HIGH SPEED FIBER OPTIC TELEMETRY SYSTEM FOR AN UNMANNED, TETHERED, UNDERWATER VEHICLE

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ABSTRACT

The Naval Ocean Systems Center (NOSC) has developed the Advanced Tethered Vehicle (ATV) that can perform a variety of tasks at ocean depths to 20,000 feet. The ATV employs a bidirectional, fiber optic telemetry system. The design of the telemetry was validated by at-sea testing and its reliability contributed to the ATV's successful deep ocean operations.

The telemetry system transmits commands to the vehicle, and two videos and sensor data to the surface over a single optical fiber. Design requirements, descriptions, and implementation of a high speed 200 Megabits-per-second (Mbps) uplink and a 5 Mbps downlink Time Division Multiplexed telemetry system are discussed in this paper.

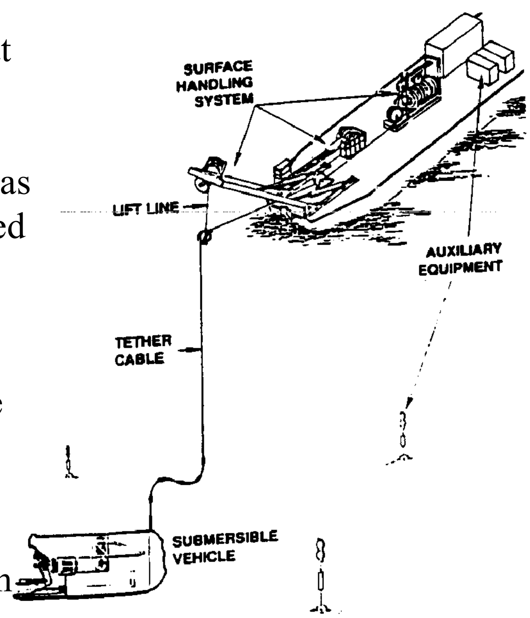

Figure 1

SYSTEM CONCEPT

Figure 1 shows the overall concept of the ATV system. The system [1] consists of an undersea work vehicle, a tether cable, a surface handling system, and a control van. The submersible vehicle performs work missions such as installation, maintenance, repair, rescue, or recovery. Five thrusters, a deep ocean navigation system, and various sensors onboard the vehicle are employed by the operator to guide the vehicle to the work site. To perform its mission, the vehicle has two state-of-the-art, position controlled, force feedback manipulators and a variety of tools. Six TV cameras, including a stereo pair, provide visual feedback.

Attached to this vehicle is a tether cable which is comprised of three electrical conductors, three optical fibers, and kevlar strength members [1]. Signals are multiplexed over one of the three optical fibers, while electrical power is transmitted over the three electrical conductors.

At the surface, the handling system launches and recovers the vehicle, and manages the tether cable. The control van houses the operators, the control consoles, and the electronics necessary to operate and to communicate with the vehicle. The auxiliary equipments include two power generators and navigation acoustic transponders.

TELEMETRY REQUIREMENTS

The telemetry system provides full duplex communications between the surface and the vehicle. Transmission of the command signals is required to control the vehicle and the transmission of video and sensor signals is required to monitor the vehicle. This full duplex communications system is required to operate over 23,000 feet of fiber optic cable.

There are two links between the vehicle and the control station: the uplink and the downlink. The uplink channel is the data link from the vehicle to the control station. The downlink channel is the data link from the control station to the vehicle. The major characteristics of the uplink and downlink signals are described in Table 1.

Uplink Signal Requirements

Signal	Data Type	Bandwidth/Bitrate
Video 1	Analog, 1Vp-p	4 MHZ
Video 2	Analog, 1Vp-p	4 MHZ
Instrumentation	Digital, TTL level	20.8 kbps
Sonar	Digital, TTL level	64 kbps
Navigation Sync	Digital, TTL level	< 1 Hz
Depth	Digital, TTL level	40 kHz
Left Manipulator	Digital, TTL level	20 kbps
Right Manipulator	Digital, TTL level	20 kbps
Hydrophone 1	Analog, 1Vp-p	130 kHz
Hydrophone 2	Analog, 1Vp-p	130 kHz

Downlink Signal Requirements

Signal	Data Type	Bandwidth
Vehicle command	Digital, TTL level	20.8 kbps
Sonar	Digital, TTL level	9.8 kbps
Left Manipulator	Digital, TTL level	20 kbps
Right Manipulator	Digital, TTL level	20 kbps
Emergency command	Digital, TTL level	I to 3.5 kHz

Table 1

TELEMETRY CONFIGURATION

Figure 2 shows the major components of the telemetry system. The use of Wavelength Division Multiplexers permits simultaneous transmission of the uplink and downlink signals over a single optical fiber. The downlink optical signal is combined with the received uplink optical signal in an optical duplexer using wavelength division multiplexing. A duplexer with a dichroic filter is used to separate and integrate the two optical wavelengths of transmission. The uplink signal is transmitted at an optical wavelength of 1300 nanometers and the downlink signal is transmitted at the 1550 nanometers. The optical power budget is described in Table 2.

Optical Power Budget

	Uplink 1300 nanometers	Downlink 1550 nanometers
Source	-3.0 dBm	-20.0 dBm
Duplexers	2.8 dB	2.8 dB
Slip ring	1.9 dB	4.1 dB
Optical switches	2.6 dB	2.6 dB
Cable loss*	5.6 dB	5.6 dB
Optical penetrator	1.1 dB	1.8 dB
Connectors	6.0 dB	6.0 dB
Received power	-23.0 dBm	-42.9 dBm
Receiver sensitivity	-32.0 dBm	-52.0 dBm
Excess power	9.0 dB	9.1 dB

*Cable loss is measured at maximum load and stress conditions.[1]

Table 2

The fiber transmitting the full duplexed signal is connected to an optical slip ring in the storage reel. The fiber from the slip ring is connected to optical switches which are connected to the three fibers in the tether cable. The switches route the full duplexed optical signal to one of the three fibers in the tether cable. The three fibers are 50/125 (core/cladding) micron graded-index multimode fibers.

The three fibers are separated from electrical conductors in a pressurized, oil-filled breakout housing at the vehicle. Because the ATV was designed with a modular approach, optical connectors were used in many places to allow quick connect and disconnect of the fibers. The three optical connector pairs in the breakout housing must withstand a differential pressure of 10,000 psi. This connector was proof tested through hydrostatic pressure qualification testing.

Each fiber is then terminated to its own Electro-Optical (E/0) housing through an optical penetrator that was invented at NOSC [2]. This pressure penetrator was a developmental item. The survivability of the penetrators was a concern even though they were hydrostatically tested to 10,000 psi. Therefore, three separate E/O housings with identical laser transmitter modules and optical receiver circuits were used to provide redundancy in an event a failure occurs in any of the E/O housings. This concern was proven to be over emphasized because there were no failures in any of E/O housing in all the dives.

A special concern during the conceptual stage of the development was the bandwidth of the multimode fibers over 23,000 feet of cable. As it turned out, the fibers were manufactured with excellent performance specifications. The three fibers were tested to have electrical bandwidths of 402, 263, and 297 MHz. If the fibers are band-limited, then an equalization filter has to be used to compensate for the band limitation. As it turned out, a simple 200 MHz PINFET optical receiver was used without the need for equalization.

UPLINK TELEMETRY CONFIGURATION

The ATV telemetry system uses Time Division Multiplexing (TDM) to transmit video and sensor information to the surface. The ATV uplink telemetry is made up of several tiers of data multiplexers. This multiplexer in the TDM scheme divides the time domain into time slots or bits. The main uplink multiplexing circuits block diagram is illustrated in Figure 3. The uplink serial data stream contains 18 bits for each message frame.

This message frame is divided into two 9-bit fields. The first field consists of a message sync bit, the 7-bit video, and the analog subchannel bit. The second field consists of the 8-bit video and the digital subchannel bit. The frame rate was chosen as 11.1 MHZ to meet the Nyquist sampling rate criteria for the NTSC video signal which is the highest bandwidth signal. The data rate is derived as follows.

7 bits (video) + 1 bit (analog subchannel) + 8 bits (video) + 1 bit (digital subchannel) + 1 bit (message sync) = 18 bits

18 bits X 11.1 MHZ = 200 Mbps

This multiplexer uses both high speed ECL circuits wherever needed and low speed TTL circuits. The use of these high speed ECL circuits demanded special design considerations. The division of the ECL and TTL circuits were critical to minimize the use of power hungry ECL circuits and to decrease circuit complexity. All vehicle electronics were limited to boards with dimensions of 3.5 by 3.5 inches and were enclosed in an underwater housing with minimal thermal transfer. The circuits were partitioned to decrease complexity and minimize thermal hot spots. In addition, the lengths of the coaxial cables between circuits were critical in properly phasing the clocks with the serial data.

UPLINK MULTIPLEXING

Multiplexers

The top tier is a 9 bits to 1 bit parallel-to-serial multiplexer. The first 9-bit field is loaded into the 9 to 1 parallel to serial shift register. The two 9-bit fields share the same bus because only a 9-bit bus was used. This 9-bit bus is actually the second tier of multiplexer because it acts as a 2 to 1 Multiplexer. After the first field is loaded and shifted out, the second 9-bit field is then loaded and shifted out. The 9 to 1 parallel-to-serial shift register loads the data at a rate of 22.2 MHZ and shifts the serial data out at a rate of 200 MHZ.

Message Sync

In a synchronous system, the successive frames are usually made up of a fixed number of bits, in this case, the frame is made up of 18 bits. The problem then becomes that of properly phasing the frame timing. This is usually accomplished by using a preamble code or reserving one bit for frame synchronization. A message sync bit is used here to identify the order of the frame as to enable the demultiplexer to synchronize the frame with the multiplexer.

A unique feature is associated with the message sync bit in order for it to distinguish it from the other video, digital and analog subchannel bits. An alternating “1” and “0” pattern is used as the sync bit to distinguish it from the other bits. A logic “1” appears on a message frame, m (t), and then a logic “0” appears on the next frame, m (t+1). Because the frame rate is 11.1 MHZ, the “1” and “0” signal appears as a square wave with a frequency of 5.5 MHZ.

Video Channels

The two video channels use most of the bits in the message frame. Each video signal is digitized with a Flash Analog-to-Digital-Converter (ADC) and data is placed on the 9-bit bus using tri-state latches at 11.1 MHZ.

Digital Subchannel Multiplexer

On the third tier of the multiplexing scheme is the Digital Subchannel. Eight low data rate instrumentation bits and one sync bit are sampled at 1.23 MHZ (11.1 MHZ + 9 = 1.23 MHZ). These eight bits are some of the vehicle sensor data such as vehicle instrumentation, sonar, navigation sync, depth, and the two manipulator data. One additional bit is used for the digital subchannel synchronization. The same alternating logic “1” and “0” pattern is used for the digital subchannel sync bit with a frequency of 0.615 MHZ. The one serial bit stream output of this digital subchannel multiplexer is multiplexed into the main message frame.

Analog Subchannel Multiplexer

Also on the third tier of multiplexer is the analog subchannel multiplexer. Forty bits of data are multiplexed into one analog subchannel bit. The 40 bits are divided into four different analog subchannel words each with 10 bits: words 0, 1, 2, and 3. Each word is sampled with a 278 kHz clock(11.1 MHZ + 40 = 278 kHz). However, each of the four ten-bit words is applied onto the bus at different times to avoid bus conflicts.

Twenty bits are from the two ADCs digitizing a narrow band and a wide band hydrophone at a rate of 278 kHz. One bit is used for analog subchannel sync with the same alternating “1” and “0” sync pattern at 137 kHz. The last 19 bits are reserved for spare bits.

UPLINK DEMULTIPLEXING

Clock Recovery/Bit Retiming

After the 200 Mbps serial data is transmitted from the multiplexer, it goes through the optics and arrives at the uplink demultiplexer. The 200 Mbps serial bit stream is first sent to a clock recovery module that extracts the 200 MHZ clock frequency from the NRZ serial stream. The clock recovery module consists of an edge detection circuit and a Surface Acoustic Wave (SAW) filter that has a center frequency of 200 MHZ. The edge detection circuit extracts all the rising and falling edge transitions in the serial data stream. With these edges and transitions, the SAW filter outputs the 200 MHZ fundamental frequency. Synchronization of the 200 MHZ clock with the 200 Mbps data is also performed by the clock recovery module.

Demultiplexer

The demultiplexing scheme is a mirror image of the multiplexing scheme. The demultiplexer shifts the 200 Mbps serial data into nine parallel bits with the retimed 200 MHZ clock. An 11.1 MHZ clock then latches the nine bits into two 9-bit fields.

Video DAC

Eight of the nine parallel bits are sent to a Digital-to-Analog Converter board. Eight bits from the first field is latched with one phase of the 11.1 MHZ clock. Then, another eight bits from the second field is latched with a clock that is 180 degrees out of phase. Only seven bits of the first field are video information. Two DACs convert the seven bits from the first field and the eight bits from the second field back to analog video signals. One remaining bit from the first field is sent to the sync detection circuit for the synchronization of the message frame.

Digital Subchannel Demultiplexer

The digital subchannel demultiplexer converts the Digital Subchannel serial data to parallel bits. A 1.23 MHZ clock is used to latch the nine parallel bits. Eight of the nine bits are usable information for the uplink digital subchannel. One bit is used for the digital subchannel sync detection.

Analog Subchannel Demultiplexer

The analog subchannel demultiplexer converts the Analog Subchannel serial data to parallel bits. Four different phases of the 278 kHz clock are needed to extract the 40 bits of data. The same sync detection circuit is used to synchronize the demultiplexer with the analog subchannel multiplexer.

DOWNLINK TELEMETRY CONFIGURATION

The downlink telemetry is used to transmit low data rate digital channels from the surface to the vehicle. A block diagram of the downlink telemetry is illustrated in Figure 4. The highest data rate of the downlink data channel is 20.8 kbps. Since only low data rate channels are transmitted on the downlink. a Manchester or biphase data format (Mil-std-1553) is used for transmission. A Universal Asynchronous Receiver Transmitter (UART) device eliminates the need for clock recovery, retiming, and synchronization circuits. The UART device is user programmable and requires very little peripheral circuits.

Downlink Multiplexing

The serial downlink message frame is made up of 12 bits. The first 3 bits are used for the synchronization of the frame. Eight bits of data are used for the downlink channels and the last bit is used for a pre-selected parity.

The downlink data channels are sampled at a frequency of 208 kHz or 10 times the highest data rate of the digital signal. Therefore, a maximum of 10% jitter appears on the received data bit due to the sampling of the data. This 10% jitter has not caused any problems to the received data. After the data channels are sampled and serialized, the output data stream appears as a 2.5 Mbps data. With the Manchester encoding, the actual downlink telemetry bit rate is 5.0 Mbps. The downlink serial data is then sent through the optics and is received in the vehicle's downlink telemetry.

Downlink Demultiplexing

At the vehicle, the downlink outputs from the three optical receivers are sent to the switching circuit. This switching circuit determines which output has the valid data and then sends this valid serial data into the Manchester UART. The fiber switching technique will be discussed in the next section. The UART then performs the bit retiming, frame retiming, and data conversion. The UART output is a NRZ format data with the sync and parity bits stripped off. The NRZ serial data is then shifted through a 1 to 8 demultiplexer which outputs the individual downlink data channels.

FIBER SWITCHING

As stated previously, the ATV telemetry system employs only one optical fiber to meet the full duplex communications requirement. Thus, the two additional fibers provide dual redundancy. The ATV design incorporated a switching scheme that enabled the operators to select any one of the three fibers even while the ATV was deployed. This switching capability has proven to be a versatile and valuable feature in the telemetry design. It has allowed diving operations to continue even when a problem occurred in the fiber link or the E/O housing circuitry. Also, this switching capability facilitated fault isolation. It enabled the operators to quickly isolate problems to either the surface equipment, the vehicle, or the fiber. This fault isolation feature helped decrease the ATVs mean-time-to-repair.

The following describes how the fiber switching scheme is incorporated in the system. At the surface, optical switches located in the tether storage reel are connected to the three fibers. The operator selects the fiber to be used by controlling the optical switches. At the vehicle, each of the three fibers is connected to its individual uplink transmitter and downlink receiver located in the E/O housing. The same electrical uplink signal is simultaneously inputted to all three uplink optical transmitters. Thus. the same uplink optical signal is transmitted on all three fibers at all times.

The downlink electrical signal output from each of the optical receivers is checked for data validity. This validity check Is performed by monitoring the detection circuit of one of the digital subchannel signals. A switching circuit in the Main Electronics housing sequentially checks the three downlink received signals. When a valid downlink signal is detected, this circuit locks onto this valid signal.

DEVELOPMENTAL TESTING & PROBLEMS

BIT ERROR RATE TESTING

The telemetry system was tested extensively throughout the development phase of the project. Because the fiber optic telemetry system is the only data link between the vehicle and the control station, the system must operate error free. The system went through system functional checks and was induced to environmental screening.

The entire vehicle telemetry electronics including the uplink multiplexing circuits, the downlink demultiplexing circuits, the uplink E/O components, and the downlink E/O components were subjected to environmental screening from temperatures of -20 to 60 degrees C (-4 to 140 degrees F). Bit error rate of the uplink and downlink were measured to be less than 10 e-9.

MODAL NOISE PROBLEM

The low data rate and the low fiber loss at 1.55 microns allow for the use of an LED source for the downlink transmitter. During the early stages of development when a laser transmitter was used, it was found that the bit error rate was very sensitive to any physical distortion of the optical fiber. This random source of noise, commonly called modal noise is typically seen in multimode fiber systems that use a coherent laser source. Modal noise can be generated at joints with a mode selective loss, such as at connectors or splices, and even at microbends.

Initial efforts to solve this problem resulted in the optimization of the connector losses and the use of different 1.55 micron laser transmitters. Better success was obtained by adding a high frequency square wave to the 5 Mbps data stream as means of decreasing the coherence of the laser by forcing it to oscillate in multi-longitudinal modes. This, however, was only partially successful in preventing bit errors from occurring when the optical fiber was moved. The only viable solution was to use an optical source with a broad optical spectrum. Modal noise was not observed when an LED was used.

OPERATIONAL TESTING

During the test and evaluation phase of the ATV system, 21 dives were performed with a total operational time of 248 hours using this fiber optic telemetry system. The deepest dive was to 20,060 feet with a bottom time of 10 hours. The ATV system demonstrated a reliability exceeding 90% based on having no critical failures in over 248 hours of operations. Critical failure is defined as one which prevents the system from performing its operational mission, and requiring it to be returned to port for repairs, spares, or supplies. During these tests, the fiber optic telemetry system operated reliably at all depths.

SUMMARY

The ATV fiber optic telemetry system is incorporated on a tethered, undersea, work vehicle. It simultaneously transmits a 200 Mbps uplink and a 5 Mbps downlink over a single optical fiber using wavelength division multiplexing. This telemetry system has contributed significantly to the overall success of the program because of its reliability and redundancy. The reliable operation of the telemetry system greatly contributed to the successful test evaluation of the ATV System.

ACKNOWLEDGMENT

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REFERENCE

[1] Hoffman, Robert T., Morinaga, Wayne S., “Advanced Tethered Vehicle Description and Test Results”, 1991 ROV Conference Proceedings.

[2] S. Cowan, “A High Performance Fiber Optic Pressure Penetrator for use in the deep ocean”, NOSC T.R. 644, February 1981.

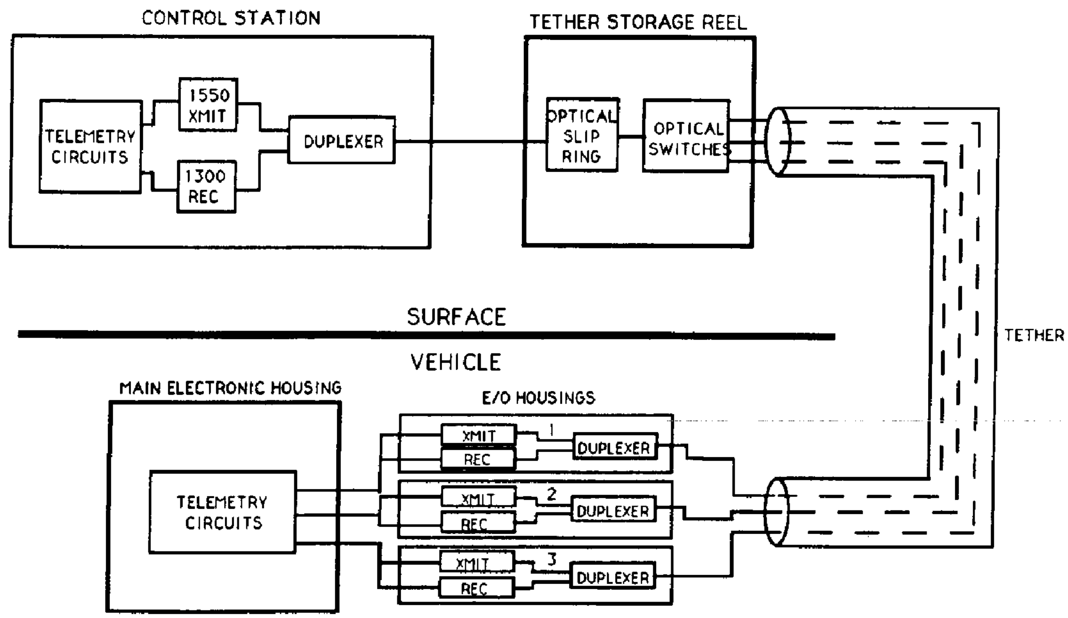
CONTROL STATION
TELEMETRY CIRCUITS
1550 XMIT
1300 REC
DUPLEXER
TETHER STORAGE REEL
OPTICAL SLIP RING
OPTICAL SWITCHES
SURFACE
VEHICLE
TETHER
MAIN ELECTRONIC HOUSING
TELEMETRY CIRCUITS
E/O HOUSINGS
XMIT
REC
1
DUPLEXER
XMIT
REC
2
DUPLEXER
XMIT
REC
3
DUPLEXER

Figure 2

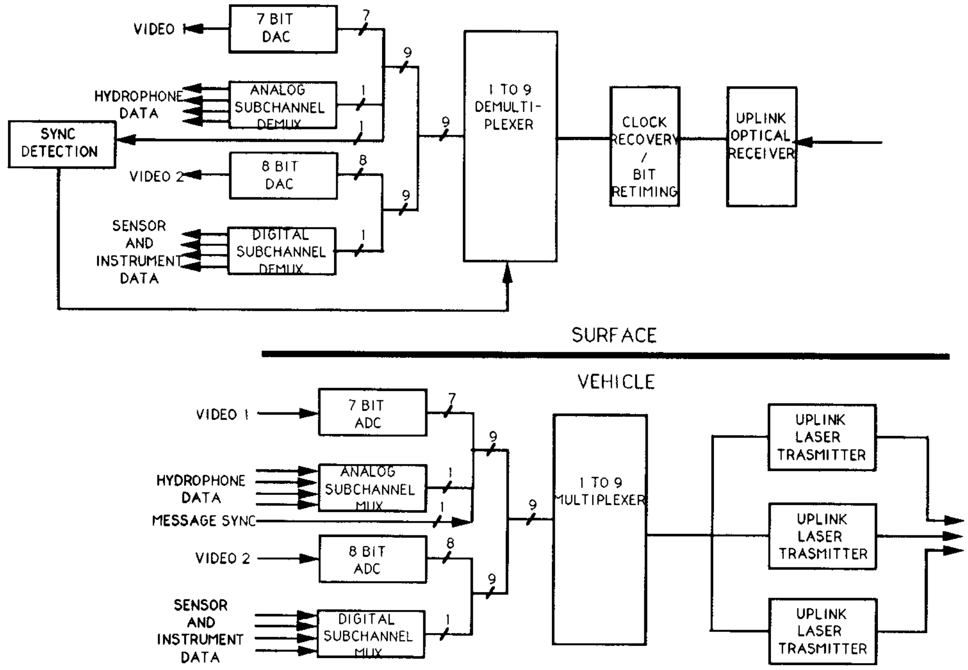

Figure 3

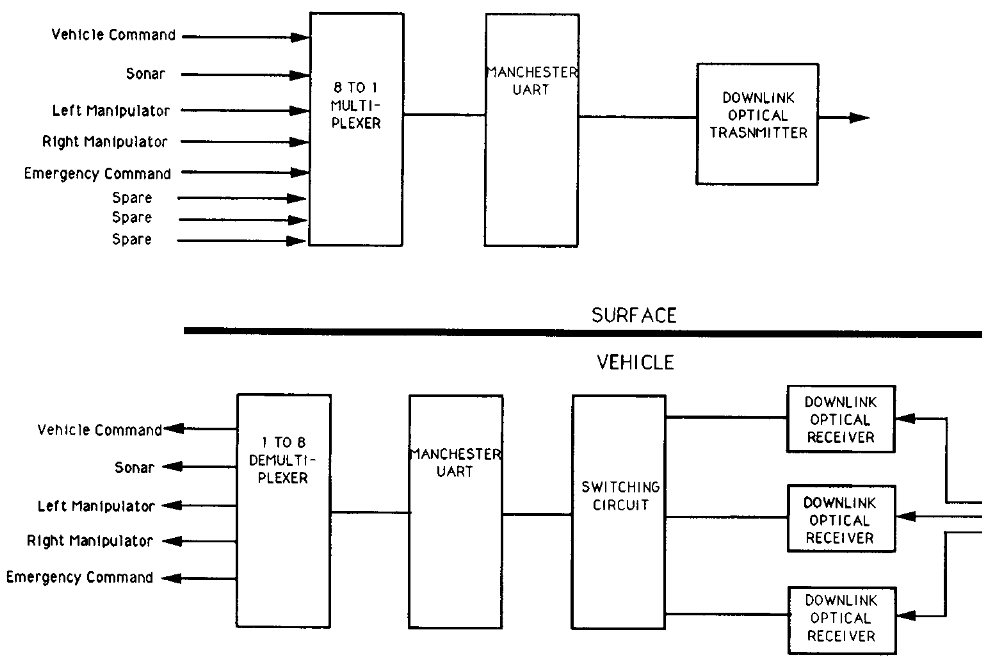

Figure 4