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Gigabit Satellite Network Using NASA's Advanced Communications Technology Satellite (ACTS): Features, Capabilities, and Operations

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***Abstract*--This paper describes the Gigabit Satellite Network (GSN) being developed under joint sponsorship of NASA and ARPA. The system will use the wide-band Satellite Switched Time Division Multiple Access (SS-TDMA) capability and hopping beam antennas of NASA's Advanced Communications Technology Satellite (ACTS). The GSN network will provide full-duplex SONET services over satellite at OC-3 (155.54 Mb/s) and OC-12 (622.078 Mb/s) rates. Typical applications will include connection of distributed SONET/ATM fiber "islands" over satellite, wide-area distributed supercomputer networking, high-definition digital TV, and high-speed file transfer.**

The RF link consists of 30 GHz uplink and 20 GHz downlink signals transmitted using a 3.4 meter offset-fed antenna and 120 Watt helix-type TWTA. The burst modem uses offset-QPSK or offset-BPSK modulations for transmission at 696 Mb/s and 348 Mb/s, respectively. Transmissions to the satellite are protected using Reed-Solomon encoding, providing almost error-free clear-sky performance and, in the case of rain-fade, bit error rates better than 10^{-11} 99% of the time.

The terrestrial side of the ground station will function as standard SONET Line Terminating Equipment (LTE), with OC-3 and OC-12 fiber interfaces, and is capable of multiplexing and demultiplexing the SONET signals down to the STS-1 (51.84 Mb/s) level. These STS-1 signals can be routed independently through the satellite between various ground stations.

Management of the network is performed using a Network Management Terminal (NMT) and is based on standard SNMP and Internet protocols. The earth stations can also be remotely monitored and controlled via the satellite channel or via the terrestrial Internet.

I) Introduction and ACTS Background

The ACTS satellite was conceived as a laboratory and demonstration platform for advanced satellite communications concepts and technology. As such, it differs from conventional communications satellites in several important aspects:

- (a) two modes of operation:
  - (i) onboard demodulation with store-and-forward capability (baseband processor or "BBP" mode),
  - (ii) wideband bent-pipe mode with high speed switching (microwave switch matrix or "MSM" mode)
- (b) electronically-switched hopping spot beam antennas (also a mechanically steered antenna)
- (c) 30 GHz uplink and 20 GHz downlink frequencies.

The Gigabit Satellite Network utilizes the MSM mode of operation. The spacecraft uplink equipment consists of essentially six receive antennas (Cleveland fixed, Atlanta fixed, Tampa fixed, East scanning, West scanning, and the steerable), waveguide switches , and an electronically switched 4 x 4 crosspoint switch (plus LNAs, frequency converters, etc.). The MSM output is connected to the downlink consisting of a complimentary set of transmit antennas and waveguide switches and associated electronics.

Figure 1 is a simplified diagram of MSM system onboard the ACTS. The receive waveguide switches are set to connect particular uplink antennas to the MSM inputs. The transmit waveguide switches are likewise used to connect the MSM outputs to particular downlink antenna. These are usually set and left in one configuration for the duration of an experiment session. The earth beam locations of the East and West scanning antennas are controlled by the beam forming networks (BFNs) which consist of ferrite switches which select various sets of horns. The selected combinations of horns produce a spot on the earth in the desired location.

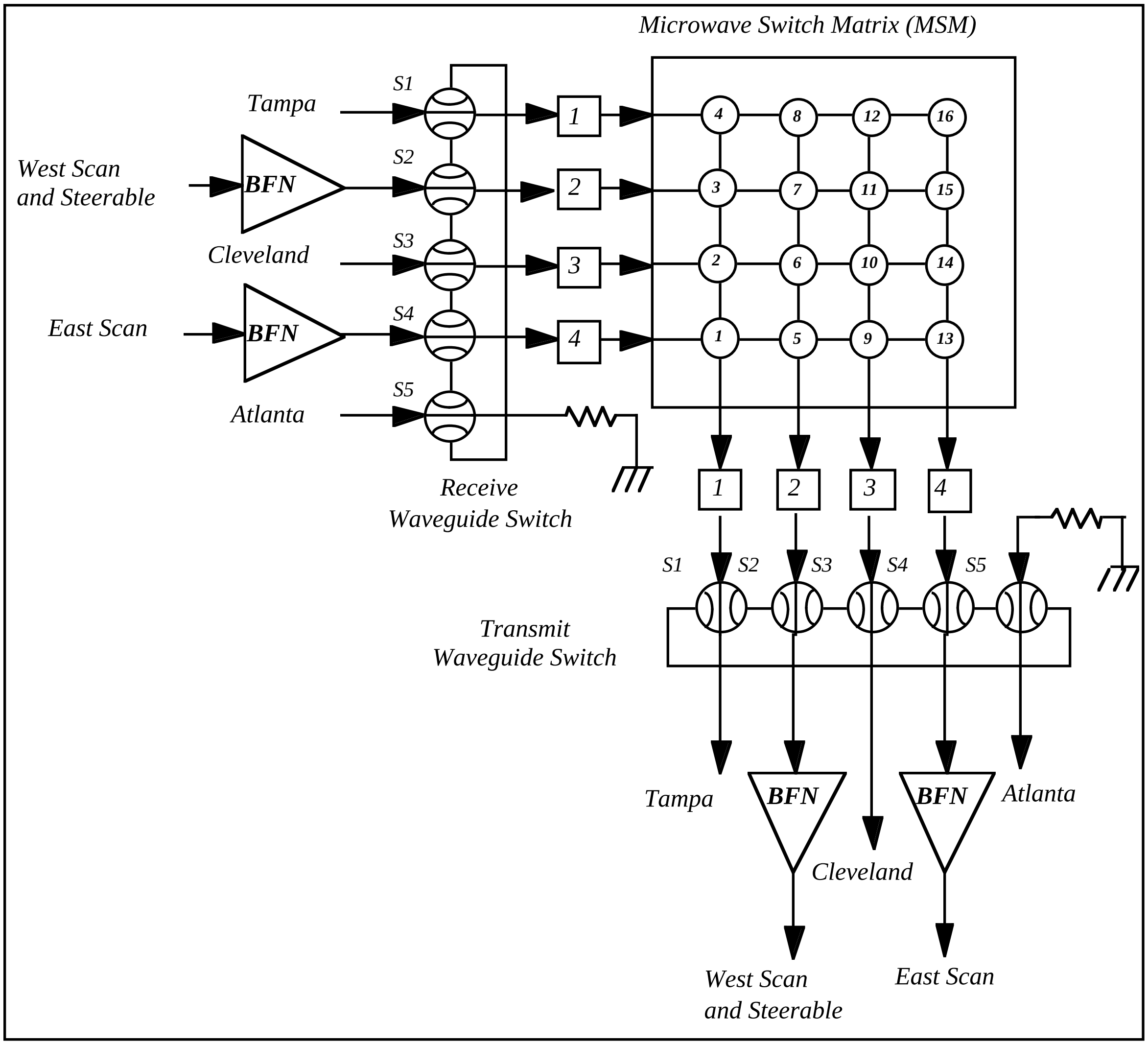

Figure 1 - Microwave Switch Matrix (MSM) Diagram

During the session, the MSM crosspoint switches are dynamically enabled according to the MSM plan stored in the spacecraft's Digital Control Unit (DCU). The DCU contains two sets of registers, referred to as the foreground and background memories. Each register is 1000 slots long, and contains the following information: the crosspoint switches to enable the spot selected for the East scan transmit antenna, the spot selected for the East scan receive antenna, the spot selected for the West scan transmit antenna, and the spot selected for the West scan receive antenna.

The DCU simply reads out the registers to the MSM and antenna beam-forming networks in sync with the TDMA frame clock. The frame time is selectable for either 1 msec or 32 msec duration. For the GSN, the 32 msec frame is used. This provides MSM and BFN time slot resolution on 32 µsec boundaries.

The background DCU memory may be programmed from the ground while the foreground memory is active. A "swap" command from the ground will select the background memory as the active one. In this way, new satellite burst time plans can be programmed in real time.

A detailed description of the ACTS satellite can be found in reference [1].

II) GSN Background

In the original design of the ACTS system, a set of very high data-rate ground stations was planned. At that time in history, high rate trunking of telephone traffic was considered to be a major application for future satellites. The introduction of optical fiber into the telephone network changed that requirement. As fiber optic networks began to emerge, so did new wideband applications.

Just as fiber networks are evolving from telephone traffic to wideband services, the requirements for an ACTS high data-rate ground system also evolved. The system as it was eventually constructed, was designed primarily to support wideband services, and extend terrestrial fiber networks. The SONET capability was a natural extension of this function. Section VII discusses some application experiments that are currently planned.

III) GSN Overview

The architecture of the Gigabit Satellite Network is illustrated in Figure 2. It is composed of transportable Gigabit Earth Stations (GES), with fiber-optic SONET interfaces, which communicate directly over satellite using the antenna beams and the on-board uplink-to-downlink beam switching capabilities of ACTS. The network control and management functions are distributed in the various GESs with the operator's interface being centralized in a Network Management Terminal (NMT). The NMT can be located at any GES site or, alternatively, at any location with terrestrial Internet connectivity to a GES designated as reference station. The end user services of this network are configurable point-to-point or point-to-multipoint 155 Mb/s and 622 Mb/s SONET "links" over satellite. The network control and management functions make use of the standard SNMP protocol and are accessible from the Network Management Terminal. Authorized operators can also access certain network control and management functions from console interfaces local to the Gigabit Earth Stations or remotely through the Internet and dial-up modems.

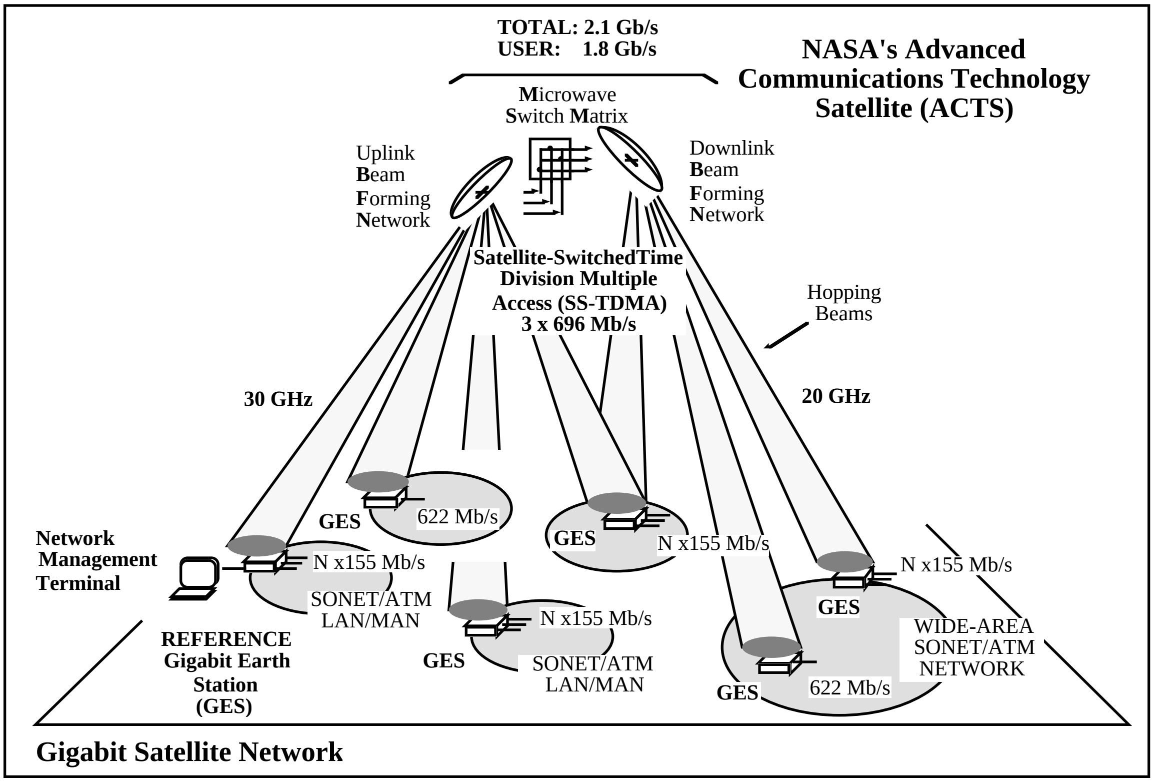

Figure 2 - The Gigabit Satellite Network supports SONET interfaces at OC-3 and OC-12 speeds and provides network operators with direct over-the-satellite access to all Gigabit Earth Stations.

Transmissions to the satellite are performed using Satellite-Switched Time Division Multiple Access (SS-TDMA) techniques with on-board space-time-space switching being performed by the High-Data-Rate section of the ACTS Multibeam Communications Package. Up to three uplink and three downlink antenna beams can be active simultaneously, that combined with 696 Mb/s burst rates per antenna beam, results in an aggregate system bit rate in excess of 2 Gb/s. Forward Error Correction (FEC) and overhead functions use approximately 10% of the total system bandwidth, resulting in end-user aggregate throughput in excess of 1.8 Gb/s (3 x OC-12).

The burst demodulator uses a patented phase rotator approach, is capable of performing both clock and carrier recovery with very short preambles (< 2 microseconds). The antenna diameter was selected as the maximum diameter possible for which satellite tracking is not required. The earth stations were designed for transportability and a trailer is used for moving the equipment from site to site. The trailer contains a weather-protected/ temperature-controlled cabin for the indoor electronics, and a sufficiently large area to transport the outdoor electronics and one disassembled antenna. The burst modem can operate with OBPSK (348 Mb/s) or OQPSK (696 Mb/s) modulations. All burst preambles, including the Unique Word (UW), and the internal signaling messages are transmitted using OBPSK modulation. SONET data can be transmitted using either OBPSK or OQPSK modulation, selectable on a per burst basis. Table 1 provides a summary of key performance parameters.

Table 1 - Key Performance Parameters

	Nominal E_b/N_0 (theory + 3 dB)	**Channel Input BER**	**(232,216) Reed-Solomon Output BER**	**Pr{miss}**
OQPSK	**10.9**	**2.4×10^{-4}**	**$< 10^{-11}$**	**--**
OBPSK	**13.9**	**3.5×10^{-7}**	**$< 10^{-15}$**	**$<10^{-15}$**

IV) SS-TDMA Subsystem

A. Frame Architecture

The MSM control memory on-board the satellite has 1000 slots and can be configured to operate either with 1-ms or 32-ms frames. The Gigabit Satellite Network uses the latter with a 32-millisecond TDMA frame synchronized to the MSM frame, illustrated in Figure 3. The TDMA frame is subdivided into eight 4-ms TDMA sub frames, with each TDMA Subframe being further partitioned in signaling (Common Signaling and Synchronization Channel - CSSC) and data areas. Each 4-ms TDMA subframe corresponds (and is synchronized) to one-hundred-and-twenty-five 32-microsecond MSM slots, with 3 slots being used for synchronization and internal network signaling (CSSC - Common Signaling and Synchronization Channel), and 122 slots being available for end user data traffic (97.6% frame efficiency). This approach was selected because it allows distribution of the CSSC time slots along the whole 32-millisecond frame and is still well within the maximum switching rates specified for the MSM (please see references [2] and [3]).

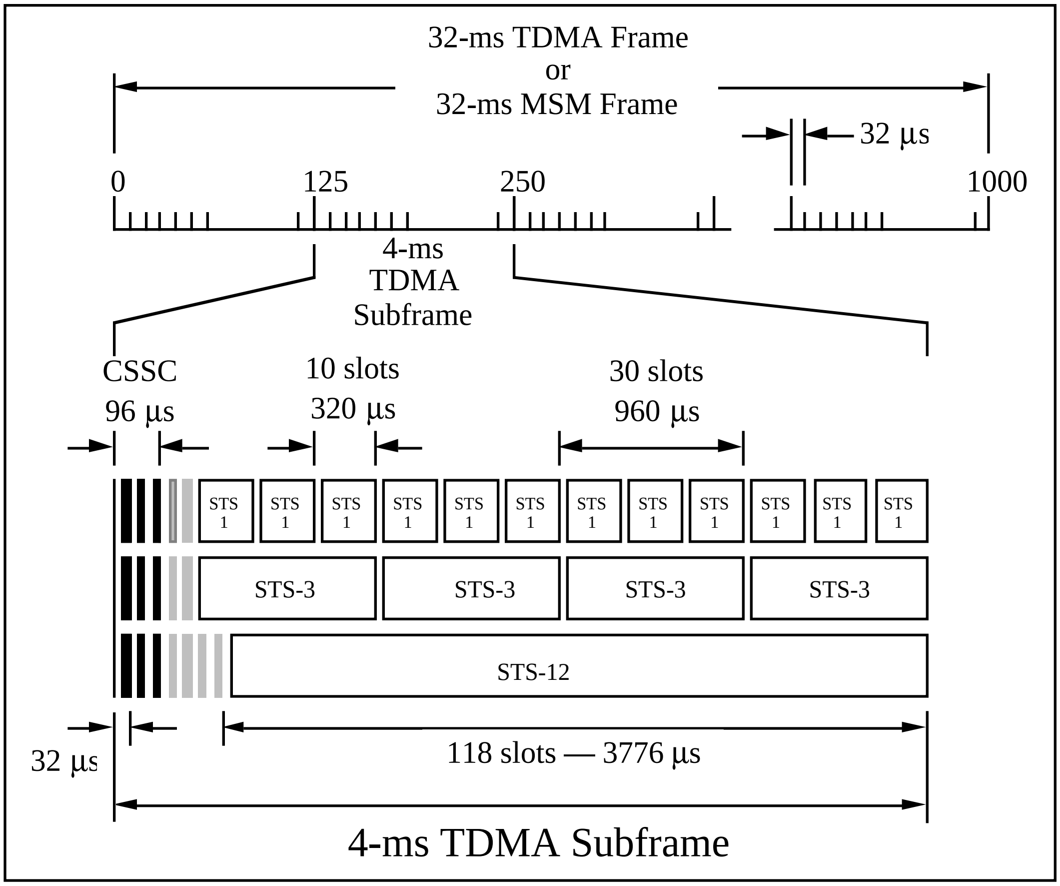

Figure 3 - The TDMA Sub frame is synchronized with the MSM frame and its structure is oriented to handle SONET STS-1, STS-3, and STS-12 signals, with minimum overhead for internal signaling and synchronization to the satellite.

This approach also allows use of longer guard times (on the order of 2 microseconds, compatible with the MSM switching times on-board the satellite), and use of longer burst preambles (on the order of 6 microseconds) without impacting the overall frame efficiency. The data area (occupying a total of 120 slots per 4-millisecond frame) is used for STS-1 (51.84 Mb/s), STS-3 (155.52 Mb/s), or STS-12 (622.08 Mb/s) bursts. In the initial implementation, the incoming data on any OC-3 or OC-12 SONET interface, concatenated or not, will be broken into STS-1 bursts to reduce the amount of data lost in the case of missed bursts and to simplify the TDMA burst time plans. The effective frame capacity utilization in this case corresponds to a net end-user efficiency of 87.1% (ratio between number of end-user payload bytes divided by total number of channel bytes), assuming transmissions at 696 Mb/s using QPSK modulation. The utilization of longer bursts (e.g., an STS-12 burst occupying 118 slots) will be reserved for potential asymmetrical services as in applications involving SONET OC-12 multicast in one direction and multiple lower speed IP channels at T1 or T1 sub-rate in the return path.

B. CSSC Subsystem and Synchronization

1) Star Signaling Architecture

All GESs in the Gigabit Satellite Network are identical. Any of the GESs can be configured (through operator commands from the NMT) to function as a Reference Terminal. The CSSC internal signaling subsystem has a star architecture with the Reference Terminal at the center of the star. The internal signaling infrastructure provides support for earth stations distributed in up to 8 different beam spots selected arbitrarily among Fixed, East Scan, West Scan, or steerable antenna spots (Figure 4).

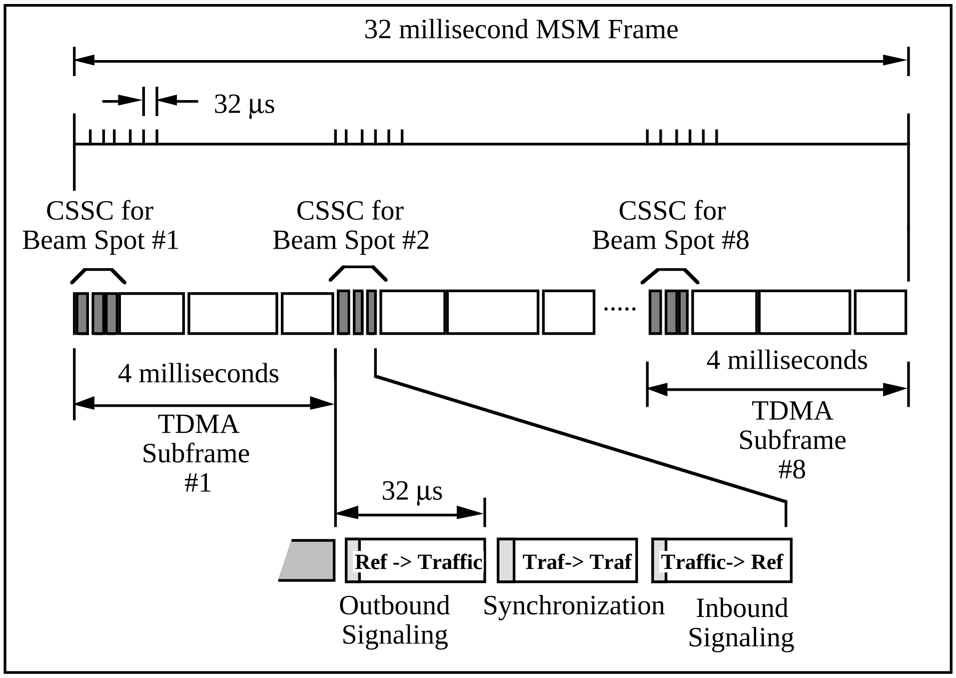

Figure 4 - The CSSC system has a star topology and supports signaling and synchronization for earth stations distributed in up to eight antenna beam spots.

The CSSC slots of successive TDMA Subframes are assigned cyclically to the different beams, in such a way that earth stations located in all participating beam spots have a chance, once per TDMA Frame, to transmit to and receive from the Reference Terminal (inbound and outbound signaling bursts, respectively). The remaining CSSC time slot is a ranging slot, used for direct loop-back synchronization. The Reference Terminal is also capable of relaying CSSC messages between Traffic Terminals.

2) Multiframe and Earth Station Initialization

The TDMA frame architecture includes a simple multiframe structure, shown in Figure 5, to allow multiple earth stations to share a single beam spot and, at the same time, to create a large enough frame area free of signaling and/or data bursts, reserved for initialization of new earth stations. The CSSC time-slots of earth stations physically located in one same beam spot are assigned to successive frames of the multiframe in a round-robin fashion.

The multiframe length (= number of 32-ms frames) can be configured by the NMT operator and is always made larger than the maximum number of earth stations in any of the beam-spots. The CSSC slot areas (96 microseconds each) of the Acquisition Frame (last frame of the multiframe) are reserved for new (or restarting) earth stations to perform initial satellite acquisition. The 96-microsecond acquisition window is wide enough to allow these new earth stations to transmit to the satellite without colliding with adjacent traffic data bursts.

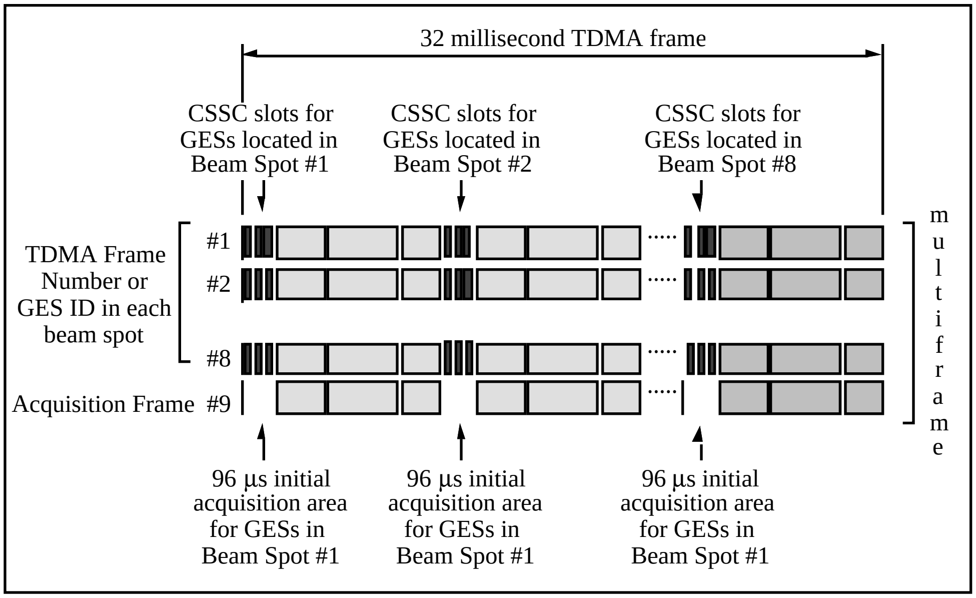

Figure 5 - The multiframe structure allows multiple earth stations to share a single beam spot and creates an acquisition frame with large unused areas for new earth station initial transmissions to the satellite.

3) TDMA - MSM Frame Synchronization

The Reference Terminal and the Traffic Terminals each transmit a Synchronization Burst every multiframe with a dual objective: (1) to perform the round trip measurements required for direct-loopback TDMA frame synchronization, and (2) to track the MSM slot transitions. The synchronization burst extends beyond the end of the MSM synchronization slot and is truncated when the downlink beam sweeps away from the earth station, during the transition from synchronization to inbound CSSC time slot (Figure 6). This truncation causes the burst modem to lose carrier synchronization and then symbol clock synchronization. These truncation times are captured by the earth stations and averaged over time to reduce eventual uncertainties. Tracking of the MSM slot transition times is used for synchronization of the TDMA slots to the on-board MSM slots, and for long-term frequency-lock synchronization of a local 10 MHz oven-controlled VXCO (located in the Digital Terminal) to the MSM frame clock. At the truncation point there is a sharp change on the channel symbol error rate (from ~10E-8 to 0.5 respectively before and after the truncation point). A convenient measuring sequence is used in the system for truncation time measurements.

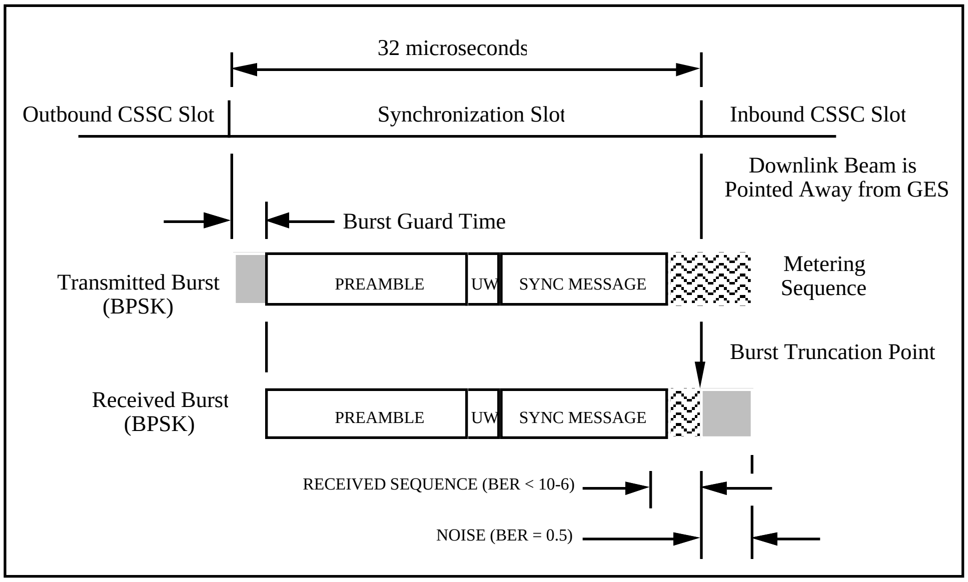

Figure 6 - The truncation of the portion of the synchronization burst that extends beyond the MSM slot boundary allows the Gigabit Earth Stations to "capture" the MSM slot transition timing.

C. System Timing and Performance Measurement

The burst modem front end in the TDMA Controller and Codec board (in the Digital Terminal) collects a number of timing and performance-related parameters for each 32-microsecond time slot. These parameter values are stored in Receive Burst Descriptors and includes information related to (1) UW detection (or not) with corresponding time offset, (2) satellite cell errors (number of valid Reed-Solomon codeword and number of channel bits in error), and (3) received RF Power level (modem AGC signal level sampled at the center of the time slot). The UW detection time provides round trip measurements, used for TDMA frame synchronization purposes. Received RF power level measurements are performed every 32 microseconds, and are used during Traffic Terminal initial acquisition, to provide initial estimates of frame and multiframe boundaries. The RF power level measurements may be used for antenna pointing and for diagnostic purposes.

Timing events are measured with a resolution of 34.5 nanoseconds, corresponding to one clock cycle at 29 MHz or 24 bits at 696 Mb/s. The Network Control Processor in the Digital Terminal can also read information related to the operational status of the burst modem, and the up/down converter 30/20 GHz synthesizers lock to the Digital Terminal 10 MHz local oscillator.

V) SONET Service Over Satellite

A. Internal Structure of the STS-1 Burst

The Gigabit Satellite Network architecture is oriented to supporting SONET-framed data and takes full advantage of the "SONET floating payload" principles to simplify synchronization of end-to-end communications and to reduce the buffers required to accommodate range and range-rate variations (Doppler shift) due to satellite movement.

Data is transmitted over the satellite Reed-Solomon encoded and arranged in blocks of 696-bytes called Satellite Cells (S-Cells). Figure 7 shows the structure of an STS-1 burst when transmitted using OQPSK modulation. It uses ten 32-microsecond time slots (or forty 8-microsecond S-cell slots), with the first S-Cell time-slot being reserved for Guard Time and Burst Preamble.

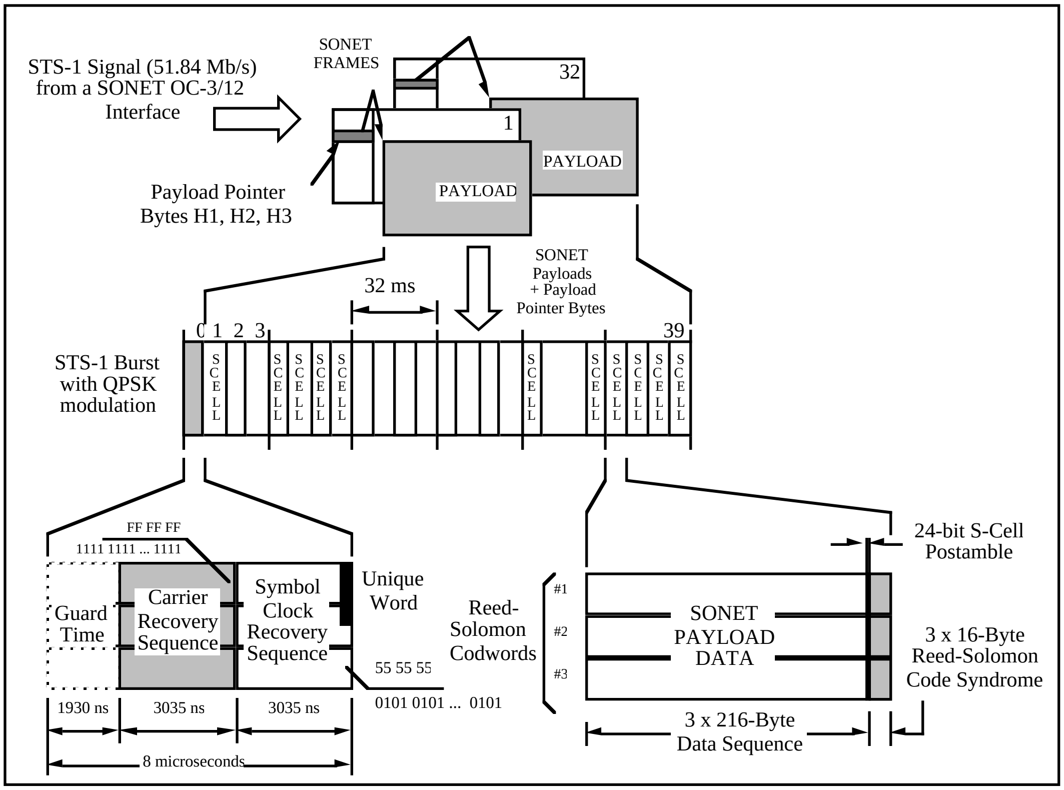

Figure 7 - An STS-1 burst corresponds to ten 32-microsecond time-slots composed of 39 S-Cell time-slots of SONET payload data and one S-Cell time-slot for Guard Time and Burst Preamble.

Each S-Cell is composed of three parallel Reed-Solomon codewords with 232 bytes each. Each codeword is formed by 216 data bytes and 16 redundant check bytes, and is capable of correcting up to 8 byte errors per codeword. Almost all codeword data bytes (215 out of the 216 bytes available) carry end-user SONET payload data, with 1 byte per codeword (3 bytes per S-Cell) used as an S-Cell Postamble. Support of an STS-1 channel over satellite requires transmission of 32 SONET frames (25,152 bytes of payloads plus payload pointers) every 4 milliseconds. This data is transmitted scrambled, in 39 S-Cells (25,155 bytes = 39 x 3 x 215 bytes). Scrambling can be disabled on a per burst basis for testing purposes. Also detailed in Figure 7 are the relative positions and lengths of the Carrier Recovery Sequence (CRS), Symbol Clock Recovery Sequence (SCRS), and UW. The UW is a 37-bit long Barker sequence that, when inserted within the preamble bits used for clock recovery (sequence of 1's and 0's) show very low partial correlation peaks.

B. SONET Interface and Services

The Digital Terminal in the Gigabit Satellite Network performs the function of a standard Line Terminating Equipment (LTE) in the SONET hierarchy [6]. The Digital Terminal can be equipped with OC-3 and OC-12 interfaces, which are individually configured to handle concatenated or non-concatenated signals. In the uplink direction, the incoming STS-1 components of a non-concatenated STS-3 or STS-12 signal first have their payloads separated from their section and line overheads, and are then individually aligned (justified) to an internal 32-ms frame signal, which is phase locked to the satellite MSM frame. The STS-1 signals stripped from their section and line overheads (payload-plus-payload pointers only) are then routed independently over satellite to different earth stations. In the downlink direction, the outgoing OC-3 or OC-12 signal is built first by assembling the aggregate signal from received STS-1 payload plus payload pointer bytes originated in different earth stations, and then by multiplexing these payload signals with locally generated SONET section and line overhead bytes. Table 2 lists the SONET transport overhead signals [7] that will be supported in the deployed network.

Table 2 - Support of Section and Line Overhead Functions in the SONET Interfaces of the Gigabit Satellite Network

Section Overhead	
Framing and STS-1 ID	yes
Section Error Monitoring (BIP-8)	yes
Section DCC, Section Orderwire, and User Channel	no
Line Overhead	
Pointer Bytes and Pointer Action Byte	
- Frequency justification	yes
- Alarm Indication Signal (AIS)	yes
Automatic Protection Switching (APS)	
- Line switchover	no
- Far End Receive Failure (FERF)	yes
Line DCC and Line Orderwire	no

VI) RF and Modem equipment

The Radio Frequency (RF) equipment used with the HDR Ground Stations consists of several unique devices. The modem used in the stations was developed by Motorola Government Systems and Technologies Group. It is a dual-mode burst modem, capable of operating with either offset binary phase-shift keyed (OBPSK), or offset quadrature phase-shift keyed (OQPSK) modulation. The OBPSK modulation is used in the internal signaling bursts (CSSC bursts) and in selected data bursts to provide better performance (at one-half the rate) on thin links--particularly those using the mechanically steerable antenna. For more details on the modem, see reference [8].

The up-and downconverters are of conventional design, translating the 3100 MHz intermediate frequency used by the modem, up to 29.64 GHz for the uplink, and down from 19.36 GHz, for the downlink.

The low-noise amplifier is an off-the-shelf device, with a noise figure of less than 2.4 dB. The transmitter used is manufactured by Varian, and provides greater than 100 Watts of uplink power. The antenna is a 3.4 meter offset-fed type, manufactured by Prodelin.

An interesting anomaly was observed when the RF terminal was first tested with the spacecraft. The RF gear and modem were developed with the assistance of SPW simulations, using a model of the spacecraft channel based on design information. Based on the SPW simulations, conventional QPSK modulation was selected, as the offset variety (OQPSK) demonstrated no performance advantage, and the conventional QPSK was simpler to implement. Although the modem and RF terminal worked properly when tested with a simulator, the performance was severely degraded when used with the spacecraft itself. A committee of various experts was formed , and several theories were developed. The heart of the problem was finally uncovered by the Motorola team, when they switched to offset modulation. The significant performance improvement obtained with offset modulation demonstrated the importance of maintaining a constant envelope RF signal through the spacecraft. Several other minor modifications were eventually incorporated, and this resulted in the entire RF system performing within the original design specification.

VII) HDR Experiments

Several experiments using the GSN are already planned and scheduled. These are primarily of two types: high-speed data transmission. and remote supercomputer access.

The four high-speed data transmission experiments are:

(a) distribution of contribution-quality high-definition television (HDTV)

This work is being led by Public Broadcasting System (PBS)

(b) remote radiology (high-speed transmission of tomographic and radiological images between diagnostic centers).

Two experiments will be performed. One by Mayo Clinic, and one by a team from the University of Hawaii, Ohio Supercomputing Center (OSC) and Georgetown University Hospitals.

(c) remote control of and image transmission from a remote astronomical telescope

This experiment is a joint project between Keck Observatory and Jet Propulsion Lab (JPL).

(d) interconnection of fiber backbones

With the assistance of Sprint Corp, ARPA will attempt to interconnect the MAGIC and ATD Net fiber networks.

The remote supercomputer access experiments are:

(a) collaborative modeling of atmospheric and oceanic systems for a regional and global climate model using paralleled supercomputers

Two experiments will be performed, one by a JPL/Goddard Space Flight Center (GSFC)/George Washington University team, and another by a team from National Center for Atmospheric Research (NCAR) and OSC.

(b) remote access by an airframe manufacturer to a supercomputer for computational fluid dynamics simulation

This experiment is a collaborative effort between Boeing Commercial Aircraft Group and Lewis Research Center.

Table 3 - Performance of Ground Stations during Testing

link	**required Eb/No (dB)**	**measured OQPSK Eb/No (dB)**
Cambridge, MA to Cambridge	**10.9**	**21.0**
Cambridge, MA to Phoenix, AZ	**10.9**	**23.0**

VIII) Link Performance

As development of the ground stations has proceeded, it has been possible to measure the actual performance of the ground stations. Table 3 lists some measured signal-to-noise ratios (Eb/No) for links used during integration and test.

As Ka-band transmissions can be severely affected by rain-fade, the satellite link parameters were selected for operation at very low BER in clear-sky weather and satellite link operation with performance that is comparable to fiber-optics (BER < 10^{-11}) during at least 99.0% of the time (rain-fade availability). Based on the measured ground station performance data from Table 3, and using the actual spacecraft performance (as measured on-orbit) it is possible to predict the expected performance for several links. Table 4 lists the expected performance for several sites. Also shown are the corresponding margins and expected availability [9]. The *uplink* margin assumes a clear sky downlink, and vice versa.

Table 4 - ACTS Link Parameters for Some Sample Links

uplink location	**downlink location**	**uplink margin (dB)**	**uplink availability (%)**	**downlink margin (dB)**	**downlink availability (%)**
Washington	**Los Angeles**	**6.3**	**99.4**	**4.0**	**99.9**
Los Angeles	**Washington**	**7.0**	**99.9**	**4.3**	**99.6**
Cleveland	**Seattle**	**10.3**	**99.8**	**5.5**	**99.9**
Seattle	**Cleveland**	**7.1**	**99.9**	**6.0**	**99.8**
Denver	**Columbus**	**7.4**	**99.9**	**4.3**	**99.2**
Columbus	**Denver**	**5.9**	**99.4**	**4.5**	**99.9**
Phoenix	**Kansas City**	**7.1**	**99.9**	**5.7**	**99.5**
Kansas City	**Phoenix**	**9.5**	**99.7**	**5.9**	**99.9**

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