

# **STAR TOPOLOGY SPACECRAFT DATA BUS**

**Anthony G. Garas  
Sperry Corporation  
Aerospace & Marine Group  
Space Systems Division  
Glendale, Arizona**

## **ABSTRACT**

Significant advances in processing power and hardware miniaturization for aerospace applications has led to new distributed avionics architectures. These architectures have driven system data transmission requirements to the point where current data communications and interconnect technologies are marginal or inadequate. Advanced spacecraft including Space Station and SDI platforms have identified the need for distributed processing and real time control, requiring large and complex data communications networks with bus data rates in the 100 to 500 MBPS range.

To address this need a new communications protocol has been developed to provide high data rate and very short transport delay performance. The protocol is implemented using a star topology fiber optic data bus. During the design of this system for spacecraft data bus applications, particular attention was paid to system robustness, redundancy, fault tolerance, autonomy, and error control.

The salient system design, hardware configuration, and performance of an eight node demonstration network jointly developed by NASA Goddard and Sperry Corporation are presented in this paper.

## **INTRODUCTION**

This paper describes a Local Area Network (LAN) that was developed to demonstrate the feasibility of 100 MBPS bus data rates, in a 32-node network, that incorporates the major features required for spacecraft operation. Over 2 years of design and development was required to define system specifications, develop a new media access protocol, and brassboard an eight Network Interface Unit (NIU) implementation of the network. The network topology, media access protocol, and network interface unit were designed to demonstrate a network with a high degree of robustness, media efficiency, and fault tolerance. The network implements distributed control concepts that provide for network

self-configuration (self-start), restart, automatic adjustment to changing network loading, and automatic redundancy.

The media access protocol developed for the network incorporates the most attractive aspects of token passing and contention protocols. The protocol provides the self-starting features and low transport delays at light network loading of Ethernet like protocols, and for the bounded transport delays at high network loading provided by fixed or demand assignment protocols. Performance evaluation of the eight node system was accomplished using a system exerciser/analyzer capable of stimulating the network at high data loading. Exerciser capabilities allowed for the full evaluation of protocol features and direct monitoring of network performance. Verification of proper network behavior was performed at bus data rates of up to 97 MBPS, and NIU-to-NIU data throughput rates of up to 20 MBPS.

This star bus demonstration network was developed under a NASA Goddard Space Flight Center contract and is called the Fiber Optic Demonstration System (FODS) or STARBUS network. During the program, primary emphasis was placed on the high speed physical and data link layers of the network. The STARBUS network layers are consistent with the International Standards Organization (ISO) reference model for Open Systems Interconnect.

## **NETWORK DESCRIPTION**

The STARBUS system derives its name from the passive star topology that implements the nodal interconnect scheme. The star topology was selected for the spacecraft data bus application over ring and linear bus topologies on the basis of providing flexibility of protocol design, ease of system configuration management and network growth, as well as yielding the lowest input power requirements for a given network size and data rate. The star topology enjoys these advantages primarily due to its broadcast property, the ability of any node to communicate with all other nodes on the network without repeating the message, and the transmissive star coupler implementation providing the lowest loss of all fiber optic distribution systems. With only 2 to 3 dB excess loss, the power splitting loss of the coupler predominates the system distribution loss, and that loss increases logarithmically with the number of network nodes. The maximum size of a passive STARBUS network is set by the level of source and detector technology employed. For a 100 MBPS bus data rate, high-radiance light emitting diodes (LEDs) and PIN photodiodes can support networks of between 20 and 32 nodes, while injection laser diodes (ILDs) and avalanche photodiodes (APDs) can support networks of 100 and 200 nodes.

The STARBUS demonstration system was scaled to provide for up to 32-node operation using LED sources, PIN photodiodes, and radiation hardened 200 micron core 400 MHz/Km fiber optic media. 20X20 and 32X32 port passive star couplers with a maximum excess loss of 3 dB were fabricated out of the same radiation hardened fiber to ensure optimal media performance. Figure 1 illustrates the STARBUS network configuration. Each network interface unit is connected to the star coupler through 25 meters of fiber optic cable, yielding a maximum extent of 50 meters for the demonstration system. A network extent of several hundred meters is possible with minor protocol parameter adjustments. The NIU-to-NIU data throughput rate of the network was selected to be 20 MBPS to accommodate high rate data sources and sinks such as imaging sensors and optical disk memories.

The network hardware elements of the demonstration system consisting of the star coupler, fiber optic cable, and network interface unit implement the physical and data link layers of the ISO model.

The physical layer of the network provides the mechanical, optical, and functional means to accomplish the physical connections for data bit transmission between data link layer entities. The functional and physical characteristics of the STARBUS demonstration system physical layer include the following:

- Bi-phase bit encoding/decoding
- Electrical to optical conversions
- Clock recovery and NRZ bit conversion
- Carrier sense and collision detection to support broadcast bus and contention access protocols
- Collision control: Collision signal transmitted to contending NIUs to affect transition to time slot protocol mode
- Redundancy: Dual NIU transmission and reception, with channel selection
- BITE: Permit test of backup bus, automatic primary/backup NIU redundancy, and blabbermouth shutdown
- Coupler: Passive star, central or distributed
- Medium: Radiation hardened multimode fiber optic-cable
- Mechanical: FSMA connectors
- Optical: LED at 815 nm

The data link layer provides the functional and procedural means to implement data link connections for data packet transfer between network entities. The data link layer performs three major functions: media access control, packet formatting, and connection control. The media access control protocol is selectable within the system by a hardware strap in each NIU and includes the primary contention protocol, and the secondary time

slot protocol. Both of these protocols provide for collision avoidance, collision detection, and contention resolution. Both access protocols are decentralized, self-starting, and insensitive to failed or unpowered nodes.

The STARBUS packet format illustrated in Figure 2 includes fields that provide synchronization, identifiers, addressing, supervisory command and control, user data, and error detection. The command control field provides network control versatility by allowing for remote diagnostic tests, configuration control, and system statistical trend data acquisition.

The network supports point-to-point message transactions and broadcast messages. Broadcast transmission addresses all NIUs, while point-to-point transmission addresses a specific node.

Point-to-point messages are verified by an acknowledge flag. Broadcast messages are verified by the successful reception of the message by the sending NIU. This is possible because with a star topology, the transmitting node knows that the message was successfully passed to the output side of the star coupler, if that node has received the broadcast message. The network can support connection retry, in the event a connection was not confirmed through an acknowledge transmission or source reception of a broadcast.

## **MEDIA ACCESS PROTOCOL**

The STARBUS demonstration network utilizes a dual mode protocol that combines the best features of both contention and fixed (or demand) access schemes. Figure 3 illustrates the CSMA/CD/TS state diagram and time line. The protocol features a primary contention mode using Carrier Sensing with Multiple Access and Collision Detection, and Time Slot contention resolution. The CSMA/CD/TS protocol dynamically adjusts to varying network loading and optimizes the network transport efficiency and transport delay parameters. Under relatively light network loading of less than 60 MBPS, the primary CSMA/CD protocol mode is in effect for nearly 100 percent of all bus transmissions. In this mode, an NIU with data to transmit monitors the bus activity and transmits a data packet only when the bus is free. If, however, two or more NIUs with data to transmit determine that the bus is available at the same time, a collision will occur on the bus. In the event of a collision, all NIUs involved sense an invalid bit coding pattern. Data packet transmission is terminated, and a collision detected (jamming) signal is transmitted. All NIUs hold off bus access and switch to the time slot mode protocol for contention resolution. The network then affects an ordered time slot bus access scheme allowing each NIU to transmit a single data packet. The time slot width is the time needed for an NIU with data ready to access the media, and/or Tgap microseconds wide. If an

NIU has no data to transmit or is not active, no transmission is required for continuation of the ordered access protocol mode. After all NIUs have been given access to the bus (one cycle of the time slot mode), the network re-enters the random access mode. During the transition from the time slot to the random access mode, a random time delay is inserted to reduce the possibility of the network immediately generating a collision due to pent up demand incurred while in the time slot mode.

The CSMA/CD/TS protocol performance is similar to other random access protocols. However as network loading increases, the CSMA/CD/TS protocol does not experience excessive transfer delays generated by the retry algorithms of CSMA/CD protocols. Even under very high network loading the transport delay is bounded, and the performance is almost identical to a similar sized token passing ring.

## **REDUNDANCY**

Node failures in some systems can have catastrophic effects on the operation of the network, preventing the operation of unfailed nodes. The most susceptible component of the STARBUS network is the star coupler. Although the coupler is passive and therefore presents an extremely reliable design, it is still a susceptible component to a single point failure. To address this possibility, the STARBUS demonstration network has been designed to support distributed redundancy, including a dual-channel, cross-strapped optical bus. Figure 4 shows the redundant configuration of the STARBUS. Thirty-two NIUs configured as 16 redundant pairs can be supported if two 32X32 star couplers are used. Up to 32 redundant pairs can be used if 64X64 couplers are incorporated. Two types of redundancy are implemented: redundant optical channels and redundant NIUs. Both types are controlled autonomously at each node with an optional network commanded override capability. This approach provides for distributed redundancy management requiring no centralized system manager.

The redundant optical interface incorporates two star couplers, dual transmitters and dual receivers. Each active NIU transmits identical information over both optical channels using two separate transmitters. The receiving NIU autonomously selects the active channel if a failure has occurred; it selects the primary channel if no failure has occurred and both channels are active. In this way, without the intervention of a centralized redundancy manager, communication is maintained, even if a transmitter, cable, coupler, or receiver fails. Another advantage of this cross-strapped redundancy technique is that the switchover to the backup optical channel is not necessary for all nodes if only one node fails.

NIUs are also capable of configuration in a redundant role. The backup NIU monitors the primary NIU's health via a toggling signal between the two units. The toggling signal's

presence is the result of properly executed built-in test sequences performed as a background task. Lack of the toggle will automatically cause the primary NIU to enter standby mode and the backup NIU to enter the active state and assume node responsibilities.

## **NETWORK INTERFACE UNIT**

Figure 5 shows the basic system operation. Each NIU is composed of a Front-End Processor (FEP) and a network interface, with the network interface handling the 100 MBPS network transactions and the FEP handling the user interfaces. The FEP in the source NIU accepts data from one of four users and will transfer the user data to the network interface for output onto the optical bus. The network interface then encapsulates the user data, provides bus access, bit encodes the total packet, and transmits the packet via the passive optical coupler to the destination NIU.

The destination NIU's network interface receives the packet. The success of this reception is determined by three parameters: Correct NIU address, reception of an error-free packet, and an empty receive buffer in the network interface. Assuming these three basic conditions are met, the network interface will respond to the received packet with a "good acknowledge" packet transmitted back to the source NIU. The network interface in the sourced NIU then verifies the successful transmission via the received acknowledge packet and, in conjunction with the FEP, logs a successful transmission. The destination NIU then, under control of its FEP, routes the user data to one of four users of the network node. Should a transmission error occur, or the receive buffer in the destination NIU be full, an acknowledge is issued indicating that the transmission has not been received successfully. The source NIU, under control of its FEP, will retransmit the packet if a bad acknowledge is received. The number and frequency of these retries is programmable within the FEP of each NIU. The packet evaluation and acknowledge transmission is performed in NIU hardware and takes less than 3 microseconds, incurring very little transport delay overhead time.

## **SYSTEM EVALUATION RESULTS**

The initial STARBUS evaluation has been completed, and four basic areas of performance have been evaluated.

Network Delay - Network delays were measured and compared to calculated results to demonstrate proper system and protocol operation. The test setup to evaluate the network delays is shown in Figure 6. It uses eight NIUs, a 20X20 star coupler, and the STARBUS test exerciser. The exerciser transmits and receives data to and from the NIUs, and subsequently measures delay and verifies data integrity. The network delays are

determined by measuring the transport delay (unloaded network delay) plus access delay due to the bus being busy or due to the occurrence of collisions. Network delays were measured under four different conditions.

<u>Condition</u>	<u>Network Busy</u>	<u>Collision</u>
1	No	No
2	Yes (1)	No
3	---	Yes
4	Yes (2)	Yes (2)

- (1) Due to known network loading from a single NIU.
- (2) Due to random network loading from other NIUs.

Conditions 1 through 3 exercise the STARBUS network to verify basic protocol operation. Condition 1 verifies point-to-point delay under a no-load condition, thus verifying proper transmission frequency and NIU-to-NIU interaction. Condition 2 verifies proper sensing of network activity (collision avoidance). Condition 3 verifies proper collision detection and subsequent time slot operation and timing.

Condition 4 is a verification of the STARBUS network under actual working conditions. Two tests were made: one with four NIUs transmitting, each at maximum throughput (20 MBPS), the second with six NIUs transmitting. These tests exercise the network for bus loads from 28 to 97.4 MBPS.

The results of the evaluation test for conditions 1 through 3 are shown in Figure 7. A 16384-bit packet was used for all tests. All measured values fall well-within the calculated values. Also note that the additional delays as a result of a collision, at about 3 microseconds (171 microseconds minus 168 microseconds), add very minimally to the network delay.

The results of condition 4 tests are shown in Figures 8 and 9. Figure 8 shows the results with four NIUs transmitting. Figure 9 shows the results with six NIUs transmitting. The actual measured delays correlate well with the predicted math model results. The differences between actual and predicted results are attributed mainly to the fact that the exerciser currently does not accurately simulate a Poisson distribution for packet interarrival times. The Poisson distribution gives longer delays than the fixed interval rates provided by the exerciser.

NIU/Network Throughput - Throughput was evaluated under two different conditions: Condition 1 - point-to-point using a 16384-bit packet with no other network loading and

condition 2 - point-to-point using 16384-bit packets with an attempted network overload. Condition 1 verifies that the NIU is capable of > 20 MBPS throughput. Condition 2 verifies the network robustness and the associated NIU throughput under an attempted overload condition.

Condition	NIU Throughput	Network Loading
1	20.28 MBPS	20.6 MBPS
2	16 MBPS (average)	97.4 MBPS

Autonomous Redundancy Operation - The test setup for the redundancy evaluation is shown in Figure 10. Both types of redundancy were evaluated. Autonomous optical bus switching was tested by putting NIU 0 into self-test, transmitting onto the optical network, and receiving and verifying its own transmissions. Transmitter A was disconnected and no change in operation was observed. Transmitter A was reconnected and transmitter B was disconnected. Again no change in operation was observed, proving the feasibility of the STARBUS dual-optical bus technique.

Autonomous primary/backup NIU switchover was demonstrated by artificially inducing a failure in the primary NIU. Upon failure, the primary NIU entered standby mode (receiving power only) and the backup NIU powered up and initialized. This was observed via the status monitor and the primary/backup console activity.

Optical System Evaluation - The measure performance of the optical system has been adequate for the present system using a 20X20 star coupler. The performance, however, was limited by 1984 component technology. Today's technology offers improved LED emitters and receivers. Figure 11 shows the measured power loss budget for the present system and the predicted power/loss budget for the upgraded system using current technology. Note that the present system works well over all but the very worst-case paths. The upgraded system goes a step further, providing at least a 7.3-dB margin using a 32X32 star coupler. With this much margin, larger couplers (64X64) could be used while still maintaining greater than 4 dB margin over the worst-case path.

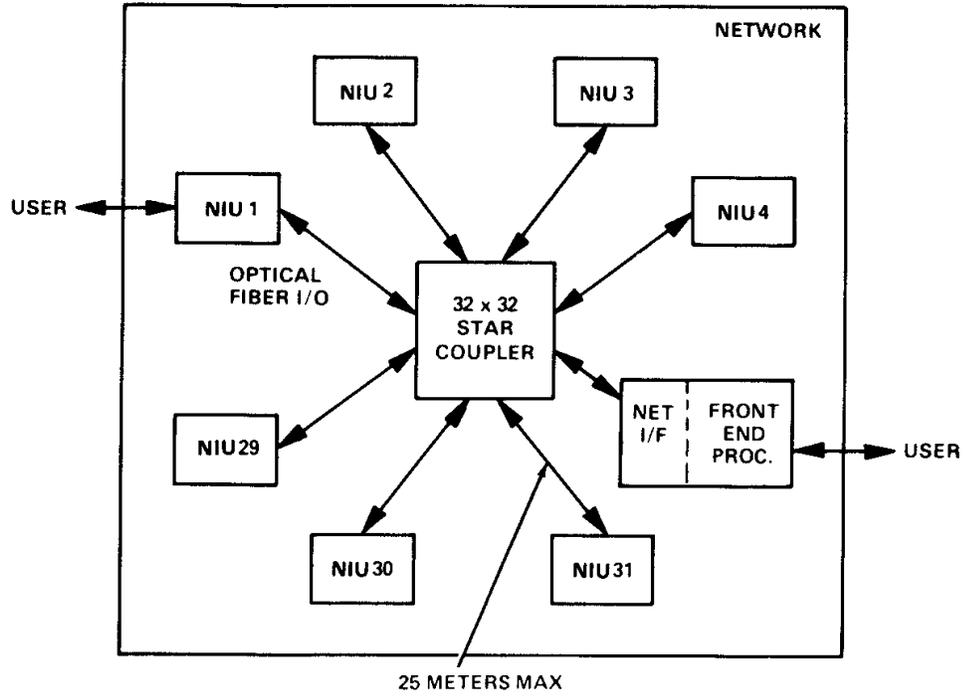
In addition to the power loss measurements, environmental tests were conducted on a 20X20 coupler. The coupler was subjected to both vibration and radiation without any adverse affects. The coupler was subsequently run successfully in the STARBUS demonstration system.

## **UPGRADE TO FLIGHT HARDWARE**

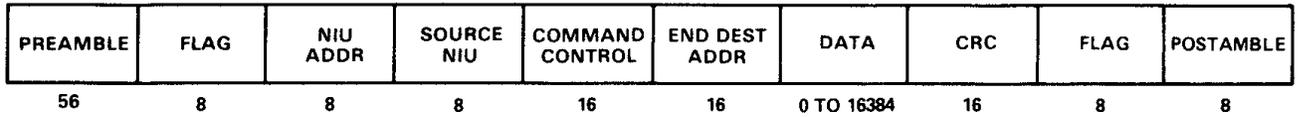
Substantial efforts are underway to continue the development of the STARBUS data link layer toward a flight qualifiable system. A second generation physical layer and Media Access Controller (MAC) design is in process. The goal of this refinement effort is to develop an implementation, with sufficient optical communications loop margin, to accommodate worst-case condition in low earth orbit environments for long duration missions. In conjunction with the hardware design effort, a portion of the high speed (and high power dissipation) ECL circuitry is being implemented in a lower power GaAs gate array. The application of this new GaAs semiconductor technology will allow the physical and data link functions to be implemented by six VLSI circuits, consuming approximately 10 watts, and residing on a single circuit card. It is anticipated that the use of the lower power GaAs VLSI circuits will allow for optical bus data rates of between 300 and 500 MBPS, and NIU-to-NIU throughputs of greater than 50 MBPS. No change in the media access protocol will be required to accommodate these higher data rates.

## **SUMMARY**

The STARBUS local area network employing the CSMA/CD/TS protocol has successfully demonstrated network performance and system characteristics that are required for advanced spacecraft data bus applications. The network provides for fully autonomous network initiation and configuration management, without a centralized controller. Both the media access protocol and hardware configuration provide for fault tolerance through robust data transfer, error control, and failure management. Hardware evaluations of the eight node network have verified the transfer delay performance over a wide range of data loading conditions. The STARBUS system attributes and demonstrated performance characteristics make it an excellent candidate for high performance spaceborne local area network applications.

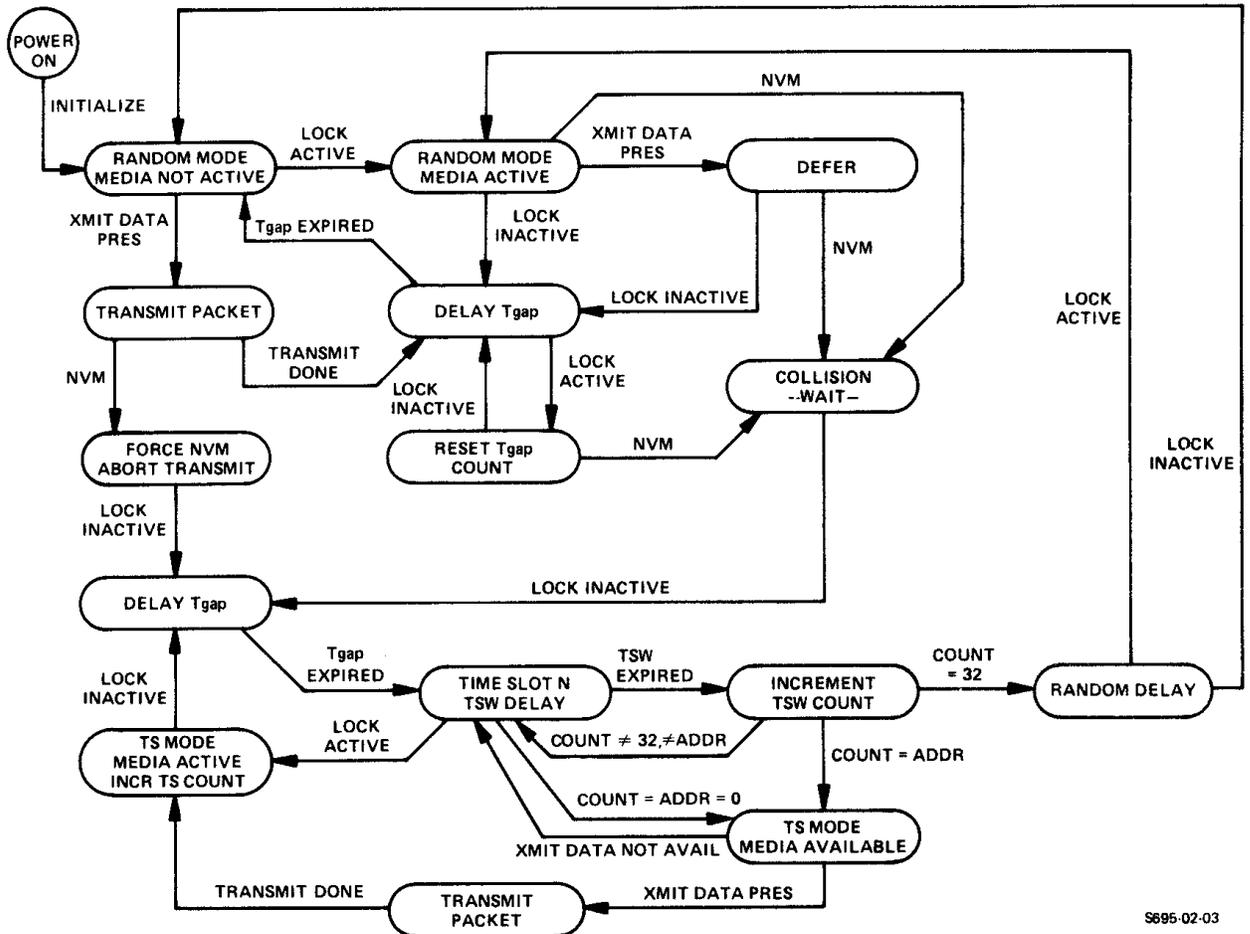


**Figure 1**  
**STARBUS Network Configuration**

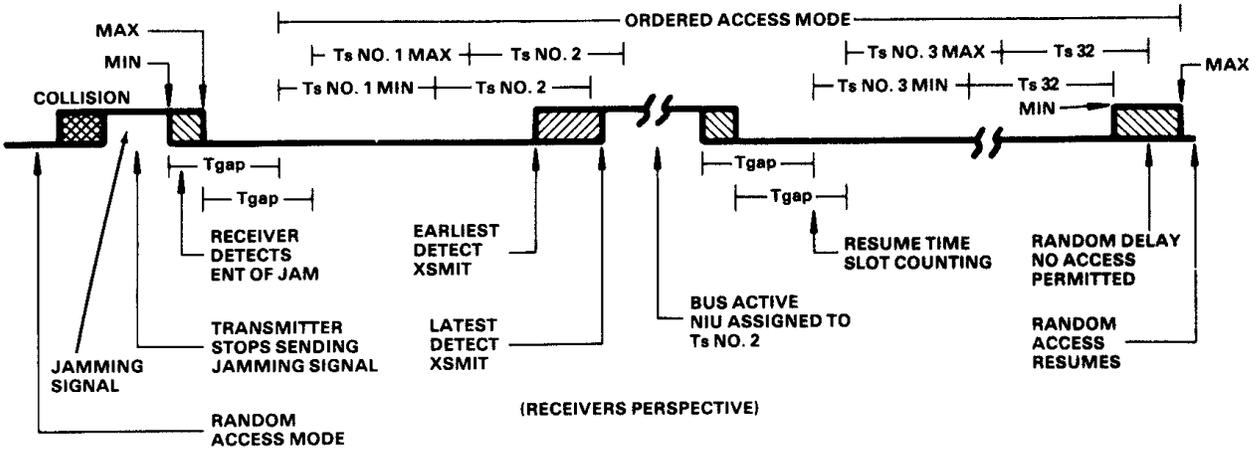


S695-02-01

**Figure 2**  
**STARBUS Protocol Data Packet Format**



S695-02-03

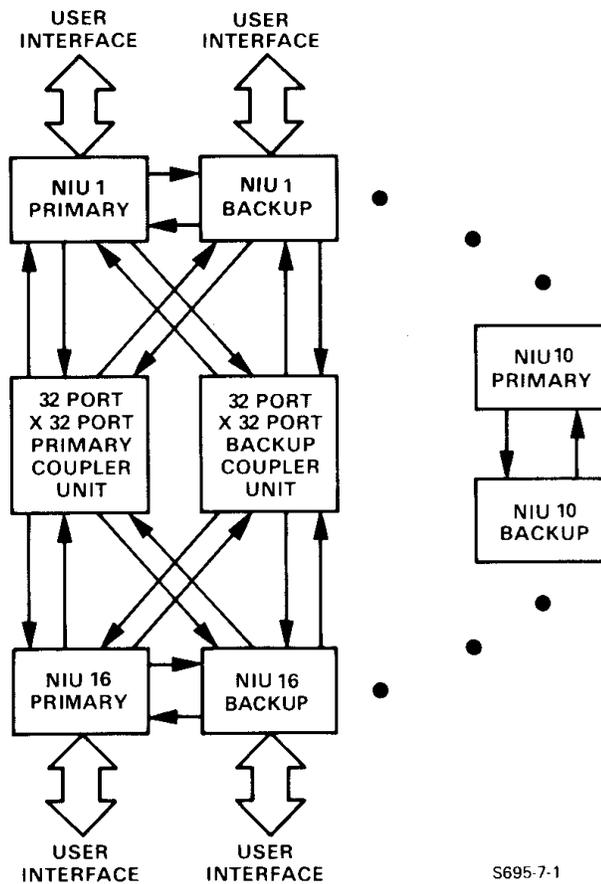


TIME SLOT WIDTH (TSW) = 1.2μS

FODS TIMELINE - TRANSITION FROM RANDOM TO ORDERED ACCESS MODE

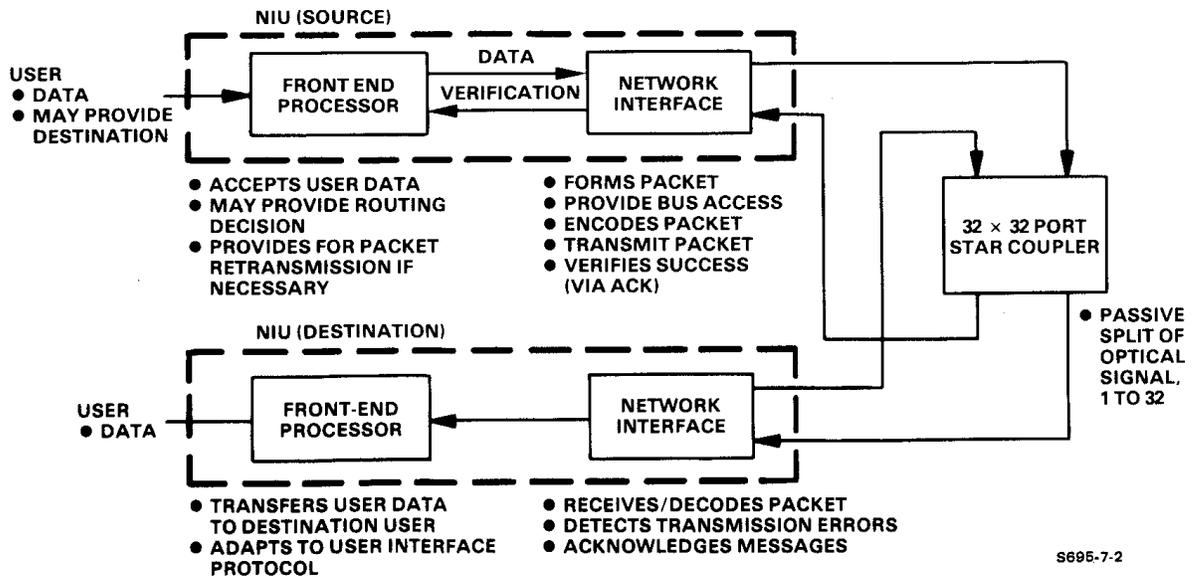
S695-02-04

Figure 3  
CSMA/CD/TS State Diagram and Time Line



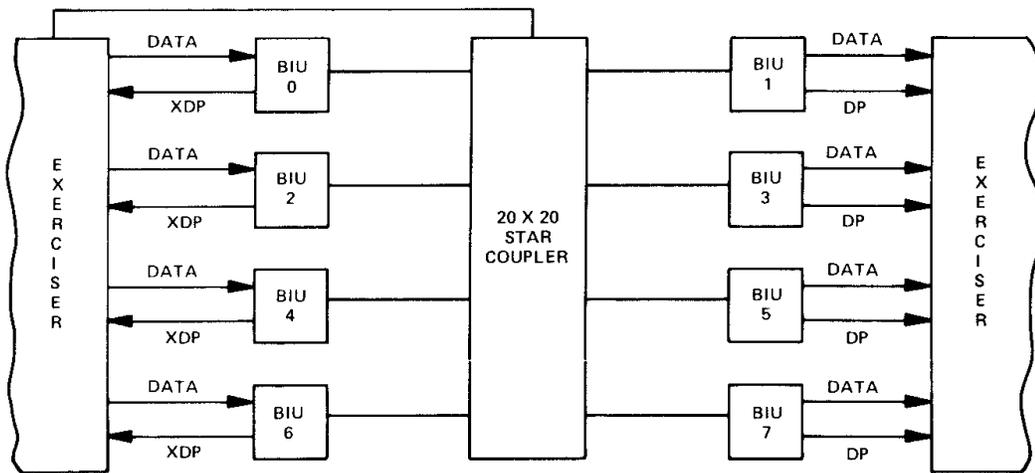
S695-7-1

**Figure 4**  
**Network Redundancy Configuration**



S695-7-2

**Figure 5**  
**Basic NIU-to-NIU Communication**



XDP, "TRANSMIT DATA PRESENT," INDICATES THE NIU HAS DATA TO PUT ON THE NETWORK.

DP, "DATA PRESENT," INDICATES THE DATA HAS BEEN SUCCESSFULLY RECEIVED.

NETWORK DELAY = TIME BETWEEN XDP AND DP.

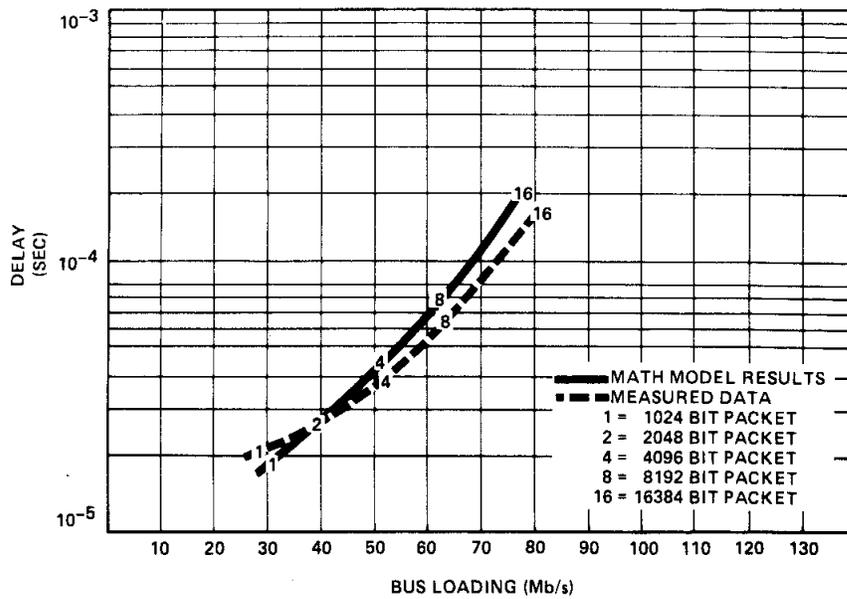
S715-32-7

**Figure 6**  
**Network Delay Test Setup**

	GOOD DATA RECEIVED	NETWORK DELAY (MICROSECONDS)	
		CALCULATED	MEASURED(AVERAGE)
<u>CONDITION 1</u>			
<b>NIU 0 TO NIU 1</b>	YES	167.7 ± 0.5	167.55
<u>CONDITION 2</u>			
<b>NIU 0 TO NIU 1 (START AT t = 0)</b>	YES	167.7 ± 0.5	167.5
<b>NIU 2 TO NIU 3 (START AT t = 10 MICROSECONDS)</b>	YES	325.4 ± 6	328.05
<u>CONDITION 3</u>			
<b>NIU 0 TO NIU 1 (START AT t = 0)</b>	YES	171.3 ± 0.5	171.05
<b>NIU 2 TO NIU 3 (START AT t = 0)</b>	YES	343.2 ± 6	343.95

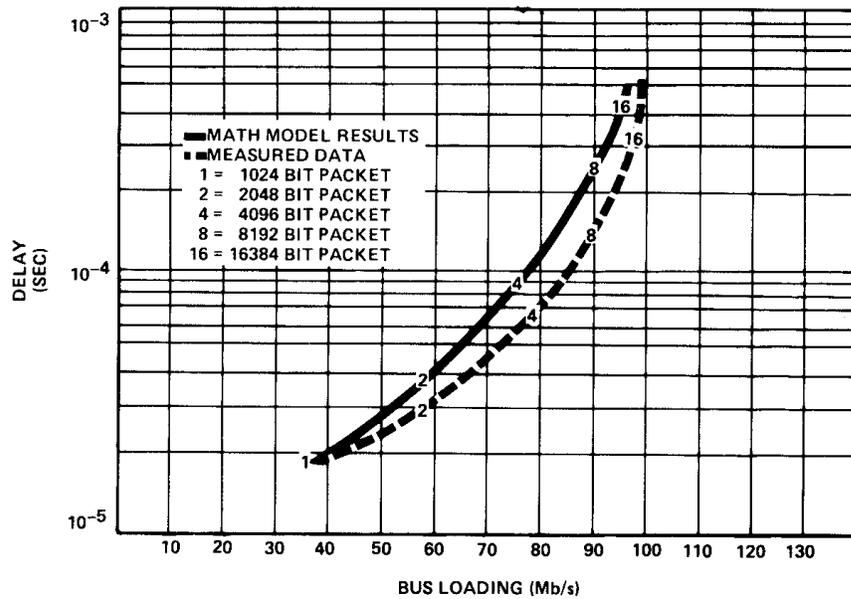
S695-7-4

**Figure 7**  
**Network Delay Test Conditions**



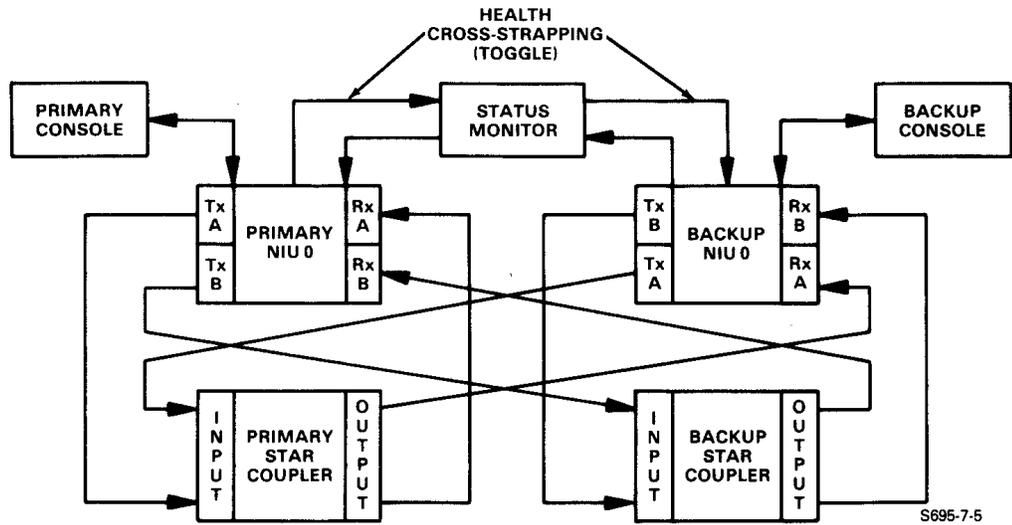
S715-32-8

**Figure 8**  
Network Delay (4 NIUs)



S715-32-9

**Figure 9**  
Network Delay (6 BIUs)



**Figure 10**  
**Redundancy Evaluation Test Setup**

PARAMETER	PRESENT SYSTEM (W/20 x 20)	UPGRADED SYSTEM (W/32 x 32)
LAUNCHED POWER	-1.6 dbm	+0.6 dbm
CONNECTOR LOSSES	2.2 db	2.2 db
FIBER LOSS	1.5 db	1.0 db
STAR COUPLER (AVG/WORSTCASE)	15.5/18.5 db	17.5/19.1 db
DETECTOR COUPLING LOSS	1 db	1 db
RECEIVER SENSITIVITY	-24.6 dbm	-30 dbm
MARGIN (AVG/WORSTCASE)	+2.8 db/ -.2 db	+8.9 db/ +7.3 db

S695-7-6

**Figure 11**  
**Optical Performance Data**