Comparison of Fiber-Optic Star and Ring Topologies for Electric Power Substation Communications

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INTRODUCTION

Electric power substation monitoring and control systems often employ intelligent electronic devices connected by fiber-optic communications. Engineers select fiber because it:

- isolates equipment from hazardous and damaging ground potential rise,
- is immune to radio frequency interference and other electromagnetic interference,
- eliminates data errors due to communications ground-loop problems,
- allows longer signal paths than EIA-232 copper connections.

This paper compares single ring, single star, dual counter-rotating ring, and redundant fiber-optic system topologies in the following areas:

- predicted reliability using fault tree analysis,
- estimated costs for equipment, fiber, installation, maintenance, and expansion,
- data transfer issues,
- ease of diagnosing system problems.

You can apply the methods described in this paper to evaluate communications within a substation or between substations. Two actual case comparison studies provide tools and methods to evaluate tradeoffs between the various topologies and select the fiber-optic communications strategy that best matches your requirements.

DEVICE FAILURE RATES AND UNAVAILABILITIES

A system is comprised of components. The reliability of the components can be expressed 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). By strict definition, MTBF is the sum of the mean time to fail (MTTF) plus the mean time to detect and repair (MTTR). For the equipment in the examples, the repair time is quite small compared to the MTBF, so this paper approximates the MTBF to be equal to the MTTF.

Availability and unavailability are often expressed as probabilities [1]. For the equipment used in the evaluations below, all of the 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.

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

where: q is unavailability
λ is some constant failure rate
MTTR is the average downtime per failure
$\text{MTBF} = \frac{1}{\lambda}$ 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 $\frac{\text{MTTR}}{\text{MTBF}}$ [1][2][3].

For the devices used in the examples, the time to detect and repair each failure is 48 hours, or downtime MTTR = 48 hours. 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.

Programmable Logic Controller (PLC)

The nuclear and process industries have evaluated PLC failure rates. Data from Reference 1 yields an MTBF of 17 years for PLCs from a variety of manufacturers. Assume that a failure can be detected and repaired within 48 hours; the unavailability is

$$q = \left(\frac{48 \text{ hours}}{17 \text{ years} \cdot 365 \text{days / year} \cdot 24 \text{ hours / day}} \right) = 322 \cdot 10^{-6}$$

$$q \cong 320 \cdot 10^{-6}$$

Substation Communications Processor

Data from one manufacturer’s experience shows an MTBF of 200 years for a communications processor designed for a substation environment. The unavailability is:

$$q = \left(\frac{48 \text{ hours}}{200 \text{ years} \cdot 365 \text{ days / year} \cdot 24 \text{ hours / day}} \right) = 27 \cdot 10^{-6}$$

$$q \cong 30 \cdot 10^{-6}$$

Protective Relay as Data and Control Component

Microprocessor-based protective relays have an unavailability of $q \cong 100 \cdot 10^{-6}$ [2]. When relays are connected in a multidrop network, some failure modes can corrupt all communications on the network. Assume that of all relay failures, only 20% prevent communications between other devices. The unavailability of the network due to the “network failure mode” of a relay is, therefore, $q \cong 20 \cdot 10^{-6}$.

Point-to-Point Fiber-Optic Modem

Data from one manufacturer's experience shows an MTBF of 600 years for a point-to-point fiber-optic ring modem designed for a substation environment [1]. The unavailability is:

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

$$q \cong 10 \cdot 10^{-6}$$

Fiber-Optic Ring Modem

Data from manufacturers' experience shows an MTBF of 68.5 years for a fiber-optic ring modem. The unavailability is:

$$q = \left(\frac{48 \text{ hours}}{68.5 \text{ years} \cdot 365 \text{ days / year} \cdot 24 \text{ hours / day}} \right) = 79.99 \cdot 10^{-6}$$

$$q \cong 80 \cdot 10^{-6}$$

Fibers in Trench Interrupted by Excavation

The customer in the Distribution Loop case below, concluded from their prior experience that once every three years the trench between substations will be inadvertently excavated, and the fibers will be broken. The unavailability is:

$$q = \left(\frac{48 \text{ hours}}{3 \text{ years} \cdot 365 \text{ days / year} \cdot 24 \text{ hours / day}} \right) = 1826 \cdot 10^{-6}$$

$$q \cong 1830 \cdot 10^{-6}$$

Table 1: Approximate Unavailabilities of Several Components

Component	**Unavailability · 10^{-6}**
Point-to-point fiber-optic modem	10
Protective relay multidrop network failure	20
Substation communications processor	30
Substation DC [2]	50
Fiber-optic ring modem	80
Protective relay hardware	100
PLC	320
Fibers in trench interrupted by excavation	1830

Note: The components most available have the smallest unavailability numbers.

DISTRIBUTION LOOP CASE

The utility has 20 small substation sites, an average of 1,325 feet apart, in a large ring. Each site, or "node," has equipment to monitor, protect, and control two line breakers and the tapped feeder. The utility is committed to underground fiber for the application and is faced with a choice of topologies. Very high availability is the highest ranked criterion, due to the sensitive nature of the attached loads. The remaining criteria, in order of importance, are cost, data transfer issues, and diagnostic ease.

To meet the needs of this utility, evaluate four systems using the stated criteria. The four alternatives are:

1. A single ring, where each node has an incoming fiber connection and an outgoing fiber connection. The input fiber is connected to the output of the node counterclockwise on the ring, and the output fiber is connected to the input of the adjacent node in the clockwise direction.
2. A star, where a pair of fibers connects a master point to each node.
3. A dual ring, where each node has a fiber-optic ring modem with four fibers. Two fibers are used identically to the clockwise single ring above, and two fibers are used for a second ring, moving data in the opposite (counterclockwise) direction.
4. Dual stars, where a pair of fibers connects a master point to each node on the distribution ring, physically clockwise in the trench from the master. A second pair of fibers is installed counterclockwise in the trench from the master site to each node.

PREDICTED UNAVAILABILITY USING FAULT TREES

Fault Tree Construction Examples

In this section, fault trees are used to determine the unavailability for four distribution loop alternatives, each employing a different topology. The analysis for the single ring alternative includes fault tree construction details.

Single Ring

A fault tree is used to determine the probability of a particular failure of interest. It models the part of the system that influences the particular failure. The "failure of interest" is called the top event. Consider the example of a single ring system where each substation has a communications processor connected to a multidrop fiber-optic ring modem. Twenty of these substations are connected to a master system through another fiber-optic ring modem. A block diagram of this single ring system is shown in Figure 1.

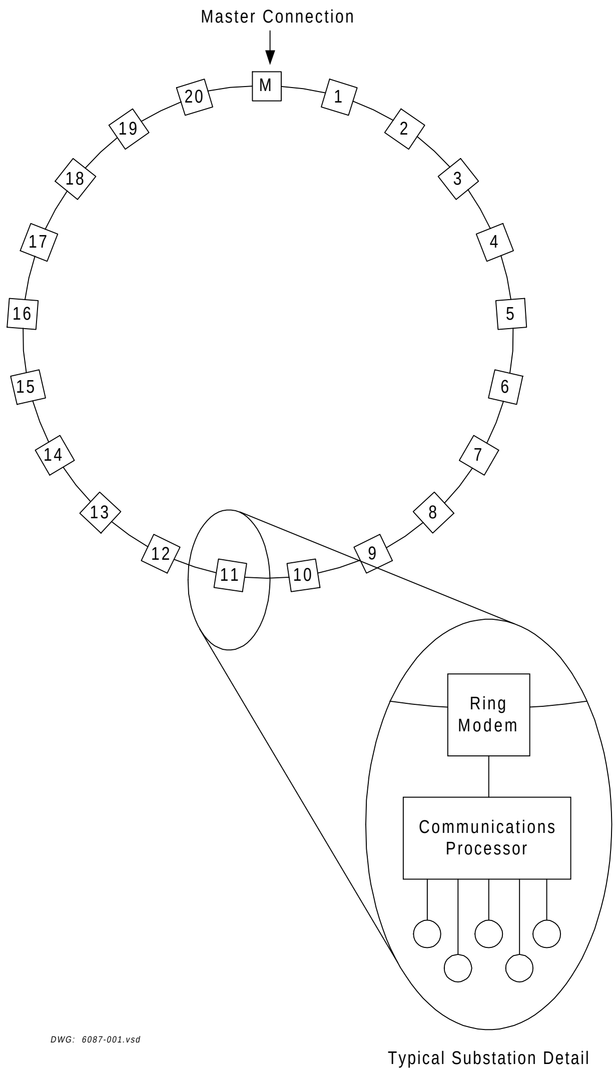

Figure 1: Single Ring System

To find the probability that communications will be unavailable at a given substation, use a fault tree. Summarize the top event in a box at the top of the fault tree as shown in Figure 2. Build the fault tree by breaking the top event into lower-level events. Use an OR gate to express the idea that any of several failures can cause the top event. Lower-level events can be basic events, which are depicted with a circle. These basic events are failures of devices such as the modems, the dc subsystem, or communications processors. If a reasonable unavailability exists for the device, no further analysis of the device is required. If a device does not have a simple unavailability, you may need to analyze it with its own fault tree and internal events to calculate an unavailability.

It is important to identify all causes of the event, both inside and outside the part of the system you are evaluating. This discipline helps you find opportunities to improve overall reliability and calibrate the contribution of alternatives relative to other common failure causes. Use OR gates to combine multiple events when any one failure will result in the failure of the event above the gate. Use AND gates to combine multiple events when all devices directly below the gate must fail in order to have a failure above the gate.

After entering event data, analysis of the fault tree shown in Figure 2 is straightforward using a single simplifying assumption known as the Rare Event Approximation. It ignores the possibility that two or more rare events can occur simultaneously. For two events, each of which occurs with probability less than 0.1, the Rare Event Approximation produces less than 5% error. When the events in question are failures, the Rare Event Approximation is always conservative. The approximate probability of failure is always greater than the actual probability of failure [2].

Employing the Rare Event Approximation, calculate the unavailability associated with each event expressed with an OR gate as the sum of the unavailability for each input to the OR gate. For example, the unavailability associated with OR Gate 2 is the sum of the unavailabilities of the three inputs to that OR gate. The unavailability associated with the top event q, is simply the sum of both basic events.

$$q = 160 \cdot 10^{-6} + 4430 \cdot 10^{-6} = 4590 \cdot 10^{-6}$$

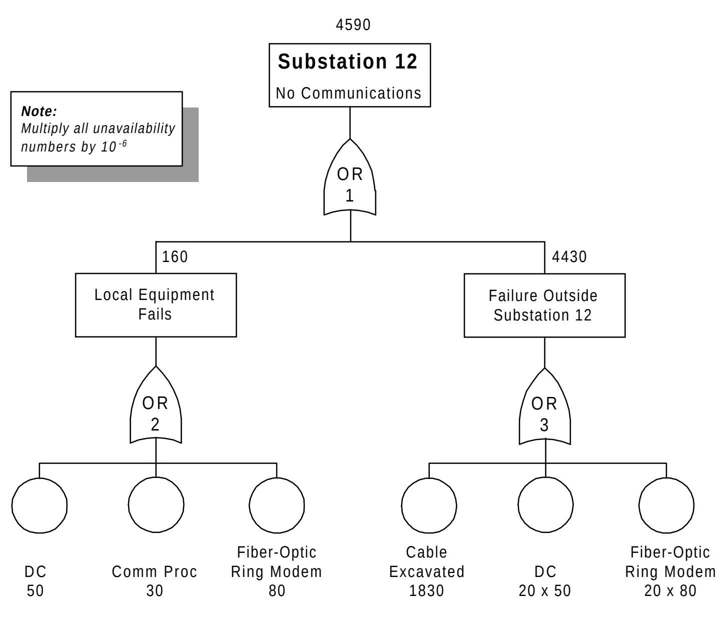

Figure 2: Fault Tree for Single Ring System

Communications Processor Star System

The system shown in Figure 3 includes the communications processor at each site connected directly to a master level communications processor through a dedicated pair of fibers and point-to-point fiber-optic modems. At Substation 10, a communications processor is the hub for Stations 11-20. The same trench configuration is used as in the ring example, but the trench has multiple fiber pairs instead of two pairs. Figure 4 is the fault tree for a failure to communicate with Substation 12 for this system. A point-to-point fiber-optic link to the communications processor at Substation 10, and the point-to-point link from Substation 10 to the master, comprise the path for Substation 12.

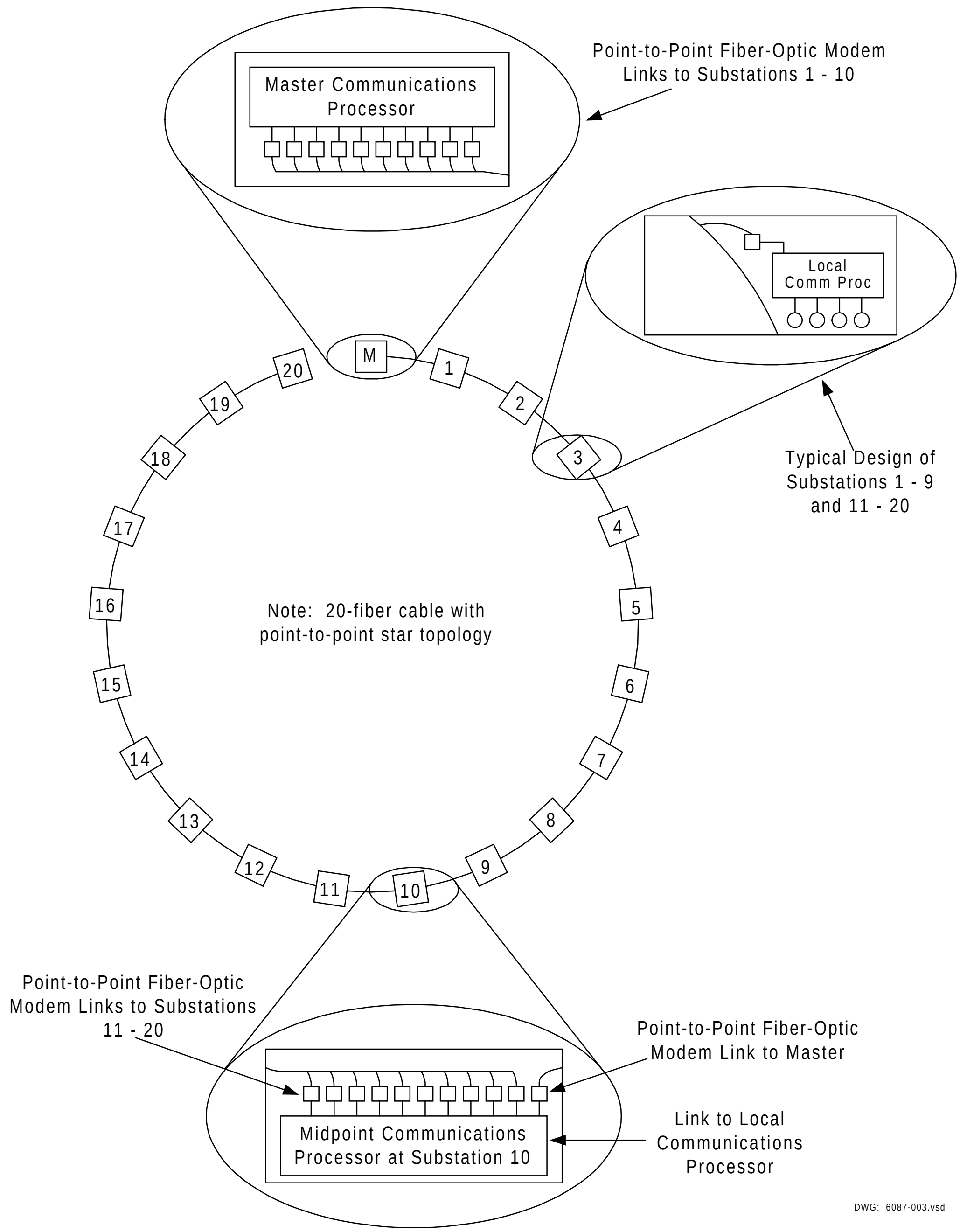

Figure 3: Communications Processor Star System

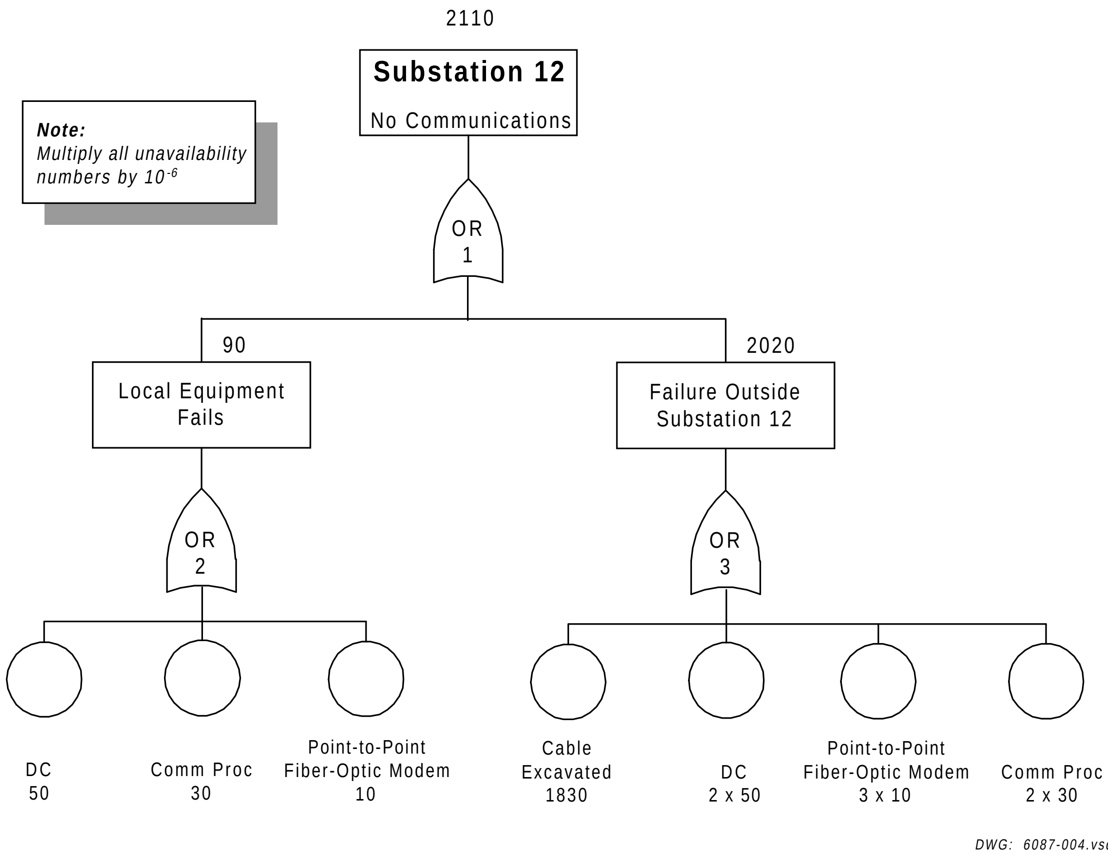

Figure 4: Fault Tree for Communications Processor Star System

Counter-Rotating Redundant Rings

The fault tree in Figure 5 is for a system with two redundant rings. These are counter-rotating rings because one is transmitting in a clockwise direction and the other in a counterclockwise direction. This topology is used so that in the event of a single excavation or modem failure, communications to a given node will be disrupted in one direction only; the other path around the ring will remain intact to the master. Each ring is as shown in Figure 1, with a fiber-optic ring modem and a communications processor connected at each of 20 substation sites.

AND gates represent a combination of components where all inputs must simultaneously be failed in order to cause the top event. To obtain the combined unavailability, multiply the unavailability values together.

Figure 5 introduces the use of a triangle as a drawing connector. The convention for the definition of the connector has a line connecting to the side of the triangle. Each reference to the defined tree-segment has a line connected to the apex of the triangle.

There are two paths to the master from Substation 12; one path is through Stations 13 - 20, the other path is through Stations 1 - 11. If the dc or fiber-optic ring modem fails at any station in a path, the entire path fails.

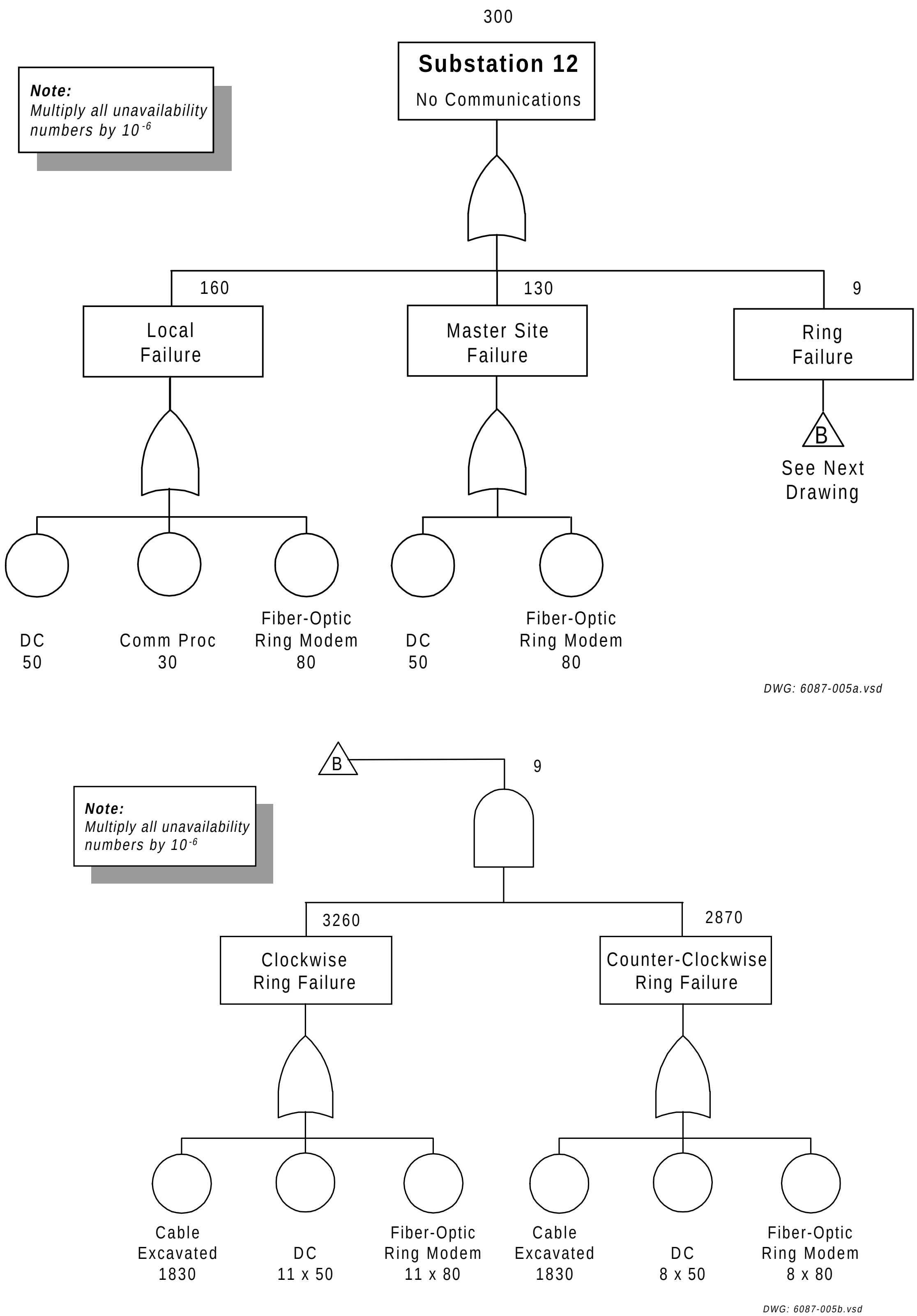

Figure 5: Fault Tree for Counter-Rotating Ring Network

Redundant Communications Processors Star System

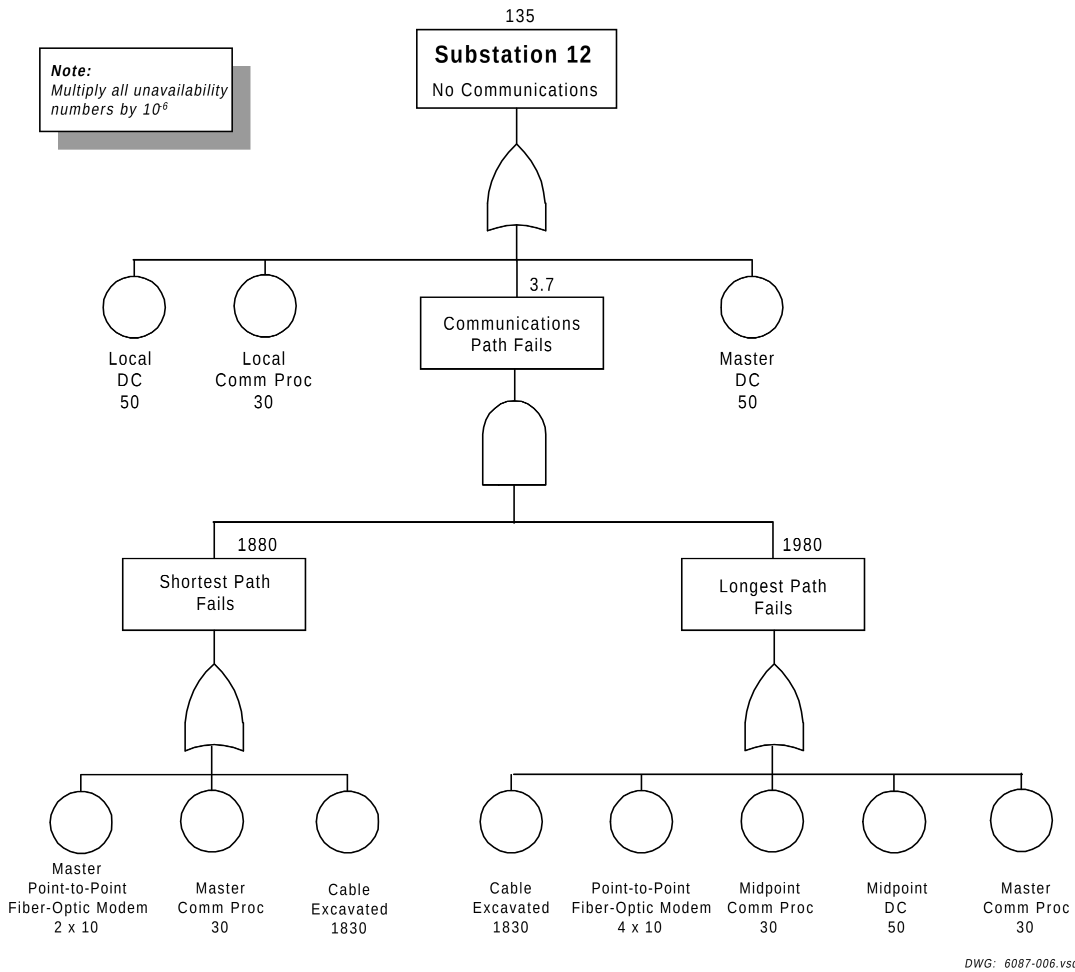

Figure 6: Fault Tree for Redundant Communications Processor Star System

Unavailability Comparison

In Table 2, observe that for these examples the least reliable system has 34 times the unavailability of the most reliable system. Independent stars have about one-half of the unavailability of counter-rotating rings, i.e., the stars are more reliable.

Table 2: Summary of System Unavailabilities

System	Unavailability $\cdot 10^{-6}$
Independent Stars	135
Dual Counter-Rotating Rings	300
Single Star	2110
Single Ring	4590

Note: The systems most available have the smallest unavailability numbers.

The reliability of the equipment connected to the master node is also important; in these examples only the master dc and communications devices were included. Alternatives for the master equipment should be subjected to similar analysis for a complete predictability rating.

INITIAL COST COMPARISON

Equipment and fiber costs are based on list prices of representative products, each with at least the MTBF used in the unavailability calculations earlier in this paper. For each fiber segment, the labor costs are based on an average of $45 to terminate each end of the fiber and test the end-to-end connection. The following costs are not included in the comparison because they are not sensitive to the topology employed: excavate and bury fiber, mount and wire equipment, and supply equipment common to alternatives at each node. See Appendix A for additional cost detail.

Table 3 summarizes initial material and termination costs of the alternatives. The ring examples use a two-fiber direct burial cable. The single star uses multiple two-fiber cables; 10 cables from the primary communications processor to each of the first 10 nodes, and 10 from the node 10 communications processor to nodes 11 - 20. The dual star uses one 20-fiber cable around the loop. For a given node, two fibers are connected in one direction to the primary communications processor and in the other direction to the backup communications processor.

The examples are based on representative costs. To evaluate actual alternatives, use the actual costs of specific products and services.

Table 3: Distribution Loop Approximate Comparative Costs*

	Single Star	Dual Star	Single Ring	Dual Ring
Initial Equipment Cost	$19,000	$38,000	$43,750	$47,500
Initial Fiber Cost	$56,990	$91,350	$10,320	$10,320
Total Initial Material Cost	$75,990	$129,350	$54,070	$57,820
Termination/Test Labor	$1,980	$3,960	$990	$1,890
Total Initial Cost	$77,970	$133,310	$55,060	$59,710

*** Note: Costs calculated with 1,325 feet between nodes.**

LIFE-CYCLE COST ISSUES

The equipment installed at each node may be in service for 10 to 20 years. In that time, it is likely that the communications protocol to the SCADA master may change. In a star system, the change to another up link protocol can be accommodated at the top tier hub, often with a software upgrade or by changing a protocol card. In a ring system, either a protocol conversion device must be added, or devices at all of the nodes must be upgraded.

The cost to repair a dig-through on a two-fiber cable will be somewhat less than the repair of a 20-fiber cable, even though either will typically be accomplished within a day. Assume that there are approximately 3 hours involved in preparing the site for splicing and in post splice work. Some suppliers of splicing equipment claim 3 minutes per splice; use 12 minutes per splice to cover setup and testing. The two-fiber cable would have 24 minutes, and the 20-fiber cable would have 240 minutes for this repair step.

If there are three dig-ins in a 10-year period, as predicted in the unavailability calculation, then an additional 648 minutes, or 10.8 hours, would be expended in 10 years for the dual star compared to the dual ring.

DATA TRANSFER ISSUES

In general, a star topology has one bidirectional communications data channel dedicated to each device. A ring topology has “n” nodes sharing the same data channel. If the two systems have the same physical data rate, then the time to transfer data from all nodes to the next level is longer for a ring than a star. Assume 100 bytes of data are transferred from each of 20 nodes, at an asynchronous bit rate of 19,200 bits-per-second. Each byte requires a start bit, 8 bits of data, and a stop bit, or 10 bits-per-byte. In a star configuration, a protocol can be employed with error checking but without overhead for collision avoidance or token passing. Using 10 bytes of overhead for the 100-byte message, the transfer time, t, is:

t = [(110 bytes/node) · (10 bits/byte) · (1 node)] / (19,200 bits/second)

t = .06 second for data transfer into star hub

The numbers below are useful in comparing the times to transfer data through the master connection. If the 100 bytes of data per node need to be transferred to a higher level, such as a SCADA master, then the SCADA master would make four block transfers, each consisting of 30 bytes of overhead and 500 bytes of data.

t = [(530 bytes/block) · (10 bits/byte) · (4 blocks)] / (19,200 bits/second)

t = 1.1 seconds to transfer all data to the SCADA master

In a ring system, additional overhead bytes in the request and response are needed for addressing and network management. Typical multidrop protocols have from 30 to 80 percent overhead. Assume 30 bytes of overhead for a block transfer. The time to transfer data from all nodes to the next level for a ring system is:

t = [(130 bytes/node) · (10 bits/byte) · (20 nodes)] / (19,200 bits/second)

t = 1.35 seconds for data transfer via ring

With a star topology, you have the option to accommodate different bit rates and protocols for each node, and to communicate with the upper level in larger blocks and at a faster bit rate. When a ring is used to gather all data and report directly to the master, then all devices on the ring must use the same protocol, and the bit rate is dictated by the maximum bit rate of the slowest device on the ring. For example, in the comparison above, if the node devices limited the bit rate to 19,200, this would be as fast as the ring system could communicate with the master. If the hub in a star system is capable of communicating at a higher bit rate with the master, it could do so, even if the nodes below it are communicating at both slower and faster speeds.

COMMUNICATIONS DIAGNOSTIC EASE

The LED indicators for each channel, found on most hubs in star topologies, make it very easy to see at the hub if there is communications traffic with a particular node. You can observe whether data requests are being sent or received. You can also detect a locked-up transmitter by observing a constantly asserted LED.

Contrast this simplicity to a shared network such as a single ring, where a single node can fail and stop communications for the entire ring. To overcome this disadvantage, some ring modems include advanced diagnostic tools to help in determining which node is causing a network problem. These diagnostics add some complexity to the system and use some of the bandwidth, but are preferable to most multidrop systems where it is very difficult to detect the cause of some problems.

ADDITIONAL CONSIDERATIONS

The alternatives are based on defined responses to a stated need. Variations in the equipment or topology impact the analysis. Consider that some ring modems support more than one virtual channel, rather than the single channel modeled in the alternatives. The main impact of using an additional virtual channel is on the data throughput. Transfer of all data takes one-half as long with two 10-node channels as it does with one 20-node channel.

The alternatives are based on dedicated use of the fiber for the instrumentation and control system. If a fiber network is shared with other electric utility or common carrier applications, these other applications may provide sufficient revenue to pay for the fiber and common equipment to provide for all of these needs. For example, if T1 multiplexors are employed to provide communications between the nodes, use fault tree analysis to assess the impact on the instrumentation and control (I&C) channels from other failure sources and the unavailability of all of the multiplexor equipment. In this case, the incremental costs for the I&C system are for channel cards and cables.

SUMMARY

The table below summarizes key comparison items for the distribution loop case. A [-] signifies a comparative disadvantage; a [+] signifies a comparative advantage.

Table 4: Key Comparisons Summary for Distribution Case

Criteria	Single Star	Dual Star	Single Ring	Dual Ring
Unavailability	[-] 2110	[+] 135	[-] 4590	[-] 300
Initial Cost	[-] 78 k	[-] 133 k	[+] 55 k	[+] 60 k
Life Cost	[+]	[+]	[-]	[-]
Diagnostic Ease	[+]	[+]	[-]	[-]
Data Transfer	[+]	[+]	[-]	[-]
IED Independence	[+]	[+]	[-]	[-]

SUBSTATION CASE

This example analysis is based on an actual case with some adjustments for more general application. A new I&C system will be provided for the distribution station depicted in the one-line diagram in Figure 7. Protection is to be upgraded to a total of 18 microprocessor-based relays, including two distance relays for the east and west transmission lines, two differential current relays to protect 2 transformers, and 14 distribution feeder relays to protect 14 distribution feeders.

The objective of the I&C system is to provide reliable remote control and data acquisition for a SCADA system, using the 18 microprocessor-based relays for data acquisition and control. The engineer selected optical fiber for communications in the substation, primarily to ensure that protective relays would not be damaged by electrical transients on copper communications lines. For compatibility with an existing SCADA master, the system must emulate a single RTU using DNP V3.00 Level 2 protocol.

For each feeder and transmission line, eight analog input points are to be reported: A-, B-, and C-phase amps and volts, and three-phase watts and vars. For each transformer, three analog inputs are retrieved: A-, B-, and C-phase amps. Another 16 bytes of digital input and virtual digital input data are retrieved per relay.

The stated design evaluation criteria are listed below, ranked in order of customer importance.

- Prevent relay damage through communications links,
- Provide lowest unavailability at lowest initial and life-cycle cost.

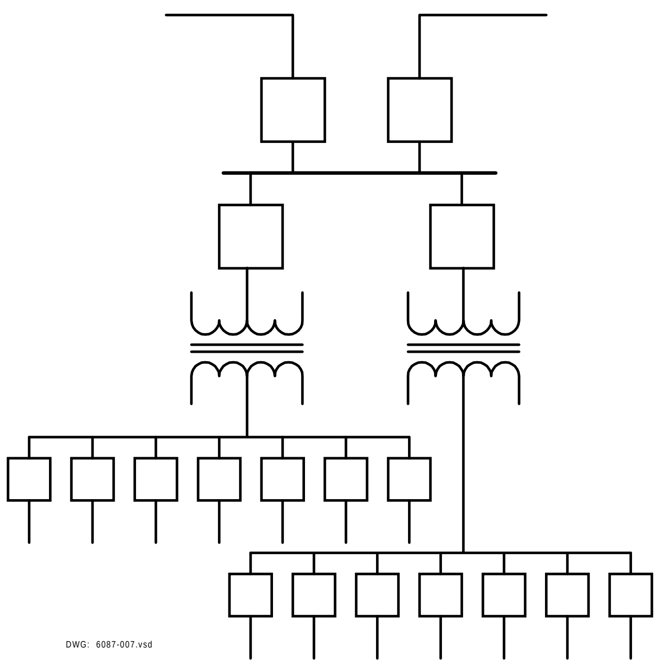

Figure 7: One-Line Diagram, Fourteen Feeder Distribution Substation

The protection, monitoring, and control options contrasted in this example are:

- Single Ring
- Dual Counter-Rotating Fiber Ring
- Redundant Protective Relays and Dual Ring
- Single Multitiered Star with Communications Processors
- Dual Star with Redundant Protective Relays and Communications Processors

PREDICTED RELIABILITY

In this example case, the fibers are inside the substation in the direct physical control of the utility. The utility has not experienced dig-throughs within substations since instituting work control processes. Therefore, no unavailability due to inadvertent excavation is included in the analysis. For a complete analysis of instrumentation and control system availability, include other devices that impact the ability to monitor, control, and communicate data, as in Reference 1. The objective of this example case is to contrast the fiber topologies, so instrument transformers, breakers, and external communications lines are not included in the analysis. All fault trees are for the top event "Unable to Control or Monitor Feeder 12."

Ring Substation Examples

The single ring includes a fiber-optic ring modem for each relay. A master fiber-optic ring modem is connected to the ring and to a PLC. The PLC provides the data conversion to present information as a single node address to the DNP V3.00 SCADA master link. The "Relay Fails Network" event reflects the failure mode that a single device can continuously broadcast and prevent communications on the loop. Figure 8 shows the fault tree for the single ring.

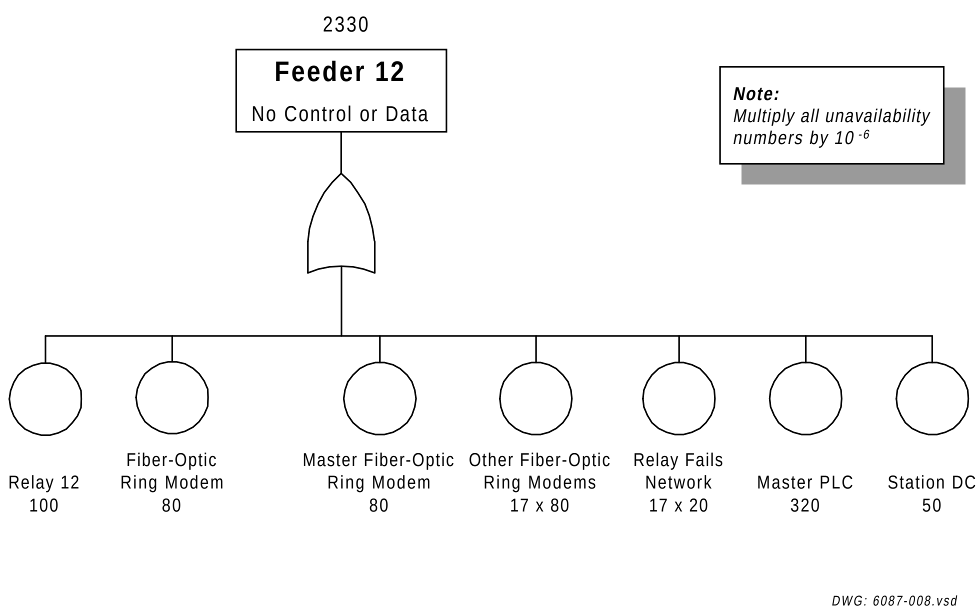

Figure 8: Single Ring Substation Fault Tree

The fault tree for a dual ring system is shown in Figure 9. The common failures have the same contribution to the top event unavailability as the single ring system, but the redundant paths of the two rings effectively eliminate the impact of the fiber rings on the overall unavailability. Figure 10 is the fault tree for redundant relays and dual rings.

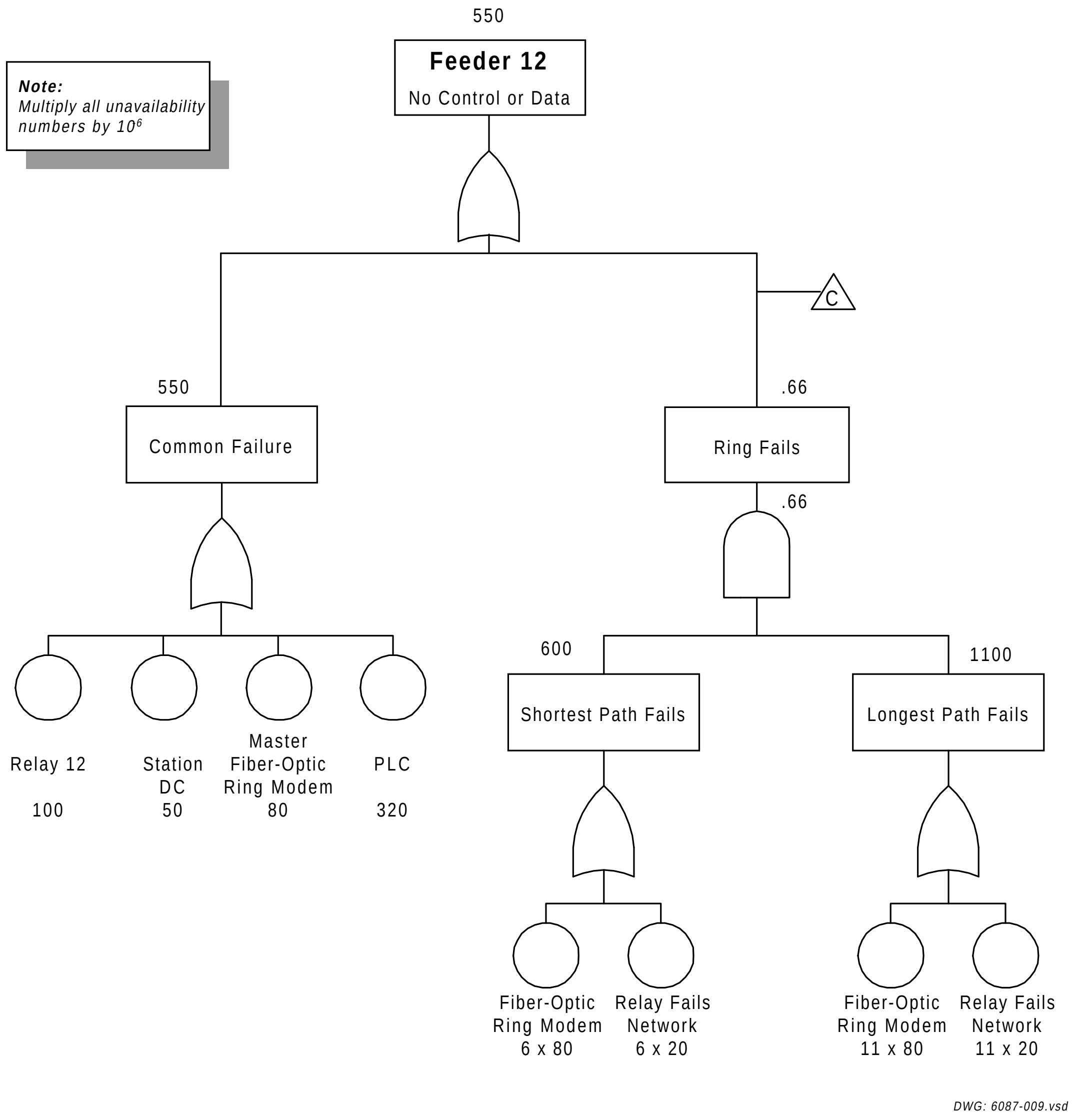

Figure 9: Dual Ring Substation Fault Tree

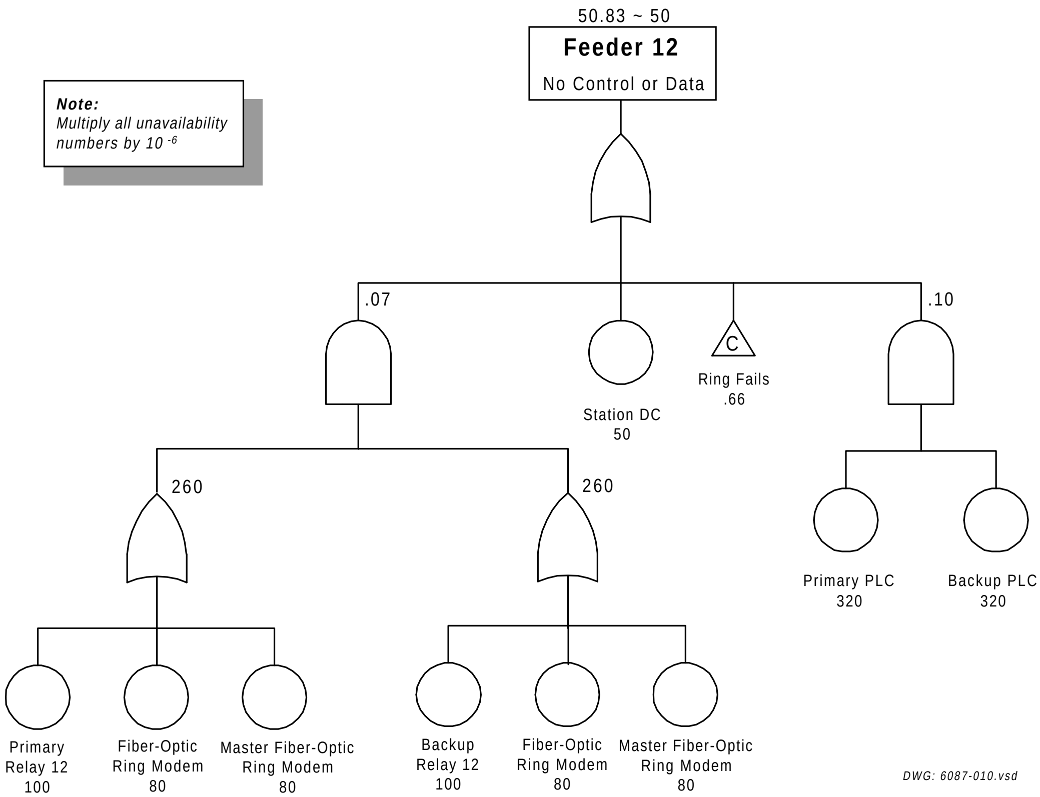

Figure 10: Redundant Protective Relays and Rings Substation Fault Tree

Star Substation Examples

Two communications processors are included to accommodate the 18 relays. Each relay is connected to one of the communications processors using two fiber-optic ring modems and a preterminated two-fiber cable. The upper tier communications processor includes information from directly connected relays and the lower tier communications processor. The single multi-tiered star fault tree is shown in Figure 11.

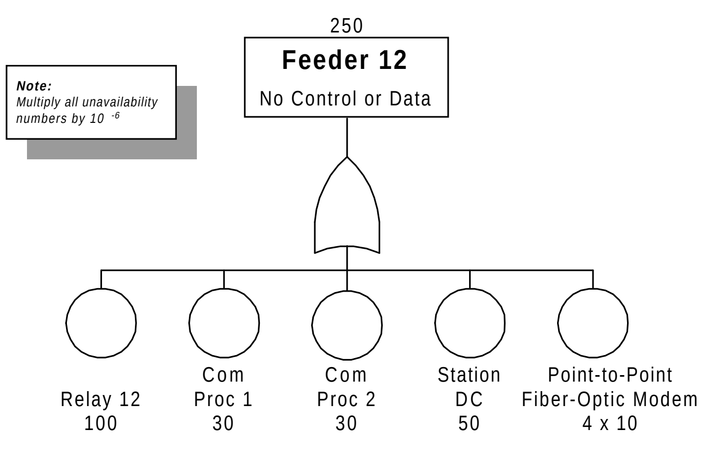

Figure 11: Single Star Substation Fault Tree

The dual star case consists of two copies of the single star case. The fault tree in Figure 12 is for a system with primary and backup protection, and communications. To maximize protection system availability, primary and backup relays are often employed, as in this case. Independent stars maximize communications availability (see Table 5).

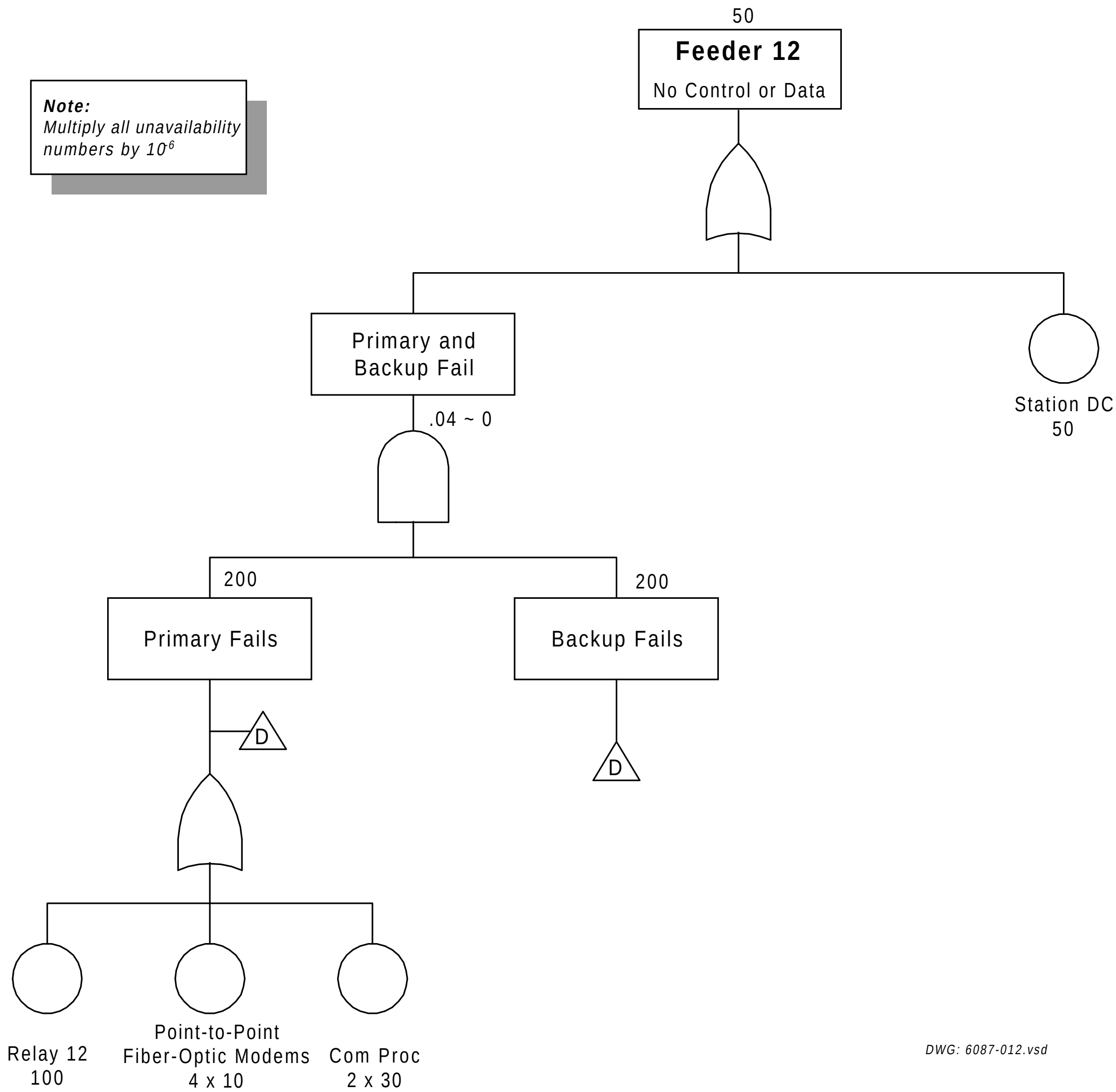

Figure 12: Redundant Protective Relays and Stars Substation Fault Tree

Unavailability Comparison

A summary of the unavailabilities for each substation topology is shown in Table 5. Note that a dual ring system has 2.2 times the unavailability of a single star system. The fully redundant topologies have essentially equal unavailabilities; the nonredundant station dc contributes the only significant unavailability.

Table 5: Unavailabilities Summary

Substation System	Unavailability $\cdot 10^{-6}$
Redundant Relays and Rings	50
Redundant Relays and Stars	50
Single Star	250
Dual Ring	550
Single Ring	2330

Note: The components most available have the smallest unavailability numbers.

COST COMPARISON

Equipment and fiber costs are based on list prices of representative products, each with at least the MTBF used in the unavailability calculations.

Table 6 summarizes initial material costs for the alternatives. The ring alternatives use cables with two fibers and ST connectors between the ring modems. The star examples use cables with two fibers and v-channel connectors between the point-to-point fiber-optic modems. The numbers are based on representative costs. To evaluate actual alternatives, use the actual costs of specific products and services.

Table 6: Substation Alternatives Approximate Comparative Costs

	Single Star	Redundant Relays and Dual Stars	Single Ring	Dual Rings	Redundant Relays and Dual Rings
Communications Equipment Cost	$11,840	$23,680	$47,200	$57,950	$94,400
Fiber Cost	$1,080	$2,160	$1,200	$2,415	$4,370
Total Communications Material Cost	$12,920	$25,840	$48,400	$60,365	$98,770
Total Protective Relay Cost	$56,400	$112,800	$56,400	$56,400	$112,800
Total Material Cost	$69,320	$138,640	$104,800	$116,765	$211,570

LIFE-CYCLE COSTS DISCUSSION

Each protective relay may be in service for 10 to 20 years. In that time, it is likely that the communications protocols in use within substations, and between SCADA masters and substations, will change. In a star system, the change to another protocol can be accommodated through settings, a software upgrade, or by changing a protocol card. In a ring system either a protocol conversion device must be added, or all devices must be upgraded or replaced. The star architecture easily accommodates a mix of protocols and bit rates, so you can select devices that best meet the application needs, rather than be constrained to only devices supporting a particular protocol.

DATA TRANSFER ISSUES

In general, a star topology has one bidirectional communications data channel dedicated to each device. A ring topology has "n" nodes sharing the same data channel. If the two systems have the same physical data rate, then the time to transfer data from all nodes to the next level is longer for a ring than a star. From the example definition, 32 bytes of data are retrieved for each of 16 relays and 22 bytes from each of two relays. Assume an asynchronous bit rate of 19,200 bits-per-second. Each byte requires a start bit, 8 bits of data, and a stop bit, or 10 bits-per-byte. In a star configuration, a protocol can be employed with error checking but without overhead for collision avoidance or token passing. Using 8 bytes of overhead for the 32-byte message, the transfer time, t, is:

t = [(40 bytes/relay) · (10 bits/byte) · (1 relay)] / (19,200 bits/second)

t = .02 seconds for data transfer into star hub

Information from one-half of the relays must transfer from the lower tier communications processor to the upper tier communications processor. The transfer time, t, is:

t = [(278 data bytes + 30 overhead bytes) · (10 bits/byte) / (19,200 bits/second)

t = .16 second for data transfer from the lower tier hub to the upper tier hub

In a ring system, additional overhead bytes in the request and response are needed for addressing and network management. Assume 24 byte-times of overhead for a request and block transfer response; the time to transfer data from all nodes to the PLC for the ring system is:

t = [(56 bytes/relay) · (16 relays) + (46 bytes/relay) · (2 relays)] · (10 bits/byte) / (19,200 bits/second)

t = .51 second for data transfer via ring into PLC

These numbers are useful in comparing the times until data are available at the next level for logic operations and concentration. In either case, the hub or PLC will need to format and respond to block transfers from the SCADA master.

With a star topology, you have the option to accommodate different bit rates and protocols for each node and to communicate with the upper level in larger blocks and at a faster bit rate.

Often, the time kept by the relays in a substation must be synchronized to a standard time source, to aid in analyzing the time sequence of events after a power outage or other system event. Typically, a time code is received from a satellite and input to an IRIG-B input on a relay. A copper connection for the time synchronization exposes the relays to a common source of damage from electrical transients via the time synchronization lines. Some point-to-point fiber-optic modems include the capability to transmit a time synchronization signal in the same fiber used for data transmission, providing isolated time synchronization. In the multidrop ring network, the protocol must employ a mechanism to synchronize the time. Accurate time synchronization is difficult in multidrop networks due in part to the unpredictable nature of communications in progress with a given node. Communications must complete before another node can be addressed. Accurate time synchronization is also difficult due to the implementation of the protocol software and hardware.

ADDITIONAL CONSIDERATIONS

Variations in the equipment or topology impact the analysis. One example is that some ring modems support more than one virtual-channel, rather than the single channel modeled in the examples. The main impact of using an additional channel is on the data throughput. Transfer of all data takes one-half as long with two 10-node channels as it does with one 20-node channel.

The substation case analysis is based on equipment currently deployed for substation automation. Another topology that can be deployed for this application is fiber ethernet. Fiber ethernet systems generally use a star topology, with a dedicated fiber pair connecting each node to a router or switch. This approach provides the reliability and throughput advantages of the star topology but limits the selection of relays available for the application.

Another approach that may be appropriate for larger substations uses hybrid systems employing fiber ethernet connections to communications processor hubs, which in turn have non-ethernet fiber connections to relays.

SUMMARY

Table 7 summarizes key comparison items for the substation example. The diagnostic ease discussed for the distribution loop case also applies to the substation case. A [-] signifies a comparative disadvantage; a [+] signifies a comparative advantage.

Table 7: Key Comparisons Summary for Substation Example

Criteria	Single Ring	Dual Ring	Single Star	Redundant Relays and Rings	Redundant Relays and Stars
Unavailability	[-] 2330	[-] 550	[+] 250	[+] 50	[+] 50
Initial Cost	[-] 104 k	[-] 117 k	[+] 69 k	[-] 212 k	[+] 139 k
Life Cost	[-]	[-]	[+]	[-]	[+]
Diagnostic Ease	[-]	[-]	[+]	[-]	[+]
Data Transfer	[-]	[-]	[+]	[-]	[+]

CONCLUSIONS

Ring and star fiber topologies can be deployed within substations or between substations. This paper includes the tools to compare the availability of alternatives and identifies items to consider for comparing reliability costs, diagnostic ease, and data transfer issues.

For the distribution loop case, the star systems have lower equipment costs and more availability, but require more fiber. When the average distance between nodes is small (175 feet or less), the equipment and fiber cost of the star systems is less than the comparable cost of the ring systems. For the substation case, with an average distance between nodes of 1,325 feet, the cost of the dual star system is 2.2 times the cost of the dual ring, and the dual star system unavailability is less than one-half of the unavailability of the dual ring. Except for very critical load applications, the higher cost of the dual star approach would generally be prohibitive, even though the unavailability is less than that of the dual ring.

For the substation case, the star topology is preferred over the ring topology in all comparison categories.

These examples are based on actual cases, but there are many more equipment options and hybrid topologies that can be deployed in substation and distribution loop applications. The equipment costs of different equipment will yield different costs than these examples, and the actual MTBF data for other equipment can yield different unavailability results. You can employ the tools and observations presented in this paper to contrast other fiber and non-fiber system alternatives.

To analyze any of these alternatives, obtain the MTBF and MTTR data for each component of the system, calculate unavailabilities, and construct and analyze fault trees for each option under consideration. Use the fault trees to identify areas that can be replicated to reduce their contribution to the system unavailability, and modify the system to reflect the improvement. Calculate the cost, and determine the importance of remaining evaluation criteria.

APPENDIX A: DISTRIBUTION LOOP COST BACKGROUND

Distribution Loop Cost Background

Table 8 shows the cost basis used for the ring systems for the distribution loop comparisons.

Table 8: Ring System Costs - Distribution Loop

Description		**Single**			**Dual**	
	Quantity	**Unit Price**	**Total Price**	**Quantity**	**Unit Price**	**Total Price**
Equipment						
Master fiber-optic ring modem	1	$3,750	$3,750	2	$3,750	$7,500
Fiber-optic ring modem at each node	20	$2,000	$40,000	20	$2,000	$40,000
Total Equipment			**$43,750**			**$47,500**
Fiber						
2-fiber cable with 22 terminations per fiber total 26,400 feet long	26,400	$0.391	$10,322	26,400	$0.391	$10,322
Total Communications Material			**$54,072**			**$57,822**
Labor						
Terminate/test each fiber link (2 ends)	22	$45	$990	42	$45	$1,890
TOTAL COST			**$55,062**			**$59,712**

Table 9 shows the cost basis used for the star systems for the distribution loop comparisons.

Table 9: Star System Costs - Distribution Loop

Description		Single			Dual	
	Quantity	**Unit Price**	**Total Price**	**Quantity**	**Unit Price**	**Total Price**
Equipment						
Communications Processor:						
At substations 10 (and 11) as midpoint hubs	1	$2,500	$2,500	2	$2,500	$5,000
At master site	1	$2,500	$2,500	2	$2,500	$5,000
Point-to-point fiber-optic modems:						
At substation nodes	19	$350	$6,650	38	$350	$13,300
At substations 10 and 11 as midpoint hubs	11	$350	$3,850	22	$350	$7,700
At master site	10	$350	$3,500	20	$350	$7,000
Total Equipment			**$19,000**			**$38,000**
Fiber						
Use one 2-fiber cable per site	145,750	$0.391	$56,988			
Use two 20-fiber cables for dual system				29,000	$3.15	$91,350
Total Communications Material			**$75,988**			**$129,350**
Labor						
Terminate/test each fiber link (2 ends)	44	$45	$1,980	88	$45	$3,960
TOTAL COST			**$77,968**			**$133,310**

Figure 13 shows the cost of fiber-optic system materials, for each option, as a function of the distance around the distribution loop.

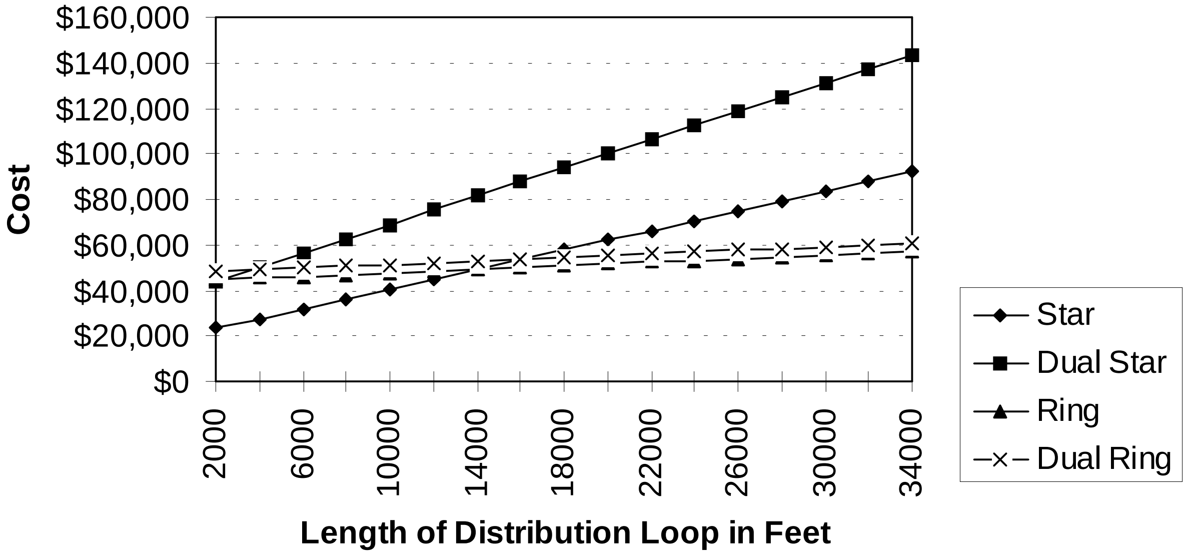

Figure 13: Material Costs - Distribution Loop Options

At the average distance between nodes of 175 feet, or 3,500 feet total, the dual star and dual ring options have approximately equal material costs. At lower distances, the star costs less; for longer distances, the rings cost less.

APPENDIX B: SUBSTATION SYSTEM COST BACKGROUND

Table 10 and Table 11 show the cost basis used for the ring systems for the substation comparisons.

Table 10: Ring System Costs - Substation

Description		**Single**			**Dual**	
	Quantity	**Unit Price**	**Total Price**	**Quantity**	**Unit Price**	**Total Price**
Equipment						
Master fiber-optic ring modem	1	$3,750	$3,750	2	$3,750	$7,500
Fiber-optic ring modem at each node	18	$2,000	$36,000	18	$2,000	$36,000
Cable relay/modem	18	$25	$450	18	$25	$450
PLC to consolidate into one protocol node	1	$7,000	$7,000	2	$7,000	$14,000
Total Equipment			**$47,200**			**$57,950**
Fiber						
Preterminated ST fiber cables Note: 2-fiber cable used even in single ring system	20	$60	$1,200	21	$115	$2,415
Total Communications Material			**$48,400**			**$60,365**
Microprocessor-Based Relays						
Distance relay	2	$5,000	$10,000	2	$5,000	$10,000
Transformer relay	2	$5,000	$10,000	2	$5,000	$10,000
Distribution relay	14	$2,600	$36,400	14	$2,600	$36,400
Total Relays			**$56,400**			**$56,400**
TOTAL COST			**$104,800**			**$116,765**

Table 11: Redundant Dual Ring System Costs - Substation

Description	**Redundant Dual Ring System**		
	Quantity	**Unit Price**	**Total Price**
Equipment			
Master fiber-optic ring modem	2	$3,750	$7,500
Fiber-optic ring modem at each node	36	$2,000	$72,000
Cable relay/modem	36	$25	$900
PLC to consolidate into one protocol node	2	$7,000	$14,000
Total Equipment			**$94,400**
Fiber			
Preterminated ST fiber cables	38	$115.00	$4,370
Total Communications Material			**$98,770**
Microprocessor-Based Relays			
Distance relay	4	$5,000	$20,000
Transformer relay	4	$5,000	$20,000
Distribution relay	28	$2,600	$72,800
Total Relays			**$112,800**
TOTAL COST			**$211,570**

The table below shows the cost basis used for the star systems for the substation comparisons.

Table 12: Star System Costs - Substation

Description	**Single Star System - Substation**		
	Quantity	**Unit Price**	**Total Price**
Equipment			
Communications processors	2	$2,500	$5,000
Fiber-optic ring modems	36	$190	$6,840
Fiber cables: preterminated	18	$60	$1,080
Total Communications Material			**$12,920**
Microprocessor-Based Relays			
Distance relay	2	$5,000	$10,000
Transformer relay	2	$5,000	$10,000
Distribution relay	14	$2,600	$36,400
Total Relays			**$56,400**
TOTAL COST			**$69,320**
Dual Star: (double cost of single star)			*$138,640*

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BIOGRAPHY

Gary W. Scheer received his B.S. in Electrical Engineering from Montana State University in 1977. He worked for the Montana Power Company and Tetragenics Company before joining Schweitzer Engineering Laboratories, Inc. in 1990 as a development engineer. He has worked in the Research and Development, Automation and Engineering Services, and Marketing and Customer Services divisions. Mr. Scheer now serves as Product Manager for automation and communications products and systems. He holds two patents. He is a registered professional engineer and member of the IEEE, NSPE, and the ISA.

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