DSG reverts to an autonomous and inherently safe mode of operation (which might be a shut-down of operations).

A satellite failure could have much greater consequences. It has been estimated that, by the year 2000, DSGs will provide between 4% and 10% of the electrical energy production in the country. Thus, a satellite failure could result in the temporary loss of the coordinated use of this energy output.

A single transponder failure can be overcome by instructing the DSG controller to attempt to communicate over the backup transponder (by switching to the appropriate crystal in the up/down converter) whenever communications has been interrupted for a prescribed period of time. Although the reliability of such a switchover procedure remains to be determined, temporary loss of control over a portion of the DSG population should not prove too serious (assuming the DSGs revert to a fail/safe mode). If the communications failure should result from a component failure in the DSG terminal, this would be evident at the controlling station, at which point appropriate maintenance procedures would be initiated.

In case of a total satellite failure, it would be necessary to repoint each DSG earth-station antenna in the direction of the backup satellite. While it could take a number of days to accomplish this task for the entire DSG population, those units with the capability to significantly impact system performance could probably be visited in a single day. Because of the low probability of a total satellite failure and the relatively small impact it would have in terms of DSG operation, this possibility should not be regarded as a serious deterrent to the adoption of satellite transmission for DSG control.

3.   Distribution System

The many functions that might be performed under the heading of DAC have been divided into two groups (in Section V), under the subheadings of operational management and load management. In addition, there is the meter-reading function, which is regarded as a third category. However, this three-way clas-

sification is inadequate to perform an assessment of satellite transmission for control-system purposes because, within the first two categories, there is considerable diversity in the nature of the physical site at which data are to be monitored or control exercised.

For example, voltage levels are most often controlled by changing the tap setting of a transformer located at the distribution substation (although a secondary transformer, located on a feeder line at some distance from the substation, can also be involved). VAR control is normally done at the substation as well.

Fault detection, on the other hand, can take place at various points in the distribution network. Occurrence of a fault is signaled by the unscheduled opening of a feeder switch or the blowing of a fuse. Switch and fuse operation is normally arranged so that only the device nearest the fault, in the direction of the substation, is affected by the fault. Unless the feeder breaker, located at the substation, is tripped by the fault, the latter cannot be physically detected at that point. Communications with RTUs located at the various switch and fuse sites permits faults to be detected, and faulted sections to be identified, from a substation control point.

Once a fault is located, service must be restored to unfaulted sections by control of mainline feeder switches, feeder tie switches, and the feeder breaker. For example, a fault on a mainline feeder is isolated by opening the switch closest to the fault on either side. The load above the faulted section is restored by closing the feeder breaker; the load below, by closing tie switches to transfer the load to adjacent feeders. A portion of the load could be switched to a feeder emanating from another distribution substation, in which case a control point above the substation level (i.e., the DDC) would become involved.

Switching within the distribution feeder network is also conducted on a scheduled basis, to isolate sections of feeder for routine maintenance and to transfer load between feeders and substations for load-leveling purposes. Feeder loads, as seen from various points, must be monitored to ensure that the planned reconfiguration does not lead to an overload of distribution-system equipment.

Physical site distinctions also arise in load management and meter reading. It is necessary to differentiate the performance of these functions for single-family houses, multiple-unit residential structures, and industrial and commercial establishments.

A 3-m earth station has been taken as representative of distribution-system sites, to assess operation with current communication satellites. This type of installation is compatible, in both size and cost with deployment at distribution substations, medium-to-large industrial sites, and large residential complexes. With respect to the choice of frequency bands, the preceding discussion regarding DSG earth-station deployment is equally applicable to distribution-system installations. In other words, where two-way communications is required, such as between a DDC and a DAC, a K_u-band uplink may be mandatory because of the large number of earth stations located in populous areas.

The same is true for load management at industrial or large residential sites, if control is exercised at the DAC level. It might be possible, should control emanate from the less numer DDCs, to use a C-band uplink. Meter reading, however, which involves du   transmission, is likely to require a K_u-band uplink from the remote sites.

The presumed need for a K_u-band uplink on DAC-to-DDC communications precludes near-term adoption of satellite transmission for this purpose, in the absence of a suitable K_u-band satellite. It has been claimed that "economic analysis and power system simulation studies have not demonstrated a significant benefit-to-cost ratio for distribution automation functions" (see Reference 5). Thus, the need for such a satellite is not immediate. However, automation of operational-management functions is expected to be widely adopted in future years, especially as it is required for DSG control.

By contrast, load management is currently being practiced at many industrial sites. For satellite transmission to be a viable communication mode for this application, two conditions must be satisfied. Firstly, communication must take place only in the command direction; and secondly, control must be exercised from a small number of points, which can be frequency-coordinated at C-band. The second condition suggests that, initially, load management should be the responsibility of the DDC. At a later time, should a K_u-band payload become available, this responsibility could be shifted to the DAC or substation level. This progression, from relatively centralized to decentralized control, is consistent with the manner in which control-system development may be expected to evolve.

Not covered by transmission with 3-m earth stations are communications needs associated with fault detection and isolation, feeder-load management, and transformer-load management, except where these functions can be performed through monitor and control operations at the distribution substation. Additionally, a 3-m earth station would be inappropriate for load management and meter reading at smaller industrial sites and at most residential structures. A special-purpose satellite is needed for these types of applications, which presumably is shared with other narrowband services and which permits the use of extremely small antennas and generally low-cost components on the ground. These requirements would be satisfied by a satellite operated to produce a high EIRP per unit bandwidth to compensate for the low receive antenna gain/receiver noise temperature (G/T) on the ground. In addition, a large satellite G/T is needed to permit a reasonable-size HPA to be used with the small ground antenna. These requirements can be jointly satisfied by the deployment of a multiple-beam (and, therefore, high-gain) spacecraft antenna subsystem.

There are several frequency bands at which such a satellite might operate. Generally, the cost of ground equipment will be less, the lower the frequency. This factor, together with the presence of significant rain attenuation at K_u-band, probably rules out this band for general distribution-system application.

C-band downlink frequencies in the bands 3.4 to 3.7 GHz or 4.5 to 4.8 GHz (i.e., those frequencies not presently used by C-band satellites) could be

considered, because there would be no possibility of interference into other satellite systems resulting from the large satellite EIRP. Correspondingly, an uplink carrier outside the band 5.925 to 6.425 GHz used by present satellites does not run the risk of interference from other satellite systems as a result of the large satellite G/T. However, components are still relatively costly at C-band, so it would be preferable to operate at a lower frequency.

A satellite system operating at S-band, the remaining FSS allocation, largely avoids the possibility of interference with other satellite systems. Moreover, component costs are more reasonable, and their performance is considerably improved, with respect to those at C-band. To illustrate possible S-band operation, consider a system operating at the PFD limit of -137 dBW/m^2 per 4 kHz, as described by the link budget of Table 6-2. For an assumed downlink carrier-to-noise ratio (C/N) requirement of 13 dB, a ground antenna gain of 16.4 dB is required. This gain can be provided by a 0.3-m (1-ft) antenna. Thus, S-band transmission with small ground antennas necessitates a spacecraft designed to operate at or close to the PFD limit.

Operation with small antennas at S-band introduces another concern. A 0.3-m antenna has a half-power beamwidth of 30 deg. At a location from which

Table 6-2. S-Band Downlink for Operation at the PFD Limit

Satellite EIRP per 4 kHz (dBW)[a]	26.0
Space loss (dB)	-192.0
Receive antenna gain (dB)	16.4
Received carrier power (dBW)	-149.6
Receive system noise temperature (dB-K)[b]	30.0
Boltzmann's constant (dB(WK^{-1}Hz^{-1}))	-228.6
Noise bandwidth (dB-Hz)	36.0
Received noise power (dBW)	-162.6
Downlink (C/N)[c]	13.0

[a]Spreading loss ($1/4\pi R^2$) is -163 dB-m^{-2}. Power flux density is therefore 26 to 163 = -137 dBW/m^2.

[b]Assumes a mixer front-end.

[c]The use of coding for error correction has been omitted for reasons of cost.

the satellite is seen at an elevation angle of 25 deg, for example, the lower half-power elevation angle is only 10 deg. Thus, a potential is created for excessive interference both into and from terrestrial systems.

The severity of these two problems (i.e., the high PFD and the radiation at low-elevation angles) can be alleviated through the use of a larger ground antenna. A 1-m, rather than a 0.3-m, antenna would reduce the satellite EIRP requirements (and thus the PFD) by 10 dB and would lessen the chances of bothersome interference with terrestrial systems. However, the 1-m antenna would also reduce the range of distribution-system applications amenable to satellite communications.

All of the interference problems described, whether with respect to other satellite systems or terrestrial links, could be eliminated by the introductionof a frequency allocation not shared with other satellite or terrestrial services. Based on traffic estimates in Section V, an allocation on the order of 1 MHz in both the uplink and downlink directions should suffice. Once again, low frequencies are favored from the standpoint of minimizing component costs. However, if too low a frequency is chosen, urban man-made noise may limit the downlink performance. At a given frequency, the magnitude of this effect depends on the directivity of the ground antenna and the elevation angle of the satellite. For a reasonably directional ground antenna, a frequency in the (1 to 2)-GHz range may offer the best compromise between these two factors.

The Boeing study of a satellite system designed for distribution-system monitor and control operations (see Reference 6) provides cost estimates of ground equipment intended for use with a multibeam (high-gain) satellite antenna. Uplink and downlink frequencies in the vicinity of 1 GHz are assumed. While the ground antenna size is not explicitly indicated, link budgets are provided elsewhere in the report for both 0.15-m (0.5-ft) and 0.3-m (1-ft) antenna diameters.

The equipment costs given pertain to load management and meter reading performed at residential sites. An earth station located at the distribution transformer is assumed to be shared by the residences receiving power from the secondary side of the transformer. Communications between the earth station and the residences takes place via the power line itself.

The estimated cost of a residential terminal which provides two-way communications (via the power line) with the earth station (for meter reading) is $175. The corresponding earth-station equipment cost is about $300 for a production volume of 1 million units. If 10 residences share an earth station, the average total cost per residence is typically $200.

When only one-way communication is required, as presumed for load management, the residential and earth-station costs fall to $40 and $150, respectively. With 10 residences sharing an earth station, the total cost per residence is $55.

The estimated earth-station cost of $300 for equipment providing two-way satellite communications should also be representative of the cost of an earth

station suitable for operational-management functions performed below the distribution-substation level. Typical of these functions is the need to monitor the status of a sectionalizing switch which, following detection of a fault, may have to be reset to an open or closed position.

No detailed breakdown of the earth-station costs cited previously is provided in the Boeing report. If, in fact, these costs can be substantiated, the advent of a special-purpose satellite could render satellite transmission a viable candidate to provide the communications needed for most distribution-system functions. The characteristics of such a satellite would resemble those advanced for the LMSS (see Reference 9) in the sense that a multibeam satellite antenna is needed to minimize the earth-station antenna and HPA requirements. Much of the technology development associated with the design of such a satellite (specifically, the large deployable antenna subsystem) would be equally applicable to a satellite payload developed for the utility application.

The proposed LMSS system uses the newly allocated (806 to 890)-MHz band for two-way vehicular communications, while conducting all base-station communications at S-band. In the distribution-system application, the remote stations would transmit and receive at frequencies newly allocated for this purpose. Communications between the satellite and the master stations could take place either at the new allocations or at S-band. The feasibility of the latter approach depends on factors already discussed.

A satellite designed for general distribution-system use could also serve the communication needs of the DSCs, although a larger frequency allocation would be required. The discussion of DSG communications in the preceding section presumed that no such satellite would be available, and therefore was focused on existing satellite designs. Because both the development of DSG as a significant energy source and widespread adoption of DAC are not expected before the 1990s, a satellite developed for the latter application would be available in the proper time frame to serve DSG needs as well.

Reliability considerations for operational- and load-management communications are similar to those governing DSG operations. In other words, communication failure to a single distribution-system site is not especially significant from a system viewpoint, provided the element involved continues to function in a fail/safe manner. Load management presents no problem in this respect, because the continued operation of a small number of units that should be turned off will not seriously affect the load on the system. Furthermore, manual backup to feeder-structure communication links is adequate, because the outages that result will be no worse than those currently experienced.

The only reliability problem of consequence is that resulting from a satellite failure. It would be necessary to have a spare satellite in orbit to avoid a prolonged period (measured in months) during which DAC functions are lost. Both the primary and spare satellites should be given orbital locations that place them simultaneously within the beamwidth of the largest ground antenna with which they are to be used. In switching from the primary to the backup satellite, the former would have to be completely disabled (with respect to distribution-system communications) to avoid interfering with operation of the latter.

C. DISTRIBUTION-SYSTEM COMMUNICATION ALTERNATIVES

As discussed in Section VI-B-3, satellite transmission can, in principle, be used as the communication vehicle to perform all DAC functions. For some applications, satellites similar to those presently in operation are appropriate. In other instances, the feasibility of satellite transmission depends on the availability of a special-purpose satellite payload to permit low-cost ground installations at numerous residential, industrial, and feeder-network sites. In either case, the attractiveness of a satellite solution depends on the communication alternatives for performing the various DAC functions.

The primary candidates, other than satellite, to satisfy the distribution-system communication requirements are:

(1) VHF or UHF radio.

(2) Power-line carrier (PLC).

(3) Switched telephone network.

(4) Private-line telephone.

(5) Cable television (CATV).

No single communications mode is best suited to perform all DAC functions. Rather, the characteristics of a given mode must be compared with the communication requirements of each DAC function to determine which combinations are feasible. The economics of the resulting candidate modes can then be compared and a preferred means of communication for each DAC function selected.

The costs associated with the different communication modes identified previously are developed in a report by Systems Control, Incorporated (SCI) (Reference 17), which was prepared for the FCC. Therefore, the present discussion is confined to establishing the feasible communication mode/DAC function combinations. Some of the factors taken into consideration in establishing these associations are:

(1) Coverage area.

(2) Penetration of coverage area.

(3) Configuration flexibility.

(4) Broadcast-mode capability.

(5) Simplex versus duplex transmission.

(6) Data rate.

(7) Response time.

(8) Reliability and availability.

Control over distribution-system RTUs can be exercised at either the DAC or DDC level. Accordingly, communication between an RTU and its control point may follow several distinct types of paths:

(1)   Direct connection to a DAC control point.

(2)   Direct connection to a DDC control point.

(3)   Connection via the DAC to a DDC control point.

(4)   Connection via a concentration point to a DAC control point.

(5)   Connection via a concentration point to a DDC control point.

The first three possibilities are self-explanatory. The concentration point referred to i: Paths 4 and 5 can assume several forms. For example, if the immediate connection to the RTU is via CATV, the concentration point would be the CATV headend. The distribution substation would itself serve as the concentration point for a PLC connection to the RTU.

The connection from the concentration point to the control point in Paths 4 and 5, or from the DAC to the DDC in Path 3, may use a different communication medium from the one used to provide the RTU connection. (This is necessarily true if the RTU connection is via PLC.) In assessing communication alternatives for compound paths of this type, attention will be restricted to the path segment providing the RTU connection.

Evaluation of communication alternatives is based largely on material in the SCI report, although the conclusions reached here do not agree in all respects with those of that source. It should also be pointed out that the SCI report considers satellite transmission a viable candidate only for low-data-rate applications. With the availability of a special-purpose satellite, however, required data rates for all DAC functions can be supported. Moreover, even without such a satellite, data rates in excess of 10 kb/s can be supported at distribution-system sites equipped with 3-m earth stations.

1.   VHF or UHF Radio

Presently, VHF-FM radio is used for load management at frequencies of 153 MHz and 174 MHz, which have been especially allocated for this purpose. The coverage area of a base station varies with the transmitting antenna height, remote antenna height, transmitter power, frequency, and the degree of natural and structural blockage. For example, in an urban area, for antenna heights of 200 m and 3 m, respectively, the mean attenuation at the above frequencies is less than 28 dB for distances up to 20 km. If the transmitter power is such that this is the maximum acceptable attenuation level, the coverage area has a 20-km radius.

Adequate communications is generally not possible to all points within the coverage area, however. The received signal at certain locations will undergo deep fades as the result of multipath propagation. Other points may have no single path of adequate strength to the base station. This problem can be alleviated to some extent through the use of space diversity or the placement of reflectors at judiciously selected locations.

The capability of radio communications for performance of DAC functions depends on the allocated spectral bandwidth in relation to the required data

rate. The highest data rate is associated with monitor, rather than control, functions. In fault detection, for example, the control station periodically scans the status of all distribution-system devices that can automatically change state because of a fault. The required data rate depends on the number of devices to be polled and the period of the polling cycle.

The number of RTUs connected to a single concentration or control point can be reduced through greater decentralization of control. However, this decentralization merely fragments the frequency assignment to a greater degree, unless frequency reuse in different portions of the service area is possible. In this case, the required frequency assignment is also reduced. Increasing the number of control points also increases the number of transmitting towers, although the height of each tower can be reduced accordingly.

The period of the polling cycle is fairly arbitrary. Since most faults occurring at a distance from the distribution substation are reported by telephone today, a polling cycle as long as 1 minute seems quite reasonable. A shorter polling cycle would reduce (by up to 1 min) the time taken to restore service to unfaulted feeder sections; however, it would not lessen significantly the time needed for repair of the fault, which would still have to be done manually.

For example, assume that a large utility, serving 1 million customers, has 1,000 distribution substations and 4,000 feeders. There are two switches per feeder to be monitored and a total of 10 control points (at the DDC level). For a typical set of message parameters (see Reference 17) and a polling cycle of 1 min, the combined poll/response bit rate for each control point is about 1 kb/s.

Because the distribution-system monitor functions are not time-critical, often it will be reasonable to choose a polling cycle that is compatible with the available bandwidth. To the extent that this is possible, radio transmission may be considered a candidate for the performance of any of the DAC functions.

Because radio transmission operates in a broadcast mode, it is suitable for such functions as time-of-day meter rates, direct load control, and voltage control for load reduction. These applications are easily implemented with present frequency allocations inasmuch as the associated data-rate requirements are quite low. Because no response to these commands is required, transmission can take place in a simplex mode.

2.   Power-Line Carrier

This communication mode consists of superimposing a carrier for data transmission on the 60-Hz power-transmission carrier. Power-line carrier communications has been used for many years on high-voltage circuits (i.e., in the bulk-power system) to transmit both data and voice. At the distribution level, however, complex attenuation and noise characteristics make it difficult

to select a universally applicable set of system parameters. Nevertheless, in recent years, several companies have developed PLC product lines in an attempt to capitalize on the vast potential market for distribution-system communications equipment.

The most vexing problem in the development of a PLC system is the choice of carrier frequency. At low frequencies, noise levels are high, necessitating large signal-injection power and low data rates. At high frequencies, attenuation is great, leading to the need for repeaters to communicate over a significant distance. It has been found (Reference 18) that the frequency range 3 to 12 kHz offers the best compromise between these opposing factors. A relatively low data rate of about 60 b/s can be supported at these frequencies.

The choice of a specific frequency in this range, and system design generally, is made difficult by the highly time-dependent and, in many cases, unpredictable nature of the propagation characteristics and disturbances. Specifically, reconfiguration of the distribution network due to switching of feeder sections (scheduled or unscheduled) can drastically alter the properties of the communication channels. As a result, there is no guarantee that repeaters introduced to compensate for line attenuation will be properly positioned following a reconfiguration.

The carrier signal is injected into the power line via a coupling transformer. It is desirable to inject the signal as close as possible to the RTUs, to minimize attenuation. However, injection below the substation level introduces the possibility of a variable propagation distance due to feeder-network reconfiguration. Additionally, as mentioned earlier, it is necessary to provide a second communication link to connect the signal-injection point to the control station. This second set of links is made more complicated by a multitude of signal-injection points. It may be concluded, therefore, that the distribution substation is the most logical point for signal injection.

A single injection point has a coverage area that is limited to RTUs on a single feeder or, at most, a group of feeders originating at the same distribution substation. To cover an entire service area, a utility would have to operate many PLC systems in parallel. This requirement is also necessitated by the limited data-rate capability of PLC systems.

Power-line carrier is inherently a broadcast-type of communications. Therefore, it can perform in an efficient manner such functions as time-of-day meter rates, direct load control, and voltage control for load reduction. Power-line carrier can also perform voltage and load monitoring, as well as remote meter reading. There is some question, however, regarding PLC-applicability to fault detection and scheduled switching, because of possible disruption of communications during these events (see Reference 17).

3.   Telephone

The switched telephone network has the virtue of providing essentially complete coverage and penetration of the service area of any given utility.

The network is also highly flexible, from a configuration standpoint, in providing point-to-point connectivity. However, performance of DAC functions (with the exception of meter reading) via switched circuits is virtually precluded by the long interrogation delay corresponding to the time needed to establish a connection. Although this delay may not be incompatible with the required response time for a specific function, it nevertheless results in an extremely inefficient polling procedure.

One alternative to the switched telephone network is the establishment of private lines to all distribution-system points of interest. (Electric utilities make extensive use of private telephone lines for data communications within the bulk-power system.) However, economic considerations clearly limit the number of points to which private connections are feasible.

Neither private lines nor switched telephone circuits can be employed in a broadcast mode. Therefore, they are not suitable, in their normal configuration, to alter meter rates or perform load-control functions.

The technical objections to telephone-network use can be largely overcome by paralleling the central-office switch with a scanning matrix interfaced directly to customer loops on the customer side of the main distributing frame. This eliminates dialing delays while providing access to all telephone-connected sites. The rapid scan of subscriber loops, which is equivalent to a very slow-speed broadcast-communication mode, can be used as a vehicle for load management. Two-way communication is also possible with this technique, so that meter reading can be accomplished (although not on busy lines).

It has been suggested that telephone companies might purchase, install, and operate the equipment necessary for line scanning, and thereby provide load-management and meter-reading services to the utilities (see Reference 20). The enthusiasm of electric utilities for this approach may be dampened by their reluctance to be dependent, for control-system communications, on the services of another type of utility. Nevertheless, a system of this type for access to customer sites, combined with the use of private telephone circuits for operational management, would be sufficient to perform all aspects of DAC.

4.   Cable Television

CATV networks are capable of high-data-rate transmission. In addition, federal regulations require that all CATV networks installed in the 100 largest U.S. markets have full duplex capability (Reference 19). Therefore, CATV has the potential to provide the communications for all DAC functions.

The principal obstacle to reliance on CATV for distribution-system communications is the low penetration of customer sites. It would probably not be cost-effective to extend the coaxial-cable system to include all residences and commercial establishments solely to perform DAC functions.

5.   Summary

The capability of each communications mode to perform the various DAC functions is shown in Table 6-3 (see Reference 17). In addition to the modes

Table 6-3. Feasible Communications Media for Performing DAC Functions

Communications Medium \ Function	Fault Detection (Polling)	Voltage and Load Monitoring	Scheduled Switching, Fault Detection (Quiescent)	Meter Reading	Time-of-day Rates & Load Control	Voltage Control
Telephone (Private)	X	X	X			X
VHF, UHF Radio	X	X	X	X	X	X
CATV	X	X	X	X	X	X
PLC (2 to 100 kHz)		X		X	X	X
PLC (Audio Frequency)					X	X
Telephone (Switched)				X		
Telephone (Scanning)				X	X	
Broadcast AM Radio					X	X

already discussed, the table reflects the capability to conduct load management and meter reading with audio-frequency (60 to 2,000 Hz) or ripple PLC, or with broadcast AM radio. The former is widely used in Europe, but far less extensively in the United States, for direct load control. The latter approach superimposes an inaudible control signal on the program material of a commercial AM radio station. Both techniques are limited in data rate to about 1 b/s.

Only one mode listed in Table 6-3, VHF or UHF radio, has the capability to perform all DAC functions while providing a high degree of penetration of the coverage area. This capability also resides in the combination of private-line telephone and scanning telephone. On the other hand, current utility-company interest is greatest in the area of load management, because there is an immediate monetary payoff in being able to reduce peak loads. Therefore, PLC techniques, which allow the utilities to retain control of the communication medium, have received more attention than other communication modes.

Of considerable interest is a major field demonstration of DAC functions under the joint sponsorship of EPRI and the U.S. Department of Energy (DOE). "The demonstration consists of 750 metered points on each of five host utility systems. Communication equipment being evaluated includes three power-line-carrier systems, one radio system, and one telephone system. Emphasis is on whether such a two-way communication system is feasible, and if it is, whether it would be cost ef ctive. This four-year, $10 million program has been completed and is in the report-writing stage. Results should be available early in 1981" (see Reference 7).

EPRI is an organization funded by the utilities themselves. This fact, together with the joint sponsorship by DOE, suggests that the demonstration results will be very influential in determining the future direction of DAC efforts.

D.   SUMMARY

Satellite transmission can be used to satisfy bulk-power-system communication requirements in either a primary or backup capacity (see Table 6-4). Present C-band satellites, which permit multiple transponder access by narrow-band carriers, are suitable for this purpose. The estimated price of fully redundant earth stations employing 4.5-m antennas (with the exception of the ECC earth station) is about $74,000. The presence of an alternate communication mode, which can be used to command a transponder switchover, guarantees that a transponder failure will produce only a momentary satellite outage. Switchover to a backup satellite, in the event of total satellite failure, can be accomplished in a matter of hours.

Integration of DSGs into utility-company control systems will not be required until the 1990s, when dispersed sources of generation are expected to represent a non-negligible fraction of the nation's total electric-utility energy output. While other means of communications can be used for DSGs located in populous areas, satellite transmission is a naturally preferred alternative for remotely located DSGs. Furthermore, the required communications can be provided with current C-band satellites using 3-m earth stations. It is possible, therefore, to demonstrate DSG control by satellite at the present time.

Table 6-4. Factors Affecting Applicability of Satellite Communications

Utility Segment	Time Period	Role of Satellite Communications	Present Satellites Applicable	New Frequency Allocations Required
Bulk-power system	Present	Primary[a] or backup	Yes	No
Dispersed storage and generation	1990s	Primary	Depends on DSG location	No
Distribution system	1980s	Primary	No	Pot....

[a]Presumes existence of alternate communications mode.

Widespread adoption of satellite transmission for DSG control would probably require the use of non-C-band frequencies, because of the difficulty in clearing a large number of sites for C-band operation in populous areas. While K_u-band should present fewer coordination difficulties, the present tendency is for K_u-band systems to be operated in a wideband TDMA mode, which is not suited to the utility application generally. It is conceivable, however, for a utility (or group of utilities) to lease a narrow band at one end of a K_u-band transponder otherwise operated in a wideband TDMA mode.

Present satellite technology is also applicable to certain distribution-system communications, such as the DDC-to-DAC links. However, frequency coordination of C-band earth stations at the numerous DAC sites would be difficult. On the other hand, load management, which only requires one-way communications, could be exercised by the DDCs, thereby greatly reducing the frequency-coordination problem.

Performance of DAC functions at sites below the substation level in most cases must be accomplished with inexpensive installations. This is generally true of operational management functions. Satellite transmission to perform these functions would have to be conducted via a spacecraft employing a high-gain, multiple-beam antenna subsystem. The requirements are similar to those for the Land Mobile Sattelite Service, for which NASA is currently developing a satellite system. Presumably this new technology could also be applied to, or shared by, the electric utilities. Of the various FSS frequency allocations, S-band is the most desirable from the standpoint of minimizing both component costs and the likelihood of interference with other satellite systems.

Satisfactory communications at S-band with small (0.3-m) ground antennas requires operation close to the PFD limit. The possibility of uplink interference into terrestrial microwave systems further complicates the

picture. However, the low ground-transmission levels made possible by the large satellite antenna gain could render these transmissions harmless to terrestrial systems.

As an alternative to S-band transmission, a new frequency allocation could be sought. Because distribution-system installations will generally be located in densely populated areas, man-made noise places a lower limit on the frequencies that might be considered. While a detailed statistical analysis would be required to determine this lower limit, it would seem to be about 1 GHz.

Adoption of satellite transmission for distribution-system communications depends on the viability of alternate communication modes such as radio, PLC, or telephone. Oi these, PLC seems to be the preferred mode of utilities, although it must be supplemented by another mode for fault detection and scheduled switching. Experiments conducted under EPRI sponsorship will help to assess the reliability and cost of each of these modes. Prospects for a satellite solution to distribution-system communication requirements should become clearer once a reasonably definitive assessment of these alternatives is available.

SECTION VII

TRANSPONDER MULTIPLE ACCESS

The general concepts of TDMA and FDMA are discussed and their potential application to the utility industry is reviewed. It is suggested that FDMA principles be used to separate the various utilities from one another and that TDMA principles be used to differentiate between stations within a given utility. An example of TDMA is presented together with a discussion of time-slot assignment and guard-space requirements. The half-duplex operational mode is examined and its technical disadvantages as compared to full-duplex are presented.

The amount of data flowing between any pair of sites in a utility system is quite small. The largest point-to-point traffic is generally found in the bulk-power system. Average data rates on links connecting generating plants, BPSs, and switching stations of a large utility with the ECC are ty y 20 kb/s, 3 kb/s, and 1 kb/s, respectively (see Reference 1). Far lu.. data rates are found in the distribution system. It was shown in Section IV-D, for example, that the average data rate per DSG, based on a 2-s scan rate, is 145 b/s.

Because of these small point-to-point data rates, practical satellite link design precludes exclusive assignment of a transponder channel to an individual pair of earth stations, except possibly for generation plant-to-ECC links. On the other hand, because of the regularity with which performance must be monitored throughout a utility system, it is reasonable to assign a time element of transponder capacity, at regular intervals, to transmissions between each pair of earth stations. These considerations lead quite naturally to the choice of a combined time-division-multiple-access/frequency-division-multiple-access (TDMA/FDMA) transmission format.[5]

A. TRANSPONDER CHANNELIZATION AND NODE ASSIGNMENT

To implement this format, the satellite transponder bandwidth (or a portion thereof devoted to the utility application) is divided into a number of separate channels, not necessarily of equal bandwidth. (This is the FDMA aspect). Each node of the control-system network is assigned to a specific channel for transmission. Half-duplex operation could be implemented by assigning each master station and the associated remote stations to the same

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[5]Current commercial satellites provide either 12 or 24 transponders, with center frequencies (for a given polarization) spaced at .0-MHz intervals. Each transponder may be accessed by anywhere from one to roughly 1,000 separately transmitted carriers, depending on the point-to-point traffic mix, with each carrier occupying a separate frequency band or channel.

channel, i.e., poll and response messages would be transmitted on the same frequency. Full-duplex operation, on the other hand, implies the use of separate channels, presumably of equal bandwidth, in the poll and response directions. Half-duplex transmission is not especially well suited to satellite communications, for reasons given in Section VII-D. Therefore, the transponder-access problem will be described in terms of full-duplex operation.

For ease of network control, nodes belonging to a common utility, at a similar level in the control system hierarchy, should be assigned to the same channel. The DACs of a particular utility provide such an example. Transmission over a channel to which a group of DACs has been assigned could include poll messages transmitted by bulk-power-system nodes as well. This arrangement is _feasible_ only if the link parameters (e.g., channel bandwidth and carrier power) are similar at all levels of the control network. It is _desirable_ only if the generation, transmission, and distribution functions are provided by the same utility. Where different utilities are involved, separate channels should be used for the poll messages.

Conversely, to allow different utilities to operate as independently as possible, a given pair of channels should be dedicated to the transmissions of a single utility, wherever possible. Accordingly, the channel bandwidth assigned to a utility should be commensurate with the peak data rate anticipated by that utility. This requirement presents no problem provided the earth station equipment (presumably manufactured to a common set of specifications) is designed to operate over a range of data rates.

There are practical upper and lower limits to the data rate. (Existence of the former will become evident in Section VIII-C.) It might be necessary, therefore, for a supervisory authority to coordinate the transmissions of different utilities over a common channel, in the case of utilities with low data rates. On the other hand, the transmissions of a utility with a relatively high data rate might have to be subdivided among two or more channels. Coordination of transmission taking place on different channels in the same transponder, from the standpoint of frequency and bandwidth assignment, is the responsibility of the common carrier operating the satellite.

A node such as a DDC, which is intermediate in the control system hierarchy, would be assigned to one channel in its capacity as a controlling station, and to another in its capacity as a controlled station. The two channels could be either paired to form a single (full-duplex) circuit or assigned to separate circuits, depending on the similarity of the link parameters in the two cases and the manner in which the utility chooses to configure its control network.

B.   TIME-DIVISION MULTIPLE-ACCESS FORMAT

The discussion thus far has centered on the way in which network nodes are assigned to transponder channels; it has not touched on the ordering of transmissions within a given channel. The need to monitor data points at regular intervals is satisfied by the choice of TDMA as a means of sharing the

channel bandwidth. In the polling direction, each master station is assigned
a time slot within the TDMA frame (Figure 7-1). In the response direction, a
similar interval is assigned to the associated remote stations.

As an example, the frame period for bulk-power-system control is taken
as 2 s, which is the shortest update interval required for any of the
monitored points. Within its assigned time slot, a bulk-power-system master
station polls each RTU under its control, indicating which points it wants
read out. (In a centralized control system, there is a single master station,
namely, the ECC.) This set of points includes all analog values and control
indicators requiring 2-s sampling, as well as a certain fraction of the points
sampled at longer intervals. For example, those points requiring 10-s
sampling are divided into five groups of equal size, which are polled
sequentially. Thus, a given group is polled every fifth frame, or at 10-s
intervals. The sets of points to be sampled in different frames are numeri-
cally coded so that they can be represented by a reasonable number of bits in
the poll message.

In the illustrative poll/response message sequence in Figure 7-1, the
RTU responses are generally longer than the poll messages, which are identical
in length. Because it is assumed that each response is triggered by the as-
sociated poll message, the poll messages must be delayed by varying amounts to
avoid having the responses overlap. These delays are indicated by the cross-
hatched areas. During these intervals the master station transmits a pre-
arranged sequence to maintain burst continuity.

The time slot assigned to each master station and its associated remote
stations must be long enough to accommodate either the normal complement of
sampled points or the monitor and control actions that might be required
during nonstandard or emergency conditions. For a given frame period, there
is clearly an intimate relationship among the maximum number of master/remote
station groups that can be accommodated on a single channel, the number of
bits required in the poll and response directions per station group, and the
channel bandwidth. Barring practical considerations that dictate otherwise
(see Section VIII-C), the channel bandwidth should be chosen large enough to
accommodate, for a significant future period, all master/remote station groups
that are on a similar level in the control system hierarchy. In this way, the
need for frequent channel reassignment can be avoided.

C.   SLOT ASSIGNMENT AND TIMING CONSIDERATIONS

Coordination of slot timing for the master/remote station groups sharing
a particular channel pair is the responsibility of a designated control
station (DCS). This station might be identical to one of the master stations
using the channel, or it could be a station at a higher level in the
control-system hierarchy. If all of a utility's satellite communications are
being conducted over the channel pair, the ECC would be a logical choice for
the DCS. If the DCS is not one of the master stations assigned to the polling
channel, a special time slot would be reserved for its use.

7-3
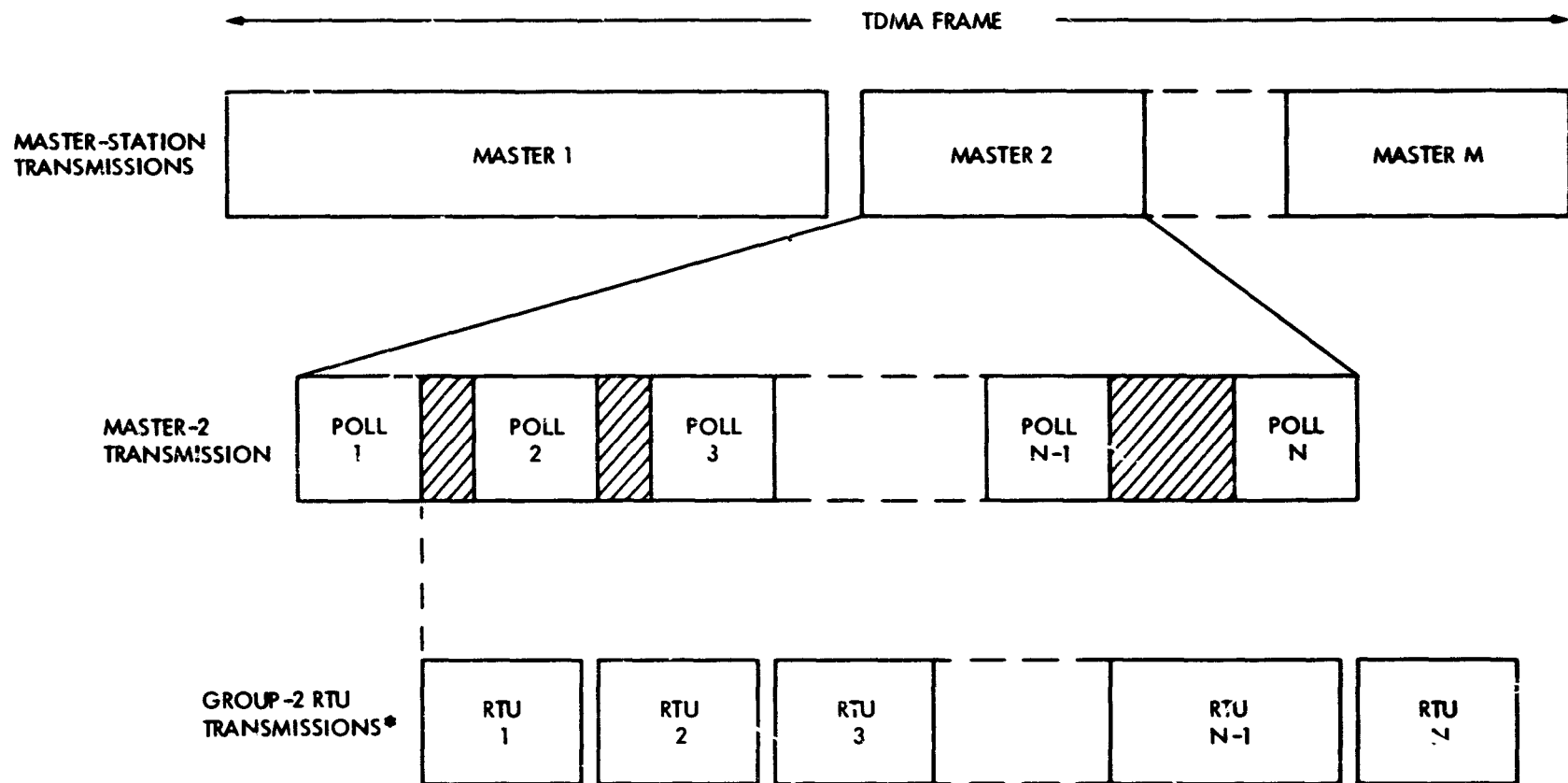
*PROPAGATION AND TURNAROUND TIMES ARE NOT SHOWN

Figure 7-1. Time-Division Multiple-Access Frame Format

Initial assignment of time slots by the DCS is based on current needs of the various master/remote station groups. The unused portion of the frame can either be held in reserve as a single undivided time slot, or it can be subdivided into extensions of the time slots assigned to different station groups. In either case, as the data-rate requirements of the station groups increase over time, reassignment of the time slots will become necessary, until eventually the capacity of the channel pair is exhausted.

When additional channel capacity (i.e., a longer time slot) is required by a station group, the master station makes an appropriate request of the DCS. This request is made during a portion of the polling time slot reserved for administrative purposes. In granting such a request, the DCS has to shift the time slots assigned to other master/remote station groups so that they remain nonoverlapping. After the new slot assignments have been transmitted by the DCS and acknowledged by the master stations, an execute command by the DCS designates the frame in which the new assignments are to become effective.

The timing information transmitted by the DCS indicates to each master station the position of its time slot relative to the start of the TDMA frame. Absolute frame timing must be acquired directly from the signal transmitted by the DCS, rather than from the binary-encoded information it represents. By assigning the DCS the first time slot of each frame, the DCS transmission can serve as a timing reference for all subsequent master-station transmissions.

There are various ways to initially position a master-station "burst" in the TDMA frame, in accordance with an assigned time slot. Once this positioning is accomplished, the burst position must be maintained to a specified level of precision. These two processes, termed acquisition and synchronization (Reference 20), can be performed in a closed-loop manner if each master station is in a position to receive its own transmissions. It is only necessary, in this situation, for a station to compare the time of reception of its own burst with that of the reference burst, and then make any necessary correction.

The requirement that a master station be capable of receiving its own transmissions will automatically be satisfied if a single satellite beam covers the region of interest. The requirement will also be satisfied, for a multibeam satellite, under the condition that master-station transmissions over a particular transponder channel are received on the same satellite beam used to repeat the transmissions to the associated remote stations.

Closed-loop burst positioning implies a fairly complex control process. However, the relatively long frame period of 2 s permits open-loop frame acquisition and synchronization to be performed with little loss of frame efficiency. In this procedure, a master station uses knowledge of the distance to the satellite to appropriately position its transmissions relative to the received reference bursts from the DCS. In so doing, it is normally necessary to account for the variaton in propagation time due to satellite motion. However, because of the long frame period, timing of master-station transmissions can be based on the mean satellite distance without necessitating excessively long guard times between bursts.

To understand the justification for this procedure, consider the
variation in round-trip propagation time anticipated for Intelsat V, which is
1.1 ms (see Reference 20). If half this much extra guard time is allowed
between the reference burst and both the immediately following burst and the
immediately preceding burst (i.e., the last burst of the preceding frame), no
overlap with the reference burst will occur as a result of satellite motion.
The extra guard time needed between all other pairs of bursts is much smaller,
because only the difference in departure from the mean satellite distance
between stations is significant. For example, if there are 20 master stations
per channel and the extra guard time per station pair is taken as 0.1 ms, the
total extra guard time required per frame is about 3 ms, or 0.15% of the
bulk-power-system frame period.

There will generally be many more remote stations sharing the response
channel than master stations sharing the poll channel. Each remote-station
burst must also be guaranteed not to overlap either of the adjacent trans-
missions. The absence of overlaps is readily achieved if each response from a
remote station is triggered by the associated poll message. The required guard
time between adjacent bursts triggered by the same master station is then
related to the instantaneous difference in distance from the corresponding
remote stations to the satellite. This differential distance will be quite
small, especially if the stations involved are in relatively close proximity.
This will normally be the case for remote stations controlled by the same
master station.

D.   HALF-DUPLEX OPERATION

It will be assumed that the remote-station responses in a half-duplex
transmission system are triggered by the corresponding poll messages, as in
the full-duplex mode. An associated poll/response message pair will therefore
arrive at the satellite separated by about 270 ms. As a result, efficient use
of a satellite channel requires that the poll and response transmissions
assume the general time pattern depicted in Figure 7-2. For a transmission
rate of 10 kb/s, for example, each contiguous set of poll or response messages
comprises about 2700 bits.

The need to alternate poll and response segments in this manner results
in a fragmentation of the basic frame structure. In general, it is necessary
either to leave unused a portion of each poll segment (and, consequently, the
corresponding response segment) or to divide the transmission of a master
station (and those of the associated remote stations) between the end of one
segment and the beginning of the following segment. The latter alternative is
depicted in Figure 7-2. Although half-duplex operation does simplify the
earth-station design somewhat, on balance, it does not seem worthwhile to
incur the associated operational complexity. An opposite conclusion could be
reached, however, should it be necessary to make the satellite transmission
compatible with an alternate means of communication. (see Section VI-B-1).
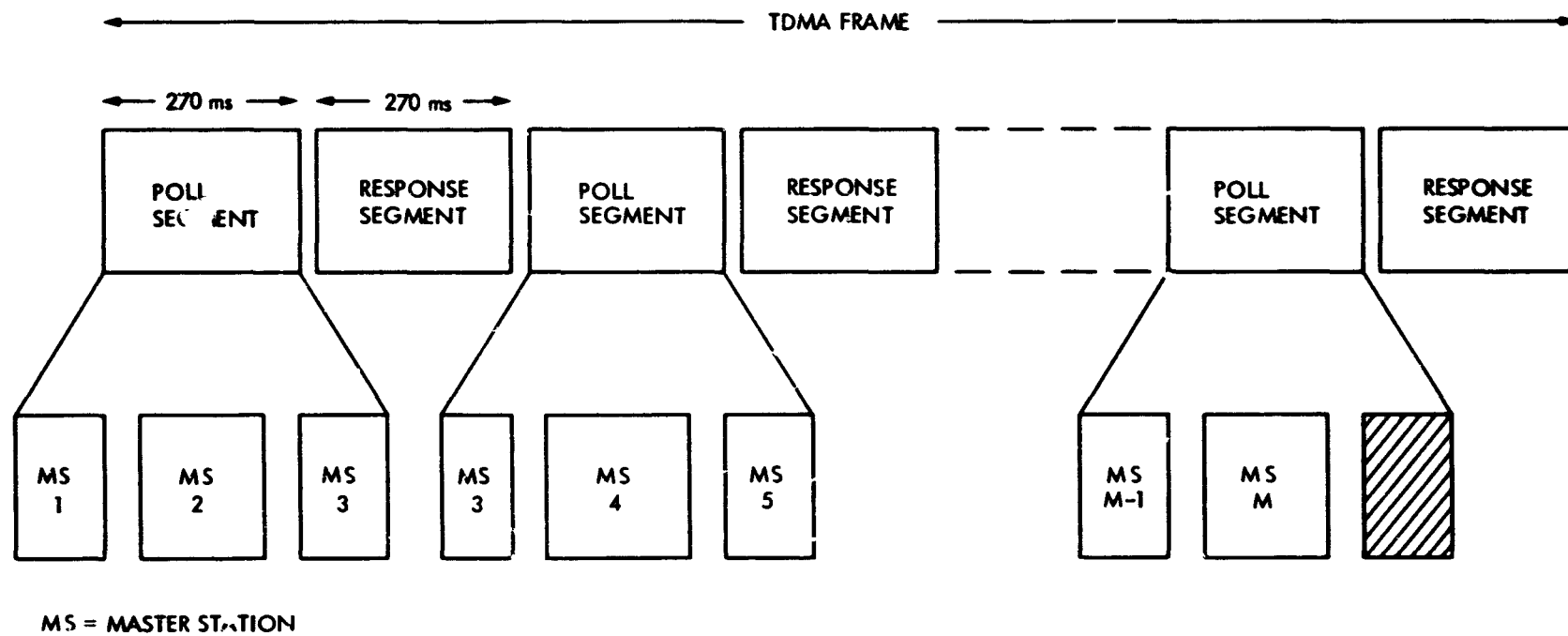
Figure 7-2. Half-Duplex Time-Division Multiple-Access Format

SECTION VIII

USE OF CURRENT C-BAND SATELLITES

General considerations relative to the use of current C-band satellites are discussed and link budgets for up and down directions are presented. A 3-m earth-station antenna, not presently approved by the FCC, and the Westar I satellite were used to develop the budgets. While the uplink performance with a 1-W HPA is more than adequate; a 3.7-dB short fall occurs on the downlink. An approach suggested to overcome this deficit requires an increase in transmitter power to about 5 W. Interference with other satellites, using the above noted system assumptions, seems to be manageable with proper coordination, even if satellite orbital spacing is reduced in the future to 3 deg. Bulk-power-system communications using the currently approved 4.5-m antennas present a lesser interference problem. Representative earth-station cost estimates are then developed. The estimate for a fully redundant, 4.5-m station for bulk-power system applications is $74K. The estimate for a non-redundant, 3-m station for the distribution system is $32K.

It is possible to satisfy all bulk-power-system and some distribution-system communication requirements using existing C-band satellites, together with modestly sized earth stations. Earth stations are often characterized by their "figure of merit" or G/T. In recent years, C-band solid-state receiver technology has improved to the point where the "T" in the figure of merit is within 2 dB of the performance attainable with uncooled parametric amplifiers. Costs of solid-state receivers have also fallen dramatically. It is more appropriate, therefore, to focus attention on the earth-station antenna size since, apart from its effect on system performance, space limitations may dictate the maximum antenna size that can be employed in many utility-company applications.

An antenna diameter of 4.5 m will be assumed for all bulk-power-system applications. This diameter is a standard size frequently used with current C-band satellites. Moreover, in size as well as cost, a 4.5-m antenna is compatible with installation at a generation plant, BPS, or switching station. Because of the relatively modest EIRP (34 dBW/transponder at saturation) currently available from C-band satellites providing CONUS coverage, some form of coding for error correction must be employed to provide digital communications of adequate quality. Simply stated, coding provides a means of exhanging an increase in bandwidth for a reduction in required signal power.

The antenna size is likely to be far more restricted in distribution-system applications than it is in the bulk-power system. A 3-m antenna has been selected for distribution-system use, largely because it is felt that this size will be compatible with most DSG and distribution-substation installations. A 3-m antenna requirement would undoubtedly preclude the use of satellites at many other distribution-system sites. It should be recognized, however, that FCC approval has not yet been granted for C-band transmission with antennas smaller in diameter than 4.5 m. Moreover, the tendency to reduce satellite orbital spacing to maximize the communication capacity of the

geostationary arc will make approval of 3-m communications more difficult in the future. For these reasons, it is felt that a 3-m antenna represents a good compromise between physical size and the requirement for regulatory approval.

The satellite downlink with a 3-m antenna suffers from a severe power shortage. This shortage can be partially overcome through the use of error-correcting codes. The remaining power shortfall can be made up by reducing the occupied bandwidth of the transponder and, in the process, assigning each carrier an increased share of the transponder EIRP. However, a second problem may be created, namely, the need for a relatively large power amplifier to produce the required uplink EIRP. These related problems can be understood through an examination of uplink and downlink power budgets for a typical communication link.

A.   DOWNLINK CONSIDERATIONS

The link budget of Table 8-1 is based on the parameters of a CONUS-coverage satellite, in the form of Westar I. The transponder is assumed to be filled with equal-power, uniformly spaced carriers, each with a noise band-width of 10 kHz. This bandwidth is merely representative; the data rate, and consequently the carrier bandwidth, will subsequently be treated as a para-meter of the system design. Should there be a mix of carriers sharing the transponder, relating to different applications, the assumption is that each utility carrier would be assigned the same fractional transponder power as in the uniform-carrier case of Table 8-1; and furthermore, that the frequencies of the other carriers and the power assigned to them would leave the intermod-ulation power falling on the utility carriers unchanged.

The system carrier-to-noise ratio (C/N) requirements are based on the use of binary phase-shift-keyed (PSK) modulation. The energy per bit/noise power density (E_b/N_o) requirement, together with conversion to an equiva-lent C/N value, is explained in Note 6 to Table 8-1.

To overcome the downlink power shortage, rate 1/2 convolutional coding, coupled with threshold decoding, has been introduced. This results in a 3-dB reduction in the E_b/N_o requirement at a bit error rate (BER) of 10^{-6}.[6] There remains, however, a 3.7-dB deficit in the thermal component of C/N for a 3-m station, as can be seen from the bottom line of Table 8-1. There is essentially zero thermal margin (i.e., just adequate signal power) in the case of a 4.5-meter earth station.

In both cases, the portion of the transponder EIRP allocated to each carrier is equal to the fractional transponder bandwidth occupied (10 kHz/30 MHz). The $(C/N)_{thermal}$ deficit of 3.7 dB in the case of a 3-m antenna may be regarded as a power shortfall on either the uplink or the downlink, because n

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[6]An additional 2-dB reduction in required E_b/N_o could be realized through adoption of soft-decision Viterbi decoding; however, the simpler implementa-tion has been selected because of the desire to minimize earth-station costs, especially in the 3-m case.

Table 8-1. Representative (4 GHz) Downlink for Westar Satellite

	Notes	Antenna Diameter	
		3 m	4.5 m
(1)	Satellite EIRP (dBW)	34.0	
(2)	Transponder backoff (dB)	-4.0	
(3)	Multicarrier power division (dB)	-34.8	____
	EIRP/carrier (dBW)	-4.8	-4.8
	Space loss (dB)	-196.0	-196.0
	Receive antenna gain (dB)	39.7	43.2
	Received carrier power (dBW)	-161.1	-157.6
(4)	Receive-system noise temperature (dB-K)	21.8	21.8
	Boltzmann's constant $(dB(WK^{-1}Hz^{-1}))$	-228.6	-228.6
	Noise bandwidth (dB-Hz)	40.0	40.0
	Received noise power (dBW)	-166.8	-166.8
	Downlink C/N (dB)	5.7	9.2
(5)	Uplink C/N (dB)	22.4	22.4
	$(C/N)_{thermal}$ achieved (dB)	5.6	9.0
(6)	System C/N required	8.0	8.0
(7)	C/IM (dB)	14.0	14.0
(8)	$(C/N)_{thermal}$ required (dB)	9.3	9.3
	$(C/N)_{thermal}$ achieved (dB)	5.6	9.0
	$(C/N)_{thermal}$ deficit (dB)	3.7	0.3

(1) Minimum EIRP over CONUS for single-carrier, saturated-transponder operation.

(2) Decrease in total carrier power with multicarrier operation, resulting from the need to "back off" the transponder to limit the magnitude of intermodulation products.

(3) Based on a single-carrier noise bandwidth of 10 kHz, a useful transponder bandwidth (for multicarrier operation) of 30 MHz, and a uniform power division per unit bandwidth.

(4) Assumes the use of a solid-state low-noise amplifier with a noise temperature of 120 K.

(5) Taken from Table 8-2.

(6) A post-decoding BER of 10^{-6} has been selected for the control-system communication links. With a message length typically in the range of 100-300 bits, a fraction of the messages somewhat in excess of 10^{-4} will contain residual errors. (These errors are detected by a BCH code incorporated in the standard message format.)

The theoretical E_b/N_o requirement to achieve a BER of 10^{-6}, in the absence of coding, is 10.5 dB. An implementation margin of 2.5 dB will be assumed, thereby making the required E_b/N_o equal to 13.0 dB. A coding gain (i.e., reduction in required E_b/N_o) of 3 dB results from the use of a rate 1/2 convolutional code in combination with threshold decoding (Reference 23). This reduces the E_b/N_o requirement to 10.0 dB.

The predetection bandwidth is taken as 1.25 times the transmitted symbol rate. In addition, the transmitted symbol rate is twice the data rate for rate 1/2 coding. Consequently, the C/N requirement corresponding to an E_b/N_o of 10 dB is 6 dB. To this is added a system margin of 2 dB, which also serves as protection against outside interference, either from other satellite systems or from terrestrial microwave transmissions. The design value for the system C/N is therefore 8 dB.

(7) This is the carrier-to-intermodulation power ratio at the center of a transponder loaded with equal-power, uniformly spaced carriers, operating at an output backoff of 4 dB.

(8) Obtained from the relation

$$\left[\text{System C/N}\right]^{-1} = \left[\text{C/IM}\right]^{-1} + \left[(\text{C/N})_{thermal}\right]^{-1}$$

increase in the allocated EIRP per carrier will lead to an improvement in up-link and downlink C/N values by the same factor.

While certain entries in Table 8-1 (space loss and antenna gain) depend on frequency, the received signal power is completely determined once the satellite EIRP and the earth-station antenna diameter are specified. In other words, the frequency factors in the space-loss and receive-antenna-gain terms are exactly offsetting. It is possible, therefore, to derive a condition, based on the entries in Table 8-1, that must be satisfied if the downlink signal quality is to be adequate and which is valid for any downlink frequency.

Attention is focused on the signal power and noise power in the frequency band occupied by an individual carrier. However, only the factors regarded as variables are included. This approach leads to the following relationship:

$$EIRP + d^2 - T - B + CG + BWX \geq -47.4 + L \qquad (1)$$

where

EIRP = satellite EIRP per carrier (dBW)

d^2 = square of earth-station antenna diameter (dB-m^2)

T = earth-station receive-system noise temperature (dB-K)

B = carrier noise bandwidth (dB-Hz)

CG = coding gain (dB)

BWX = bandwidth expansion factor due to coding (dB)

L = other propagation factors (i.e., rain attenuation plus excess receive-system noise temperature, polarization loss, multipath fading, etc.) (dB)

The right-hand side of the above equation was obtained by substituting the Table 8-1 values for the left-hand-side quantities, adding the indicate $(C/N)_{thermal}$ deficit, and making provision for any non-free-space propagation effects.

It is apparent from Equation (1) that, if the earth-station parameters (d and T) and the coding parameters are fixed, the only possibility for improving the link performance is to increase the EIRP per unit bandwidth. For a given satellite, this increase can be accomplished by loading the transponder with fewer carriers and assigning each carrier a correspondingly larger share of the transponder EIRP. For example, to make up the 3.7-dB downlink deficit with a 3-m antenna, it is necessary to allocate 3.7 dB additional EIRP to each carrier, relative to the value that would be assigned based on a uniform distribution of EIRP with bandwidth. Increasing the EIRP per carrier in this manner results in a larger earth-station transmitter

requirement. This aspect of the system design will be considered once the transmitter requirements correspond ug to the carrier sizing in Table 8-1 have been established.

B.   UPLINK CONSIDERATIONS

An uplink power budget which is consistent with the downlink power budget of Table 8-1 is shown in Table 8-2. In this case, the received carrier power is a given quantity (see Note 1), with the required transmitter power a derived quantity. As pointed out in Note 3, the HPA rating should be about 3 dB higher than the indicated transmitter power in Table 8-2. With a 3-m antenna, therefore, a 1-W amplifier is more than adequate to provide the indicated carrier power at the transponder input. As has been seen from Table 8-1, however, the corresponding output power is insufficient (by 3.7 dB) to provide the required downlink signal quality.

It is desirable to develop a general relationship that must be satisfied by the uplink power variables, as was done previously for the downlink variables. In this case, attention will be focused on carrier power directly, rather than on received signal quality (C/N). The reason for this focus is that a certain level of carrier power must be realized at the satellite antenna terminals, relative to the power required to saturate the transponder, to produce the desired downlink EIRP. It may be assumed that the satellite designer will have chosen the input saturation level, in conjunction with the receiver noise figure, to provide adequate uplink signal quality for any reasonable application.

As before, only the quantities regarded as variables are considered. Accordingly, the following condition can be placed on the earth-terminal and satellite-repeater parameters:

$$P_T + d^2 + G_R - P_S - B \geq 87.7 + L \tag{2}$$

where

P_T = earth-station transmitter power (dBW)

d^2 = square of earth-station antenna diameter (dB-m^2)

G_R = minimum satellite receive antenna gain (dB)

P_S = transponder input saturation power (dBW)

B = carrier noise bandwidth (dB-Hz)

L = non-free-space propagation losses (dB)

The right-hand side of Equation (2) was obtained through substitution of values from Table 8-2, addition of the indicated $(C/N)_{thermal}$ deficit, and

Table 8-2. Representative (6 GHz) Uplink for Westar Satellite

Notes	Antenna Diameter	
	3 m	4.5 m
(1) Earth-station transmitter power (dBW)	-4.5	-8.0
Transmit antenna gain (dB)	43.2	46.7
EIRP (dBW)	38.7	38.7
Space loss (dB)	199.5	
(2) Receive antenna gain (dB)	27.0	
(3) Received carrier power (dBW)	-133.8	
(4) Receive-system noise temperature (dB-K)	32.4	
Boltzmann's constant $(dB(WK^{-1}Hz^{-1}))$	-228.6	
Noise bandwidth (dB-Hz)	40.0	
Received noise power (dBW)	-156.2	
Uplink (C/N)	22.4	

Notes for Table 8-2

(1) The HPA rating should be about 3 dB greater to allow for backed-off operation. (The HPA is assumed to be mounted at the antenna termi-nals, so that no transmission-line losses need be incurred.)

(2) Minimum value for CONUS coverage.

(3) Corresponds to a transponder input backoff of 7 dB (which is required to produce an output backoff of 4 dB, for multicarrier operation of a typical TWT amplifier) and division of the corresponding receiver input power (-99 dBW) into uniform 10-kHz increments.

(4) This noise temperature is characteristic of early, but still operational, Westar satellites. The receiver on Westar IV, cur-rently in production, has a noise-figure specification which is 4 dB lower. Consequently, the same uplink C/N value (22.4 dB) can be achieved with 4-dB lower carrier power. However, because the transponder input saturation level has been reduced by only 2 dB, the decrease in uplink carrier power must be limited to a similar amount, if no degradation in downlink C/N is to result.

C-2

inclusion of a term for additional propagation losses. For P_g, the Westar I value of -92 dBW has been used. Although a CONUS-coverage beam will always have a minimum gain of about 27 dB, inclusion of the G_R term allows for higher gains achieved through the use of spot beams. For Equation (2) t· be valid at any frequency, the earth-station antenna must be represented by a term proportional to its area, rather than by its gain.

Current satellites use traveling-wave-tube (TWT) final amplifiers, all of which have similar transfer characteristics (i.e., output versus input backoff), regardless of the saturation output power level. Therefore, Equations (1) and (2), which are based on corresponding values of input and output backoff (7 dB and 4 dB, respectively) for multicarrier operation, constitute a consistent pair of conditions for any TWT final amplifier. The numerical values in these equations will vary somewhat if system consider-ations dictate a different operating point. In addition, the transfer charac-teristics of the transponder will be somewhat different, should solid-state amplifiers replace the TWT amplifiers presently in use. Despite these qualifications, Equations (1) and (2) provide a reliable rough guide to the satellite and earth-station parameter values required to establish communications of satisfactory quality.

C.   CHANNEL DATA RATE

It is appropriate at this point to consider the question of assigning each carrier a disproportionate share of transponder EIRP relative to the fractional bandwidth it occupies. With the satellite parameters previously assumed, this assignment is the only means of overcoming the $(C/N)_{thermal}$ deficit exhibited in Table 8-1 for a 3-m earth station. Although the choice of a 10-kHz carrier noise bandwidth was arbitrary, the $(C/N)_{thermal}$ deficit would be the same for any other bandwidth.

The required uplink transmitter power, on the other hand, is directly proportional to the carrier noise bandwidth, as well as to the downlink EIRP per unit bandwidth. There will generally be an upper limit placed on the transmitter power by either technology or cost considerations. It may be necessary, therefore, to reduce the carrier noise bandwidth, through a reduc-tion in data rate, as the downlink EIRP per unit bandwidth is increased.

The power rating of an HPA just capable of making up the $(C/N)_{thermal}$ deficit of 3.7 dB is shown in Figure 8-1 as a function of the channel data rate. For this purpose, the data rate has been taken as 0.4 times the carrier noise bandwidth (see Note 6 to Table 8-1). In addition to the nominal trans-ponder input saturation power of -92 dBW used in Table 8-2, two lower values are considered in Figure 8-1. Because of recently improved satellite receiver noise figures, the input saturation level on soon-to-be-launched satellites can be reduced without sacrificing uplink signal quality (see Note 4 to Table 8-2). It should also be recognized that the satellite receive antenna gain listed in Table 8-2 is a minimum value over CONUS. Where the gain is actually higher, a corresponding reduction in transmitter power is possible.
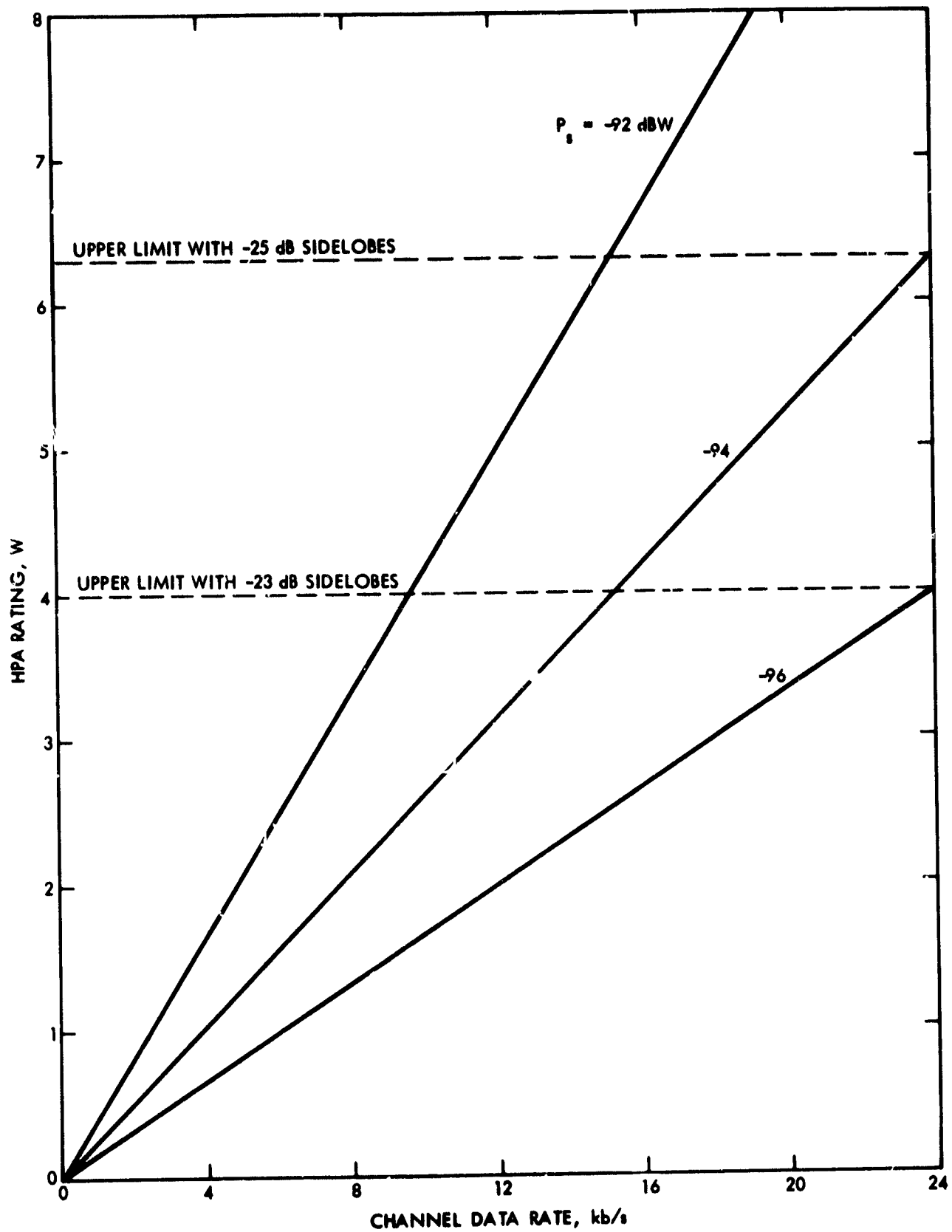
Figure 8-1. Earth-Station Transmitter Requirements with 3-m Antenna

In computing the power requirements illustrated in Figure 8-1, no improvement in the C/IM ratio was assumed as a result of the increased power per carrier. Because the power in each carrier must be increased by 3.7 dB to make up the $(C/N)_{thermal}$ deficit of like amount, there is only enough power per transponder to support 43% of the number of carriers permitted by the transponder bandwidth. If these carriers are uniformly spaced in frequency, the C/IM ratio will in fact be unchanged. On the other hand, if the frequencies to be occupied are selected in a random manner, the C/IM ratios for the occupied frequency slots will typically be reduced by 3.7 dB. This C/IM reduction may be treated as an additional margin to guard against a situation in which dissimilar carriers, occupying the same transponder and representing other services, generate larger-than-anticipated intermodulation products.

Presently, manufacturers of solid-state amplifiers at 6 GHz are producing units rated from a couple of watts up to (in one or two cases) 10 W. A 5-W rating will be taken as representative of amplifiers that will be readily available in the next few years, at prices that will not significantly impact the cost of a 3-m earth station. From Figure 8-1 it is seen that, with current operational satellites (P_S = -92 dBW), a 5-W amplifier is consistent with a channel data rate of 12 kb/s. With Westar IV, on the other hand, which will have an input saturation level of -94 dBW, a data rate of 19 kb/s could be supported. The latter figure is essentially equal to the 20-kb/s composite DSG polling rate projected for a large utility in the year 2000.

D.   INTERFERENCE WITH OTHER SATELLITE SYSTEMS

Interference may be injected into other satellite systems on either the uplink or the downlink. There is the potential for excessive uplink interference because of the small (3-m) antennas suggested for distribution-system use. Antenna sidelobe gain tends to be invariant to the antenna diameter. For example, the CCIR recommended sidelobe pattern, $32 - 25 \log \theta$, is independent of antenna size for antenna diameters greater than D/λ = 100. To satisfy a fixed on-axis EIRP requirement, the transmitter power must be increased as the diameter, and hence the on-axis gain, is decreased. The EIRP in a particular off-axis direction, therefore, must increase as the antenna size is reduced.

Use of a 3-m antenna with a Westar satellite would require that a coordination procedure be initiated with the operators of satellite systems that could be adversely affected. This procedure is necessary because the original Western Union filing with the FCC did not provide for transmission with antennas of this size. Failure to reach agreement on a set of operating conditions satisfactory to all parties would, in all likelihood, preclude FCC approval for the proposed satellite links.[7]

In evaluating a new application, the FCC is likely to consider a proposed CCIR Recommendation setting limits on the permissible values of uplink EIRP (Reference 22). According to the proposed Recommendation, earth stations transmitting at 6 GHz shall be limited in their emissions as follows:

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[7]Private communication with R.G. Gould, Telecommunications Systems, Inc.

Angle Off-Axis	Maximum EIRP
$2.5 \deg \geq \theta \quad 48 \deg$	$(35 - 25 \log\theta)$ dBW/4 kHz
$48 \deg \geq \theta \quad 180 \deg$	-7 dBW/4 kHz

Attention will be focused on the closest pair of satellites, for a minimum
satellite spacing of 3 deg along the geostationary arc. The maximum permis-
sible EIRP in any 4-kHz band, in the direction of such an adjacent satellite,
is 23 dBW.

The on-axis gain of a 3-m antenna at 6 GHz is 43 dB. Let $G_r(\alpha)$ represent
the antenna gain in dB, relative to the on-axis gain, in a direction α deg
off-axis. In addition, let P_T be the transmitter power in dBW. The
condition to be satisfied is then

$$43 + G_r(3) + P_T \leq 23 \tag{3}$$

Note that P_T is the total transmitter power, rather than the power per 4 kHz.
The reason is that, regardless of the data rate, and thus the occupied band-
width, the carrier-acquisition portion of the preamble is assumed to be trans-
mitted as an unmodulated carrier. During this interval, therefore, the full
transmitter power is concentrated in an extremely narrow band.

In Figure 8-1, the HPA rating corresponding to the maximum permissible
transmitter power is indicated for relative sidelobe gains of -23 dB and
-25 dB. The latter value permits use of an HPA rated at 6.3 W, corresponding
to a data rate of 15.2 kb/s, with $P_S = -92$ dBW. In a study of a large
number of existing small antennas (Reference 23), Janky et al., found that the
off-axis gain was upper-bounded in nearly all cases by the expression,
$6 + 30 \log(\theta/\theta_0)$ dB, where is the off-axis angle and θ_0 is the half-power
beamwidth. The half-power beamwidth of a 3-m antenna at 6 GHz is 1.2 deg. At
an angle of 3 deg off-axis, therefore, virtually any commercially available
3-m antenna will have a gain of at most 18 dB. This gain is equivalent to a
relative gain of -25 dB, because the on-axis gain at 6 GHz is 43 dB.

On the other hand, some of the antennas examined had sidelobe gains as
much as 10 dB below that given by the upper-bound expression. It is not
possible, from the data presented, to associate specific antennas with quoted
performance levels. However, "no correlation was found between sidelobe
performance and antenna cost on the one hand or between sidelobe performance
and antenna size (in wavelengths) on the other" (see Reference 23).

In general, no attempt was made at sidelobe suppression in the design of
the antennas examined. A reduction in sidelobe level can be achieved by
increasing the taper of the feed pattern across the aperture of the reflector.
Specific sidelobe-reduction results using the tapered-illumination technique
are cited by Yokoi, et al (Reference 24). The measured radiation pattern of
an offset-Gregorian antenna was found to have a sidelobe envelope bounded by
the expression, $32 - 40 \log \theta$ dB. In particular, the peak of the second side-

lobe, which corresponds to a direction 3 deg off-axis for a 3-m antenna at
6 GHz, was 34 dB below the on-axis gain. Similar performance is reported for
an offset-Cassegrain antenna.

It is evident from the preceding discussion that -25 dB, and perhaps
several dB lower, sidelobe performance (for the second sidelobe) is routinely
attainable. Relative gains below -30 dB, although attainable, generally
require some form of sidelobe suppression. These lower gains should not be
necessary for the present application, because a relative gain of -25 dB
permits the use of an HPA rated at 6.3 W, according to the proposed CCIR
Recommendation.

The adequacy of the interference criterion set forth by this proposed
Recommendation can be assessed as follows. The earth-station EIRP needed to
saturate a current C-band transponder is about 84 dBW. If the maximum level
of interference, stated for a 4-kHz band, were maintained across the full
transponder bandwidth of 30 MHz, the carrier-to-interference ratio (C/I) at
saturation would be $84 - 23 - 10 \log (30 \times 10^6/4 \times 10^3) = 22.2$ dB. (Iden-
tical satellite antenna gain in the directions of desired and interfering
earth stations has been assumed.) An equal amount of interference could, in
principle, be received from the other adjacent satellite, thereby reducing C/I
to 19.2 dB. If, in addition, the interfered-with transponder is operated in a
multicarrier, backed-off fashion, C/I would be lower by an amount corresponding
to the input backoff. Clearly, the proposed Recommendation does not provide
adequate protection from adjacent-satellite-system interference under an
arbitrarily chosen set of operating conditions.

The permissible level of interference (per 4 kHz) in a specific situation
depends on the total power and spectral characteristics of the signals involved.
Certainly, one or several narrowband carriers will not interfere significantly
with a wideband TV or FDM/FM telephony carrier, provided the remaining carriers
in the interfering transponder present a considerably lower interference pro-
file. On the other hand, single-channel-per-carrier (SCPC) transmissions in
an adjacent satellite would be especially vulnerable to interference of the
type described, because of their narrow bandwidth.

The variable effect of interference from a set of narrowband utility
carriers demonstrates the need for coordination with the administration of
adjacent satellite systems. Although the proposed CCIR Recommendation has
been used as a guide in determining permissible levels of interference, as
much margin as possible should be built into this aspect of the system design.

As an illustration of the significance of carrier bandwidth on potential
interference into an adjacent satellite system, American Satellite Corporation
(ASC) is planning to petition the FCC in early 1981 to permit duplex trans-
mission with Westar satellites using 3-m earth-station antennas. With the
present 4 deg-spacing of C-band satellites, ASC will request permission to
transmit at data rates up to 56 kb/s. If the minimum satellite spacing is
reduced (by the FCC) to 3 deg, a lower maximum data rate will be requested.[8]
The plans of ASC reinforce the idea that 3-m earth stations can be combined

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[8]Private communication with ASC.

with current C-band satellites for distribution-system communications, especially if the channel data rate is restricted to 20 kb/s.

Bulk-power-system communications with 4.5-m antennas presents a lesser interference problem, because the additional 3.5 dB of on-axis gain reduces by a similar amount the transmitter power needed to produce a specified on-axis EIRP. The reduced transmitter power results in a smaller off-axis EIRP.

E. EARTH-STATION PRICES

Two different earth-station antenna sizes have been suggested for operation with C-band satellites: 4.5 m for bulk-power-system operations and 3 m for distribution-system applications (including DSGs). Because of the extreme reliability required in the bulk-power system, complete redundancy (with the exception of the antenna) is assumed for the 4.5-meter stations. The 3-m stations, on the other hand, can be made nonredundant.

Component prices for an operational station of each type are given in Table 8-3. These should be regarded as elements of the price that would be paid to an earth-station integrator, rather than prices of component manu-

Table 8-3. Earth-Station Price Estimates ($K)

Component	Antenna Diameter		
	4.5 m		3 m
	Single Unit	Per Station	
Antenna subsystem	7.0	7.0	3.0
Low-noise receiver	1.5	3.0	1.5
HPA and power supply	3.5	7.0	3.5
Up/down converter	9.0	18.0	9.0
Baseband equipment	12.0	24.0	12.0
Automatic redundancy		10.0	
Test and integration		5.0	3.0
Total		74.0	32.0

facturers. The $9,000 up/down converter is a recent microstrip design that is representative of devices presently used in C-band communications. Stability of oscillators incorporated in these units results in frequencies at the outputs of the up/down converter that are typically within 1 kHz of nominal values. (Frequency shifts due to instability of the satellite frequency-translation oscillator are eliminated through use of a pilot tone transmitted by the master station.)

The up/down converter is of the double-conversion type, so that operation through an alternate transponder requires only a change of crystal. This operational flexibility is essential in a bulk-power-system earth station, where the duration of any outage must be minimized. It is also highly desirable for the DSG population. Substitution of a single-conversion up/down converter would reduce the unit price from $9,000 to perhaps $5,000; however, the required retuning process for transmission through a second transponder makes this an undesirable alternative.

The cost of baseband equipment for a TDMA earth station of the type under consideration is difficult to establish with any precision. Most TDMA earth stations are designed for combined voice and data traffic, at high data rates, and consequently are quite costly. In Reference 21, Husted and Dinwiddy describe a TDMA earth-station design, for data only, that has an estimated recurring cost of $10,100 for the baseband equipment. The TDMA burst rate is 4 Mb/s, while the data rate of an individual channel is 128 kb/s. The estimated non-recurring cost to develop an engineering model and production prototype is $260,000.

Baseband equipment developed for the present application would differ in several respects from that described in Reference 23. The TDMA burst rate and the data channel (RTU data) rate in the present case would be limited to perhaps 100 kb/s and 5 kb/s, respectively, for a bulk-power-system network. On the other hand, the frame period of 2 s is 10 times larger than the value assumed in the paper. In addition, a coding/modulation combination best suited to the present application would have to be selected. Despite these differences, both the recurring and nonrecurring costs should be similar to those of the baseband equipment described in the paper. However, to account for the effects of inflation, the recurring baseband-equipment cost will be taken as $12,000.

The $10,000 allocated to equipment that automatically switches over to a redundant unit in the event of a component failure is little more than an educated guess at this point. A form of "chain" redundancy is assumed whereby no attempt is made to identify the failed component by electronic means; instead, a redundant chain of components, from baseband to RF, is substituted for the chain originally in use whenever a failure is detected.

The need for automatic-switchover capability is a subjective matter. At a manned generation plant, with the earth station assumed to be close by, a failure can be rectified in minutes by manually switching to the redundant component. During this brief period, the alternate communication mode would be employed. In the case of an unmanned BPS or switching station, reliance on the alternate communication mode would be required for a longer period of time.

The price of a fully redundant 4.5-m earth station with automatic-switchover capability is estimated at $74,000; that of a nonredundant 3.5-m station, at $32,000. These prices are based on recurring costs only. However, if satellite transmission should be widely adopted for bulk-power-system and DSG control, a sufficient number of earth stations would be ordered so that nonrecurring costs would not significantly impact the earth-station price.

If it were desired to demonstrate the use of satellite transmission for control-system communications, it would be necessary to use baseband equipment that is more general-purpose in nature than would be the case for equipment developed especially for the utility application. For example, Digital Communications Corporation markets a 4.5-m earth station called a DYNAC terminal with demand-assigned TDMA capability. The terminal has 42 ports (i.e., it can accommodate 42 data channels) and has considerably more diagnostic capability than would be required for the utility application. In small quantities and without redundancy, these earth stations sell for about $50,000.

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that bulk-power-system communications can be provided via satellite, at reasonable cost, using present technology. Whether used in a primary or backup capacity, satellite transmission can significantly improve the overall communication-system reliability. It is anticipated that the attractiveness of satellite links for a particular utility will depend in part on the extent to which the communications capability needs to be upgraded as the result of control-system modernization.

Because bulk-power-system satellite links would presumably provide one of two alternate communication modes between each pair of installations, the two modes would have to be made mutually compatible. For example, if the other (terrestrial) mode is already established and operates with half-duplex transmission, two possibilities exist. Either the satellite links would have to operate in the same manner, with an attendant increase in operational complexity, or a separate set of protocols would have to be established for satellite transmission. The latter choice implies a replication of certain functions and equipment that would not be necessary if a common set of protocols could be adopted.

DSG communications via satellite is also feasible using present C-band satellites, for those units large enough to warrant the estimated $32,000 expenditure for a 3-m earth station. Pending FCC approval of C-band transmission by 3-m stations, a 4.5-m antenna could be employed, at an additional cost of about $5,000, at sites where physical size is not a problem.

C-band communications would seem to provide an ideal means of control for remotely located DSGs, where the terrain renders the terrestrial alternatives infeasible, or at least unattractive. In more populous areas, the number of sites that can be coordinated with terrestrial services for C-band operation may be limited. Although K_u-band transmission would largely avoid this problem, operation in this band depends on the deployment of a satellite intended to accommodate narrowband transmission. On the other hand, the advent of a satellite payload designed for general distribution-system use could serve DSG needs as well.

The feasibility of communicating via satellite to distribution-system sites for operational- and load-management purposes hinges on two factors: the need for a new frequency allocation and the cost of earth-terminal equipment. These two factors are interrelated, as equipment prices generally increase with frequency. Because of these potential hurdles, the feasibility of using S-band frequencies deserves further examination. Specifically, the compatibility of satellite transmission with terrestrial services at S-band should be investigated.

Regardless of the frequency selected, a high-gain satellite antenna would be required to permit the use of low-cost ground equipment. There are plans to demonstrate low interference, multiple spot-beam, high-gain antenna

technology for the Land Mobile Satellite Service, but the frequency band allocated to this service is not available to the utility application. Nonetheless, there are many attractive features of this technology which seem appropriate and attractive to the projected future needs of the electric-utility industry. These include ease of wide area coverage, potentially low-cost ground terminals, network flexibility, relative independence from the power system, and high information transfer rate capability. These characteristics argue for further investigation of utilization of satellites with large antennas as an option for many electric-utility functions. If necessary, the currently available frequency allocation should be reexamined.

The cost effectiveness of a satellite network when applied to, or shared by, the electric utility industry remains to be established, but shared use seems most promising. Besides the Land Mobile Satellite Service, other potential users having similar requirements might include oil and gas distribution, production, and exploration companies, medical data exchange networks, emergency warning networks, etc.

In light of the above, the following near-term actions are recommended:

(1)   Conduct a follow-on traffic study to include mobile communications requirements of electric utilities and the special requirements of major transmission utilities such as TVA, Bonneville, or the Western Area Power Administration.

(2)   Conduct a follow-on frequency managment study to investigate interference, coordination, and assignment issues in greater depth, particularly at S-band and lower.

(3)   Forumulate a program of experimentally exploring, in partnership with a utility, the feasibility of key concepts developed in this and the follow-on studies, but using existing C-band satellites. Such a program might include, for example, the establishment of an experimental link for monitor and control of various bulk-power-system units.

(4)   Identify and survey other potential users of a "narrow band," fixed-satellite service system. Identify user requirements and develop estimates of potential communications traffic.

SECTION X

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APPENDIX A

DISPERSED STORAGE AND GENERATION DEFINITIONS[1]

Hydroelectric Pumped Storage

A bidirectional hydro plant pumps water from a lower reservoir to a higher one during periods when the utility is under light load. During heavier load periods the hydro plant generates power from the flow of water down to the lower reservoir. These flows may be combined with a net average flow for irrigation or municipal water supply. Economies of scale have favored large installations, but smaller ones (of only a few megawatts) are under active consideration, especially on the West Coast.

Solar Thermal Electric

These systems collect solar radiation to heat a working fluid to high temperatures to operate a mechanical-electrical generating system. Thermal energy storage may be included in the approach, and excess heat from the system can be used for other purposes, such as space heating. A wide range of power levels and equipment types can use this approach; however, the method is not presently fully commercialized.

Photovoltaics

Photovoltaic cells convert light energy directly into electrical energy by the stimulation of the junctions of dissimilar materials by solar photons. Low solar intensity at the earth's surface (about 1 kW/m^2) and relatively low cell efficiency (5 to 20%) combine to require extensive land areas to produce significant amounts of power. Insolation cycles and variable weather conditions further limit the amount and availability of photovoltaic power; conversion equipment is required to couple the dc output of the solar array to an ac power system. Consequently, a significant problem faced by users of photovoltaic systems is the high initial capital cost. Because considerable resources are presently being devoted to the reduction of these costs, competitive photovoltaic equipment should become available by the mid 1980s.

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[1]Taken from a preliminary version of Reference 10.

Wind

Wind generation systems employ a propeller or a wind turbine to drive an alternator either directly or through a gearbox. For utilities, these systems may consist of one or more moderate-sized units (200 kW to 3 MW). Control systems for wind generators must decouple the generator in very light winds to avoid having the propeller driven by motor action. In very heavy winds the system must again be shut down to avoid damage. Because of this, and because wind is not generally a steady resource, wind systems presently are uneconomical. However, like photovoltaics, this is a dynamic situation.

Storage Battery

Storage batteries are not truly sources of electrical power. In fact, their normal inefficiency involves a net power loss. However, the availability of power that can be rapidly controlled in combina- tion with a non-controllable power source (such as wind or solar) can provide a steadier output to the power system. Batteri. employ electro-chemically dissimilar electrodes in conjunction with an electrolyte to provide a means of con- verting electrical energy to chemical form. This stored chemical energy may be sub- sequently released as electrical energy through a suitable external circuit. For utility systems, an inverter is required to change the stored dc energy into ac power although transformation and rectifi- cation are required to charge the battery from ac lines.

Storage, in general, improves the utility load factor and thus reduces the net cost of energy by improving the use of existing equipment.

Hydroelectric

Hydroelectric plants convert the energy of naturally flowing water to electrical energy by using water turbines to drive electrical generators. Small units located on minor rivers or streams may use this source of energy to supply local needs through connection to distribution feeders.

The economies of scale are such that relatively small hydro-generators are economical. The technology is already developed.

Co-generation

Co-generation is the combined production of process heat and electricity. Industries and utilities needing both of these forms of energy can generally achieve a net reward in cost benefit by using a facility that fully uses the heat of combustion. For example, some exhaust steam from a steam turbine may be sent to nearby commercial or industrial facilities, while the remaining heat and steam is used for local space heating or manufacturing processes. Because many co-generation facilities use oil-fired gas turbines, they do not contribute toward a national goal of reduced oil imports. However, co-generation does employ a fully developed technology and is of immediate economic benefit. Co-generation must be considered in any discussion of DSG.