5. Electrical Links

During early development of Fibre Channel, interest was focused on the use of optical interfaces due to their superior distance, data rate, and electrical noise immunity. Fibre Channel was viewed primarily as a system interface where the number of interfaces would be relatively small and span intermediate distances. As technology progressed, it became apparent that Fibre Channel could also be used as a device interface. In this type of application, the cost per connection was critical, while distance capabilities were secondary. A prime example of this type of application is a disk-storage subsystem that provides high data rates through the interconnection of a large number of individual disk drives, all relatively close together.

To accommodate the need for high-speed interfaces over short distances, Fibre Channel standards defined electrical links based on several different transmission line types. None of the electrical transmission lines can match the distance capabilities of optical fiber without the need for intermediate repeaters, but for many short distance applications, electrical connections may provide the most cost-effective solutions.

There are three types of electrical interfaces distinguished by the transmission line and modulation method; unbalanced transmission lines using coaxial cable and single-ended drivers and receivers, balanced transmission lines using twinaxial cable or shielded twisted pair and differential drivers and receivers and FC-BaseT links using unshielded twisted pair.

5.1 Single-Ended Links

Coaxial cable consists of a center conductor that carries the signal, an insulating layer, and an outer shield. The shield confines the electrical signals to the cable and provides a ground return path for the electrical circuit. Coaxial cable is an unbalanced transmission line that is driven with a single-ended electrical driver. A one bit corresponds to the state where the center conductor is positive (above a certain threshold) with respect to the shield. An example of an unbalanced transmission line is shown in Figure 31. While single-ended links are defined in the standard, they are not commonly used in products.

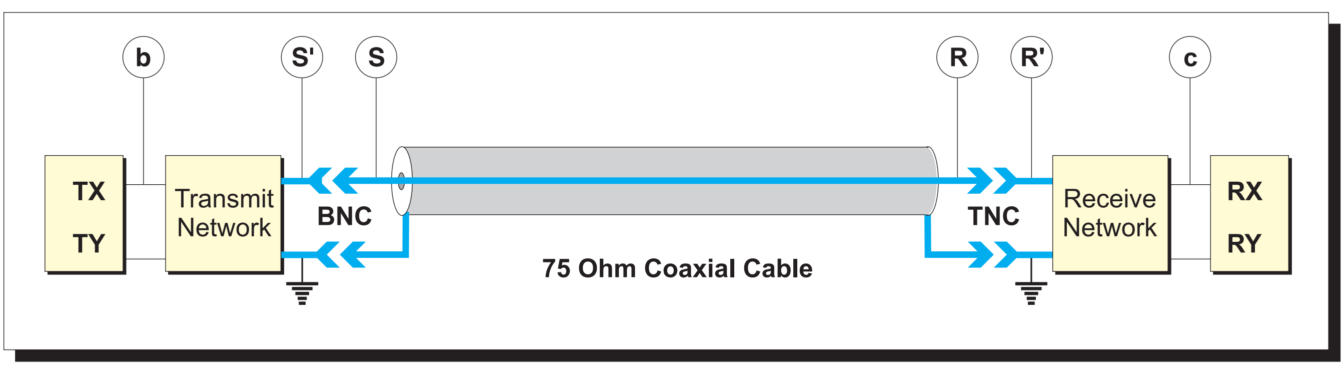

Figure 31. Single-Ended, Unbalanced Link

5.2 Differential Links

Electrical signals can be sent using balanced transmission lines. In this type of transmission line, two wires carry the signal in each direction as shown in Figure 32. The majority of electrical links in Fibre Channel products use differential signaling. In general, balanced transmission lines can be either shielded or unshielded depending upon the application. In Fibre Channel, all balanced transmission lines are shielded to prevent excessive signal radiation.

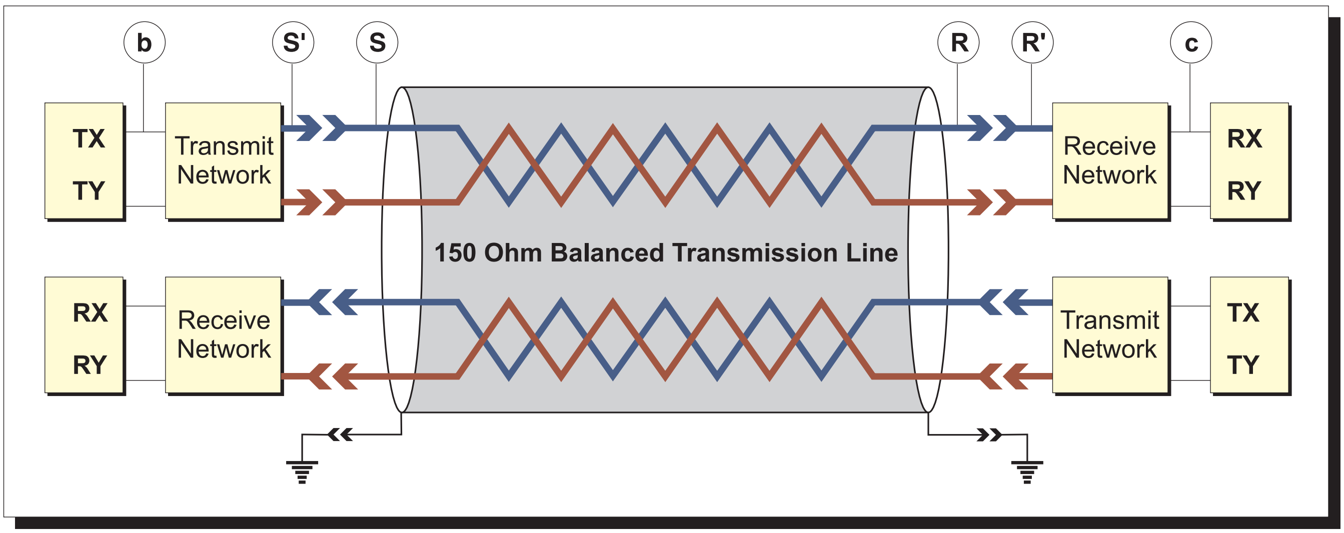

Figure 32. Differential, Balanced Link

Differential signaling uses two drivers and two receivers, one for each of the conductors in the pair. Whenever one of the conductors is driven to the positive signal level, the other is driven to the negative signal level. When transmitting a bit of the opposite polarity, the levels are reversed. To identify the two conductors, one is labeled "+" and the other "-". When the "+" conductor is positive with respect to the "-" conductor, the transmission line is carrying a one bit. When the "-" conductor is positive with respect to the "+" conductor, the transmission line is carrying a zero bit. This is shown in Figure 33 on page 65 (this example shows a 600 mv. peak-to-peak signal swing, the standards specify a minimum voltage swing of 300 mv. and a maximum of either 800 or 1000 mv. depending upon the signaling rate).

Differential signaling provides several advantages when compared to single-ended signaling:

- Improved noise immunity: Noise that is coupled into both signal lines is cancelled out at the receiver. The behavior is referred to as common-mode rejection.
- Lower signal radiation: Less signal is radiated from the cable because energy radiated from one conductor is cancelled out by that radiated from the other conductor.
- Low voltage signaling: The signal swing is normally smaller than when using single-ended links because the voltage swings on the two conductors are additive at the receiver.
- Less power and heat dissipation: The smaller voltage swing translates into less power consumption and head dissipation.
- Higher signaling rates: Lower voltage swings make higher signaling rates possible.

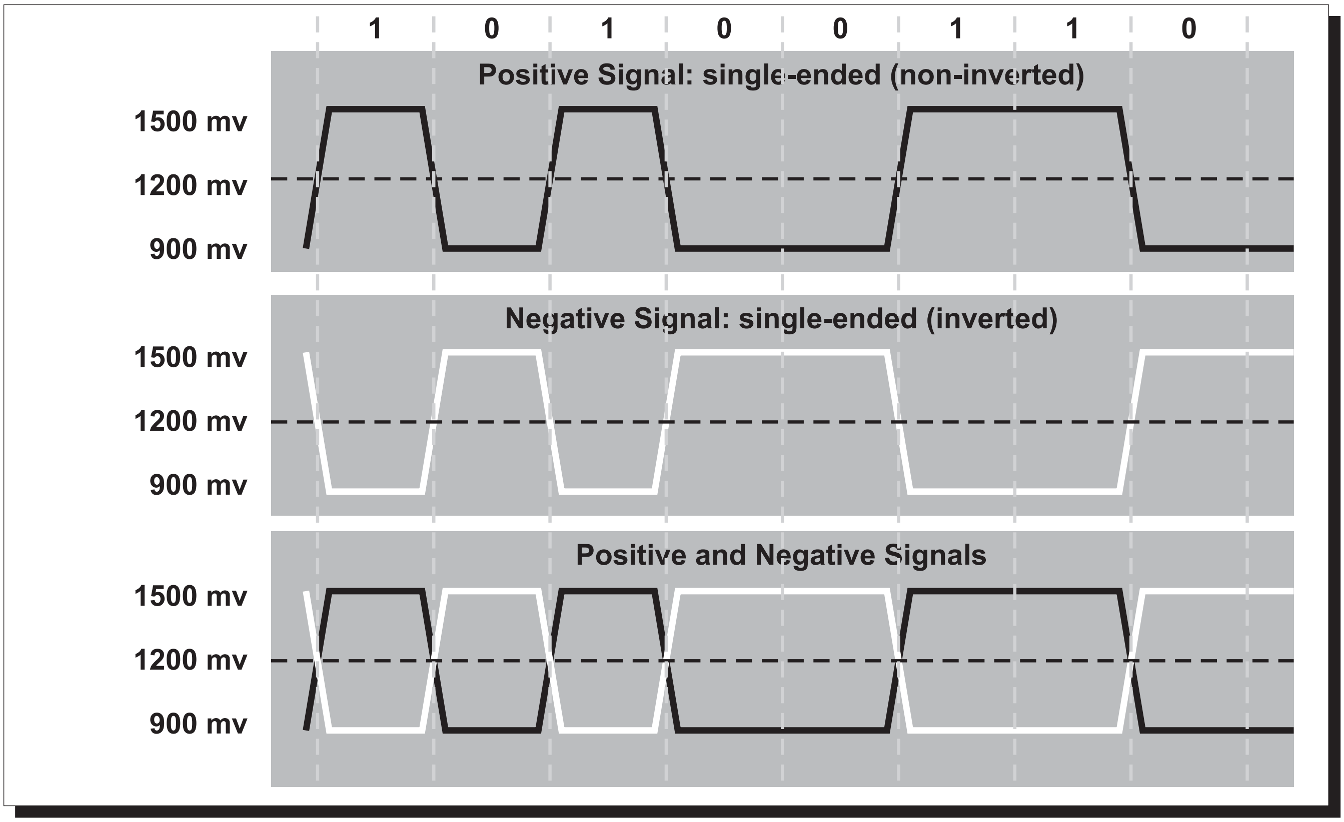

Figure 33. Differential Signaling Example

5.2.1 Signal Coupling and Equalization

Electrical links use capacitive coupling to couple the signal into, and out of, the link. There is no DC connection between the actual transmitter and receiver. An example of transmit and receive networks for use with balanced transmission lines is shown in Figure 34. While this example includes an equalizer, this may or may not be necessary depending upon the length, and characteristics, of the transmission line. Equalization is discussed in more detail in *Receiver Equalization* on page 68.

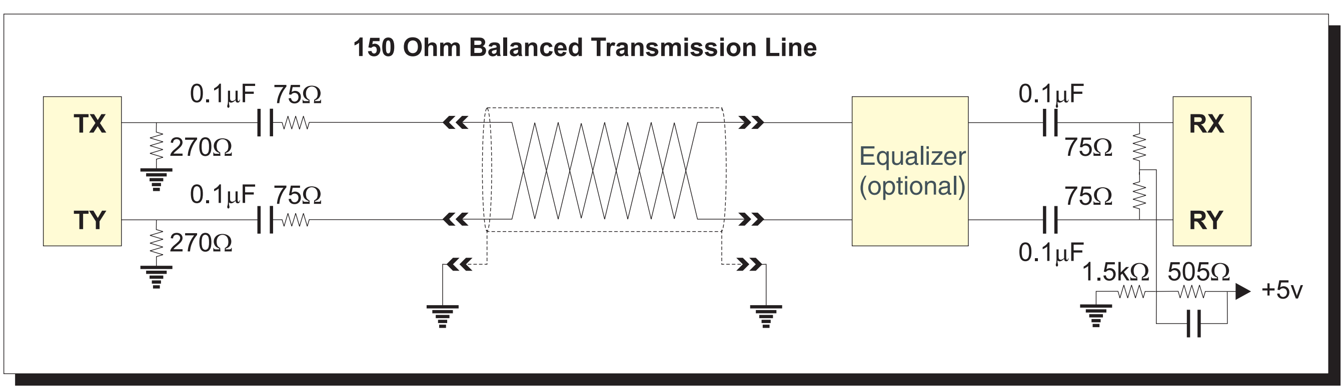

Figure 34. Differential Transmit and Receive Networks

Due to the wide variations in cable performance, maximum electrical cable distances are not specified by the standard. Rather, transmit and receive signal criteria and cable characteristics determine the maximum distance. The maximum distance for 1.0625 Gbps differential links is approximately 30 meters, falling to about 15 meters for 2.125 Gbps links and 7.5 meters for 4.25 Gbps links.

5.2.2 Cable and Connector Losses

Figure 35 shows a measured signal waveform at the end of a 1 meter electrical cable. This example shows a good eye opening that does not violate the mask and provides the receiver with a wide margin for sampling the received bit stream.

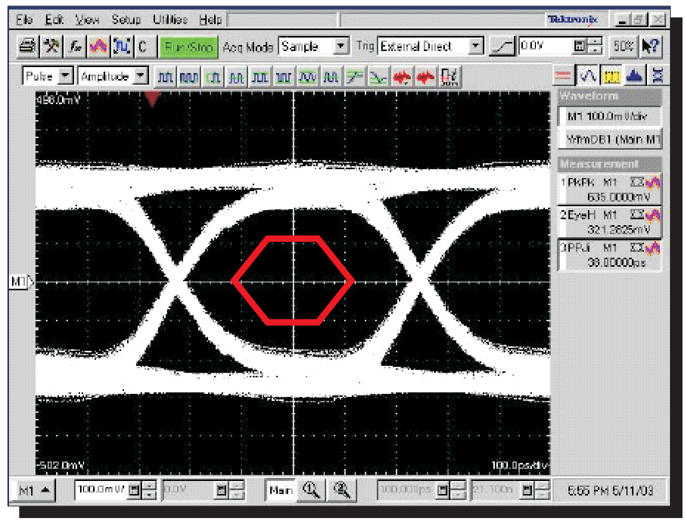

Figure 35. Eye Diagram (1 Meter Cable)

Compare the signal in Figure 35 to the one shown in Figure 36. This is the same signal at the end of a 10 meter electrical cable. As can be seen from this example, there is significant closure of the eye opening due to the loss introduced by the cable and connectors. Because of the signal degradation caused by the cable and connectors, the received signal shown in Figure 36 violates the eye mask and may result in an excessive bit error rate.

Failure to meet the required bit error rate may result in an excessive number of transmission errors and operational failures or degraded performance.

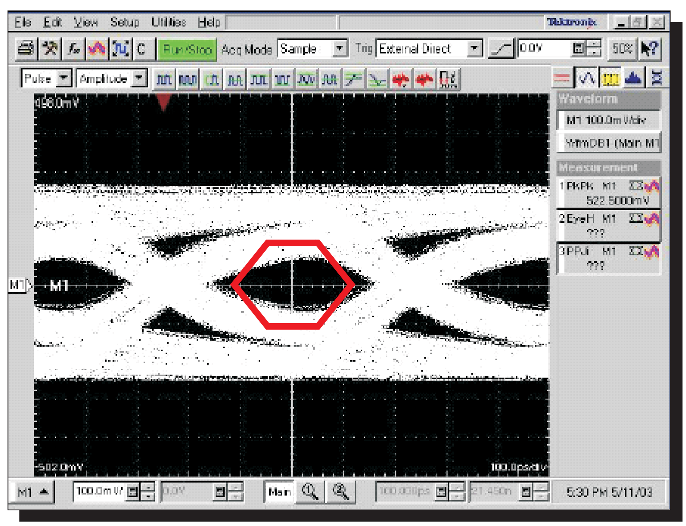

Figure 36. Eye Diagram (10 Meter Cable)

Electrical cables (and printed circuit board wiring) and connectors cause signal loss between the transmitter and receiver. The amount of signal loss is determined by the characteristics of the cables and connectors used. When the cable and connector loss is known, along with the transmitter output and required receiver input, the maximum allowable cable length can be determined.

There are two primary methods for countering signal loss and degradation caused by an electrical cable plant.

- Transmitter de-emphasis changes the transmitted signal waveform to counter the expected interconnect loss.
- Receiver equalization changes the interpretation of the received signal realizing it has been altered by the interconnect.

5.2.3 Transmitter De-Emphasis

When a signal is transmitted via an electrical cable, energy is stored by the cable capacitance. When a series of consecutive bits of the same polarity are transmitted, the stored charge accumulates and interferes with the next bit of the opposite polarity (the next bit must discharge the energy stored by the cable capacitance). This reduces the amplitude of the first bit following a transition as shown by the lower set of waveforms in Figure 37 (the gray band in this figure represents the receiver threshold). Note how the amplitude of the final zero bit may not be sufficient for reliable detection at the receiver.

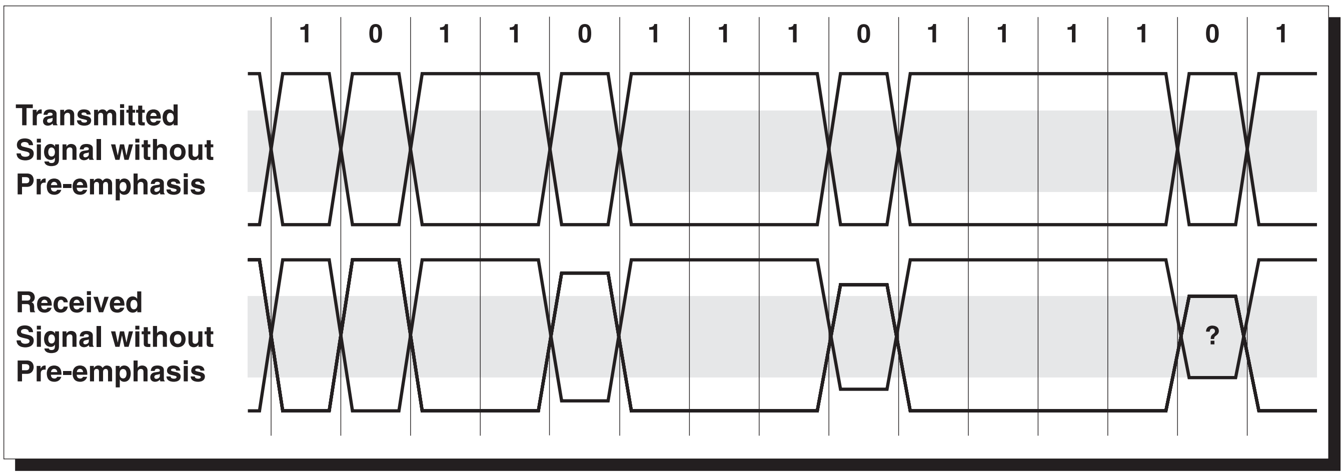

Figure 37. Transmit Signal Without De-Emphasis

Transmitter de-emphasis compensates for this effect by transmitting the first bit after a transition at full amplitude and reducing the amplitude of subsequent bits to reduce the stored charge in the cable as shown in the top set of waveforms in Figure 38. The lower set of waveforms show the resulting signal with transmitter de-emphasis and intersymbol interference. All of the bits are now above the receiver threshold, even the final zero bit after the four one bits.

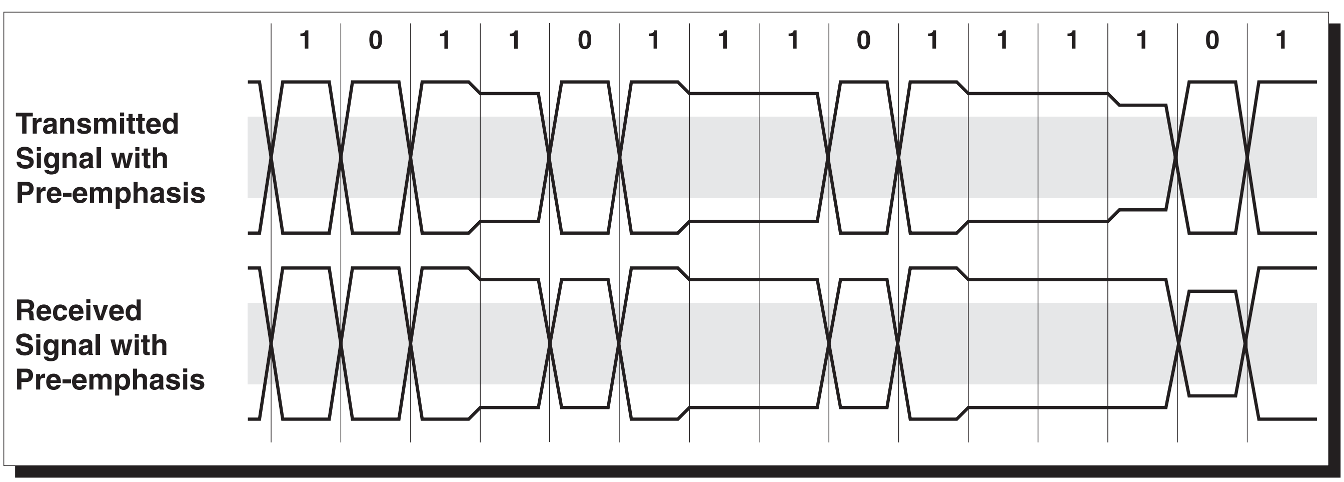

Figure 38. Transmit Signal With De-Emphasis

Figure 39 shows a measured signal waveform at the end of a 1 meter electrical cable when transmitter de-emphasis is used (this is the same cable plant as shown in Figure 35 on page 66). In the figure, you can clearly see how the first bit following a transition has a higher amplitude than subsequent bits.

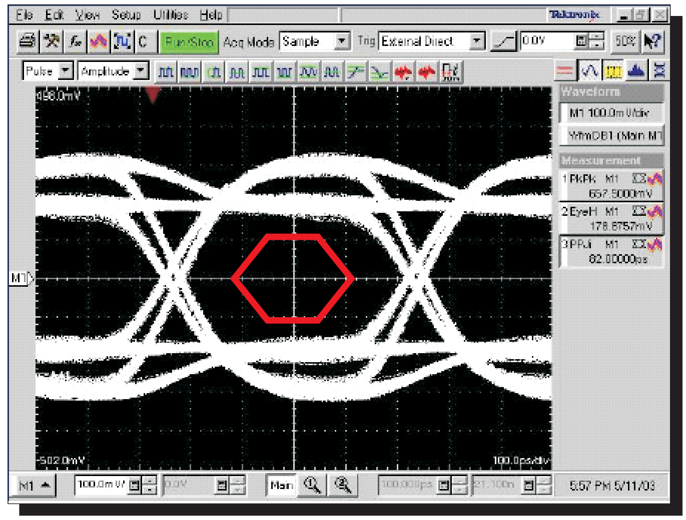

Figure 39. De-emphasis (1 Meter Cable)

The amount of de-emphasis required depends on the characteristics of the electrical link. Implementations supporting de-emphasis may provide just a single-level of de-emphasis or multiple levels as was shown in Figure 38 on page 67. Implementations that supporting electrical links may provide a fixed amount of de-emphasis, or allow the behavior to be varied depending on the link's characteristics.

Figure 40 shows the same signal at the end of a 10 meter electrical cable as was shown earlier but now with transmitter de-emphasis. Compare the eye opening in this figure to the one shown in Figure 36 on page 66. The increased opening of the eye is due to the de-emphasis applied to the transmitted signal.

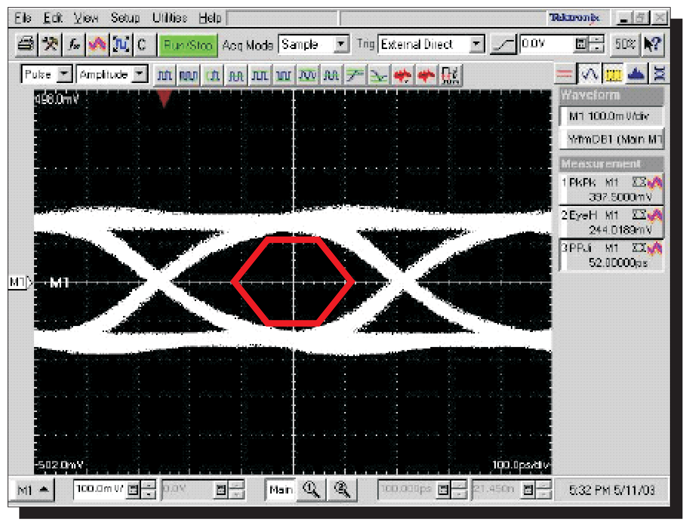

Figure 40. De-emphasis (10 Meter Cable)

5.2.4 Receiver Equalization

Receiver equalization is another strategy to improve signal quality. Receiver equalization can be used in conjunction with transmitter de-emphasis or by itself.

Receiver equalization amplifies higher frequency signal components in order to offset the high-frequency attenuation of the cable.

With receiver equalization, the receiver amplifies (boosts) input frequencies near the signaling rate while attenuating higher and lower frequencies. This results in increased amplitude when a bit transition occurs. As with transmitter de-emphasis, the goal is to compensate for the cable attenuation associated with bit transitions. Equalization can potentially recover signals when no eye is apparent at the receiver. An example of receiver equalization is shown in Figure 41 on page 69.

One advantage of receiver equalization is that it can automatically adapt to the cabling environment. On the other hand, it may also amplify noise, and because equalization is applied after the signal is received, it may not be possible to observe the resulting received signal.

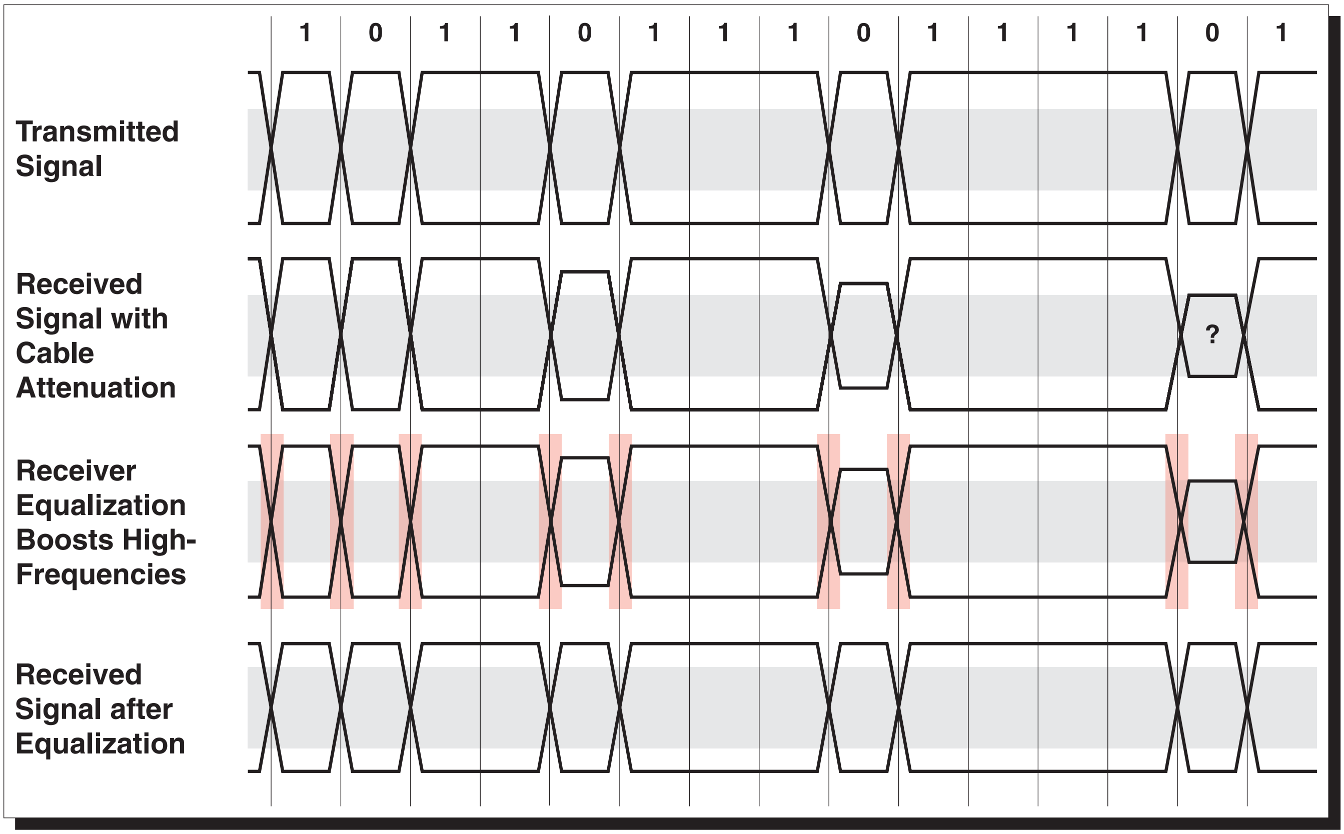

Figure 41. Receiver Equalization

5.3 FC BaseT

To provide an even lower-cost electrical link, the standards committee developed an electrical variant based on the popular Ethernet category 5e (enhanced) or better unshielded twisted pair. This variant is referred to as FC BaseT and uses the link configuration shown in Figure 42. The hybrids shown in the figure couple the signal into, and out of, the cable and isolate the transmit signal from the incoming receive signal.

Because of the relatively low bandwidth provided by each signal pair in the cable, bidirectional signaling is used on each signal pair in the cable (the same wires are used for both transmitting and receiving). In addition, a more sophisticated modulation method, called Pulse Amplitude Modulation (PAM-8), is used. Both of these techniques were pioneered by the development of 1 Gbps Ethernet (1000BASE-T) and have been proven in the field.

36-bit words (eight data bits and the D/K indication) are transcoded into a 33-bit word consisting of one control bit (D/K indication) and 32-data bits. The 33-bit word is then converted into three PAM-8 symbols. Each PAM-8 symbol corresponds to 2.75 information bits. Doing a bit of math, (2.75 bits per symbol) x (3 symbols per word) x (4 wire pairs) = 33 bit word.

The technical details of the PAM-8 encoding and modulation are beyond the scope of this book and the reader should consult the Fibre Channel FC-BaseT standard for detailed information and descriptions.

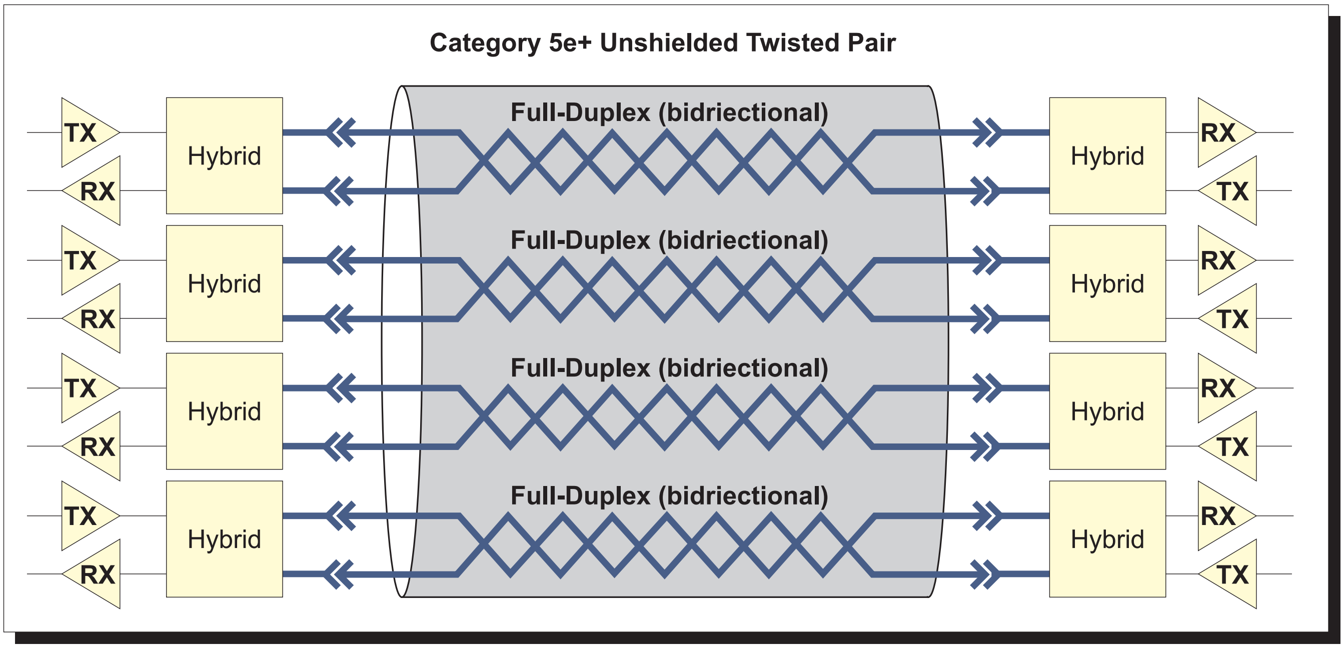

Figure 42. FC BaseT Electrical Link

The expected distances for the different types of Ethernet cabling are listed in Table 3.

Signaling Rate	Cat 5e	Cat 6	Cat 6a
1 Gbps	100 m.	100 m.	100 m.
2 Gbps	60 m.	70 m.	100 m.
4 Gbps	30 m. (expected)	40 m.	100 m.

Table 3. FC BaseT Distances

5.4 Electrical Connectors

Multiple electrical connectors have been specified by the standards to accommodate the different transmission line types and various cost and performance objectives. Electrical connectors are shown in Figure 43 on page 71.

5.4.1 Single-Ended Electrical Connectors

Single-ended transmission lines use coaxial cable and matching connectors. Two different styles of coaxial connectors have been approved. The first is the familiar BNC connector and its threaded equivalent, the TNC connector. The BNC connector is used on the transmit end of the cable, the TNC on the receive end. To provide a full duplex link, two cables are required.

The second style of coaxial cable connector is the industry standard 50Ω SMA. When this style of connector is used, both ends of the cable are terminated with a male connector. Because this arrangement does not provide polarization of the transmit and receive signals, any incorrect connection must not result in damage to any component in the system.

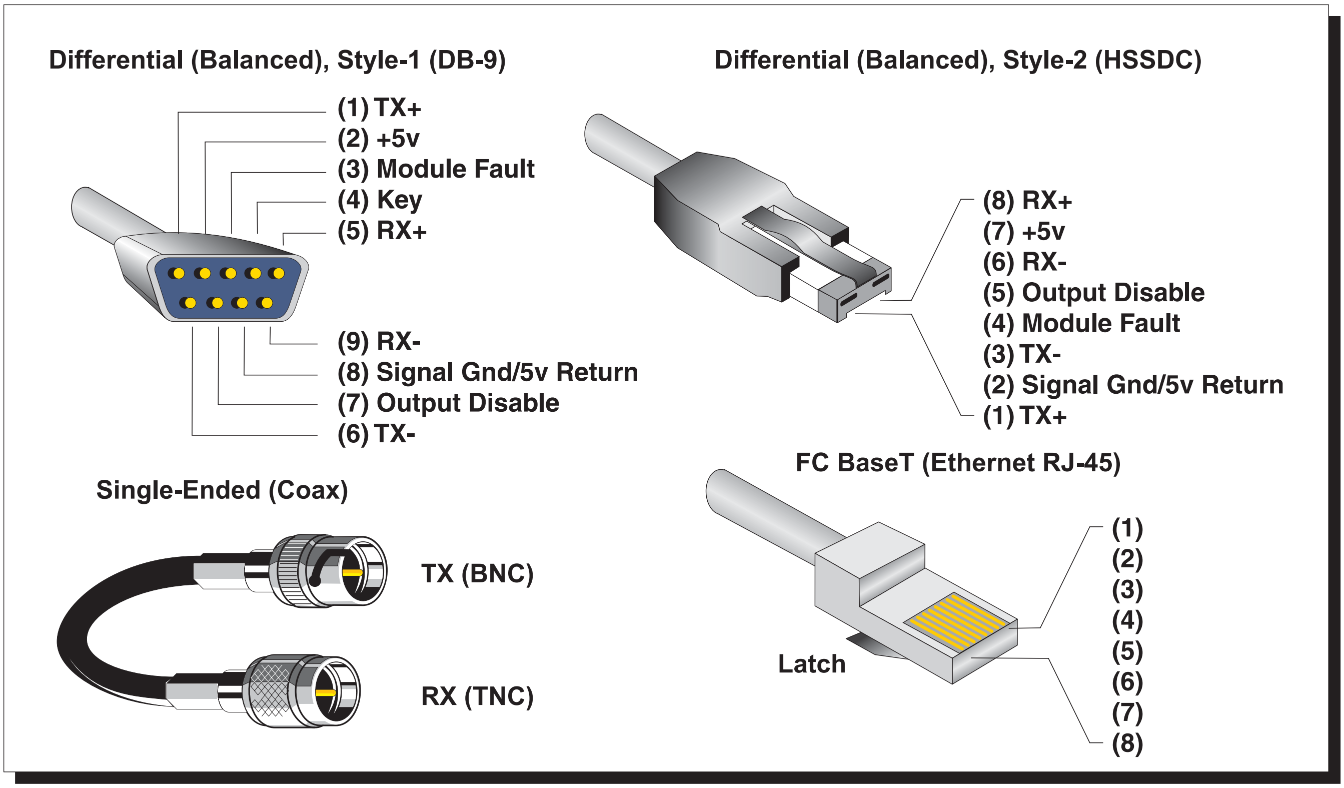

Figure 43. Connectors for Electrical Interfaces

5.4.2 Differential Electrical Connectors

Differential transmission line, either shielded twisted pair or twinax (twinaxial) cables contain four active conductors and a shield. Between the two ends of the cable, a crossover occurs so that the transmit pair at one end of the cable is connected to the receive pair at the other end.

The initial connector specified for use with balanced transmission lines was the industry standard DB-9 connector conforming to IEC 807-3. This connector is referred to as the style-1 connector. Pins 1 and 6 are used for the transmit pair and pins 5 and 9 for the receive pair. The connector shell is connected to the cable shield.

To provide a higher-density connector options, FC-PH-3 added a second connector, referred to as the Style-2 connector in the standards. This connector is based on the AMP High-Speed Serial Data Connector (HSSDC) design.

5.4.3 FC BaseT Connector

FC BaseT links use the standard RJ-45 Ethernet connector and category 5e, 6 or 6a cables.

5.4.4 Fibre Channel SCA-2 Disk Drive Connector

Fibre Channel disk drives use an integrated 40-position SCA-2 connector. The connector contains all of the drive’s signal and power connections in a single connector. This connector is designed for hot swap applications and provides guide pins with early ground mating for ESD discharge. A photograph of a Fibre Channel disk drive and the SCA-2 connector is shown in Figure 44 on page 72.

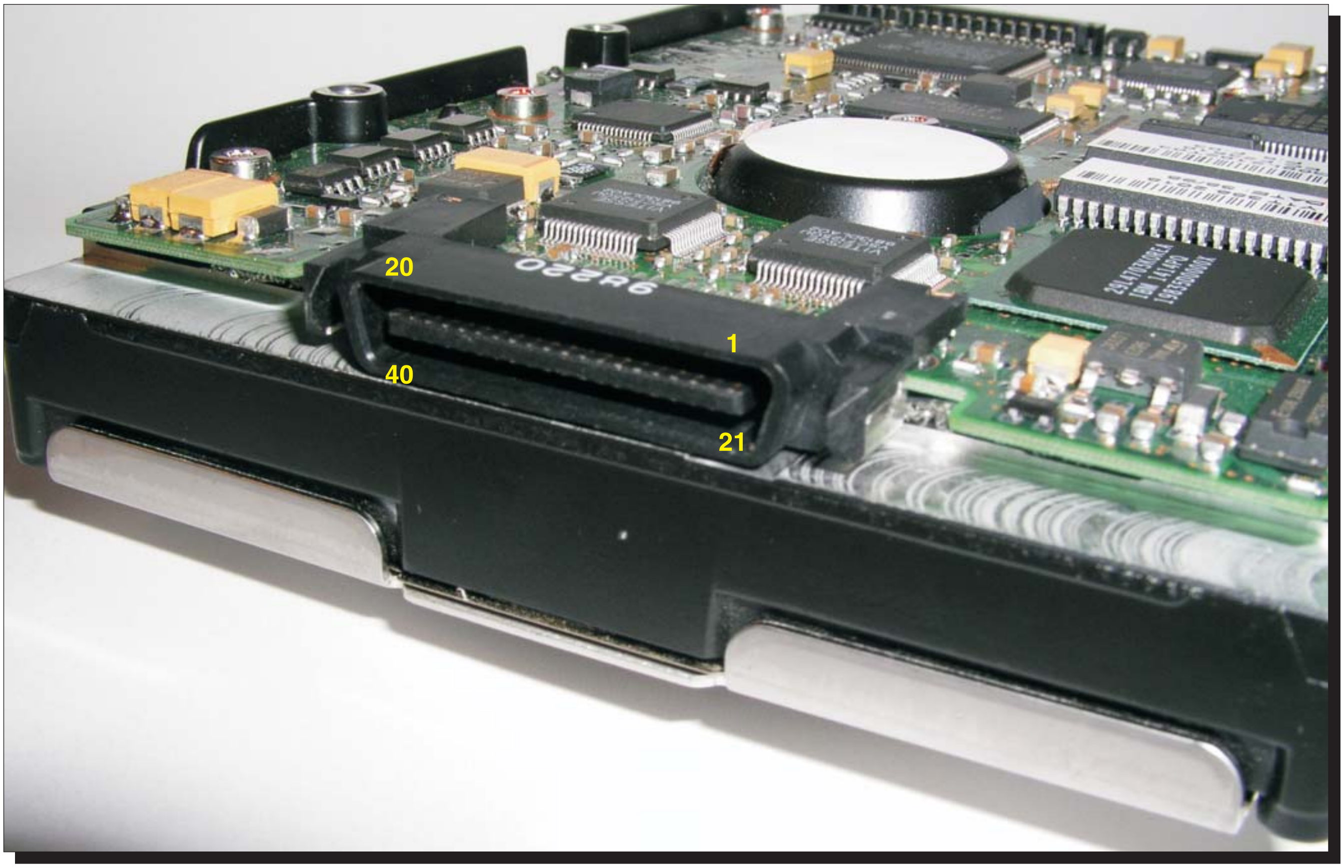

Figure 44. SCA-2 40-Pin Disk Connector

In addition to the power, ground and Fibre Channel signal lines, the connector contains several control signals. Table 4 on page 73 lists the SCA-2 connector pinout.

ENBL Bypass CH1 and CH2. These signals enable to drive to control an external port bypass circuit (PBC). These signals are used on an arbitrated loop to bypass a non-functional drive.

Power Control. When this optional signal is asserted by a backplane and supported by the drive, 5v and 12v power is supplied to the drive circuitry. When negated, power is removed from the drive circuitry.

Ready LED. The Ready LED signal is used to indicate the state of the device.

1. If the drive is not mated, the signal is not asserted and the LED is off.
2. If the drive is mated, but not spinning, the signal is asserted when a SCSI command or Task Management Function is received by the drive. The LED is mostly off but presents and indication when a command is received.

Pin	Signal Name	Pin	Signal Name
1	-EN Bypass Port A	21	12v Charge
2	12v	22	Ground
3	12v	23	Ground
4	12v	24	+Port A_In
5	-Parallel ESI	25	-Port A_In
6	-Drive Present (connected to drive's ground)	26	Ground
7	Ready LED out (bidirectional signal)	27	+Port B_In
8	Power_Control	28	-Port B_In
9	Start_1 / Mated	29	Ground
10	Start_2 / Mated	30	+Port A_Out
11	-EN Bypass Port B	31	-Port A_Out
12	SEL_6 / -EFW	32	Ground
13	SEL_5 / -P_ESI_5	33	+Port B_Out
14	SEL_4 / -P_ESI_4	34	-Port B_Out
15	SEL_3 / -P_ESI_3	35	Ground
16	Fault LED Out (bidirectional signal)	36	SEL_2 / -P_ESI_2
17	DEV_CTRL_CODE_2	37	SEL_1 / -P_ESI_1
18	DEV_CTRL_CODE_1	38	SEL_0 / -P_ESI_0
19	5v	39	DEV_CTRL_CODE_0
20	5v	40	5v Charge

Table 4. FC Disk 40-Pin SCA-2 Connector Pinout

3. If the drive is mated and in the process of spinning up, the signal is asserted so that the LED alternates between on and off at a 0.5 second rate.
4. If the drive is mated and ready, the signal is asserted continuously, except when a SCSI command or Task Management Function is received. The LED is mostly on but presents and indication when a command is received.

Start / Mated Controls. The motor Start / Mated signals control the drive motor spin-up behavior as described in Table 5 on page 74. A backplane may optionally assert case 1 shown in the table to signal the drive to prepare for removal.

Parallel ESI. The Parallel ESI is an optional input specifying how the drive should interpret the SEL_ID inputs. When this signal is asserted, the SEL_ID inputs are interpreted as enclosure status information. When this signal is not asserted, or not supported, the SEL_ID inputs are interpreted as the Hard Address to be requested during loop initialization.

Drive_CTRL_CODE. These inputs provide encoded values used to control the drive and signal the link rate. Following completion of power-on reset and a 250 msec. delay, the

Case	Start_2/Mated	Start_1/Mated	Behavior
1	OPEN	OPEN	Drive is not mated - no spin-up will occur.
2	OPEN	GROUND	Drive is mated. After a 250 msec. delay, the drive will spin up after a SCSI START command is received.
3	GROUND	OPEN	Drive is mated. After a 250 msec. delay, the drive will spin up after a delay of 12 x the modulo(8) value of the SEL)ID.
4	GROUND	GROUND	Drive is mated. After a 250 msec. delay, the drive will spin up after completion of it reset and POST functions.

Table 5. Start/ Mated Signal Behavior

drive samples these inputs to determine the link rate. Subsequently, it samples these inputs at least once a second to detect a changed link rate of power failure warning.

Value	Behavior
7	1.0625 Gbit operation
6	2.125 Gbit operation
5	4.250 Gbit operation
4	8.500 Gbit operation
3:1	Reserved
0	Power Failure Warning

Table 6. Start/ Mated Signal Behavior

5.5 RFI and EMI Considerations

Due to the high frequencies associated with Fibre Channel links, attention must be given to the potential for radio frequency interference (RFI) resulting from signal leakage of Fibre Channel cables, connectors, and associated logic. Various regulatory agencies have set strict standards on the amount of energy emitted at specified frequencies. The data rate of a Fibre Channel link is rich in radio frequency components. The signal contains strong harmonic components, especially the odd-order harmonics. Balanced transmission lines offer superior performance in regards to radiated energy because the signals in the two lines tend to cancel one another and it is not surprising balanced transmission lines predominate.

All electrical cables specified for use in Fibre Channel are shielded to limit the amount of radiated energy. In most cases, a single level of shielding is not sufficient to adequately contain the leakage below acceptable levels and most external cables are double shielded. Another potential source of radio frequency signal leakage is the connectors associated with the cables. Grounding of the cable shield is accomplished by the shell of the connector. The DB-9 connector was not originally designed for use at these frequencies and the shell may not provide complete grounding around its circumference. In addition, the relatively large plastic center insulator (that holds the contacts) results in another potential source of leakage.

5.6 Chapter Summary

Electrical Links

- Optical fiber got much of the early attention in Fibre Channel
- However, there is significant use of electrical links
  - Electrical links are lower cost than optical
  - Electrical links are easier to use in many applications, such as disk arrays
- The distance achievable with Electrical links is less than optical
- Users need to trade off the cost savings versus the distance limitations

Electrical Links

- There are three kinds of electrical links
- Single-ended links
  - Use standard coaxial cable
  - Single-ended drivers and receivers
  - Single-ended links are not generally used due to RFI problems
- Differential links
  - Uses balanced transmission lines
  - Shielded twisted pair, twinax cable (a coaxial cable with two center conductors)
  - Differential drivers and receivers
- FC-BaseT links

FC BaseT

- FC-BaseT completed in late 2006
- Uses existing Ethernet cables and connectors
  - Provides a low-cost cabling infrastructure
  - Familiar to network installers
  - Users can install cables and connectors
- FC BaseT uses a different modulation scheme
  - 8-Level Pulse Amplitude Modulation (PAM-8)
  - Each PAM-8 symbol = 2.75 bits
  - Each word consists of 12 symbols
- Symbols are sent via four bidirectional signal pairs in the cable
- Technology is based on Ethernet 1000BASE-T

Cable and Connector Losses

- Cables and connectors cause signal loss and distortion
  - Cables attenuate high-frequencies
  - Cable and connector losses reduces signal levels
  - Cable capacitance causes inter-symbol interference
  - Can result in an excessive error rate
- Two main approaches to countering cable loss and distortion
  - Transmitter de-emphasis
  - Equalization

Transmitter De-Emphasis

- Modify the transmit signal waveform to compensate for cable distortion
  - Cable capacitance stores charge as bits are sent
  - More consecutive bits of the same polarity, the greater the stored charge
  - Next bit of opposite polarity must overcome this stored charge
- Send first bit after a transition at full amplitude
  - Send subsequent bits at a lower amplitude
  - Reduces the amount of stored energy a bit must overcome

Equalization

- Electrical cable plant causes high-frequency signal loss
- Equalization compensates by either:
  - Introducing a corresponding amount of low-frequency attenuation (done in the cable), or
  - Boosting the high-frequency components of the signal (done in the receiver)
- Improves the eye opening for marginal signal conditions

Coupling

- Electrical links can be either capacitor or transformer coupled
- Capacitive coupling:
  - Is lower cost and provides higher signal levels
  - Although, may limited to inside an enclosure
- Transformer coupling:
  - Provides better noise immunity
  - May be used outside the enclosure

Electrical Connectors

- Different style connectors are used for single-ended and differential interfaces
- Single-ended uses coaxial connectors:
  - BNC and TNC
  - SMA connector
- Differential connections use:
  - DB-9 (most common at 1 Gbps)
  - High-speed serial data connector (HSSDC)
  - SCA-2 connector for disk drives
- FC BaseT
  - Standard RJ-45 Ethernet connector

RFI and EMI

- Electrical interfaces create radio frequency interference (RFI)
- Regulatory agencies (FCC) limit the amount of RF that a product can emit
- Designers need to be sensitive to RFI issues due to the high-frequency components associated with Fibre Channel's data rates
  - Fundamental frequency is 531 MHz (for a 1.0625 Gbps link)
- Also, electrical transmission lines are susceptible to induced interference (EMI)
- Careful attention to layout and shielding is necessary