Keywords: RS-485,rs485, EIA/TIA-485, data transceiver, preemphasis, pre-equalization, equalization,Long-Distance RS-485, High-Speed RS-485

APPLICATION NOTE 643

PRE-EMPHASIS IMPROVES RS-485 COMMUNICATIONS

Abstract: Driver preemphasis extends the distance and increases the data rate of reliable RS-485 communication by reducing intersymbol interference (ISI) caused by long cables. The original application note was published to explain the principles of preemphasis and in Appendix A demonstrate MAX3291 and MAX3292 products. The introduction of new products MAX22500E and MAX22502E extend RS-485 performance to 100Mbps, and these new products are described in Appendix B to show how Maxim continues to expand the applications and use of popular RS-485 transceivers.

Signal-transmission systems contend with two major obstacles: losses that reduce the signal amplitude and energy storage that alters the signal's shape. A signal-transmission system is the electrical channel between an information source and its destination (**Figure 1**). Preepmhasis is applied at the source of a transmitted signal, before the electrical channel, and improves the signal quality at the destination. Reemphasis reduces noise and distortion by increasing the magnitude of some frequency components. To restore the signal and improve the SNR, a system usually follows preemphasis by its converse: deemphasis.

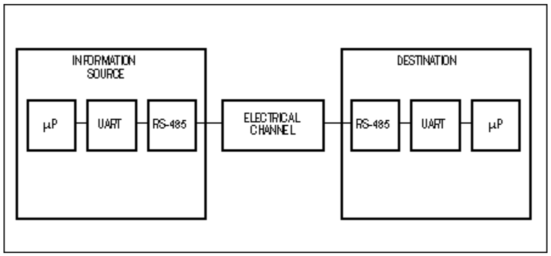


Figure 1. A signal-transmission system includes the electrical channel between the information source and its destination.

Many applications use preemphasis techniques. In IC-layout programs, for instance, preemphasis adjusts the line widths to compensate for etch-rate variations that occur around corners. In disk-drive controllers, preemphasis compensates for poor frequency response near the center of the disk. Another type of preemphasis, Dolby B, reduces tape hiss by boosting low-level signals in the middle- and high-frequency audio bands when recording and then reversing this process during playback.

Distance vs. Data Rate

You can also apply preemphasis techniques to RS-485 communications. Most RS-485 users want to know the answer to one crucial question: How far can you reliably transmit and receive data at a specified data rate? The EIA/TIA-485 standard requires that RS-485 transceivers be able to transmit and receive data across up to 4000ft/1219m and at 10Mbps, but not, necessarily, at the same time. Traditionally, the trade-off has always been less distance at a higher rate or greater distance at a lower rate.

Preemphasis does not allow you to run high speed data across very long distances, like 4000ft/1219m, but it can considerably improve the situation (**Figure 2**). RS-485 transceivers without driver preemphasis or receiver equalization generally attain 10% jitter across 11700ft/518m at a fixed data rate of 1Mbps. At that data rate, adding driver preemphasis allows you to double the distance to 3400ft/1036m without noticeably increasing the jitter. Similarly, preemphasis can increase the data rate for a fixed-cable distance. Non-preemphasis parts operating at 400kbps generally attain 10% jitter over 4000ft/1219m. Adding preemphasis enables you to transmit as much as 800kbps for this distance.

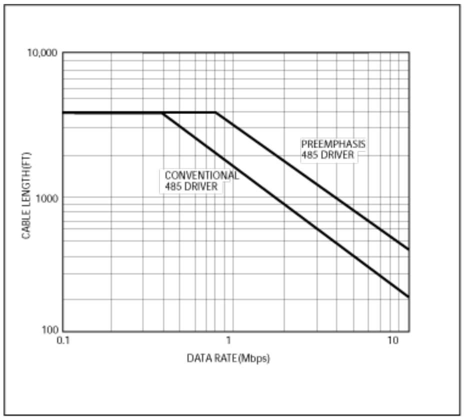


Figure 2. At 10% jitter, preemphasis enables a greater transmission distance.

IR Losses and Jitter Impose Limits

The two major limitations on the maximum length for a given type of transmission line in RS-485 communications are: (1) current-times-resistance (IR) losses and (2) signal jitter. Transmission-line resistance is usually negligible relative to the termination resistance at the end of the line. However, when transmission lines are greater than 4000ft/1219m, you can no longer ignore the line resistance. IR losses result from the resistor-divider created by the cable resistance and the termination resistor. These losses diminish the signal magnitude by -6dB (typically) at 4000ft/1219m (down 50%) for a PVC-insulated, #24 AWG twisted-pair cable with a characteristic impedance of 100Ω.

Signal jitter is primarily due to intersymbol interference (ISI). ISI is the net effect of several causes of signal degradation, including the attenuation and the dispersal of frequency components that result from signal propagation down a transmission line. The variation of rise and fall times that follow the varying sequences of ones and zeros known as "pattern-dependent skew" also contributes to ISI. A data pulse responds to these effects with a loss of amplitude, displacement in time, rounded edges, and a "smearing" of the pulse into adjacent time slots, or unit intervals.

For a fixed amount of jitter (10%, for example, as shown in Figure 2), the cable-length-versus-data-rate curves exhibit a "breakpoint" that represents the cable's bandwidth at the receiving end after 4000ft/1219m. This breakpoint occurs at data-rate values that depend on the shape and the slew rate of the signal at the transmitting end. Because of the cascaded lumped-element network of the cable, the rolling-off slopes are identical.

One way to extend distance for a given data rate, then, is by reducing the effect of the jitter that ISI causes. The preemphasis line in Figure 2 shows this type of reduction: preemphasis pushes the curve to the right, enhancing reliable communications by increasing the allowable maximums for data rate and transmission distance.

To fully understand how preemphasis works, let's analyze the technique in both the time and the frequency domains. First, consider ISI and preemphasis in the time domain.

A UART determines when to sample a received data stream by looking for the first transition from one to zero. The UART then waits for one-half of a unit, or bit interval ($t_b/2$), to see whether the signal is still zero. ISI is problematic for a UART because the difference, or spread, in transition times can eventually increase the bit-error rate (BER). **Figure 3** shows the ISI, or pattern-dependent time skew, that results from three bit patterns. Data reliability decreases sharply when the total jitter on an RS-485 signal becomes more than 10% of the baud period. The cable's RC time constant, which limits the bandwidth, causes part of the jitter to depend on bit patterns in the data. This pattern-dependent ISI accounts for a majority of the jitter in an RS-485 system.

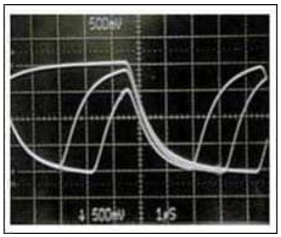


Figure 3. Intersymbol interference depends on bit patterns in the data, such as a 1111 0000 pattern (top trace), a 0011 0011 pattern (middle trace), and a 0001 0111 pattern (bottom trace).

A series of ones followed by a zero, for instance, causes the transmission-line voltage at the end of the string of ones to rise to the highest possible level, such as the level of signal 1 in **Figure 4**. A signal at this high level takes the longest time to reach the zero crossing. On the other hand, if the data pattern consists of a string of zeros followed by a one and then a zero, the one-to-zero transition (signal 2 in Figure 4) starts from a voltage much closer to the zero crossing. Therefore, signal 2 takes less time to reach the zero crossing. A signal's propagation delay depends on its preceding bit pattern; this pattern-dependent skew is ISI.

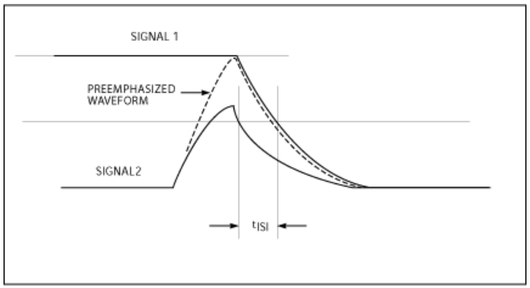


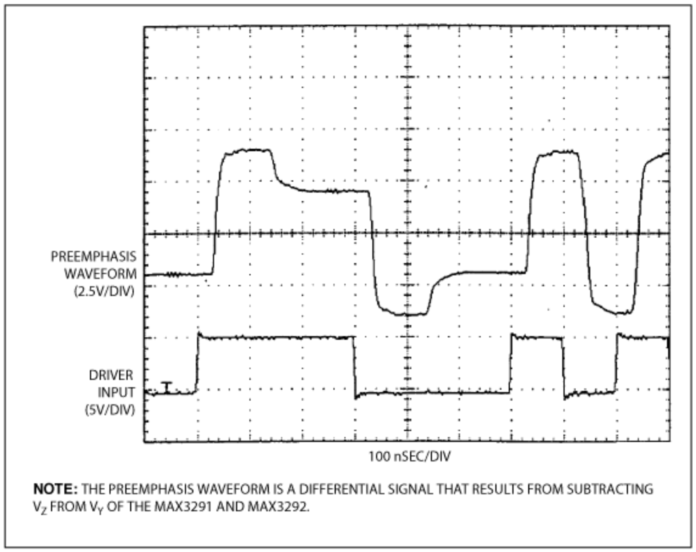
Figure 4. Adding amplitude for a specified amount of time to the waveform that results from a 0000 0010 bit pattern (signal 2) produces a preemphasized waveform (dotted line) that minimizes ISI time skew (t_{ISI}) with respect to the waveform that results from a 1111 1110 bit pattern (signal 1).

Four Voltage Levels

A preemphasis driver that incorporates four voltage levels (strong high, strong low, normal high, and normal low) counteracts this effect (see Appendix A, RS-485 Transceivers Implement Preemphasis). Preemphasis is necessary only when the data pattern changes and not during the intervals when the signal voltage remains at the same logic level. On the other hand, the need for preemphasis is constant for signals with logic-level changes at every bit interval.

If the driver input changes from logic-low to logic-high, the differential output voltage switches to a strong high. This action eliminates time skew by forcing the signal to a high-voltage level comparable with the voltage level following a constant string of ones. A typical waveform, such as the dotted line in Figure 4, demonstrates how preemphasis reduces skew by boosting the amplitude of signal 2 to that of signal 1. This strong-high level, minimizes ISI by counteracting the signal-voltage attenuation that results when a data pattern constantly changes its logic state.

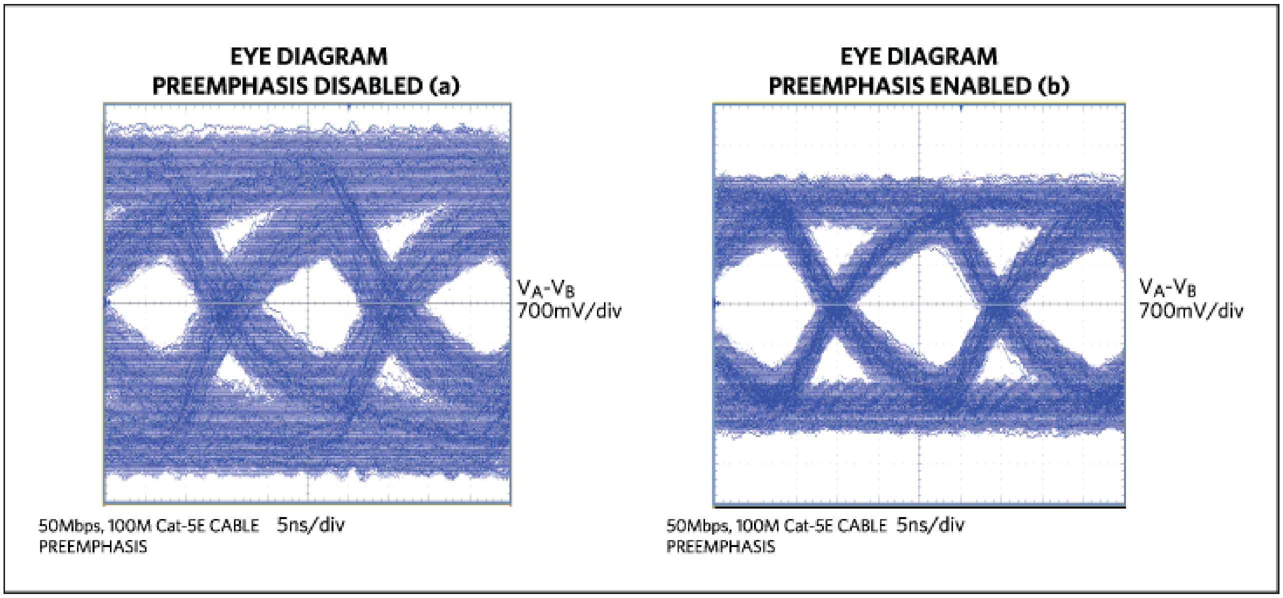
The typical differential preemphasis waveform changes with bit patterns at the driver input (**Figure 5**). For instance, if the driver input switches from logic-low to logic-high, the differential preemphasis waveform goes to the strong-high voltage level. The strong-high level returns to normal high at the end of the preemphasis interval, which in this case is 100ns. If the driver input switches back to a logic-low before the end of a preemphasis interval, the differential output switches directly from strong high to strong low. Similar but opposite output transitions occur in response to a high-to-low driver-input transition.



NOTE: THE PREEMPHASIS WAVEFORM IS A DIFFERENTIAL SIGNAL THAT RESULTS FROM SUBTRACTING V_Z FROM V_Y OF THE MAX3291 AND MAX3292.

Figure 5. The output of a differential preemphasis driver varies with logic changes at the driver input.

To quickly evaluate your circuit configuration, view an eye diagram (see Appendix B, Eye Diagrams Provide Quick Answers). Eye diagrams let you measure the total time variation, or jitter, at the differential 0V crossing, which you can then express as a percentage of one bit interval, t_b: % jitter = (total jitter/t_b)3100. Limiting this percentage to 10% generally ensures error-free operation. Typical eye diagrams illustrate the improvement in signal quality when using a preemphasis driver instead of a non-preemphasis device under the same conditions (**Figure 6**).


EYE DIAGRAM
PREEMPHASIS DISABLED (a)

EYE DIAGRAM
PREEMPHASIS ENABLED (b)

Figure 6. Eye diagrams based on 5Mbps data over 1000ft/304m feet show the advantage of using a preemphasis driver, (a) the MAX3292 in this case over a non-preemphasis industry-standard 75180 (b).

Preemphasis in the Frequency Domain

To analyze how preemphasis works in the frequency domain, consider the typical model of an infinite transmission cable, which consists of an infinite number of cascaded lumped-element LRCG networks (**Figure 7**). The R and C components cause most of the major effects in RS-485 applications, as you can easily see when viewing the differential response at the receiver input following a long cable. The cable response resembles the response of an RC lowpass filter (**Figure 8**). For practical purposes and ease of discussion, you can assume that the transmission cable acts as a simple RC lowpass filter.

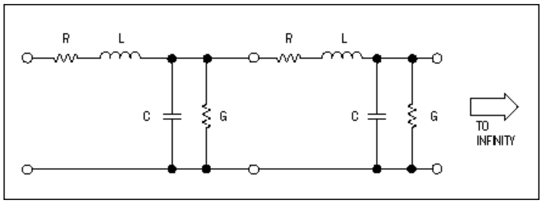
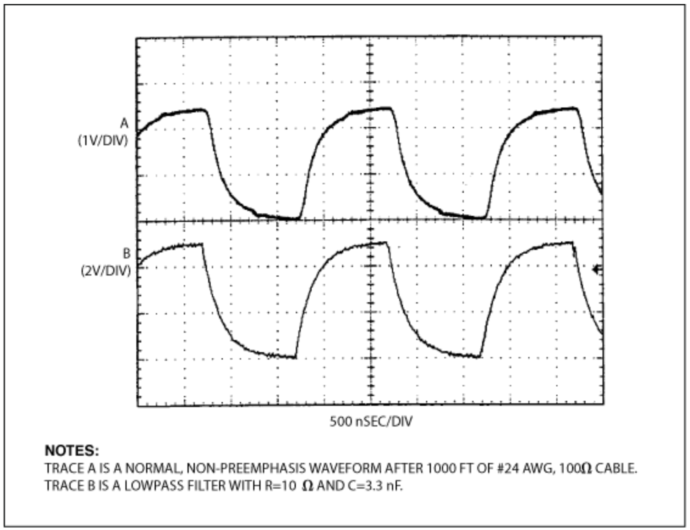


Figure 7. A standard model for a transmission line comprises an infinite number of cascaded LRCG networks.



NOTES:
TRACE A IS A NORMAL, NON-PREEMPHASIS WAVEFORM AFTER 1000 FT OF #24 AWG, 100Ω CABLE.
TRACE B IS A LOWPASS FILTER WITH R=10 Ω AND C=3.3 nF.

Figure 8. The step response following 1000 feet of cable (trace A) is similar to that of a simple RC lowpass filter (trace B).

Preemphasis adds high-frequency components to counteract high-frequency attenuation by the transmission cable. RS-485 transmitters currently transmit at two voltage levels (high and low), producing square waves with 50% duty cycle that contain only odd harmonics of the fundamental frequency (**Figure 9a**). A square wave with non-50% duty cycle (25%, for instance) produces both even and odd harmonics of the fundamental frequency (**Figure 9b**).

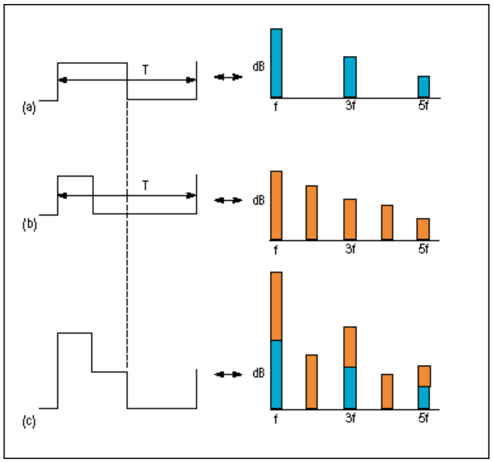


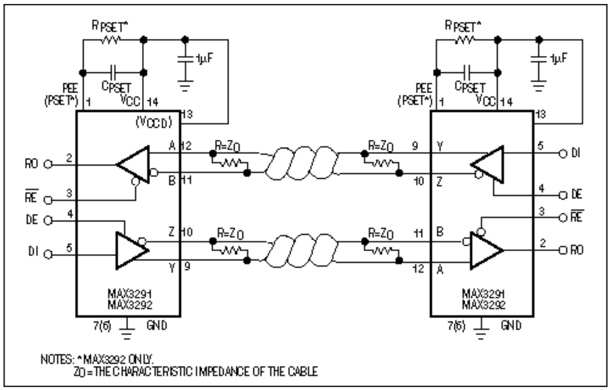
Figure 9. Adding the odd-harmonic spectrum of a 50%-duty-cycle square wave (a) to the even-odd spectrum of a 25%-duty-cycle square wave (b) forms one of the many spectra possible for a preemphasis waveform (c).

In contrast, transmitters with preemphasis, such as the MAX3291/MAX3292, generate four voltage levels, as in Figure 5. For a specified preemphasis interval, the extra levels boost the amplitude at every transition edge, producing an additional pulse in amplitude that contains both odd and even harmonics of the fundamental frequency. These odd and even harmonics of the preemphasis pulse add to the frequency spectrum of the original square wave, thereby reducing ISI by counteracting the lowpass-filter response of the cable (Figure 9c). This figure demonstrates the preemphasis-high, normal-high, and normal-low voltage levels but omits the preemphasis-low level for clarity.

Appendix A

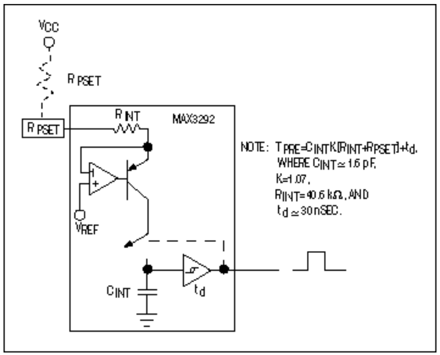
MAX3291/MAX3292 RS-485 Transceivers Implement Preemphasis

Engineers at Maxim found that ISI places the main limit on the maximum distance for RS-485 communications and that preemphasis is extremely effective in reducing this interference. Based on this finding, these engineers developed two RS-485 transceivers that incorporate internal preemphasis (**Figure A**). Each transceiver includes a timer for generating the preemphasis interval (**Figure B**).



NOTES: *MAX3292 ONLY.
Z_0 = THE CHARACTERISTIC IMPEDANCE OF THE CABLE

Figure A. RS-485 preemphasis transceivers easily fit into 75180 sockets.



NOTE: $T_{PRE} = C_{INT} K [R_{INT} + R_{PSET}] + t_d$,
WHERE $C_{INT} \simeq 1.6$ pF,
$K = 1.07$,
$R_{INT} = 40.6$ kΩ, AND
$t_d \simeq 30$ nSEC.

Figure B. Internal preemphasis timers provide for fixed or adjustable preemphasis intervals.

The MAX3291 is pin-compatible with the industry-standard 75180 and has a fixed preemphasis interval that optimizes it for data rates from 5Mbps to 10Mbps. The MAX3292 has a variable preemphasis interval, set by an external resistor between V_{CC} and PSET, that allows data rates to 10Mbps. This resistor and its corresponding capacitor are the only modifications necessary to operate the MAX3292 in a 75180 socket. The proximity of V_{CC} and PSET (pins 1 and 14) lets you implement the change with minimal effect on the circuit layout.

Appendix B

MAX22500E/MAX22502E,drive up to 100Mbps for long cables. In the years since the MAX3291/2 family first introduced integrated preemphasis up to 10Mbps, the data rates used in modern RS-485 communications have continued to increase. The MAX22500E/MAX22502E series are point-to-point, half- and full-duplex transceivers (respectively) with integrated preemphasis optimized for up to 100Mbps data rates, 10x that of the MAX3291/2.

The MAX22500E (**Figure C**) and MAX22502E (**Figure D**) feature a variable preemphasis interval for data rates up to 100Mbps, which is set by connecting a single external resistor between GND and the PSET pin. Note that, unlike the MAX3291/2 transceivers, the MAX22500E and MAX22502E do not require a corresponding capacitor, thereby simplifying the overall circuit. The logic interface is powered on a separate supply from the RS-485 transceiver, allowing for flexible logic levels between 1.8V and 5V.

The MAX22501E does not include preemphasis or a separate logic supply offering. Instead, it includes a simple and tiny high-speed RS-485 interface capable of data rates up to 100Mbps to minimize the circuit footprint.

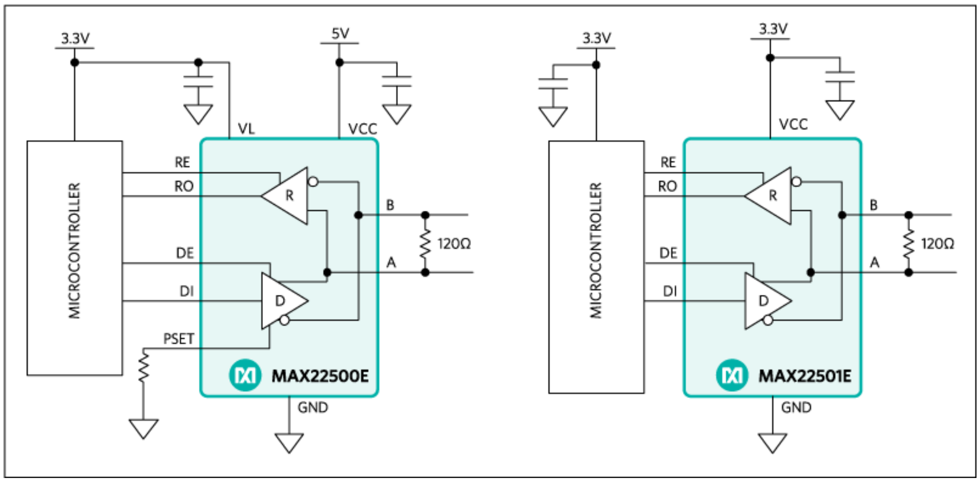


Figure C. MAX22500E and MAX22501E application circuits.

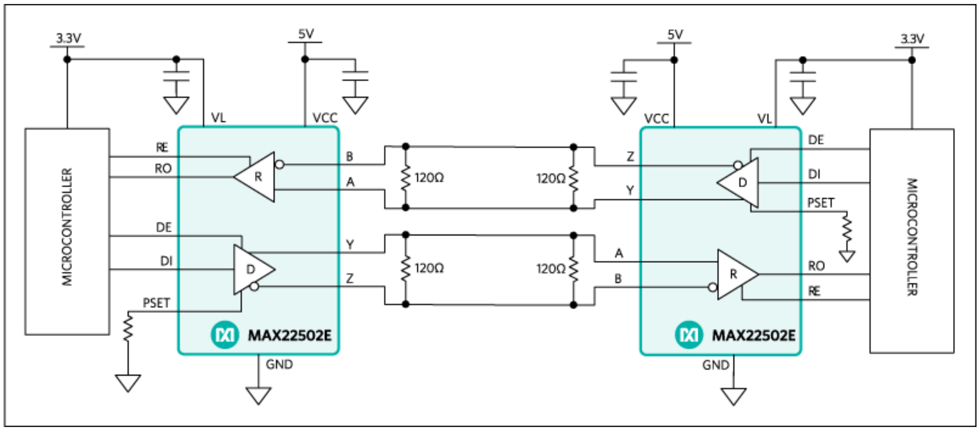


Figure D. MAX22502E application circuit.

The effectiveness of preemphasis depends on the length of the cable. If the cable is short, the cable effects on the signal are limited and there may be only minimal difference in performance when preemphasis is applied. If a very long cable is used, and the dominant cause of the signal degradation is no longer due to ISI, but rather due to IR losses, preemphasis may not be enough to overcome these losses for a readable signal at the receiver. Under these circumstances, a repeater can be required. These tests show the maximum data rate that can be transmitted over a length of TIA/EIA-568-B Cat6 cable while maintaining a BER less than one error per 100 million bits (BER < 1E-08).

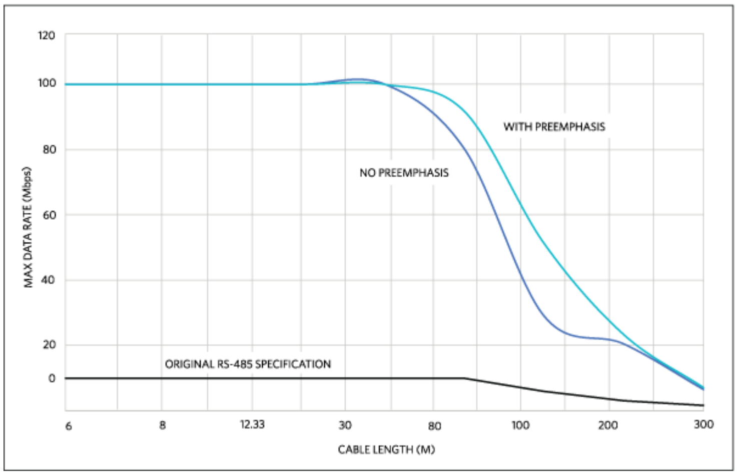


Figure E. Maximum data rate vs. cable length data from MAX22500E.

For MAX22500E, preemphasis is most desirable for transmission over Cat6 cables between 30m and 100m in length. Shorter cables do not warrant preemphasis, and longer cables do not show significant improvement in transmission quality.

Appendix C

Eye Diagrams Provide Quick Answers

As a tool for designers of digital transmission lines, the eye diagram provides quick answers to the following basic questions without the need for a complex mathematical analysis: What is the maximum allowed line length and data rate for my proposed system and how much transition jitter will it exhibit?

An eye diagram is simply an oscilloscope display of random digital data on the line, triggered on every nth cycle of the associated clock signal. The resulting superposition of waveforms, which should include every bit sequence possible within the n-cycle window, produces an eyelike opening that repeats for each unit interval (Figure 6).

For a given pulse code, such as NRZ, an eye diagram lets you determine the condition, such as ISI = 10%, that significantly degrades the system timing and amplitude margins and for which the BER increases sharply. An increase in the BER also depends on the type of UART in the system.

The eye diagram also reveals other useful information, based on the following facts:

- tolerance for timing and amplitude variations is proportional to the size of the eye,
- channel-noise margin is proportional to the height of the eye,
- allowed timing errors are proportional to the width of the eye, and
- jitter, BER, and the difficulty of recovering a clock signal from the asynchronous data stream are all proportional to the width of the transition region.

The "transition region" refers to a spread in signal transitions with respect to the ideal sampling instants that occur in the system UART. For RS-485 systems, the major component of this spread, or jitter, is ISI, which is the ratio of the transition region to the unit, or bit, interval.

A similar version of this article appeared in the June 10, 1999 issue of *EDN*.

Related Parts		
MAX22500E	100Mbps Half-Duplex RS-485/RS-422 Transceivers for Long Cables	Free Samples
MAX22501E	100Mbps Half-Duplex RS-485/RS-422 Transceivers for Long Cables	Free Samples
MAX22502E	100Mbps Full-Duplex RS-485/RS-422 Transceiver for Long Cables	Free Samples
MAX3291	RS-485/RS-422 Transceivers with Preemphasis for High-Speed, Long-Distance Communication	Free Samples
MAX3292	RS-485/RS-422 Transceivers with Preemphasis for High-Speed, Long-Distance Communication	Free Samples

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