Digital Communications Improve Contact I/O Reliability

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INTRODUCTION

Engineers in many industries are using digital communications instead of discrete wires to transfer the state of each input or output (I/O) contact in their plants. Before applying this design philosophy to electric power substations, engineers want to know about the relative reliability of systems that use digital communications versus those that use hardwired communications.

This paper compares the reliability of traditional contact wiring to multiplexed I/O via optical fiber and the resulting impacts on reliability. The paper also addresses adjustments to improve reliability, and summarizes the comparative reliability, costs, and other tradeoffs. We use an application example of a substation yard with I/O at four locations, connected to a main station panel.

We compare the following approaches:

- Traditional hardwired I/O
- Fiber-optic links with multiplexed I/O
- An Ethernet network with multiplexed I/O

These examples demonstrate the tools and methods to evaluate tradeoffs between these approaches and to select the I/O strategy that best matches specific requirements.

DEVICE FAILURE RATES AND UNAVAILABILITIES

A system consists of components, for which reliability can be expressed in more than one way. One useful measure is the probability that a device will be unavailable to perform the functions vital to system operation. If this "unavailability" is known for the components of a system, fault tree construction and analysis are useful to predict the overall system unavailability.

The device failure rate provides the number of failures expected per unit of time. It is common to express failure information as the mean time between failures (MTBF).

Availability and unavailability are often expressed as probabilities [1]. For the equipment used in the evaluations below, all failure rates are based on field data or assumptions that devices of comparable complexity and exposure will have similar failure rates.

Calculate unavailability given a failure rate and the time it takes to detect and repair a failure as follows:

$$q \cong \lambda MTTR = \frac{MTTR}{MTBF}$$

where: q is unavailability
λ is some constant failure rate
MTTR is the average downtime per failure
$MTBF = \frac{1}{\lambda}$ is Mean Time Between Failures

Each failure causes downtime MTTR. The system is unavailable for a fraction of the total MTBF. The system unavailability is therefore $\frac{MTTR}{MTBF}$ [1][2][3].

For each device with automatic failure detection, we used a time to detect and repair each failure of 48 hours, or downtime MTTR = 48 hours. For other devices, we explain the basis for the MTTR. These average unavailabilities are useful for general comparison of alternatives. To evaluate actual alternatives, use the MTBF of the specific make and model of each device if it is available. The unavailabilities used in the case studies are summarized in Table 1, after the calculations.

Point-to-Point Fiber-Optic Modem

Data based upon the experience of one manufacturer show an MTBF of 600 years for a point-to-point fiber-optic modem designed for a substation environment [2]. The instrumentation and control system detects channel failures, so we use an MTTR of 48 hours. The unavailability is:

$$q = \left(\frac{48 \text{ hours}}{600 \text{ years} \bullet 365 \text{ days/year} \bullet 24 \text{ hours/day}} \right) = 9.13 \bullet 10^{-6}$$

$$q \cong 10 \bullet 10^{-6} \tag{1}$$

Remote I/O Module

Data based upon the experience of one manufacturer show an MTBF of 300 years for an I/O module designed for a substation environment:

$$q = \left(\frac{48 \text{ hours}}{300 \text{ years} \bullet 365 \text{ days/year} \bullet 24 \text{ hours/day}} \right) = 18 \bullet 10^{-6} \tag{2}$$

Ethernet Switch

Several manufacturers provide high-reliability Ethernet switches. For each of these switches, the manufacturers quoted an MTBF of 500,000 hours:

$$q = \left(\frac{48 \text{ hours}}{500{,}000 \text{ hours}} \right) = 96 \cdot 10^{-6} \quad (3)$$

Ethernet Switch With Dual Power Supply

One way to improve the system availability of the Ethernet option is to use an Ethernet switch with dual power supplies. For a switch with a dual power supply, one manufacturer quotes an MTBF of 928,845 hours. For a system reliability analysis, this MTBF is appropriate. (For a maintenance prediction analysis, two power supplies instead of one is double the unavailability). Substituting this number into the device availability calculation instead of 500,000 yields a switch unavailability of $52 \cdot 10^{-6}$.

$$q = \left(\frac{48 \text{ hours}}{928{,}845 \text{ hours}} \right) = 52 \cdot 10^{-6} \quad (4)$$

Ethernet I/O Module

Several manufacturers provide Ethernet remote I/O modules with an MTBF of 500,000 hours:

$$q = \left(\frac{48 \text{ hours}}{500{,}000 \text{ hours}} \right) = 96 \cdot 10^{-6} \quad (5)$$

Ethernet Interface for Relay

Data based upon the experience of one manufacturer show an MTBF of 2,500 years:

$$q = \left(\frac{48 \text{ hours}}{2{,}500 \text{ years} \cdot 365 \text{ days / year} \cdot 24 \text{ hours / day}} \right) = 2 \cdot 10^{-6} \quad (6)$$

Wire Connection

Reference [4] states that:

> panel factory statistics show that wiring points have 1 failure per about 500 connection points after the first point-to-point continuity check. After functional testing, this failure rate decreases 100 times. Then a 1/50,000 failure rate after testing when the scheme is new and tested is a good estimation.

Over time, wiring terminations fail. Reference [4] used 10 times the failure rate of the newly tested wiring to account for these failures, yielding a 5000-year MTBF per wiring point. A second source of failure data for terminal block connections [5] yields an MTBF of more than 4,400 years.

Electric utility practice does not generally include automated detection and reporting of wiring failures, so the average detection-time component of the MTTR is half of the time between periodic manual testing. For our examples, we assumed an average testing interval of two years.

$$q = \left(\frac{1\,\text{year}}{5{,}000\,\text{years}} \right) = 200 \bullet 10^{-6} \tag{7}$$

Monitored Fiber-Optic Connection

In lieu of alternative data, we assumed that the failure rate for an optical fiber termination is comparable to the failure rate for a wired connection. The communications links are automatically monitored, so the assumed MTTR is 48 hours:

$$q = \left(\frac{48\,\text{hours}}{5{,}000 \bullet 365\,\text{days/year} \bullet 24\,\text{hours/day}} \right) = 1.1 \bullet 10^{-6} \tag{8}$$

Table 1 Approximate Unavailabilities of System Components

Component	Unavailability ($1 \bullet 10^{-6}$)	Availability	Equivalent Annualized Downtime (Minutes)
Monitored Fiber Connection	1	99.99989%	0.58
Relay Ethernet Interface	2	99.99978%	1.15
Point-to-Point Fiber-Optic Transceiver	10	99.99909%	4.48
I/O Module	18	99.99817%	9.60
Ethernet Switch/Dual PS	52	98.99483%	27
Ethernet I/O Module	96	99.99040%	50.46
Ethernet Switch	96	99.99040%	50.46
Wire Connection	200	99.98000%	105.12

Substation Yard Application Requirements

An example electric utility substation has four remote termination box locations in the yard. Other utilities use the terms “marshalling kiosk” or “junction box” to identify the termination boxes. At each location, there are eight contacts transmitted to the control house and eight contact outputs sent from the control house. In the control house, microprocessor-based protective relays use the contact outputs for remote control, including opening and closing a circuit breaker. The relays use sensed contact input states in control logic. The relays are connected to a local station processor that communicates with a central Supervisory Control and Data Acquisition (SCADA) system.

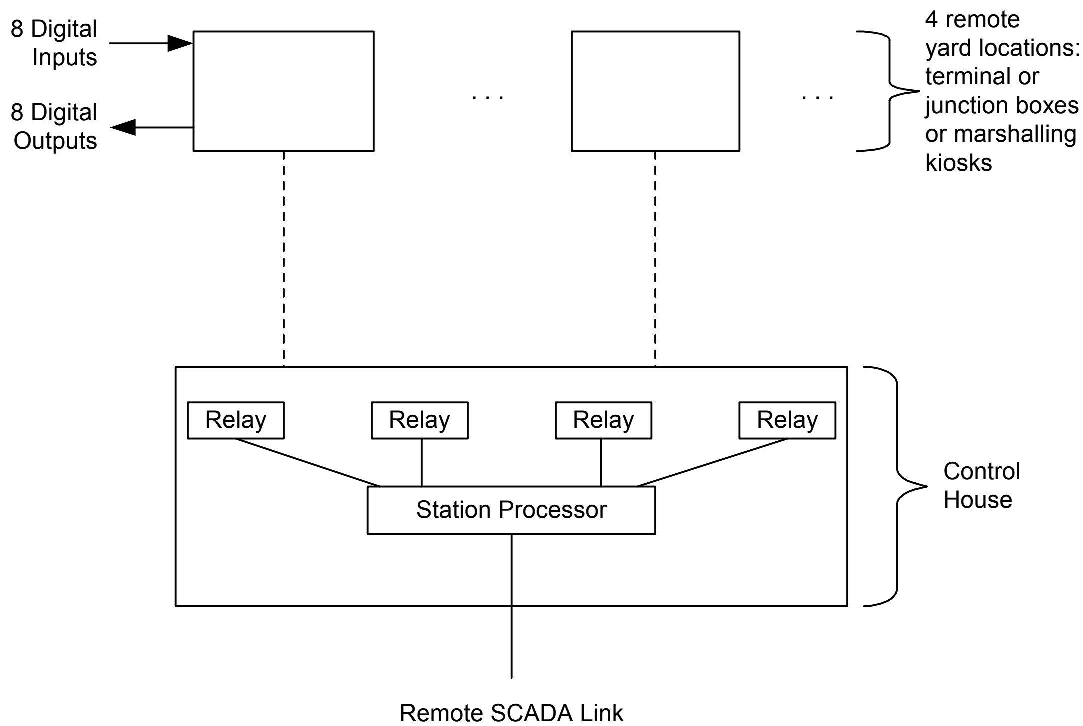


Figure 1 Substation Yard Application Case Block Diagram

Very high availability is the highest ranked criterion. The remaining criteria, in order of importance, are initial and long-term costs and diagnostic ease. To meet the needs of this utility, we evaluate the following alternatives:

1. Traditional hardwired I/O. Each I/O point has two wires connected to terminal strips in the termination box and to terminal strips on the relays in the control house.
2. Fiber-optic links with multiplexed I/O. Each I/O point is connected to an I/O module at the remote location. Two optical fibers transfer data to fiber-optic transceivers on the protective relays.
3. An Ethernet network with multiplexed I/O. Each I/O point is connected to an I/O module at the remote location. Two optical fibers connect to an Ethernet switch in the control house. Relays in the control house also communicate with the Ethernet switch.

Predicted Unavailability for Substation Yard Application Alternatives

This section includes a description and block diagram of each implementation alternative, and the predicted unavailability based on fault-tree analysis.

Traditional I/O Wiring

System Description

At each site in the yard, a termination cabinet provides terminal points to connect the wires from each external I/O point and a second terminal point for each wire in a cable to the control house.

Since we are using fault tree analysis to compare several alternatives, we focus on the differences between the alternatives. The wiring from the remote I/O to each cabinet is common to all alternatives, so we do not need to include those connections in the analysis. We do need to consider the connections for each wire from the cabinet to the terminal block on a relay, including the following:

- Cable connecting yard termination cabinet to control house terminal strip
- Cable connecting control house terminal strip to relay

The two wires for each I/O point each have four terminations, for a total of eight terminations per I/O point. For the 16 I/O points at each yard termination cabinet there are 128 connections. Figure 2 shows the block diagram of the hardwired alternative.

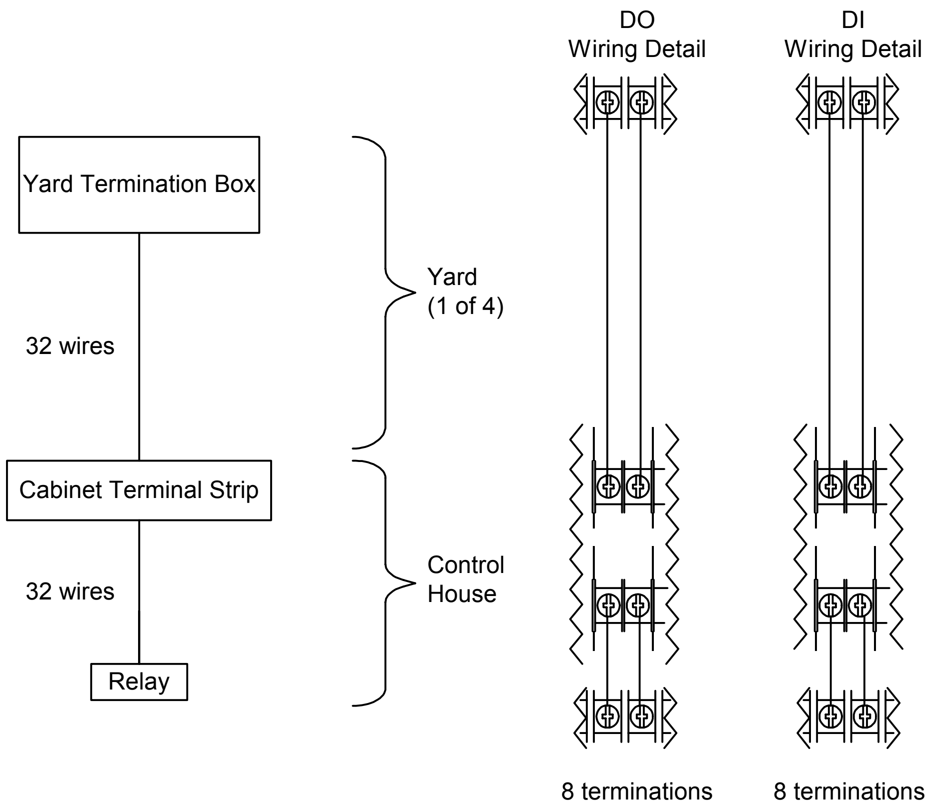
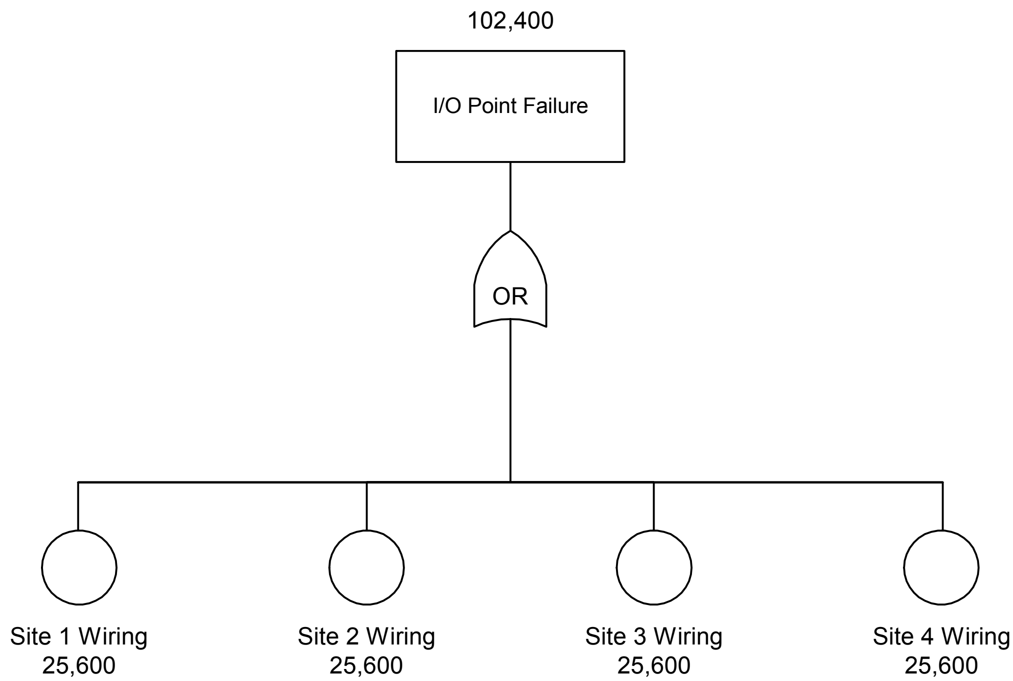


Figure 2 Hardwired I/O Block Diagram

Predicted Unavailability

The fault tree for this alternative is shown in Figure 3. The top event is "I/O Point Failure" and there is one OR gate with input for each of four sites. For each site, the unavailability "q" is 128 connections, multiplied by the hardwired connection unavailability of $200 \bullet 10^{-6}$.

The OR gate designates addition of the inputs to calculate the overall system unavailability.



Note: Multiply all unavailability numbers by 10^{-6}.

Figure 3 Hardwired I/O Fault Tree

Fiber-Optic I/O

System Description

At each site in the yard, a termination cabinet provides terminal points to connect the wires from each external I/O point. Figure 4 shows a block diagram of the system. A remote I/O module includes the terminal points for the I/O wires, so there are no other intermediate connections. The module requires two wires for dc power. Two fibers connect the I/O module to the control house.

In the control house, the fibers terminate on a fiber-optic transceiver, which is mounted on the serial port connector of a relay.

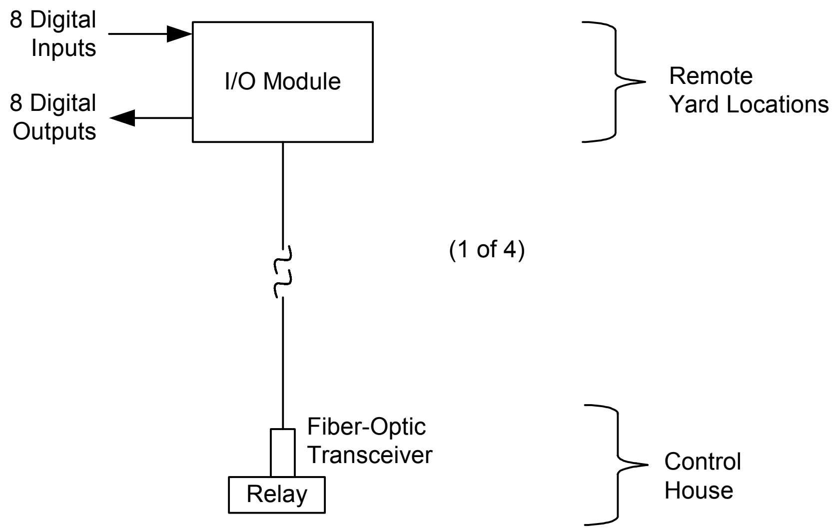


Figure 4 Fiber-Optic I/O Block Diagram

Predicted Unavailability

The fault tree for this alternative is shown in Figure 5. The top event is again "I/O Point Failure" and there is one OR gate with an input for each of four sites. For each site, another OR gate indicates summation of the following unavailabilities:

- I/O module
- Power wiring terminations
- Fiber terminations
- Fiber-optic transceiver in control house

There are four sites with identical unavailabilities, so the overall unavailability is four times that of the per-site value.

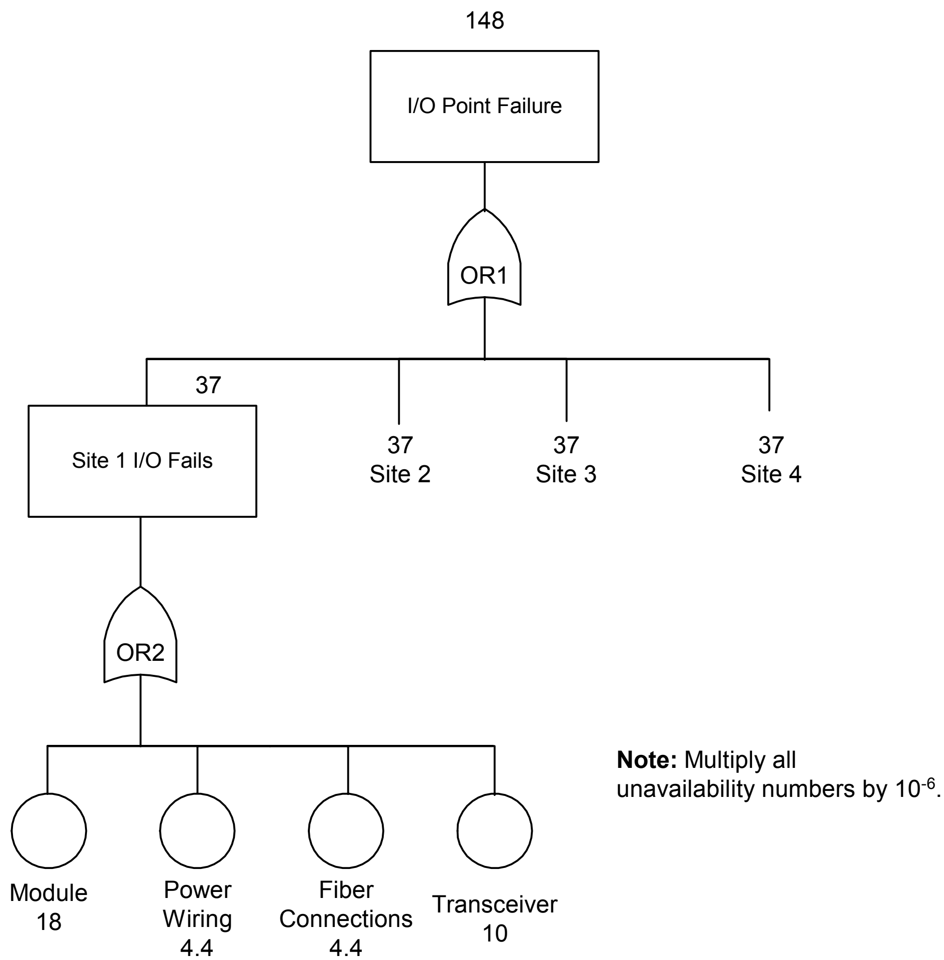


Figure 5 Fiber-Optic I/O Fault Tree

Fiber-Optic Ethernet I/O

System Description

At each site in the yard, a termination cabinet provides terminal points to connect the wires from each external I/O point. Figure 6 shows a block diagram of the system. A remote I/O module includes the terminal points for the I/O wires, so there are no other intermediate connections. The module requires two wires for dc power. Two fibers provide the Ethernet connection from the I/O module to the control house.

In the control house, the fibers terminate on a fiber-optic Ethernet switch. Two fibers connect the Ethernet interface in each relay to the switch.

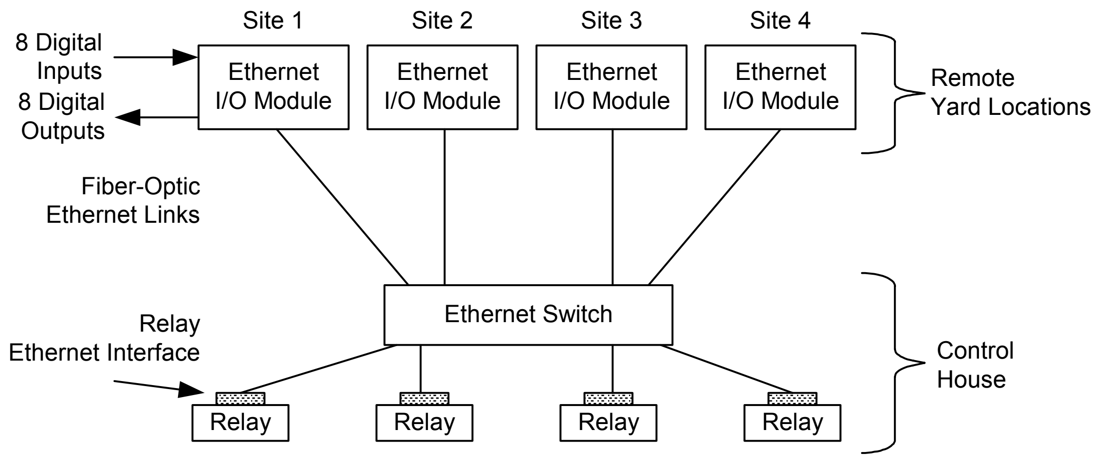


Figure 6 Fiber-Optic Ethernet I/O Alternative Block Diagram

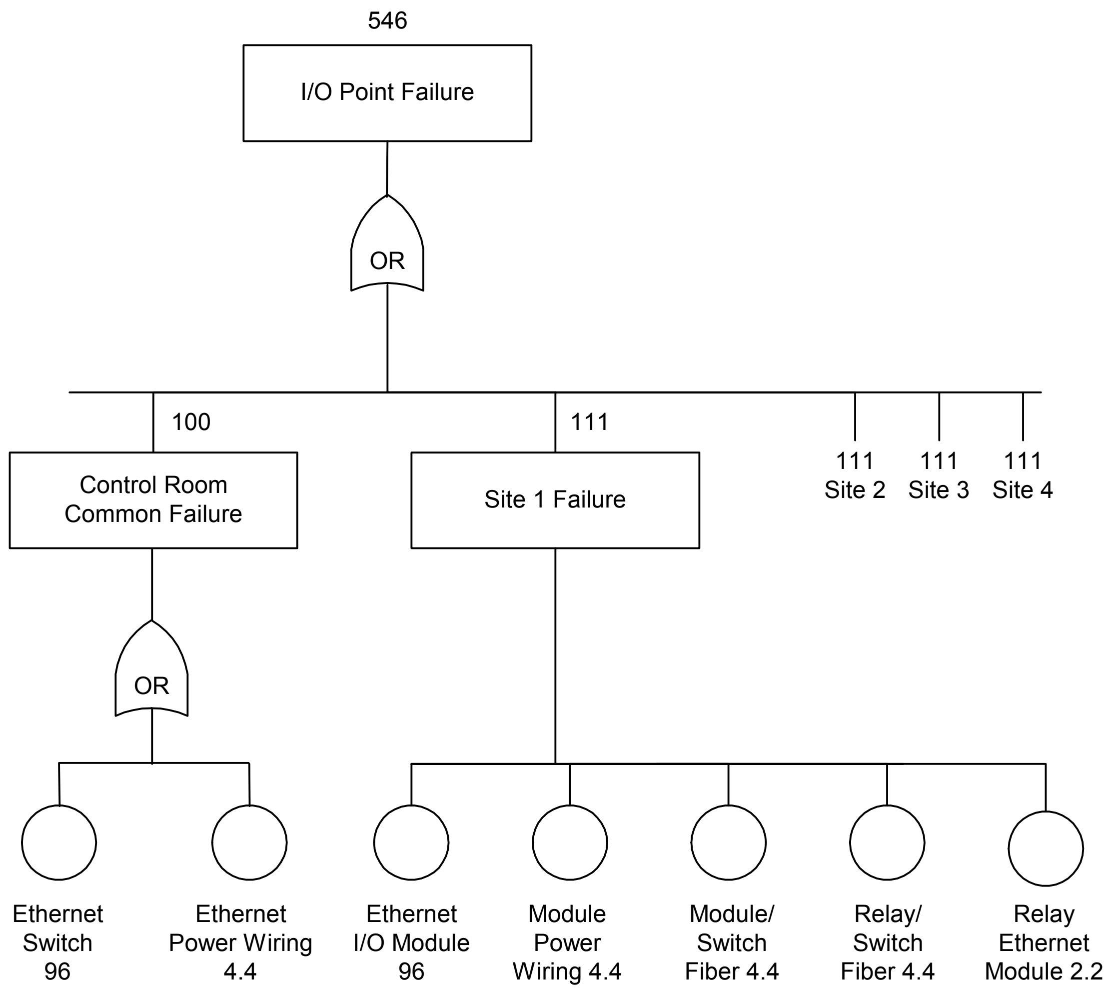
Predicted Unavailability

The fault tree for this alternative is shown in Figure 7. The top event is again "I/O Point Failure." There is one OR gate with an input for each of four sites, plus the Ethernet switch. For each site, another OR gate indicates summation of the following unavailabilities:

- Ethernet I/O module
- Power wiring terminations
- Fiber terminations between yard and Ethernet switch
- Fiber terminations between switch and relay
- Relay Ethernet interface card

The system unavailability is the sum of the four site values, plus the switch and switch power wiring. This fault tree considers only the hardware failures. Based on our assumption that the station LAN is lightly loaded, the analysis does not include failures resulting from Ethernet network overloading. Ethernet topologies and loading issues are addressed in references [6] and [7].

Substituting an Ethernet switch with dual power supplies changes the total system unavailability to $501 \cdot 10^{-6}$.



Note: Multiply all unavailability numbers by 10^{-6}.

Figure 7 Fiber-Optic Ethernet I/O Fault Tree

Unavailability Comparison

Table 2 summarizes the unavailability of each of the example systems. Another column shows the equivalent downtime per year for a large population of systems. Digital communications between the yard and the relays is 700 times more reliable than hardwired I/O. Digital communications through Ethernet is 160 times more reliable than hardwired I/O.

Table 2 Summary of System Unavailabilities

System	Unavailability ($1 \cdot 10^{-6}$)	Availability	Equivalent Annualized Downtime (Minutes)
Multiplexed Fiber-Optic Serial I/O	147	99.98529%	77
Multiplexed Fiber-Optic I/O Ethernet with Dual Power Supply Switch	501	99.94986%	264

System	Unavailability ($1 \cdot 10^{-6}$)	Availability	Equivalent Annualized Downtime (Minutes)
Fiber-Optic Ethernet I/O	546	99.94543%	287
Hardwired I/O	102,400	89.76000%	53,821

Additional Fault Tree Analyses

Fault tree analysis helps answer reliability questions, as summarized by the top event. The top event of "Any I/O Failure" addresses the question "What is the likelihood that any of the 64 I/O points will fail?"

If one of the signals for each yard site is to trip the breaker, then another valuable question to ask is "What is the likelihood that a trip signal will fail?" This top event translates to alternate fault trees that ignore the failures of the other 60 I/O points in the examples. Table 3 summarizes the availability for the trip-only top event. The value is different for only the hardwired case.

Table 3 Summary of System Unavailabilities Trip Only

System	Unavailability ($1 \cdot 10^{-6}$)	Availability	Equivalent Annualized Downtime (Minutes)
Fiber-Optic Serial I/O	147	99.98529%	77
Fiber-Optic Ethernet I/O	546	99.94543%	287
Hardwired I/O	800	99.92000%	420

One way to improve trip signal availability is to use two output points for each trip signal. This is shown on a fault tree through use of an AND gate, signifying that both signal lines must fail for a trip to fail.

Adjustments for Other Approaches

The primary example application in this paper includes field termination cabinets in the remote yard locations. Using termination cabinets, marshalling kiosks, or junction boxes is a common practice around the world for many transmission and distribution substations. Alternatively, at some substations electric utilities connect cables directly from the control house to cabinets mounted on or in electrical apparatus (e.g., breaker cabinets). To adapt the unavailability analysis to this approach, several adjustments are needed. For the hardwired alternative, the fault tree is the same as in the main example; the connections farthest from the control house are landed in the equipment cabinet instead of a termination cabinet. For the multiplexed I/O alternatives, the scope of the analysis includes the connections between the I/O modules and the equipment terminal strips. This adds 32 connections to each of four modules, plus the connections to the corresponding equipment terminal strips, for a total of 256 connections.

These connections contribute to the unavailability as shown below:

$$(256\,\text{connections}) \bullet \left(200 \bullet 10^{-6}\right) = 51{,}200 \bullet 10^{-6} \tag{9}$$

To compare the alternatives that use an approach with no intervening cabinets, add 51,200 • 10^{-6} to each multiplexed I/O alternative. To compare these options to all of the alternatives in the main example, you must also add 51,200 • 10^{-6} to every alternative in the original example.

A fully redundant protection and control system consists of two identical systems, each with an identical fault tree. The redundant system is represented by connecting the outputs of these fault trees into an AND gate. The unavailability of the total system is the square of the unavailability for each half of the system.

TRADEOFF SUMMARY

This paper primarily addresses equipment reliability, but other factors also impact I/O architecture comparisons.

We used fiber-optic links in the multiplexed I/O examples because they are safer, protect equipment, and have higher data integrity than systems that use wire.

To compare specific installations, use the actual quoted prices for the job. As a general guideline, using example equipment prices and termination labor guidelines, the alternatives are ranked below in order of ascending costs:

1. Fiber-Optic Serial I/O
2. Fiber-Optic Ethernet I/O
3. Hardwired I/O

The difficulty of diagnosing I/O problems impacts the amount of training required, the cost of specialized test equipment, and the MTTR. Using the equipment for our example cases, below we have ranked the alternatives in ascending order of diagnostics ease:

1. Serial Fiber-Optic I/O

Indication LEDs on the I/O modules show the status of digital inputs and outputs. Point-to-point links share no communications with other devices, allowing easier isolation of problems.

2. Hardwired I/O

It is time consuming to check continuity on the large number of wiring connections. It is often difficult and time consuming to find I/O wiring problems that inadvertently connect the station battery to ground.

3. Fiber-Optic Ethernet I/O

Indication LEDs on the I/O modules show the status of digital inputs and outputs. If there is a problem on the Ethernet network, specialized equipment and training are required.

Table 4 summarizes the tradeoff factors for the alternatives.

Table 4 Summary of Comparison Factors

System	Unavailability ($1 \bullet 10^{-6}$)	Safety/Noise Immunity	Cost Ranking	Diagnostic Ease
Fiber-Optic Serial I/O	147	Yes	1	1
Fiber-Optic Ethernet I/O with Dual Power Supply Switch	501	Yes	3	3
Fiber-Optic Ethernet I/O	546	Yes	2	3
Hardwired I/O	102,400	No	4	2

METHODOLOGY SUMMARY

This paper documents easily applied methods to compare the reliability of I/O subsystem architectures, using example or average failure rates. We used representative equipment failure rates based on actual field data and from published reliability data sources. Beyond the example cases, there are many more possible configurations and equipment options available to transfer I/O status. The reader can apply the same steps that we used in our examples to compare the reliability of alternatives:

1. Obtain the MFBF for each device under evaluation, if possible. Alternatively, use published averages for the device class, or for other devices of similar complexity.
2. Determine a reasonable MTTR that includes the average time to detect, repair, and fully restore the device and system to service. For failures that are automatically detected and reported, the MTTR will be much lower than for failures that are detected only via periodic testing.
3. Calculate the unavailability by dividing the MTTR by the MTBF, with care to use the same time units for both quantities.
4. Construct a fault tree using these unavailabilities, for the portions of the system that are different between the alternatives.
5. Compare the results of the fault tree analysis for each alternative.
6. Identify opportunities to improve reliability through adding redundancy, as appropriate.

CONCLUSIONS

Of the examples we examine in this paper, the most reliable and least expensive alternative for providing I/O is multiplexed I/O with point-to-point fiber-optic links. The alternative of using Ethernet over fiber to accomplish the same thing is somewhat less reliable and costs more. Other uses of the same Ethernet network spread the cost over more functions, but increased loading can impact the I/O transfer time. The alternative with the lowest reliability and highest overall cost is the hardwired I/O.

It is important that system designers understand the reliability of the systems that they design. Manufacturers should be willing to provide MTBF data to help them analyze and compare their alternatives.

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Biographies

Gary W. Scheer received his B.S. in Electrical Engineering from Montana State University in 1977. He worked for the Montana Power Company and the MPC subsidiary, The Tetragenics Company, before joining Schweitzer Engineering Laboratories, Inc. in 1990 as a development engineer. He has served as Vice President of the Research and Development Division, and of the Automation and Engineering Services Division of SEL. Mr. Scheer is now in the Marketing, Research and Development Division as Senior Marketing Engineer for automation and communications products. His biography appears in Who's Who in America. He holds two patents related to teleprotection. He is a registered professional engineer and member of the IEEE and the ISA.

Roy Moxley has a B.S. in Electrical Engineering from the University of Colorado. He joined Schweitzer Engineering Laboratories in 2000 as Market Manager for Transmission System Products. Prior to that, he was with General Electric Company as a Relay Application Engineer, Transmission and Distribution (T&D) Field Application Engineer, and T&D Account Manager. He is a registered Professional Engineer in the State of Pennsylvania.