Understanding Bit-Error-Rate with HOTLink™

Understanding Bit-Error-Rate

The concept of an error rate for digital systems may seem somewhat foreign to many digital designers. The message has always been that digital circuits always switch to either a one or a zero, and that if the circuit doesn't do it correctly then it must be broken.

The real world is quite different. Typical computer networks lose or corrupt packets, disk and tape storage require re-reads of data (or even error correction), and large DRAM memory arrays may have bits corrupted by α-particles and require ECC correction. These random events occur regularly in these computer systems, and the necessary error detection and recovery mechanisms are planned for in their design. Under conditions that can cause these types of errors, the system's performance is determined both by the circuit design, and by *probability.*

Serial data communications systems, such as those based on HOTLink™, must also deal with probabilistic forms of errors. The amount of error detection and recovery built into the system is often determined by the tolerance of the system to bit errors, and how often these errors occur. In these types of systems the errors are (for the most part) caused by either intrinsic or extrinsic noise sources that can affect any or all parts of a data link. The measurement and specification of a bit-error-rate (BER) exists as a way to quantify the susceptibility of a digital link to these noise factors.

Bit-Error-Rate Definition

Bit-error-rate is the relationship of the number of bits received incorrectly, compared to the total number of bits transmitted. This relationship is shown in Equation 1.

$$BER = \frac{\text{\# of bits in error}}{\text{\# of bits transmitted}} \qquad \text{Eq. 1}$$

This simple relationship is the basis for all BER measurements and specifications. It assumes that all transmitted bits were sent error free.

BER is usually specified as a number times 10 raised to a large negative exponent. Common requirements for serial links are generally in the range of 1×10^{-6} to 1×10^{-15}.

BER numbers by themselves do not represent any period of time. They are only a ratio of numbers of bits sent and received. A specific BER, when related to time, can yield an MTBF (mean time between failure) for a serial link. This relationship is shown in Equation 2.

$$MTBF_{(hours)} = \frac{1}{BER \times \text{bits per hour}} \qquad \text{Eq. 2}$$

HOTLink operates at bit rates of 150 Mbits/sec to 400 Mbits/sec. An operating BER of 10^{-12} for a 400 Mbits/sec data stream would have an MTBF of 0.69 hours. This is equivalent to detecting an average of one bit in error for every 0.69 hours of operation. This same link at the same BER, but operating at 150 Mbits/sec, would detect an average of one bit in error for every 1.85 hours of operation.

Link-Based Errors

The BER for a specific link is not based on the HOTLink components used at either end of the link. A HOTLink Transmitter connected directly to a HOTLink Receiver (when operated within their datasheet parameters) has a BER of zero. As other components are added to the link (transformers, transmission lines, opto-electric transceivers, connectors, optical fiber, etc.) the link BER begins to grow. These components add distortion to the transmitted signal. This distortion can come in many forms, including attenuation, dispersion, increased jitter, and DC offset. The unpredictable element that is also added is susceptibility to noise.

Sources of Errors

In a communication link, errors are generally separated into two categories: intrinsic and extrinsic. Intrinsic errors are those caused by the components used to create the link. Extrinsic errors are those caused by external influences that affect the operation of the link.

Intrinsic Errors

Intrinsic errors are those errors due to the design, components, and implementation of a link. These errors can be caused by internal noise sources (i.e., thermal noise), poor electrical connections, and (with some systems) receiver sampling errors.

Optical Links

Optical links are often used in areas where strong electrostatic and electromagnetic fields are present, to limit the number of errors caused by these extrinsic noise sources. In the absence of these noise sources, many users are surprised to find that optical links are often more error prone than an electrical or copper based link. These errors are due to the physical components used to make the link (optical driver, optical receiver, connectors, optical fiber, etc.) and not to the serializer and deserializer components used at the ends of the link.

Optical fibers, even the best ones, contain numerous impurities and flaws. As light strikes these minute flaws it gets vectored off at different angles or absorbed in the cladding. This is not generally a problem for short links, but long ones contain many such flaws. These flaws work to both reduce the amount of light that reaches the receiver (attenuation), and to spread out the transmitted pulsewidth (dispersion).

Each optical connector also causes signal loss and pulse degradation similar to the flaws inside the fiber. Here the main loss mechanism is back reflection and attenuation due to contamination, cleaving faults, or poor polish of the fiber end. These types of signal degradation are translated into increased jitter by the opto-electric receiver. This jitter (within certain limits) does not increase the BER of a link. As long as the opto-electric receiver's output jitter remains within the receiver's (deserializer) jitter tolerance, the link should remain error free.

One of the largest causes of random or noise-induced errors is the optical receiver. Here light received from the fiber is converted to an electrical signal through a transimpedance amplifier. This amplifier must respond to current changes in the PIN photodetector of less than 1 µA to detect the presence or absence of light. This low signal-level makes the receiver preamplifier susceptible to thermal and shot noise, and converts these into random jitter. This random jitter has a Gaussian distribution and is directly influenced by the signal-to-noise ratio (SNR) of the optical link.

The optical receiver is also quite sensitive to external EMI sources. External static discharges or power supply transients often make their way to the optical receiver where they manifest themselves as erroneous bits.

Electrical Links

Electrical or *copper* based links are also subject to errors, however, errors in these types of links are (in almost all cases) due to extrinsic sources. While the components used to make an electrical link are still sources of noise in a system, the amplitudes of these noise sources are tens of dB below any of the electrical thresholds used in the receiver.

The one possible exception to this deals with an improperly installed or maintained system. If low quality components are used in a non-benign environment (corrosive atmosphere, salt spray, etc.) it is possible for the interconnections and even the cable itself to degrade. The galvanic action of dissimilar metals in such an environment can generate significant noise in the system.

Transmitter (Serializer)

In a communication link the transmitter is generally never considered to be a source of errors in the link. This is due primarily to the pseudo-synchronous nature of its design. In the case of HOTLink, the transmitter operates fully synchronous to its internal synthesized bit-clock. So long as the clock, incoming data, and power, meet their specified parameters the part should not generate any errors.

The one exception to this is the possibility of disturbances at the subatomic level. While it is theoretically possible for SEU (single event upset) to occur due to α, β, or some other subatomic particle emission, this event is not expected. High-reliability design practices, coupled with the robust nature of BiCMOS circuitry used to make HOTLink, make this highly improbable.

Receiver (Deserializer)

The HOTLink Receiver is based on a high-reliability fully differential analog PLL (phase-locked loop). It is designed to remove all intrinsic error sources from the receiver, and to block many of the extrinsic error sources.

As long as the HOTLink Receiver is presented with valid power and data (meeting its data sheet requirements), it is effectively error-free in operation just like the HOTLink Transmitter. As with any electronic component, it may be susceptible to SEU phenomena, however none have ever been observed.

For electrical connections where no external receiver preamplifier is present, the receiver sensitivity may also have an effect on the link BER. The HOTLink Receiver typically will only require 10 mV of differential signal (50 mV worst case) at the receiver input for proper operation. These enhanced low-amplitude inputs of the HOTLink Receiver permit operation with much longer external cables, or cables having much more equalization present, at very low bit-error-rates.

Extrinsic Errors

Extrinsic errors are those caused by external or outside influences. These errors are caused by things like spikes, sags, and surges in the power mains, electrostatic discharges, RF emissions, and cable/connector vibrations.

Power Supplies

In some cases normal power-supply noise and ripple is grouped in with extrinsic sources of errors, however a good design will place this as part of the intrinsic errors. Power-supply noise becomes extrinsic when externally generated noise is allowed to *pass through* the power supply and reach the serializer, deserializer, and media driver/receiver. These external noise sources can be as small as an ESD discharge from someone touching a cabinet, or as large as a lightning strike. Depending on the characteristics of the noise source (and how much is allowed to reach the serial-link components), it may be able to induce link errors.

Many standard appliances operate with motors that generate very strong noise fields. Some examples of these are electric drills, vacuum cleaners, mixers, etc. Basically anything using a motor that contains brushes. As these appliances operate they radiate strong RF fields, and reflect large amounts of RF energy back into the power mains. Limiting the effects of such power-coupled sources usually involves various types of power filters or conditioners on the front-end of the system power supply.

Optical Links

Optical links are fortunate in that the fiber-optic cables themselves are immune to externally generated noise. The weak link in an optical connection is the susceptibility of the receiver to external noise. In many cases the largest cause of noise for an optical receiver is the optical transmitter mounted directly adjacent to it. This requires careful layout and isolation techniques to keep the noise generated in the optical driver from affecting the sensitive optical receiver.

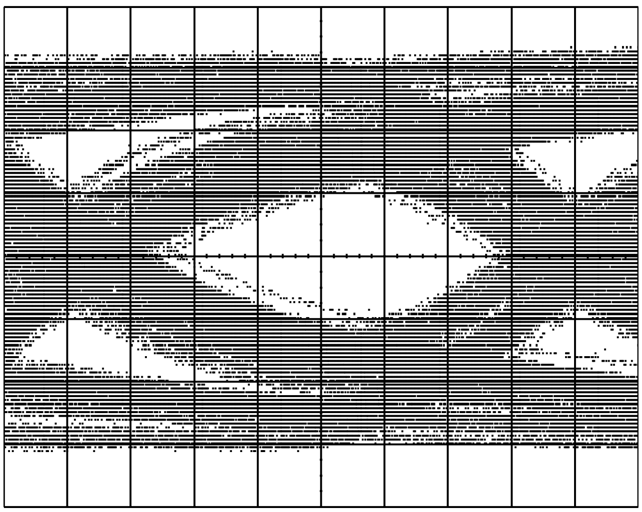
Electrical Links

Electrical links are in some ways at a disadvantage when compared to optical links in that they *are* affected by external electromagnetic fields. Just how much they are affected is based on many different characteristics. These are primarily the cable-type used, the data rate, and the strength of the external field.

Cypress has tested multiple types of copper media (different impedances and diameters of coaxial and twisted-pair cable) to determine how far a reliable link can be operated. What was learned was that higher-impedance and lower-attenuation cables allowed error-free communication for the greatest distances.

Some of these links were also tested in the presence of an uncalibrated noise source (i.e., an electric drill). This testing, while not directly quantifiable, does allow numerous observations to be made as to how a copper-based link responds to external noise.

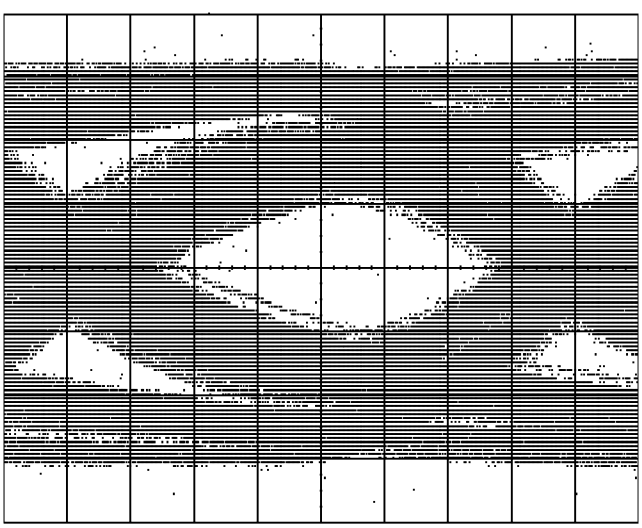
The first observation was that short copper-based links ($\leq$100m), when implemented with shielded cables (coax or shielded twisted pair (STP)), are relatively immune to the noise generated by the noise source. *Figure 1* shows the "eye" at the end of a 91.2m (300-foot) piece of RG-59 coaxial cable running the HOTLink BIST (built-in self-test) at 25 MHz with normal office electrical noise present. At this cable length there is significant ($\leq$30%) jitter present in the link, and the eye (as viewed on a digital sampling scope) is reasonably open (see the Cypress Semiconductor application note "HOTLink Design Considerations" for an explanation of jitter and eye patterns).



Ch. 1 = 200.0 mV/div Timebase = 500 ps/div

Figure 1. Eye Pattern without Forced Noise

For noise testing, a small number of turns (six) of the cable were tightly wrapped around the body of an electric drill to maximize the noise coupling. The eye pattern with the noise generator enabled is shown in *Figure 2*. Under these conditions the eye becomes a bit fuzzy around the edges, but the center remains mostly open.



Ch. 1 = 200.0 mV/div Timebase = 500 ps/div

Figure 2. Eye Pattern with Forced Noise

This "fuzz" is in fact multiple sample points created when the external noise caused the received signal to move from its normal positions. Rather than being just a single dot on the screen, each of these points is actually part of a continuous waveform. Because of the random nature of the noise source (relative to the scope trigger and serial data) and the repetitive sampling used to display a signal, it is not possible to view the actual altered waveform.

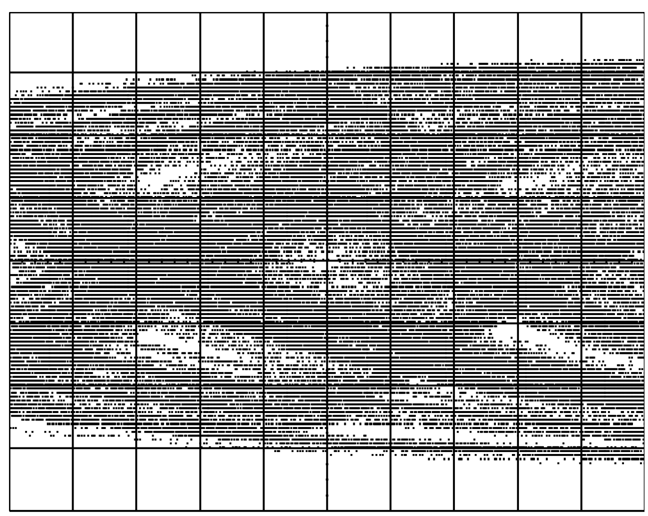
Even with this strong of a noise source, the HOTLink Receiver detected no errors during the 15-minute period of this test. This does not mean that such a link would remain error free indefinitely, just that the SNR in this configuration is sufficiently large that most received pulses still fall within the normal range of the receiver for a correct 1 or 0 to be detected.

As the cable gets longer the signal continues to degrade and the eye closes. This closure is not a linear function; it is more logarithmic in nature. At 121.4m (400 feet) the eye (for this cable-type and data-rate), as shown in *Figure 3*, is effectively closed ($\leq$5% eye opening). Under these conditions the HOTLink Receiver (in the absence of strong external noise sources) will still correctly detect the data as an error-free stream. Now however, when the noise source is enabled, the receiver detects multiple and near continuous errors.

Jitter

A popular misconception is that the reason for the detected errors in a communications link is the jitter accumulation in the link. While jitter definitely does play a part in determining the BER for a system, it alone does not cause errors.

The link measurement in *Figure 3* shows a very large amount of jitter present, yet the link operates error free. A link of this type can meet a BER of 10^{-12} (or better) as long as the external noise remains controlled. In a similar fashion, a link measuring minimal jitter (<10%) could become unusable if presented with a strong enough noise source.



Timebase = 500 ps/div Ch. 1 = 100.0 mV/div

Figure 3. Error Free Eye Pattern at Maximum Cable Length without External Noise

Specifying BER

The BER for optical links is usually specified as a transfer function relative to signal-to-noise ratio. This is due to the way an optical signal is modified as it moves down a fiber. This specification does not take into account any of the extrinsic noise sources that can effect the opto-electric converters that are part of the link, and assumes that all errors are due to pulse degradation and how the signal is interpreted by the electro-optic receiver.

For copper cables it is a bit more complex. The specification is still based on SNR, but now is a set of N curves in N-dimensional space. These curves must take into account such things as the launched power, the spectral content of the source signal, the type of shield on the cable, the receiver sensitivity, and how much (if any) equalization is present. Unlike optical cables, the BER specifications for copper links must take into account extrinsic noise sources because these are the primary cause of bit-errors in an electrical link.

BER Floor

A bit-error-rate floor is that point in a link where the BER is limited by something other than the SNR. This occurs in links when no increase in launched power into the cable or optical fiber will yield an improvement in the BER.

For electrical cables the BER floor sits at the point where the eye effectively closes and signal transitions can no longer be properly detected. In these cables, the shape of the eye is determined only by the spectral characteristics of the signal launched into the cable and the cable's attenuation characteristics (and any signal conditioning if present).

Figure 4 shows the BER floor for Type-1 shielded twisted-pair (STP) cable when used with HOTLink. This testing was performed on four different CY9266-T HOTLink Evaluation Boards, under room temperature conditions, with no cable equalization or special conditioning of the environment (see also the "CY9266 HOTLink Evaluation Board User's Guide" for additional information on the CY9266). All areas under the curve allow normally error-free link operation, with all detected errors due to extrinsic noise sources. All areas above the curve identify where the link will operate with near continuous errors, regardless of the presence or absence of external noise sources.

This same curve is plotted with the data rate axis on a logarithmic scale in *Figure 5*. Now the portion of the curve determined by the cable characteristics is effectively a straight line. This shows that the transfer function for the BER floor relative to frequency is actually an exponential function. Two other limits actually exist in the BER floor for HOTLink. These are the upper and lower frequency limits of the HOTLink Transmitter and Receiver circuits.

The upper frequency limit can actually be identified in *Figures 4* and *5* as the flat horizontal section between 50 and 150 feet. In this area the operating limit is not due to the cable, but is instead due to characteristics of the phase-locked loops in the transmitter and receiver.

The lower frequency limit (not directly identifiable on the graphs) is that frequency below which the HOTLink Transmitter and Receiver cannot remain in a proper phase-lock to communicate valid data. For those parts used in this evaluation this is somewhere around a 13-MHz byte-clock rate (130 Mbits/second).

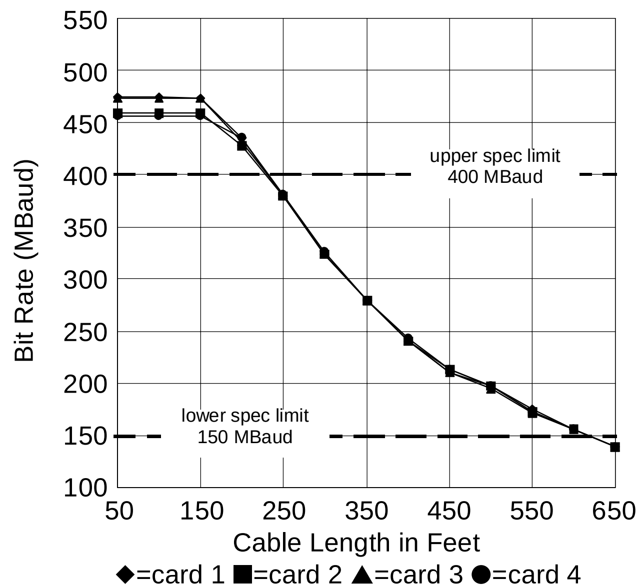


Figure 4. BER Floor for Type-1 STP Cable, Linear Frequency Scale

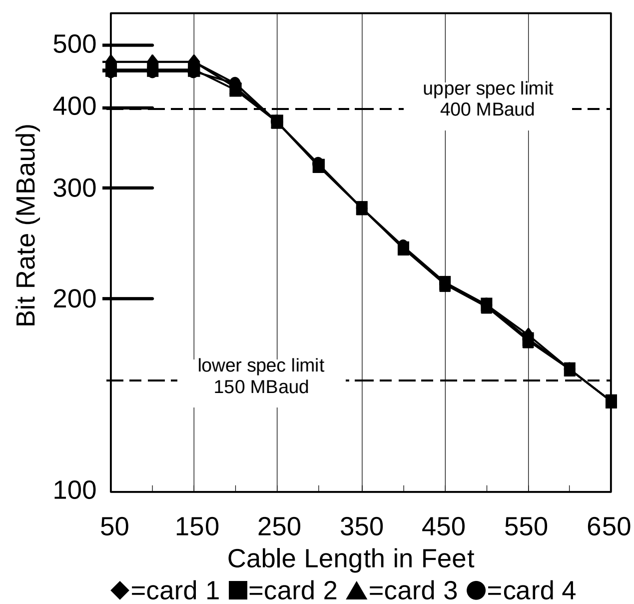


Figure 5. BER Floor for Type-1 STP Cable, Log Frequency Scale

Conclusion

The key observations for bit-error-rate measurements with HOTLink are:

- The HOTLink Transmitter and Receiver have an intrinsic error rate of zero.
- Optical links suffer primarily from intrinsic noise sources in the optical transmitter and optical receiver, and extrinsic sources in the optical receiver.
- Electrical links suffer primarily from extrinsic noise sources.
- The exceptional BER floor of HOTLink is due primarily to the very high jitter-tolerance of the receiver and low jitter generated in the transmitter.

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