Inexpensive 2 to 70 MBd Fiberoptic Solutions for Industrial, Medical, Telecom, and Proprietary Data Communication Applications

Application Note 1122

Introduction

Low-cost fiberoptic data-communication links have been used in place of copper wire in numerous industrial, medical and proprietary data communication systems. The fiberoptic transmitter and receiver circuits recommended in this publication address a wide range of applications. These circuits are compatible with existing copper wire protocols, which encode the data before it is sent through the serial communication media. A complete TTL-compatible digital transceiver solution, including the schematic, printed-circuit artwork and material list, is presented in this application note. This complete solution makes it easy for potential users to imbed this low-cost fiberoptic technology into new products because no analog design is required. System engineers interested in using the recommendations contained in this publication are encouraged to embed these reference designs in their products, and various methods to download these reference designs are described.

Why Use Optical Fibers?

Although copper wire is an established technology that has been successfully used to transmit data in a wide range of industrial, medical and proprietary applications, it can be difficult or impossible to be used in numerous situations. By using differential line receivers, optocouplers or transformers, conventional copper wire cables can be used to transmit data in applications where the reference or ground potentials of two systems are different. However, when using copper wires great care must be taken during and after the initial installation to assure that the data is not corrupted by noise induced into the cable's metallic shields from adjacent power lines or differences in ground potential. Unlike copper wires, optical fibers do not require rigorous grounding rules to avoid ground loop interference, and fiberoptic cables do not need termination resistors to avoid reflections. Optical transceivers and cables can be designed into systems so that they survive lightning strikes that would normally damage metallic conductors or wire input/output (I/O) cards. In essence, fiberoptic data links are used in electrically noisy environments where copper wire fails.

In addition to all of these inherent advantages, there are two other reasons why optical fibers are beginning to replace copper wires. The first reason is that optical connectors suited for field installation with minimal training and simple tools are now available. The second reason is that when using plastic optical fiber (POF) or hard clad silica (HCS) fiber, the total cost of the data communication link is roughly the same as when using copper wires.

Wire Communication Protocols and Optical Data Links

Many existing serial wire communication protocols were developed for use with differential line receivers or optocouplers that can sense the dc component of the data communication signal. This type of serial data is often called arbitrary duty factor data because it can remain in the logic “1” or logic “0” state for indefinite periods of time, and therefore has a duty factor or average value which arbitrarily varies between 0% and 100%. Some existing wire communication protocols require an optical receiver that is dc coupled or capable of detecting if the data is changing from high-to-low or low-to-high logic state, i.e. the receiver needs to be an edge detector. At relatively modest data rates between zero and 10 M-bits/second, it is possible to construct DC coupled TTL compatible fiberoptic receivers. The Avago Technologies HFBR-2521Z is a TTL compatible DC to 5 M-bit/sec receiver, and the HFBR-2528Z is a DC to 10 M-bit/sec CMOS or TTL compatible receiver. Additional information about DC to 5 M-bit/sec applications can be found in Avago Technologies' AN-1035, and applications support for DC to 10 M-bits/sec applications can be obtained by reading AN-1080. This application note will focus on optical data communication links that work at much higher data rates and much greater distances than achievable with the DC coupled HFBR-2521Z or HFBR-2528Z components. The optical transceivers shown in this application note are intended for use with data that has been encoded so that the average value of the data is equal to approximately 50% of the data's amplitude. If your communication system sends unencoded arbitrary duty factor data, or burst mode data where the average value of the signal can instantaneously be anywhere between 0% and 100% please refer to the solutions provided in Avago Technologies' Application Note 1121.

The Pros and Cons of Encoding Data

One of the most important reasons for encoding the data is that the sensitivity of the fiberoptic receiver improves dramatically. A receiver circuit designed for use with encoded data is typically 4 dB to 10 dB better than receiver circuits optimized for use with arbitrary duty factor data, or burst-mode data. Encoded data normally has a 50 % duty factor, or restricted duty factor variation, which allows the construction of optimal noise-limited fiberoptic receivers which provide very high performance. The arbitrary duty factor or burst mode receivers described in Avago Technologies' Application Notes 1035, 1080, and 1121 are considerably less sensitive than the fiberoptic receiver solution described in this publication. The optimized receiver in this application note is capable of providing excellent sensitivity because it was designed specifically for use with encoded data.

As the data rate increases, other reasons for encoding quickly become apparent. When unencoded arbitrary duty factor data is transmitted through an optical communication system, a separate fiberoptic link must be used to send the clock if synchronous serial communication is desired. In most high-speed serial communication systems, the data and clock are merged onto a single fiberoptic link to avoid problems with time skew, which can occur when data and clock signals are sent through two different optical fibers. Asynchronous data communication systems, which oversample the serial data using a local clock oscillator located at the receiving end of the fiberoptic data link, are limited to lower-speed applications, because the sampling frequency required to assure low pulse-width distortion rises dramatically as data rates increase.

The most apparent drawback of encoding data is the additional complexity of the encoder function, which must be added to the integrated circuits that convert parallel data to serial data at the transmitting end of the communication link. At the receiving end of the data communication link, a corresponding decoder function must also be added to the circuits that convert serial-data back to parallel-data. At first glance, encoding and decoding seem to add too much complexity, but encoder and decoder circuits actually do not have a significant impact on the cost of the complex serializer and deserializer integrated circuits already needed to connect two parallel architecture systems via a serial communication channel. In fact, many off-the-shelf protocol chips for serial communications applications imbed encoding and decoding features for all of the reasons that have just been described.

High Performance ac Coupled Receiver Topology

When data is encoded, the fiberoptic receiver can be AC coupled as shown in Figure 1. Without encoding, the fiberoptic receiver would need to detect DC levels or edges to determine the proper logic state during long periods of inactivity, as when there is no change in the transmitted data. AC-coupled fiberoptic receivers tend to be lower in cost, are much easier to design, provide better sensitivity and contain fewer components than their DC-coupled counterparts.

No matter which type of fiberoptic medium is used, the receiver’s PIN diode pre-amplifier should be AC coupled to a limiting amplifier and comparator as shown in Figure 1. Direct coupling the PIN pre-amp to the post amplifier and comparator (also known as quantizer) will reduce the sensitivity of the fiberoptic receiver, since this allows low-frequency flicker-noise from the first transistor in the PIN pre-amp to be applied to the receiver’s comparator. Any undesired noise coupled to the comparator will reduce the signal-to-noise ratio at this critical point in the circuit, and reduce the sensitivity of the fiberoptic receiver. Another problem associated with direct-coupled receivers is the accumulation of DC offset. With direct coupling, the receiver’s gain stages rapidly multiply the PIN pre-amplifier’s small offsets and voltage drifts due to temperature change. Sensitive receivers require high-gain amplifiers, which will quickly magnify relatively small PIN pre-amp offsets. The amplification of DC offset will saturate the quantizer’s amplifiers, resulting in undesired pulse-width distortion, which limits the maximum data rate and sensitivity of inexpensive DC-coupled receivers. Problems with DC drift and low-frequency flicker-noise can be avoided by constructing AC-coupled fiberoptic receivers as recommended in Figure 1.

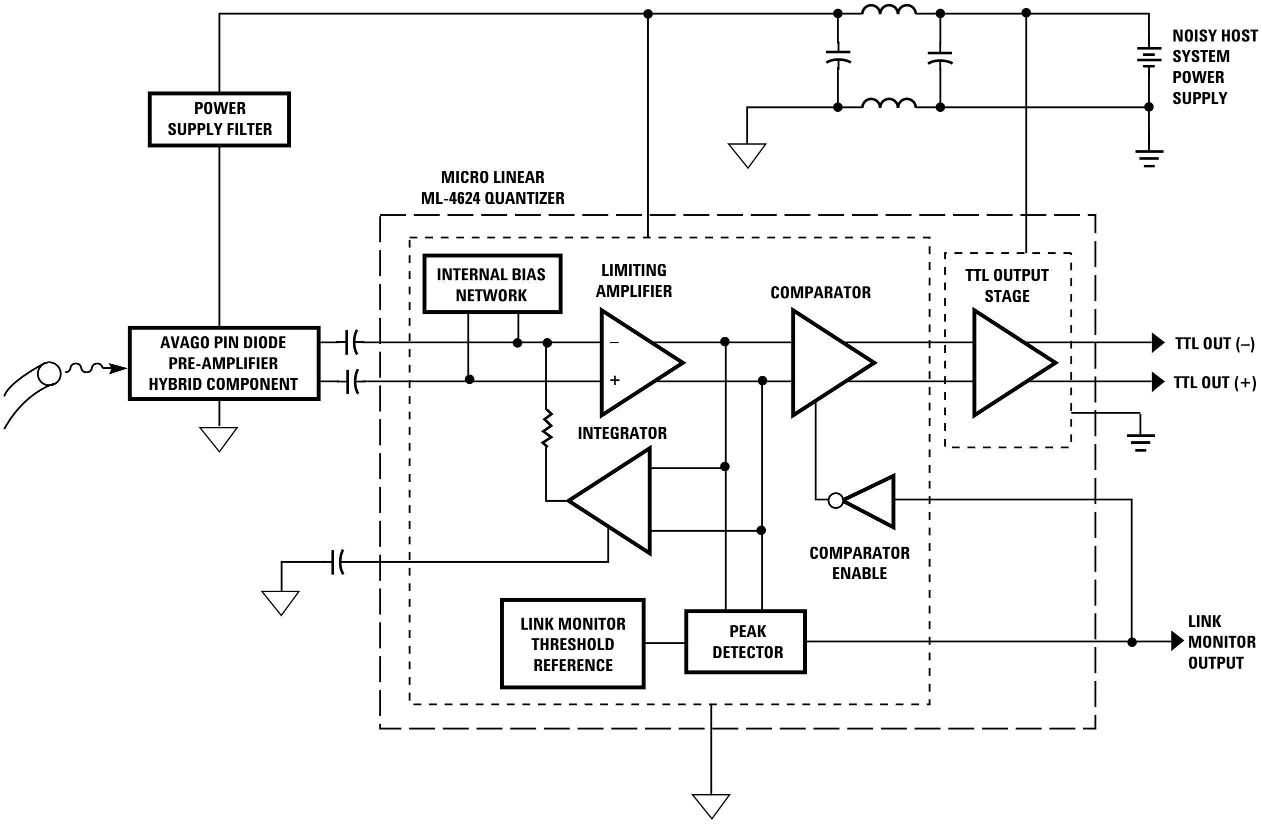


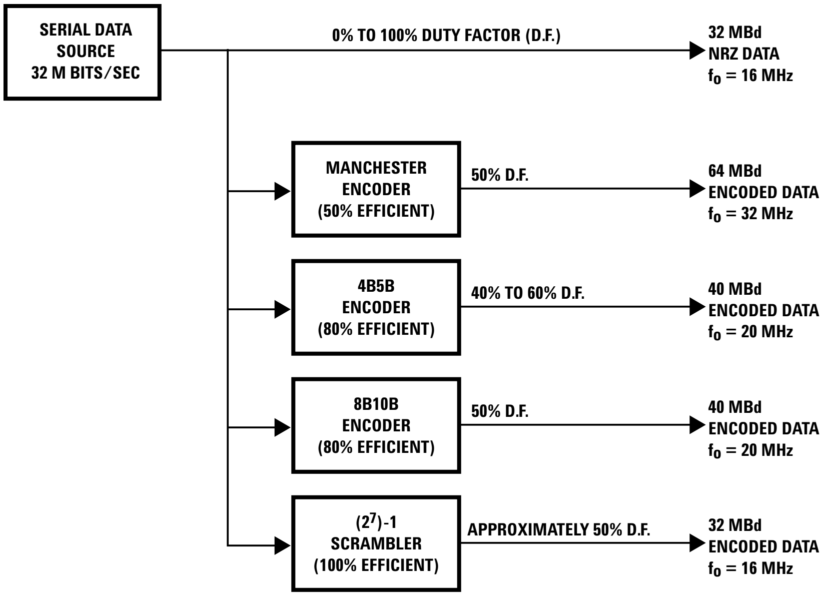
Figure 1. Simplified TTL-Compatible Fiberoptic Receiver Block Diagram for Applications with Encoded Data

Relationships Between Bits/sec, Baud and Hertz

Figure 2 shows more details about encoding techniques that are commonly used with inexpensive fiberoptic solutions. Simple Manchester encoders which send two symbols for each bit can be used in low-speed data communication applications, but high efficiency block substitution codes, such as 4B5B and 8B10B, are preferred for serial communication systems that operate at symbol rates greater than 32 MBd. When using a high efficiency encoding scheme, the channel bandwidth needed to carry the serial data is minimized, and the distances achievable with low-cost fiberoptic technologies increase. Figure 2 illustrates several important relationships between bits/second, symbols/second, expressed in Baud (Bd), and the fundamental frequency of various digital data communication signals. Note that arbitrary duty factor unencoded data is one of the few instances when data rate in bits/second, and the symbol rate in Bd are equal.

Only One Transceiver Design Needed

This application note will show that various Avago Technologies LED transmitters and PIN-diode pre-amplifiers can be used in a single transceiver design that can be downloaded and embedded into a wide range of products to provide very low-cost data communication solutions. Without changing the form-factor or printed circuit design, the transceiver shown in this publication can be populated with components that are capable of sending digital data via various types of fiberoptic cables. When the recommended circuits are electronically imported and embedded into your system, the same inexpensive transceiver can be used with a variety of fiberoptic cables so that one design can be used to address an extremely wide range of data communication applications.



NOTE THAT f_0 IS THE MAXIMUM FUNDAMENTAL FREQUENCY OF THE ENCODED DATA.
THE MINIMUM FUNDAMENTAL FREQUENCY OF THE ENCODED DATA IS DETERMINED BY THE ENCODER'S RUN LIMIT.

Figure 2. Attributes of Encoding

Distances and Data Rates Achievable

The simple transceivers recommended in this application can be used to address a very wide range of distances, data rates, and system cost targets. The maximum distances allowed with various types of optical fiber and Avago Technologies' broad range of fiberoptic components are shown in Table 1. Only one simple calculation is needed to optimize the receiver for use at the desired maximum symbol rate of your system application. No transmitter or receiver adjustments are needed when using fiber cables that vary from virtually zero length up to the maximum distances specified in Table 1.

Table 1

LED Transmitter Component Part # and Wavelength	Receiver Component Part # and Wavelength	Fiber Diameter Type	Maximum Distance at 50 MBd with the Transceiver Circuits Recommended in this Publication
HFBR-15X7Z 650 nm	HFBR-25X6Z 650 nm	1 mm plastic step index	80 meters with transmitter in Fig. 3 and receiver in Fig. 4
HFBR-15X7Z 650 nm	HFBR-25X6Z 650 nm	200 µm HCS step index	300 meters with transmitter in Fig. 3 and receiver in Fig. 4
HFBR-14X2Z 820 nm	HFBR-24X6Z 820 nm	200 µm HCS step index	300 meters with transmitter in Fig. 3 and receiver in Fig. 4
HFBR-14X4Z 820 nm	HFBR-24X6Z 820 nm	62.5/125 µm multimode glass	1.5 kilometers with transmitter in Fig. 3 and receiver in Fig. 4
HFBR-13X2TZ 1300 nm	HFBR-23X6TZ 1300 nm	62.5/125 µm multimode glass	3.8 kilometers with transmitter in Fig 3. and receiver in Fig. 4

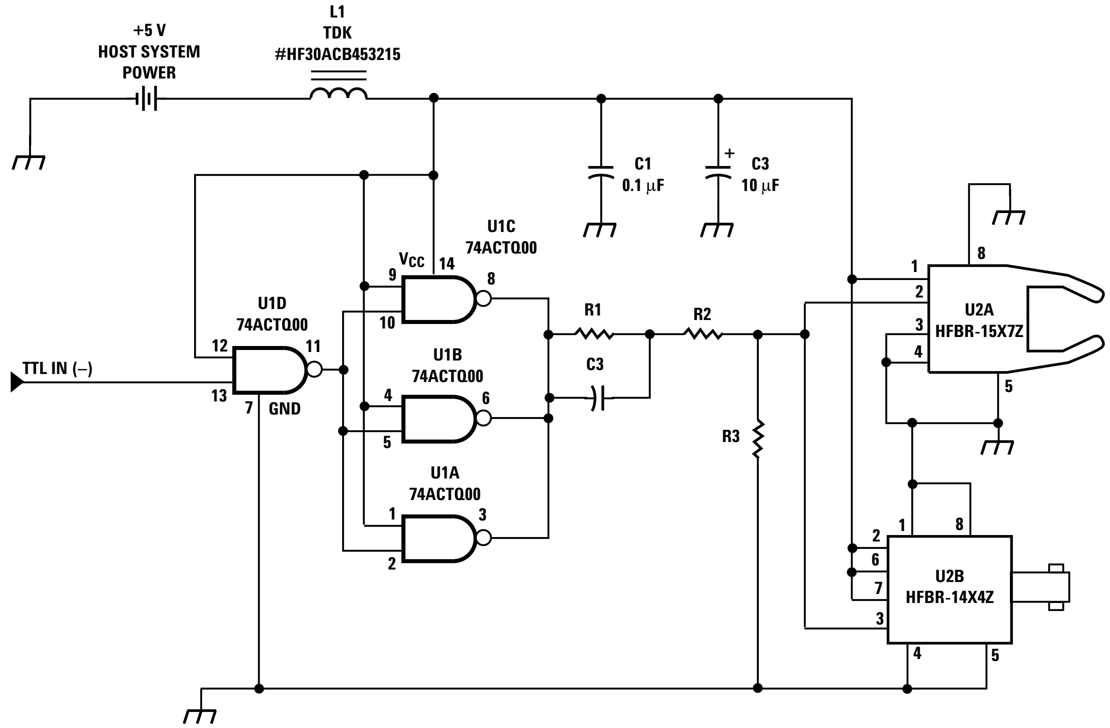


Figure 3. TTL-Compatible Fiberoptic Transmitter

Table 2

Transmitter	HFBR-15X7Z 650 nm LED		HFBR-14X4Z 820 nm LED	HFBR-13X2TZ 1300 nm LED
Fiber Type	1 mm Plastic	200 µm HCS	62.5/125 µm	62.5/125 µm
R1	120 Ω	33 Ω	33 Ω	22 Ω
R2	120 Ω	33 Ω	33 Ω	27 Ω
R3	390 Ω	270 Ω	270 Ω	∞
C3	82 pF	470 pF	75 pF	150 pF

Simple TTL-Compatible LED Transmitter

A high performance, low cost TTL compatible transmitter is shown in Figure 3. This transmitter recommendation looks deceptively simple but has been highly developed to deliver the best performance achievable with a wide range of Avago Technologies LED transmitters. The recommended transmitter is also very inexpensive since the 74ACTQ00 gate used to current modulate the various LED transmitters can typically be obtained for under $0.40. No calculations are required to determine the passive component needed when using the broad selection of Avago Technologies' LEDs with various optical fibers. Simply use the recommended component values shown in Table 2, and the transmitter shown in Figure 3 can be used to address a wide range of applications.

Simple High-Sensitivity, TTL-Compatible Receiver

A very simple TTL-compatible receiver that has excellent sensitivity and is suited for many different applications is shown in Figure 4. Equation 1 allows the designer to determine the value of C9 that optimizes the quantizer's bandwidth for best receiver sensitivity at data rates ≤20 MBd. At data rates >20 MBd the bandwidth limitations of the quantizer's amplifier provide the low pass filtering required, so no capacitor should be connected between the CF1 and CF2 terminals of the ML-4624. The receiver shown in Figure 4 can be configured to address the unique requirements of various applications; simply refer to Table 3 to find the component values best suited for your specific application.

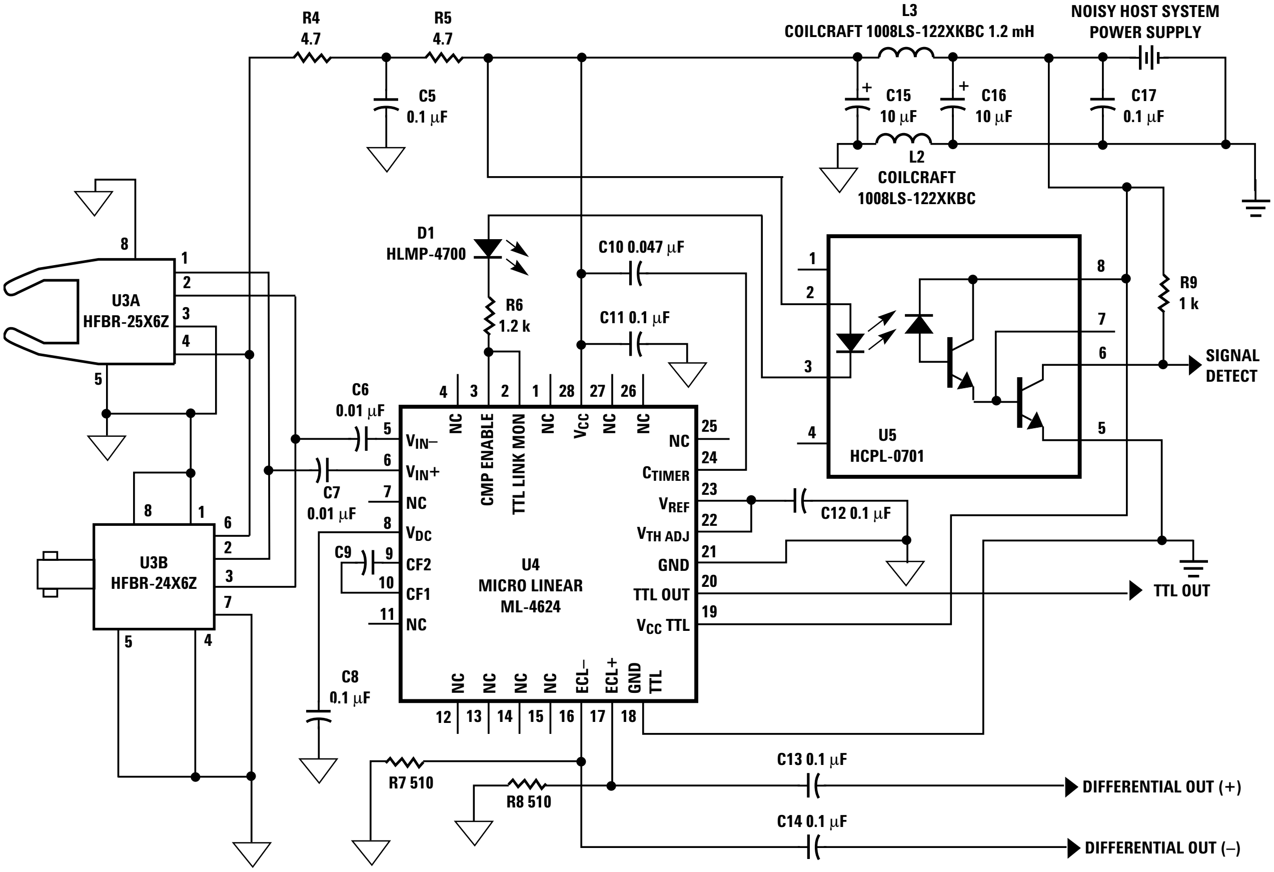


Figure 4. Simple High-Sensitivity TTL-Compatible Receiver

Equation 1

When data rate is 20 MBd then C9 = $\left[\frac{1}{2 \pi \, 800 \, (Bd)} \right] - [\, 4 \, (pF) \,]$

Table 3

Receiver	**HFBR-25X6Z** **650 nm**		**HFBR-24X6Z** **820 nm**	**HFBR-23X6TZ** **1300 nm**
Fiber Type	1 mm Plastic	200 µm HCS	62.5/125 µm	62.5/125 µm

The receiver in Figure 4 uses the Micro Linear ML-4624 quantizer that has been used successfully with Avago Technologies HFBR-2416Z 820 nm PIN pre-amps in numerous 20 MBd Ethernet and 32 MBd Token Ring LAN applications since 1992. The ML-4624 quantizer maximizes the sensitivity of the fiberoptic receiver when used with a broad range of Avago Technologies' PIN pre-amps. The ML-4624 can be used with the HFBR-2526Z PIN pre-amp to build a 650 nm receiver that is compatible with 1 mm plastic optical fibers (POF) or 200 µm hard clad silica (HCS) fibers. The ML-4624 quantizer can also be used with the Avago Technologies HFBR-2316Z PIN pre-amp for 1300 nm miltimode glass fiber applications.

The ML-4624 quantizer provides the best digital receiver sensitivity possible no matter which Avago Technologies' PIN pre-amp is used, provided the modulation code that encodes the data does not allow excessive time intervals between transitions from one logic state to another. The maximum time interval allowed between the edges of encoded data symbols is known as the encoder's run limit. For a better understanding of how the encoder's run limit affects receiver performance, refer to Figure 1. To obtain optimum performance from the ML-4624 quantizer, the encoder's run-limit time interval must be orders of magnitude shorter than the time constant of the integrator embedded in the ML-4624 quantizer's feedback loop. As the encoder's run-limit approaches the time constant of the ML-4624's integrator, the DC bias voltage applied to the inverting input of the quantizer begins to slew up or down and the receiver's sensitivity decreases. The maximum run-limit time recommended for use with the ML-4624 quantizer should be ≤ 500 ns.

Printed Circuit Artwork

The performance of transceivers that use Avago Technologies fiberoptic components are partially dependent on the layout of the printed circuit board on which the transceiver circuits are constructed. To achieve the fiberoptic link performance described in Table 1, system designers are encouraged to embed the printed circuit design provided in this application note. The printed circuit artwork in Figure 5 is for the transmitter in Figure 3 and the receiver in Figure 4. Electronic copies of the Gerber files for the artwork shown in this application note can be obtained by using the Internet to download the printed circuit designs located at the following URL:

http://www.avagotech.com

Download the file named **rll70.exe** to obtain the artwork for the transmitter shown in Figure 3 and the receiver shown in Figure 4.

Parts List

The TTL-compatible fiberoptic transceiver recommended in this publication is very simple and inexpensive, so only a few external components are needed. To simplify the process of obtaining the passive and active components required to assemble the transceiver, a complete parts list is provided in Table 4. All of the components described in the parts list were selected to assure that they are compatible with the printed circuit artwork shown in Figure 5, thus minimizing the design time and resources needed to use the low-cost, fiberoptic transceiver shown in this application note.

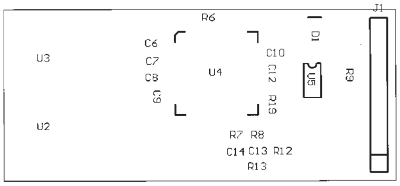


Figure 5a. Top Overlay

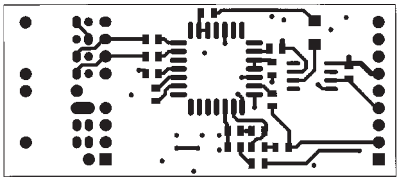


Figure 5b. Top Layer

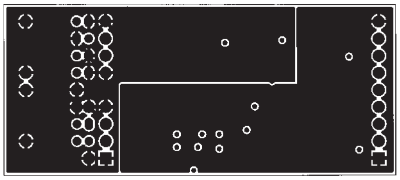


Figure 5c. Mid Layer 2

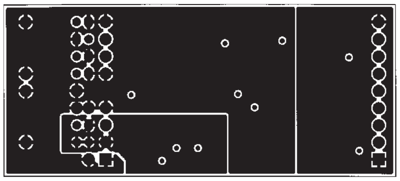


Figure 5d. Mid Layer 3

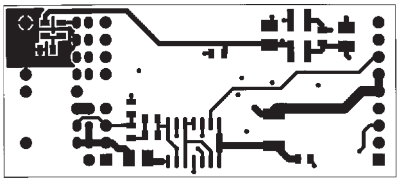


Figure 5e. Bottom Layer

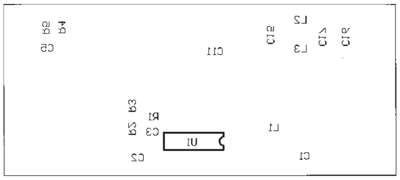


Figure 5f. Bottom Overlay

WARNING: DO NOT USE PHOTOCOPIES OR FAX COPIES OF THIS ARTWORK TO FABRICATE PRINTED CIRCUITS.

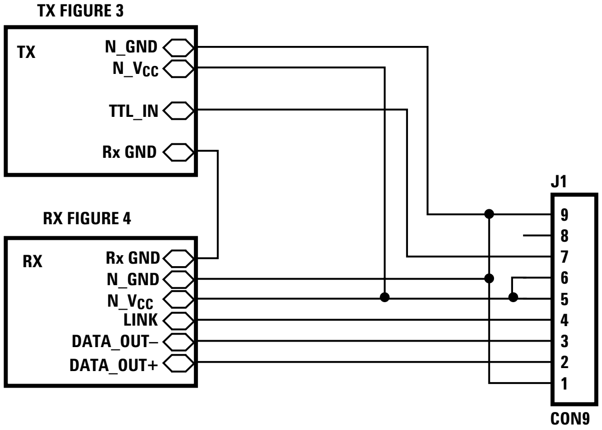


Figure 5g. Trans 3 Schematic

Figure 5. Printed Circuit Artwork for Transmitter Shown in Figure 3 and Receiver in Figure 4

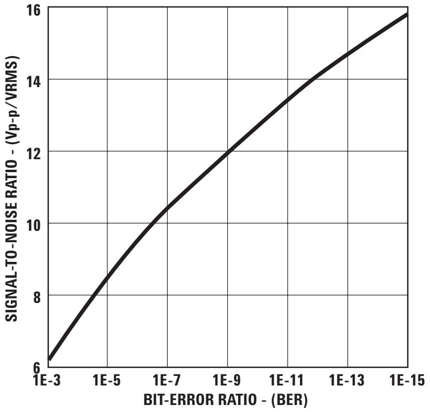


Figure 6. Receiver Signal-to-Noise Ratio vs. Probability of Error (aka BER)

Error Rates and Noise Immunity

The probability that a fiberoptic link will make an error is related to the receiver's own internal random noise and the receiver's ability to reject noise originating from the system in which it is installed. The total noise present in any fiberoptic receiver is normally the sum of the PIN diode pre-amplifier's noise and the host system's electrical noise. As the optical signal applied to the receiver increases, the probability that the receiver's total noise will alter the data decreases. Small increases in the receiver's signal-to-noise ratio will result in a very sharp reduction in the probability of error. Figure 6 shows that the receiver's probability of error is reduced by six orders of magnitude (from 1x10^{-9} to 1x10^{-15}) when the receiver's signal-to-noise ratio improves from 12:1 to 15.8:1.

At any fixed temperature the total value of the receiver's random noise plus the host system's noise can be assumed to be a constant, so the most obvious way to reduce the probability of error is to increase the amplitude of the optical signal applied to the receiver. A less obvious but better technique for lowering the error rate is to improve the receiver's ability to reject electrical noise from the system in which it resides. The fiberoptic receiver recommended in this application note has sufficient noise immunity to be used in most systems without electrostatic shielding. The Avago Technologies PIN diode pre-amps that are used in the receiver's first stage are small hybrid circuits, and these small hybrid components do not function as particularly effective antennas. For extremely noisy applications, Avago Technologies offers PIN diode pre-amps in electrically conductive plastic or all-metal packages. Avago Technologies manufactures a wide range of conductive and non-conductive fiberoptic components that mate with various industry-standard fiberoptic connectors, but the overwhelming majority of the fiberoptic applications successfully implemented with Avago Technologies' fiberoptic components have not required conductive plastic or metal receiver housings.

The most insidious and the most overlooked source of noise is usually the host system's +5 V power supply. Many applications utilize a solitary +5 V supply that powers the fiberoptic receiver, the fiberoptic transmitter and an entire system comprised of relatively noisy digital circuits. The receiver circuit in Figure 4 uses very inexpensive power supply filter inductors that are located in the receiver's +5 V and 0 V connections to the host system's power supply. The simple and inexpensive power supply filters recommended in this publication have been proven to work in a wide range of noisy system applications, but in extremely noisy applications additional power supply filtering could be needed.

The HCPL-0701 optocoupler shown in Figure 4 allows the TTL LINK MONITOR output of the ML-4624 quantizer to be connected to electrically noisy TTL circuits. If the communication protocol chosen for the data communication system requires that the quantizer's link monitor must be connected to higher level protocol circuits, then some type of noise isolation circuit, or an optocoupler, must be used to assure that digital circuits in the communication system's physical layer do not inject noise into the low-level analog circuits of the Micro Linear ML-4624 quantizer. Note that the TTL LINK MONITOR output (pin 2) of the ML-4624 quantizer is low when a sufficient amount of optical power is applied to the PIN pre-amp, but the HCPL-0701 optocoupler inverts the TTL LINK MONITOR output so that the signal detect (SD) output of the circuit in Figure 4 is high when a sufficient amount of light is applied to the fiberoptic receiver's input.

Conclusion

The complete TTL compatible fiberoptic transceiver solutions provided in this publication can be used to improve the noise immunity of existing data communication systems currently using encoded data protocols originally developed for use with copper wire. When copper wire transceivers are replaced with comparably priced optical transceivers, industrial and proprietary communication systems have a much better probability of surviving large noise transients caused by utility power switch gear, motor drives or lightning strikes. The optical data communication solutions shown in this application note can also send high-speed, 70 MBd data over long distances that would be impractical with copper wire cables. By embedding the complete solution shown in this application note, system designers can quickly develop noise-immune optical communication links in a very short time with minimal R&D costs.

Table 4. Parts List for the Transmitter in Figure 3 and the Receiver in Figure 4

Designator	Part Type	Description	Footprint	Material	Part Number	Quantity	Vendor 1
C1	0.1 µF	Capacitor	805	X7R or better	C0805X7R500104KNE	8	Venkel
C5	0.1 µF	Capacitor					
C8	0.1 µF	Capacitor					
C11	0.1 µF	Capacitor					
C12	0.1 µF	Capacitor					
C13	0.1 µF	Capacitor					
C14	0.1 µF	Capacitor					
C17	0.1 µF	Capacitor					
C19	0.1 µF	Capacitor					
C6	0.01 µF	Capacitor	805	X7R or better	C0805X7R103KNE	2	Venkel
C7	0.01 µF	Capacitor					
C9	See Equation 1	Capacitor	805	NPO/COG		1	Venkel
C10	0.047 µF	Capacitor	805	NPO/COG		1	Venkel
C2	10 µF	Capacitor	B	Tantalum, 10 V	TA010TCM106MBN	3	Venkel
C15	10 µF	Capacitor					
C16	10 µF	Capacitor					
C3	See Table 2	Capacitor	805	NPO/COG		1	Venkel
D1	HLMP-4700	LED lamp			HLMP-4700	1	Avago Technologies
U1	I.C.	Nand Gate	S014		74ACTQ00	1	National
U2	Fiberoptic	Transmitter		See Table 2	HFBR-1XXXZ	1	Avago Technologies
U3	Fiberoptic	Receiver		See Table 3	HFBR-2XXXZ	1	Avago Technologies
U4	ML4624	IC, quantizer	PLCC28		ML4624CQ	1	MicroLinear
U5	HCPL-0701	Optocoupler	S08		HCPL-0701	1	Avago Technologies
L1	CB70-1812	Inductor	1812		HF30ACB453215	1	TDK
L2	1.2 µH	Inductor		10%	1008LS-122XKBC	2	Coilcraft
L3							
R4	4.7 Ω	Resistor	805	5%	CR080510W4R7JT	2	Venkel
R5	4.7 Ω	Resistor					
R1	See Table 2	Resistor	805	1%		2	Venkel
R2	See Table 2	Resistor					
R7	510 Ω	Resistor	805	5%	CR080510W511JT	2	Venkel
R8	510 Ω	Resistor					
R3	See Table 2	Resistor	805	1%		1	Venkel
R6	1.2 kΩ	Resistor	805	5%	CR080510W122JT	1	Venkel
R9	1 kΩ	Resistor	805	5%	CR0805510W102JT	1	Venkel
J1	Pins				343B	9	McKenzie

For product information and a complete list of distributors, please go to our web site: **www.avagotech.com**

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