Isolated RS-485 Repeaters

The Backbone of Industrial Long-Haul Networks

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Abstract

Data transmission networks in Atmospheric Monitors Systems (AMS) of large coal mines, sulfur recovery systems of petrochemical plants, and other, large-scale industrial operations, often use RS-485 as their physical layer. The low equipment, installation, and maintenance cost associated with RS-485 makes it an attractive low-cost alternative to fiber-optics installations, commonly considered for long-haul networks.

Spanning several miles in length, these networks use signal repeaters to connect multiple bus segments together. Minimizing cabling efforts, network nodes, and repeaters must operate in half-duplex mode. With segment length reaching up to one mile (1600m), external failsafe biasing is applied at each repeater input and output. Eliminating the common-mode effects of large ground potential differences between remote network notes, repeater input and output are galvanically isolated from one another.

To ease the design of long-haul networks, this application note:

- Provides a short overview of the network structure of long distance and wide area RS-485 networks.
- Explains the functional principle of a half-duplex repeater, and shows the design differences between single- and dual-isolated repeaters.
- Discusses the impact of repeater signal skew on the maximum possible data rate.
- Equations for calculating the resistor values of the external failsafe networks

Contents

List of Figures

1. Network Structures

Long distance networks consist of a series of multiple bus segments, connected by half-duplex repeaters (Figure 1). Each bus segment allows for the connection of multiple I/O bus nodes, however, with the requirement for relative short distances between the actual transceiver inputs and the main cable trunk. Thus, the network layout is governed and limited by the locations of the I/O bus nodes it must be connected to.

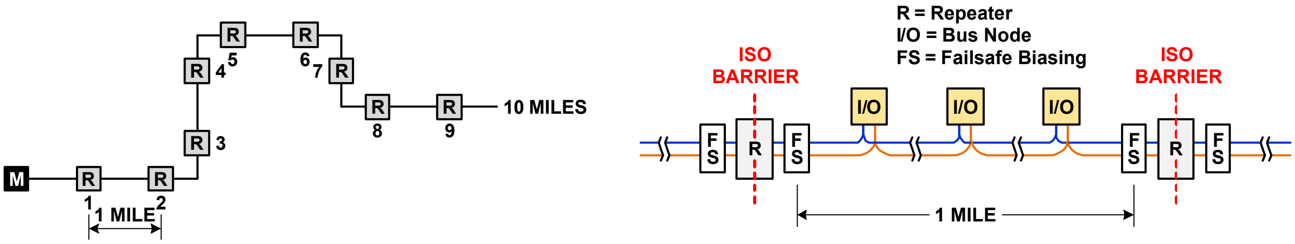
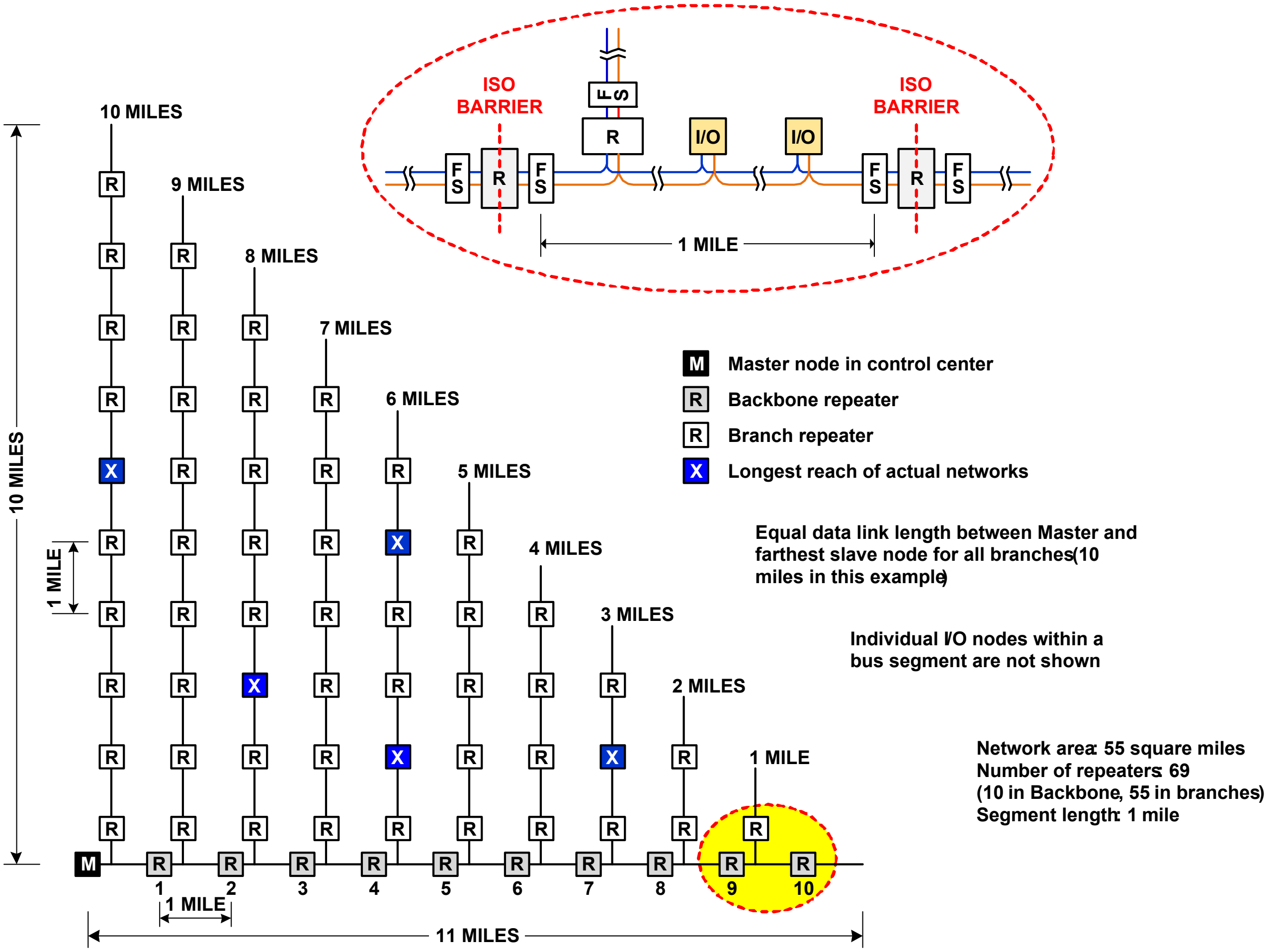


Figure 1. Long Distance RS-485 Network Shown Left with Single Bus Segment Shown on the Right

Overcoming the limitations of purely long distance networks, large area networks utilize a long distance bus as a network backbone, while adding branch capability to each bus segment. An example of a possible network structure is shown in Figure 2.



Equal data link length between Master and farthest slave node for all branches (10 miles in this example)

Individual I/O nodes within a bus segment are not shown

Network area: 55 square miles
Number of repeaters: 69
(10 in Backbone, 55 in branches)
Segment length: 1 mile

Figure 2. Large Area RS-485 Network with a Single Branching Bus Segment Shown at the Top

While the network of Figure 2 on page 3 is hypothetical, it demonstrates the network layout capabilities when using half-duplex repeaters, commonly available as repeater modules. This approach enables network architects to plan ahead in anticipation of future network growth, an important aspect for many industrial startup enterprises in industrial automation and coal mining that must extend network coverage from an initially smaller network.

Another important aspect of the above network structure is that the distance between the master node and the farthest slave node in any branch is always constant. Thus, the maximum propagation time and propagation skew are fixed, making this RS-485 network deterministic.

2. Repeater Operating Principle

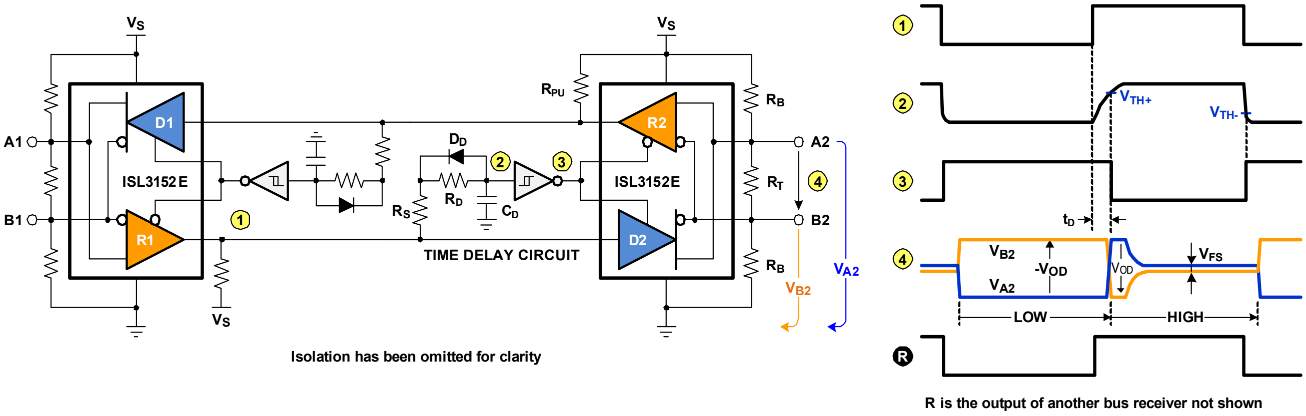
A half-duplex repeater consists of two, back-to-back connected, half-duplex transceivers (Figure 3). The driver and receiver enable functions of one transceiver are controlled by the logic states of the other transceiver's receiver output. Here, the underlying operating principle is to actively drive the bus with a negative bus voltage ($-V_{AB}$) when the driver input is low, and to disable the driver when its input is high. In this case, a positive V_{AB} (representing a high) in form of the failsafe voltage V_{FS}, is generated by the external failsafe biasing network. This switching method makes repeater operation largely independent of data rate and packet length.

However, additional time-delay circuits are required, to prevent the receiver output of the active transceiver from glitching. For a better understanding of the repeater's operating principle, Figure 3 shows the repeater schematic with the corresponding timing diagram for a signal flow port 1 (A1, B1) to port 2 (A2, B2).

After power-up and during an idle-bus condition, both transceivers are in receive mode, and the capacitors, C_D, fully charged. A negative bus voltage at port 1 drives the output of receiver R1 and the input of driver D2 low. The low potential forward biases diode D_D, which starts conducting, bypassing resistor R_D, and immediately discharging C_D through resistor R_S. Note that R_S is only required to limit the large discharge current spike into the output of R1.

When the voltage at C_D drops below the negative input threshold of the Schmitt-trigger inverter V_{TH-}, the inverter output turns high, activating D2. Now Port 2 is actively driving its bus with the negative driver output voltage, $-V_{OD}$.

When the bus voltage at port 1 turns positive, R1's output and D2's input go high and C_D is slowly charged through $R_S + R_D$. This extends D2's drive time by the time delay, t_D. With D2 still active, the bus voltage at port 2 assumes the positive driver output voltage ($+V_{OD}$). When the voltage at C_D reaches the inverter's positive input threshold, V_{TH+}, the inverter output turns low, disabling D2 and enabling R2. At this moment, the bus voltage, while remaining positive, drops from its V_{OD} level to the failsafe level, V_{FS}.



Isolation has been omitted for clarity

R is the output of another bus receiver not shown

Figure 3. Half-Duplex Repeater with Signal Timing Diagram

The time delay helps prevent bus signal interruption and data errors caused by differences in the driver and receiver switching characteristics. Referring to the above example: without delaying D2's turn-off time, during the transition from active-low to high-impedance, receiver R2 might detect the receding low condition on the bus, turning its output temporarily low. This low pulse would switch the transceiver at port 1 from receive into transmit mode, thus interrupting the reception of the incoming bus signal and causing data errors.

Therefore, to prevent R2 from glitching, D2 must remain enabled to actively drive the bus high. Once its positive V_{OD} has been fully established on the bus, D2 can be disabled. This way, R2 never experiences a low condition when port 2 transmits data.

To determine the time constant (T) of the delay circuit, apply the well-known, generic charge equation: $V_{(t)} = V_{PK}(1-e^{-t/T})$ and solve for T:

$$T = \frac{-t}{\ln(1 - V_{(t)}/V_{PK})} \qquad \text{(EQ. 1)}$$

The time constant must be calculated such that for a given peak voltage ($V_{PK} = V_{CC}$), the time for charging C_D to the inverter's earliest switching threshold, ($V_{(t)} = V_{TH+\ MIN}$), is at least as long as the time it takes for V_{OD} to fully establish on the bus, which is the total of the driver's maximum prop-delay plus half of its maximum rise time ($t_D = t_{PLH\text{-}MAX} + 0.5t_{r\text{-}MAX}$). This is explicitly shown in Figures 4.

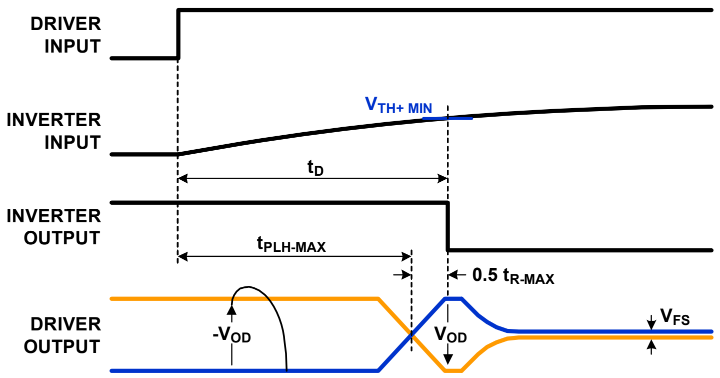


Figure 4. Time Delay Requirement: $t_D = t_{PLH\text{-}MAX} + 0.5\ t_{R\text{-}MAX}$

With C_D ($R_S + R_D$) making up T, (EQ. 1) is rewritten:

$$c_D(R_S + R_D) = \frac{-(t_{PLH-MAX} + 0.5t_{R-MAX})}{\ln(1 - V_{TH+MIN}/V_{CC})} \qquad \text{(EQ. 2)}$$

Further simplification can be made that reduces (EQ. 2) to an equation that delivers only a single resistor value, namely, R_D.

(1) To minimize the impact of the inverter's input capacitance on the time constant while maintaining a low time constant during discharge, set C_D to a value between 50pF and 100pF:

$$C_D \approx 50\text{pF}\ldots100\text{pF} \qquad \text{(EQ. 3)}$$

(2) Calculate the value of the current limiting resistor, R_S, limiting the discharge current spike, by dividing the difference between the diode forward voltage, V_F and the maximum voltage across C_D, V_{CC}, by the specified receiver output current, I_O:

$$R_S = \frac{V_{CC} - V_F}{I_O} \qquad \text{(EQ. 4)}$$

Inserting EQs. 3 and 4 into (EQ. 2) and solving for R_D results in:

$$R_D = \frac{-(t_{PLH-MAX} + 0.5t_{R-MAX})}{C_D \bullet \ln(1 - V_{TH+MIN}/V_{CC})} - R_S \qquad \text{(EQ. 5)}$$

3. Calculation Example 1

For a new repeater design, Intersil's powerhouse transceiver ISL3152E has been selected because of its large driver output voltage, capable of driving segment lengths of up to 2 miles (3200m). The major device parameters are:

- Supply voltage: $V_{CC} = 5V$
- Maximum data rate: $DR_{MAX} = 115kbps$
- Driver minimum output voltage: $V_{OD-MIN} = 2.4V$
- Driver maximum prop-delay: $t_{PLH-MAX} = 1300ns$
- Driver maximum rise-time: $t_{R-MAX} = 1600ns$
- Receiver rated output current: $I_{O-MAX} = 8mA$

The positive input threshold of the selected Schmitt-trigger inverter is specified such that $V_{TH+MIN} = 1.58V$, and the diode forward voltage with $V_F = 0.65V$.

The following steps explain how to calculate the delay circuit's component values:

(1) Making $C_D = 100pF$

(2) Calculating R_S using (EQ. 4) yields:

$$R_S = \frac{5V - 0.65V}{8mA} = 544\Omega$$

From the E-96 series of 1% resistor values choose $R_S = 549\Omega$.

(3) Calculating R_D using (EQ. 5) results:

$$R_D = \frac{-(1300ns + 800ns)}{100pF \bullet \ln(1 - 1.58V/5V)} - 549\Omega = 54.74k\Omega$$

From the E-96 series, choose $R_D = 55.6k\Omega$.

4. Single and Dual Isolated Repeaters

Long-haul networks possess large Ground Potential Differences (GPDs) between remote network nodes, which in non-isolated data links manifest themselves as large common-mode voltages between a transceiver's bus terminals and local ground. In noisy electrical environments these voltages can exceed a transceiver's Common-Mode Voltage Range (CMVR), causing data errors and even device damage. To eliminate the common-mode effects of large GPDs, repeater input and output must therefore be, galvanically isolated from each other.

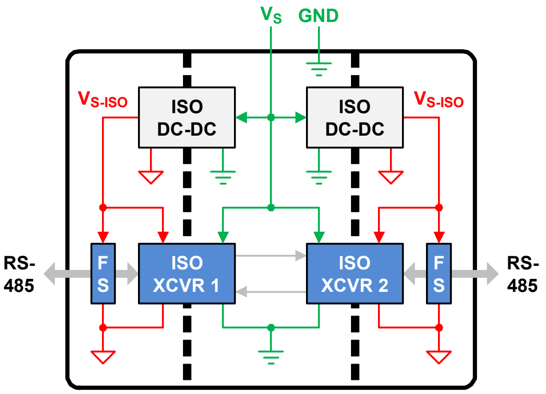


Figure 5. Dual-Isolated HD Repeater

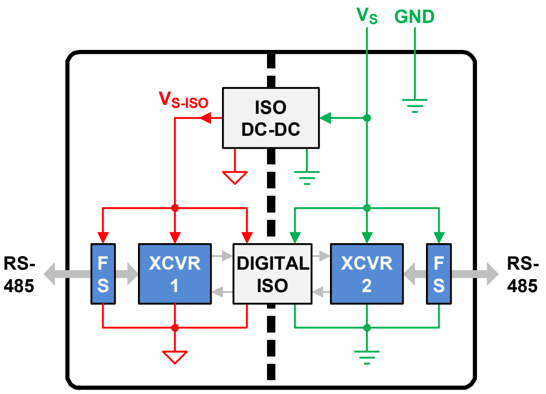


Figure 6. Single-Isolated HD Repeater

In applications with high isolation voltage requirements, the use of dual-isolated repeaters might be necessary (Figure 5). The repeaters often utilize two RS-485 transceivers with integrated isolation barriers and two isolated DC/DC converters that provide the transceiver supplies across the barriers. A third supply, powering the central repeater logic as well as the DC/DC converters, is referenced to local Earth-ground. High component count combined with the use of dedicated, isolated RS-485 transceivers make the dual-isolated repeater a rather expensive design.

Most long-haul networks however, rely on basic insulation, thus only requiring a single isolation barrier (Figure 6). A single isolated repeater has an isolated port and a non-isolated port that is referenced to local Earth ground. The non-isolated port is always located on the repeater's downstream side, facing away from the master node. This port drives a bus segment of isolated bus nodes, including the isolated port of a remote repeater at the other cable end. The concept of a grounded signal source driving an isolated bus is referred to as a single ground reference design (Figure 7). It is used to keep repeater cost low as its design requires only two standard transceivers, a digital signal isolator and an isolated DC/DC converter.

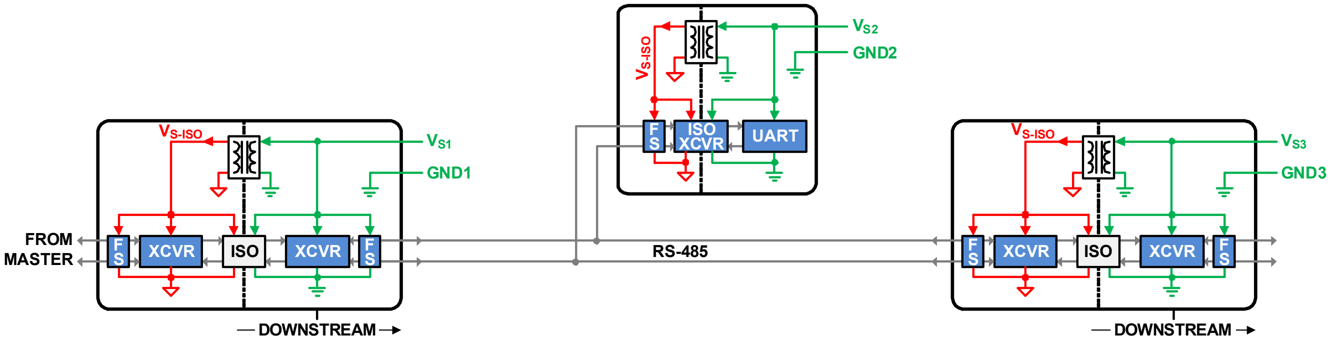


Figure 7. Single Ground Reference Design of a Repeater Link

5. Failsafe Biasing Networks

Long distance buses use two failsafe biasing networks, one at each cable end, to maintain a relative constant bus failsafe voltage (V_{FS}) during bus idling (Figure 8).

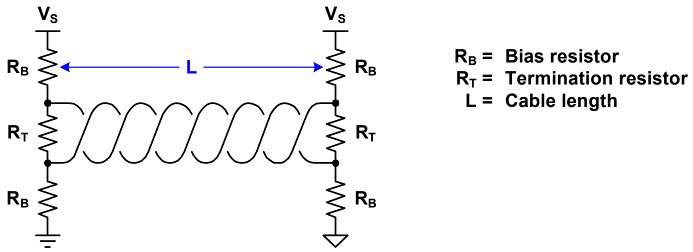


Figure 8. Failsafe Biasing Networks for Long Data Links

Here, the biasing resistors are calculated for maximum differential loading ($R_L = 54\Omega$):

$$R_B(k\Omega) = \frac{V_S / V_{AB}}{L/1296 + 18.52} \quad \text{(EQ. 6)}$$

where:

R_B = Failsafe bias resistor (kΩ)

V_S = Transceiver supply voltage (V)

V_{FS} = Failsafe voltage (V)

L = Bus segment length (m)

For line impedance matching, the series combination of the two biasing resistors in parallel with the termination resistor, R_T, must match the characteristic cable impedance of $Z_0 = 120\Omega$. Thus, for a given value of R_B, R_T becomes:

$$R_T = \frac{2R_B \bullet 120\Omega}{2R_B - 120\Omega} \quad \text{(EQ. 7)}$$

For detailed information on the derivation of EQs 6 and 7, refer to application note AN1987 “External Failsafe Biasing for Isolated Long-Haul Buses”.

6. Calculation Example 2

Assuming a bus segment length of L = 1600m (1 mile) with maximum differential loading of R_{INEQ} = 540Ω, while assuring a minimum failsafe voltage of V_{AB} = 200mV, at a nominal supply of V_S = 4.5V requires a minimum R_B value of 1.14kΩ:

$$R_B(k\Omega) = \frac{V_S / V_{AB}}{L / 1296 + 18.52} = \frac{4.5 / 0.2}{1600 / 1296 + 18.52} = 1.14k\Omega$$

The termination resistor required to match the line impedance is 127Ω as calculated with (EQ. 2):

$$R_T = \frac{2R_B \bullet Z_0}{2R_B - Z_0} = \frac{2 \bullet 1.14k\Omega \bullet 120\Omega}{2 \bullet 1.14k\Omega - 120\Omega} = 127\Omega$$

7. Maximum Bus I/O Nodes per Segment

Calculate the maximum number of bus transceivers per segment by dividing the single transceiver input impedance through the equivalent input impedance:

$$n_{XCVR} = \frac{R_{IN}}{R_{INEQ}} \tag{EQ. 8}$$

For the ISL3152E, the differential input impedance R_{IN} = 192kΩ. Using (EQ. 8), the maximum possible number of transceivers to be connected to the bus is 355:

$$n_{XCVR} = \frac{192k\Omega}{540\Omega R} = 355$$

8. Maximum Segment Length

In TSB 89 “Application Guidelines for RS-485” the recommended maximum cable length for data rates up to 100kbps is 1200m or 4000ft (Figure 9). At this length, the cable DC resistance approaches the value of the termination resistor, thus attenuating the bus voltage by about 6dB (or half). This means that a standard compliant driver with a minimum output of V_{OD} = 1.5V causes a minimum input voltage of V_{ID} = 750mV at the receiving end, which often provides sufficient noise margin for a standard compliant receiver of ±200mV input sensitivity.

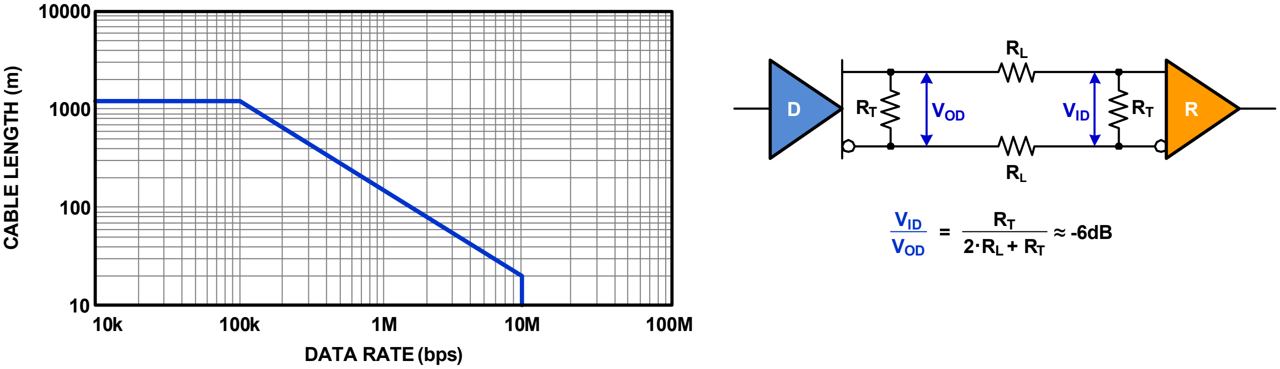


Figure 9. TSB-89 Recommended Maximum Cable Length for Low Data Rates is Based on 6dB Voltage Drop

Many industrial networks aim for segment lengths of up to one mile (1600m) by tolerating even lower V_{ID} levels of 650mV. Applying the same V_{ID} limit to the ISL3152E transceiver with -50mV to -200mV input sensitivity yields 700mV of noise margin, which is 150mV more than for a standard compliant receiver. However, the ISL3152 also has a significant higher V_{OD} of 2.4V minimum, thus allowing for much longer cable runs. Use the equation in Figure 8 on page 9 to calculate the maximum cable length for R_L.

$$R_L = \frac{R_T}{2} \bullet \left(\frac{V_{OD}}{V_{ID}} - 1\right) \qquad \text{(EQ. 9)}$$

Since the line resistance, R_L (Ω), is the product of cable length, L (m), and the specific cable DC resistance, DCR (Ω/m):

$$R_L = L \bullet DCR \qquad \text{(EQ. 10)}$$

We can insert (EQ. 9) into (EQ. 10) and solve for L. Using the above values of V_{OD} = 2.4V and V_{ID} = 0.65V, and applying an RS-485 cable, such as Belden 3105A with a DCR of 48.2mΩ/m, the maximum segment length is 3351m (2.1 miles):

$$L = \frac{R_T}{2DCR} \bullet \left(\frac{V_{OD}}{V_{ID}} - 1\right) = \frac{120\Omega}{2 \bullet 0.0482\Omega/m} \bullet \left(\frac{2.4V}{0.65V} - 1\right) = 3351m \ (2.1 miles) \qquad \text{(EQ. 11)}$$

9. Maximum Stub Length

The distance between the actual transceiver inputs and the main cable trunk is known as a stub. As a stub presents a piece of unterminated transmission line, its length must be limited to avoid signal reflections. A common rule of thumb is to limit a stub's one-way signal delay, (electrical length), to one tenth of the driver's minimum rise time:

$$L_S \le \frac{t_{R-MIN}}{10} \bullet v \bullet c \tag{EQ. 12}$$

where:

- L_S is the stub length (m),
- c is the speed of light ($3 \cdot 10^8$m/s)
- v is the signal velocity of the transmission medium as a factor of c

For example, if connecting an ISL3152E transceiver with a minimum rise time of 700ns through a stub using a Belden 3105A cable with 78% velocity, the maximum stub length must not exceed 16.4m (54 ft):

$$L_S \le \frac{700\text{ns}}{10} \bullet 0.78 \bullet 3 \bullet 10^8\text{m/s} = 16.4\text{m (54 ft)}$$

10. Maximum Data Rate

The maximum applicable data rate depends on the pulse distortion of the entire data link, which is from the driver input in the master node to the receiver output of the farthest slave node. Pulse distortion is caused by the multiple driver and receiver skews within the data link. Pulse skew is the difference in propagation delays for the rising and falling edges of drivers and receivers ($t_{SKEW} = |t_{PLH} - t_{PHL}|$). The pulse distortion of a single repeater is the sum of its driver and receiver skews. Figure 10 depicts a 20-mile long network with 20 bus segments of one-mile length and 19 repeaters.

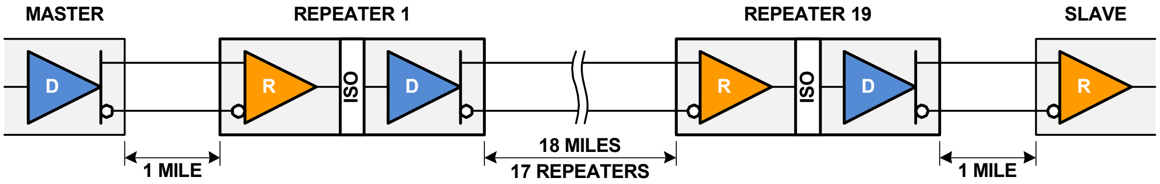


Figure 10. 20-Mile Long Network with 20 Bus Segments of One-Mile Length and 19 Repeaters

As RS-485 uses asynchronous data transmission, data recovery at the receiving end is accomplished with UARTs oversampling the receive signal by eight to sixteen times the data rate. To ease data recovery, the recommended limit for pulse distortion is about 20% of the pulse width or the time unit interval, t_{ui} (Figure 11).

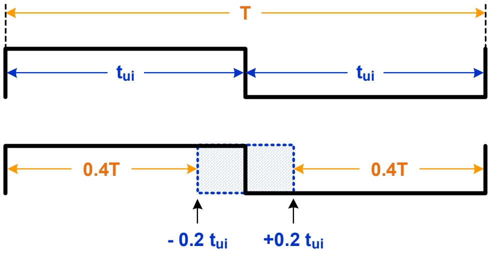


Figure 11. ±20% Pulse Distortion Allows for Easy Data Recovery

To determine the maximum pulse distortion of the data link, identify the distortion of a single repeater and multiply it with the number of repeater stations in the link.

Using ISL3152 transceivers, the skew of a single repeater is 70ns (10ns receiver skew, 10ns isolator skew, and 50ns driver skew). Multiplied by 20 repeater stations yields a total skew of 1.4µs for the entire data link, which according to the pulse distortion limits, equals 0.2 t_{ui}. Thus, the minimum pulse width, $t_{ui\text{-}MIN} = 1.4\mu s/0.2 = 7\mu s$, and the maximum data rate $DR_{max} = 1/\ t_{ui\text{-}MIN} = 1/7\mu s = 143kbps$, which exceeds the transceiver's maximum data rate of 115kbps.

The 20-mile network can therefore be operated at maximum transceiver speed without exceeding the pulse distortion limit.

11. Switching Performance

Figures 12 and 13 show the switching waveforms of an actual half-duplex repeater at 20kbps and 100kbps, respectively. These real-world signals confirm the operating principle described in Figure 3 on page 5 and Figure 4 on page 6.

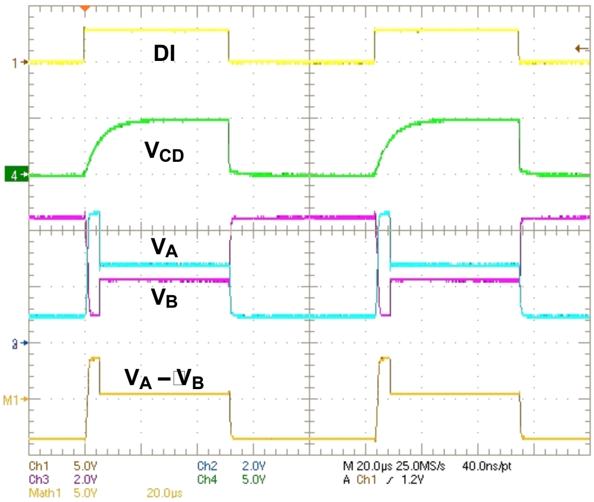


Figure 12. Repeater Waveforms at 20kbps

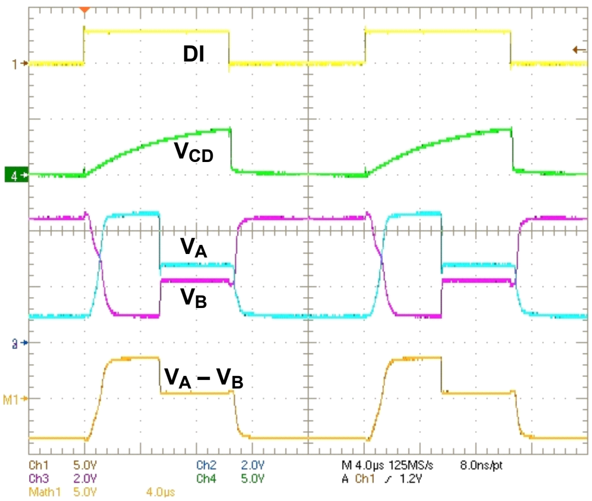


Figure 13. Repeater Waveforms at 100kbps

12. Conclusion

Isolated half-duplex RS-485 repeaters using the ISL3152E transceiver enable the design of the fastest and longest RS-485 networks ever accomplished, with more than twenty two-mile bus segments and up to 355 bus nodes per segment, while operating at data rates of up to 115kbps.

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