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SYSTEM DESIGNERS CAN USE RECEIVER EQUALIZATION TO EXTEND RS-485 DATA TRANSMISSION WITH LONGER CABLE AND HIGHER SIGNALING RATES.

Equalization enhances RS-485 links

RS-485 DATA TRANSMISSION, conforming to the ANSI TIA/EIA-485-A standard, is a common method of communicating data across distances as far as 1200m at signaling rates as high as about 30 Mbps. The nonideal characteristics of the typical twisted-pair network force a trade-off between signaling rate and transmission distance. However, system designers often must push the boundaries of these constraints. In a typical RS-485 application, losses due to the cable dominate the characteristics of the interconnection chain. This situation is especially true for applications that use long cables at moderate signaling rates. The magnitude and frequency of the signal losses depend on the cable characteristics. In general, the attenuation increases with frequency, so the losses significantly reduce high-frequency content. At a high level, the BER (bit-error rate) specifies performance in number of errors per bits transmitted. Testing involves observing the data at the receiver while stimulating the driver with a known data pattern. Another common measure is the "eye-pattern," which displays the transceiver- and cable-induced signal effects on a stream of data bits. The eye pattern can illustrate and contrast receivers with and without receiver equalization.

One straightforward option is to invest in the best available cable with low losses. Several books and cable manufacturers offer detailed technical data, including curves of attenuation versus frequency for various cable types (**references 1** to **6**). However, other factors, including cost, size, and weight, are often competing with signal fidelity when you select cable. Beyond these factors, many applications are forced to use existing cable. If you are replacing the electronics on an installed network, the cost of upgrading the cable infrastructure may be prohibitive. Similarly, if you are expanding network, the new cable should be compatible with the existing installation. These situations may constrain a network designer to use cable other than the best cable for optimum signaling performance.

In theory, several methods can compensate for the degraded signal components, reproducing the significant features of the intended signal. If you are to transmit a signal *s*(-) through a medium with loss characteristics *l*(-), the resulting signal *s*'(-) will be a distorted version of the original signal. If there is some function that can invert, or undo, the effect of the transmission medium, then you can recover the original signal. The goal is to find and implement the function *m*(-)=1/*l*(-) as effectively as possible. Part of this approach involves choosing whether to precompensate at the driver end, such as with driver pre-emphasis, or whether to apply a recovery method at the receiver end, as with receiver equalization.

HIGH-FREQUENCY BOOST

Driver pre-emphasis alters the signal at the source to boost the high-frequency content. If the attenuation characteristics of the cable are known, theoretically, the pre-emphasis can exactly compensate for the cable losses. One method of pre-emphasis is the time-domain technique of boosting the drive-signal amplitude for a short period at each transition (**Reference 7**). Another method is the frequency-domain technique of adding tuned highpass filters to the

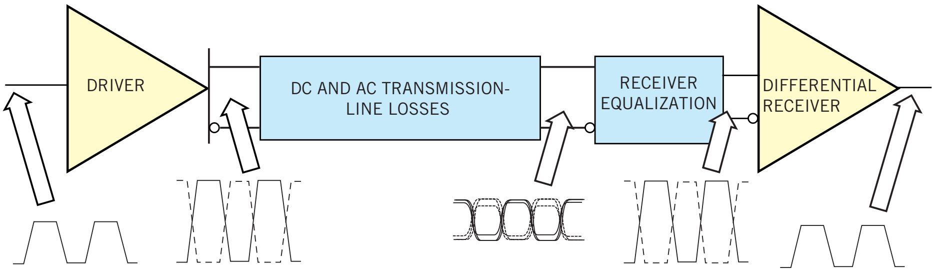


Figure 1

Receiver equalization restores the characteristics of the original signal.

driver. Driver pre-emphasis has limitations. First, the correct amount of emphasis needed is typically unknown, so overemphasis or underemphasis is common. A second limitation for RS-485 applications is that the signal with driver pre-emphasis may not conform to the TIA/EIA-485-A standard, which allows less than 10% overshoot during signal transitions. A third issue is the increase in high-frequency electrical noise emissions from a signal with pre-emphasis. This issue is of special concern in situations in which EMC (electromagnetic-compatibility) requirements restrict the generation of emissions.

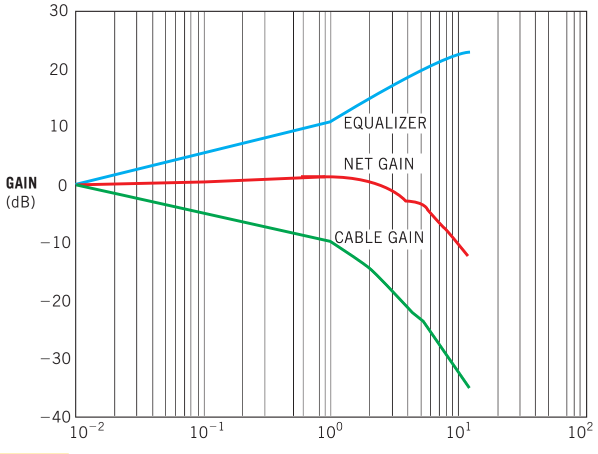


Figure 2

In this cable-loss-and-equalizer design example, you can approximate receiver equalization with a finite number of poles.

Receiver equalization restores a signal's high-frequency components, which media losses may preferentially attenuate. This method occurs at the receiver and equalizes the relative amounts of signal across all frequencies of interest. Previous discussions have described receiver equalization for high-speed backplane applications (**Reference 8**); the interest here is in slower, long-cable applications. **Figure 1** illustrates the concept of receiver equalization. The driver can be any standard RS-485 differential transceiver. After passing through the transmission line, the signal has been attenuated according to the frequency-dependent characteristics of the cable. If the receiver equalization is well-tuned to the cable losses, you can restore the original signal at the receiver. An advantage of receiver equalization is that the impact is limited to the receiving end of the bus. You can use receiver equalization in an existing system with no effect on the bus-signal levels.

A few other techniques compensate for cable loss. The simplest one is to increase the receiver's sensitivity. However, this method implies that all frequencies will be gained by the same factor. Therefore, the receiver with higher gain will be more sensitive to noise across its entire bandwidth. Another option is to encode the data with the aim of shifting the frequency content of the signal. You sometimes employ this method using Manchester or 8B10 encoding, which codes the data to give zero dc content. In many RS-485 applications, however, there may be protocol restrictions on data coding. In other applications, hardware limitations may make the higher signaling rate required infeasible.

IMPLEMENTING EQUALIZATION

You can implement receiver equalization using several approaches. You can use passive filters, made entirely of resistive, capacitive, or inductive elements, or all three to make a frequency-selective filter. Typically, the filter attenuates low-frequency components but leaves the high-frequency components, which are already attenuated by the cable, intact. This method will produce an overall flat response. The disadvantage is that the resulting signal levels are attenuated for all frequencies, providing less signal energy overall.

Active filters, using discrete transistors or operational amplifiers, can overcome the signal-loss limitations of passive filters. Using proven filter-design techniques, you can design an appropriate highpass filter to compensate for high-frequency losses in the cable. The design parameters for any application will be the order of the filter, the shape of the filter, and the critical frequencies. Transmission-line-theory models the cable as an infinite series of RLC (resistor-inductor-capacitor) elements, which leads to a frequency-domain model of the cable as a lowpass filter with an infinite number of poles. In practice, you can approximate the cable attenuation and, therefore, the corresponding receiver equalization with a finite number of poles. For example, you can approximate the attenuation of 500m of cable with a third-order lowpass function (**Figure 2**). For frequencies as high as 10 MHz, the third-order approximation is relatively accurate. If you know or can estimate the characteristics of the data-transmission channel, you can design an appropriate equalization function to compensate for the losses over the frequency range of interest. Note that the net gain (cable plus equalizer) is relatively flat for frequencies to about 1 MHz.

RS-485 presents additional challenges in designing a receiver-equalization stage, due to the signaling rate, balanced differential signaling, and the wide com-

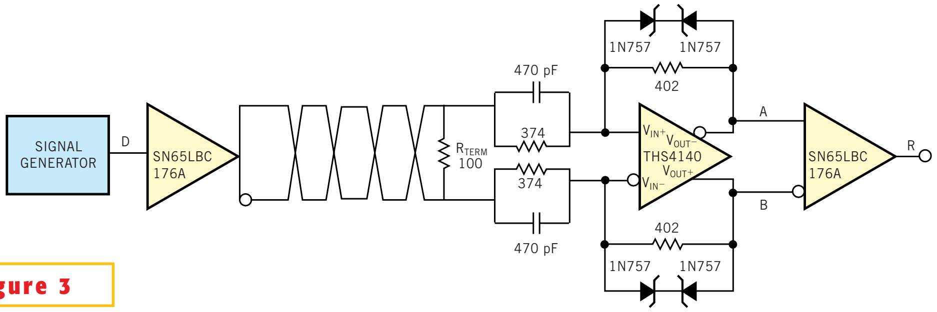


Figure 3

A highpass filter and the THS4140 differential operational amplifier form a single-pole receiver-equalization stage.

mon-mode range that the TIA/EIA standard specifies. The THS4140 high-speed, fully differential operational amplifier is one option. It offers true differential inputs and outputs, with unity-gain frequency response as high as 160 MHz. The common-mode input range for the THS4140 is up to ±15V, which accommodates the RS-485 range of −7 to +12V. Designing a differential highpass filter creates a single-pole receiver-equalization stage (**Figure 3**). Note that a designer selects R and C values for highpass characteristics that match the cable attenuation to be equalized. In this example, the components give a highpass corner frequency near 1 MHz.

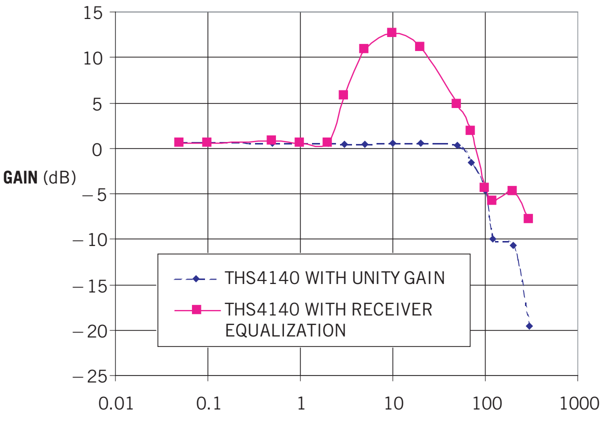


Figure 4

The frequency response of the THS4140 receiver-equalization stage reduces sensitivity to high-frequency noise.

Some off-the-shelf RS-485 transceivers integrate receiver-equalization features. For example, the SN65HVD23 and SN65HVD24 from TI have receiver equalization based on third-order active filters. The critical frequencies have been designed to match particular application ranges. The HVD23 is optimized for signaling rates of approximately 25 Mbps with cable lengths up to 200m. It targets applications with relatively high signaling rates that need moderate cable length. Examples of such applications include industrial networks operating at 12 Mbps and motion-control applications, in which faster signaling rates correspond to higher allowable positioning resolution. The HVD24 is optimized for signaling rates of approximately 5 Mbps with cable lengths reaching 500m. Relevant applications include building automation and security networks.

TEST RESULTS

To compensate for the high-frequency losses through the cable, the receiver-equalization stage must have increased gain for these frequencies of interest. **Figure 4** shows this gain and illustrates how you use the inherent bandwidth of the THS4140 operational amplifier to roll off the high-frequency gain, reducing the sensitivity of the receiver-equalization stage to high-frequency noise. The oscilloscope traces in **Figure 5** illustrate the benefits of adding a receiver-equalization stage. In each case, the top trace is the driver output of an SN65LBC176A, switching according to a pseudorandom sequence. The bit time is 100 nsec, corresponding to a signaling rate of 10 Mbps. The middle trace is the input to a receiving LBC176A, and the bottom trace shows the output of the receiver. **Figure 5a** shows that with 1m of cable, you can reliably sample the signal for most of the bit time. Little signal degradation has occurred through the short cable. In **Figure 5b**, the cable length is 300m. Note that the long cable has significantly degraded the eye pattern. You can reliably determine the received signal (bottom trace) during only about 20% of the bit time. During the other 80% of the bit time, the data may still be transitioning between states. In **Figure 5c**, receiver equalization improves the eye pattern. Note that you can determine the receiver output signal with receiver equalization during about 80% of the bit time.

Figure 6 illustrates the benefits of integrated receiver equalization as implemented in the HVD24 transceiver, compared with the performance of the HVD21 (without receiver equalization). Other than the receiver-equalization feature, these transceivers are similar. In the test setup, a differential signal generator applied a signal voltage at one end of the cable, which is Belden 3105A shielded twisted-pair. Channel 1 (top) shows the eye pattern of the PRBS (pseudorandom bit stream) of NRZ (non-return-to-zero) data. Channel 2 (middle) shows the eye pattern of the differential voltage at the receiver inputs after the cable attenuation. Channel 3

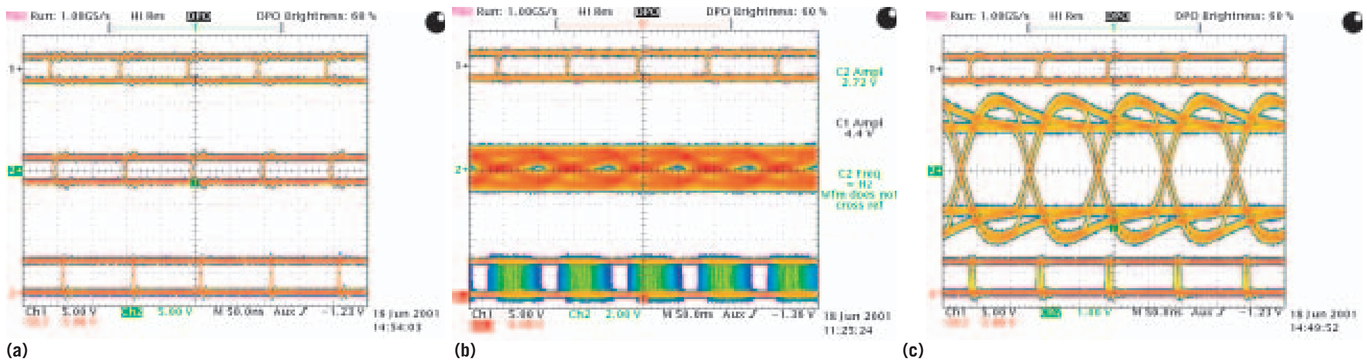
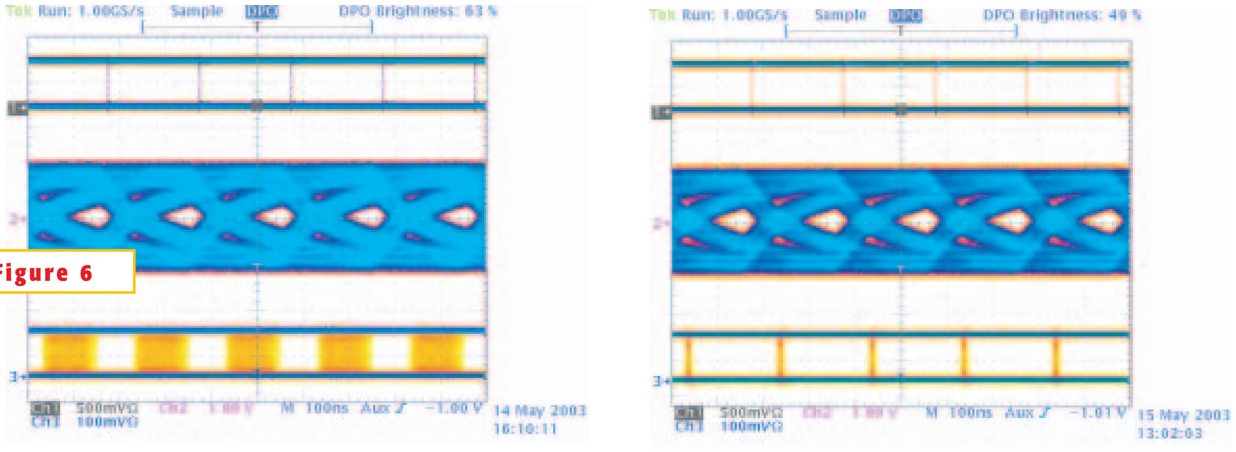

(a)
(b)
(c)

Figure 5

Eye patterns show cable compensation after 1m with no equalization (a), 300m with no equalization (b), and 300m with THS4140 equalization (c).

Figure 6

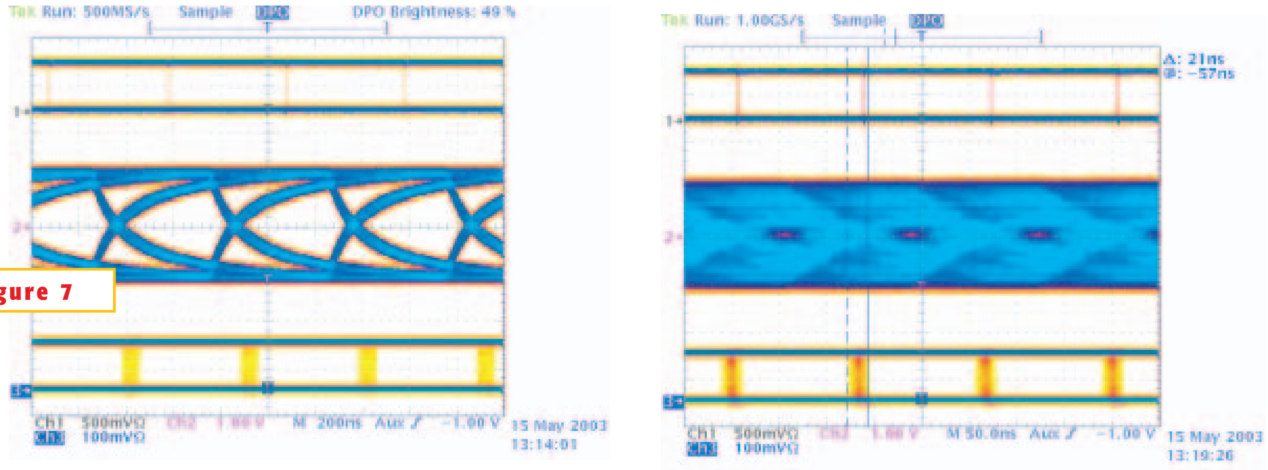


(a)

(b)

Oscilloscope patterns show RS-485 signaling through a 500m cable at 5 Mbps without receiver equalization (a) and with receiver equalization (b).

Figure 7



(a)

(b)

Integrated equalization allows faster RS-485 data signaling though a 500m cable at 2 Mbps without receiver equalization (a) and 7.5 Mbps with receiver equalization (b).

(bottom) shows the receiver output.

Without receiver equalization, there is about 50% jitter on the receiver output (**Figure 6a**). With receiver equalization, the jitter is less than 10% (**Figure 6b**). Performing BER testing for two typical RS-485 cases, using transceivers with and without receiver equalization, shows that the systems with receiver equalization communicated at a significantly higher data rate than nonequalized transceivers, with no errors (**Table 1**).

EQUALIZATION LIMITATIONS

As with any other advanced feature, receiver equalization has limitations. The effectiveness depends on knowledge about the data-transmission system. There is no magic in recovering data from attenuated signals. Receiver equalization simply uses the designer's knowledge about the expected signal, including its voltage levels and signaling rate, and about the communications channel, including the cable properties, length, and attenuation. Receiver equalization produces significant benefits only with the system designer's intelligent judgment on these factors.

One issue to consider is whether the

TABLE 1–RESULTS OF BER (BIT-ERROR-RATE) TESTING

	Highest signaling rate with no errors		
Case	Without receiver equalization	With receiver equalization	Note:
150m cable	41 Mbps (HVD20)	73 Mbps (HVD23)	Testing with an Agilent 81250 Parallel BER Tester with a $2^{15}-1$ PRBS (pseudorandom-bit-stream) differential signal. All testing at nominal conditions of temperature and V_{CC} with Belden 3105A cable.
500m cable	5 Mbps (HVD21)	17 Mbps (HVD24)	

receiver's increased sensitivity to high-frequency signals can cause excessive response to electrical noise. Ideally, the filter response would match only the needed frequency band. The filter responses of the HVD23 and HVD24 are relatively narrow, but they still give some degree of latitude in signaling rate. Because the equalizing filter must be limited in bandwidth, the system designer must select the proper equalization for the application. Typically, the system signaling rate is within some predefined range, so knowledge of the critical frequencies are at least somewhat established. Even with an appropriately designed frequency range, receivers with equalization exhibit more sensitivity to electrical noise than nonequalized receivers. To counter this effect, the HVD23 and HVD24 receivers have higher levels of input hysteresis than typical receivers. The hysteresis keeps the receiver from changing state in the presence of small differential noise.

A typical factory-automation-network application illustrates the benefits of receiver equalization. In a large factory, users may need to install controllers, sensors, and actuators as far as 500m from the HMI (human/machine-interface) station. Without receiver equalization, signaling rates of only about 2 Mbps may be possible, depending on system design, quality of cable, and other factors. **Figure 7** illustrates this situation, in which the high-frequency attenuation is evident in the differential signal (middle trace) but the receiver output signal (bottom trace) has acceptable jitter. Using an HVD24 transceiver can raise the signaling rate to 7.5 Mbps (**Figure 7b**). Note that, although the differential signal is degraded, the receiver output is acceptable, comparable with the 2-Mbps case without receiver equalization. This significant increase allows more throughput on the network, enabling faster system response for critical functions.

Another application is building automation for HVAC or security functions, in which distance extension is beneficial. For networks with a signaling rate of 5 Mbps, you could extend the maximum length from 150 to 500m using receiver equalization, realized discretely or with the HVD24.

Finally, any application in which cable-cost reduction is a benefit should evaluate receiver equalization. Consider a building-automation example, in which the installed cable is adequate for supporting signaling up to 500 kbps. Suppose you are to upgrade electronics with additional functions for increased energy efficiency, such as thermostats, lighting control, and other functions, and better security, such as motion detectors, audio sensors, badge readers, and other devices. To support these features, the network may require signaling at 1 Mbps or higher. The cost of upgrading the cable for the higher signaling rate would include labor, downtime, material costs, and other expenses. If you could use receiver equalization to reduce this cost, the benefits would be substantial. ☐

REFERENCES

1. Harper, Charles A, Editor, *Handbook of Wiring, Cabling, and Interconnecting for Electronics*, McGraw-Hill, New York, 1972.

2. Crisp, John, *Introduction to Copper Cabling*, Newnes (Elsevier Science), Oxford, 2002.

3. Belden Wire and Cable Co, www.belden.com.

4. CommScope, www.commscope.com.

5. General Cable Corp, www. generalcable.com.

6. Madison Cable Corp, www.madisoncable.com.

7. Salazar, Ted and Larry Suppan, "Pre-emphasis improves RS-485 communication," *EDN*, July 10, 1999.

8. Zheng, Dong, "Receiver equalization increases link distance without adding EMI," *EDN*, March 6, 2003.

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