White Paper

Avoiding Data Bottlenecks in Rotating Systems - Copper or Fiber

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Key Messages

- This paper is geared toward helping system designers of scanning or rotating sensor systems make critical decisions about transmission media, data compression, and system architecture
- Collecting data with high performance sensors, converting this data to digital data streams and transmitting the data from rotating platforms to stationary processors is a challenge to system designers as the bandwidth expands into multiple Gigabit / second territory

Introduction

The challenge of small, state-of-the-art gimbaled sensor systems that are common Unmanned Aerial Vehicle (UAV) payloads is transferring data speeds of Gigabit / sec+ across the rotating interface. This challenge has become one of the primary design challenges to the industry and has an important impact on system architecture. Traditionally, this functionality was handled with slip rings that handled power, signal, and data transfer. This paper will discuss the options that are available and currently in development to transfer data well above a Gigabit / sec. Specific formats will be discussed including High Definition (HD) video, Gigabit Ethernet (GigE), and other high speed data formats while addressing special requirements presented by each of these formats, as well as overall system architecture. Collecting data with high performance sensors, converting this data to digital data streams and transmitting the data from rotating platforms to stationary processors is a challenge. Decisions should be made based on a survey of the overall system requirements and not just on individual components. This paper is geared toward helping system designers of scanning or rotating sensor systems make critical decisions about transmission media, data compression, and system architecture. This is accomplished by examining five primary technology areas: slip rings, Fiber Optic Rotary Joints (FORJ), High Speed Data Links (HSDL), multiplexers, and media converters.

High Performance Sensor Data with Rotary Interfaces

With the proliferation of high performance, real-time sensing applications, the bandwidth capabilities of the transmission lines that carry these signals are highlighted. Much of the advancement in sensing and imaging technologies has been accomplished by digital conversion of sensor data. The aggregate data rate of sensor systems continues to increase due to the increase in the fidelity of individual sensors, as well as the increased use of multiple sensors to expand the versatility of sensor systems. Sensor fusion techniques that combine the output of a variety of sensors are expanding into a variety of applications adding additional bandwidth pressures on transmission lines.

Figure 1: Digitalization of radar, day and IR camera in electro-optic gimbals and x-ray detector sensor information in medical CT scanners are examples of three sensor applications that push the bandwidth limits of rotary data transfer.

In most sensor applications, data must be transferred to the processor along a transmission path in real time with sufficient bandwidth to maintain the signal integrity. Since the data transmission path is only as fast as its slowest element, it is important to analyze the bandwidth characteristics of each element of the path. In cases where these sensors must rotate, one of the areas of interest is how the data gets across the rotational interface — traditionally the job of a slip ring. There are a number of tools to increase the bandwidth of this rotational interface to avoid a data bottleneck.

Passive devices transmit signals without any signal processing and can be analyzed and specified using typical transmission line properties, e.g., signal attenuation and noise properties. The two passive components for transmitting high speed data to and from rotating platforms are slip rings and Fiber Optic Rotary Joints (FORJ). Active rotary transfer devices transmit signals using signal processing electronics to convert the signal into a form that can be transmitted across the interface and then, of course, convert them back to the original form. There is a whole family of components that use this active approach and vary the manner used to transmit the signal across the interface; however, since the transmission method is transparent to the user and the specification method is fairly universal, it is useful to consider these techniques as a single type of active component which will be referred to as a High Speed Data Link (HSDL).

Transmission Media

One of the most important data path decisions to be made is the transmission line media decision, namely copper or optical fiber. This media decision should be made on the basis of optimizing the overall system performance and not solely on the basis of the rotational interface. For example, choosing fiber as the transmission media simply because of a perception that a fiber optic rotary joint (FORJ) is the best way to transmit high speed data from a rotary platform can limit system options. On the other hand, if the decision is made that fiber is the best transmission media because of typical fiber advantages such as Electromagnetic compatibility (EMC) and Electromagnetic Interference (EMI) isolation, bandwidth properties, or weight savings, then the rotary transmission device selection becomes a natural part of this decision process and an appropriate FORJ can be selected. Copper is still a useful transmission media in many high speed data applications as advanced techniques for data transmission on copper continue to expand the bandwidth of copper solutions.

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 and include EMI / EMC immunity, virtually unlimited bandwidth, and light weight. However, copper offers environmental robustness, simpler interfaces, easier field repair, and normally lower cost. 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 1 summarizes the guidelines for various high-speed data formats. This table considers the lossy characteristics from any transmission line (attenuation, amplitude distortion, phase distortion) and relates these losses and distortions to the ability of the data format to tolerate or compensate these affects. Digital data is typically transmitted on cable with controlled impedance lines. Since most data is transmitted differentially, these cables are typically twisted pairs. Normally the impedance of the cable is specified in the format specification and the higher the bandwidth the more important it is to control the cable impedance.

It is important to note that the bandwidth requirements of this table reflect not only the bandwidth capabilities of the cabling and the data rate of the signal but also the ability of the electronics associated with specific data formats to compensate for transmission line loses and mismatching. Specifically, it is important to note that Firewire© (IEEE 1394) and USB 2.0 have very short transmission line guidelines. These two formats were designed for computer peripherals and communication. Neither were designed for long cable connections and are very sensitive to long cable lengths or any impedance mismatched components placed in the transmission line such as connectors or slip rings. On the other hand, the two SMPTE formats also illustrate the benefit of active cable equalizer electronics used to compensate for cable losses and phase delay.

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

Table 1: Cable length guidelines for data formats

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 on a final configuration can be made.

System designers often treat terminations as equivalent length of cable in terms of this degrading effect. This is a very subjective method, but probably the best available. The analysis that engineers typically use to ensure that its hardware does not have a significant impact on the effective length of transmission length is the "quarter wave length analysis."

This quarter wave analysis looks at the effect of any impedance discontinuity on the bandwidth of the transmission line, i.e., the maximum signal frequency that can be transmitted on the transmission line. Transmission line theory tells us that if an impedance mismatch in a transmission line is close to 1/4 of the wave length of the signal then significant signal attenuation and distortion can occur. These losses are due to signal reflections and standing waves on the transmission line. Therefore, in the determination of the effect of any mismatch inserted into a high speed data line, it is important to understand the total length of the discontinuity and the relationship this length has to the wavelength of the signal frequency. When this length approaches 1/4 of the wavelength of the signal frequency being carried on the transmission line, the signal begins to degrade beyond acceptable limits. In the case of slip rings, we refer to this 1/4 wave length as the bandwidth limit of the slip ring.

This quarter wave analysis is a worst case analysis since it does not take into effect that closely matching the transmission line impedance can significantly improve the bandwidth of the device by minimizing the 1/4 wave effect. However, in the absence of actual test data, the 1/4 wave analysis can provide a conservative estimate.

Data-Bandwidth

The short discussion above outlines the considerations for determining the bandwidth of the physical media, i.e., the cable in the case of copper transmission lines. What methods do we use to determine the bandwidth required by the digital data being transmitted? The transmission line analysis strategies used above refer to signal frequencies as if these signals are sine waves. However digital data are normally square waves. The first problem is to understand how to discuss digital data in the frequency domain.

Digital data is a series of voltage shifts (ideally instantaneous) that represents logic shifts (of ones and zeros). Fourier theory shows that these resultant square waves can be represented by a series of sine waves using a Fourier series approximation. Figure 2 shows a square wave approximated by the 1st, 5th, 11th, and 49th fundamental frequency.

Data transferred as 1's and 0's at a specific Megabits / sec (Mbps) rate has a first harmonic of (Mbps / 2) Mhz. Under normal circumstances, transferring the fundamental frequency and the first two odd harmonics will normally reproduce the square wave pattern very well as shown by the second graph of Figure 2 (i.e., K=5). When transmission lines are analyzed for their ability to transmit digital data, the transmission line "bandwidth" refers to the maximum frequency that can be transmitted on the line without "unacceptable" signal degradation which is ultimately evaluated as a bit error rate (BER) that is unacceptable for the specific application. It is important to point out that bandwidth does not equal data speed, but it can be related to data speed using these Fourier relationships. Engineers have found that maintaining a bandwidth of at least the 3rd harmonic of the fundamental frequency of the data provides a signal transfer of acceptable quality in real world situations.

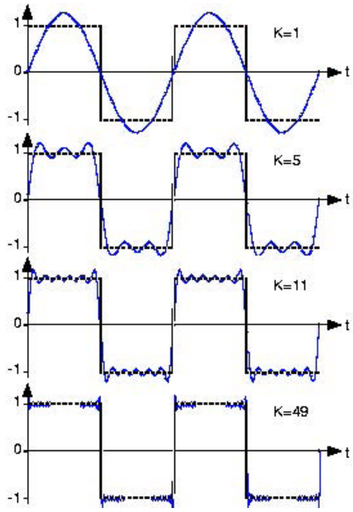

Figure 2: Fourier series approximation of square wave

The bandwidth analysis can become more complicated when features like encoding patterns come into play. The matter of encoding and its relationship to the bit rate of digital data is important and can be illustrated by looking at actual data. Figure 3 shows the frequency components of output from Cypress Hotlink II running at 150 Mbps. The horizontal axis shows frequency (150 MHz / div). The energy peaks at 75, 225, and 375 show the fundamental (75 MHz) and the odd harmonics. At least 225 MHz of bandwidth (third harmonic) is sufficient for a good signal quality as predicted by our analysis above and 375 would be ideal. But before we make the conclusion that 225 MHz of bandwidth is required to transfer 150 Mbps of data consider 100Base-T Ethernet.

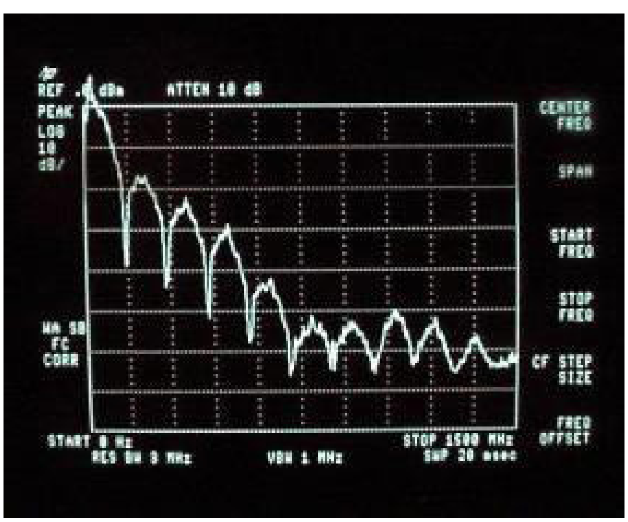

Figure 3: Frequency spectrum of 150 Mbps hotlink

In contrast to the signal of Figure 3, Figure 4 shows the frequency components of a 100Base-T Ethernet signal up to 500 MHz. Ethernet uses a unique encoding scheme that allows 100Base-T to transmit 100 Mbps worth of data using a 25 Mbps square wave. In terms of signal fidelity, a bandwidth of 100 MHz passes 99% of the energy of the Ethernet signal and gives excellent signal fidelity. This "more data per bandwidth" is one of the advantages of Ethernet. We can carry this analysis even further by looking at the spectrum for 1000Base-T (Gigabit) Ethernet. The goal of the IEEE P802.3 Task Force was to allow 1000Base-T to be implemented on existing media infrastructure. 1000Base-T utilizes all four twisted pairs of CAT 5 or CAT 6 cable. Therefore it should not be a surprise to see that Figure 5, a Frequency Spectrum of a 1000Base-T signal is almost identical to Figure 4. This similarity means the bandwidth requirements for each pair of a 1000Base-T signal are almost precisely that of a 100Base-T signal pair. There are other critical characteristics of GigE signals that place constraints on the transmission and these are discussed in published documents that provide a more detailed discussion of 1000Base-T Ethernet or GigE.[1]

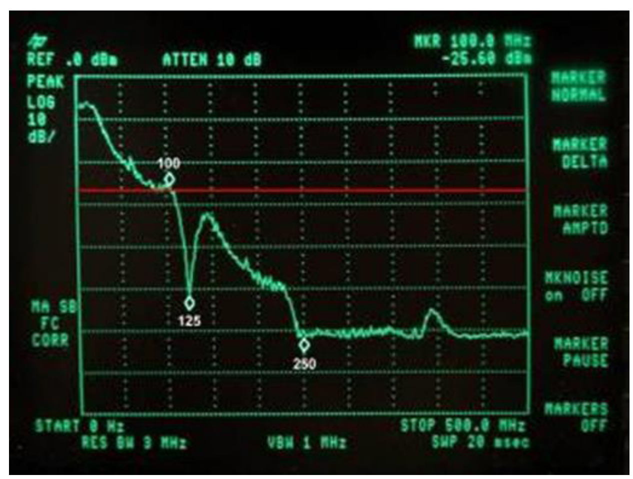

Figure 4: Frequency spectrum of 100BaseT-Ethernet

These figures should illustrate that it is important to understand the actual Baud rate of the data signal to approximate the bandwidth. Another commonly used method of evaluating bandwidth, if the rise time($\mathbf{T_r}$) of the digital square wave is known, is to express the bandwidth by using a Nyquist approximation:

$$BW = {}^{0.5}/_{Tr}$$

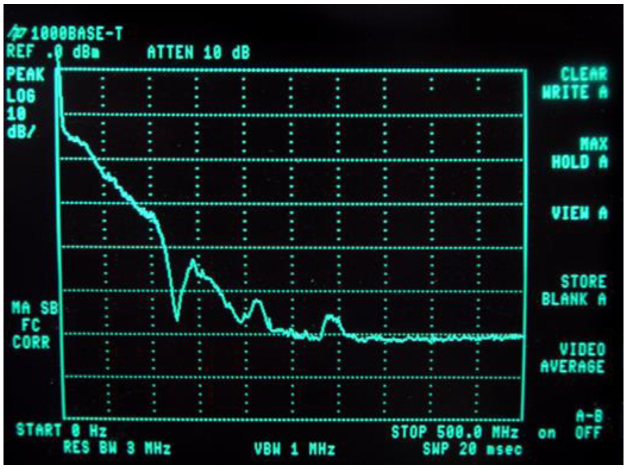

Figure 5: Frequency spectrum of gigabit ethernet (1000Base-T)

This equation typically produces results similar to the Fourier analysis, but the rise time analysis can give more representative results in the case of data with very fast rise time requirements and fairly infrequent pulses. There are a number of other very important parameters that must be considered when evaluating the ability of a transmission line to transmit high speed digital data, such as crosstalk, shielding, and phase delay. We will consider these parameters specifically in the discussion on slip ring performance parameters.

Slip Ring Parameters

What are the important parameters to understand when reviewing a transmission line component, specifically a slip ring, for suitability for high speed data or high definition digital video signals? As the previous discussion outlined, the primary task is to compare the bandwidth capability of the slip ring with the bandwidth requirements of the data. Broadband slip ring designs are now able to successfully transmit data up to 1.5 Gbps in a passive device and beyond 10 Gbps with signal conditioning. 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 electromagnetic interference shielding (EMI / EMC).

Bandwidth

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 and the effective length of discontinuity are 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. 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.

Since the mismatch length is the most critical parameter, the slip ring diameter has a significant effect on the bandwidth of a slip ring and larger diameter rings typically have lower bandwidth capability. If we consider the slip ring to be a discontinuity in the copper transmission line, this diameter effect can be understood as a fraction of the wavelength of the signal's bandwidth. As discussed earlier, when the length of an impedance discontinuity approaches 1/4 of the signal bandwidth, the signal quality becomes compromised:

$$L = c * \vartheta p \Big/ (4 * f)$$

Where: L = critical path length
c = speed of light vacuum
Op = velocity of propagation factor (~ 0.6)
f = signal bandwidth

In the case of 500 MHz bandwidth for example, the critical length (1/4wavelength) is 9 cm. This means that any transmission line discontinuity or perturbation of length greater than 9 cm will begin to have a significant impact on signal quality. This 9 cm length equates to 2.87 cm diameter.

How do we get from this critical bandwidth to a maximum Baud rate that can be transferred over the slip ring?

1. Find the frequency that has as 1/4 of its wavelength the maximum signal path in the slip ring (length of discontinuity). This frequency is the fundamental frequency of the bandwidth of the slip ring (or the media). We know however that there are harmonics of this fundamental frequency that are critical and the media must also support those.

2. Divide the fundamental frequency by three to find the frequency of the signal that is the third harmonic that should be transmitted on the slip ring without+ excessive attenuation. This is the maximum signal bandwidth.

3. Multiply this frequency by 2 to derive the baud rate corresponding to this maximum signal bandwidth.

This estimate is a worst case analysis since the assumption is that nothing has been done to ameliorate the impedance mismatch. Figure 6 provides a graph of these calculations for the standard commercial slip rings. Using the equation above, we can estimate the effect of diameter on the bandwidth limit of slip rings. These calculations assume that the transmission line cable is terminated within 1/2 inch of the rings and brushes inside the slip ring capsule itself, thereby minimizing the effect of cable mismatches. One published application note discusses the bandwidth of commercial slip rings with these diameters in more detail.[2]

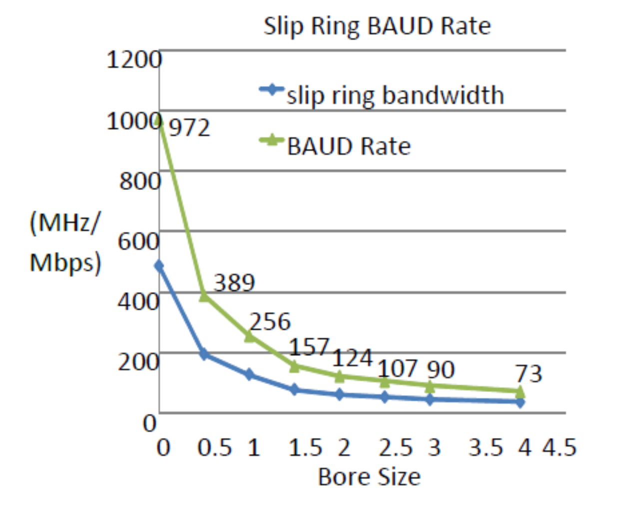

Figure 6: Bandwidth limit of slip rings as a function of bore size

This length (or diameter) effect can be minimized by minimizing the impedance mismatch between the discontinuity and the transmission line, but it is impossible to completely eliminate. The two insertion loss plots of Figure 7 are of data channels that are identical except for diameter. The top rings are approximately 6.4 cm in diameter and the rings in the bottom chart are approximately 15 cm in diameter. The critical diameter calculations graphed above would tell us that these rings would have a bandwidth of about 220 MHz and 95 MHz respectively. However, impedance matching of the rings to the transmission line allows extension of the bandwidth to 800 and 600 MHz respectively. However, the charts do illustrate that diameter is still an important consideration.

We can use the graphs of Figure 7 to illustrate how engineers use actual measured bandwidth values (typically insertion loss vs. frequency) to evaluate the data rate capability of a specific slip ring design. If we assume that the data rate must have its third harmonic below the -6 dB loss marker on each graph, the data rate that can be transmitted on these two ring pairs is 533 Mbps (800 MHz) and 400 Mbps (600 MHz).

Frequency resonances resulting from impedance discontinuities will cause time domain distortions called "group delay". This spreading of the edges of the square waves across the time domain results in the received data rise and fall times having edge jitter or amplitude jitter. Jitter is normally measured as an "eye pattern", and these eye patterns are often used to determine if a transmission line will transmit a specific data signal with an acceptable bit error rate (BER).

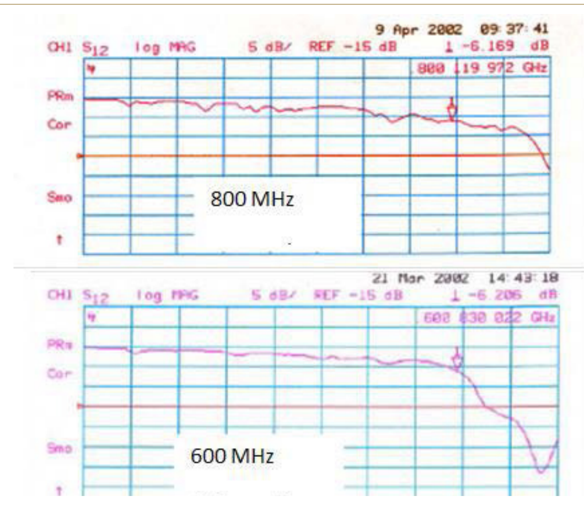

Figure 7: Insertion loss vs. frequency of two different diameter ring pairs

Figure 8 shows an eye pattern of an IEEE 1394 B (Firewire-800 Mbps) signal transmitted through a slip ring showing the 1394 B mask for an acceptable eye opening. This mask appears as the black diamond in the center of the eye and the black bars at the top and bottom of the pattern. The size of the eye pattern opening can be correlated to BER. A more restrictive eye mask correlates to a higher BER. Since eye patterns are often quicker tests to run than BER tests and they provide more diagnostic information than BER tests, eye patterns are universally used to communicate the ability of a specific circuit or transmission line to handle digital data. Data specifications typically contain eye pattern masks that must be satisfied for successful data transmission.

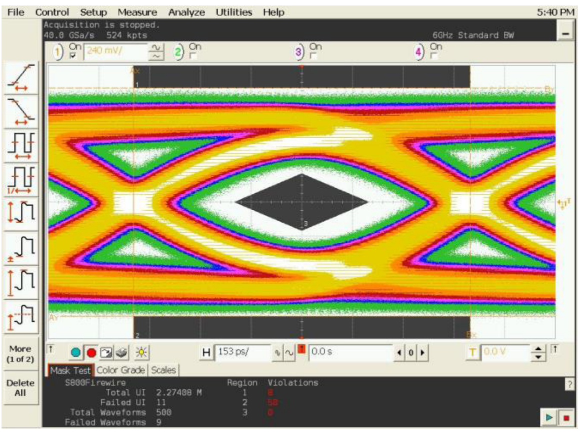

Figure 8: Eye patterns of 1394 B (Firewire)

Table 2 shows three of the most common methods of determining if the bandwidth of the transmission line is sufficient to transmit the desired data rate.

Test	Parameter measured	Advantage
Insertion loss	Insertion loss over the frequency of interest	Provides attenuation and a snapshot of resonant frequencies to assist in design
Eye pattern	Data jitter data amplitude	Provides diagnostic signal quality information at the data speed in question
BER	Bit error rate over time	Provides go / no-go information about data quality over time

Table 2: Bandwidth measurements

Crosstalk and Intersymbol INterference (ISI)

Bandwidth is not the only parameter of concern when dealing with high speed data in slip rings. Second to the bandwidth in evaluating the ability of a slip ring to transmit high-speed digital data is crosstalk. Crosstalk (in dB) between a noise emitting channel V1 and a noise sensitive channel, V2, is:

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

This relationship is shown graphically in Figure 9. When a number of channels are incorporated into a relatively small physical package, capacitive coupling is the primary cause of this crosstalk. The relationship that governs crosstalk (Kc expressed in dB) from a primary, or emitting, circuit to a capacitively coupled circuit, when the frequency (f) and capacitance (C) are known is:

$$Kc = 20\log(2\ \ C)$$

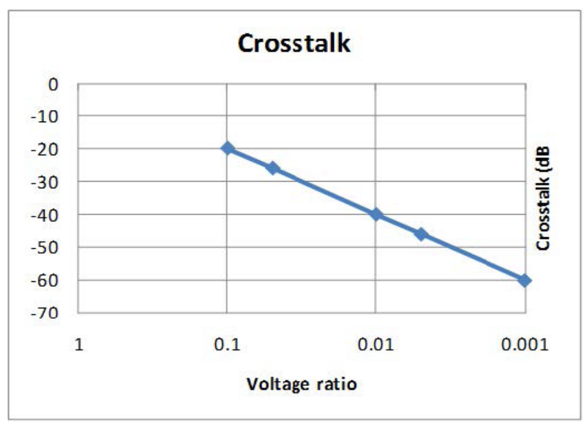

Figure 9: Crosstalk and frequency

Figure 10 shows an example of crosstalk between two data rings prior to several design changes to improve the crosstalk performance. This graph shows that the relationship of crosstalk to frequency is more complex than strictly linear (on a log scale) as predicted by the equation above. Other factors are at work besides capacitive coupling. This graph suggests by its bimodal appearance that two resonant frequencies at 200 and 400 MHz are generating significant electromagnetic (EM) radiation, which is being coupled into the susceptible circuit. The solution to this problem goes back to ensuring that the slip ring has the appropriate bandwidth. The standing waves and resonances that create the bandwidth limitation of high speed signals also generate the resonant frequencies of high EM radiation and radiation coupling.

It is important to evaluate the crosstalk requirements of a high speed slip ring properly. High speed data lines are the greatest risk of being noise emitters due to their high frequency components. The primary frequency of this noise is the fundamental frequency of the data. For example 100 Mbps data has a fundamental frequency of 50 MHz and it is at this frequency that the greatest crosstalk will occur. There is some coupling at the odd harmonics (3rd, 5th, etc.), but this coupling is of secondary effect.

Inductive coupling can have an effect in the coupling of noise into sensitive signals circuits in the case of power circuits with very high switching frequencies or sharp surge spikes, i.e., very large $\frac{di}{dt}$. However, inductive effects are almost always secondary effects and are normally handled by using care in isolating sensitive signals from power as much as possible using physical distance.

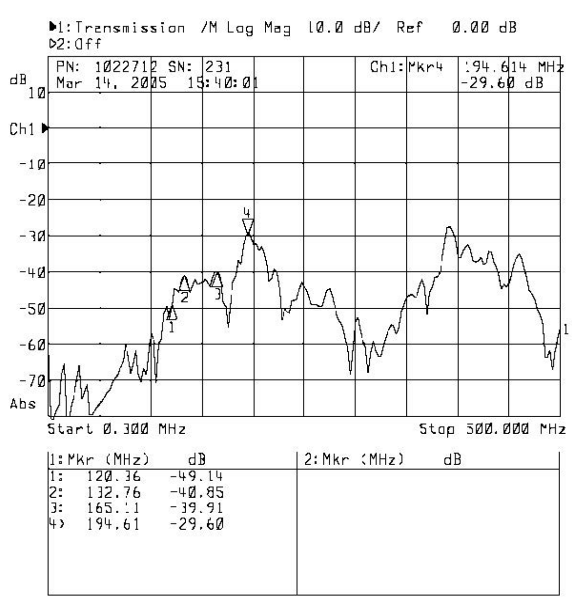

Figure 10: Crosstalk vs frequency in slip ring assemblies

The risk of the crosstalk from digital lines is primarily due to sensitive low level analog signals. As the graph of Figure 10 shows, a 5 volt digital signal with -40 dB crosstalk will produce 50 mV (i.e., 5 V x .01) of crosstalk noise. This could be a significant noise contributor to a low level analog signal (analog video for example). On the other hand, 50 mV is relatively insignificant on a data channel, especially differential data since this crosstalk will normally not be seen as differential noise. It is also important to consider the frequency of the crosstalk noise. As stated earlier, this noise will be primarily the fundamental frequency of the data line, which can often be filtered on analog channels.

Electromagnetic Interface

Electromagnetic Interference (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. And finally, proper cable termination practices are important at all cable terminations with a clear definition of shield termination strategies and techniques. Proper utilization of these techniques will allow slip ring assemblies to meet even the harshest EMI / EMC requirements.

The magnifying effects of slip ring resonances and standing waves were discussed in the crosstalk section, but these effects are also part of the overall effect on the EMI performance of the slip ring.

The Effect of Rotation

What is the effect of rotation on the performance of slip rings at high data rates? The issue that first comes to mind is the effect of contact noise on the signal. A study of this issue[3] shows that contact noise in a properly designed slip ring does not have a significant impact on the reliability of data transfer during its usable life, irrespective of data speed. This contact noise is a small variation in resistance that is produced by resistance changes that occur at the point of contact between the rotating ring and the stationary brushes. Typically there are at least two brush contacts to reduce this resistance change. Slip ring contacts are normally precious metal to prevent the formation of high resistance oxidation films and very small amounts of contact lubricant prevent the formation of uncontrolled, high resistance organic films. Contact resistance variation is normally 10 to 40 milliohms / revolution when a slip ring is rotated between 10 and 120 RPM. Since the current level of a digital signal is normally around 20 milliamps, this 10-40 milliohm value represent 0.2 to 0.8 microvolts of noise. This equates to -75 dB of noise on a 5 volt circuit. Since it is common to see -40 dB or more of crosstalk noise, -75 dB of contact noise is inconsequential. As a matter of fact, the contact noise has to get close to one volt to start to have the same order of magnitude effect as crosstalk.

A more significant effect of rotation on digital data is the change of the effective length of the discontinuity of the slip ring. Wire or cable is typically terminated to the ring in one radial location on the ring. When the brush contact rotates around the ring, the length the signal travels from the lead termination to the brush varies as the brush changes location with variation. This variation has an effect on the bandwidth of the slip ring, and depending on the diameter this effect can be significant. This effect can be counteracted by terminating leads at multiple locations on the ring, but normally the bandwidth is simply calculated at the worst case location of the lead termination.

Case Study: Data on a 0.5 inch Diameter Slip Ring

Figure 11 below is a commercial slip ring with a 0.5 inch through-bore. Testing was performed on this slip ring to confirm the bandwidth estimations calculated using the guidelines discussed.

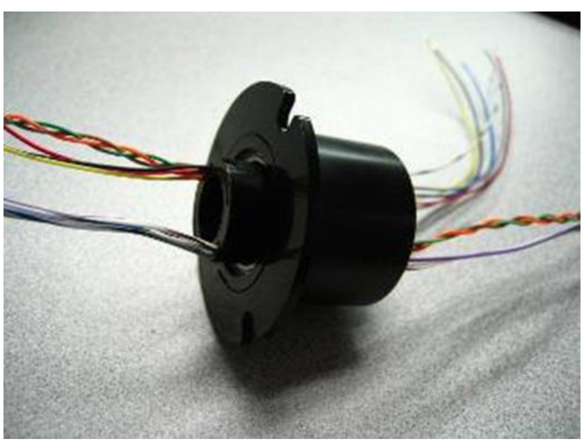

Figure 11: 0.5 Through-bore slip ring

Figure 12 shows insertion loss data from the 0.5 inch bore slip ring. The picture of the unit shows that the cable was twisted up to the exit point of the slip ring, but the wire was not twisted inside the unit. This is a very short unit so this lack of internal twisting likely won't have a big impact. If Figure 5 is used to estimate the bandwidth limit of a 0.5 through bore slip ring, the value is approximately 200 MHz. The insertion loss data of Figure 6 suggests that the -6 dB value of this slip ring configuration is approximately 300 MHz, but the data also shows that the roll-off starts at approximately 200 MHz.

Figure 12: (0.5 Bore) Slip ring bandwidth

The data show that the resonances in transmission line are complex and there is little value in trying to look past the -6 dB point. This data, along with other tests and evaluation, leads us to the conclusion that the estimates represented by Figure 6 are somewhat conservative and a useful method of predicting usable bandwidth of a slip ring of known diameter.

Figure 13 highlights the effect of bandwidth limitations even better. This attenuation is the effect of mismatch losses associated with impedance mismatches in the transmission line. Again, it should be noted that the roll-off starts again at around 200 MHz.

A look at crosstalk data also highlights the need for using a slip ring with the appropriate bandwidth. Figure 14 shows the differential crosstalk between circuit pairs as a function of frequency. We see the familiar frequencies showing up as crosstalk peaks. The same resonance nulls that play havoc with the bandwidth result in EMI radiation that can be coupled to other circuits. This is in addition to the capacitive coupling that can be predicted from the circuit capacitance.

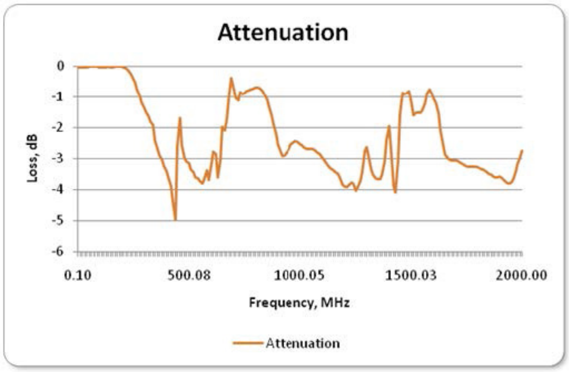

Figure 13: Attenuation vs frequency

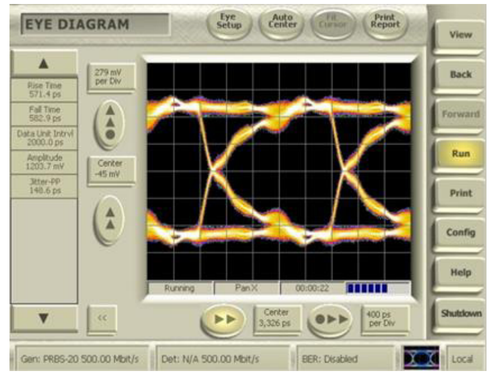

Figure 15: 500 Mbps data transfer

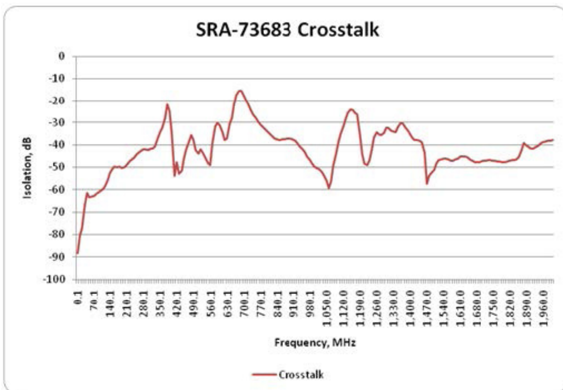

Figure 14: Crosstalk vs frequency

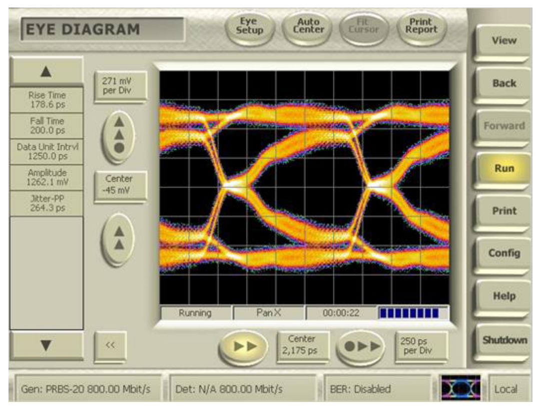

Figure 16: 800 Mbps eye pattern

The 200 MHz bandwidth limit suggests that the maximum data we should put across this ring is 400 Mbps. Figures 15 and 16 show eye patterns for 500 and 800 Mbps data streams. The eye diagram is used to analyze the quality of a digital signal. The eye diagram plot provides a qualitative and quantitative description of system performance and is obtained by overlapping multiple cycles of the signal on the screen of an oscilloscope. The eye opening / closure is indicative of the signal integrity. The deviation of the signal crossing shows the jitter in the signal and its complement. A larger eye opening lowers the probability of bit errors. Figure 15 shows the 500 Mbps rise time. The "eye" is relatively open with little jitter, but the leading edge rise time degradation is fairly significant, likely the result of the attenuation that starts at around 350 MHz. However, this eye pattern would likely be acceptable for 500 Mbps data, and the conclusion is that 500 Mbps is the maximum data rate of this slip ring with this wiring configuration. The eye pattern at 800 MHz shows an even more pronounced edge degradation.

These data all suggests that the 400 Mbps Baud rate predicted by Figure 6 is slightly conservative and the data rate 600 Mbps that is estimated by Figure 12 (-6 dB point) is the maximum rate that would be reliable.

Passive Fiber Optic Rotary Joints (FORJ)

The slip ring fiber optic equivalent is the fiber optic rotary joint (FORJ). A FORJ does not have the bandwidth limitations found in slip rings, but there are some limitations on the number of optical fiber paths that can be incorporated. FORJs are available in one, two and multi-channel versions and are optimized to accommodate either singlemode or multimode fibers. In the case of the one and two channel FORJ, lenses on the axis of rotation are used to achieve the transfer of the signal across the rotating interface. Multi-channel FORJs use several techniques for transferring three or more lines, but these techniques all involve optical transfer along the axis of rotation. Two channel and multi-channel FORJs can mix single and multimode fibers in the same assembly. All fiber channels in passive FORJs are bidirectional, i.e., light can be transferred in either direction, and they are able to support multiple wavelengths on each channel just as typical optical fiber.

The important performance figure of merit for transferring digital data across a FORJ is insertion loss. Components inserted into a fiber optic transmission line typically produce some signal attenuation and the system designer must account for all these losses to insure that the optical signal received at the detector has sufficient power to produce a reliable signal. The advantages of fiber transmission lines apply to FORJs, namely, almost unlimited bandwidth and no EM interference. However, there are two important issues to understand when considering the use of a FORJ in a system:

1. For all practical purposes a passive FORJ with a through-bore does not exist

2. The complexity (size, weight and cost) of a FORJ increases significantly with the use of more than two fiber channels

Figure 17: From left to right, is a one, two and thirteen channel FORJ showing appropriate size relationship

This multi-channel FORJ issue becomes important when considering system architecture. In the case of copper lines when more channels are needed, it is simple to just add more wires. The incremental cost of adding wires and adding rings to slip rings is typically low. This copper model becomes less useful when considering the use of fiber optic transmission with a FORJ. Figure 18 shows that the cost and size of a FORJ jumps dramatically at three points: between 1 and 2 channels, between 2 and 3 channels, and between 19 and 20 channels. These jumps provide a strong incentive to limit the number of discrete fibers through the rotary interface to one or two fibers. This fiber reduction is typically accomplished by multiplexing, and multiplexing schemes will be considered later. Sometimes the most effective method of reducing the number of channels in a FORJ is to utilize active high speed slip ring channels where possible even if media conversion is necessary to convert from fiber to copper and then back.

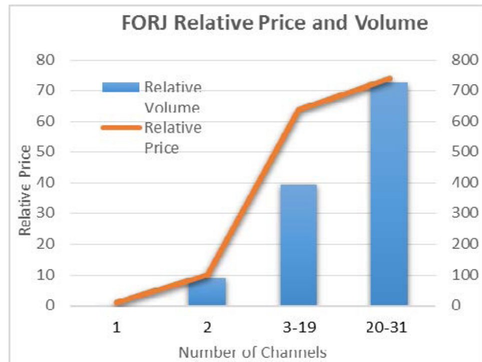

Figure 18: This figure shows the relative difference in price and volume of multi-channel FORJs compared to a single channel FORJ (relative values of 1). These differences occur in jumps.

Active High Speed Data Links (HSDL)

Active High Speed Data Link devices serve an important role in bridging the bandwidth gap between passive copper and passive fiber optic rotary joints. Active devices can be non-contacting or contacting. Non-contacting designs include optical, capacitive and RF coupled high speed channels. Contacting designs utilize sliding contacts to transfer data but special techniques are used to avoid standing waves that ultimately limit the bandwidth of standard slip rings. There are advantages of each of these data transfer techniques, and overall system requirements such as rotational speed, diameter and bandwidth all factors into the decision of which rotational interface option to choose. The important feature of all of these designs is that signal processing is used on both ends of the device to condition the signal for transmission across the rotary device. As mentioned earlier, one of the primary issues with passive slip rings is that the continuous ring allows reflected signals to establish standing waves in the case of high frequency bandwidth components and/or large diameter rings. The key to the HSDL technology is eliminating the continuous ring to avoid dual, uneven and variable signal paths during rotation. In addition, signal injection techniques are used to avoid reflections at the interfaces between the rotary device and the transmission line. Active electronics are required to implement these techniques.

Four basic techniques are used in these High Speed Data Link devices: contacting or DC coupled, capacitive, RF and optical. The media of the system transmission line plays a minor role in the decision of which of these techniques to use. In all cases, the input signal is modified by the interface electronics and this modification can include media conversion if necessary. High Speed Data Link (HSDL) technology can be useful in a number of different instances:

1. A through-bore is required for high speed data eliminating the option of a passive FORJ.

2. Bandwidth exceeds the limit of a passive slip ring and copper input/output is desired.

3. The number of fiber optic lines exceeds two.

Role of Media Converters

Media converters are devices that convert optical signals to electrical and/or electrical signals to optical. Media converters let the engineer change between fiber and copper and also change encoding formats on the transmission media. By utilizing media converters in the overall system architecture an engineer can minimize the impacts of having to utilize the best transmission lines based on the slip ring. For instance, a system can use fiber optic cables to and from the rotating interface for EMI/ EMC and by utilizing media conversion a copper based slip ring can be used to obtain an open bore for things like targeting LASERs. Media converters can also change the format of the data to provide the ability to reuse existing legacy products in new designs. One example of that is conversion from RS-170 Video (NTSC) to one of the newer digital formats like GigE Vision. Another example of a common use of a media converter is data that is handled electrically within a small rotating sensor head but converted to fiber to accommodate long transmission line distance at the sensor head output.

Media converters are particularly useful in the case of rotating sensor data to maximize the options available for digital data transfer across the rotating interface. Small media converters fit in extremely small gimbals and allow the use of different transmission media within a system.

Figure 18: Media converters convert fiber signals to copper. One common use is for conversion of optical signal for a copper backplane.

Role of Multiplexers

Multiplexers play a critical role in the design of data transmission architectures for rotating systems. Fiber optic systems provide the best illustration. Fiber optic transmission lines of modest length provide a data pipeline of hundreds of Gigabit / second capability, but it is quite common to use fibers for data at one Gbps or less. In non-rotating systems it is fairly inexpensive and lightweight to run a separate fiber for each individual signal. However, as we have seen when a fiber optic rotary joint is part of the system, a disproportionate penalty is paid in size, weight and cost when the number of fibers exceeds two. Multiplexing is a method to take advantage of the bandwidth capability of fiber by combining a number of fiber channels onto one fiber.

Multiplexers come in two "flavors," time division and wave division. Time Division Multiplexing (TDM) is accomplished by sampling discrete signals and then assigning discrete sampled parts of each signal a time slot (thus "time" division multiplexing) in an outgoing, higher speed data stream. This 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. Although the output is usually an optical signal, TDM is essentially an electronic process and normally accomplished using electronic parallel-to-serial (SERDES) converters or Field-Programmable Gate Arrays (FPGAs).

Wave division multiplexers use a different wavelength of light for individual data channels and then combines these different wavelengths onto a single fiber for transmission. The wavelengths can be separated by only a few nanometers in the case of Dense Wave Division Multiplexing (DWDM), or by a wider spread of wavelength, typically 20 nm, in the case of Course Wave Division Multiplexing (CWDM). CWDM is growing in popularity in sensor systems since the wavelength separation is wide enough to avoid the use of temperature control of the lasers to prevent wavelength drift over temperature.

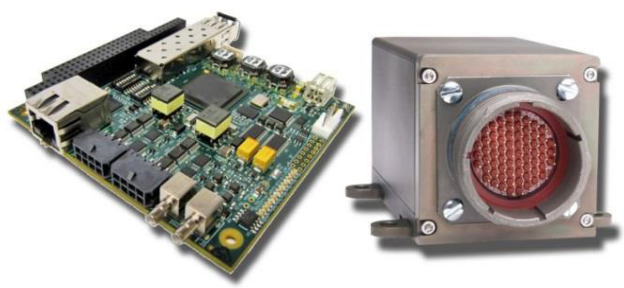

Figure 20: Two examples of multiplexers are shown. A board level multiplexer that supports multiple uncompressed HD video channels, multiple serial data channels and a single Gigabit Ethernet port. A small Camera Link® multiplexer is shown that converts copper Camera Link signals into a single fiber channel.

Many optimum multiplexing schemes utilize TDM and WDM techniques together to fully utilize the bandwidth capability of fiber. Time division multiplexing can be used to combine a fairly large number of data (or video) channels of modest bandwidth and the resultant high speed channel can be wave division multiplexed with other high speed channels. The persistent theme with the optimum use of fiber is to use the full bandwidth capability of each fiber and multiplexing is the method to achieve this goal.

One of the primary uses of multiplexing and fiber solutions is the ability to "future-proof" sensor systems. Placement of one or two fibers through the rotary interface provides a data pipeline of almost limitless capacity. Upgrades can be accomplished by a simple change in electronics without impacting the rotary joint design.

System Solutions

Collecting data with high performance sensors, converting this data to digital data streams and transmitting the data from rotating platforms to stationary processors is a challenge to system designers as the bandwidth expands into multiple Gigabit / second territory. Decisions should be made based on a survey of the overall system requirements and not just on individual components. Examples of solution options include:

- A rotation interface that combines high speed copper (HSDL) and fiber channels to provide redundancy and increase the number of solution options.
- Multiplexing lower bandwidth analog video and utility bus signals to provide highly desired system size and weight advantages especially at the rotational interface.
- Increased utilization of Ethernet providing a useful 1 G or 10 G backbone for multiplexed data and driving the need for increased Ethernet capability through the rotary interface.[4] There are a variety of Ethernet solutions for the rotary interface.
- Full utilization of high speed data channels in slip rings to handle utility bus and 10/100/1000 Ethernet and provision of one or two optical fibers to provide a high speed data path for "future-proofing."

Multiplexers, media converters and active high speed data rotary links serve to significantly expand the options over purely passive rotary joints when solving rotary interface problems.

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Figure 1	Images provided by Moog.
Figure 2	Fourier series approximation of a square wave data provided by Moog.
Figure 3	Frequency data provided by Moog.
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