A Frequency-Division Multiple-Access System Concept for 30/20 GHz High-Capacity Domestic Satellite Service

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The paper summarizes a feasibility study of a multibeam frequency-division multiple-access satellite system operating in the 30/20 GHz band. The system must accommodate a very high volume of traffic within the restrictions of a 5 kW solar cell array and a 2.5 GHz bandwidth. Multibeam satellite operation reduces the dc power demand and allows reuse of the available bandwidth. Interferences among the beams are brought to acceptable levels by appropriate frequency assignments. A transponder design is presented that is greatly simplified by the application of a regional concept. System analysis shows that minimum shift keying modulation is appropriate for a high-capacity system because it conserves the frequency spectrum. Rain attenuation, a serious problem in this frequency band, is combated with sufficient power margins and with coding. Link budgets, cost analysis, and mass and power calculations are also discussed. A satellite-routed, frequency-division multiple-access system compares favorably in performance and cost with a satellite-switched, time-division multiple-access system.

Introduction

A DOMESTIC satellite system must serve major cities in the continental United States (CONUS) since most industrial, educational, and governmental establishments are located near population centers. Whether or not uniform coverage of CONUS is justifiable is a debatable issue; this work concentrates solely on providing communications service to 45 specified traffic centers in CONUS. Coverage tailored to a specific traffic situation is more efficient and desirable for servicing a large volume of traffic with limited bandwidth and power.

Traffic Model

The ground segment consists of customer premises service (CPS) terminals that give direct satellite access for local users, and trunking terminals that support high-volume multiplexed traffic. The network consists of 2200 CPS terminals with a total peak-hour traffic of 3 Gb/s and 39 trunking terminals with a total traffic of 6 Gb/s. Cross traffic of 0.8 Gb/s between the two services is also envisaged.

The size of the terminals varies from small CPS terminals to quite large trunking terminals. The smallest CPS terminal supports 12 voice channels, 1 data channel, and 1 low-rate video channel; the largest supports 240 voice channels, 22 data channels, 1 video (6.3 Mb/s), and 15 low-rate video channels. The smallest trunking terminal supports 12.6 Mb/s and the largest supports 548 Mb/s.

The traffic in a given traffic center is assumed to be approximately proportional to its population. Several traffic centers may be covered with a single satellite beam; the total traffic in a beam is important because the traffic routing in the satellite is on a beam-to-beam basis.

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Multibeam Operation

A high-capacity communications system as specified by the traffic model requires a very wide bandwidth and a high-power satellite. The available bandwidth in the 30/20 GHz band is limited to 2.5 GHz; the radio frequency (rf) power generated onboard the satellite is limited by the available dc power, which is projected to be about 5 kW for a solar cell array of reasonable size and weight.[1] A multiple-beam, high-gain satellite antenna allows frequency reuse of the available bandwidth and reduces the power requirements of both the spacecraft and the Earth terminals.[2]

Careful examination of the 45 specified cities shows that many of them lie about 0.3 deg apart when viewed from a geostationary satellite. Selecting a beamwidth of 0.33 deg permits many single beams to cover more than one city, thereby simplifying the satellite design. A beamwidth of 0.33 deg is also about the smallest beam size consistent with a forecasted beam pointing accuracy of 0.05 deg. With a beamwidth of 0.33 deg, the 45 cities can be covered by 32 beams as shown in Fig. 1.

Frequency Reuse

Frequency reuse is possible with multibeam satellite antennas.[3] Beams that are sufficiently spatially separated can operate in the same frequency band with acceptably low cochannel interference. Based on typical radiation patterns, the following rules insure acceptably low interference[4]:

1) Beams that lie farther apart than three beamwidths (from beam center to beam center) can operate without restrictions in the same frequency band.

2) Beams that are between two and three beamwidths apart can operate in the same frequency band only if they are cross polarized.

3) Beams that are less than two beamwidths apart cannot operate in the same band regardless of their polarization.

Transponder Design

The transponder design is governed by practical considerations such as high reliability, minimal power consumption, and weight and size restrictions. A higher degree of reliability is achieved through the use of passive components (such as filters) for traffic routing rather than active components (such as switching diodes and drivers) that are found in switching matrix architectures. The power consumption is

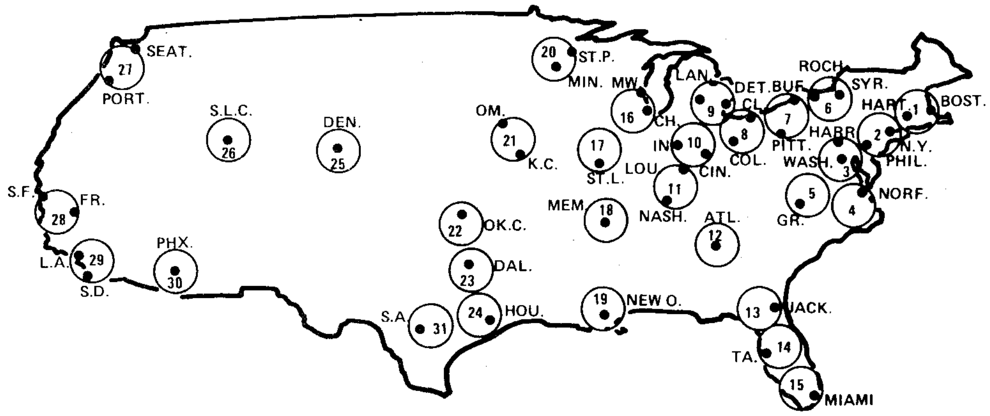

Fig. 1 Beam plan using 0.33 deg half-power beamwidth cells to cover 45 specified traffic centers in CONUS.

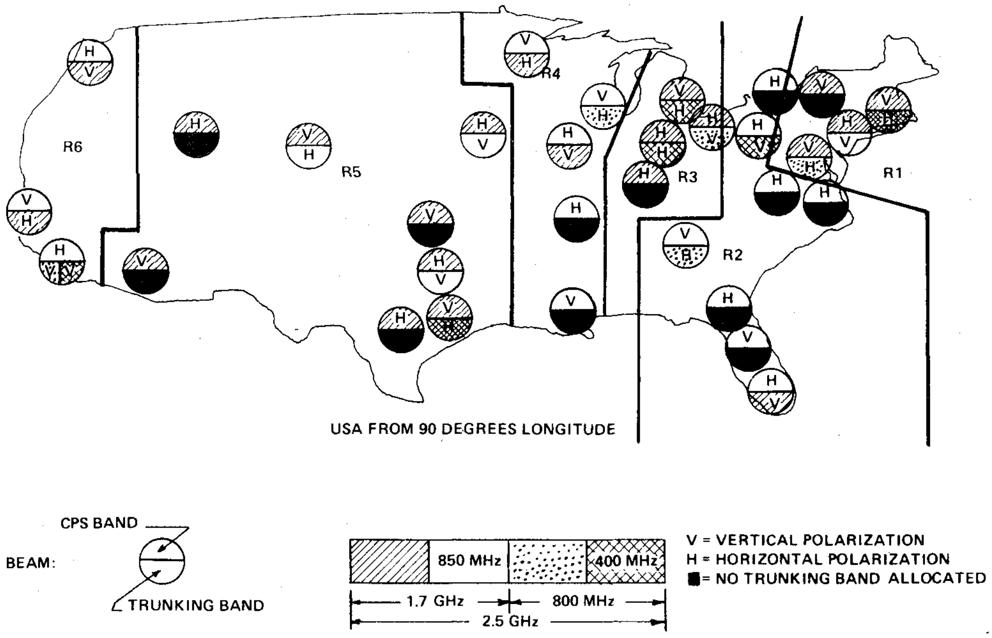

Fig. 2 Regional beam plan showing frequency and polarization assignments.

minimized by using a high-gain antenna system. The mass of the satellite is reduced by using the regional concept.

Although bandwidth and power provisions have been set aside for the trunking traffic, the following discussion will treat only the CPS traffic in detail.

Traffic Routing

Connectivity among frequency-division multiplexed (FDM) users is achieved by frequency slot assignment and filtering in the satellite in contrast to a time-division multiplexed (TDM) system where it is achieved by time slot assignment and switching in the satellite. A satellite control center assigns specific transmit and receive frequencies for every link on a *dynamic* basis. The receive and transmit horns of the satellite are connected by hard-wired bandpass filters. The routing between the beams is accomplished by appropriate (interference-free) band assignments. The distribution to individual users within a beam is by means of conventional FDM and is not discussed here.

Regional Concept

Paths between all uplink and downlink beams must be provided in the satellite. In this system a beam is generated by a single horn; therefore, every receive horn must be connected with every transmit horn by means of traffic-routing bandpass filters. For N uplink and N downlink beams, the number of filters is N^2 (a total of 1024 for a 32-beam system). A great reduction in the number of filters can be achieved by using a regional organization of the beams. A region is a continuous geographical area that contains a number of beams whose combined traffic is equal to the traffic of any other region. Nonoverlapping uplink frequency segments are assigned (on a dynamic basis) to the beams of a region, i.e., no frequency reuse is allowed within a region. Consequently, the receive antenna horns of a region can be combined into a single output port without interfering with the individual radiation patterns. In the design described here, CONUS is divided into six regions as shown in Fig. 2. With six regions, the number of routing filters drops from N^2 to $6N$ (or 192 for a 32-beam system).

Frequency Organization

By definition, no frequency reuse is allowed within a region; therefore, adequate bandwidth must be allocated to each region. In order to simplify the band allocations, the regions are arranged so that they contain equal amounts of CPS traffic. CONUS is divided into six regions in such a way that this requirement is met. In every region, a bandwidth of 850 MHz is allocated exclusively for CPS traffic. Alternate 850 MHz bands are assigned to adjacent regions to prevent

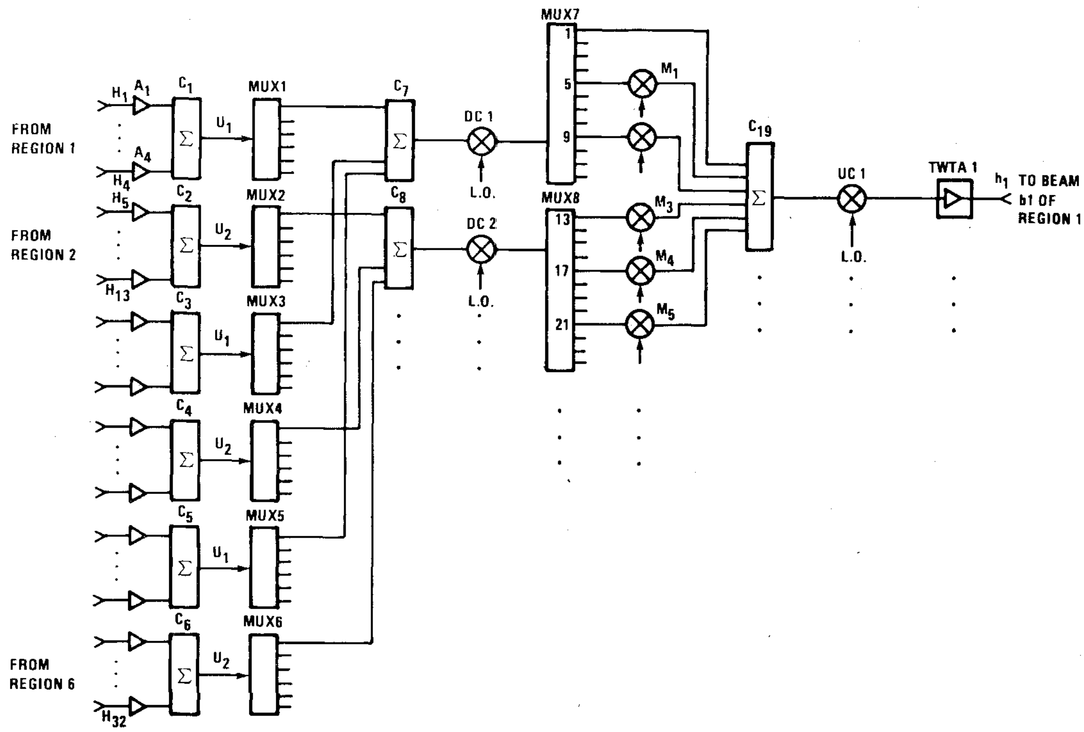

Fig. 3 Simplified block diagram of FDMA satellite transponder for six-region network.

cochannel interference between them. The uplink CPS band of a region is divided into six destination subbands, one for each destination region. Each subband is further divided into beam subbands, one for each beam in the addressed region. The bandwidth of these bands depends on the amount of traffic carried by the individual beams. The downlink 850 MHz CPS band is divided into beam subbands that consist of smaller subbands corresponding to the source regions. The remaining 1650 MHz bandwidth is left for trunking traffic, divided into two 400 MHz bands and one 850 MHz band. The two 400 MHz bands are allocated exclusively for trunking traffic. Beams can use the 850 MHz band not assigned to CPS traffic in their region for trunking traffic only if they are sufficiently separated from other beams in the adjacent regions. Cross polarization is assigned to adjacent beams of two different regions. Within a region, cross polarization separates the CPS from the trunking users wherever possible. Figure 2 shows the allocation of subbands and polarizations for all regions.

Transponder Architecture

A simplified block diagram of the transponder is shown in Fig. 3. Its operation is explained with reference to Fig. 4, which shows the frequency band translations in the transponder.

Every region is covered by several spot beams; for example, region 1 is covered by four beams. The corresponding horns, H_1 through H_4, are indicated in Fig. 3. The instantaneous frequency distribution of the received signals is shown in Fig. 4a. Note that the received frequencies do not overlap; this is consistent with the presumption that no frequency reuse is allowed within a region. The receive horns are connected to a common output by means of antenna combiners C_1 through C_6. Low-noise preamplifiers precede the combiners in order to offset the insertion loss introduced by the combiners. The frequency bands at the output of the combiners are shown in Fig. 4b. The combiners are followed by rf multiplexers MUX_1 through MUX_6, which split the uplink band into six destination subbands. Figure 4c shows the subbands destined for region 1. The hybrid combiner C_7 assembles the subbands originating in regions 1, 3, and 5 that are destined for region 1; the spectrum at the output C_7 is shown in Fig. 4d. The hybrid combiner C_8 assembles the subbands originating in regions 2, 4, and 6 that are destined for region 1. Downconvertors DC_1 and DC_2 translate the spectrum to a convenient intermediate frequency band where the realization of narrowband filters becomes feasible. The multiplexer pairs MUX_7, MUX_8 through MUX_{17}, MUX_{18} consist of narrowband filters whose passbands are tailored to the projected traffic loads. Multiplexers MUX_7 and MUX_8 channelize the traffic destined for region 1 into individual transmit beam subbands. The subbands destined for downlink beam b_1 are shown shaded in Fig. 4f. Intermediate frequency mixers M_1 through M_5 align these disjoint subbands into a continuous downlink beam band as shown in Fig. 4g. Combiner C_{19} collects these subbands. Aligning the subbands into a continuous spectrum reduces the bandwidth that must be amplified by the satellite traveling wave tubes (TWT). Upconvertor UC_1 translates the intermediate frequency band into a 20 GHz downlink band. TWT amplifiers feed the downlink horns. The power delivered by these amplifiers is tailored to the beam traffic capacity. Higher power is obtained by combining two lower power TWTs in parallel.

System Design

Conservation of the frequency spectrum is important in a high-capacity system. Various kinds of interference must be taken into consideration. The interference analysis assumes that channels in a beam adjacent in frequency operate at the same bit rate and interfering channels from adjacent beams operate at exactly the same frequency.

Serious consideration must be given to rain attenuation in a 30/20 GHz system. The link budget must include large margins to accommodate rainstorms. Analysis shows that the downlink is critical; the system operation is insured by using large Earth terminal antennas.

Modulation and Interference

The interference in multibeam, frequency-division multiple-access (FDMA) systems can be divided into four independent contributions: additive white Gaussian noise (AWGN), crosstalk (modulation-spread) interference, cochannel (interbeam) interference, and intermodulation. The

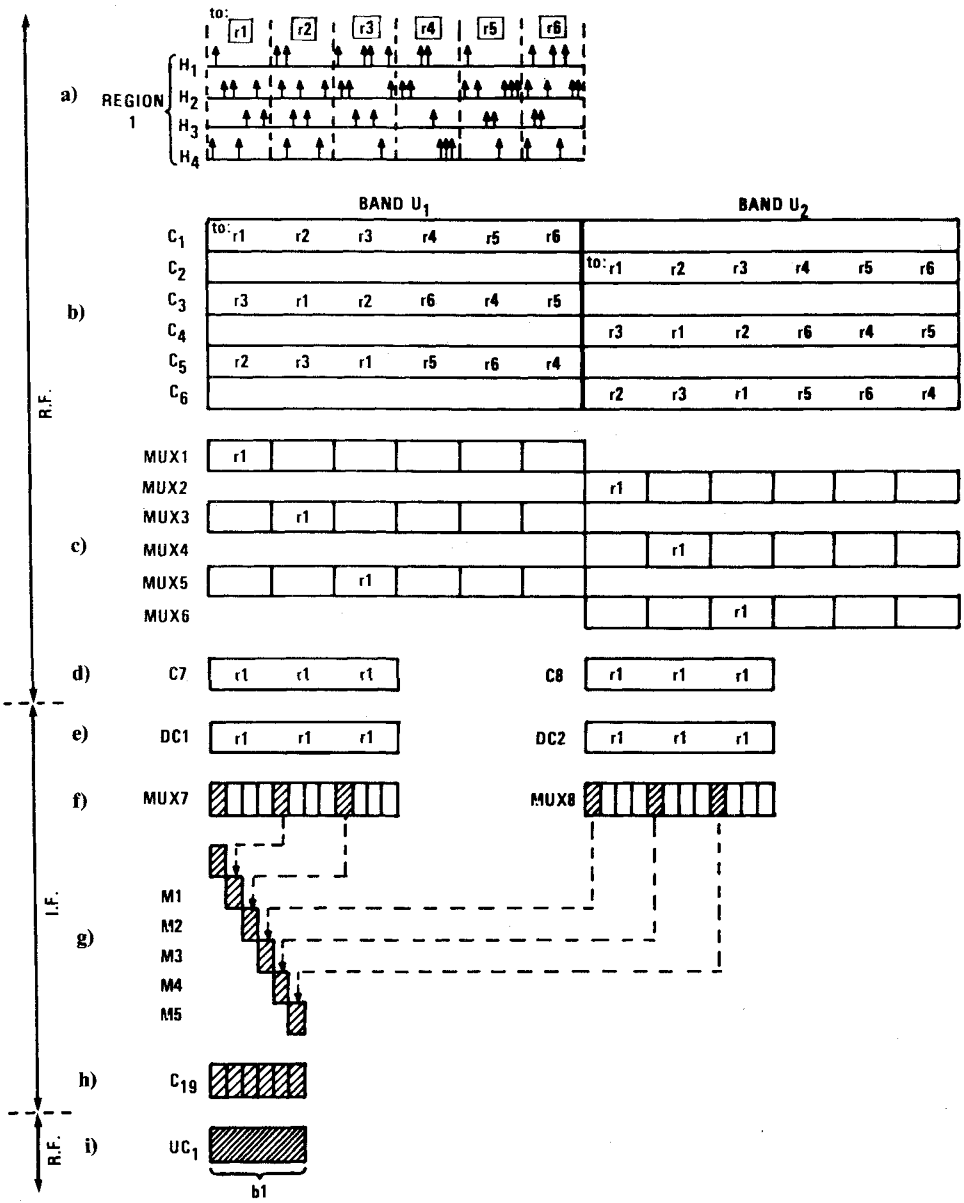

Fig. 4 Frequency bands at the outputs of various transponder devices.

signal-to-total interference ratio, which is the ultimate measure of the link quality, must exceed a certain value in order to achieve the specified bit-error probability. The desirable signal-to-total interference ratio must be apportioned into four contributing factors,

$$\frac{1}{(S/I)_{\text{TOT}}}=\frac{1}{(S/N_0)_{\text{AWGN}}}+\frac{1}{(S/I)_X}+\frac{1}{(S/I)_{\text{CO}}}+\frac{1}{(S/IM)} \tag{1}$$

The signal-to-AWGN for quadrature phase-shift keying (QPSK) modulation is

$$(S/N_0)_{\text{AWGN}}=2E_b/N_0 \tag{2}$$

where E_b is the energy per bit and N_0 is the single-sided noise power density. The apportioned value of signal-to-AWGN is used for the link budget calculations.

The signal-to-crosstalk ratio is[5]

$$(S/I)_X=1/2A^2C(\beta) \tag{3}$$

where the factor 2 reflects the assumption that only the two immediate neighbors interfere significantly, A^2 accounts for rain attenuation of the desired channel and is equal to the interference-to-signal power ratio, $C(\beta)$ is a crosstalk measure that depends on the autocorrelation function of the baseband modulation shape, and $\beta \triangleq \Delta f/R$ is the intercarrier spacing relative to the bit rate. The relationship $C(\beta)$ vs β is shown in Fig. 5 for three modulation schemes. The figure shows that for intermediate values of β minimum-shift keying (MSK) gives the highest carrier-to-crosstalk ratio and, therefore, is a desirable bandwidth-efficient modulation scheme. The apportioned value of signal-to-crosstalk ratio can be used for determining the minimum carrier spacing.

The signal-to-cochannel interference ratio is

$$\left(\frac{S}{I}\right)_{\text{CO}}=\frac{1}{KA^2X^2C(0)} \tag{4}$$

where K is the number of interfering beams (using the same frequency as the desired beam) and X^2 ($X^2<1$) the interbeam isolation. The apportioned value of signal-to-cochannel

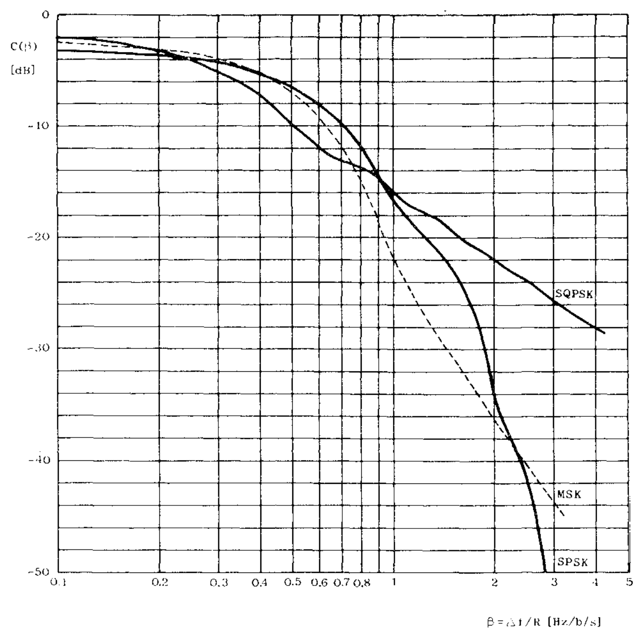

Fig. 5 Crosstalk measure vs normalized channel spacing.

interference ratio can be used for determining the minimum isolation between two beams of the same frequency.

Finally, the carrier-to-intermodulation ratio depends on the TWT backoff and the number of carriers[6] and is supplied by the tube manufacturers. The apportioned value of signal-to-intermodulation ratio is used for determining the minimum TWT backoff.

Design Example

An example illustrates the procedure for determining the carrier spacing and the interbeam (spatial) isolation. If MSK modulation is used, about a 10.5 dB signal-to-total noise ratio, including an implementation margin, is required for a bit-error probability of 10^{-3}. As mentioned above, four factors contribute to the total interference. If they contribute equally, the signal-to-interference ratio for each of them must be four times higher than the signal-to-total noise ratio, or 16.5 dB. Let the desired channel be at f_0; the adjacent channels in the *same beam* are at $f_0 - \Delta f$ and $f_0 + \Delta f$. Assume that the desired channel experiences a rain attenuation of 10 dB, i.e., $A^2 = 10$, then, solving Eq. (3) for $C(\beta)$ gives

$$C(\beta) = -16.5 - 3 - 10 = -29.5 \text{ dB}$$

From Fig. 5, $C(\beta) = -29.5$ dB corresponds to $\beta = \Delta f/R = 1.4$ (for MSK), which determines the carrier spacing for a given bit rate. Since the system employs frequency reuse, other beams will operate at the same frequency f_0. Let the number of such beams be four, i.e., $K=4$, and let them be equally spaced from the desirable beam. Assume that the desirable channel experiences a rain attenuation of 10 dB, i.e., $A^2 = 10$; then, solving Eq. (4) for X^2 gives,

$$X^2 = -16.5 - 6 - 10 + 2.3 = -30.2 \text{ dB}$$

This is the required isolation between two beams that use the same frequency. The derivation uses $C(0) = -2.3$ dB (for MSK) from Fig. 5.

Rain Attenuation

Rain attenuation is a very serious problem in the 30/20 GHz band. Certain areas of CONUS experience very high precipitation and require large rain margins for a link availability that is comparable to terrestrial links.[7] The system described here envisages a fixed-link margin of 4 dB for rain in the downlink path and adaptive compensation for rain in the uplink path. The Earth stations have a built-in rf power margin of 10 dB for uplink compensation and can gain an additional 5 dB improvement by switching to rate ½ coding. In order to prevent intermodulation in the satellite, the terminal transmit power should be adjustable dynamically in several steps. An uplink margin of 10 dB, a downlink margin of 4 dB, and the use of rate ½ coding results in a link availability exceeding 99.5% for most of CONUS; for Florida these margins give a link availability of better than 99.3%.[8] The link margin for the heavy-rain regions can be further improved by reducing the interchannel (modulation-spread) noise. This can be easily implemented by a satellite control center that assigns a larger intercarrier separation for the heavy-rain regions than for the rest of the country. Fortunately, the heavy-rain regions (Florida and the southern states) have relatively low volumes of traffic.

Link Budget

The downlink is the weak link in the system because the dc power (5 kW) that a reasonably large solar array can generate is limited. The total satellite rf power is 800 W. The antenna gain is fixed by the 0.33 deg beamwidth. Under these circumstances, the downlink can be closed only with a sufficiently large receiver sensitivity G/T. However, the system noise temperature of the Earth terminal cannot be cost effectively much smaller than 850-1000 K, corresponding to a 400-500 K GaAs field effect transistor (FET) preamplifier. Therefore, the CPS Earth terminals must have large antennas of 4.5 to 8 m, depending on the total data rate.

Four factors contribute to the overall system noise: AWGN, cochannel interference, interchannel interference, and intermodulation. Equal noise power is assumed for these four contributions. With an implementation loss of 2.5 dB and E_b/N_0 of 10.6 dB (corresponding to a bit error rate of 10^{-6} for MSK and QPSK), the residual link margin is 3 dB.

A detailed link budget calculation is given in Table 1.

Earth Terminal Design

The smallest CPS terminal uses a 4.5 m antenna that is equipped with a step-track antenna system capable of following the satellite with a 0.05 deg accuracy. The transmitter employs a 2 W solid-state power amplifier that is preceded by a dual upconvertor. The latter upconverts the signals from the 70 MHz modem-interface through a 2-4 GHz intermediate frequency to the 30 GHz transmit band. The receiver uses a low-noise GaAs FET amplifier and dual downconvertors. The up- and downconvertors are supplied with local oscillator frequencies from a common reference oscillator-synthesizer and multiplier chains.

The Earth terminals service several users that communicate with different destinations and, therefore, operate on different frequencies simultaneously. Consequently, every user requires dedicated intermediate frequency (IF) up- and downconvertors.

System Performance

A satellite that has a mass exceeding 2700 kg and consumes more than 6000 W can support only 75% of the specified traffic. A possible solution is to divide the CPS and trunking traffic between two satellites. A CPS satellite that has a mass of about 2200 kg and consumes 5000 W of dc power would satisfy 100% of the CPS traffic. Two such satellites (one active and one redundant) would be needed. The estimated cost of two CPS satellites (launched by a single Shuttle vehicle) is $226 million. The estimated CPS ground-segment cost is $1176 million for 2200 Earth terminals.

System Capacity

A total CPS traffic of 3 Gb/s, trunking traffic of 6 Gb/s, and cross traffic of 0.8 Gb/s must be supported with a single

Table 1 Link budgets for the CPS terminals

Parameter	Terminal type and data rate E, 33.0 Mb/s	F, 5.5 Mb/s	G, 0.88 Mb/s
Uplink at 30 GHz			
Antenna size, m	8.0	4.5	4.5
Antenna gain, dB	65.5	60.5	60.5
Terminal Equivalent Isotropic Radiated Power, dBW	76.2	68.5	60.5
Path loss, dB	−213.0	−213.0	−213.0
Rain loss, dB	−10.0	−10.0	−10.0
Misc. rf losses, dB	−5.0	−5.0	−5.0
S/C antenna gain, dB	48.0	48.0	48.0
S/C noise T, K	1150.0	1150.0	1150.0
S/C G/T, dB/K	17.4	17.4	17.4
C/kT, dB-Hz	94.2	86.5	78.5
Margin, dB	16.0	16.0	16.0
Downlink at 20 GHz			
S/C antenna gain, dB	48.0	48.0	48.0
S/C EIRP, dBW	49.0	49.6	41.6
Rain loss, dB	−4.0	−4.0	−4.0
Misc. rf losses, dB	−5.5	−5.5	−5.5
Path loss, dB	−210.0	−210.0	−210.0
Terminal noise T, K	400.0	850.0	850.0
G/T, dB/K	36.0	27.7	27.7
C/kT, dB-Hz	94.1	86.4	78.4
Margin, dB	10.0	10.0	10.0
Overall C/kT, dB-Hz	91.1	83.1	75.1
(E_b/N_0), dB	16.0	16.0	16.0
Net link margin, dB	3.0	3.0	3.0

Table 2 Estimated CPS satellite weight and power budget for six-region system

Components or subsystem	Six-region satellite system: Mass unit, kg	Total mass, kg	Total power, W
Antenna system	25	100	–
RF MUX	1.1	7	36
IF MUX	0.6	63	173
Transponder	5.2	755	3000
Other electrical and	–	136	375
battery		–	250
Tracking /Telemetry and control		18	300
Structure		90	–
Solar array		142	196
Allowance End of Life			800
Commercial payload		1311	5130
Liquid fuel	134	910	
Apogee/perigee engines			
	Total	2356	5130

satellite that has a mass of less than 2200 kg and uses a 2.5 GHz bandwidth in the 30/20 GHz band. The system must be based on projected 1987 technology and be operational in the 1990s. The FDMA system described here can support only approximately 75% of the specified CPS and trunking traffic with a satellite that has a mass of about 2200 kg, consumes approximately 6000 W from the solar cells, and requires a larger bandwidth than is available. The bandwidth limitation can be overcome by dividing CONUS into a larger number of regions; this solution increases the satellite complexity, mass, and power consumption. A dc power consumption in excess of 5000 W requires a solar cell array that is unreasonably large and heavy. The satellite dc power consumption and mass problems can be resolved by using two satellites, one for CPS and the other for trunking traffic. If the two satellites are placed close in orbit, the frequency organization presented here will be preserved; if they are placed far apart, a 2.5 GHz bandwidth will be available to each of them.

Satellite Mass and Power

The satellite mass is calculated by using a mass-counting method that includes most active and passive subsystems. The antenna mass is computed from a mass vs size relationship.

A 5000 W solar cell array requires an area of 31 m^2 and mass of 142 kg. These numbers are consistent with the 160 W/m^2 and 35 W/kg figures projected by industry for 1985.[9]

It is assumed that 56% of the available dc power is used by the rf power amplifiers. Assuming further a 30% dc-to-rf conversion efficiency of the TWT amplifiers at a 5 dB output backoff yields a total rf power of approximately 800 W. With 32 transponders, the average rf power per transponder is 25 W.

The mass limit for a Shuttle launch is set at 2200 kg including apogee/perigee motor and liquid propellant. The calculated mass for the CPS satellite is 2357 kg of which 1311 kg are apportioned to the communications payload and 1045 kg for motors and propellant.

Table 2 summarizes the CPS satellite mass and power budget.

Satellite and Terminal Cost Analysis

The space-segment cost is estimated for four satellites: a CPS satellite, a trunking satellite, and their spares. The satellite cost is calculated from a widely used cost vs mass model,[9]

$$\text{Recurring costs} = 0.065\ W^{0.93}\ \text{(in millions of dollars)} \quad (5)$$

$$\text{Nonrecurring costs} = 0.04\ W^{1.16}\ \text{(in millions of dollars)} \quad (6)$$

where W is the communications payload (dry) mass in kilograms. The recurring cost for the first satellite is $52 million; the estimated nonrecurring cost is $156 million. Adding a satellite launch fee of about $15 million per launch results in a total space segment cost of $367 million for a four-satellite system.

The ground-segment cost is estimated for various types of Earth terminal. The estimated cost of the smallest CPS terminal (12 voice channels, 1 video and 1 data channel, 4.5 m antenna, and 2 W transmitter with redundancies) is between $470,000 and $570,000. The cost of the largest CPS terminal is about $1.5 million. These figures include assembly, integration, testing, engineering, program management, general and administrative costs, and profit. The total ground-segment cost for CPS users (80 large, 300 medium, and 1824 small terminals) is $1176 million. This cost greatly exceeds the space-segment cost. The elements that contribute most to this ground-segment cost, in order, are: antenna, transmitter, frequency convertors, and modems.

Summary

The satellite system must provide communications capabilities for 2200 CPS terminals and 39 trunking terminals. The CPS terminals service at least 12 voice channels and each voice channel can have a different terminal destination. Therefore, the satellite is accessed by tens of thousands of users. Information must be supplied for the destination of every user. In such an environment, a pure-TDMA approach does not appear to be a practical solution because of the very high burst rate and the enormously large satellite switching matrix that would be required. For this reason, an FDMA system is evaluated in this paper.

Hence, the system presented here is an FDMA *satellite-routed* system, as opposed to time-division multiple-access (TDMA) *satellite-switched* systems prevalent in the current literature. Since the communications channels are multiplexed in frequency, it is logical to use frequency division for routing in the satellite. Banks of filters connect the uplink beams with the downlink beams. A received signal falls within the passband of a particular filter, depending on its frequency, and thus is routed to a given downlink destination. Slowly varying traffic distribution can be accommodated by interchanging filter bandwidths (by means of a small rf switching matrix); however, this topic has been omitted from the paper. The number of routing filters, IF amplifiers, frequency mixers, and downconvertors in the satellite can be greatly reduced by using the regional concept. The transmit and receive frequencies of every link are assigned by a satellite control center on a dynamic basis.

The specified system throughput is very large, 3 Gb/s for the CPS users and 6 Gb/s for the trunking users. In order to accommodate such high capacity within the confines of a restricted dc supply and a finite rf bandwidth, multibeam satellite antennas must be used. They improve the link margins and conserve bandwidth through frequency reuse. Spatial isolation allows several beams to use the same frequency band with acceptably low cochannel interference. Appropriate frequency plans and cross polarization reduce the interference. Another interference, the crosstalk (modulation-spread) interference is combatted with sufficient intercarrier spacing and a bandwidth-efficient MSK modulation scheme. Finally, the intermodulation interference, which is inevitable in an FDMA system, is reduced by sufficient TWT backoff.

In order to appreciate the problems (mass, power consumption, and cost) of such an FDMA system, the evaluation includes a transponder design. The detailed calculations reveal that a satellite of 2700 kg that consumes 6000 W of DC power can satisfy 75% of the specified traffic. The estimated cost of this high-capacity CPS system (space and ground segments) is about $1.5 billion using present-day cost information provided by manufacturers of satellite communications system hardware.

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