Document Number 204
By: Glenn Dorsey, PE
Slip Ring Product Line Manager

High-Speed Data Transmission and Rotary Platforms:
Slip Rings, Fiber Optic Rotary Joints, and Multiplexers

Abstract
This paper will review recent developments in slip ring and fiber optic rotary joint (FORJ) technology for the transmission of high-speed data on military vehicles. Computer systems that control military vehicles are incorporating Local Area Network (LAN) based architectures. In addition there is an increased sophistication in systems such as Reconnaissance, Surveillance and Target Acquisition (RSTA) and vehicle navigation technologies. These changes are pushing the data rates in vehicle systems higher. Vehicle systems that traditionally ran on 1553 data buses of 1 Mbit/sec now require aggregate data rates of 1.0+ Gbit/sec. To accomplish these data speeds, system designers are integrating high-speed copper and fiber optic transmission lines into their harness assemblies. There are two areas on vehicles where circuits carrying high-speed data must transfer across rotating surfaces: (1) turrets and (2) gimbaled sensor systems, such as infrared and visible video. Slip rings have traditionally been used to transfer data, power, and control signals across these rotating interfaces. New technologies are enabling slip rings to carry higher speed data than they have in the past. Fiber optic data transmission across rotary interfaces has been accomplished with fiber optic rotary joints (FORJ). In addition to the performance of slip rings and FORJ's, this paper will review alternative technology for transmitting data across rotary interfaces. Techniques for multiplexing circuits through the rotating interface will be discussed which allow a single fiber or electrical line to accommodate several high-speed data circuits.

Introduction
Military vehicles often require rotary platforms to perform their missions. Vehicles with rotating turrets are one obvious example of a critical rotating platform. The other common applications are Military vehicles often require rotary platforms to perform their missions. Vehicles with rotating turrets are one obvious example of a critical rotating platform. The other common applications are gimbaled sensor suites that provide vital intelligence on battlefield conditions to the vehicle commander or driver. Both types of rotating platforms require power and signal exchange with the stationary vehicle hull. The turret to hull interface must often transmit electrical power, as well as safety interlocks, digital data, video data, and other signals. A low resistance bonding ground is often required for lightening strike protection and a low impedance ground path for electro-magnetic interference (EMI) protection. These functional requirements must be provided in a mechanical package that meets the battlefield environmental requirements including electro magnetic interference/electro-magnetic compatibility (EMI/EMC).

Military vehicles often carry a gimbaled sensor suite (independent of the turret) that provides battlefield information. This is especially true for Unmanned Ground Vehicles (UGV) since these systems must incorporate driver replacement sensors. The US Army Tank and Automotive Research, Development and Engineering Center (TARDEC) outlines the sensor systems required for Unmanned Ground Vehicle (UGV) technology as shown in Table 1(1). These sensor systems normally require less power than the turret slip rings, but the video and data requirements are typically greater due to the data requirements of the sensor detectors or detector arrays. These detectors often need cooling fluid and the systems need precise positional information, therefore the rotary interface often includes fluid rotary unions and rotary position feedback devices.

TABLE 1: Unmanned Ground Vehicle (UGV) Sensor Systems

Function	Sensors
Mobility	Day/night stereo vision; Scanning laser range-finder; Two radar systems (4GHz radar to penetrate vegetation, and 77 GHz radar for imaging obstacles at longer ranges)
Trafficability	Multi-spectral imager Polarizing imager Small ultrasonic sensors (for close-in safeguarding functions)
RSTA mission module	TV camera High resolution forward-looking infrared (FLIR) sensor; Laser range-finder/designator; An array of acoustic sensors
Other configurable mission modules	Undefined

Traditionally, slip ring assemblies provide the functionality of this rotary interface. These assemblies contain discrete precious metal rings for each electrical circuit and corresponding sliding wipers (or brushes) to conduct the power and signals from the rotating rings to the stationary member. Figure 1 shows this arrangement in a turret slip ring. Notice the large power rings and brushes on the left and the smaller signal rings and brushes on the right.

The slip rings used for the sensor gimbals normally contain more channels than the turret slip rings and require a denser circuit packaging. A typical sensor gimbal slip ring assembly is shown in Figure 2. Smaller gold alloy contacts and gold alloy rings provide the electrical continuity through the slip ring.

As military vehicle Vetronics and sensor systems become more sophisticated and the digital battlefield continues to push for greater information density, system architects are starting to view the rotational interface as a potential bottleneck for data flow. Of course not all network data must go onto these rotating platforms, but in many systems there must be data communication with the turret and/or sensor.

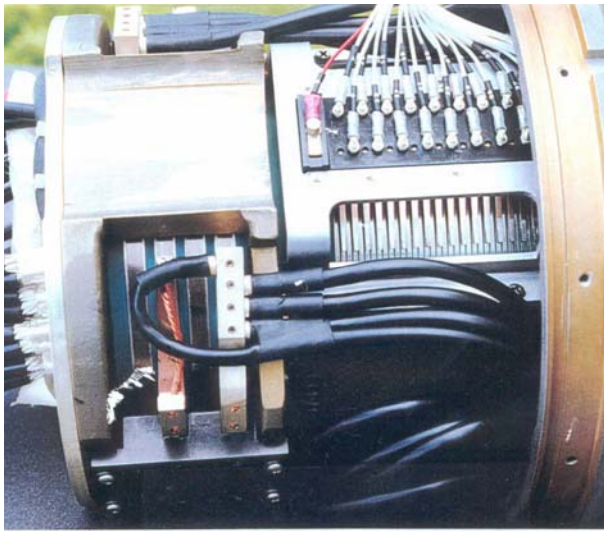


Figure 1: Close up of slip ring assembly with power (left side) and signal circuits (right side)

This paper will show that there are a variety of options available to transmit high-speed data across the rotational interfaces of a typical military vehicle. A good understanding of these options will allow the system designer to optimize the system performance. It is also important to consider these options in terms of "future proofing" the system, given the changes in datacom requirements and capabilities. Considerations given to eliminate bottlenecks in data throughput can simplify the task of future system upgrades and thereby "futureproof" the design against obsolescence.

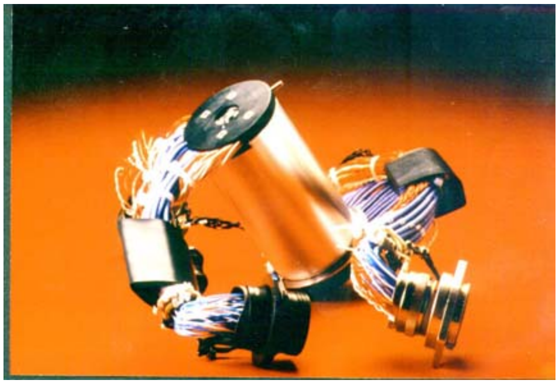


Figure 2: Slip Ring used in Military Vehicle Commander's Viewer

High-Speed Data and Physical Media

The decision to use copper or fiber as the transmission line media is one of the most critical that a system designer must make. The advantages of fiber are well documented (2, 3) and include EMI/EMC immunity, unlimited bandwidth, and lightweight. However, copper offers environmental robustness, simpler interfaces, and easier field repair. A number of factors go into the fiber/copper decision, but the important question is whether the anticipated data rate exceeds the bandwidth limit of the copper transmission line. A good place to start is to understand the maximum length of copper transmission line that can support the chosen data format. Table 2 summarizes the guidelines for various high-speed data formats (4, 5, 5, 7, 8, 9, 10, 11)

TABLE 2: Media Length Guidelines for Data Formats

Data Format	Media or Speed	Length
10BASE2	RG58 coax	185m
100BASE-TX	EIA/TIA Category 5 unshielded twisted pair (2 pair)	100m
1000BASE-T	Cat 5 UTP (4 pair)	100m
1000BASE-CX	Shielded twisted pair	25m
IEEE-1394	400 Mb/s	4.5m
IEEE-1394b	Beta 800; 800 Mb/s	4.5 m
Fibre Channel	1062.5 Mb/s	30m
Hotlink	400 Mb/s	50m
SMPTE 259M	270 Mb/s	300m
SMPTE 292M	1485 Mb/s	150m
USB 2.0	480 Mb/s	5 m

It can be seen that many vehicle systems have transmission lines well under these maximum lengths, and either copper or fiber can be used for many of these data formats. Of course discontinuities in the transmission line at connectors and other terminations have a degrading effect on the performance, so the overall transmission line characteristics must be evaluated before a final determination can be made. Frequently in the case of embedded networks in military environments a simple transmission line length determination is inadequate for suitability for use decisions. Requirements for non-standard network terminations to meet military connector requirements, an increased termination number for system packaging requirements, special shielding and grounding requirements for EMI/EMC considerations, and other unique transmission line considerations often complicate the evaluation.

A technique frequently used to evaluate the data capability of a copper transmission line is bandwidth of the line when terminated with the appropriate load resistance. For this evaluation it is important to understand the bandwidth requirements for various data formats. Under normal circumstances transferring the fundamental frequency and the first two odd harmonics will normally reproduce the square wave pattern sufficiently well. Figure 3 illustrates the Fourier components of 150 MBAUD data stream (pattern 10101010) with NRZ and RZ encoding. A transmission line with 450 Mhz of bandwidth will transmit this square wave accurately.

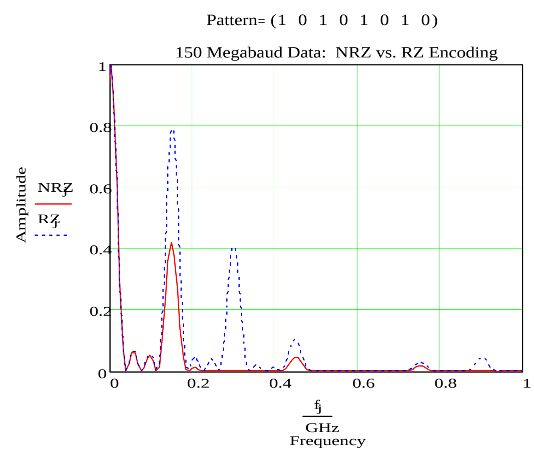


Figure 3: 150 Mhz square wave Fourier components

Figures 4—6 show bandwidth measurements made on actual data types, including 100 Base-T Ethernet, Gigabit Ethernet, and Cypress Hotlink II (400 Mbit). The spectrum analyzer was operating in Max-Hold mode to acquire the peak energy at each frequency, which gives the overall energy envelope of the emission. The Y-axis is a logarithmic scale of signal amplitude at 10 dB/division and the X-axis is the frequency displayed linearly at the most appropriate scale in Mhz/division.

Figure 4 is a spectrum analyzer plot of the 100 Base-T Ethernet signal showing the frequency distribution up to 500 MHz. Virtually all the energy is below 250 MHz. The 250 MHz marker at –60 dBm indicates that signals at that level have *one-millionth* the signal power of the zero dBm reference at the top of the plot. Similarly, the 100 Mhz marker at –25.6 dBm is about 20 dB down from the peak energy at 20 MHz, i.e. 99% of the signal is at frequencies below 100 MHz. All the frequency components under the horizontal line (about 20 dB down from the peak energy level) represent only 1% of the signal power. In terms of signal fidelity, a bandwidth of 100 MHz passes 99% of the energy of the Ethernet signal and gives excellent signal fidelity.

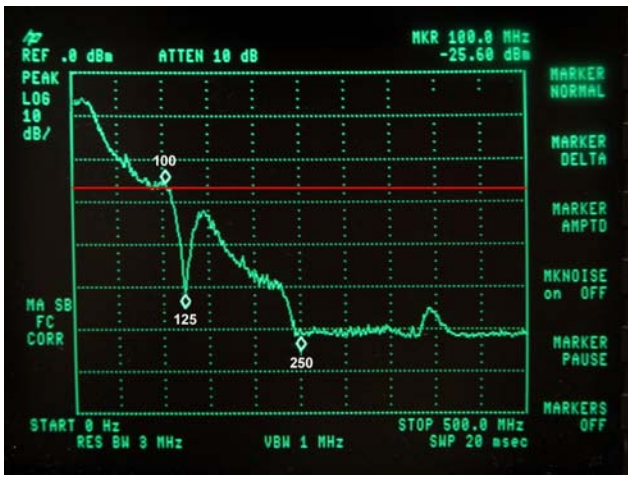


Figure 4: Frequency Spectrum of 100 BASE Ethernet

Figure 5 shows the output from the Cypress Hotlink II running at 150 Mbps. The horizontal axis shows frequency (150 MHz/ div). The energy peaks at 200, 400, 600, etc. show the fundamental and harmonics. 500 MHz of bandwidth is sufficient for a good signal quality.

Figure 6 shows the spectrum for 1000 Base T Ethernet. This implementation of GbEthernet uses all four pairs in a CAT-5 cable. It can be seen that Figure 6 is almost identical to Figure 4, which means the bandwidth requirements for each pair are almost precisely that of 100BASE-T. The reason that 10 times the data throughput can be achieved is the 4X multiplier of using all four CAT-5 pairs, plus the throughput gained by using PAM-5 (5-level) encoding. Any transmission line feature (such as a slip ring) that can handle 100BASE-T (Fast Ethernet) should also handle 1000BASE-T, provided of course that there are sufficient lines for the eight CAT-5 wires. Reference 27 provides a detailed discussion of 1000Base-T performance requirements and parameters.

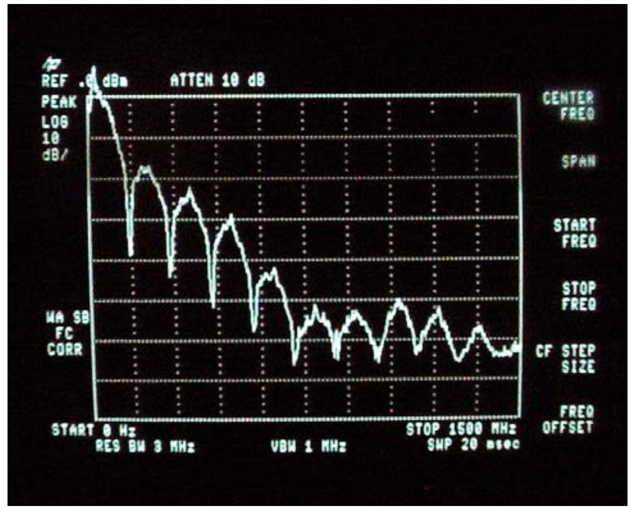


Figure 5: Frequency Spectrum of 150 Mbps Hotlink

Figure 6: Frequency Spectrum of GbEthernet (1000 Base T)

In the case of 1000 Base CX Ethernet, the full signal bandwidth is carried on twisted pair and the transmission line must be capable of supporting a bandwidth of over one GHz.

In the case of optical fiber transmission lines, such bandwidth evaluations are normally not necessary for vehicle systems. With respect to optical fibers, the bandwidth does not correspond to changes in frequency to the extent that it does with copper cable, but is more directly related to distance. However, there are sufficient differences between the two major classes of optical fiber so the system designer must make the decision in regards to the use of single or multi-mode fiber. Single mode fibers allow the propagation of a single mode of optical energy due to their small core size and small numerical aperture, and for this reason they exhibit very high bandwidths, often in excess of 100 GHz/km (bandwidth for fiber is typically reported as a bandwidth-length product). Consequently these fibers are used extensively in long distance telecommunications applications. Most singlemode fiber systems operate with the 1300 nm and 1550 nm wavelengths because of lower fiber attenuation at these wavelengths. Wavelength division multiplexing options are also greater for single-mode fiber with dense and coarse WDM options, but this is changing in the latter case as course wave division multiplexing options with multimode fiber are being developed (12).

Multimode fibers have large cores and large numerical apertures and subsequently allow the propagation of multiple modes of optical energy. These features allow larger amounts of light to be transmitted from incoherent sources such as LED's, but result in higher attenuation and dispersion. Because of these attenuation and dispersion features, multimode fiber systems have been used for shorter datacom links, and multimode systems have traditionally been used for lower data speeds (less than 633 Mbps) due to the limited modulation speeds of LED's.

Recent advances in laser-based transceivers have made it possible to use multimode fiber at data rates of 1.25 Gbps at distances of a few hundred meters (4). Advances in fiber (13, 14) have addressed the Differential Mode Delay (DMD) problem experienced in the past with launching laser light into multimode fiber and have created a multimode solution for GigE or GigaBit Ethernet (1000 BASE SX) and data of similar bandwidth (4). The 10 Gigabit Ethernet Alliance (10GEA), and industry consortium of about 100 equipment vendors working in support of the 802.3ae Standards Committee, has defined a distance goal for 10 GigE of 65 meters on 500 Mhz 50/125 micron multimode fiber (the advanced fiber noted above). Since the typical Vetronics or sensor system is well under the 65 meter fiber length noted, the choice of singlemode or multimode fiber should be based on an overall system analysis and careful consideration of future needs, but the options continue to expand rapidly as optical fiber and components improve and enabling technologies are developed and improved (17). With almost unlimited bandwidth capability, the incorporation of fiber provides the systems designer with virtually unlimited future upgrade potential on a fiber data bus. The addition of additional electronics and subsequent capability to a system can be accomplished by simply multiplexing the signals into the existing fiber data line.

Digital Data and the Rotary Interface

How does the rotary interface factor into the decision to use fiber or copper, and what is its effect on data speed?

There are various ways to characterize rotary interface devices. One practical method is to determine if the device is passive or active. Passive devices simply transfer signals across a rotating interface using no active electronics. The two prime examples of passive rotary data transmission systems are slip rings and fiber optic rotary joints (FORJ's). Active devices modify the input signal using electronics to produce an optimum signal for transfer across the rotary interface. Examples of active rotary data transmission devices are capacitive (or RF) coupled rotary joints and active optical rotary joints. The passive devices—slip rings and FORJ's—are still the primary rotational interface solution and will be discussed in the greatest detail.

Slip Rings

Slip rings are the most common device used to transmit signals across a rotating interface. In the past 10 years there have been significant improvements in the ability of slip rings to handle high-speed digital data. Broadband slip ring designs are now able to successfully transmit data up to 1.2 Gbps. Addressing the question of high-speed data through slip rings requires some discussion of the critical performance parameters. The most important parameters that limit the speed of digital data in slip rings are: bandwidth, crosstalk, and EMI/EMC.

A slip ring represents a discontinuity, or perturbation, in a transmission line as a result of an impedance mismatch of the rings and brushes and the transmission line. The degree to which the impedance of the rings and brushes can be matched to the impedance of the transmission line is the best indicator of how effective the slip ring will transmit high-speed data. Various micro-stripline design techniques have been adopted to match the slip ring impedance to the line impedance (16). Although these stripline techniques allow the slip ring designer to approximate the transmission line impedance, it is impossible to perfectly match this impedance. The goal is to minimize the mismatch as well as the length of the mismatch. One of the best measures of the ability of a slip ring to handle high-speed data is to look at the time domain response and the transformed frequency bandwidth.

The time domain response has a unique transform to the frequency domain while the reverse is not true. However, it is simpler to speak in terms of frequency response and bandwidth. A typical expression for this purpose is: 0.5/ rise time (10 to 90 % of the waveform) expressed as a frequency bandwidth. As discussed earlier, each digital data format has a transmission line bandwidth requirement that allows the data stream to be transmitted without distortion. Broadband slip ring designs show bandwidth capability of up to 2.1 GHz

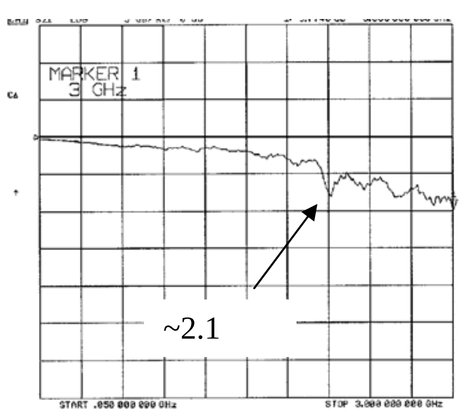


Figure 7: Insertion loss vs. frequency on broadband slip ring design

with increases likely in the future. Figure 7 shows an insertion loss plot to illustrate this point. The bandwidth limit is identified as the –6dB insertion loss point.

Physical constraints affect the bandwidth of slip rings. Larger diameter rings typically have lower bandwidth capability as Figure 8 illustrates. These two insertion loss plots are of data channels that are identical except for diameter. The top rings are approximately 64 mm in diameter and the rings in the bottom chart are approximately 150 mm in diameter. Other factors limit the bandwidth of these particular rings, but these charts illustrate the difference created in identical rings with simply a change in diameter.

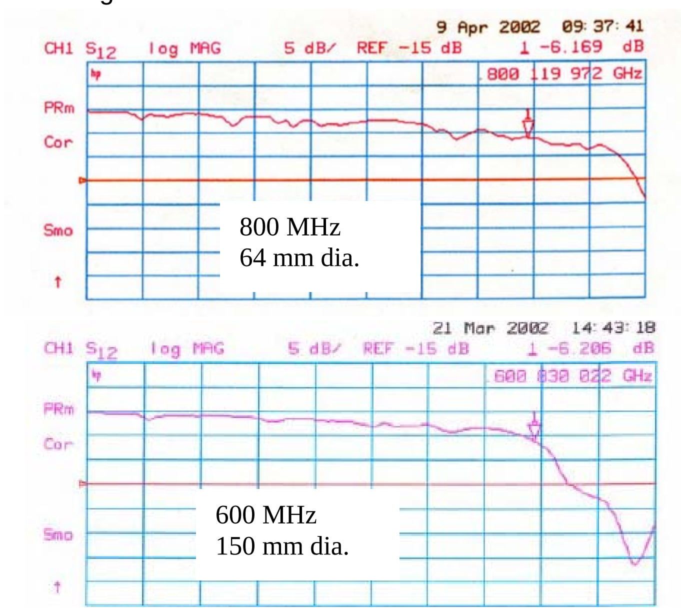


Figure 8: Insertion loss vs. frequency for two different diameter ring pairs

The physical size and placement of the slip rings internal components are also an important consideration in the time domain. The possibility of component frequency resonances and impedance discontinuities can cause time domain distortions called "group delay". This can be visualized by looking at the serial data stream as a series of multiple frequency pulses being transferred through the slip ring with unequal path lengths. This spreads the energy from the different length pieces of data in the data stream across the time domain and causing distortion of the transition points resulting in the received data rise and fall times to have serious edge jitter (or placement in time issues with respect to the data clock) or serious amplitude distortions. The resultant distorted data waveforms stress the decision-making hardware to correctly detect the data versus the fixed frequency of the data clock. When this becomes large enough, data errors occur. This process can occur within the frequency response bandwidth of the device. Time domain reflectometry (TDR) can be used to locate the physical position and degree of change in a transmission line through a slip ring. A transmission phase measurement can be made when using a network analyzer to determine the bandwidth of the slip ring. It should appear as a linear phase change across the bandwidth to be used. Abrupt changes (TDR) or phase slope changes or reversals (network analyzer) are signs of major time domain distortions.

Second to the bandwidth in evaluating the ability of a slip ring to transmit high-speed digital data is crosstalk. Crosstalk between any two channels is defined as:

$$X_{TK}(dB) = 20\log\frac{V_2}{V_1}$$

where, V1 is the voltage of the offending signal and V2 is the voltage coupled onto the victim circuit.
When a number of channels are incorporated into a relatively small physical package, capacitive coupling is the primary cause of this crosstalk in the case of high-speed data channels. Proper isolation of digital channels from each other and from other channels can be a significant challenge to a slip ring designer, especially when dealing with very compact physical sizes (18). Proper shielding and grounding techniques must be incorporated to ensure that sufficient isolation can be provided among multiple high-speed data channels. Figure 9 shows an example of crosstalk between two data rings prior to several design changes to improve the crosstalk performance. It can be seen from this chart that the relationship of crosstalk to frequency is more complex than strictly linear as is sometimes modeled.

EMI is the final performance parameter that should be highlighted in regards to high-speed data and slip rings. Because of the high frequency components of high rate data transmission lines, it is important that proper shielding and grounding principles be applied at the rotational interface. Specifically a low impedance ground path should be maintained at each rotational interface and all shields must maintain their continuity and proper reference level to ground through the interface. The slip ring should be designed to be a Faraday cage to prevent EMI leakage into or out of the housed contacts and EMI sealing techniques should be used that are appropriate to the specified frequencies. Proper utilization of these techniques will allow slip ring assemblies to meet the harshest EMI/EMC requirements.

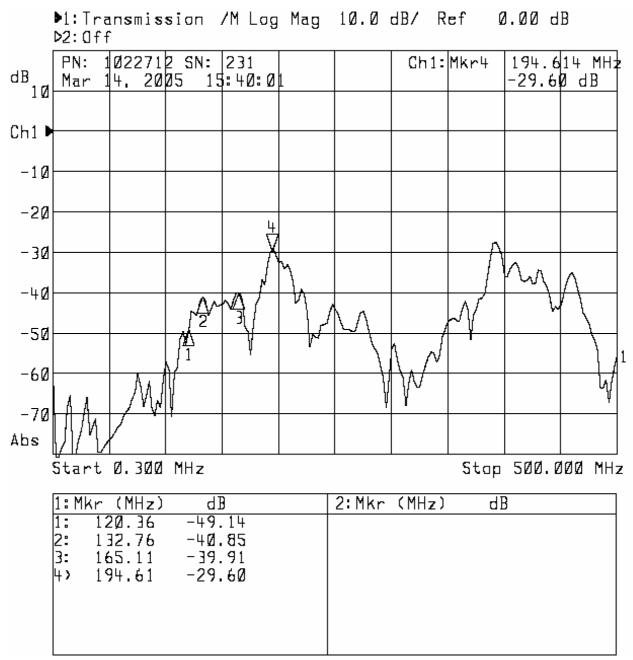


Figure 9: Crosstalk vs. frequency in a slip ring assembly

Fiber Optic Rotary Joint (FORJ)

In the case of systems that utilize optical fiber to carry high-speed data, the most straightforward rotational interface is a passive fiber optic rotary joint (FORJ). These devices are characterized by the numbers of optical fibers that are carried through on discrete physical fibers (passes) and by whether the fibers are single or multi-mode. For example, a single pass, multi-mode FORJ contains one discrete multi-mode fiber channel. It is much simpler to discuss high-speed data performance of a FORJ than a slip ring since a FORJ has no discernible effect on the bandwidth response of a fiber transmission line. Crosstalk between fiber lines and electrical lines is non-existent, and between fiber lines in a multi-channel FORJ is minimal. And finally fiber lines are immune to EMI effects. The primary effect that a FORJ has on a fiber data transmission line into which it is inserted is an impact on the loss budget of the fiber and in most cases this effect is quite minimal. There is a very minor change in this insertion loss value as the FORJ is rotated and this number is typically given in the specification. Back reflection (or return loss) is a value that is typically specified since reflected light can contribute to the signal to noise value of some laser-based systems.

The design and performance principles of the single channel FORJ are well documented (19, 20), however great improvements have been made in the performance characteristics of these devices since their first development. Table 3 shows typical performance parameters for single and multi-mode FORJs, in this case Moog Components Group FO 285 and 286. Since these devices are bi-directional the performance parameters are independent of the direction of the signal. The size of the single channel FORJ is quite small (see Figure 10) with the length of less than 15 mm and the diameter less than 10 mm. The environmental robustness of these devices has been well proven in military as well as harsh commercial marine environments.

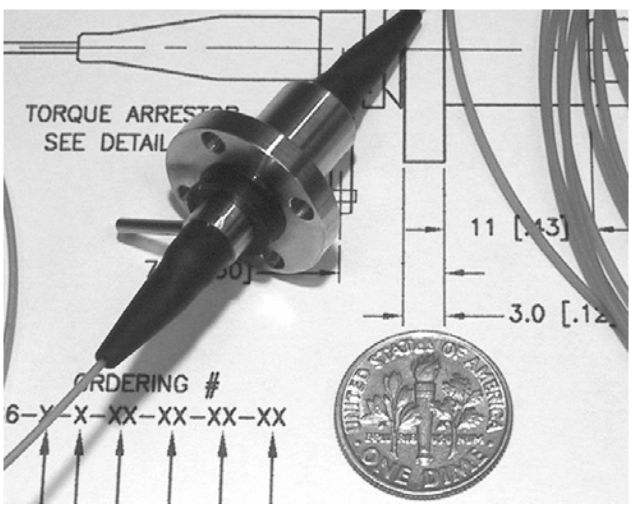


Figure 10: Single channel FORJ

Table 3: Performance specifications of Single Channel FORJ's

It is important to understand the bandwidth possibilities of a single optical channel through a FORJ. Data rates in the 0.1-10 Gbps (and higher) range can be supported, and since the device is bi-directional data can flow in both directions. The techniques of bi-directional transmission in optical fiber communications are well documented (21). The most common method of bi-directional transmission is to use different wavelengths of light for the uplink and downlink (1550 nm and 1310 nm are frequently chosen). Multiplexing of multiple signals (to be discussed later in this paper) allows multiple data, video, and control signals to be combined onto one fiber. Reference (21) provides a very thorough discussion of bi-directional data on fiber. Using multiplexing techniques and bi-directional data transmission, it is possible to carry all the information required by a system on one fiber through a single pass FORJ.

There are many practical considerations that make this single fiber optimization challenging to implement. Reliability requirements for redundant lines, security requirements for separate lines for encrypted data, data generated in multiple locations, all conspire to prevent this "optimum solution" from being adopted. In these cases a multiple-pass FORJ is required. The most practical alternative to a single pass FORJ is a dual pass FORJ. Two optical channels allow redundant data channels, separate channels for encrypted data, or full duplexing (i.e., a discrete uplink and downlink fiber). Table 4 summarizes the typical performance parameters of single and multi-mode, 2- pass FORJ's.

	Single Mode 285	Multi-mode 286
Insertion loss	3.5 dB (typical < 2.0 dB)	2.5 dB (typical < 2.0dB)
Back reflection (or return loss)	< -18 dB (<–35 dB option)	< -18 dB
Loss variation with rotation	1.5 dB (typical 1.0 dB)	1.0 dB (typical 0.5 dB)

TABLE 4: Typical Performance Specifications

The 2-pass FORJ's are bi-directional, and all the bi-directional transmission techniques available for the single pass FORJ are also available on the 2-pass FORJ. This means that using multiple wavelengths of light for uplinks and downlinks can result in two fully duplexed data channels. Or one fiber could be used with bi-directional encrypted data and one with bi-directional un-encrypted data.

The single and dual channel FORJ's are powerful tools for "futureproofing" any rotary data interface. These simple and compact devices provide a data bus for data at speeds of well over 10 Gbps, allowing a convenient upgrade path for years to come. However, both the single channel and dual channel FORJ's must be on the center axis of rotation. In the cases where the center axis is required for other purposes, for example, in the case of fitting around a shaft or mast, other alternatives must be explored for the rotating interface. The most common alternatives are active devices, which will be discussed later in this paper.

Multi-channel FORJ's are available for applications that require greater than two fibers. The largest application for these multi-channel FORJ's has been the underwater tethered remotely operated vehicle (ROV) market. Fiber is used to carry multiplexed video and data to and from the ROV to the cable winch and then to the "pilot". For example the Moog Components Group FO 190 (Fig. 11 a) is a modular design that allows the number of modules to dictate the number of fiber passes. Over the past 10 years thousands of these modules have performed well in a very harsh marine environment transmitting video and data to tethered underwater ROV's. Another example of a multi-channel FORJ is the Moog Component Group FO 5707, which utilizes a dove prism to provide common optic path for all the fiber passes (Figure 12). This design allows a space efficient design for FORJ's with multiple fiber channels.

It should be noted that with more than two fibers comes additional mechanical complexity, increased size, and higher cost. The most practical option for Vetronic and sensor systems is to take full advantage of the bandwidth available on one or two fibers. Multiplexing options (see following sections) are available that allow multiple data channels, as well as video, to be combined onto one or two fibers. However, in many cases requirements for redundancy, security, and physical constraints require the use of a FORJ with greater than one or two fibers. These FORJ's are available with application heritage is very harsh environments.

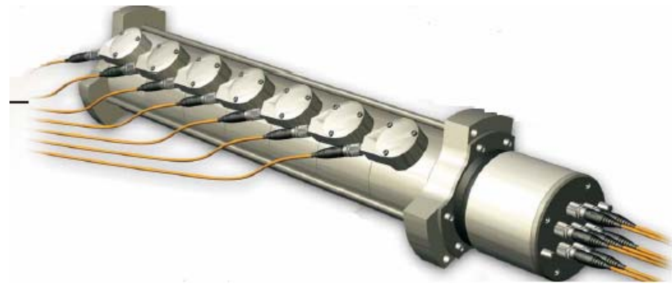


Figure 11(a): Multi-channel (7) FORJ, FO 190

Figure 11(b): Multi-Channel FORJ with common optical path

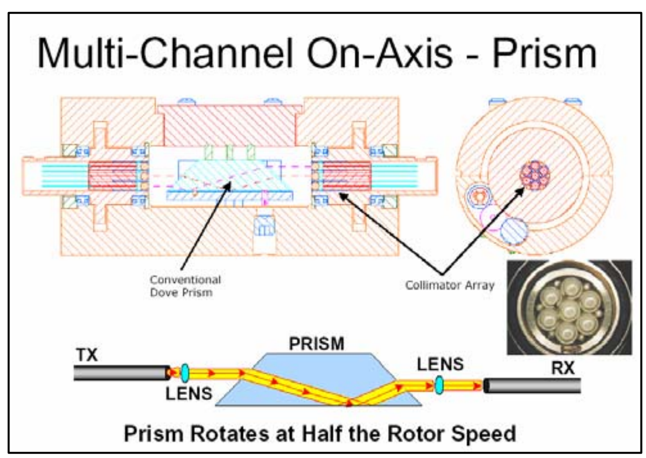


Figure 12: Dove Prism as a common optical path

Hybrid Systems

Many rotary interfaces are hybrid systems with a slip ring and a FORJ. The slip ring can be utilized for transmitting power and signals, including multiple high-speed data lines. Incorporation of a FORJ into the assembly serves to allow one or more fiber channels. This provides an upgrade path, since the almost unlimited bandwidth of the FORJ allows the addition of additional channels by multiplexing. Fluid rotary unions are often required to provide cooling fluid for the electronics and/or the detector arrays.

A good example of a hybrid assembly is the slip ring/ fiber optic rotary joint assembly used in the Cost Effective Targeting System (CETS) being designed by DRS for the US Army. The CETS is intended for RSTA applications on UGV's, unmanned air vehicles and manned platforms. The CETS payload (Figure 13) is an integrated sensor suite employing a low power uncooled infrared camera for search, a monoblock laser for ranging and illumination, and a short wave infrared active gated camera for target identification at long ranges. In addition there are color TV and ultra wide field-of-view uncooled IR cameras.

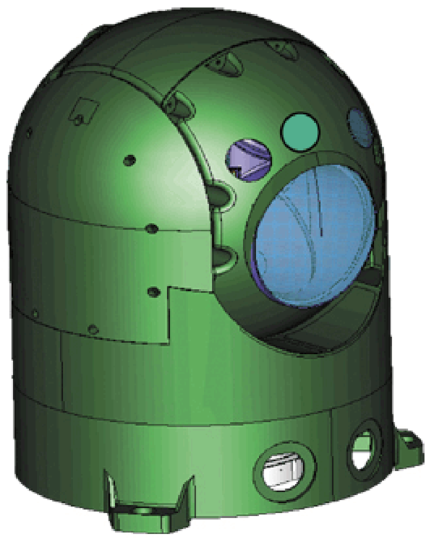


Figure 13: Cost Effective Targeting System (CETS) Payload

The off-board microprocessor uses an Ethernet interface to the platform. All this information passes across the azimuth axis through a slip ring/ fiber optic rotary joint assembly. Figure 14 shows the solid model of the compact low profile slip ring that provides the rotational interface on the CETS azimuth axis. A single fiber optic line, carried through on a single pass FORJ provides the optical interface. Fifty-four discrete electrical channels with data, control, and servo signals as well as a variety of power channels provide the electrical interface.

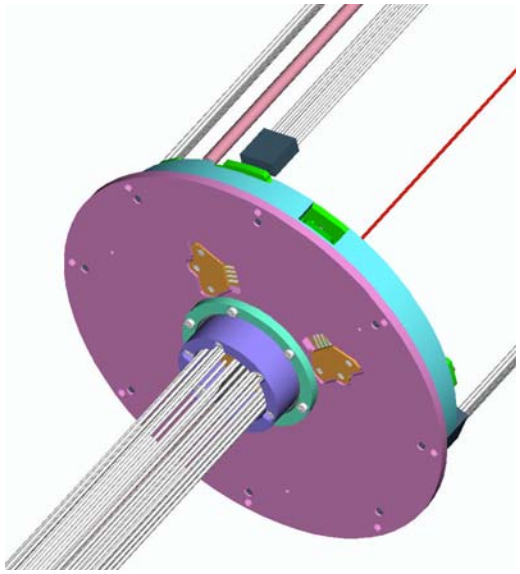


Figure 14: Solid Model of CETS Slip Ring

This CETS example illustrates the small and lightweight form-factors that can be achieved with these hybrid packages. The optimum rotary data interface design will often be a compromise between data on copper lines and data on fiber lines. Considering that systems require electrical lines for power, discrete circuits, and many servo circuits, additional data circuits can be added at a very low incremental cost. The hybrid electrical slip ring/ FORJ provides present performance and virtually unlimited upgrade potential.

Active Contacting Systems

The most straightforward active system for transmitting high-speed data across a rotating interface is a device that is a modification of a slip ring and brush assembly (Moog's High Speed Data Link or HSDL). The ring is split and terminated with an impedance matching resistor. Stripline design techniques are used to control the ring and brush impedance, minimizing any impedance mismatches. Figure 15 shows a time domain reflectometer (TDR) plot of a 50-ohm channel demonstrating excellent impedance control measured out to 12 GHz.

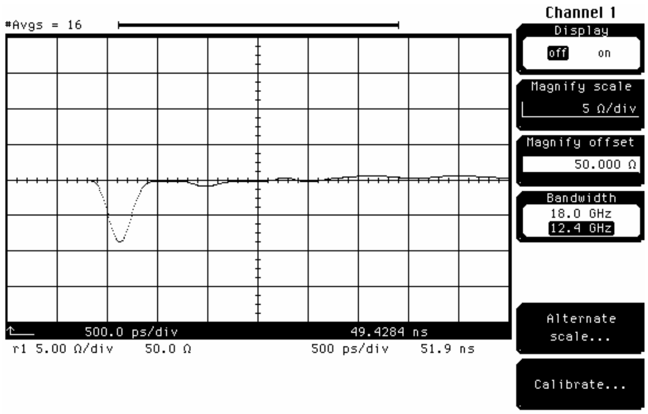


Figure 15: TDR plot of Active Contacting Device (High Speed Data Link)

The technique of splitting the ring and terminating each end with a resistor allows excellent impedance matching and elimination of reflections, however this results in insertion losses in this device of approximately 20dB. Therefore, a simple MMIC amplifier is required to boost the signal level to original input levels. This small amplifier is mounted on the ring, and the size of each channel is very close to standard slip ring spacing. This device has been tested with 2.4 Gbps data with good results. An eye pattern with 1.2 Gbps data is shown in Figure 16. Most of the jitter in this eye diagram is from the data source.

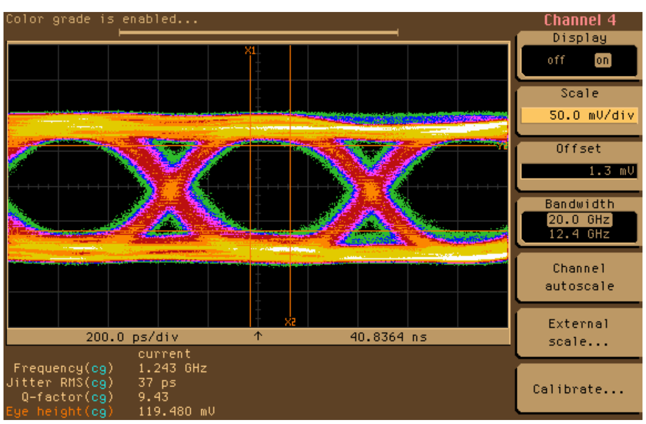


Figure 16: Eye Pattern of High Speed Data Link (HSDL)

These devices provide a well-matched impedance line from DC to over 2.4 Ghz. The addition of an electrical-to-optical converter on the input end and an optical to electrical converter on the output end allows the transmission of optical signals. This device is a good alternative for copper or fiber signals when the centerline is occupied and an on-axis FORJ cannot be used and high-speed data is required to be transmitted across a rotating interface. The HSDL is not bi-directional so proper directionality must be observed in the interface.

Active Capacitive Systems

Capacitive systems can also be used to transmit data across a rotating interface. These systems are more complex than the contacting systems since more signal processing is required on the receive end to provide some signal reconstruction. Figure 17 shows one configuration for this system. This particular design for high-speed differential data has a rotating ring composed of a controlled impedance microstrip. The stationary probe contains a similarly impedance-controlled microstrip that is capacitively coupled with the microstrip on the rotating member. Techniques are used to minimize EMI emissions and sensitivity. These capacitively coupled systems

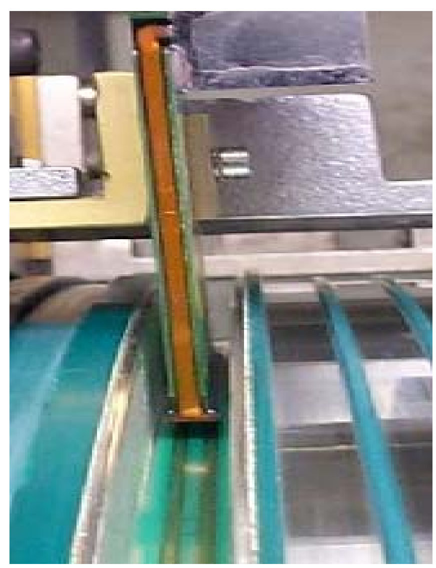


Figure 16: Capacitive Coupled Data Channel

have the advantage of being non-contacting, but they suffer the disadvantage of more complicated electronics and potential crosstalk issues with multiple high-speed lines. These devices can have a very large center hole, so in cases where the rotary interface must have a large through-bore this option is attractive. The capacitive coupled system can have a fiber interface by using appropriate EO converters. This device is not bi-directional.

Active Optical Systems

Active optical systems have also been developed to accommodate designs that cannot use passive FORJ's (primarily, again because the unavailability of the centerline or axis of rotation). These active optical systems have been utilized primarily to transmit x-ray detector array data off the rotating gantry of modern medical CT Machines. These devices have large diameters of close to 1 meter. Figure 18 illustrates one configuration of an active optical system. In this case, the high-speed data input is used by a rotating transmitter board to modulate multiple lasers. The optical output from these lasers is accepted by a stationary array of detectors that accept the laser output and transmit it to a receiver board. The output from the detectors of the receiver board is used to

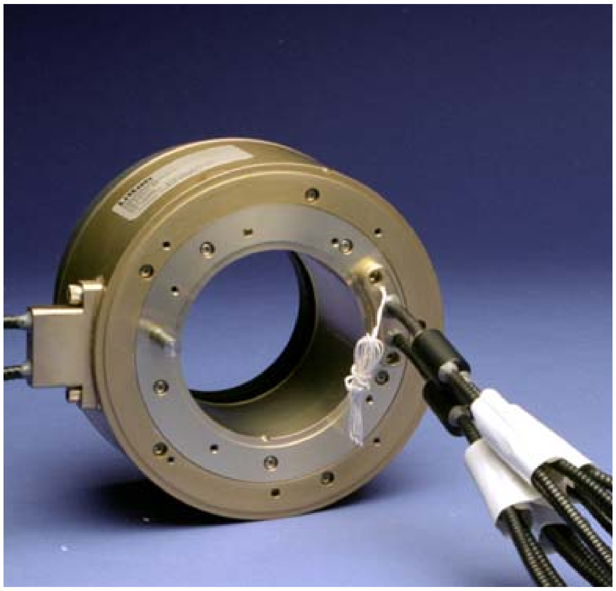


Figure 18: Off axis optical FORJ

reconstruct the input signal. A variety of reclocking and signal reconstruction techniques can be used to ensure low bit error rates. This system can have a fiber or copper interface and it can have a large through-bore. These devices can accept a composite data rate up to 40 Gbps.

Multiplexing

There has been a significant amount of investigation into robust, fault tolerant local area network (LAN) architecture of vehicle systems (22, 23, 24). The primary role of this intravehicle network is to provide the data communications infrastructure for controlling various devices and subsystems within a vehicle. It is also likely that other data buses will exist for various sensor data. The movement towards single or multiple vehicle networks should serve to reduce the number of discrete channels or circuits required through cable harnesses and across rotating platforms as more devices become nodes on a the network. In the case of fiber optic cables there should be a concerted effort to take full advantage of fiber bandwidth to reduce the number of optical fibers required. In many cases this could mean multiplexing some or all of these high- speed data lines onto one or two. Of course redundancy, security, and maintainability requirements will play a critical role in this MUX strategy.

Multiplexing is a technique that allows full utilization of the bandwidth capabilities of optical fibers. Time division (TDM) and wavelength division multiplexing (WDM) are the two most commonly used multiplexing techniques. Both play a different and important role in fully utilizing the bandwidth of optical fiber.

TDM

Time division multiplexing (TDM) is commonly used to combine video and/or relatively low-rate (typically under 10 Mbps) digital signals.The various signals to be multiplexed are combined into a single high-speed signal that can be subsequently converted to an optical signal or left as a high-speed electrical signal. This multiplexing is accomplished by assigning discrete parts of each signal a time slot (thus "time" division multiplexing) in the outgoing data stream. The single high-speed signal is then transmitted along the appropriate high-speed transmission line and then reconstructed, or broken out into the discrete signals, at the receiving end by a de-multiplexer. Asynchronous signals can be combined by over-sampling using a common clock. Although the output is often an optical signal, TDM is essentially an electronic process and normally accomplished using electronic parallel-to-serial converters like the Agilent G-Link or the Cypress Hotlink.

Figure 19 shows the principle of combining a number of signals and launching them as an optical signal onto an optical fiber. The rotational interface is accomplished with a FORJ and then de-multiplexed at the output end. This illustration shows bi-directional communication using different wavelengths of light through a single channel. This TDM multiplexing technology has an extensive heritage in harsh-environment unmanned vehicle applications. This technology is used extensively in tethered, remotely operated vehicles (ROV's) for underwater applications. These work-class ROV's are used in structure inspection, structure repair, and exploration. Many of these vehicles transmit multiplexed control data lines, video, and all other signals bi-directionally on one or two fiber cables, many kilometers long, through a fiber optic rotary joint at the cable winch. This application illustrates the survivability of the FORJ's and MUX's in harsh environments.

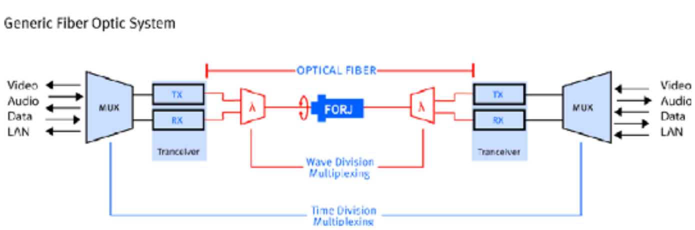


Figure 19: Multiplexing solution for multiple signal paths with bidirectional light transmission.

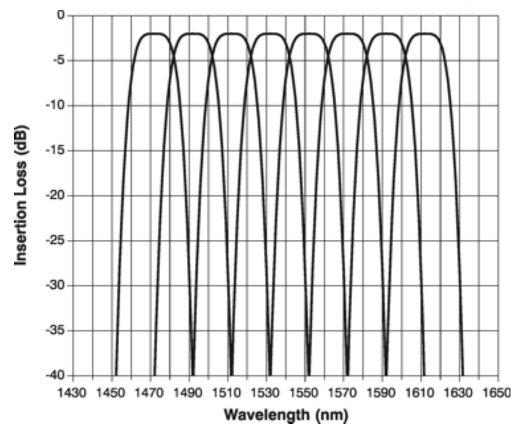
At present affordable components limit the top end bandwidth to about 2.5 Gbps, but the presence of devices that allow aggregate data rates of 10-40 Gbps for telecommunications applications, suggest that the bandwidth ceiling of reasonably priced components will rise quickly. TDM is typically the first step in maximizing the bandwidth potential of optical fiber by combining many low speed signals into one high-speed signal. These high-speed optical signals can subsequently be combined using a process known as wavelength division multiplexing.

WDM

Wavelength division multiplexing (WDM) is the technology that allows fiber bandwidth to be utilized to the fullest. This technique is used to transmit different signals on different wavelengths of light on the same optical fiber. Different wavelengths (or colors) of light can be transmitted on the same fiber without interference. Special passive devices that employ optical filters or gratings are used to combine and separate the signals. This is an optical process and therefore is not limited by the speed of electronic hardware. WDM's for 1310 and 1550 nm are common and, as pointed out earlier, are commonly used to provide bi-directional transmission on a single fiber. These are compact (2mm x 50 mm) fairly inexpensive devices.

Dense wave division multiplexing (DWDM) uses precision, temperature controlled filters and lasers to achieve 80 or more channels on a single fiber (25). Although commonly used in the telecomm-unication industry, this is not a very practical technology for military vehicle applications due to the cost of components and the need for precise temperature control to maintain the precise wavelength output from the lasers.

Figure 20: Example of 8-channel Course Wave Division Multiplexing (CWDM) wavelength



However in the past few years coarse wave division multiplexing (CWDM) has become commercially available. This technology can optimally provide around 8 channels with around 20 nm wavelength spacing. Figure 20 illustrates the wavelength separation for an 8 channel CWDM multiplexer.

High reliability commercial transceivers and WDM's are available, but at this time the temperature requirements of military vehicles limit the availability of some components.

Conclusion

There are a number of options for transmitting high-speed digital data across a rotating interface on a military vehicle in either a turret or a sensor application. Passive options such as a slip ring and a fiber optic rotary joint should be considered the primary options.

Slip ring technology has progressed to the point where data up to 1 Gbps can be supported on copper. Single and dual pass FORJ's provide almost unlimited bandwidth for digital data. This unlimited bandwidth provides a very practical upgrade path.

There are three active technologies available that allow high-speed data to be transmitted across rotating interfaces. These are used primarily to accommodate a though-bore in the assembly since a hole on the centerline precludes the use of a simple, on-axis FORJ. The simplest and most straightforward active device is a contacting system that has DC to 2.4 GHz bandwidth. Other techniques include capacitive coupled and optically coupled technologies.

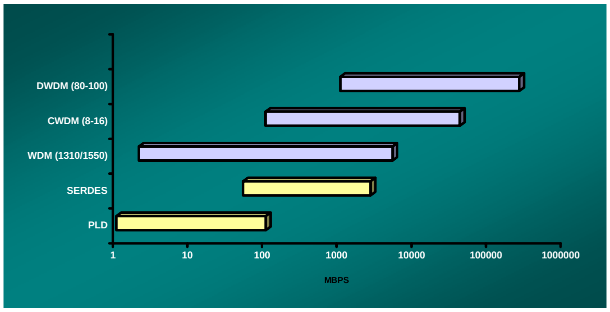


Figure 22: Bandwidths of MUX Options

The best method for fully utilizing the bandwidth potential of fiber is to multiplex multiple signals through one or two channels. This multiplexing is accomplished by two primary methods. Time division multiplexing allows a variety of low speed, video, and control signals to be combined into one signal. Wave division multiplexing combines multiple signals onto one fiber by utilizing differently light wavelengths. Figure 22 shows the possible bandwidths available with present technologies.

One of the primary methods of utilizing WDM in bi-directional fiber data communication is to use one light wavelength for the uplink and a different wavelength for the downlink. This allows full duplexed communication on a single fiber.

If we look at the optimum multiplexing techniques that would take the full advantage of the bandwidth of optical fiber, the system would likely involve both TDM and WDM techniques (26). Figure 23 shows what this system might look like. TDM techniques would be used to multiplex various control lines, video, and other low speed data lines onto a single fiber, or onto several fibers. These TDM signals, as well as other high-speed data channels, could be combined using CWDM techniques onto a single fiber.

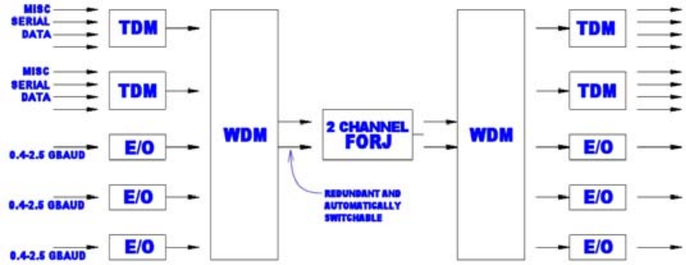


Figure 23: Optimum MUX solution

References:

1. Jeffrey J. Jaczkowski, "Robotic Technology Integration for Army Ground Vehicles," *IESS Systems*, June 2002.
2. Tom Brown, *Handbook of Optics*, Volume II, Chapter 10: "Optical Fibers and Fiber-Optic Communications." McGraw Hill, Inc., New York. 1995
3. David Bailey, Edwin Wright, *Practical Fiber Optics*. Newnes Press, Burlington, MA. 2003.
4. Paul Bedell, *Gigabit Ethernet for Metro Area Networks*, McGraw-Hill, New York, 2003.
5. IEEE Std 1394-1995, *IEEE Standard for a High-Performance Serial Bus*, IEEE, New York, 1995

6. IEEE Std 1394b-2002, *IEEE Standard for a High-Performance Serial Bus—Amendment 2,* IEEE, New York, 2002.
7. *Fibre Channel Physical and Signaling Standard*, ANS X.3230-1994 American National Standards Institute, 1994.
8. "Hotlink Design Considerations Application Note," Cypress Semiconductor, 1999.
9. *SMPTE-2591997 Television 10-Bit 4:2:2 Component and 4fsc Composite Digital Signals-Serial Digital Interface*, SMPTE, White Plains, NY. 1997.
10. *SMPT-292-1998 Television-Bit-Serial Interface for High-Definition Television Systems*, SMPTE, White Plains, NY. 1998
11. *Universal Serial Bus Specification, Rev. 2.0*, Compaq Computer Corporation, Hewlett-Packard Company, Intel Corp., Lucent Technologies Inc., Microsoft Corp. NEC Corp, Koninklijke Philips Electronics N.V., 2000.
12. Ray Chen, Jian Liu, and Xuegong Deng, "Multi-mode-fiber compatible WDM/WDDM with an ultra-large wavelength dynamic range", published in conference proceedings *Wavelength Division Multiplexing,* SPIE Optical Engineering Press, Bellingham, WA, 1999*.*
13. Peter Pondillo, "Multimode Fiber for use with laser sources, White Paper," Corning Inc., Corning NY. 2001.
14. Wolfgang Rieger, "Next Generation Multimode Fibers, Technical Newsletter,"
15. Tyco / AMP NETCONNECT Solutions Division.
16. Brian C. Wadell, *Transmission Line Design Handbook*, Artech House, Boston, MA, 1991.
17. Milorad Cvijetic, *Optical Transmission Systems Engineering.* Artech House, Boston, MA, 2004.
18. Charles S. Walker, *Capacitance, Inductance and Crosstalk Analysis.* Artech House, Boston, MA, 1990.
19. J. Alexander Speer and Walter W. Koch, "The Diversity of Fiber Optic Rotary Connectors (Slip Rings)", *SPIE Vol. 839 Components for Fiber Optic Applications II* (1987).
20. Glenn F. Dorsey, "Fiber Optic Rotary Joints—A Review," *IEEE Transactions on Components, Hybrids and Manufacturing Technology*, Vol. CMT-5, No.1, March 1982.
21. M. Oskar van Deventer, *Fundamentals of Bidirectional Transmission over a Single Optical Fibre,* Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.
22. Paul C. Richardson, Ali Elkateeb, Larry Lieh, "An Adaptive Real-Time Intravehicle Network Protocol for Intelligent Vehicle Systems," *IEEE Transactions on Vehicular Technology*, Vol. 53, No. 5, September 2004
23. L. Fredriksson, "CAN for critical embedded automotive networks," *IEEE Micro*., vol. 22, pp 28-35, July/August 2002.
24. Paul Richardson, Larry Sieh, "Real-time LAN's in combat vehicles: feasibility criteria for nonpreemptive messages and multiple message streams originating from individual nodes," *IEEE Int. Conf Conf. Computers, Communications, and Networks (ICCCN '99),* Boston, MA, October
25. Krishna M. Sivalingam, Suresh Subramaniam, *Optical WDM Networks: Principles and Practice*. Kluwer Academic, Boston, MA 2000.
26. Casimer DeCusatis, *Fiber Optic Data Communication: Technological Trends and Advances*, Academic Press, San Diego, 2002.
27. F. Mlinarsky, "Gigabit Ethernet over Category 5 (Internal White Paper)". Scope
28. Communications, Inc., Marlborough, MA, June 6, 1998

This paper was delivered at the 5th Annual Intelligent Vehicle Systems Symposium in Traverse City, MI on June 15, 2005