HOTLink™ Copper Interconnect— Maximum Length vs. Frequency

Introduction

The most common question asked about any serial interface is, “How long of a link can I have?” The answer comes down to a mixture of transmission line characteristics, and the jitter generation and tolerance of the serial data transmitter and receiver.

While the jitter characteristics of both the CY7B923 and CY7B933 HOTLink™ Transmitter and Receiver are very stable across frequency, temperature, and voltage, such is not the case for copper cables. The signal distortion introduced by these cables is very non-linear with respect to distance and frequency. In addition, there are large variations in these non-linear characteristics based on the specific type of cable selected.

Cable Testing

To determine just how these cable characteristics affect data transmission, a number of tests were performed to determine the maximum data-rate versus distance characteristics of a number of common cable types. These tests were performed using multiple CY9266−T and CY9266−C HOTLink Evaluation Boards, and nine different types of copper cable.

Equipment

The following equipment was used for the cable evaluations:

- HP8116A pulse/function generator
- Three CY9266−C HOTLink Evaluation Boards for testing coaxial cable
- Four CY9266−T HOTLink Evaluation Boards for testing twisted-pair cable
- Multiple segments of each cable type, capable of being combined to length multiples of 50 feet

The specific cable types evaluated are not meant to be inclusive of all possible cable types that may be used with HOTLink. Instead they were selected to represent a relatively wide range of commonly available cable types that are often used for communications or networking. The cables evaluated are listed in *Table 1*.

The electrical configuration used for the testing, between the HOTLink Transmitter and Receiver, is shown in *Figure 1*. This figure is somewhat simplified from the actual circuit on the CY9266 boards, but serves to illustrate the transmitter and receiver bias, coupling, and termination networks.

The only changes made to the CY9266 boards (to accommodate the different cable types), was to change the termination resistors to match the cable impedance of the specific cable under test.

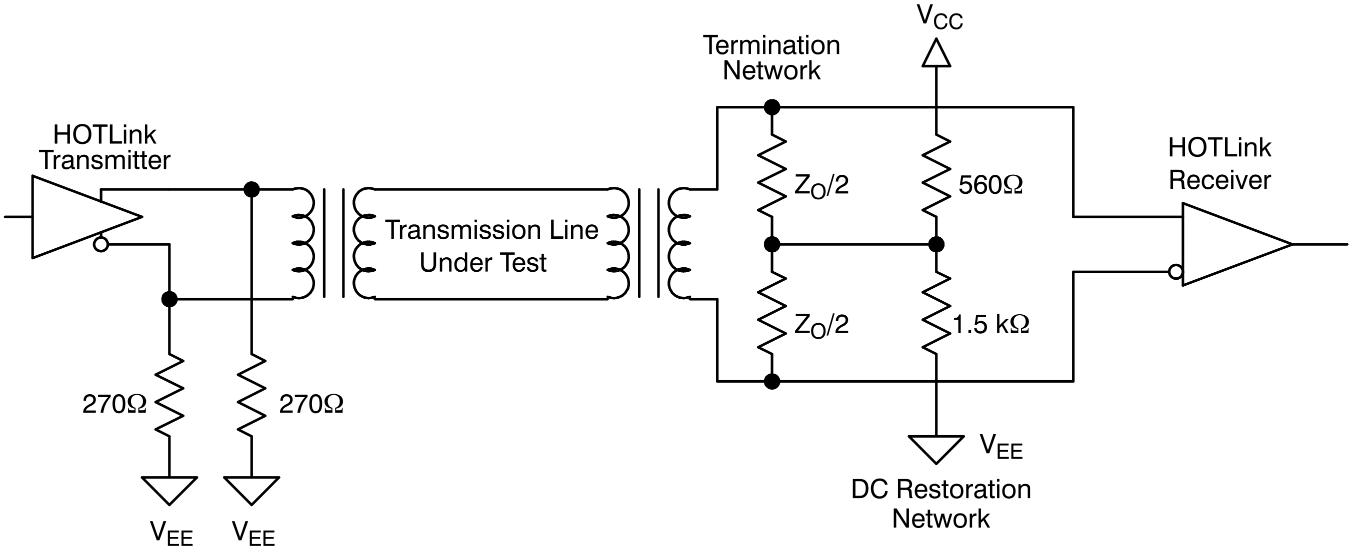


Figure 1. Cable Test Configuration

Table 1. Tested Cable Types

Cable Type	Mfgr.	Model	Type	Z_O
Coax	Belden	8219	RG58	50Ω
Coax	Belden	9259	RG59	75Ω
Coax	Belden	8255	RG62	93Ω
Coax	Belden	9066	RG6	75Ω
Coax	Belden	8218		75Ω
Coax	Belden	83264	RG179	75Ω
Shielded twisted pair	Belden	9688	IBM® Type-1	150Ω
Twisted pair	Comtran	PCC−FT4	UTP-3	100Ω
Twisted pair	Comtran	PCC−FT6	UTP-5	100Ω

Test Procedure

The testing consisted of using the built-in self-test (BIST) capability of the HOTLink Transmitter and Receiver to determine where the link was usable (error free) and where errors started to occur. An external frequency source was applied to both the transmitter and receiver and adjusted (both up and down) in frequency while monitoring the BIST error display for any link errors.

The criteria selected for an error-free link was that no errors be detected for a period of 20 minutes at a specific operating frequency and distance. This allows a large number of bits to be sent and received, and allows the HOTLink Transmitter and Receiver to stabilize at an operating temperature.

It is understood that this period of time does not guarantee an error-free link forever. Any link, no matter how good, will still have some error rate characteristic associated with it. However, observations of these copper based links (made in the process of these tests) has shown that if a link runs error free for this 20-minute period of time, it will remain so for a much longer period (i.e., multiple days).

Test Results

RG58—50Ω Coaxial Cable

The first system tested used the 50Ω RG58 coaxial cable. This cable is commonly used in the Ethernet physical variant known as 10BASE2 or ThinNet. The test results for this cable are plotted in *Figure 2*.

Of the three cards used in the testing, one used coupling transformers that had approximately twice the inductance of the other two. For this specific cable type (and for all other coaxial cables tested with this card) the maximum error free lengths at a specific operating frequency were always shorter than the

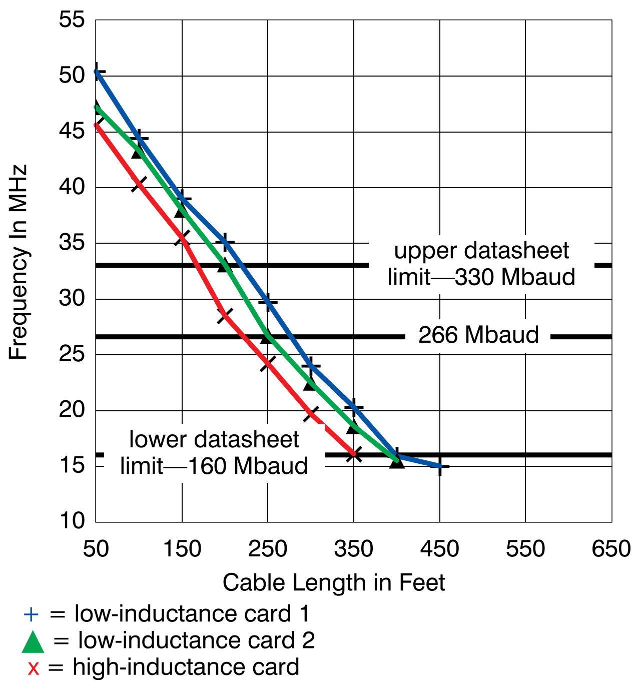


Figure 2. RG58 Test Results, Linear Frequency Scale

equivalent lengths on the cards with low inductance transformers.

Two reasons exist for this difference in operational length. First is based on the high-frequency bandwidth of the transformers. The high-inductance transformer (per the manufacturer's data) has a high end −3 dB bandwidth of around 250 MHz. Around this frequency point in the transformer, significant attenuation and phase shifts occur in the transmitted signal. Since it is these upper frequencies that provide a reasonable shape to the signal, their attenuation and distortion in the transformer causes less of these signal components to be available at the receiver.

The second effect is caused by the low-frequency bandwidth of the transformer. The higher the transformer inductance, the better its low-frequency response. Unfortunately it is the low-frequency content of the transmitted signal that induces most of the data-dependent jitter (DDJ) in the serial link.

In *Figure 2*, the frequency scale shows the clock rate delivered to the HOTLink Transmitter and Receiver. This clock rate is the byte rate for the transmitter and receiver. Because of the 8B10B encoding used to send serial information, the actual bit-rate on the serial interfaces is ten times this rate (i.e., 25 MHz=250 Mbits/second).

This figure shows that with an RG58-type cable (having the same attenuation characteristics of the cable tested here), that it is possible to reliably transmit information at all distances ≤200 feet when operating at the maximum HOTLink datasheet limit of 330 Mbits/second (when using low-inductance transformers). As the data-rate is reduced, the maximum operable length increases, such that at the minimum datasheet limit of 160 Mbits/second, the link may be operated at all lengths ≤400 feet.

Note: These distances are all based on uncompensated (non-equalized) links. By adding frequency-selective filter components to either the source or destination ends of the cable it is possible to greatly extend the error-free link lengths. All test data presented in this application note is only for uncompensated links.

RG59—75Ω Coaxial Cable

RG59 is a 75Ω coaxial cable manufactured in a similar size and construction to RG58. The main difference between them is the ratio of inner to outer diameters that determine the characteristic impedance of the cable. When tested to the same criteria as the RG58 cable (as shown in *Figure 3*), numerous differences in operation become apparent.

The most obvious difference is that the operable lengths have increased significantly: as much as 50% at 330 Mbits/second and 37% at 160 Mbits/second. In addition there is now a flat portion at the top end of the operating frequency range where changing the cable length has no effect on the maximum data-rate.

At this top-end frequency the interconnect system still modifies or distorts the transmitted signal. However, the amount of distortion is small enough that a different factor is limiting the maximum operable distance of the link. At this frequency, the phase-locked loops (PLLs) in the transmitter and receiver are up against their maximum operable limit. Because the received signal characteristics remain within the minimum acceptable limits of the

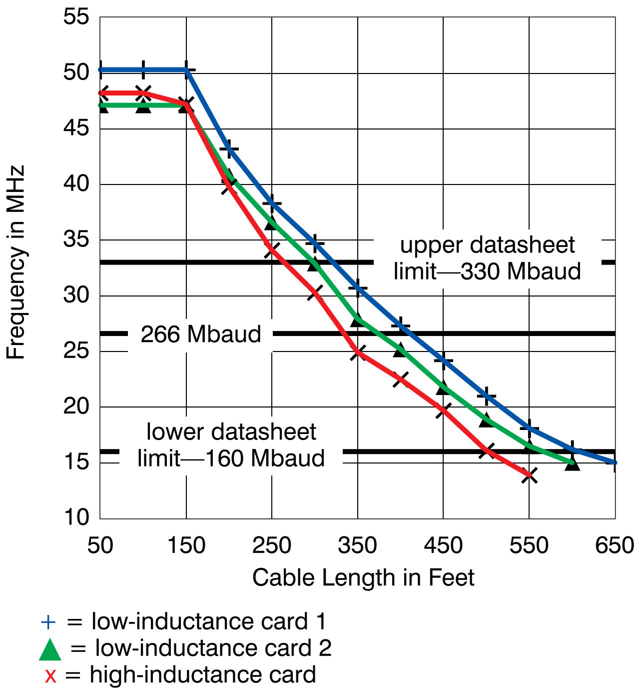


Figure 3. RG59 Test Results, Linear Frequency Scale

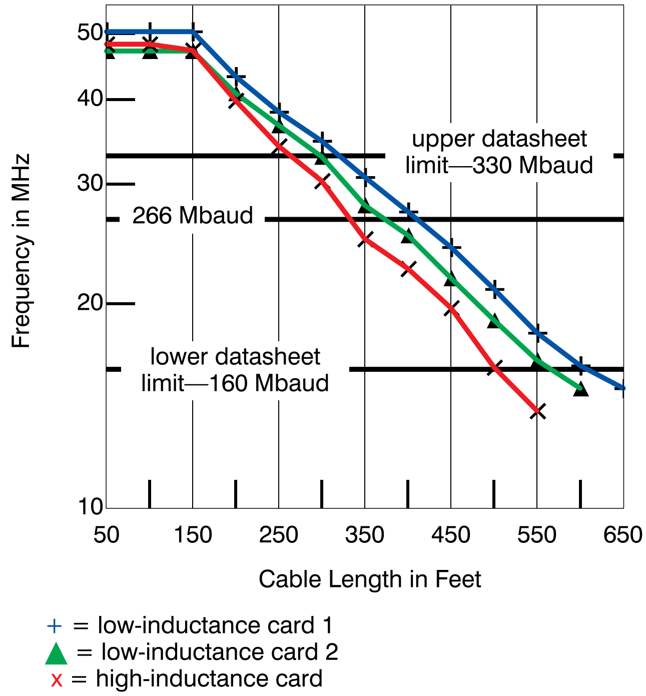


Figure 4. RG59 Test Results, Log Frequency Scale

receiver through the 150-foot distance, the line remains flat.

Beyond the 150-foot length the received signal is distorted enough such that the operating frequency must be reduced in order to bring the signal back to where the receiver can accurately capture it.

By taking the same data in *Figure 3* and plotting it on a logarithmic frequency scale in *Figure 4*, another characteristic becomes visible. Now the curves for data-rate versus distance appear as a straight line. This means that this is actually an exponential function.

Other Cable Types

Data-rate versus distance information was taken for all the cable types listed in *Table 1*. By plotting a composite chart of all these cable types, it is possible to see how the different cable characteristics affect the maximum operable length. This information is shown in *Figure 5*.

RG62—93Ω Coaxial Cable

RG62 is a 93Ω version of RG59 cable. It is made by removing some of the dielectric in the RG59 cable and replacing it with air, lowering the dielectric constant. Since the cable impedance is based on the dielectric constant of the spacer (in addition to the dimensions of the conductors), lowering the dielectric constant raises the impedance to 93Ω

Comparing the operable length characteristics of this cable with that of the RG58 and RG59 cables shows that the higher impedance RG62 again improves the maximum usable distance at all frequencies.

RG6—75Ω Coaxial Cable

RG6 is a 75Ω coaxial cable commonly used for CATV applications. While this cable does have the same impedance as the RG59 cable, its construction is quite different, as are its data transmission characteristics. This cable has larger inner and outer diameters for the conductors used in the cable. While the ratios of these diameters do maintain a 75Ω system, the increased dimensions create larger surface areas for the conductors and therefore lower losses.

When compared to the RG59 cable, RG6 allows operable distances of nearly twice as far. At the low end (160 Mbits/second) of the HOTLink operating range, this approaches 1000 feet.

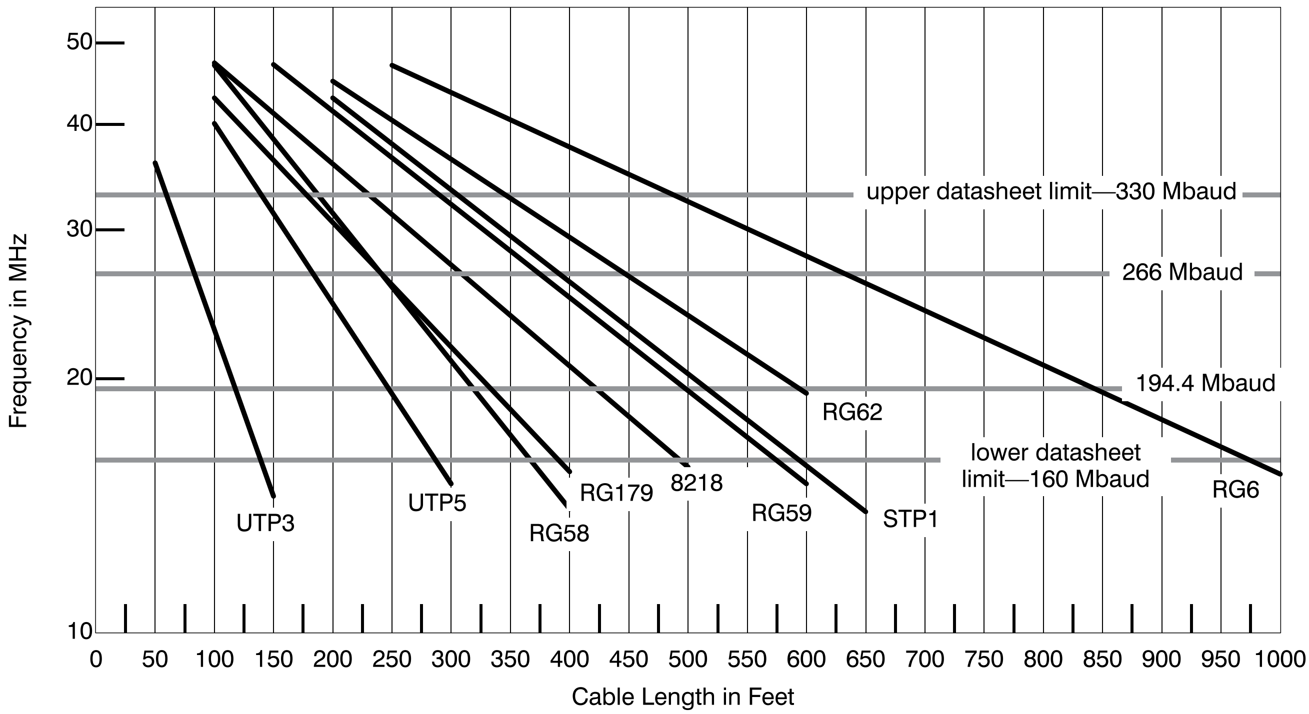


Figure 5. Maximum Data-Rate versus Distance Comparison

RG179 and Belden 8218—75Ω Coaxial Cable

The RG179 and Belden 8218 cables are also 75Ω types. These cables, however, are designed for different environments where signal loss is not the primary concern. The 8218 cable type is a miniature form of RG59. With the smaller diameters (and smaller surface area) its losses at all frequencies are greater than those of RG59.

RG179 is a cable designed both for tight spaces and harsh environments. Its Teflon® jacket allows it to be used where most cables cannot. If it was manufactured using the same materials as RG59 or 8218 cable, its losses would be much higher than they currently are. To limit the losses, the inner copper conductor is plated with silver to improve the skin-depth for high-frequency signals.

Twisted-Pair Cables

The other family of cables supported by HOTLink are known as twisted-pair cables. These cables were tested with the CY9266−T HOTLink boards.

IBM Type-1—150Ω Shielded Twisted-Pair Cable

The IBM Type-1 cable (STP1) consists of two individually shielded twisted pairs in a single cable. The cable itself was designed for token-ring network applications operating at 4 or 16 Mbits/second. These network speeds are much less than those supported by HOTLink. Due to the excellent signal generation and handling characteristics of the HOTLink components, this same cable is usable over even greater distances at more than ten times its designed data rate.

This cable has similar distance characteristics over frequency to the RG59 coaxial cable. Because two signal pairs are present in the same cable, a bidirectional link can be built using a single cable.

Note: Other coupling mechanisms exist that permit bidirectional signal transmission on a single set of conductors. The theory and implementation of these specialized structures is beyond the scope of this document.

Mechanically different forms of this cable exist with slightly modified signal characteristics. These variants (Type-2, Type-6, etc.) add extra non-data conductors or uses stranded-conductor construction to improve flexibility. If the variant selected has similar attenuation characteristics to Type-1, it should operate with a similar data-rate versus distance curve.

UTP3 and UTP5—100Ω Unshielded Twisted Pair

UTP3 and UTP5 are unshielded twisted-pair cables, most commonly used for 10BASE-T Ethernet or telephone installations. UTP3 (also known as category 3) is rated for Ethernet use at 10 Mbits/second at distances up to 100 meters (329 feet), while UTP5 is rated at 100 Mbits/second at the same distance. In these unshielded cables (unlike STP1 or the coaxial cables), crosstalk becomes a significant link-limiting factor.

Crosstalk occurs because of the close proximity of the two signal pairs. With no shield to keep their respective signals separated, the cable itself becomes both a long coupling transformer and coupling capacitor. This crosstalk combines with the attenuation characteristic of the cable to distort the signals on the cable.

These unshielded cables will work fine for short- to medium-length interconnections when used with HOTLink. However, the lack of a cable shield may limit their use to environments where radiated emissions are not a concern; i.e., inside a shielded cabinet or other enclosure.

General Observations

- Lower inductance transformers allow greater operating distance due to wider bandwidth.
- Higher impedance cables have lower losses and allow greater operating distance.
- Larger diameter cables have less attenuation and allow greater operating distance.

Eye Pattern Testing

While measurement of errors in a link does yield a significant amount of information about link operation, it does not explain the actual failure mechanism; i.e., why a signal is received in error. To do this requires looking at the actual signal. The following eye patterns and oscilloscope diagrams are used to explain the signal failure mode. All measurements are made with error free links based on RG59 cable.

Figure 6 shows the wide-open eye at the source end of a link for both a normally driven and a source terminated (series resistance added to the driver,

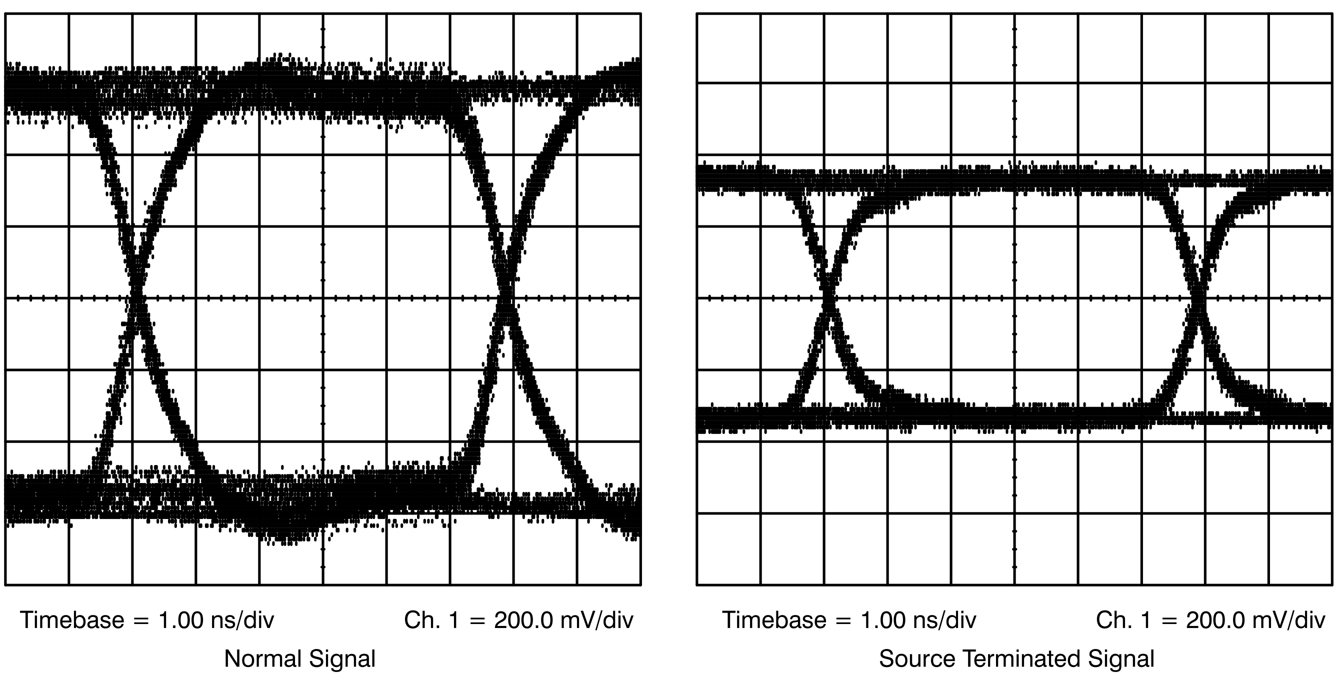


Figure 6. Error-Free, 173-Mbit/second Signal at the Driver End of a 550-Foot RG59 Cable

equal to the cable impedance) system. The eye has minimal distortion in both systems, but the added source resistance reduces the source signal amplitude by 6 dB for the source terminated link. These links both operate error free at 173 Mbits/second with 550 feet of cable attached.

The same two systems are shown in *Figure 7* at the receiver end of 550 feet of cable. Things look a bit different here. Now the eye is almost completely closed. The width of the opening in both configurations is approximately 500 ps. The only significant difference between the two links is that the source terminated signal has a smaller noise margin.

To view the effect on high data-rate signals, two new links were configured at 363 Mbits/second with 300 feet of cable. At this data rate the bit-cell time is approximately half that of the pervious configuration. The source-signal eye diagrams for these systems are shown in *Figure 8*. Again, at the source end of the cable the signals are clean. While the edges appear to have somewhat slower ramp rates, this is due to the change in sweep frequency for the oscilloscope from 1 ns/division to 500 ps/division.

Figure 9 shows the signals at the receiving end of the 300-foot cable. These signals look similar to the 550-foot link. The overall amplitude is somewhat larger, due to the lower attenuation of the shorter cable, but the eye is still almost completely closed. At this faster data rate, the minimum eye opening is again approximately 500 ps.

The fact that the minimum eye opening of approximately 500 ps remains the same at both data-rates is not just a coincidence. This number is based on the jitter tolerance and static alignment characteristics of the HOTLink receiver PLL and data-capture circuits.

Linear Time View

The minimum-eye handling capability is a fixed characteristic of the HOTLink receiver. Changing the source-signal amplitude or data rate has no significant effect on this characteristic. But this still does not explain why the eye closes in the first place. To see this, it is necessary to look at how individual bits interact with each other.

To see bit interaction on an oscilloscope it is necessary to change from a random data pattern (like the BIST pattern that was used for the previous tests), to a fixed pattern. To show the worst-case bit interaction it is also necessary to use a data pattern that contains the maximum and minimum run-lengths of

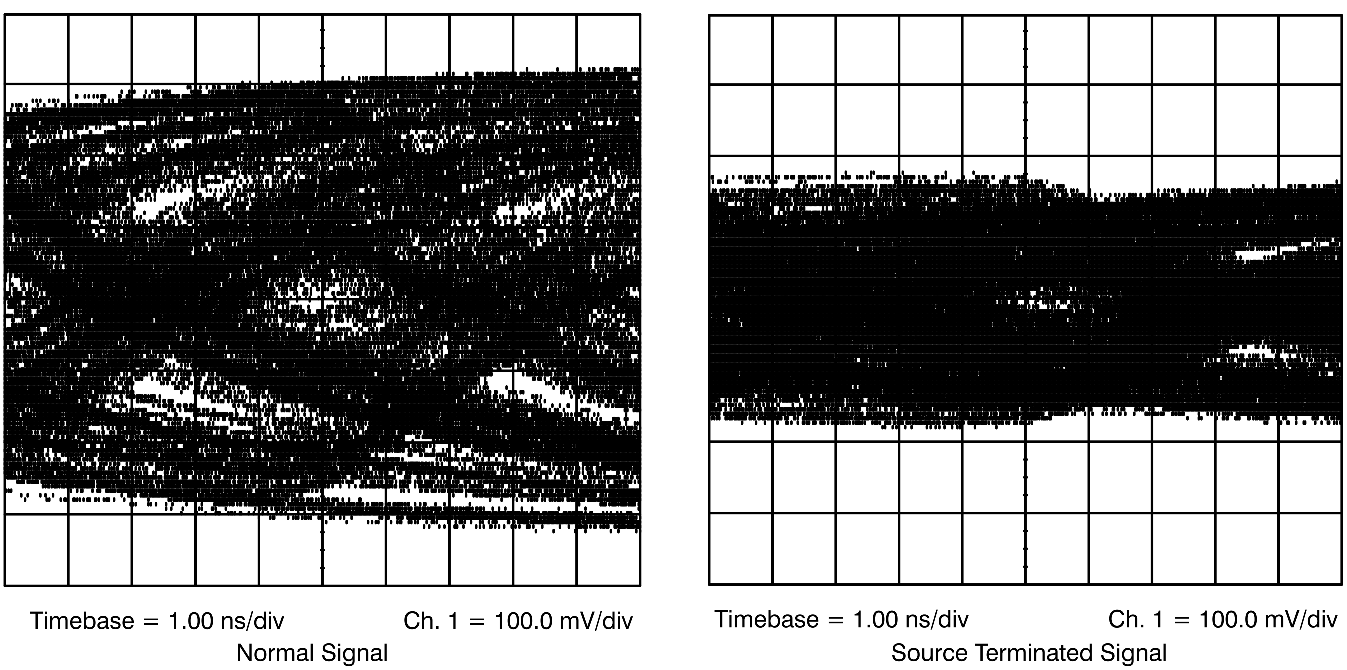
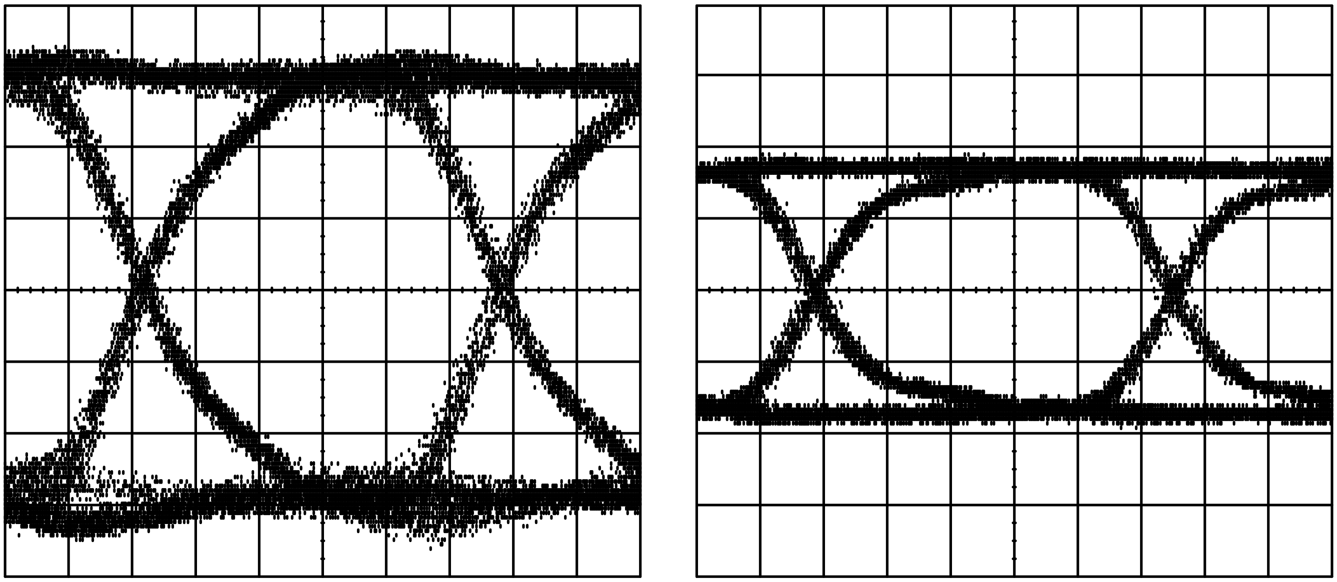


Figure 7. Error-Free, 173-Mbit/second Signal at the Receiver End of a 550-Foot RG59 Cable



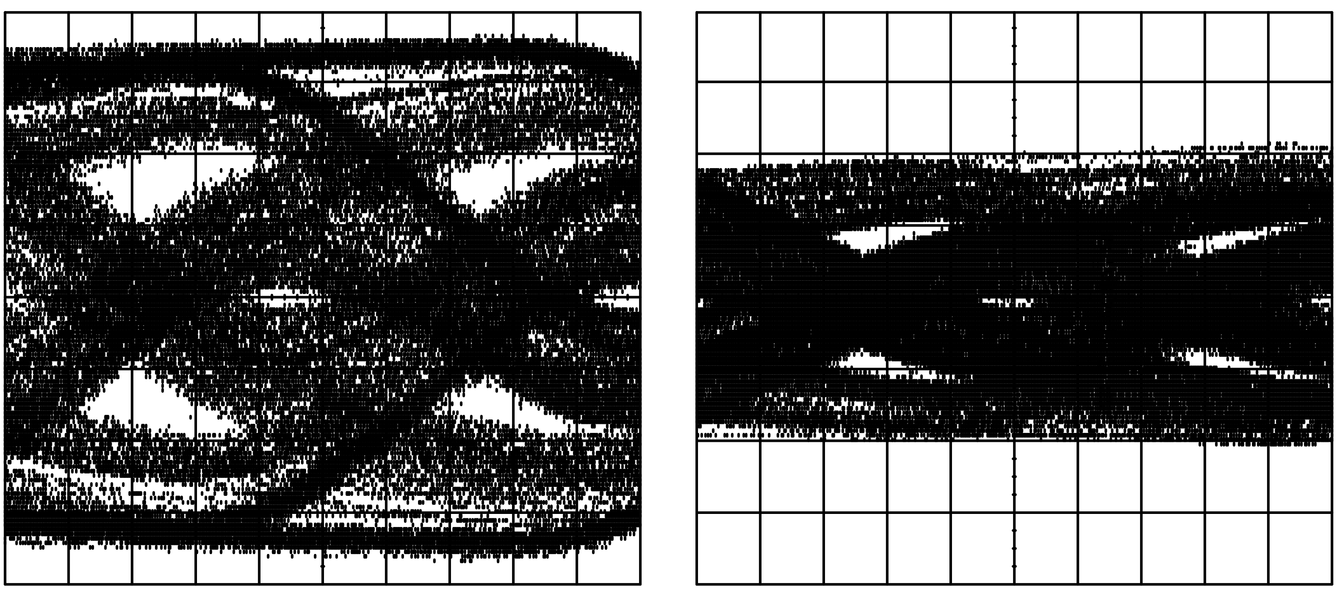
Timebase = 500 ps/div Ch. 1 = 200.0 mV/div
Normal Signal

Timebase = 500 ps/div Ch. 1 = 200.0 mV/div
Source Terminated Signal

Figure 8. Error-Free, 363-Mbit/second Signal at the Driver End of a 300-Foot RG59 Cable

1s and 0s. Fortunately, a pattern meeting these characteristics is automatically generated by the HOTLink Transmitter when both $\overline{\text{ENA}}$ and $\overline{\text{ENN}}$ are disabled. The character sent under these conditions is known as a K28.5 code, which (following the 8B/10B disparity rules) generates a repeating 20-bit pattern of 00111110101100000101.

This pattern, when viewed at the end of the cable under the same data-rate and cable lengths of the



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

Timebase = 500 ps/div Ch. 1 = 100.0 mV/div
Source Terminated Signal

Figure 9. Error-Free, 363-Mbit/second Signal at the Receiver End of a 300-Foot RG59 Cable

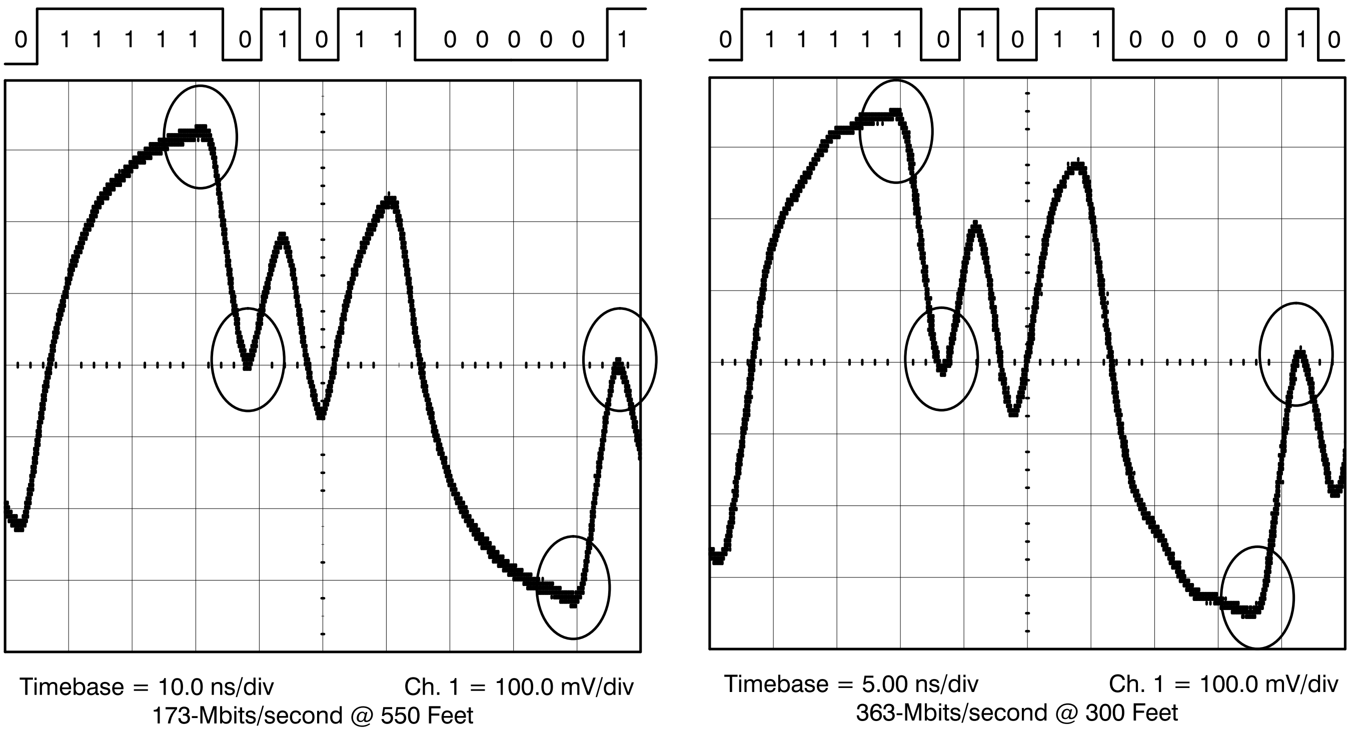


Figure 10. Error-Free, K28.5 Character at Maximum Data Rate

previous two tests, is shown in *Figure 10*. The highlighted areas in each configuration show the bits that interact to cause the eye to close. In both configurations, two of these bits (at this worst-case data-rate) barely cross the receiver threshold. The long 1s and 0s immediately preceding them cause the signal to move the farthest from the receiver threshold.

The K28.5 character will always generate a signal that looks approximately the same at the maximum length limit of an uncompensated link. This is due both to the physics of the transmission line, and to the exceptional jitter tolerance of the HOTLink Receiver. The addition of an equalizer would level out the transitions and keep them centered around the receiver threshold.

General Observations

- Signal amplitude is not the length-limiting factor for most links.
- The HOTLink Receiver's jitter sensitivity window is approximately 500 ps in size.
- Equalization will allow much longer links.
  - — HOTLink Receiver only requires 50 mV of signal.
  - — Equalization may allow link lengths of four times that of a non-equalized link.

Conclusion

The CY7B922 and CY7B933 HOTLink data communications components can be used in communications links with almost any configuration of copper media. In these links the frequency attenuation characteristics of the copper media are the primary length limiting factors for a link. The enhanced sensitivity of the HOTLink receiver allows usage of forms of signal equalization that allow operation over much greater distances than non-equalized links.