Substation Communications: When Should I Use EIA-232, EIA-485, and Optical Fiber?

Karl Zimmerman and Edmund O. Schweitzer, III
Schweitzer Engineering Laboratories, Inc.

Presented at the
23rd Annual Western Protective Relay Conference
Spokane, Washington
October 15–17, 1996

Originally presented at the
32nd Annual Minnesota Power Systems Conference, October 1996

SUBSTATION COMMUNICATIONS: WHEN SHOULD I USE EIA-232, EIA-485, AND OPTICAL FIBER?

Karl Zimmerman
Schweitzer Engineering Laboratories, Inc.
Pullman, Washington USA

Edmund O. Schweitzer, III
Schweitzer Engineering Laboratories, Inc.
Pullman, Washington USA

ABSTRACT

This paper compares EIA-232, EIA-485, and optical fiber communications with respect to speed, security, safety, network configuration, troubleshooting, and economics. The paper first identifies the characteristics of the communications as physical channels. Then it discusses ways to best use these channels, including bus and star topologies and the data throughput involved in each.

The result is a comparison table and discussion, which makes clear the tradeoffs, advantages, disadvantages, performance, and costs of each option.

Protection engineers are faced with making decisions about the best ways to communicate with protection devices. This paper provides background and data needed to make informed decisions, including when these communications tools are appropriate and when still higher-performance tools may be needed.

INTRODUCTION

Industry standards EIA-232 and EIA-485 describe the most common communications hardware used in digital relays in the field. They are likely to appear in tomorrow's developments, even in products having more advanced communications. In addition, new developments make fiber optics a practical, economical, and safe alternative to metallic communications cable.

What are the objectives of communicating with relays and other IEDs?

1. Use relay data for protection and control.
2. Do not endanger protection.
3. Make power system safer, more reliable, and more economical.

Here are some specific examples:

- Scan and update metering, demand, and targeting data each second.
- Perform breaker control (trip/close) functions in less than one second.
- Archive relay event reports for later retrieval.
- Time-synchronize multiple IEDs over the same physical connection.
- Access multiple IEDs through a port switch.
- Send control or trip functions from one relay to another in less than one-half cycle.

How can we tie devices together to perform these functions? In this paper, we wish to discuss applications of EIA-232, EIA-485, and fiber-optic communications at speeds below 40 kbits/sec.

SEVEN LAYER MODEL

The seven layer open systems interconnect (OSI) model produced by the International Standards Organization is shown in Figure 1.

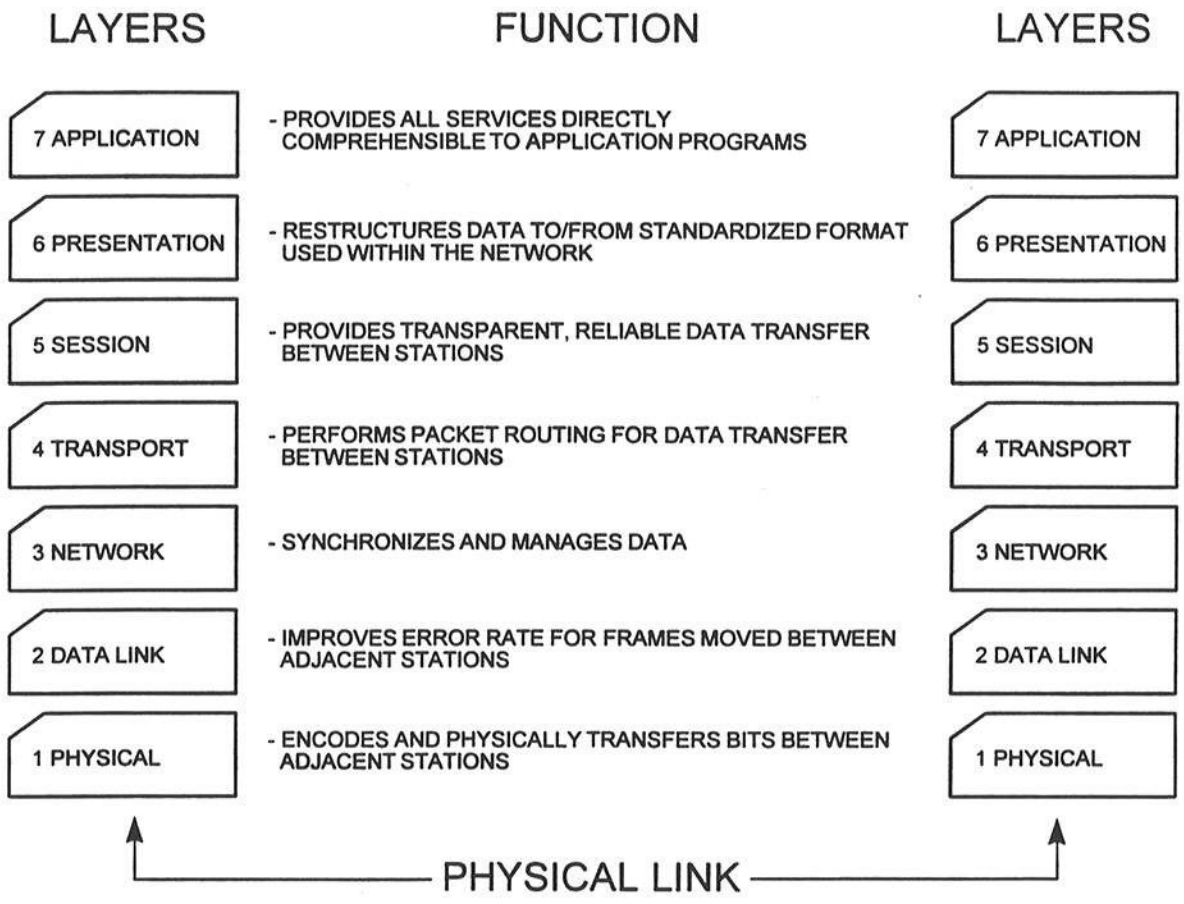


Figure 1: ISO Open Systems Interconnect Model

Here are some common physical layer protocols and their general characteristics:

EIA-232

- Point-to-point applications
- Limited distance
- Low speed (<20 kbits/sec)

EIA-485

- Multidrop applications
- Good distance
- Low and intermediate speed (up to 10 Mbit/sec)

IEEE 802.3: Carrier-Sense Multi-Access with Collision Detection (Ethernet)

Intended as local area network (LAN)
High speed (up to 100 Mbit/sec)
Many physical media options

IEEE 802.5: Token Ring

Alternate LAN configuration
Provides deterministic communications

Physical layers EIA-232 and EIA-485 support many application layers, including those listed below:

Table 1: Some Protocols That Can Use EIA-232 or EIA-485

ASCII Commands and Responses	Includes the "human-oriented" commands and responses used by many manufacturers' relays and other IEDs, like "METER," "SET," or "STATUS."
Binary Commands and Responses	A separate software program required to communicate with relays or a data format for interfacing with other devices.
Modbus	Low-speed, master-slave protocol supported by most system integrators, PLC's, and other devices.
IEC 870-5	Low-speed, master-slave protocol primarily used in Europe.
DNP 3.0	Based on IEC 870-5, allows peer-to-peer communications, report-by-exception for better throughput. DNP 3.0 is a recommended practice by the IEEE Substations Committee.
SYMAX	Square D PLC protocol, master-slave data link.
HDLC (High-Level Data Link Control)	Data-link layer protocol used with point-to-point connections. It handles some basic error-checking and retries.
ADLC	Variant of HDLC for multidrop applications. 3-layer variant of UCA version 2 uses ADLC on EIA-232/485 with MMS as an application layer.
Data Highway	Allen Bradley PLC-based protocol, master-slave bus topology.

HIGH-SPEED COMMUNICATIONS

Certain protection and control applications require higher speeds, but they come at an increased cost and complexity. For example, if we wish to move large blocks of data in a short time, like DFR records or long event reports from protective relays, we may desire speeds far greater than 40 kbits/sec.

Consider a breaker failure application. A trip from one of several devices starts a timer. If the breaker does not interrupt fault current before the timer expires, we must trip all breakers adjacent to the failed breaker. Now consider this protection using communications instead of control wiring and lockout relays. All breaker trip signals are to be transmitted over the communications path. Each connected device needs to respond within a few milliseconds. This may require higher speeds and systems that accommodate peer-to-peer communications.

However, several obstacles face high-speed communications systems. Can a single failure of the communication system prevent proper protection of the power system? What type of redundancy must we implement? How much does advanced communications increase the cost of each IED? While high-speed communications systems show promise, designers should consider all factors.

Sometimes a 10-20 kbits/sec channel is fast enough for high-speed protection. Consider that a 9600 bits/sec channel transmits data at:

$$\frac{9600 \text{ bits / sec}}{60 \text{ cycles / sec}} = 160 \text{ bits / cycle}$$

Suppose a message used to transmit a transfer trip signal to a remote relay in a pilot trip scheme is 2 bytes (16 bits) long. At 160 bits/cycle, it theoretically takes only 1/10 of a cycle (16/160) to transmit this message from point to point.

Behrendt [6] shows a practical application of using EIA-232 to communicate signals from one relay to another in one-half cycle.

STAR VS. BUS TOPOLOGY

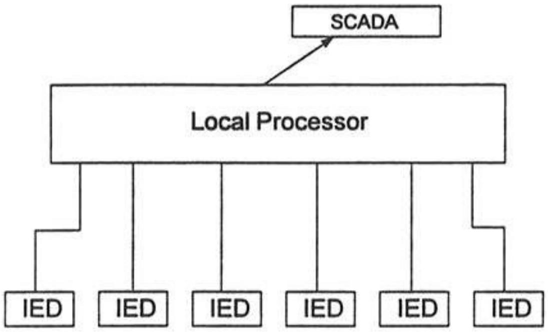


Figure 2: Star Topology

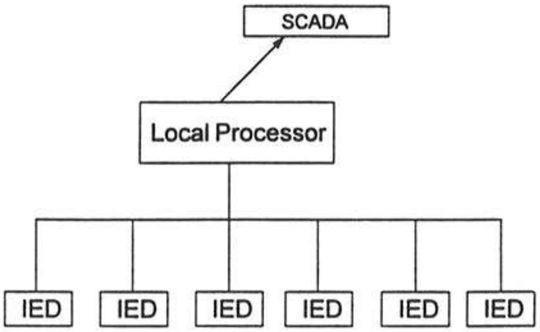


Figure 3: Bus Topology

Star Topologies

The star topology is extremely common in today's substation communications. The SCADA master is the hub that communicates with RTUs on spokes. Telephone systems also widely apply star topologies on a local switching level before branching into networks on a system level.

From an installation standpoint, star topologies are straightforward. All of the communications are "home runs" back to the processor.

In practice, EIA-232 is most often employed in star topologies with a "master" communications processor, computer, or PLC to control and handle data from the interconnected "slave" devices. EIA-485 devices can be employed in star topologies but are more frequently used in bus topologies.

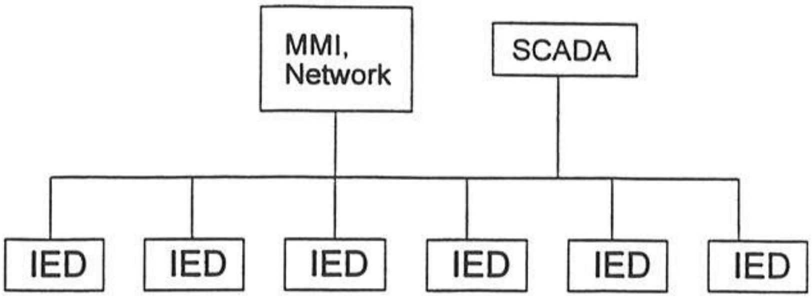


Figure 4: Peer-to-Peer Bus Topology

Bus Topologies

EIA-485 was designed for bus topologies. Bus topologies can be master-slave or peer-to-peer. In a peer-to-peer network, any device can communicate with any other device. A bus topology using EIA-485 can be much slower than a star topology because the overall system throughput depends on the number of interconnected devices. EIA-232 can be applied on bus topologies if we apply interface devices to convert EIA-232 to EIA-485 and use a multidrop protocol.

REVIEW OF EIA-232, EIA-485, AND OPTICAL FIBER CHARACTERISTICS

EIA-232

The EIA Standard EIA/TIA-232-E defines the interconnection between data terminal equipment (DTE) and data communication equipment (DCE) employing serial binary data interchange. By definition, the interface is a point-to-point mode of communications. The standard defines:

- Electrical signal characteristics.
- Interface mechanical characteristics.
- Functional description of interchange circuits.
- Standard interfaces for some specific system configurations.

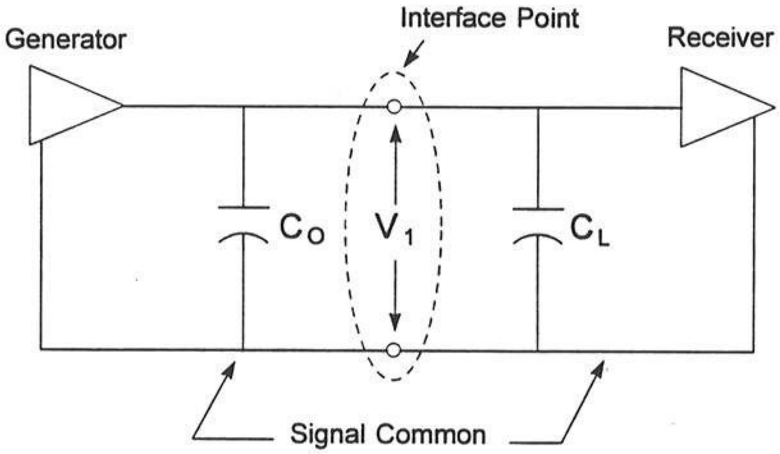


Figure 5: EIA-232 Equivalent Circuit

C_O is the total effective driver capacitance, measured at the interface point, including any cable to the interface point.

C_L is the total effective terminator capacitance, measured at the interface point, including any cable to the interface point (< 2500 pF).

V1 is the voltage at the interface point (-5 to -15 V and +5 to +15 V).

For data interchange circuits, the signal is in binary 1 (also called "Marking") when the voltage is more negative than -3 V. The signal is in binary 0 (also called "Spacing") when the voltage is more positive than +3 V, with respect to the signal ground. Between +3 and -3 V is called the transition region. The standard states that, for data interchange circuits, the time required for the signal to pass through the transition region must be 1 ms or 4% of the unit interval (bit time), depending on the nominal duration of the signal element.

EIA-232 specifies a 25-pin connection, but we can use a 9-pin connection for most applications.

Table 2: EIA-232 Pin Assignments

EIA-232 Description	DTE (Computer, Relay, or Communications Processor) Pin Assignments
Shield	1
Transmitted Data	2
Received Data	3
Request to Send (Ready for Receiving)	4
Clear to Send	5
DCE Ready	6
Signal Ground/Common Return	7
Received Line Signal (Carrier) Detector	8
Data Terminal Ready	20

Request to Send, Clear to Send, DCE Ready, Received Line Signal Detector, and Data Terminal Ready are used for hardware handshaking. If the EIA-232 interface uses software handshaking, these signals may not be used. The vacant pins can supply IRIG-B time code signals or voltages for external devices.

What is the Maximum Length I Can Run a Cable for EIA-232 Applications?

Appendix A of EIA/TIA-232-E provides a simplified calculation of the maximum cable length for an interconnecting cable between DCE and DTE devices.

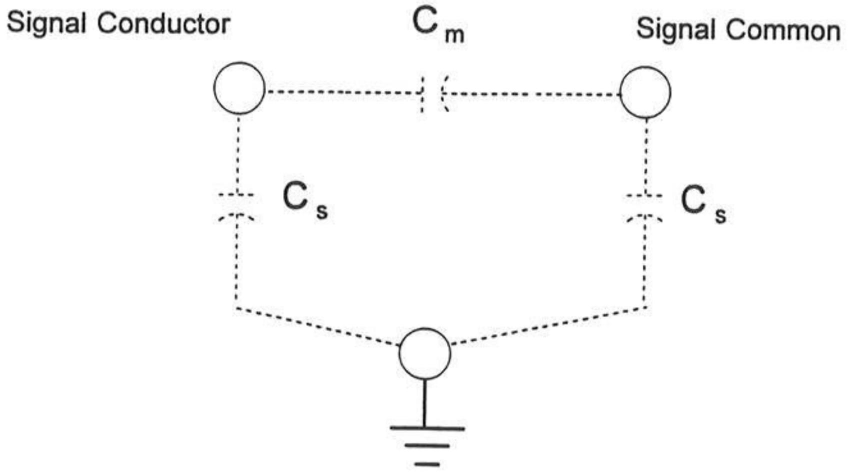


Figure 6: Capacitance of an EIA-232 Interchange Cable

C_m is the mutual capacitance between conductors. For shielded cables, C_s is the conductor to shield capacitance. For unshielded cables, C_s is the stray capacitance to earth ground. In this example, we neglect imbalance between conductors and shield. C_c in Figure 7 is the sum of C_s and C_m.

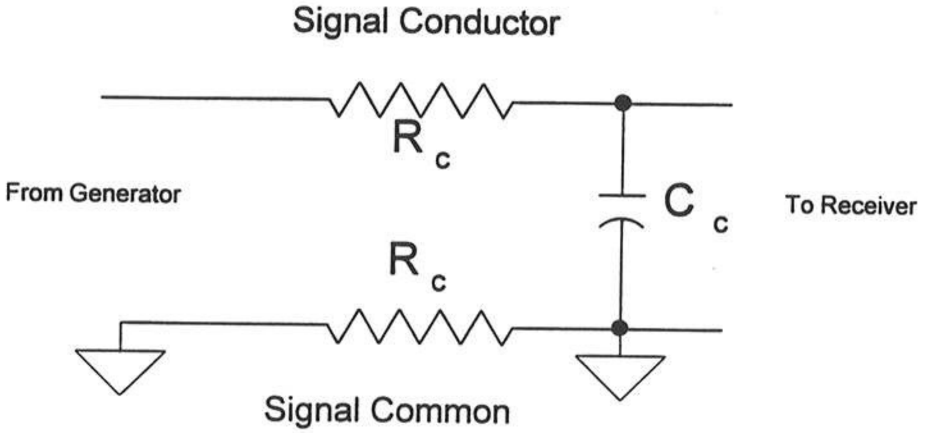


Figure 7: Simplified Model of the EIA-232 Interchange Cable Showing Cable Resistance, R_c, and Capacitance, C_c

For EIA-232, the maximum total capacitance is 2500 pF. A typical cable has about 50 pF/foot. Therefore, if we strictly adhere to the EIA-232 standard, cable runs are limited to 50 ft, and this does not account for capacitance on the receiver input.

The major consequence of violating the 2500 pF requirement is the amount of time needed to go from Logic 1 (-3 V) to Logic 0 (+3 V) and vice versa will be greater than the 4% of the unit interval allowed by the EIA-232 standard. The higher the capacitance, the greater the wave distortion. This type of distortion, called "bias distortion," can cause data errors.

In order to find practical limits, we tested an EIA-232 circuit between a communications processor and a relay at different baud rates and cable lengths. We measured the bias distortion for each case. We executed a continuous script file to check for data errors. We detected no data errors up to 1000 ft at 2400 and 9600 baud. At 19.2 kbaud, we detected data errors above 700 ft. It appears that UARTs (Universal Asynchronous Receiver/Transmitter), the chips used for these communication tasks, handle bias distortion up to 40% quite well.

At 19.2 kbaud:

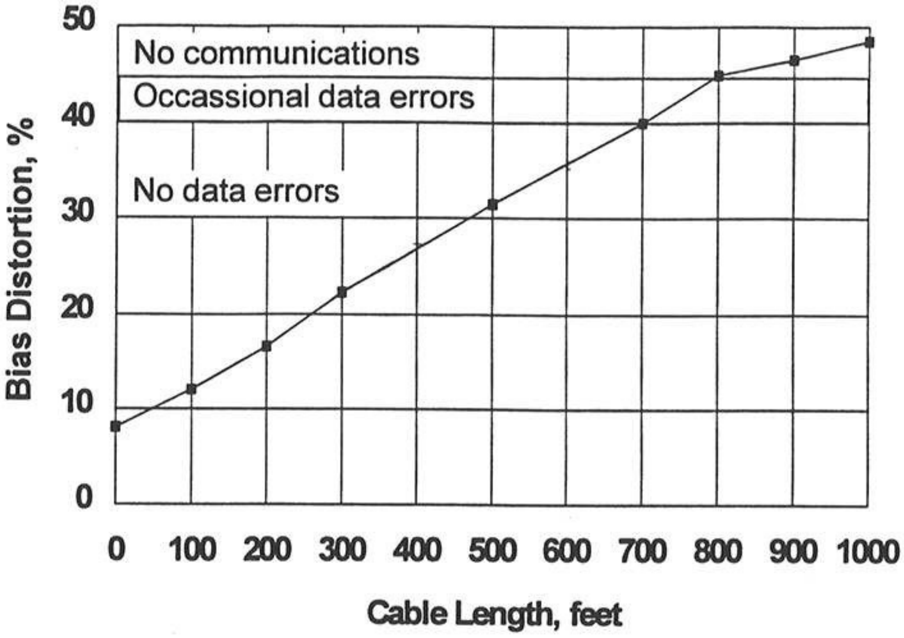
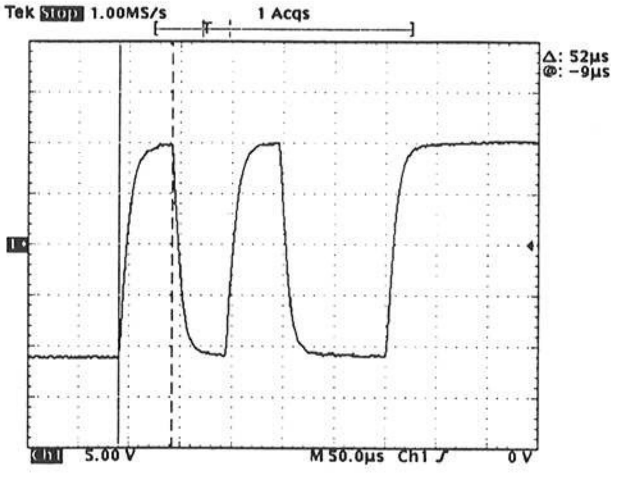


Figure 8: Bias Distortion vs. Cable Length for EIA-232 Test

Here are two waveforms, one showing 10% and one showing 40% bias.



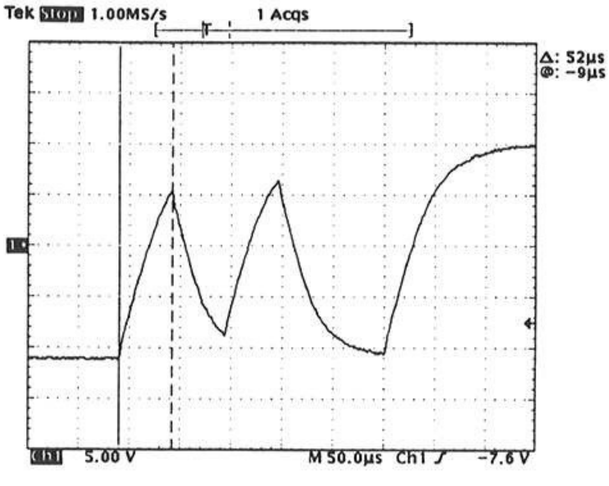


Figure 9: 10% Bias Distortion

Figure 10: 40% Bias Distortion

Since we detected no errors with up to 40% bias distortion, choosing an application upper limit of 10% gives us a very comfortable margin. The following table provides conservative maximum shielded cable lengths for baud rates of 2400, 9600, and 19.2k, if we allow a 10% bias distortion, keeping in mind that this does not strictly conform to EIA-232. An independent source [2] observed even longer acceptable cable lengths on EIA-232 and also permitted a 10% bias distortion.

Table 3: Cable Length Limits Due to Cable Capacitance, Permitting 10% Bias Distortion

Baud Rate	**Maximum Cable Length**	
	(Relay testing)	(Independent testing [2])
2400	400*	1000
9600	100	250
19200	50	(not given)

* Limit to 100 ft if cable is not electrically isolated from sources of electrical interference.

We believe the difference between relay testing and independent testing is most likely due to capacitors in the relay that we add for surge protection.

Sources of Interference

Modems and other auxiliary devices require a source of power (e.g., "wall warts"). These power sources introduce other paths of electrical interference. We can reduce electrical interference by supplying voltage from the communications port to power modems or other externally connected devices.

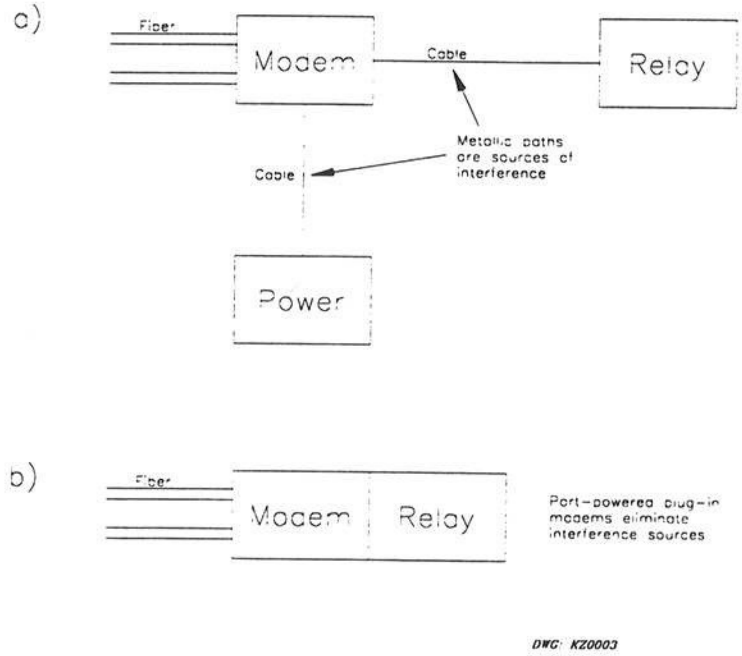
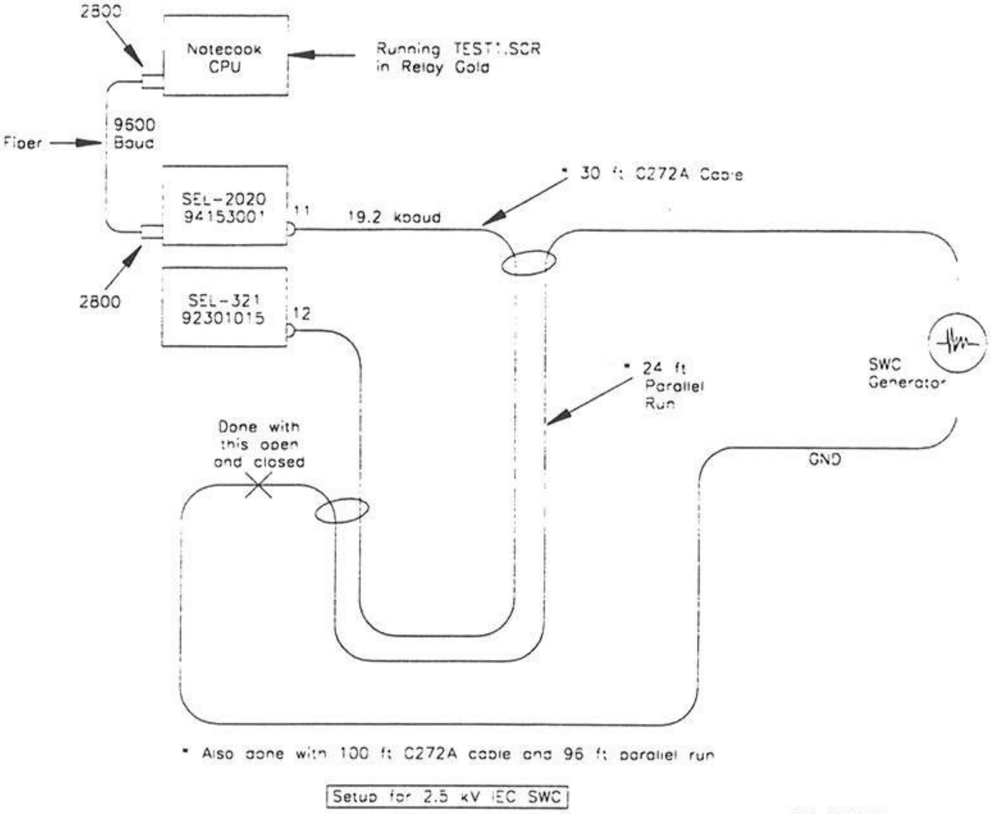


Figure 11: Eliminate Sources of Interference with Plug-In Modems

How well do EIA-232 circuits withstand surges? We endeavored to determine how a severe SWC waveform affects communications with respect to cable shield grounding, cable lengths, and baud rates.

For this test, we placed a transient on a conductor parallel with the communications cable between a communications processor and a relay. We used cable lengths of 30 and 100 ft. Here is the test setup:



DWG: KZ0002

Figure 12: EIA-232 Test Interface Setup

We applied 2 minutes (4 · 30 sec) of continuous SWC (40 times per second), based on IEC Standard IEC-255-22-1, Class III, but more severe. Below is a summary of results.

All EIA-232 ports are not created equal. We applied the SWC waveform with and without our standard capacitor-resistor-MOV port protection circuit on the input.

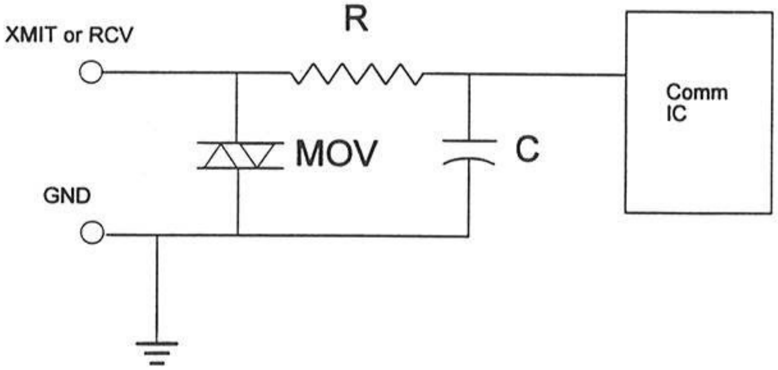


Figure 13: EIA-232 Port Protection Circuit Used by This Manufacturer

Without the input protection it only took one burst of SWC to damage the unprotected EIA-232 input. With protection on the input, no damage occurred on any EIA-232 inputs, regardless of shielding. (Port protection is seldom found in commercial equipment.)

Next, we applied the test to protected circuits with and without grounds on the cable shields. If either end of the cable had a shield not grounded, data errors occurred. Lengthening the cable (30 to 100 ft) or disconnecting the shield ground at both ends increased the number of errors. With both ends shielded, no data errors occurred at 30 feet. At 100 feet, only a few data errors occurred. (Remember, this is applying 2 minutes of continuous SWC!!). In summary, we conclude:

- Always ground cable shield at both ends.
- Apply EIA-232 inputs with protection against voltage surges. (Standard on SEL relays.)
- Limit cable length to 50 ft for 19.2 kbaud, 100 ft for 9600 baud and below.
- If you are not sure about port protection or interference, then eliminate the problem with fiber optics.

EIA-485

A typical EIA-485 application consists of a master device and a twisted pair cable that runs from master to one IED, then from that IED to another IED, etc. By definition, EIA-485 is a network "daisy-chain" connection between multiple devices. Up to 32 transmitter/receivers can share the same data channel.

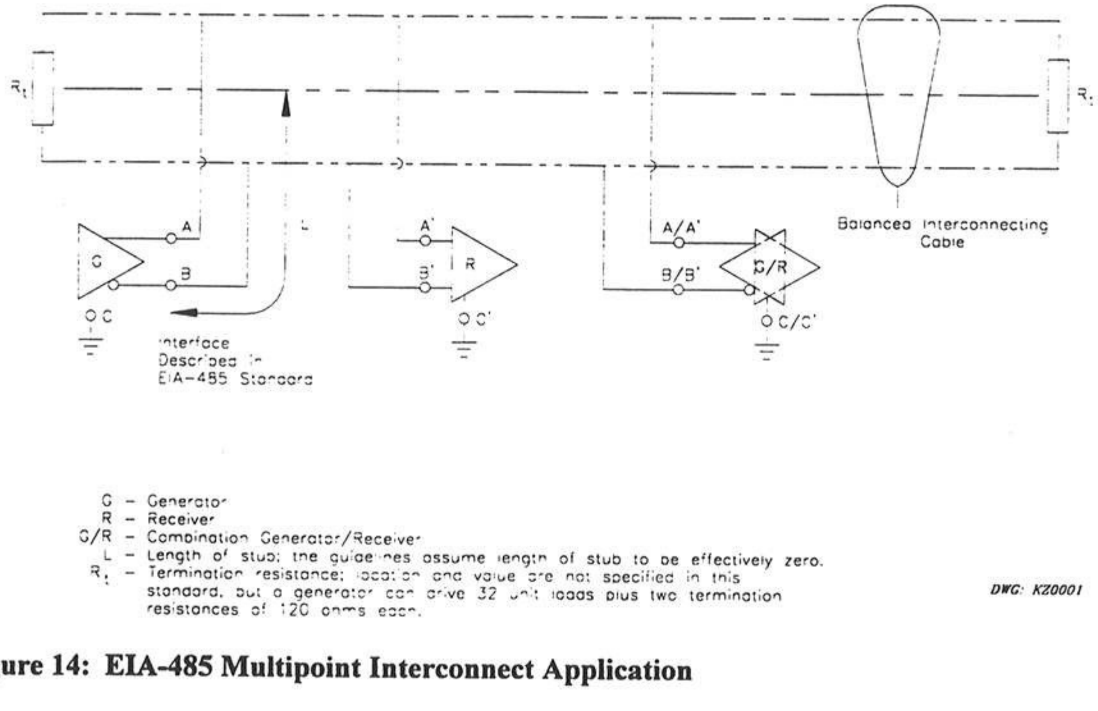


Figure 14: EIA-485 Multipoint Interconnect Application

The source open circuit voltage (generator) measured between the two output terminals must be 1.5 to 6.0 volts. The voltage measured along the interconnecting cable must be 1.5 to 5.0 volts.

The most significant difference between EIA-232 and EIA-485 is that the EIA-485 receiver determines binary 1 (MARK or OFF) and binary 0 (SPACE or ON) on the voltage from terminal A to terminal B (Figure 14), not from terminal to ground. The A terminal shall be negative with respect to the B terminal for a binary 1 state. The A terminal shall be positive with respect to the B terminal for a binary 0 state.

The EIA-485 Standard defines the electrical characteristics of generators and receivers connected in this arrangement. Below is a short summary of other important aspects of EIA-485.

Cable Lengths: EIA-485 can generally operate over longer distances than EIA-232. Like EIA-232, the distributed capacitance of the cable limits speed and distance. The following table shows some practical limits for EIA-485 cable lengths [2]:

Table 4: EIA-485 Cable Length Limits

Speed (baud rate)	Maximum Cable Length
90 kbaud	4000 ft
1 Mbaud	400 ft
10 Mbaud	40 ft

Each connected device adds capacitance. If designers are not careful, the internal capacitance of the EIA-485 transmitters and receivers can reduce the practical speed and distances of the network.

Connection: One (half duplex) or two (full duplex) twisted pair cables. Four wire implementation of EIA-485 requires two conductors each for transmit and receive. The advantage of full duplex is that the master has full control of the system. The master can transmit a high priority message while receiving a response from an IED, without interrupting it.

Speed: The maximum data rate for EIA-485 is 10 Mbits/sec. This appears to be an excellent alternative for bus arrangements, where all connected devices have advanced communications capability. However, most installed devices are restricted to lower speeds.

An EIA-485 bus operating at high speeds must be treated as a transmission line. It needs to be terminated at its characteristic impedance, typically 100 ohms, at each end. Designers must avoid stub lines off the bus to prevent unwanted reflections.

Sources of Interference

We performed tests on an EIA-485 circuit similar to the SWC waveform tests we performed on the EIA-232 circuit. For a 100 foot cable length at 19.2 kbaud, we had no data errors, as long as we observed the rules for correctly grounding the circuit. We had one data error if we connected the chassis reference to the circuit reference at one of the "slave" devices. Figure 15 shows a typical four-wire (full duplex) connection.

EIA-485 performs better because the voltage references are independent of a ground conductor. For example, the transmit circuit is based on the voltage from A (T+) to B (T-), not A to ground or B to ground.

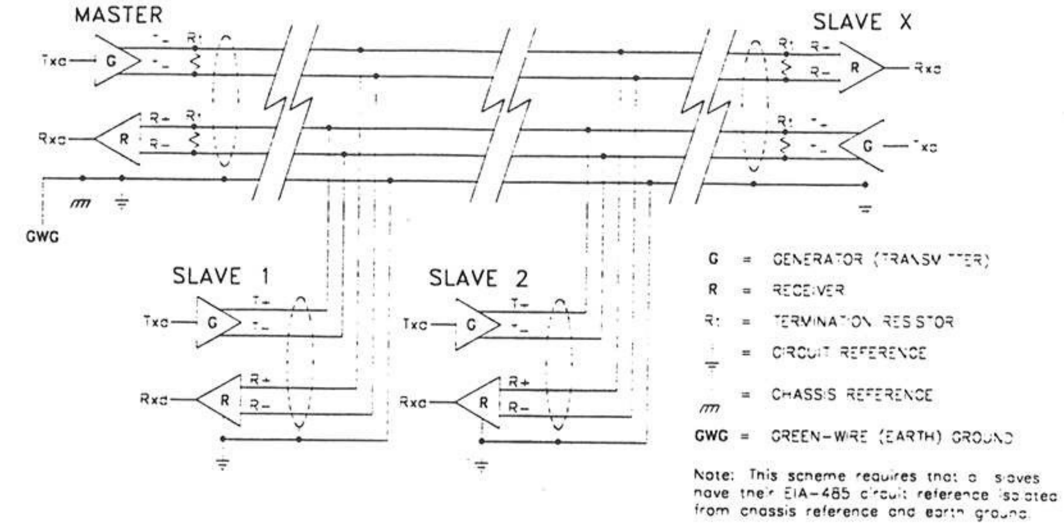


Figure 15: Typical (Recommended) EIA-485 Four-Wire Multidrop Network

Optical Fiber

Optical fiber provides electrical isolation between communicating devices and isolates personnel and equipment from dangerous voltages and Ground Potential Rise (GPR). It is totally immune to noise produced by electromagnetic fields and can be routed in areas where using metallic cable would be dangerous or would corrupt data. New developments make fiber optics a practical, economical, and safe alternative to metallic communications.

We can apply optical fiber as an enhancement to virtually any physical layer protocol. Optical fiber has several modes, physical diameters, and bandwidths.

Single mode fiber uses much smaller diameters (for example 9 μm) and is used for longer distances and higher speeds.

Multimode fiber is ideal for communications within the substation. Higher attenuation produces a lower quality signal. Higher bandwidth means higher data rates are possible. The following table shows typical characteristics of multimode fiber.

Table 5: Multimode Fiber Characteristics

		(Attenuation, db/km)			**(Bandwidth, MHz • km)**		
Diameter (μm)	**Index**	**650 (visible)**	**850**	**1300 nm**	**650**	**850 (visible)**	**1300 nm**
50.0	graded		2.7	0.7		400.0	400.0
62.5	graded		3.2	0.9		160.0	300.0
100.0	graded		4.0			100.0	200.0
200.0	step	8.0	6.0	30.0	10.0	20.0	

Application and cost comparison of smaller (50 μm) vs. larger (200 μm) diameter fiber optics:

Table 6: Application and Cost Comparison of Two Optical Fiber Designs

Cable diameter	50 μm	200 μm
Connector style	ST connectors	V-pin connectors*
Cable cost	$0.90/ft	$1.25/ft
Connector termination cost	$13 per end	$2 per end
Connector termination process	require epoxy and polishing	crimp and cleave
Connector termination time	10-15 min per end	1 min per end
Bandwidth	Up to 400 MHz • km	10 to 20 MHz • km
Attenuation	3 db/km	6-8 db/km
Wavelength	Nonvisible infrared	Visible wavelength, easy signal testing
Transceiver cost	$150 each end	$150 each end

* V-pin is a registered trademark of SpecTran Corporation.

COMPARISON AND RECOMMENDATIONS

In this section, we examine the advantages and disadvantages of using EIA-232, EIA-485, and optical fiber for substation communications with respect to:

Speed
Which devices can I connect?
Safety
Troubleshooting
Cost

Speed

In order to compare speed, we must consider number of connected devices, the data we wish to receive, and how fast we must collect this data. We must determine what protection and control functions, if any, we need to perform through the communications.

Below is an estimate of the size and transmit times of typical data objects.

Table 7: Estimated Size and Transmit Times of Typical Data Objects

Data Object	Size (bytes)	Transmit time @ 9600 baud
Fast Breaker Operate Command	6	7 ms
Binary *Fast Meter* Response	80	92 ms
ASCII Meter Command	200	229 ms
ASCII Event Report (11 cycle, 4 samples/cycle)	6 k	7 sec
ASCII Event Report (11 cycle, 16 samples/cycle)	21 k	25 sec
ASCII Event Report (300 cycles, 16 samples/cycle)	570 k	11 min

The size and transmit times of the data objects span one or two orders of magnitude. Fortunately, the smallest objects (binary *Fast Meter*, fast breaker operate) are the most time critical. However, transmission of a large object (e.g., ASCII Event Report) could potentially delay small ones (e.g., metering). Solutions include:

1. Separate the small, critical objects from the large, less critical objects into two networks. Redundant systems might justify duplication, but this doubles the network cost.
2. Use a channel that is sufficiently fast to handle the largest object and not excessively delay the small critical objects. This requires the channels to be two to three orders of magnitude faster, which is not generally available in devices deployed today. Furthermore, given any channel capacity, there is a message large enough to unacceptably delay the fast, critical data.
3. Break larger objects into smaller packets and poll both critical and noncritical messages at the same rate. This enables receipt of the larger objects at a slower rate, without delaying the critical messages.
4. Prioritize metering and control at a higher level than event reports so the small, critical message can get through the long, less critical messages by briefly interrupting the longer messages. In this case, the fast binary messages co-exist with the slower messages.

Example 1: EIA-485 Bus System vs. EIA-232 Star System

Consider a simple system with ten IEDs connected to a local processor (e.g., communications processor, PLC, or computer). The local processor is scanned by the SCADA system. We wish to read metering data from the IEDs as quickly as possible, with all devices communicating at 9600 baud.

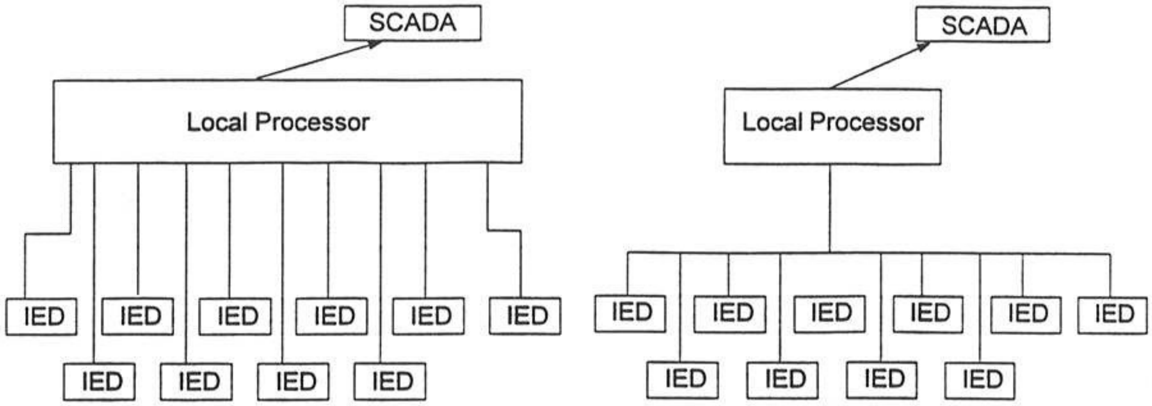


Figure 16: Ten Device Star and Bus Systems

Now, consider how EIA-232 and EIA-485 systems compare if each metering message is 80 bytes long. We wish to refresh that data to the master as quickly as possible.

For the EIA-232 star system, each device communicates with the local processor at 9600 baud. If we assume that the local processor is available 75 percent of the time, we have a new effective bandwidth of about 7200 bits per second. No addressing is necessary.

EIA-485 system performance depends on the number of connected devices. In this example, the system is designed to handle a maximum of 9600 baud so the available bandwidth to each IED for data transfer is just 960 baud. Moreover, each device requires an address which further slows data transfer because the messages are longer. If this overhead is 25 percent, the new effective bandwidth per IED is 720 baud. Since there is inherent delay in the communications link, we need not add delay for the local processor.

We assume that each byte contains 1 start bit, 8 data bits, and 1 stop bit (10 bits = 1 byte of data). Therefore, for the 9600 baud, 10-device system:

EIA-232 star:	800 bits / 7200 bits per second = 0.1111 seconds per packet of data
EIA-485 bus:	800 bits / 720 bits per second = 1.1111 seconds per packet of data

For this system, EIA-232 is 10 times faster than EIA-485. Put another way, the EIA-485 bus system would require a speed of:

> $9600 \cdot (1.1111/0.1111) = 96{,}000$ baud to give the same throughput as the 9600 baud EIA-232 star system to the local processor. For either system, the local processor must extract and format the data to communicate with the SCADA master.

Example 2: Comparison of Three Network Configurations: a) Simple EIA-485 Bus, b) Three-Tier EIA-232 Star, and c) Two-Tier EIA-232 Star

Parameters

Speed: 19.2 kbaud with 11 bits/byte (1 start, 8 data, and 2 stop bits) so each byte requires 11/19200 = 0.00057 sec = 0.57 ms.

Data to Collect: Metering data and status of inputs and outputs from each IED. Each IED metering data and status response is 20 bytes long. A total of 30 IEDs.

Local Processor: In this example, the local processor uses the Modbus protocol to extract data from the connected devices. Data acquisition consists of an 8-byte request, a response message of 5 bytes, plus 20 bytes of data. We add a device response delay (based on using Modbus protocol) of 500 ms. Also, depending on the application, the local processor may have to wait a short time to assure that each request is responded to by the connected devices (T_{wait}).

Device response delay is the time from when an individual device receives a request until it responds to the request. We chose a device response delay of 500 ms as a conservative, worst-case delay.

T_{wait} is the time that the local processor waits from receiving a message until issuing its next request. For these examples, T_{wait} is 115 ms.

Parameter n equals the number of IEDs from which data is collected for a single response.

$T_{response}$ is the time from when a local processor sends a request until it receives a complete response.

T_{scan} is the time required to collect data from all of the connected devices. For one connected device, $T_{scan} = T_{response} + T_{wait}$.

For a Modbus data request with n = 1, the response time is:

$$\begin{aligned} T_{response} &= (13 + 20 \cdot n) \cdot 0.57 + 500 \\ &= 11.4 \cdot n + 507.4 \text{ ms} \\ &= 519 \text{ ms} \\ T_{scan} &= T_{response} + T_{wait} \\ &= 519 + 115 \\ &= 634 \text{ ms} \end{aligned}$$

Note: In all of the data timing calculations, the device response delay is the dominant portion of the time. Be wary of any analysis that does not include this factor.

Example 2a: Simple EIA-485 Bus

In this example, each IED is considered a Modbus "slave" device and can communicate directly with the local processor, using the parameters described previously.

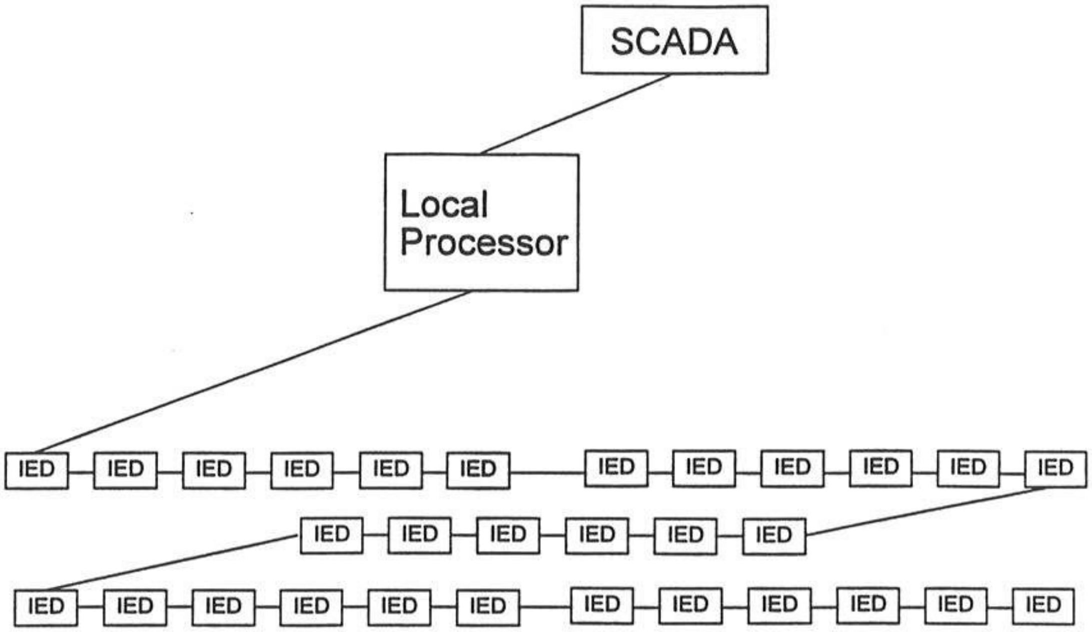


Figure 17: EIA-485 Bus Network

We collect metering data using Modbus, with a full duplex EIA-485 connection. The local processor requests data from one IED at a time. Therefore, $n = 1$. The response time is:

$$T_{response} = 11.4 \cdot 1 + 507.4 \text{ ms} = 519 \text{ ms}$$

We must issue this request 30 times (1 per IED). Therefore, our best scan time is:

$$T_{scan} = (T_{response} + T_{wait}) \cdot 30 = 19.02 \text{ sec}$$

If our design calls for a one second scan time, and $T_{wait} = 0$, the system would require a device response delay of less than 14 ms (vs. 500 ms) at 19.2 kbaud. Even if the baud rate were infinity, the device response delay would have to be less than 33 ms!

Example 2b: Three-Tier EIA-232 Star Using Communications Processors

Examples 2b and 2c utilize a communications processor. We can apply a communications processor to extract and format data from numerous IEDs and other communications processors. Once data is collected, it can be moved into registers to be read by the local processor. Essentially, the communications processor (CP1 in Figure 18) acts as a Modbus "slave" device.

At the same time, the communications processor acts as a hub for a star topology, extracting data from IEDs and refreshing its data registers simultaneously. In this example, we connect ten IEDs to each communications processor.

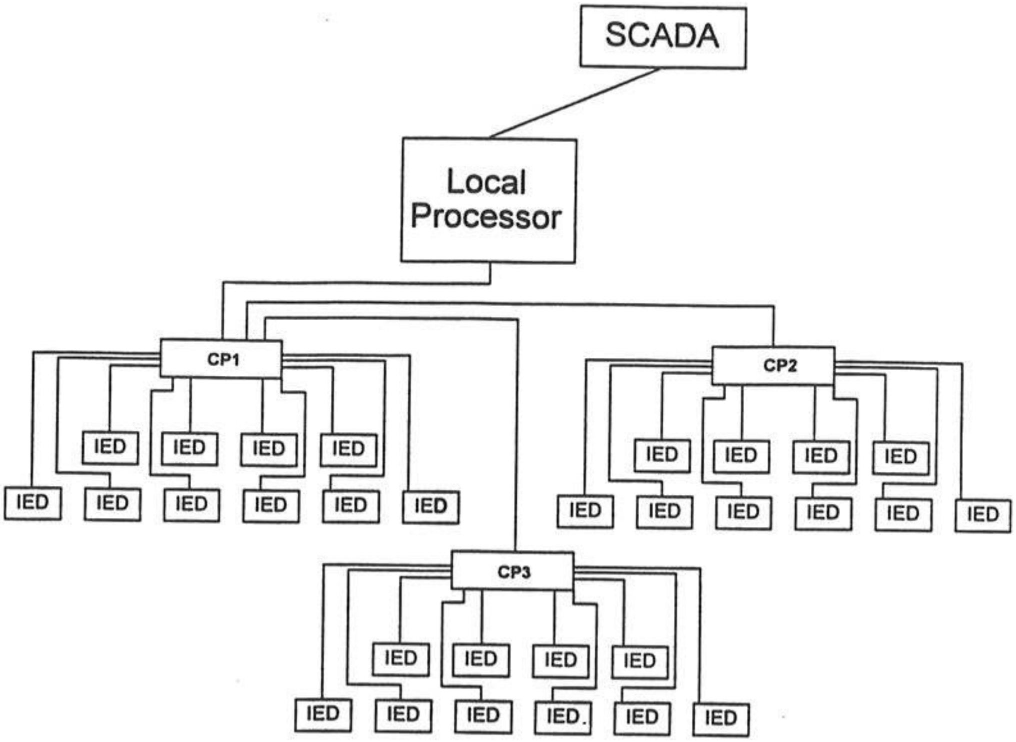


Figure 18: Three-Tier EIA-232 Star Network

The communications processor uses a binary *Fast Meter* protocol to communicate with the connected IEDs. This protocol consists of a 2-byte request, a 130-byte response, and 300 ms of IED response latency. At 19.2 kbaud, the total time for this message to be processed is:

$T_{Fast\,Meter} = (132 \text{ bytes} \cdot 0.57 \text{ ms/byte}) + 300 \text{ ms} = 375 \text{ ms}$

It takes an additional 500 ms for the communications processor to parse and move that *Fast Meter* data into registers suitable for the local processor to read. Therefore, the data is refreshed every 875 ms in the communications processor, available to be read by the local processor.

The data from the IEDs connected to CP2 and CP3 "passes through" CP2 and CP3 to CP1. The local processor reads the data in CP1 using the Modbus protocol. Each acquisition from the communications processor requires $11.4 \cdot 10 + 507.4$ ms (using the initial parameters), where $n = 30$ because each data acquisition is collecting 30 IEDs worth of data.

With $n = 30$, our response time from each communications processor is:

$T_{response} = 11.4 \cdot 30 + 507.4 = 849 \text{ ms}$

Therefore, our best scan time is:

$$\begin{aligned} T_{scan} &= T_{response} + T_{wait} \\ &= 849 + 115 \\ &= .964 \text{ sec} \end{aligned}$$

Also, we must account for the latency for the communications processors. It takes 375 ms to extract data from the IEDs, plus 500 ms to move the data within a communications processor (875 ms total). If we add another "tier," we must add another 1 sec of latency. Therefore, the data being scanned is 0.964 + 0.875 + 1.000 = 2.839 sec old, worst case.

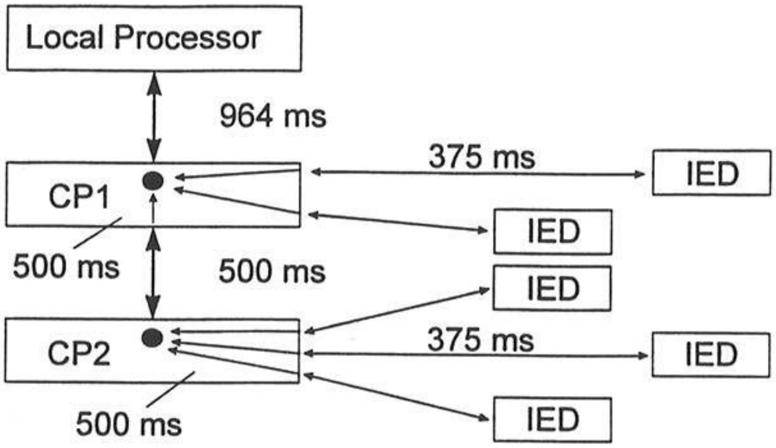


Figure 19: Three-Tier EIA-232 Star Network Times

Example 2c: Two-Tier EIA-232 Star System

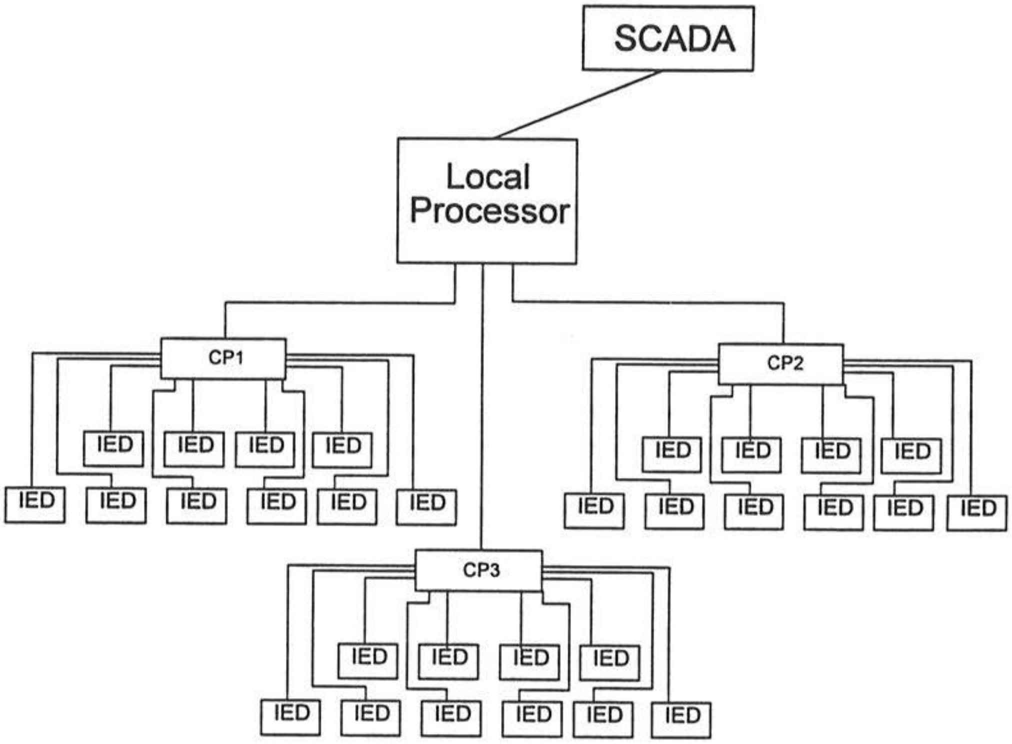


Figure 20: Two-Tier EIA-232 Star System

Now consider the 30 IEDs connected to three communications processors, similar to Example 2b. In this case, however, we use the local processor to issue data requests via Modbus EIA-232 to all three of the communications processors simultaneously. This requires a direct connection between the local processor and each of the three communications processors. Also, the local processor must run three Modbus applications simultaneously (one to each communications processor).

Since each data acquisition is collecting ten IEDs worth of data, n = 10. Our response time is:

$$T_{response} = 11.4 \cdot 10 + 507.4 = 621 \text{ ms}$$

Our best scan time is:

$$\begin{aligned} T_{scan} &= T_{response} + T_{wait} \\ &= 621 + 115 \\ &= 0.736 \text{ sec} \end{aligned}$$

If we add the 875 ms latency for the communications processor, the entire database is updated every 0.736 + 0.875 = 1.611 sec.

Table 8 compares the speed of the three example systems. The table shows the best scan times at baud rates of 9600 and 19200, and maximum data latency at 19200 baud.

Table 8: Speed Comparison of Three System Configurations in Example 2

System Configuration	Best Scan Time		Maximum Data Latency
	9600 baud	19.2 kbaud	19.2 kbaud
Simple EIA-485 Bus	19.590 sec	19.020 sec	19.020 sec
Three-Tier EIA-232 Star	1.320 sec	0.964 sec	2.839 sec
Two-Tier EIA-232 Star	0.860 sec	0.736 sec	1.611 sec

Which Devices Can I Connect?

EIA-485 bus systems appear ideal for interconnecting any IED which supports a given protocol. In practice, however, all of the connected devices are usually from the same manufacturer and have the same communications port drivers. Unfortunately, the industry-wide quality of protocol implementation today is not foolproof. Even if an effort is made to use the same protocols, difficulties resolving mismatches can still result.

It is a challenge to integrate systems using arbitrary devices from multiple manufacturers, but with a communications processor in a star topology and a mix of EIA-232, EIA-485, and fiber (where required), we can connect devices with different software protocols. Communication with each device can be conducted at a different baud rate when required. Time critical functions, like updating metering and status data or operating breakers, can usually be accommodated when all of the devices are properly connected and set. Less critical functions, like collecting event reports or checking settings, are usually easier to implement.

Safety

EIA-232 and EIA-485 both require metallic conductors to tie together the interconnected devices. Inside the control house, metallic conductors are subject to electrical noise, but induced voltages are typically within safe limits. For EIA-232, grounding a shielded cable at both ends improves immunity to electrical noise. However, outside the control house, metallic cables are subject to dangerous levels of voltage due to ground potential rise and electromagnetically induced voltages. The temptation to install longer cable length is particularly high for EIA-485, where cables can be run longer distances. However, we would hate to be the technician or electrician who happens to be terminating a long metallic cable when a ground fault occurs!

Ground Potential Rise and Electromagnetically Induced Voltages: When a ground fault occurs, the zero-sequence fault current distributes through power system ground system sources like grounded wye-connected transformer windings, generator grounds, and shunt capacitors. The fault current also returns through alternate paths such as neutral conductors, unfaulted phases, overhead ground wires, and metallic cable sheaths. Ground faults produce ground potential rise (GPR) voltages that a station ground grid attains relative to a remote ground point. IEEE Standard 80, Guide for Safety in AC Substation Grounding, does not specify a maximum safe GPR. However, some utilities permit GPR up to 20 kV.

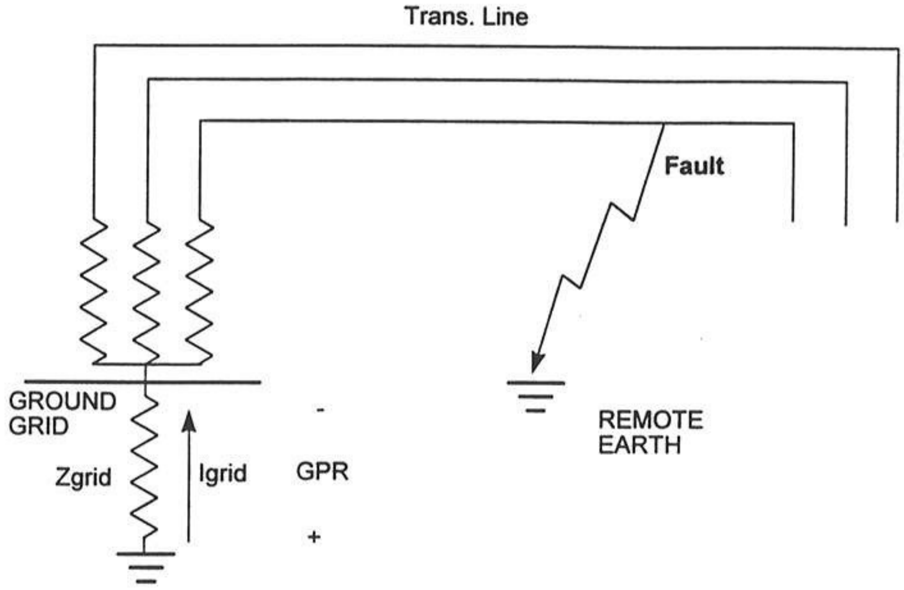


Figure 21: Ground Potential Rise Due to Remote Fault

Moreover, ground faults produce electromagnetically induced voltages which can be transmitted to metallic communications cables. The magnitude depends on the separation and length of the inductive exposure between the supply and communication lines, fault current magnitude, and earth resistivity. Even under normal conditions, electrical noise can be transmitted to communications cables. Shielded cable improves protection against electrical noise but is not immune to dangerously high induced voltages to equipment or personnel.

Our recommendation is: ***Never use metallic communications outside the control house at a substation***. Here are some of the possible consequences of doing so:

1. Risk of shock or electrocution.
2. Damage to protection and control.
3. Damage to communications circuitry.
4. Data transfer errors in the communications path.

As we have discussed, fiber-optic cable is immune to electrical interference and dangerous potentials. Converting signals from the EIA physical layers to optical fiber is low in cost and easy to do with modern devices.

Another dangerous practice is to design IEDs which electrically isolate the EIA port from the rest of the relay. In this case, the voltage at the port can be significantly different than the voltage at the relay ground reference. The technician becomes the electrical path for the potential difference. Always use optical fiber for these applications to avoid the risk of this safety hazard.

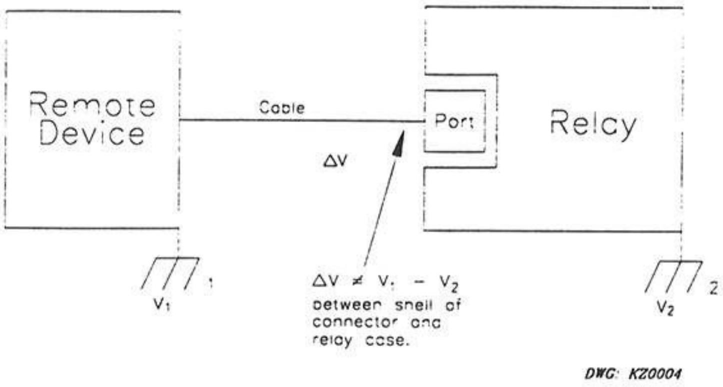


Figure 22: Isolated Ports Can Be Dangerous

Troubleshooting

In a master-slave EIA-485 daisy chain arrangement, troubleshooting can be difficult. For example, you may install the first and second devices on a string of connections with good results, then install a third device and lose communications with the first device. Because the connection starts at a single master and extends between each IED, finding the problem can be likened to finding a faulty connection on a string of Christmas lights.

Star topologies are much easier to troubleshoot. If one of the interconnected devices fails to communicate properly, it can be easily isolated and repaired. In a master-slave arrangement using EIA-232 in a star configuration, each device has a single connection to the master.

Cost

Comparing costs depends greatly on the system (i.e., number of connected devices, cable lengths, inside/outside the control house, speed requirements, etc.). For example, the cost of metallic twisted pair used for EIA-485 is less than the cost of fiber-optic cable; however, the gap is closing. EIA-485 full duplex requires two cables. Inside the control house, cable costs should be slightly lower if we can daisy chain between each device.

Besides serious safety risks, installing metallic cable outside the control house has hidden costs. For example, if the IEDs are located in breakers in the switchyard, a separate trench or conduit may be required to connect between IEDs. Otherwise, we must run wires from the IED, back through the control house, and back out to another IED.

Using a daisy chain EIA-485 connection is probably less expensive for systems where:

- speed is not an issue
- all of the connected devices are inside the control house
- all connected devices readily accommodate EIA-485

EIA-232 and fiber can accommodate IRIG-B time code signals on the same cable.

CONCLUSIONS

EIA-232 and EIA-485 are common physical layers. Hundreds of thousands of relays and other IEDs that use these interfaces are already in service. Numerous application layer protocols use EIA-232 and EIA-485. High-speed communications systems using bus topologies may become more common as hardware costs decrease and application layer protocols open up.

For speeds less than 40 kbits/sec, EIA-232 employed in a star topology with a communications processor is much faster for retrieving critical metering data or performing control functions than EIA-485 in a bus topology. Using EIA-232 and EIA-485 together can improve speed, depending on the system.

EIA-232 run from relay to relay at 10-20 kbits/sec is fast enough for high-speed protection.

EIA-485 is less expensive and preferred for applications in the control house where much slower speeds are acceptable for noncritical functions.

Never run metallic cable for communications outside the control house. If IEDs are located in the switchyard, use optical fiber for safety and noise immunity. Even for some installations inside the control house, we may prefer optical fiber as costs decrease.

Star topologies are generally easier to troubleshoot than bus topologies because we can isolate and test each device individually.

The following table summarizes the comparison between EIA-232, EIA-485, and two types of optical fiber.

Table 9: Applications and Cost Comparisons of EIA-232, EIA-485, and Optical Fiber

Category	EIA-232 Star	EIA-485 (full duplex) Bus	50 μm Optical Fiber	200 μm Optical Fiber
Speed	Limited to 20 kbits/sec. Can achieve 1-2 sec scan times for metering and I/O status, less than 1 sec for breaker control.	Up to 10 Mbits/sec. However, very slow scan rates (>10 sec) when applied with most IEDs. Adequate for slower noncritical functions.	Greater than 1000 Mbits/sec	Greater than 100 Mbits/sec
Cable lengths	50 ft (19.2 kbaud), 100 ft (9600 baud and below).	40 ft (10 Mbaud) 4000 ft (90 kbaud)	>5 miles	1500 ft (longer for many applications)
Connected Devices	EIA-232 ubiquitous. Must have 9- or 25-pin connector for EIA-232. With communications processor, can accommodate different application protocols.	Uses 1 (half duplex) or 2 (full duplex) twisted pair cables. All connected devices must use the same application protocol.	Fiber termination or EIA to fiber converter required.	
Safety	Metallic cable, susceptible to electrical interference. Okay for 50-100 ft runs in control house. Ground shield at both ends.	Metallic cable, susceptible to electrical interference. Okay for longer runs in control house. Observe recommended grounding practice. Long cable runs outside of control house expose personnel and equipment to dangerous levels of voltage.	Fiber-optic cable recommended for any cable runs outside the control house.	
Troubleshooting	Point-to-point connections generally easier to diagnose.	More difficult to isolate problems in daisy chain.	Infrared, special equipment required.	Visible wavelength ideal for substation applications.
COST OF:				
Converting from EIA to Fiber			$150-500	$150
Communications Port	$10/IED	$55/IED	$125-300/IED	$125-300/IED
8 ft cable, with terminations	$30	$5	$33	$14
50 ft cable, with terminations	$43	$34	$71	$67

ACKNOWLEDGMENTS

Special thanks to Randy Norheim of SEL for performing the EIA-232 and EIA-485 electrical interference testing and to David Wood of SEL for providing invaluable insight in reviewing this paper.

REFERENCES

1. EIA/TIA Standard, EIA/TIA-232-E, Interface Between Data Terminal Equipment and Data Circuit - Terminating Equipment Employing Serial Binary Data Interchange, July 1991.
2. John E McNamara, *Technical Aspects of Data Communication*, 2nd Ed., Digital Press, 1982.
3. ANSI/IEEE Standard 367-1987, IEEE Recommended Practice for Determining the Electrical Power Station Ground Potential Rise and Induced Voltage from a Power Fault.
4. EIA Standard, EIA-485, Standard for Electrical Characteristics of Generators and Receivers for Use in Balanced Digital Multipoint Systems, April 1983.
5. Graham Clough, Tony Guilante, Jay Gosalia, *Basic Communications for the Relay Engineer*, 20th Annual Western Protective Relay Conference, October 1993, Spokane, WA, USA.
6. Kenneth C. Behrendt, P.E., *Relay-to-Relay Digital Logic Communication for Line Protection, Monitoring, and Control*, Minnesota Power Systems Conference, October 1996, St. Paul, MN, USA.