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Packet-Switched  
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Satellite Network

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National Aeronautics and  
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Office of Management  
Scientific and Technical  
Information Program

## Summary

A major goal of the Digital Systems Technology Branch at the NASA Lewis Research Center is to identify and develop critical digital components and technologies that either enable new commercial missions or significantly enhance the performance, cost efficiency, and/or reliability of existing and planned space communications systems. NASA envisions a need for low-data-rate, interactive, direct-to-the-user communications services for data, voice, facsimile, and video conferencing. The network would provide enhanced very-small-aperture terminal (VSAT) communications services and be capable of handling data rates of 64 kbps through 2.048 Mbps in 64-kbps increments. Efforts have concentrated heavily on the space segment; however, the ground segment has been considered concurrently to ensure cost efficiency and realistic operational constraints. The focus of current space segment developments is a flexible, high-throughput, fault-tolerant onboard information-switching processor (ISP) for a geostationary satellite communications network. The Digital Systems Technology Branch is investigating both circuit and packet architectures for the ISP. This report concentrates on destination-directed, packet-switched architectures for geostationary communications satellites.

## Introduction

In the mid 1980's NASA began the Advanced Communications Technology Satellite (ACTS) Program to develop a 30/20-GHz geostationary communications satellite to be launched in 1993. This satellite will open up the Ka-band frequency for commercial communications and demonstrate multibeam and hopping-beam antennas and onboard processing technology. The ACTS system utilizes time-division multiple access (TDMA) uplinks and time-division-multiplexed (TDM) downlinks. One drawback of TDMA uplinks is that the Earth terminals are forced to transmit at a much higher data rate than their actual throughput rate. For example, in the ACTS system an Earth terminal wishing to transmit a single voice channel at 64 kbps would have to transmit at a burst rate of 27.5, 110, or 220 Mbps. This, in effect, drives the cost of the Earth terminals up dramatically by requiring either substantially higher power transmitters or larger antennas, both of which are major cost drivers in a low-cost Earth terminal. Therefore,

recent emphasis has been placed on reducing the cost of the Earth terminals. One way to accomplish this is to eliminate the need for high-power transmitters on the ground by allowing the user to transmit at a lower data rate by using one of the following uplink access techniques: frequency-division multiple access (FDMA), a hybrid multifrequency time-division multiple access (MFBTDMA), a hybrid or multifrequency code-division multiple access (MFBCDMA). TDM has been chosen for the downlink transmission technique because the high-power amplifier onboard the satellite can then be operated at maximum power, thereby increasing the downlink signal strength and enabling the use of very-small-aperture terminals, or VSAT's (ref. 1).

NASA envisions that mesh VSAT satellite communications systems will be needed for direct distribution of data to experimenters and direct control of space experiments. In the commercial arena NASA envisions a need for low-data-rate, direct-to-the-user communications services for interactive data, voice, facsimile, and video conferencing. Such a system would enhance current communications services and enable new services. For this type of satellite system to exist, it must be cost competitive with terrestrial systems at the user level while enhancing the existing quality of service. The key to making this system cost competitive is to drive the cost of the Earth terminals down and spread the cost of the satellite among tens of thousands of users. NASA has completed and is continuing to perform a number of studies on such communications systems (refs. 2 to 7).

Mesh VSAT satellite networks can be implemented by using either a circuit-switched architecture, a packet-switched architecture, or a combination of the two. Intuitively, it appears that a circuit-switched network would be far simpler to implement; however, a packet switch has many potential advantages over circuit switching. The Digital Systems Technology Branch at NASA Lewis has investigated both circuit- and packet-switched architectures for FDMA/TDM satellite networks (ref. 8 and 9). Many problems have been identified with the front-end onboard processing requirements, satellite hardware complexity, and inefficient utilization of the uplink spectrum for FDMA uplinks. Therefore, NASA Lewis has redirected its efforts to investigating mesh VSAT networks utilizing MFBTDMA uplink access techniques in order to alleviate some of the problems associated with FDMA. This report summarizes the initial findings of those efforts.

The report describes the overall network requirements, the network architecture, the multicasting requirements, the protocols and congestion control, and the individual subsystems of a destination-directed, packet-switched (DDPS) MF-TDMA/TDM geostationary satellite network for commercial communications.

## Network Requirements

In order to begin designing the conceptual satellite architecture, a list of salient requirements has to be created: First, the system must be economically viable and cost competitive with existing terrestrial telecommunications systems while enhancing existing services and adding new ones. Second, the system must provide voice, data, facsimile, datagram, teleconferencing, and video communications services. In order to provide these services, the Earth terminals will transmit fixed-length packets in increments of 64 kbps through 2.048 Mbps. All terrestrial data entering an Earth terminal will be packetized in order to simplify the onboard processing hardware. Third, the system must be capable of point-to-point, multicast, and broadcast transmission. Multicast capability is necessary for teleconferencing and video conferencing services. Broadcast transmission may be necessary for network control. Fourth, the satellite has to accommodate destination-directed packets on a packet-by-packet basis. Fifth, the satellite network must be designed so that contention and congestion are handled in the Earth terminals and packets are not dropped at the satellite. Because of the long round-trip delay times to geostationary satellites (on the order of 250 msec) if packets are dropped, the window for requesting a retransmission and the data buffering involved are unacceptable.

## Description of Network Architecture

The baseline network consists of as many as four satellites. Only one satellite is required for an operational system. However, a minimum of two satellites are required to market the system – one acting as a spare. Without two satellites it is extremely unlikely that any service supplier would subscribe. Two additional satellites are considered in the network design to accommodate transoceanic communications. Also, it is necessary to consider a four-satellite system in order to fully understand the multicasting and broadcasting requirements and limitations. In order to determine the Earth terminal size, the numbers of beams, etc., operation is assumed to be 30 GHz up and 20 GHz down, although all switching and processing are relatively independent of carrier frequency. Transmission is MF-TDMA up and TDM down. There are eight uplink beams with  $2^{14}$  addresses per beam and eight downlink hopping beams per satellite. Each downlink beam has eight dwell

locations with 2048 addresses per dwell. Associated with each uplink beam is a multichannel demultiplexer that can demultiplex thirty-two 2.084-Mbps channels. Following each demultiplexer is a demodulator/decoder pair and a packet buffer. Associated with each downlink is a burst buffer, an encoder, and a 160-Mbps burst modulator. The switch performs both space and time switching. The switching, routing, and congestion control are the responsibility of the satellite control and monitor system onboard the satellite (figs. 1 and 2).

Many of the relative numbers used to establish the network size and data rates are taken from architecture studies performed by TRW and Space Systems/Loral. These reports include a complete link budget and hardware analysis in sufficient detail to estimate size, weight, and power requirements.

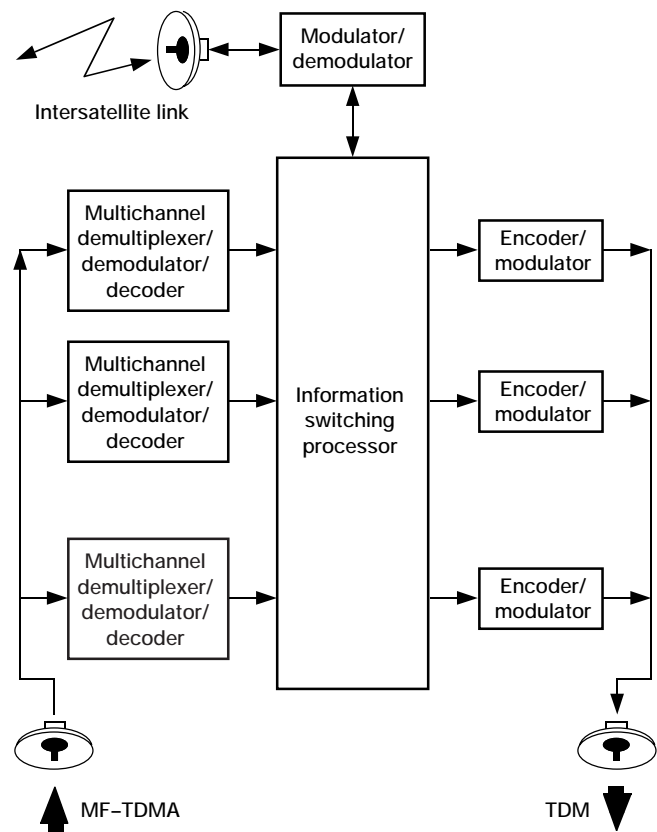


Figure 1.—MF-TDMA/TDM network for satellite and Earth terminals (refs. 10 to 12).

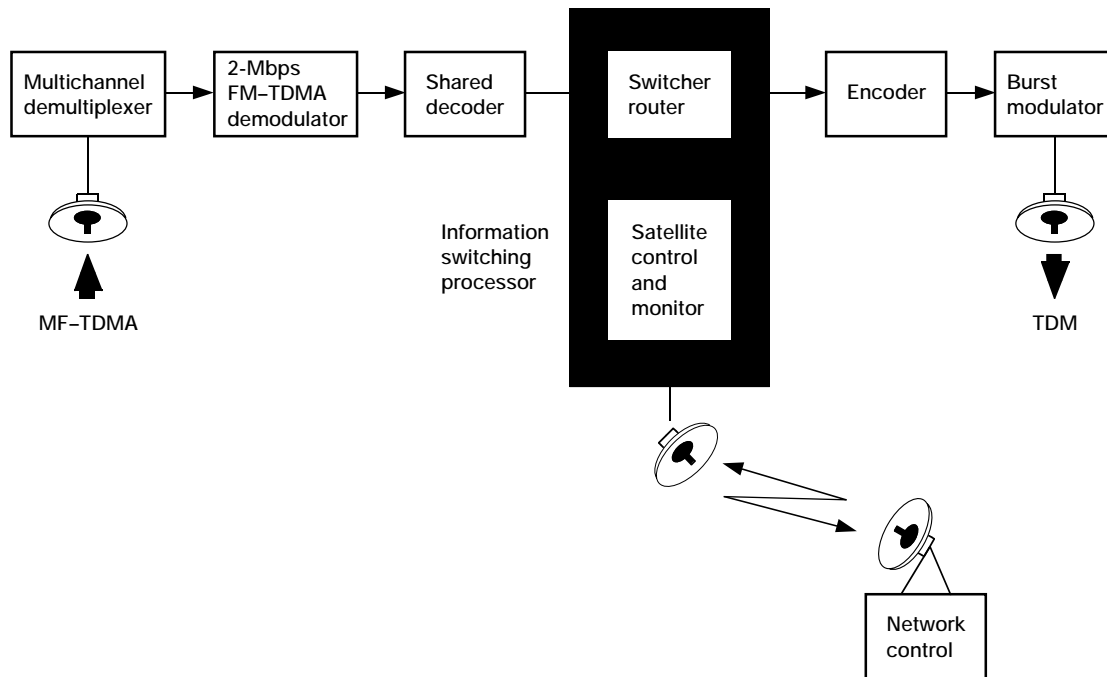


Figure 2.—Mesh VSAT processing satellite.

## Multicasting and Broadcasting

For this DDPS satellite network the degree of multicasting and broadcasting must be limited or the address header will become unrealistically large and the packet efficiency (information-to-overhead ratio) unacceptable. In the extreme limit, for four satellites each with eight downlink beams and eight dwells per beam, there are 256 different dwell locations giving  $2^{256}$  different combinations of multicasting. A minimum of 256 bits would be required in the header just to specify multicasting. Obviously, this is unworkable. The other extreme would be to accommodate only point-to-point communications. In this case, only 19 bits would be required to specify the destination. Table I shows a variety of possible multicasting scenarios and the number of required mapping bits. Figure 3 shows the number of possible multicast locations and figure 4 shows a possible mapping that would occur onboard the satellite. Notice that the hardware mapping may require additional bits to be added to the header for easy hardware implementation.

The following observations can be made about multicasting: First, intradwell multicasting requires only predefined group addresses. No additional packet regeneration or switching and routing hardware is required because every location within a dwell receives all transmissions. However, because the users need to know which transmissions are intended for them, they need a list of destination addresses: one defining its location and an additional address to define multicast groups that the

TABLE I.—BROADCAST OPTIONS  
[Assume 8 dwells/beam, 8 beams/satellite, 4 satellites, and 2048 addresses/dwell.]

Multicasting description	Number of multicast locations	Number of combinations	Minimum number of destination bits <sup>a</sup>
Single dwell (intradwell)	1	1	2+3+3+11+0=19
Multiple dwells in a beam (interdwell)	8	256	2+3+8+11+0=24
Multiple beams, all dwells (interbeam)	8	256	2+8+3+11+1=25
Multiple satellites, all beams and dwells (intersatellite)	4	16	4+3+3+11+1=22
Interbeam and interdwell	64	2 <sup>64</sup>	2+8+8+11+0=29
Intersatellite and interbeam	32	2 <sup>32</sup>	4+32+3+11+1=51
Intersatellite, interbeam, and interdwell	256	2 <sup>256</sup>	4+32+256+11+0=303
Interbeam or interdwell	16	512	2+8+8+11+1=30
Intersatellite or interbeam	12	272	4+8+3+11+1=27
Intersatellite or interdwell	12	272	4+3+8+11+1=27

<sup>a</sup>Minimum number of bits = Satellites + Beams + Dwells + Address + Multicasting.

user belongs to. Second, in order to reduce the packet header substantially, inter-dwell multicasting will not be accommodated. This is a reasonable constraint particularly because it seems unlikely that a user would wish to multicast to more than one dwell in a single beam without broadcasting to all dwells within the beam. Third, for a four-satellite network with eight beams per satellite a total of 32 multicast locations exist. This requires 32 bits (one per beam) to specify the multicast location.

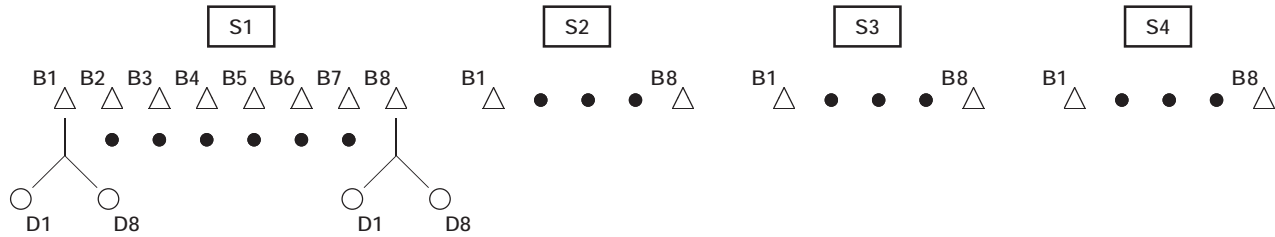


Figure 3.—Four-satellite network (4 satellites, 32 beams, and 256 dwells).

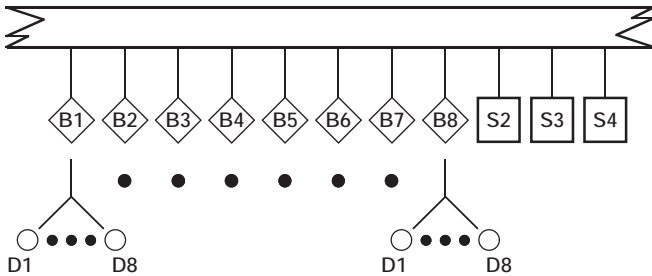


Figure 4.—Shared-bus/distributive memory mapping.

If all 32 beams were on the same satellite, only 32 bits would be required. However, because routing occurs by first mapping to the satellite and then mapping to the beam (fig. 4), 36 bits are required: 4 bits to specify the satellite and 32 bits to specify the beam. Fourth, when multicasting is not specified down to the specific dwell (i.e., 256 bits for 256 dwell locations in a four-satellite system), an additional bit is necessary to specify multicast versus nonmulticast transmission. Without the multicasting bit one could not determine whether to map a message to one dwell or all dwells within a given beam.

## Protocols

### Initial Access and Disconnect

Initial access into the system would be through a reserved signaling channel. One or two timeslots of one preselected channel for each multichannel demultiplexer would be reserved for requesting entry into the system. This channel would be set up in a slotted aloha format and would accept packets containing a request for a data transmission rate and the type of transmission: point to point, multicast, or broadcast. Additional information that may be conveyed during initial access would be related to the type of data being transmitted (voice, video, facsimile, datagram, etc.) and to the effective data throughput rate. This information may help the network controller anticipate and correct for congestion problems. Upon reception of the initial access request, the satellite will respond by a downlink inband orderwire message as to whether the request is granted or denied and giving a corresponding frequency and timeslot allocation. Disconnect requests will be handled by inband

orderwires. A disconnect packet will be sent to the network control. The network control will then initiate a request-granted orderwire to the requesting terminal, thus freeing up the previously occupied channel allocation.

Ideally, the portion of the network control that accepts and rejects access and disconnect requests would reside onboard the spacecraft in order to minimize delay. Because of the greater onboard complexity that this would entail and the direct effect that this complexity has on network reliability, placing this portion on the network control onboard may not be optimal. Further studies are needed in this area before a reasonable conclusion can be made.

### Packet Formats

The Earth terminal will translate incoming data (packets, voice, continuous data, etc.) into fixed-length message packets that are specific to the satellite network. This simplifies the onboard processing.

The tradeoff on packet length is between improved packet efficiency and increased onboard storage. The longer the packet, the greater the packet efficiency owing to a reduction in the overhead-to-information ratio; however, the longer the packet, the greater the onboard storage requirements. The length of each message packet has been chosen to be 2048 bits. In order to reduce the amount of onboard storage, each packet is further divided into two types of subpackets: a header subpacket and an information subpacket. Each subpacket will be 128 bits long. Each message packet consists of 16 subpackets: 1 header subpacket and 15 information subpackets. An analysis of the packet structure is given in the appendix.

The header subpacket consists of three fields: source address, destination address, and parity (table II). The source address consists of three subfields: source-satellite, source-beam, and source-user address. A source address must accompany each packet in a DDPS because the destination user has to know where each received packet originated. The source-satellite and source-beam subfields are not required during transmission to the satellite because they can be reconstructed onboard. However, they are required in the packet received at each Earth terminal. The destination address consists of five subfields: multicast, destination-satellite, destination-beam, destination-dwell, and destination-user address. The destina-

TABLE II.—HEADER SUBPACKET FIELDS

Header address bits	Number of bits
Source bits:	
Four satellites	2
Eight beams per satellite	3
16 384 addresses per beam	14
Total	19
Destination bits:	
Multicast	1
Four satellites	4
Eight beams times four satellites	32
Eight dwells per beam	2
2048 addresses per dwell	11
Total	51
Parity	58
Total address bits	128

tion address provides routing information to the onboard switch and is required as part of the uplink packet structure. The multicast, destination-satellite, destination-beam, and destination-dwell subfields are not required as part of the packet received by the Earth terminal. The parity field uses the remaining bits and provides forward error correction and detection. It is imperative that the header subpacket be received at the satellite and the Earth terminals correctly, or the quality of service will be unacceptable. Transmission errors that are detectable but not correctable will result in dropped packets. Transmission errors that exceed the decoder's error detection capability may result in packets being misrouted, causing multiple problems: The destination user will not receive the packet, and users not expecting the packet will receive it. Errors occurring in the destination-satellite, destination-beam, or multicast fields are extremely severe because this condition results in multiple misrouted or dropped packets. Therefore, the choice of error correction code to be used in the header subpacket is extremely important.

The information subpacket consists of two fields: an information field and a parity field. The information field contains communications data that are being passed from Earth terminal to Earth terminal. These can be continuous-transmission data such as voice or standard packets that have the satellite network packet structure overlaid. The parity field provides error correction that is necessary to maintain a desired quality of service—assumed to be approximately  $10^{-7}$  through the satellite network.

### MF-TDMA Uplink Frame Structure

Each 40-MHz uplink beam has 32 wideband channels separated in frequency and transmitting at 2.048 Mbps (uncoded transmission rate). The uplink frame is 32 msec long. This length allows transmission of one complete message packet per frame (see the appendix. Each frame is further divided into sixteen 2-msec subframes, and each subframe is further separated into thirty-two 62.5- $\mu$ sec timeslots. Each timeslot corre-

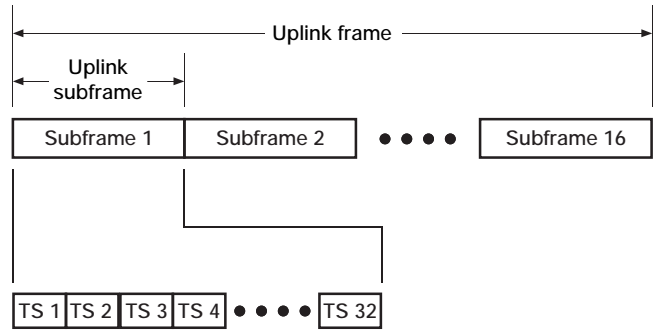


Figure 5.—Uplink TDMA frame. (Frame, 32 msec; subframe, 2 msec; time slot, 62.5  $\mu$ sec.)

sponds to a 64-kbps channel (fig. 5). Because the MF-TDMA system requires bit synchrony at the satellite, there are no guardbands or preambles in the frame structure.

### TDM Downlink Frame Structure

Two types of downlink frame structures have been identified for this architecture (ref. 13): the dedicated reference burst format and the integrated reference burst format (figs. 6 and 7).

For the dedicated reference burst format the reference bursts occur as the first eight bursts of a frame (one burst per dwell) and are followed by the traffic bursts. The advantage here is that the user always knows where the reference burst is relative to the beginning of the frame. This eases network synchronization because the reference burst locations do not change with changing traffic patterns. Three problems exist with this structure: First, some additional downlink frame inefficiency is associated with the added bursts when considering preambles and guard times. However, this additional frame inefficiency is minimal for frame lengths of 1 msec or more. Second, and most important, the dwell time for the reference burst would be extremely fast and may overstress the beam-forming electronics. Sending the equivalent of a one-packet burst at approximately 160 Mbps would require the beam to fully reconfigure in less than 12.5  $\mu$ sec. Third, the reference burst message would have to be treated (assembled) differently than information messages because the reference burst would be received as one complete packet and the information messages would be received as a series of subpackets.

For the integrated reference burst format the reference burst control messages would be the first message in each dwell. This structure is slightly more efficient than the first because it requires eight fewer bursts, thus eliminating preamble overhead associated with those bursts. Another advantage is that the reference burst message can be assembled on the ground exactly like an information message. The disadvantage of this method is that the reference burst location will change as the burst time plan is modified.

RBD Reference burst dwell  
 SPD Subpacket dwell  
 CBTR Carrier and bit timing recovery  
 UW Unique word  
 RB ID Reference burst ID (header subpacket)  
 CM Control message (control subpackets)  
 SPKT Subpacket

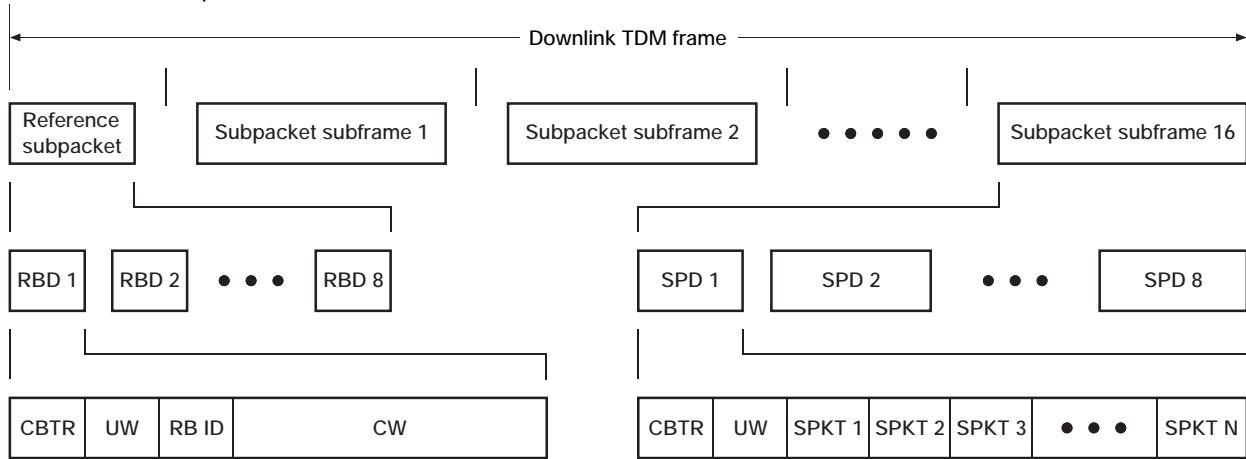


Figure 6.—Dedicated reference burst.

SPD Subpacket dwell  
 CBTR Carrier and bit timing recovery  
 UW Unique word  
 SPKT Subpacket

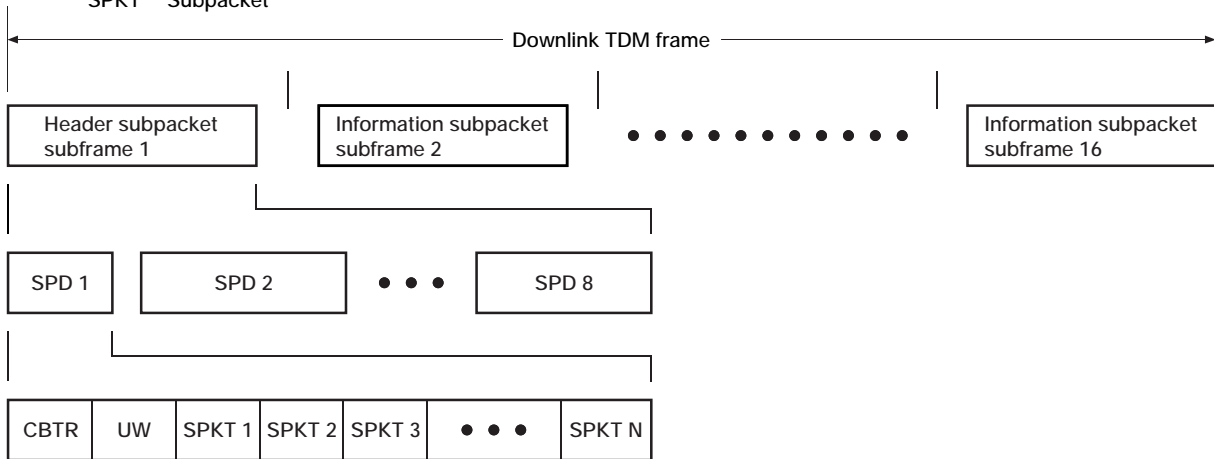


Figure 7.—Integrated reference burst.

The downlink frame format has not been chosen. For ease in network timing the dedicated reference burst format is better and would be the preferred choice. However, for simplicity in satellite hardware the integrated reference burst format has greater potential, although a detailed hardware design has not been completed. The choice will be made by first considering satellite complexity and reliability and then considering the networking.

In order to simplify network timing, the downlink frame time is identical to the uplink frame time of 32 msec. The minimum dwell size of 80  $\mu$ sec corresponds to a requirement of at least 100 packets (100 subpackets transmitted in 16 subframes) being transmitted to any single dwell (4 percent of the total frame). An analysis of this is given in the appendix.

A superframe structure will be placed over the TDM frame structure. Various orderwire messages will be reserved for particular frames within a superframe.



## Downlink Orderwire Message Format

Orderwires will be used to convey satellite switch status, system timing information, initial access granted and denied messages, etc. The downlink orderwire message will be either the first packet of each dwell for a distributive flow control downlink frame structure or be transmitted independently and in its entirety for the dedicated reference burst format.

## Congestion Control

In a DDPS satellite network congestion control is a major concern. Congestion occurs when more information than is available is destined for a specific downlink dwell. This can occur because the data packets are self-routing and the routing information is not available until the packet arrives at the satellite. Because of the long propagation delay from the satellite to Earth (125 msec), “handshaking” and requests for retransmission are impractical. In addition, the limited storage capability on the spacecraft also makes buffering of numerous packets for thousands of users impractical. Therefore, a congestion control method has to be developed that is specific to this DDPS satellite system.

Numerous methods have been identified to deal with this problem (refs. 14 to 16). The methods consist of ground-based and combined ground-and-satellite-based control (distributive flow control) algorithms. Analysis has shown that ground-based methods alone are unacceptable because the switch is underutilized owing to the conservative nature of these algorithms. The most promising approaches utilize global feedback from the satellite, indicating onset of congestion combined with a ground rate-based and bursty self-feedback control.

For distributive flow control algorithms the onboard portion of network control continually monitors the downlink burst buffers to determine the current capacity of each downlink dwell location. The network control periodically transmits

information regarding the current state of the downlink buffers to all Earth terminals. This information indicates the relative capacity of each downlink dwell. The network control then sets a threshold for capacity. Once that threshold is exceeded, all Earth terminals transmitting to that dwell location have to reduce their effective transmission rates. It is up to the Earth terminals to institute the flow control. All flow control, acknowledgments, and buffering are performed at the Earth terminal.

Determining the satellite buffer thresholds is a major area of study. The threshold is set by the network control in order to allow the Earth terminals adequate time to institute flow control before a congestion problem occurs in the downlink burst buffer. Setting the threshold too high will allow congestion to occur. A conservative threshold setting will cause underutilization of the satellite resources. Because the traffic patterns are not deterministic, neural networks are being considered to solve this problem.

## Network Hardware

### Earth Terminals

The Earth terminal is composed of indoor and outdoor units (fig. 8). The indoor unit consist of a terrestrial interface, a protocol converter, a packet formatter, a message queue, a 2-Mbps MF-TDMA burst modulator, a message assembler, a decoder, a 160-Mbps burst demodulator, an orderwire processor, and timing and control. The outdoor unit consists of a frequency conversion unit, a high-power amplifier, a diplexer, and a low-noise receiver.

The Earth terminals will interface to the terrestrial telecommunications network at the data service unit zero (DS0) (64 kbps); the Integrated Services Digital Network (ISDN) basic service rate, 2B+D (144 kbps); T1-type rates (1.544 or

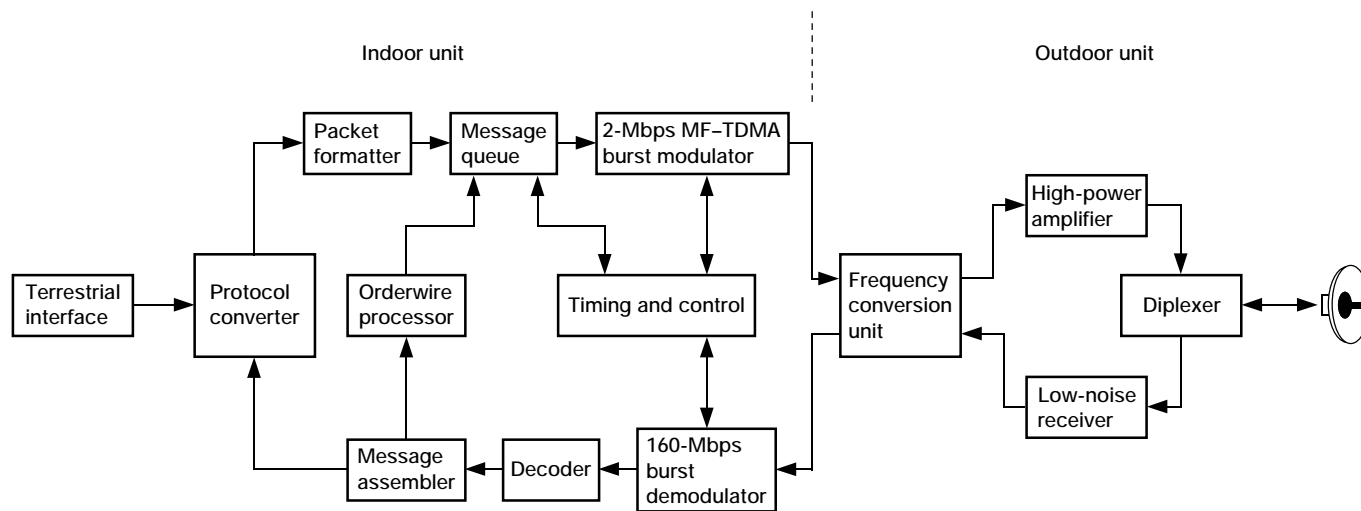


Figure 8.—Earth terminal.

2.048 Mbps); and any rate from 64 kbps to 2.048 Mbps in 64-kbps increments. In addition, the Earth terminal will be capable of interfacing to commercial communications equipment and will be compatible with commercial standards.

The protocol converter provides an interface between the commercial communications packet-switching standards and the internal packet-switching protocol. All handshaking, acknowledgments, and flow control with the terrestrial networks will occur here.

The packet formatter breaks (or appends) terrestrial packets into satellite network packets of constant length. Each packet is further subdivided into information subpackets. The source and destination addresses are generated as a separate header subpacket. The header and information subpackets are encoded and passed on to the message queue for transmission.

The decoder decodes header and information subpackets. Because the header and information subpackets will be encoded with different codes, the Earth terminal decoder subsystem will consist of either a reconfigurable codec or two separate codecs.

The modulator and demodulator are two completely separate units. Presently, it is envisioned that the uplink modulator will produce a differentially encoded quaternary phase-shift-keyed (QPSK) signal and will burst at approximately 2.048 Mbps. On the downlink a burst demodulator is required. The data rates will be approximately 160 Mbps, and the modulation format has yet to be determined. A continuous phase-modulation format is desired in order to run the transmitter at saturation while maintaining spectral efficiency.

The message assembler reads the demodulated data, strips off the source address fields, and reassembles the orderwire messages and any messages destined for that Earth terminal. The reassembled messages are then passed on to either the orderwire processor or the protocol converter for entry into the terrestrial communications network. Assuming the integrated reference burst format, the messages would be reassembled in the following manner: The first subframe would contain all header information. The message assembler would read each subpacket and record the timeslots of the subframe in which each message destined to that terminal resides. During the remaining subframes the information subpackets residing in the stored timeslot locations would be appended to the previously stored subpackets, requiring that all messages are routed through the satellite in exactly the same way for the duration of a frame. This requirement should not be a problem in an MF-TDMA/TDM architecture.

Because this communications network utilizes time-division multiplexing on both the uplink and the downlink with downlink-burst data transmission in the 160-Mbps region, the timing and control of the communications channel are critical. The timing and control system (T&CS) is responsible for obtaining and maintaining synchronization with the satellite. The T&CS informs the burst demodulator of the approximate time of burst arrival and receives a signal indicating actual burst

arrival times. The T&CS uses the information obtained from the demodulator to adjust the Earth terminal's receiving side timing in order to synchronize the Earth terminal to the network. The T&CS also receives network control information from the orderwire processor and uses this information to determine what type of information is entered into the control fields of the transmitted packets. In addition, the T&CS will turn off the transmitter and the modulator during periods when the Earth terminal has relinquished access to the satellite uplink channel.

The outdoor unit contains the RF equipment consisting of a frequency conversion unit, a high-power transmitter (HPA), a diplexer, an antenna system, and a low-noise receiver (LNR). The HPA is required to produce approximately 2 W of transmitting power. The required noise figure for the LNR is approximately 2.6 dB. The outdoor unit accounts for most of the Earth terminal cost.

### **Multichannel Demultiplexer/Demodulators**

The multichannel demultiplexer/demodulator (MCDD) is a multifrequency channelizer and shared demodulator. Onboard demultiplexing of wideband channels is performed by the multichannel demultiplexer (MCD). The channelizer operates relatively independently of the modulation scheme although some optimization for the channelizer may be performed if the modulation format has been identified early on. The MCDD has been identified as a critical subsystem that needs to be developed for an MF-TDMA/TDM architecture. Acousto-optical, optical, and digital signal-processing technologies have all been identified as candidates for implementing an MCD. NASA is investigating each of these approaches through contracts, grants, and in-house activity (ref. 17).

Amerasia Technology Incorporated has completed the second phase of a Small Business Innovative Research Contract, NAS3-25862, to develop a proof-of-concept (POC) MCDD (ref. 18). The MCD uses a convolve-multiply-convolve technique (fig. 9) to perform the demultiplexing function and is implemented by using a reflective array compressor. The demodulator was implemented for binary phase-shift-keying (BPSK) modulation.

Westinghouse Electric Corporation Communications Division is under contract to NASA Lewis (NAS3-25865) to develop a POC MCD that demonstrates the capability of demultiplexing 1000 low-data-rate FDMA uplinks (ref. 19). The multichannel demultiplexer is implemented as a coherent acousto-optic radiofrequency spectrum analyzer utilizing heterodyne detection with a modulated reference (fig. 10). Like the reflective array compressor's (RAC) surface acoustic wave surface acoustic wave implementation, the optical MCD is expected to have better size, weight, and power requirements than a fully digital MCD and does not require a high-speed analog-to-digital (A/D) converter at the front end. The POC model will have a dynamic range of approximately 80 dB and

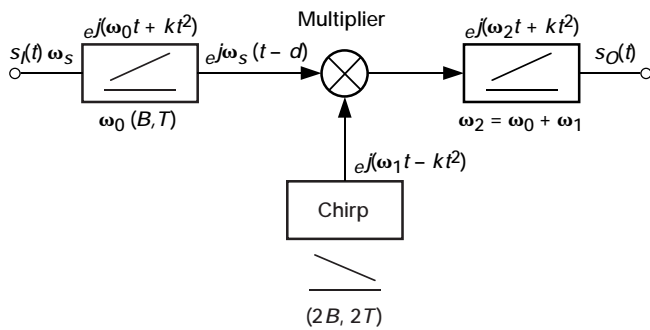


Figure 9.—Convolve-multiply-convolve chirp transform, where  $s_I$  is input signal;  $t$  is time;  $\omega_s$  is signal frequency in radians;  $k$  is linear rate of change;  $\omega_0$ ,  $\omega_1$ , and  $\omega_2$  are frequency in radians;  $B$  is bandwidth;  $T$  is time;  $d$  is delay; and  $s_O$  is output signal.

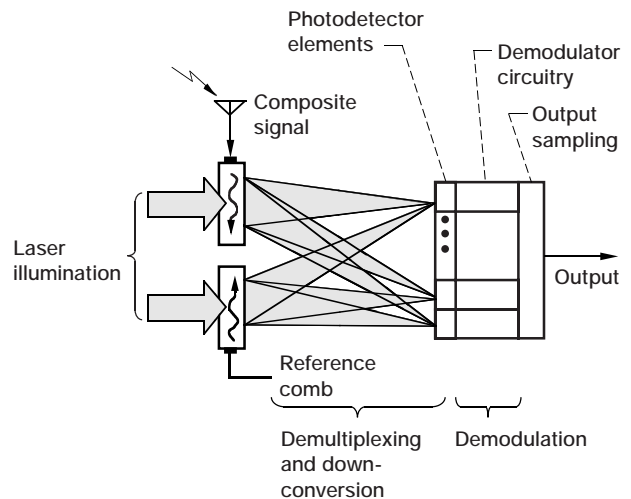


Figure 10.—Optical multichannel demultiplexer.

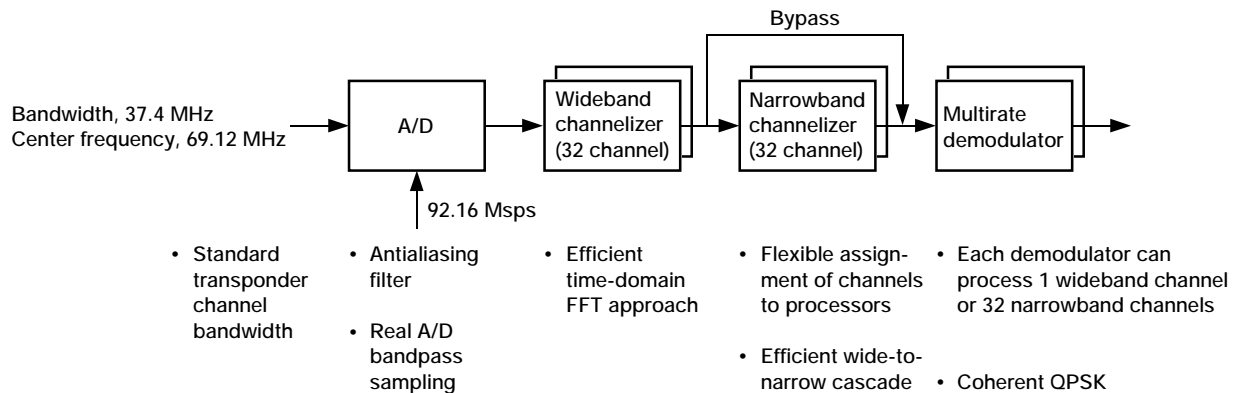


Figure 11.—Digital MCDD.

will be capable of demultiplexing 1000 45-kHz channels. Because most of the components are passive acousto-optic devices, this implementation of the MCD is highly reliable and radiation tolerant.

TRW is under contract with NASA Lewis (NAS3-25866) to develop a POC MCDD using advanced digital technologies (ref. 20). The composite FDM signal is A/D converted and channelized into wideband channels of 2.048-MHz bandwidth. Each wideband channel is then either further channelized into 32 narrowband 64-kbps channels (28 of which are high quality) or passed directly on to the multirate demodulator as a 2.048-MHz channel. The modulation format used is differentially encoded (offset quaternary phase-shift keyed, or OQPSK) and the overall bandwidth efficiency of this system is 1.42 bps/Hz. The multirate demodulator can demodulate either one 2.084-MHz channel or thirty-two 64-kbps channels. This demodulator is designed as a continuous demodulator (fig. 11).

The University of Toledo is in the fourth year of a grant (NAG3-799) to develop a programmable architecture for multicarrier demodulation that will be based on parallel and pipeline digital design techniques for increased throughput.

The hardware architecture and designs have been optimized for variable channel rates and variable numbers of channels. A POC model to demonstrate small-scale operation is under development.

### MF-TDMA Demodulator

Once the demultiplexing function has been completed, the individual channels have to be demodulated. There will be one active demodulator per frequency channel. Currently, differential QPSK is being considered for this approach. In order to simplify the demodulator hardware by eliminating the phase tracking problem, differential QPSK has been selected over coherent QPSK. The MF-TDMA concept requires all transmissions to be bit synchronous at the satellite. Therefore, network synchronization is a major concern. Studies have indicated that uplink transmission will have to be within 1/40th of a bit time in order to maintain quality transmission (ref. 21). Earth terminals will be notified of timing offsets. Timing offset will be tracked as part of the demodulation system.

The MF-TDMA demodulator is a critical component that has yet to be demonstrated in hardware. The European Space Agency currently has a program to develop such a device (refs. 22 to 24).

### Shared Decoder

The decoder subsystem decodes each subpacket on a subpacket-by-subpacket basis. There will be one decoder subsystem per demodulator. The decoder subsystem will consist of either two separate block decoders (one for header subpacket decoding and one for information packet decoding) or a reconfigurable block decoder. The MF-TDMA environment simplifies the decoder subsystem because it forces packet and subpacket alignment. All header subpackets are contained in the first subframe with all information subpackets in the remaining subframes. This requires a reconfiguration or switch between header and information block decoders only on the subframe boundary.

A quality of service throughout the satellite network of at least  $10^{-7}$  is desired. The information subpacket code rate will be selected to meet this criterion. We expect that the extra bits available to the header subpacket will allow for sufficient header coding to meet the overall network bit error rate of  $10^{-7}$ . A formal analysis needs to be completed in this area—particularly with regard to the effect of misrouted packets and multicasting.

### Information-Switching Processor

The information-switching processor is one of the major systems within the mesh VSAT onboard-processing satellite. It consists of the baseband switching and routing elements and the satellite control and monitor subsystem—particularly those portions that monitor and control the downlink burst buffers and dwell times.

### Switching and Routing Elements

A major consideration in designing the switch is contention. Contention occurs when two or more inputs attempt to route to the same output simultaneously. This is extremely difficult to avoid. Therefore, the switch must be designed to accommodate such occurrences. Studies have indicated that both contention-based and contention-free switch architectures can be utilized (refs. 13 and 25). However, contention-based switch architectures require excessive buffering and, in some instances, packet reordering. Also, contention-based switches have a greater tendency toward dropping packets than a contention free switch. Contention-free switches having a throughput capacity of approximately 1.5 Gbps can be implemented with today's technology. Because our switch throughput is in the 500- to 600-Mbps range and one of our requirements is maintaining a negligible packet loss rate, only contention-free switch archi-

tectures are being considered. Two types of contention-free switches have been identified: shared memory and shared bus.

### Shared Memory Packet Switch

The shared memory packet switch utilizes a single data memory for storing and switching packets onboard the satellite. Incoming packet data are written into the data memory at the first available unused memory location. Temporal and spatial switching of the packet data to the correct destination beam and dwell is achieved by controlling the order in which data are read from the memory. Data memory reads are controlled by the beam address memories and the control memory. Because this data memory is shared by all of the output (downlink) ports of the satellite, the shared-memory approach more efficiently uses the memory resources than other switching architectures. The shared-memory architecture is nonblocking and free of output contention. Congestion control must be considered with this approach to avoid output buffer overflows.

The block diagram of the shared-memory packet-switch architecture is shown in figure 12. It is assumed that the packets arriving at the 256 input ports to the ISP switch are fully assembled packets which are synchronized so that the headers are aligned. The data packets arriving at the 256 input ports of the switch are stored into first-in, first-out memories (FIFO's), which provide rate buffering and staggering of the input data to allow data from all 256 inputs to be multiplexed onto a single TDM bus. The data rate into each FIFO is equal to the uplink burst rate of 2.048 Mbps; the FIFO output data rate, 524.288 Mbps, is the aggregate rate of all the input ports combined ( $256 \times 2.048$  Mbps). Data are read out of each FIFO in fixed-size blocks. The minimum block size is one packet length and the size of the FIFO is directly proportional to the chosen block length. Each of the 256 FIFO's is accessed one at a time in order from FIFO number 1 to FIFO number 256. The 256 output FIFO data buses are then combined into a single TDM bus by using a 256-to-1 multiplexer.

As the packets are routed on the TDM bus from the multiplexer to the data memory, the headers are tapped off and sent to the header decoder. The headers indicate the destination downlink beam and dwell for point-to-point communications traffic. They also signify multiple destination beams, dwells, or both for multicasting and broadcasting. The header decoder determines the packet destinations and creates the proper addresses and enables so that the control memory pointers can be written into the address memories.

When a new packet arrives at the input to the data memory, an available memory address is fetched from the address pool FIFO. This data memory address is written into the next sequential address in the control memory and that control memory address is written into the address memory location determined by the header decoder. An address memory is allocated for each of the eight downlink beams, and each

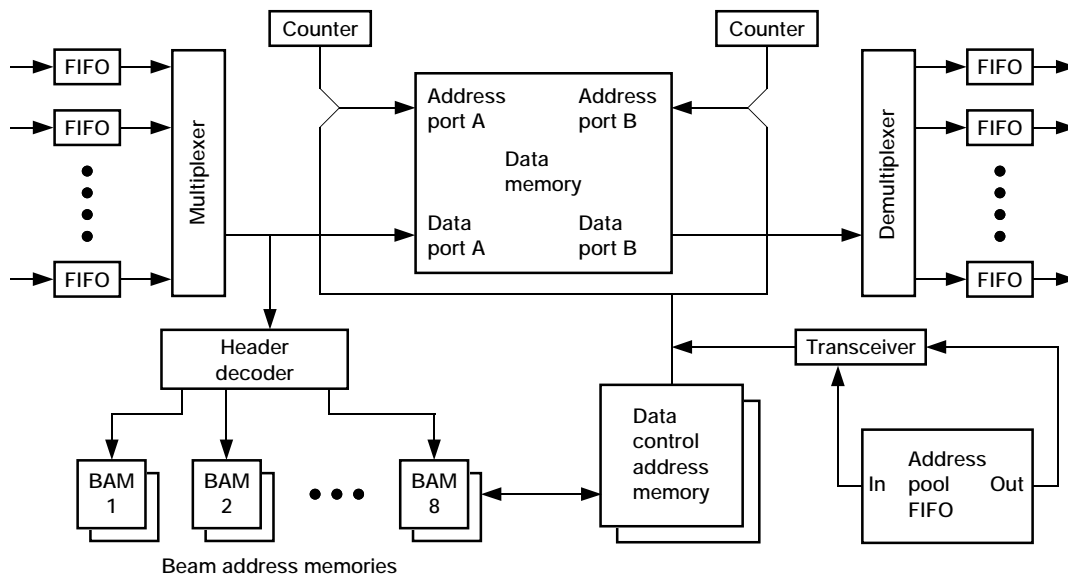


Figure 12.—Shared memory.

memory is divided into a maximum of eight dwell locations of variable lengths. The locations of the dwells within the downlink frame and the length of the dwells are controlled by network control according to the current satellite traffic situation. The remainder of the packet is then stored in the sequential data memory address locations following the initial data memory address.

The address pool FIFO contains all currently unused data memory addresses. At startup the address pool FIFO contains all the data memory addresses starting with address 0 and located every 1024 bits (total packet length) thereafter. If the TDM bus is chosen to be 32 bits wide, the available data memory addresses will be spaced 32 address locations apart ( $1024/32 = 32$ ). When a data memory address is used, it is removed from the address pool FIFO.

The data memory is designed in a dual-port configuration so that data memory reads and writes can occur simultaneously. At startup a full frame of data are written into the data memory before any data is read out and routed to the downlink ports. Subsequently, frame M will be written into the data memory while frame M - 1 is read out of the data memory. As each packet exits the data memory, the address location that contains the packet becomes available and is written into the address pool buffer. The data memory will be sized slightly larger than a full frame of data so that there will always be available addresses in the address pool buffer.

In order to read the downlink data out of the data memory, first the address memories are sequentially accessed. For the first read the address memory corresponding to the first packet in downlink beam 1 and dwell 1 is read. The address memory data contents point to a control memory address. This control memory address contains the data memory address that holds the data packet destined for downlink beam one and dwell one.

The address memories are then rotated through sequentially until one packet is read from the data memory for each sequential downlink beam. Then address memory one is accessed again for the second packet for downlink beam one, dwell one. This process continues until all data for that frame has been read. Both the address memories and the control memory are arranged in a ping-pong configuration so that one memory is written to while the other is read (and visa versa). The write and read functions are switched on frame boundaries.

Multicasting and broadcasting services are readily supported by the shared-memory switch architecture. When a multicasting or broadcasting packet is received by the switch, only one copy of the packet must be stored in the data memory. The header decoder maps the multicasting (or broadcasting) header information into multiple beam address memory locations corresponding to the multiple destinations of the packet. At each of these multiple beam address memory locations a single identical control memory address is written. This control memory address points to the location in the data memory where the multicast packet is stored. Special control must be provided to avoid writing the data memory address of the multicast packet into the address pool FIFO before the last copy of the packet is transmitted to the destination beams. One technique for handling this situation is to include a count field in the data memory with each packet. Each time a packet is used, the count field is decremented. When the count field is 1, the packet is used for the last time and the data memory address is written into the address pool FIFO.

Modifications to the shared-memory architecture are being examined to further improve memory utilization. The modifications under consideration include eliminating the use of the ping-pong memories, using in-place data memory design, and using subpacket transmissions. In using the first approach the

size of the beam address memories and the control memories is halved by using single memories rather than ping-pong memories (ref. 25). Doing this would complicate the switch timing and control circuits, and the memory savings is minor relative to the size of the data memory. The second approach, adopting an in-place switch concept for the data memory implementation, would require an incoming packet to be written to the address location of the current outgoing packet. As in the first approach this technique would require more sophisticated timing and control mechanisms. Memory saving would include eliminating the address pool FIFO and slightly downsizing the data memory to hold exactly one frame of data. Additionally, the control memory could become a simple look-up table with unchanging contents or could be eliminated altogether. Again, only small memory savings are realized with this approach. The third approach segments the incoming packets into smaller blocks called subpackets, with the block size as small as the header length. Using subpackets could result in a significant decrease in the size of data memory. In this approach only subpackets are stored in the data memory, rather than full packets. The packet header reaches the switch first, sets up the beam address memories and the control memory, and is stored in the beam memory. On the next cycle of the data memory the headers are forwarded to their destination beams, and the next subpackets are received and stored in the data memory. The beam address memories and the control memories stay the same until the entire packet has been received and forwarded to its destination and a new header subpacket is received.

### Shared-Bus Packet Switch

A shared-bus architecture is similar to the shared-memory architecture except instead of having a common output memory, the output memories are distributed—one memory per beam or one memory per dwell. Data are transmitted from input ports to output ports over a shared bus with the bus operating at the sum of the incoming traffic rates. For this system the bus would have to operate at more than 524,288 Mbps. Multicasting and broadcasting are readily accommodated with this architecture.

The shared bus operates in the following manner: Packets are stored at the input ports corresponding to each wideband input channel. Each packet has a header and data associated with it. The packets are multiplexed onto a time-shared bus at a high rate. Each destination reads the address and determines whether or not the packet is for that particular destination. If so, the packet is forwarded to the downlink burst memory.

The shared-bus architecture may be implemented as an electrical bus or a fiber-optic ring (figs. 13 and 14). The electrical bus has noise, interconnect, and loading problems that must be overcome. Both implementations require the address-processing electronics to operate at an extremely high speed in order to process the headers and then forward the data. In addition, the shared-bus architecture works best with full packets that include header and information in one packet. This

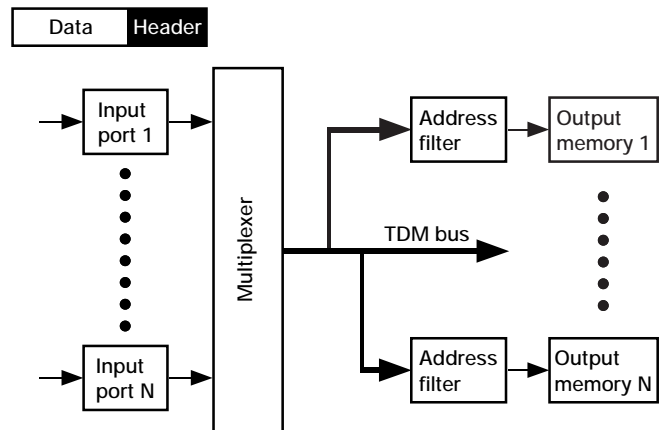


Figure 13.—Electronically implemented shared bus.

forces complete packets to be assembled and buffered onboard the satellite before switching. The memory required to accommodate this is considered excessive.

A modification of the shared-bus architecture is being considered that uses subpackets. Similar in operation to the TDM downlink, the subpacket would be used to set up the routing. Once the routing is determined, each receiver will know where, in each subframe, the appropriate information subpackets reside—almost identical in operation to the message assembler in the Earth terminal. This requires that all information subpackets are transmitted and routed throughout the satellite network in the same order as the header subpackets. This does not appear to be a problem in an MF-TDMA environment.

### Codec

The encoder is required to provide coding gain on the downlink. Because the information to be transmitted is in subpackets, a block encoder capable of operating at 160 Mbps will be used. Encoding is simpler and requires less power than decoding, making an onboard 160-Mbps block encoder very practical to implement. A corresponding decoder is required at the Earth terminal. Because power is not a significant problem on the ground, implementation of the more complex decoder is reasonable. Block decoders that handle these rates are available as commercial products.

### Modulator

A burst modulator capable of a bandwidth-efficient modulation scheme is required. A continuous phase-modulation format is desired in order to run the satellite's high-power amplifiers at saturation, thus improving the downlink efficiency. NASA Lewis has as an ongoing program in modulation and coding directed at such requirements. Among these are two completed contracts for burst modems for satellite-to-ground applica-

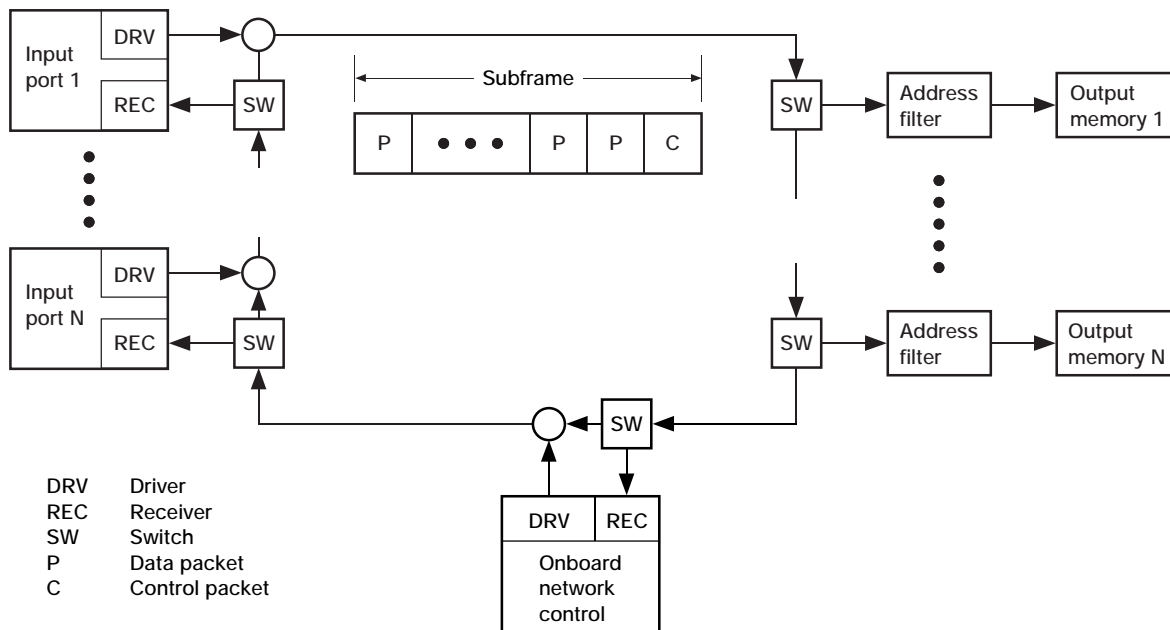


Figure 14.—Optically implemented shared bus.

tions: a 16-continuous-phase, frequency-shift-keyed (CPFSK), 200-Mbps modem; and an 8-phase-shift-keyed (8-PSK), 160-Mbps modem (refs. 26 and 27). Additional work is being performed by COMSAT Laboratories under contract NAS3-319317 for a programmable digital modem capable of binary, QPSK, 8-PSK, and 16 quadrature amplitude modulation with as many as 300 Mbps of data throughput (ref. 28).

### Satellite Control and Monitor

The satellite control and monitor (SCM) system is responsible for allocation of the space and ground resources and for real-time health monitoring and fault recovery of the onboard communications systems in addition to performing those networking functions required onboard the satellite. The SCM will monitor the downlink burst buffers' capacity, forward the burst buffer status to the Earth terminals by downlink orderwires, and vary the length of the downlink dwells to accommodate changing traffic patterns. In addition, the SCM will control the burst transmissions and the hopping-beam antenna system. Ideally, traffic allocation and routing functions will be placed onboard to shorten call setup and disconnect times. However, processing requirements, reliability issues, difficulty in modifying software, and the inability to update hardware make this practice inadvisable in the near term.

### Network Control

The network control resides on the ground. It is responsible for allocation of all network resources and handles requests for connection, disconnection, and bandwidth. Network control is also responsible for bringing new terminals into the system, monitoring traffic patterns, and updating the burst time plans (satellite beam dwell allocations). By keeping these functions on the ground, hardware and software can easily be updated and greater network flexibility is achieved. Also, reliability and fault tolerance are easily handled on the ground.

### Concluding Remarks

Any onboard processing system requires fault-tolerant implementation. With size, weight, and power at a premium, traditional fault-tolerant methods, such as simple two-for-one redundancy of components and systems or majority voting, will not suffice. NASA Lewis plans to address these issues in all aspects of the satellite design and is pursuing innovative fault-tolerant approaches that optimize redundancy requirements. Presently, the issue of fault tolerance in the digital multichannel demultiplexer is being address through a grant with the University of California, Davis (NAG3-1166). A

simulation of the proposed protection scheme for a polyphase multichannel demultiplexer using C language modules coupled with MatLab operations has been constructed. An approach that protects the operations of the analog-to-digital converters at the front end is included in this simulation. A new protection scheme for a practically implemented fast Fourier transform realization that employs only a few processing elements is being considered. Techniques are being developed for scheduling butterfly operations on processors while still preserving the error-detecting capabilities.

## Status and Future Directions

NASA plans to develop a proof-of-concept information-switching processor (ISP) and desires to develop a proof-of-concept multiple-frequency-time-division-multiple-access (MF-TDMA) modem and a reconfigurable block codec. The ISP will be constructed in-house at the NASA Lewis Research Center and may be supplemented by advanced fault-tolerant components developed under contracts if critical, stand-alone components are identified. The ISP will be demonstrated in a satellite network simulation. The switching hardware will be simulated by using traffic patterns generated by means of network simulation software. The downlink dwell buffers of the ISP will be monitored for congestion. The dwell buffer status will be fed back to the network simulation model, which will then institute various congestion control algorithms that, in turn, will modify the simulated user traffic patterns. This will demonstrate both the switching and flow control that are considered two of the more critical elements of a destination-directed, packet-switched communications satellite network.

The MF-TDMA modem is a critical element in the MF-TDMA/time-division-multiplexed (TDM) architecture that has yet to be demonstrated in hardware. NASA has great interest in seeing such an element developed and fully tested. Testing would require multiple modems and the ability to either simulate uplink delay or utilize an actual satellite link in order to fully test the bit-synchronous timing aspects required for MF-TDMA.

A reconfigurable block decoder subsystem would be necessary for an experimental flight demonstration but is not considered a critical element relative to the MF-TDMA modem and the ISP. This system may be developed at a later date.

Lewis Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio  
March 10, 1993.

## Appendix—Network Timing Analysis

### Uplink Packet Analysis

Because maintaining an uplink packet efficiency of approximately 85 percent or greater is desired, we have chosen each message packet to consist of 16 subpackets: 1 header subpacket and 15 information subpackets. This appendix gives an analytical explanation of these choices.

Let  $B_{UH}$  and  $B_{UI}$  be the number of uncoded header bits and information bits per subpacket. Let  $B_{CH}$  and  $B_{CI}$  be the number of coded header and information bits per subpacket. We need to add forward error correction to the header and information bits and desire to have more robust coding on the header bits. Let  $CR_H$  and  $CR_I$  represent the header and information subpacket code rates. Then, the number of transmitted bits per header and information subpacket,  $B_{CH}$  and  $B_{CI}$ , is given by

$$B_{CH} = \frac{B_{UH}}{CR_H} \quad (1)$$

$$B_{CI} = \frac{B_{UI}}{CR_I} \quad (2)$$

In order to simplify the hardware, we force

$$B_{CH} = B_{CI} \quad (3)$$

This gives

$$CR_H = \frac{B_{UH}CR_I}{B_{UI}} \quad (4)$$

We define the packet efficiency  $\eta_P$  to be the number of information bits per packet divided by the total number of transmitted bits, where  $N_I$  is the total number of information subpackets per packet:

$$\eta_P = \frac{N_I B_{CI} CR_I}{N_I B_{CI} + B_{CH}} \quad (5)$$

Substituting equation (3) into equation (5) gives

$$\eta_P = \frac{N_I}{N_I + 1} CR_I \quad (6)$$



TABLE III.—PACKET EFFICIENCY

$N_I$	$N_I/(N_I + 1)$ , percent	$\eta_{p CR_I=89}$ , percent	$\eta_{p CR_I=11/12}$ , percent
7	87.5	77.7	80.2
8	88.9	79.0	81.5
9	90.0	80.0	82.5
10	90.9	80.8	83.3
11	91.7	81.5	84.1
12	92.3	82.1	84.6
13	92.8	82.6	85.1
14	93.3	83.0	85.5
15	93.8	83.3	86.0
16	94.1	83.7	86.3
32	97.0	86.2	88.9
$\infty$	100	88.9	$\sim 91.7$

Table III shows the packet efficiency for various numbers of information subpackets per packet. Note that the packet efficiency depends not on the size of the packets but on the number of information subpackets and the information subpacket code rate.

### Uplink MF-TDMA Frame Analysis

Each 40-MHz uplink beam has 32 wideband channels separated in frequency and transmitting at 2.048 Mbps (uncoded transmission rate). Each wideband channel is further separated into 32 timeslots with each timeslot corresponding to a narrowband channel with an uncoded information rate  $R_{UI}$  of 64 kbps. The narrowband packet transmission rate  $R_P$  is given by the coded narrowband transmission rate divided by the number of coded bits per packet.

$$R_P = \frac{R_{UI}/CR_I}{N_I B_{CI} + B_{CH}} \quad (7)$$

From equations (1) to (3) and (7)

$$R_P = \frac{R_{UI}}{(N_I + 1)B_{UI}} \quad (8)$$

For 64 kbps, 128 bits per subpacket, and 16 subpackets per packet the packet transmission rate is 31.25 packets per second. Assuming we want at least one full packet per frame gives us a 32-msec uplink frame, a 2-msec subframe, and a 62.5- $\mu$ sec timeslot.

### Downlink TDM Frame Analysis

In order to ease network timing, we desire the uplink and downlink frames should be equal. Therefore, the downlink frame time  $T_F$  is 32 msec. Now, we wish to determine the minimum dwell time  $T_{DM}$  the inverse of the minimum beam

update rate. First, we define  $T_{TDM}$  as the total minimum amount of time a dwell will be illuminated in one frame.

$$T_{TDM} \equiv kT_F \quad (9)$$

$$k \equiv \frac{N_{DM}}{N_P} \quad (10)$$

Here,  $k$ , the minimum total illumination time that any dwell receives during a frame, may be specified as a fraction of a frame or the minimum number of packets that the smallest dwell will be required to service  $N_{DM}$ . And  $N_P$  is the total number of packets per frame and is given by

$$N_P = \frac{R_D}{B_P} T_F \quad (11)$$

where  $R_D$ , the downlink burst rate, is defined as the rate at which uncoded packets are transmitted exclusive of preambles and forward error correction coding and  $B_P$  is defined as the total number of bits per packet. The minimum dwell time is given by

$$T_{DM} = \frac{T_{TDM}}{N_I + 1} \quad (12)$$

For a downlink burst rate of 160 Mbps, a 32-msec frame, and a packet length of 2048 bits, 2500 packets are transmitted every frame. We will assume that a beam's dwell location should service at least 100 packets ( $k = 0.04$ ). Therefore, the minimum dwell time will be 80  $\mu$ sec (1/16 of the total dwell time in a frame), which is a reasonable amount of time for updating the beam-forming network.

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<b>13. ABSTRACT</b> ( <i>Maximum 200 words</i> )  A major goal of the Digital Systems Technology Branch at the NASA Lewis Research Center is to identify and develop critical digital components and technologies that either enable new commercial missions or significantly enhance the performance, cost efficiency, and/or reliability of existing and planned space communications systems. NASA envisions a need for low-data-rate, interactive, direct-to-the-user communications services for data, voice, facsimile, and video conferencing. The network would provide enhanced very-small-aperture terminal (VSAT) communications services and be capable of handling data rates of 64 kbps through 2.048 Mbps in 64-kbps increments. Efforts have concentrated heavily on the space segment; however, the ground segment has been considered concurrently to ensure cost efficiency and realistic operational constraints. The focus of current space segment developments is a flexible, high-throughput, fault-tolerant onboard information-switching processor (ISP) for a geostationary satellite communications network. The Digital Systems Technology Branch is investigating both circuit and packet architectures for the ISP. This report concentrates on destination-directed, packet-switched architectures for geostationary communications satellites.			
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