Technologies, Inc.

SYSTEM RELIABILITY IMPROVEMENTS THROUGH FIBER OPTIC SYSTEMS

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Introduction

It was only as recent as 1960 when the concept of using glass fibers for communications was first proposed by researchers at Standard Telecommunication Laboratories, Ltd. Since then the use of fiber optic cables has expanded into nearly every part of our lives in many diverse industries. The most common being long distance and local telephone service providers boasting of the clarity and reliability of their FO networks. Studios in Hollywood are using fiber networks to pass movie footage between production and editing departments. Transportation Industries are upgrading communications along highways, city streets and railroads. Other industries and functions include cable television, video conferencing, local area networks, wide area networks, Internet, etc. Increased bandwidth requirements are the primary reason for the sharp increase in fiber optic use worldwide. Researchers are continuing to push the upper limits for the amount of data that can be transferred over a single FO cable pair.

The Electric Utility is also taking advantage of the many benefits of Fiber Optics. The remainder of this paper will deal with this segment of industry. We will not delve too deeply into the marketing aspects of selling or leasing dark fibers or bandwidth to organizations outside the Utility. Although this clearly has been a driving force for Utilities to install thousands of miles of fiber in recent years, this was not the case in the beginning. During the 1980s it was frequently the protection engineer who was installing fiber to enhance the security and reliability of his relaying network. At that time an engineer could justify one pair of fibers for one relay system. In 1982 Westinghouse Electric Corporation introduced the LCB current differential relay as the first protective relay to use integrated fiber optics for its communication path. Today this is considered by many to be wasteful of the capacity of fiber, since a single fiber can be used to carry several hundred thousand telephone conversations. When you combine this thinking with the possibilities of selling excess fiber capacity to outside interests, it becomes even more difficult for some Utility Management personnel to understand why the protection engineer wants to use his fiber for one, two or only a handful of functions.

Today there is a surplus of fiber in some parts of the country and a shortage in others. The protection and communications engineers are generally able to apply fiber where they need it. Advances in digital multiplexers have given the engineer something he did not have before in the single fiber, single function approach. Now alternate routes and self-healing rings can be built which are making it easier for the engineer to accept using the fiber for multiple functions.

This paper will concentrate on how the use of fiber has helped the Protection and Communication Engineers by increasing the reliability of their protective relaying and SCADA systems. Fiber optic communication channels can drastically increase the reliability of pilot protective relaying while offering the user advantages over other types of pilot channels.

Pilot Relay Channels

Pilot channels have the responsibility of carrying information between pilot relays to permit these relays to offer high speed clearing of faults for 100% of the protected line. See Figure 1. Distance based relays by themselves cannot accomplish this due to their inability to precisely set their reach for exactly the line length. There are five common types of communication channels available for pilot relaying. These include audio tones over leased circuits, microwave or power-line carrier (SSB), power-line carrier by itself, metallic wire pairs, RS-232 or n x 64 kb digital and fiber optics. All of these have the basic goal of securely transferring a trip, block or trip permission signal to the opposite end of the protected line. The type of signal is up to the protection engineer and is dependent on the level of dependability and security desired or dictated by the importance of the protected circuit.

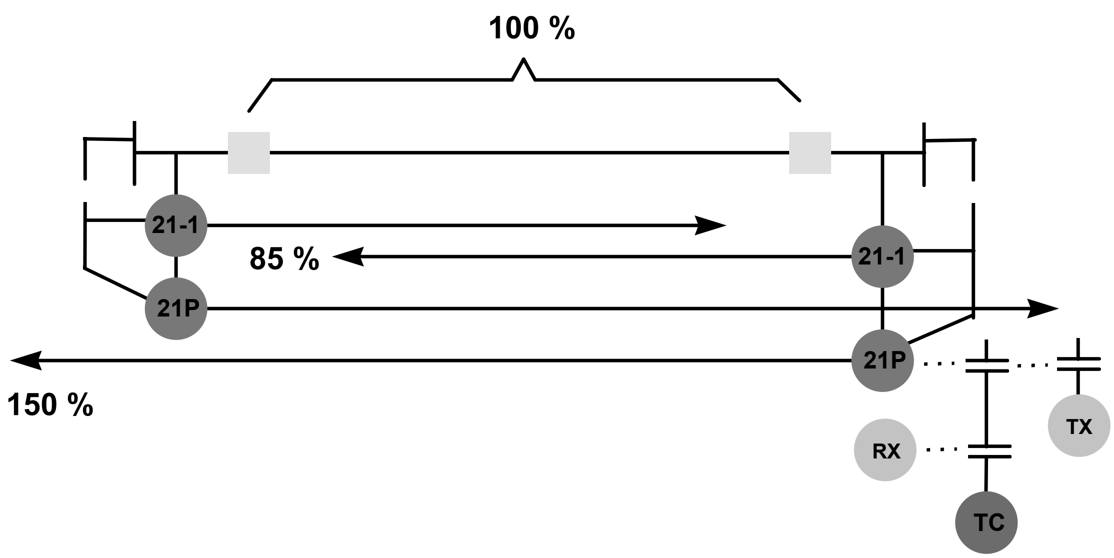

Figure 1 - Basic Distance Pilot Relay System

Audio Tones

Audio tones offer a very flexible method which lends itself for easy integration with other communication systems. Here a specialized tone transceiver set is used to transfer the status of an input contact securely from the transmit end to the receive end. Under normal conditions a guard frequency is sent which is shifted to a trip frequency when the input contact is active. The receiver detects this frequency shift and, provided certain security checks are satisfied, issues a trip output. A loss of guard condition without a corresponding receipt of trip signal is an indication of channel trouble. Microwave, whether analog or digital, is designed to accept and transport four wire audio circuits from point A to point B. Generally, audio tones for relaying applications will contain extensive noise monitoring to reduce the possibility of a noise transient or frequency excursion from being falsely interpreted as a trip condition. Typically, audio tones will block the trip output for 150 to 300 ms after detecting noise to ensure the channel has been restored before permitting a trip output. Inherent delays in the filters required when applying audio tones will introduce 7 to 12 ms of delay into the overall system. Tones over metallic circuits do not see the same delays as microwave (additional 4 ms) but do have their own problems with lightning and surge protection, induced voltages and transients, ground potential rise, corrosion, attenuation, etc. In the past these limitations of filter delay, noise blocking times and susceptibility to surges and induced voltages have always been accepted as normal and unavoidable for the relay engineer.

Power-Line Carrier

Power-Line Carrier (PLC) is an ideal solution for many applications. A typical PLC terminal is shown in Figure 2. It is not dependent on other systems in the same manner as are tones over either leased circuits or microwave radios. Propagation delays and back-to-back trip times are generally improved over audio tone channels. Four to 12 ms is typical for total trip times of today's wide or narrow band dedicated PLC systems. Wider bandwidths will produce faster channels and therefore quicker back-to-back trip times. All PLC channels are affected by noise, which can delay tripping if the noise is severe enough. Noise circuits will add to total channel time by delaying tripping until the signal is received long enough to provide confidence that the trip is legitimate. Fifteen to 25 ms is a common delay setting when the channel is being used for direct tripping. Much shorter security delays are acceptable for PLC channels used in permissive tripping or blocking schemes.

A potential disadvantage with PLC lies in the extra equipment needed to apply it. Line traps, line tuners and spark gaps play an important role in the reliability of the entire system. Improper maintenance of these items can greatly decrease the reliability of a PLC-based pilot scheme.

Pilot Wire

Pilot wire circuits consist of continuous metallic wire pairs routed between substations to connect either audio tones or specialized pilot wire differential relays. The ABB HCB-1 and GE SPD are two examples of pilot wire relays. The distance between substations is limited to 7 to 10 miles in order that the impedance and capacitance of the pilot wires can be kept within required limits for proper relay operation. Tones used over this medium will operate much the same as tones over leased circuits or microwave channels discussed earlier but with shorter propagation delays. Metallic circuit channels are completely self contained, eliminating any reliance on external systems. No amplifiers or other line conditioning equipment can be used for a circuit to be useable for the application of pilot wire relays. Although acceptable for tones over pilot wire, this equipment will prevent pilot wire relays from operating properly.

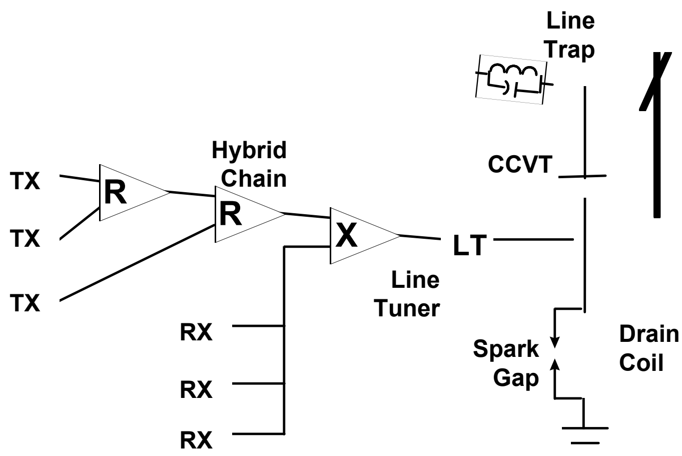

Figure 2 - Typical Power Line Carrier Terminal

The primary disadvantage of any scheme using metallic wires is the difficulty of maintaining the circuits. Over time the wire insulation will begin to crack, creating short circuits. See Table I that follows. If the circuits are provided by the local Bell company, they may also begin to disappear as they are replaced by FO or microwave paths for economic reasons. These types of circuits are also very susceptible to induced voltages, ground potential differences and maintenance errors.

Table I

Past	Present	Effect
New pilot wire cable	Pilot wire cables are old	Circuits are failing
Insulation good	Insulation is cracking causing short circuits	Relays block for all faults
Easy to lease wire pairs from telephone Co.	Telephone Co. ending leases and maintenance	Utilities turning to alternate relay schemes
Healthy connectors and splices	Corrosion in connectors and splices causes open circuits	Relays act as non-directional overcurrents

Digital

For an RS-232 channel to be used for directional comparison pilot relaying, it must utilize some type of embedded secure protocol to ensure that the data received is the same as the data transmitted. “Mirrored Bits” is one example of such an RS-232 protocol used by the SEL321 and 351 relays. Unlike tone and PLC channels, the RS-232 channel has no knowledge of the correctness of the data it is carrying and therefore no ability to detect if the data has been corrupted within the channel. Consequently, this type of relay system is much more reliant than other systems on the internal relay logic to ensure proper pilot relay operation is maintained. RS-232 channels offer the user some advantages over other methods of which lower cost is probably the most notable. An RS-232 channel can also be converted into a four wire tone signal for transmission over conditioned analog channels when digital data circuits are not available. Care must be taken to ensure the modem used for converting the RS-232 data into tones includes features like low throughput delay and fast retrain times. If not included, the user could experience longer than acceptable channel delays and extended channel blocking times for momentary disturbances which significantly decreases the reliability of the connected relay system. The MBT9600 is one example of a modem with these highly desirable features.

The 64KB channel is similar to RS-232 channels in that it too has no knowledge of the correctness of the data it is carrying. It must rely on the connected relay system to determine if the data has been corrupted. Today ABB, GE, Alstom and RFL offer differential relays that can make use of 56, 64 or 128 KB channels. These channels lend themselves to easy integration into digital networks like T1, SONET or even leased 64KB circuits using cables connecting the relay to the digital channel. Some multiplexer manufacturers offer FO interfaces for the 64 KB data to eliminate the exposure of these cables to transients within the substation. Since channel delay is critical to reliable current differential operation, some relays include automatic channel delay monitoring which adapts the relay to changing channel delays. This is especially helpful for leased circuits and any circuits routed over self-healing paths.

Fiber Optics

Fiber is probably the most expensive channel alternative to install. Unlike tones and PLC, the user must install fiber the complete distance between the substations. Fortunately it is not necessary to be routed in the same right of way. The added benefits of fiber will many times justify the extra cost. It is inherently immune to mutually induced voltages and station ground potential differences. The channel capacity (bandwidth) available with a fiber system is unmatched by any other channel alternative. Reduced channel delays permit very fast back-to-back channel times.

NOTE: It should be noted that fiber cables typically include 48, 96 or greater individual fibers. The overall cost of installing fiber can be spread across the users for all fibers, thereby decreasing the effective cost to the protection engineer.

One hundred percent digital relay channel interfaces are used to connect directional comparison pilot relays to the fiber, replacing the functionality of audio tone sets, PLC or metallic circuits. This direct digital approach also eliminates most of the noise blocking and filter delays required for alternative methods, which result in channel times as fast as 2 ms. Most digital transfer trip interfaces use an 8-bit message structure sampled at an 8,000 Hz rate, which yields a 64 kbps data stream. The 64 kbps data stream is designed to work into a T1 or greater bandwidth multiplexer as a single DS0 channel. The message structure must include some form of built-in error detection to ensure no corruption of data bits has been introduced by the channel.

What makes fiber optic channels even more attractive is their ability to include redundancy for automatic rerouting of critical circuits in the event of a link or node failure. These “self-healing” ring options will be described in greater detail later in this paper. It is important to note that, with the exception of PLC, all types of channels described above can also be routed over fiber using appropriate channel interface cards. It is therefore possible for tones, RS-232, 64 kb and metallic circuits (pilot wire) to also benefit from the self-healing ring architecture.

Fiber Optic Basics

Either lasers or LEDs can be used to send data through fiber optic cable. Today, lasers are almost exclusively applied for multiplexed communication systems. LEDs are still used within a substation yard or for short line differential relay systems.

The laser produces a focused light source which is efficiently transmitted into either single or multimode FO cables (see Figure 3).

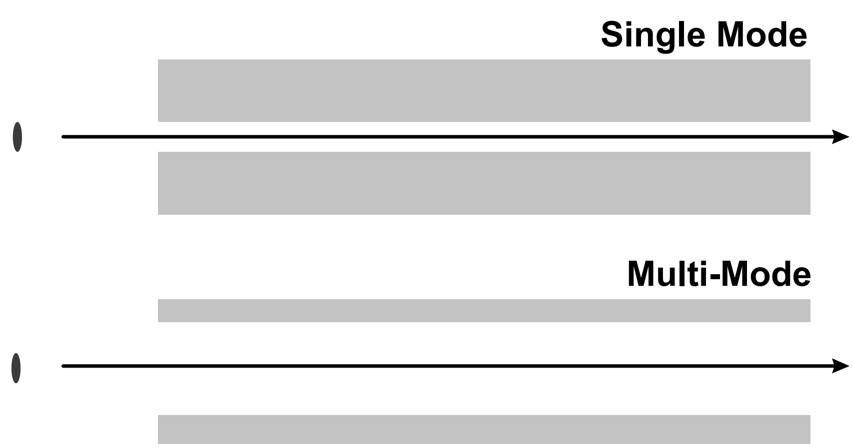

Figure 3 - Laser into Single Mode vs Multi-Mode Fiber

The majority of installed cable uses single-mode fiber, as do almost all new installations. An LED source will lose most of its energy at the junction to the fiber due to the large difference in area, as illustrated in Figures 4 and 5. This greatly limits the maximum permissible distance between multiplexers. It is common for lasers used in today's multiplexers to reach as far as 100 km without requiring use of a repeater.

Dispersion of the light pulses can also become critical when high data rates and their associated narrow pulses are transmitted over multimode fiber. A rounding off of the pulses occurs (Figures 6 and 7) when light being sent through the fiber takes varying amounts of time to reach its destination due to some of the light bouncing off the fiber walls. Dispersion is much less of a problem when single-mode fiber is used and is never a problem at low T1 data rates.

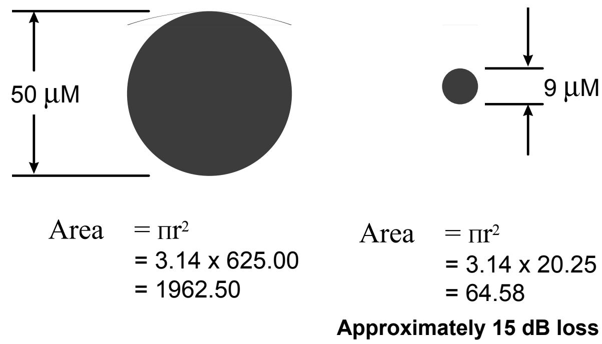

Fig. 4 - LED vs Laser

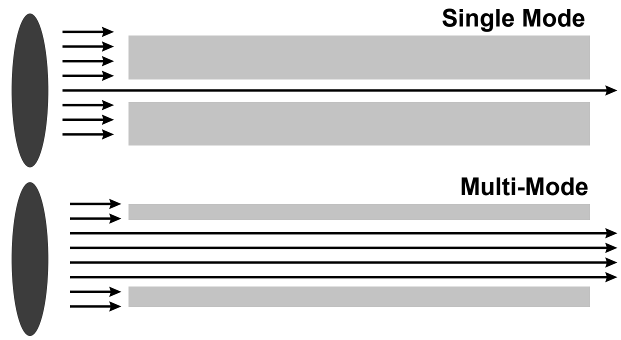

Fig. 5 - LED into Single Mode vs Multi-Mode Fiber

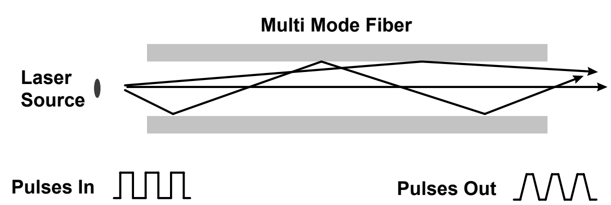

Fig. 6 - Dispersion for a Multi-Mode Fiber

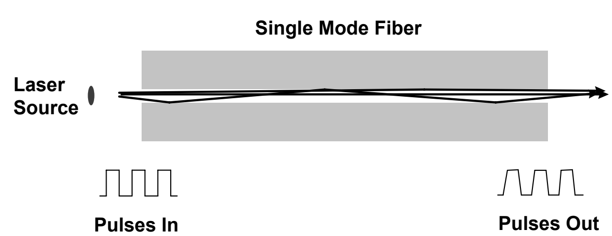

Fig. 7 - Dispersion for a Single Mode Fiber

Digital PCM Theory

Pulse Code Modulation (PCM) is used as the basic building block for a digital network. Analog inputs (tones or voice) are encoded using three steps:

- Sampling
- Quantizing
- Coding

This will be the same way the telephone company encodes your voice to route through its digital network. The reverse occurs at the receiving end. This is not the way purely digital channels for relaying systems operate, since they do not make use of audio tones. Digital channels directly encode a bit pattern into the data stream which includes error detection code to prevent false operations. To simplify the PCM explanation, this paper will describe the operation of a standard 4-wire voice interface.

Sampling - (Refer to the illustration in Figure 8.) The instantaneous magnitude of the wave form is measured at predefined precise intervals. For most digital systems the interval is fixed at 125 μS.

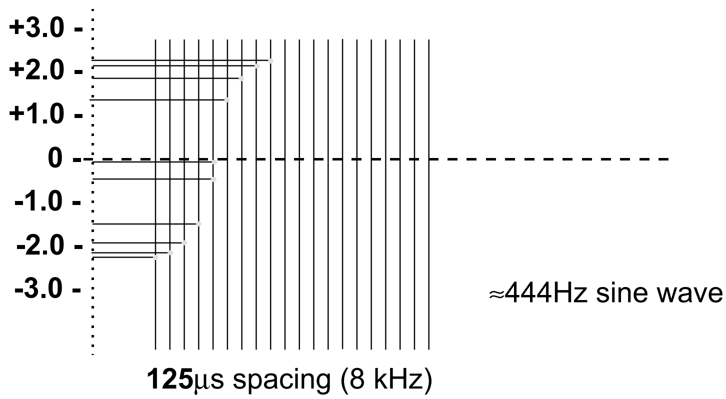

Figure 8 - Sampling

A standard for quantizing/encoding analog waveforms is a technique called μ-law and is used in ANSI - based countries to convert these instantaneous measurements into digital information. Use of this standard permits multiplexers from different manufacturers to communicate channel information between each other at the DS0 level.

Quantization - A measured sample is taken to be the nearest level that it either equals or exceeds. This is called quantizing. Also note that the magnitude differences can be more closely defined as the level approaches zero. This permits finer delineation between quieter levels to reduce the quantization noise at lower volumes. Quantization noise occurs when differences from the sample's exact value and the nearest quantized level exists. This causes subsequent audible distortion in the actual demodulated waveform. At higher volumes quantization errors are less noticeable. The quantizing levels and code are shown in Figure 9.

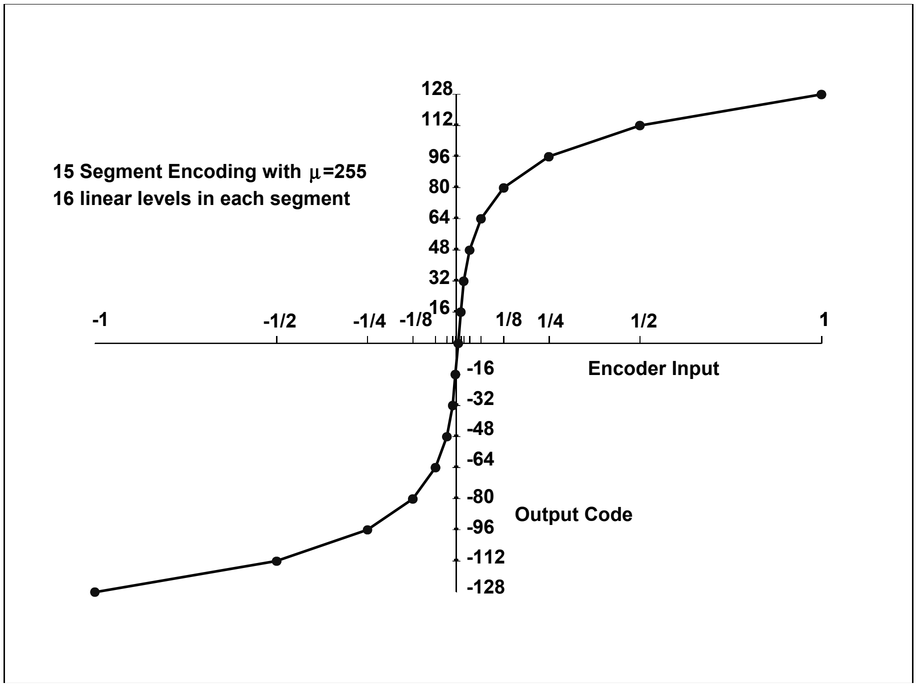

Figure 9 - μ-law Quantizing/encoding

Encoding - The final PCM step is to encode these quantized samples to be sent over digital medium. The values are encoded as binary numbers, since digital mediums can accept only 1s and 0s. Eight bits are used for every sample to allow all 256 possible values to be represented. The μ-law encoding process approximates a log curve by using 15 linear segments, as shown in Figure 9. The segments on each side of zero are counted as one segment even though the segment code is different. The most significant bit of the 8 bit code tells if the segment is on the negative or positive side of the axis. It is 0 if the segment is on the negative side and 1 if it is positive. The next three bits in the code identify the segment number 1 to 7 above and below the axis. The segment code starts at 000 for the most negative segment counting up to 111 for the segment just below zero. The segment code starts at 111 for the first positive segment above zero and counts down to 000 for the highest positive segment. The last four bits in the code are for the 16 linear samples within the segment.

Now that the waveform is encoded, the numbers are sent along with the other 23 encoded waveform samples to the receiving end. This creates a serial data stream, as shown in Figure 10, which includes one 8 bit sample from every channel in the first 125 μS then the second 8 bit sample from every channel in the second 125 μS, etc. etc. To help the receiving end "frame" the incoming data, synchronizing information in the form of one bit is added to every set of 24 samples at the transmit end which makes up a complete frame. This synchronizing bit repeats a specific pattern every 24 frames. It is the function of the framer at the receive end to find the bit with the repeating pattern (synch bit) and use this information to frame and lock in the incoming 24 DS0 channels.

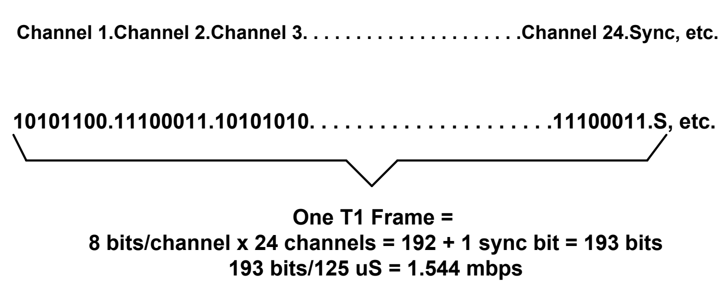

Figure 10 - Encoding

Once the incoming data is synchronized, it is separated back into 8-bit bytes, decoded into one of the 256 levels, and used to reassemble the waveform.

The 8-bit sample (DS0) is the basic building block of digital communications. As shown in Figure 11, a system that has a capacity of 24 DS0 channels is called a DS1 or T1 system. A system that has a capacity of 672 DS0 channels (or 28 DS1s) is called DS3 or T3 system. Many digital microwave systems offer the user 28 DS1 channels.

Traditionally T1 channel banks were applied in pairs using one of these 28 DS1 microwave channels or dedicated fiber as a pipe between locations to carry up to 24 channels each.

Drop and insert (D/I) channel banks can be used to make better use of the available bandwidth within a DS1 pipe or on a dedicated fiber. A D/I channel bank contains at least two T1 transceiver ports (East and West) connected in opposite directions into either microwave DS1 pipes or fiber. The DACS (digital and cross-connect system) within the channel bank operates much like a telephone operator's old patch panel. It can pick off a group of DS0 channels from the West transceiver to drop locally to channel cards and simultaneously "pass-through" another group of DS0 channels to the East transceiver untouched. This "grooming" allows a system to make much better use of the available DS1 channels within the microwave system or fiber network without using back-to-back channel banks with separate external DACS equipment. Drop and insert channel banks are also required for creating self-healing ring configurations.

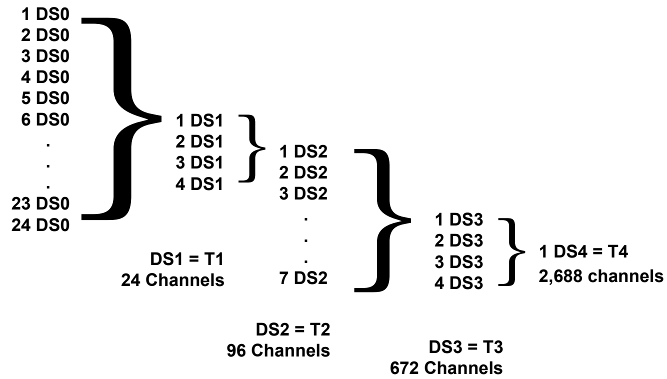

Figure 11 - PCM Hierarchy

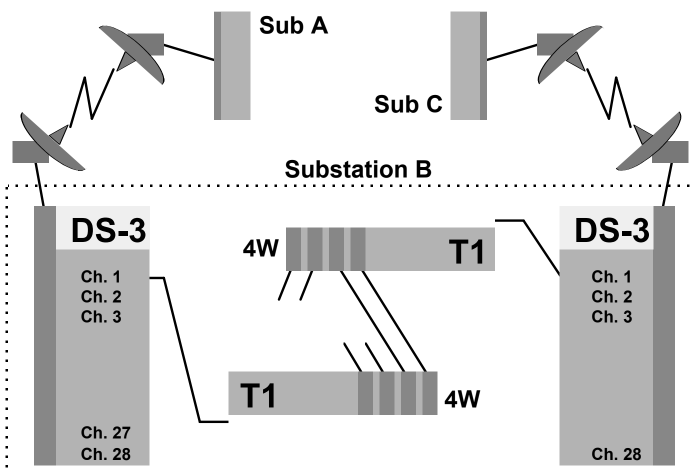

Figure 12a -
Typical Microwave with Pt to Pt Channel Bank Application

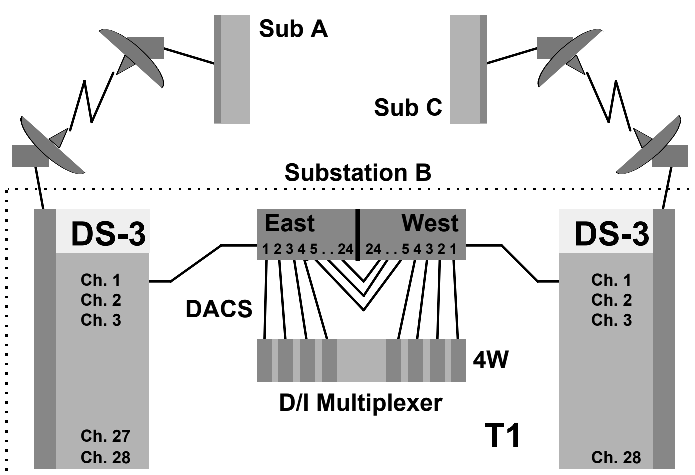

Figure 12b - Typical Microwave with D/I Multiplexer Application

Self-Healing Rings

Arranging the multiplexer terminals (nodes) in a ring configuration is required for self-healing operation. Self-healing is defined as the automatic reconnection of data paths which are disrupted by a fiber break (link) or node failure such that the channels are reconnected in a different path quickly and without user intervention. Each node in a ring will be equipped with two transceivers, each pointing in opposite directions around the ring. The transceivers from adjacent nodes are connected by fiber (or other digital channel) to form the ring. Channels are formed by installing channel interface modules at the two nodes where the channel is to begin and end. This is sometimes referred to as dropped and inserted. From one of these nodes the desired time slot (channel) is inserted (mapped) to one of the two transceivers in either a clockwise or counterclockwise direction. This is normally determined by selecting the route with the shortest number of nodes between the two end nodes. "Pass-through" connections are made in every node between the two end nodes, using the same time slot throughout the ring, until the node containing the dropped end of the channel is reached, where it is dropped (mapped) to the channel card.

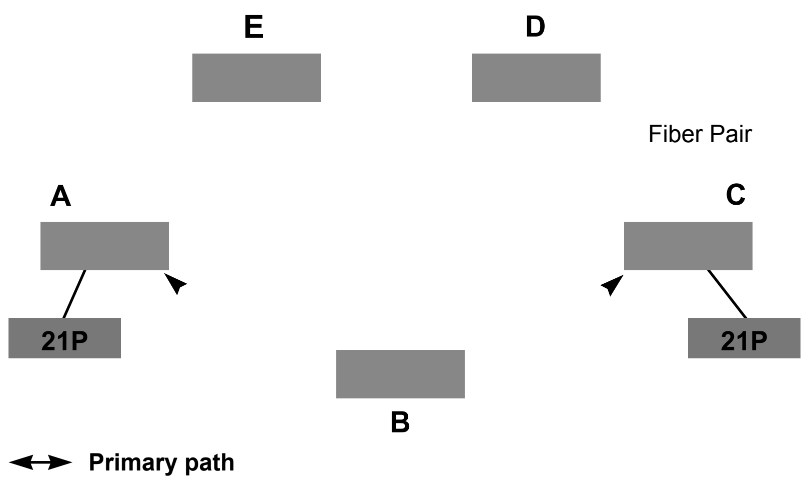

Figure 13 - Path-Switched System

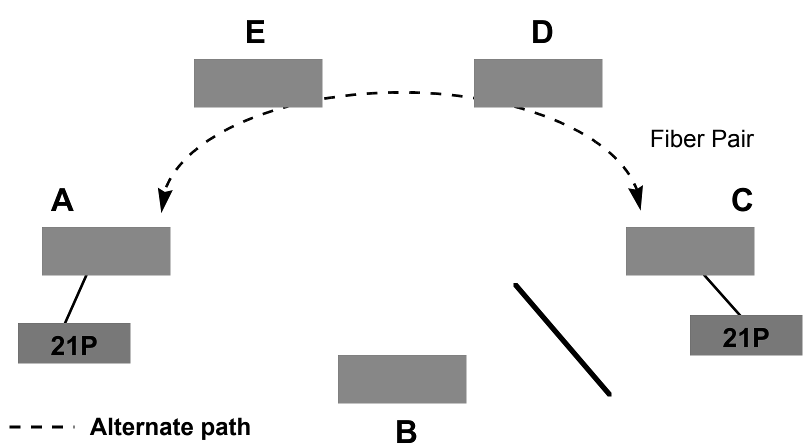

Figure 14 - APM Ring in Self-Healing Mode

Path-switched and line-switched schemes are two possibilities for implementing self-healing rings. Both approaches begin with channels being mapped as above. Both methods can only protect circuits within the ring for a single break between two nodes or a single node failure. Path switched schemes are considered to be a software solution, while line switched schemes are more of a hardware solution to self-healing. A path switched scheme changes the direction of a channel affected by a link failure at both dropped nodes, rerouting it in the opposite direction around the back side of the ring. The rerouted path uses the same time slot as the normal path but in the opposite direction. Figure 13 shows the primary path, while the alternate path is depicted in Figure 14. A line switched scheme makes use of an alternate pair of fibers or digital channel to reroute the affected link around the back side of the ring. Path switched self-healing schemes, sometimes referred to as Alternate Path Mode or APM, will be described first. Figures 15 and 16 illustrate this from a time slot point of view.

Path Switched

Multiplexers have a capacity based on the data rate of the channel. T1 multiplexers have a capacity of 24 channels while SONET® OC-1 has a capacity of 672 channels. Some SONET® systems group these channels into T1 blocks allowing 28 VT (virtual tributary) paths, each of which has a capacity of 24 channels (24 channels x 28 VTs = 672 total channels). SONET® OC-3 systems have a capacity equal to three times this. A SONET® system using the VT approach must map all 24 channels of a VT between the same two end points. The choice on which type of system to apply (T1, OC-1, OC-3) is determined by the number of channels required for the application while taking cost into consideration.

No matter how many channels or VTs the system contains, the path switched (APM) approach allows every channel to be self-healed in the event of a failure by using just two fibers (or one DS1 pipe) between adjacent nodes.

Once a given channel (or VT) is applied within a ring, that channel is unavailable for use elsewhere in the same ring. This is necessary because the system "heals" during a failure by changing the direction of the data path between the two end points while keeping them on the same channel.

Systems vary in how this is accomplished. Some systems require the user to pre-assign alternate maps for every node at system setup to reroute the channels based on the specific location of the break. Other systems will actively determine which channels are affected at the time of the break and reroute them accordingly without pre-assigning alternate maps. The former system has the advantage of faster switching to "heal" affected channels. The automatic system requires no pre-engineering, but it does take slightly longer to heal affected channels.

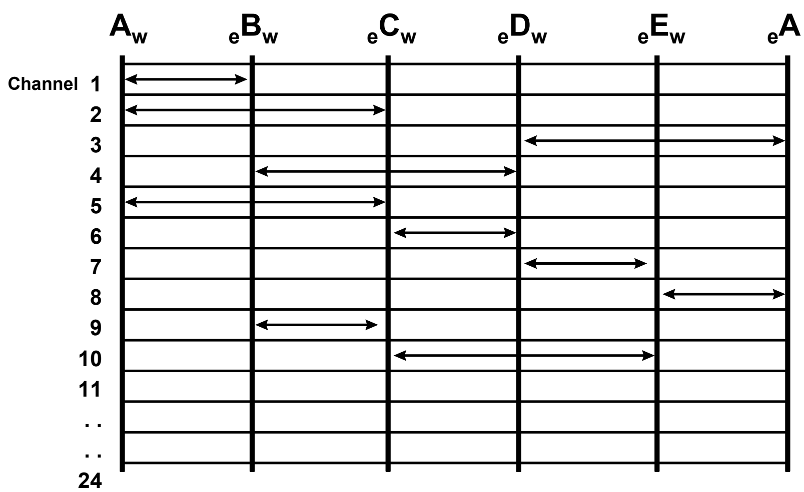

Figure 15 - APM Channel Map

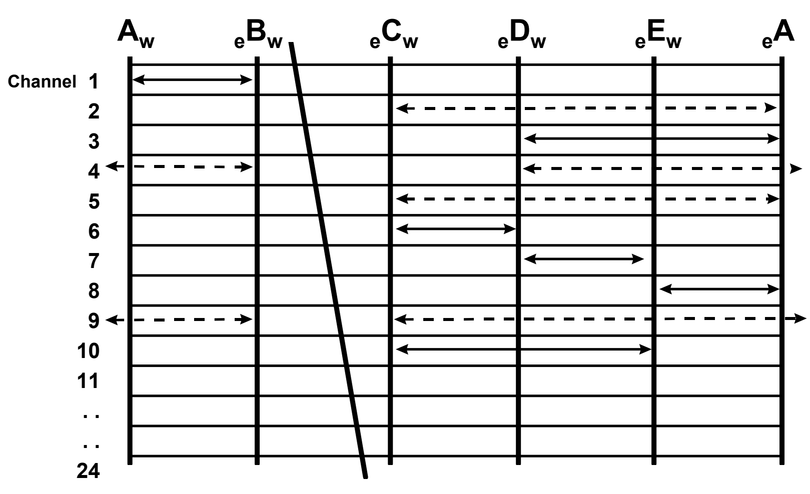

Figure 16 - APM Channel Map in Self-Healing Mode

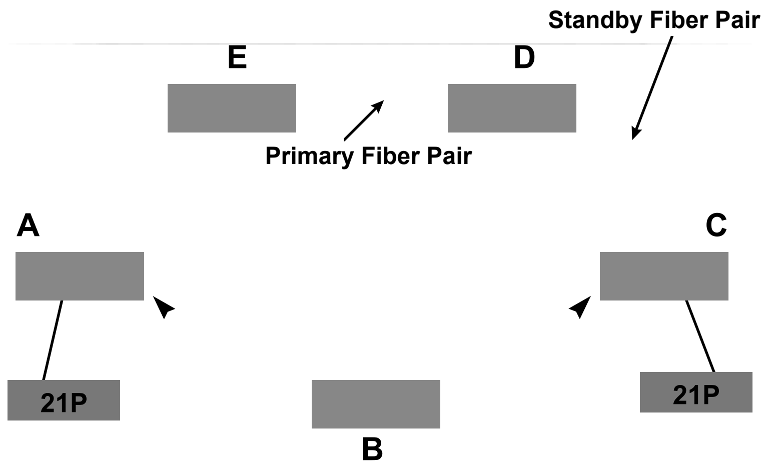

Figure 17 - Typical FFHS ring

Rings using the pre-assigned method can generally heal affected channels in less than 50 milliseconds. Rings using the automatic approach will typically heal affected channels in 150 and 300 ms depending on the size of the ring and whether or not both the transmit and receive fibers in the affected path were broken. Either approach is generally considered acceptable since the delay is not long enough to adversely affect most channel functions. At this point it is worthwhile to point out that some specialized channel cards are designed to provide very fast "healing" for link failures (less than 1 ms) without using the multiplexer's self-healing system. This has proven to be beneficial to some protective relay applications.

Line Switched

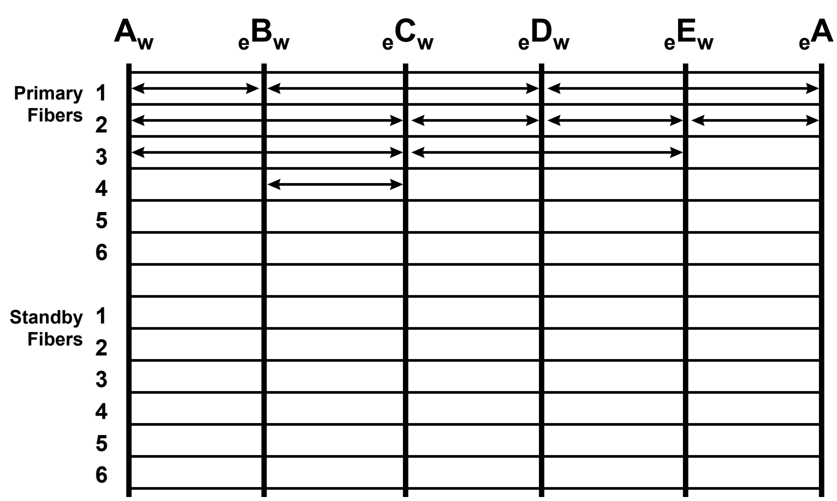

Figure 18 - FFHS Channel Map

The "Line Switched" approach to self-healing rings uses four fibers between adjacent nodes instead of two as with an APM scheme (Figures 17 and 18). This approach is sometimes referred to as a Four-Fiber-Hot-Standby (FFHS) system. The primary advantage of FFHS over APM schemes is that channels may be reused any number of times around the ring and still be included in the self-healing algorithm. Unlike the 24 channel limitation of an APM T1 system, a 10 node FFHS T1 ring could include up to 240 self healing channels, providing all are routed between adjacent nodes.

This is possible because when a link failure occurs, all broken channels (whether carrying data or not) are switched to the backup fibers and routed the reverse direction around the ring. This is considered a hardware approach because all of the circuitry and logic for performing the self-healing resides on the transceiver module.

Under normal operation, a heartbeat signal is continuously circulated around the backup fiber ring. This serves two purposes. First, it permits monitoring of these fibers so the user has assurance that the fibers are intact and ready for use when needed. Second, the heartbeat keeps the backup transceivers at all nodes in an optical repeater mode. When a low signal or high error rate is detected on one or both of the primary fibers in a link, the nodes on either side of the break reverse their affected transmit and receive directions onto the backup fibers in the reverse direction around the ring. This is shown in Figures 19 and 20. All nodes around the back side of the ring are already in repeater mode, so the signal is almost instantly reconnected to heal the affected channels. Once the break is repaired, the primary path is restored after a short security delay. Channel reconfiguring with this approach occurs in 8 to 50 ms, depending on the number of nodes in the ring and whether or not both transmit and receive primary fibers are broken.

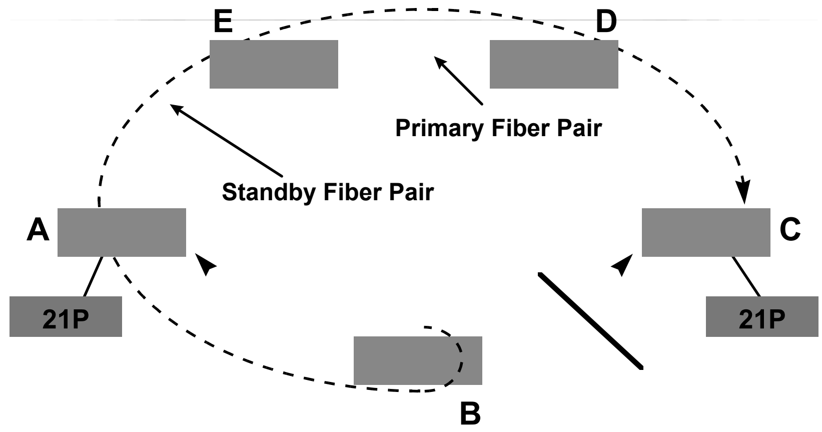

Figure 19 - FFHS Ring in Self-Healing Mode

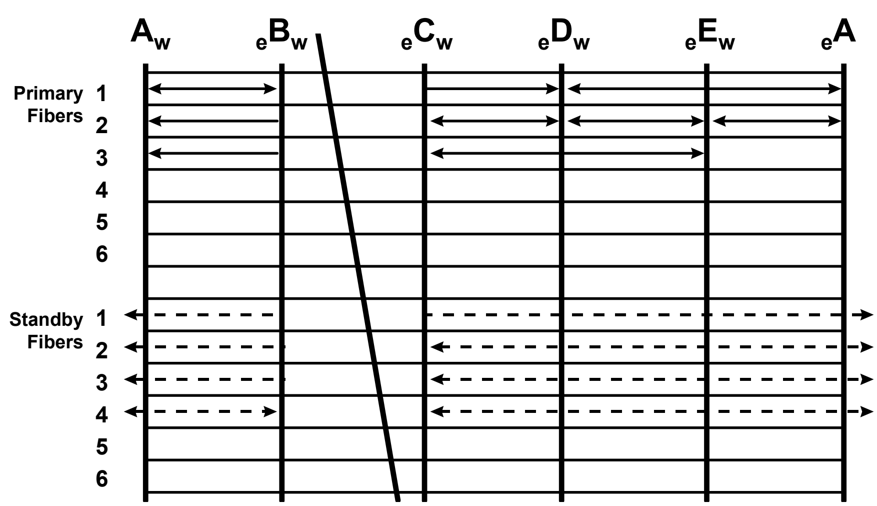

Figure 20 - FFHS Channel Map in Self-Healing Mode

Another benefit of the FFHS solution is lowered delays for rerouted circuits. This becomes significant when pilot wire relays are being applied to rings with large numbers of nodes. The pilot wire relay becomes significantly less sensitive to fault current as the channel delay exceeds 1 ms. The APM approach routes affected channels through the cross-connect of every pass-through node around the back side of the ring to carry the re-routed circuits. Typical pass-through delays range from 20 µS to 250 µS for different systems. Since the reversed direction will always have more delay than the primary direction, due to the additional pass-through nodes, the delay can become critical to permitting proper pilot wire operation. Depending on the manufacturer’s cross-connect delay, the number of nodes in a given ring may be limited to as few as five to still yield reliable pilot wire operation. The delays associated with the speed of light through the fiber also begins to be significant as the ring size grows over a larger geographical area. Five μS per kilometer of fiber is a good estimate of the added delay caused by distance.

There is also no advance engineering required with the FFHS approach. The system will automatically reroute traffic around a failed link or node without the user pre-defining alternate maps.

Delays are much less of a problem for FFHS schemes because they bypass most of the cross-connects in a ring through the use of optical repeaters in the backup path around the ring. The delay of an optical repeater in these systems is about 6 μS. This lower delay allows pilot wire and other time critical channels to be applied to much larger rings without adversely affecting performance. Rings with pilot wire relays and up to 17 nodes are currently in service using the FFHS scheme.

City of Garland - Installation and History

The City of Garland services approximately 50 square miles of residential and industrial territory located just northeast of Dallas Texas. The transmission system consists of 30 miles of 69 kV overhead lines and 80 miles of 138 kV lines arranged basically in two loops we will call North and South. The city also maintains 370 miles of 15 kV overhead and 400 miles of 15 kV underground circuits which were not included in the fiber project.

The relays of choice for high speed transmission line protection were either the CPD from General Electric Company or the HCB-1 from ABB Power T&D Co. (Westinghouse Electric Corporation). These relays were chosen many years ago for their easy application to short lines and excellent selectivity for isolating faults to the proper line segment. Both relays operate over a single metallic wire pair and transmit phase and amplitude information between the end terminals. By comparing the two end currents, the relays determine if observed fault current flow is due to an internal or external fault and will either trip or restrain accordingly. The CPD uses a circulating current technique to transmit the phase and magnitude information for trip conditions, while the HCB-1 uses an opposing voltage technique to accomplish the same thing. During the course of the project, most of the existing CPD relays were replaced with new HCB-1 relays since the selected manufacturer's fiber multiplexing equipment had a well-proven interface available for the HCB-1.

The majority of pilot wires used by these relays were installed between 1965 and 1980. In addition to pilot wire relaying, pilot wires were also used for SCADA, telephone and tone relaying. Over time, the effects of aging on the pilot wires were becoming apparent in higher error rates for SCADA, improper relay operations and generally more frequent maintenance. According to T&D Superintendent Randy White, "the pilot wire relaying could be expected to misoperate every time it rained." When a pair went bad due to short circuits from broken insulation or other failures, the pair was taken out of service and another pair was used. The number of good pairs available were dwindling fast. In April of 1993, Randy persuaded city management to replace the ailing pilot wires with a new fiber optic network, which would greatly improve the reliability of all communication systems. They had also considered leasing T1 bandwidth from the local telephone companies to each substation. As it turned out, the pay back period period for purchasing and installing their own fiber was less than five years.

It was decided to install a single system which would incorporate not just relaying, but all substation communication requirements. To lessen the fear of putting SCADA, tone and pilot wire relaying at the mercy of one system, it was decided to implement a self-healing ring architecture in two loops (North and South).

The next step was selecting a method for installing the fiber. Integral aerial fiber duct using Siecore fiber was chosen for its ease of retrofit to existing lines and faster repair times in the event of a broken fiber. Once the duct is installed beneath the phase wires, it is possible to pull or push new fiber through the duct as needed for increasing the number of fibers or repairing broken sections.

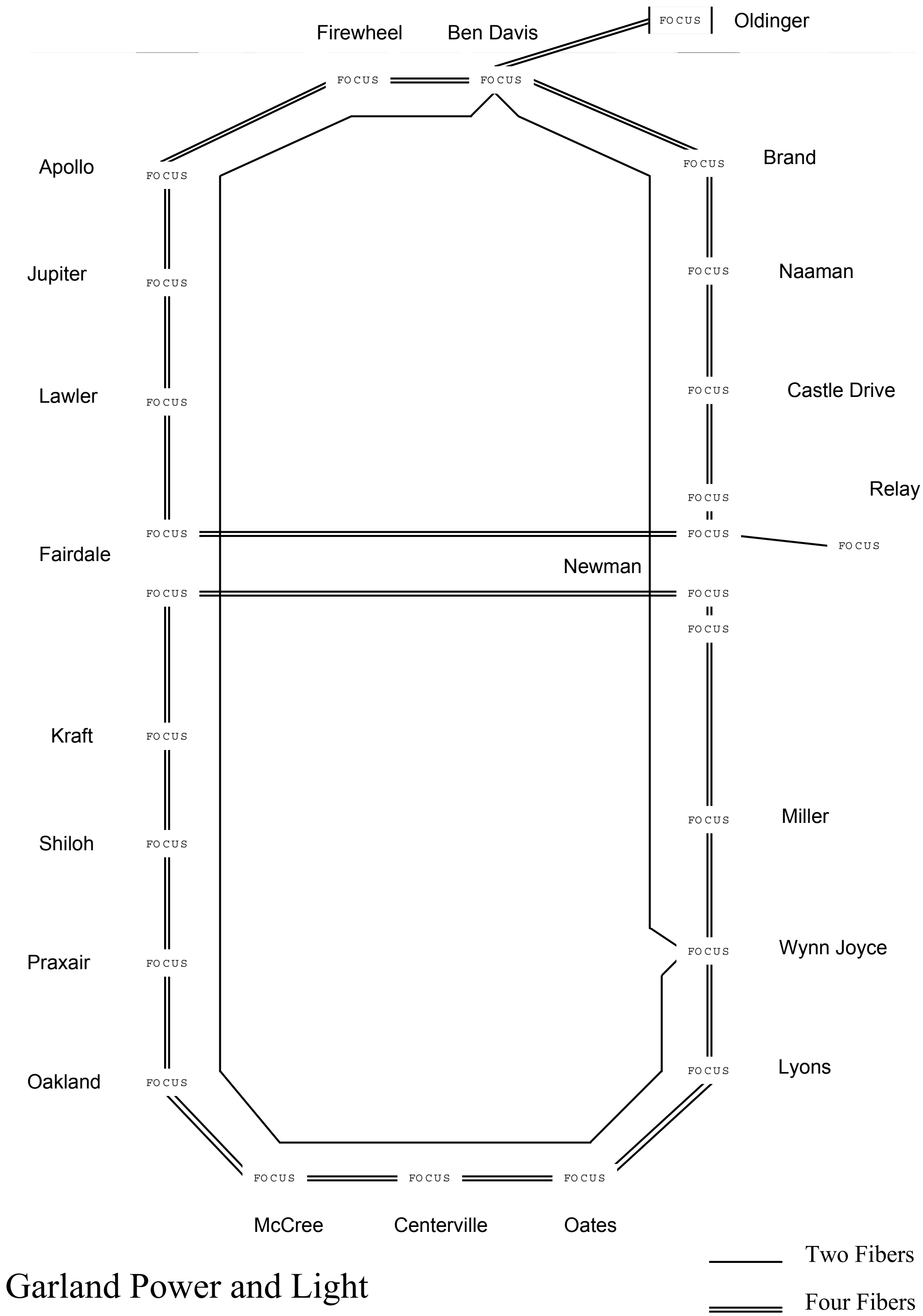

Figure 21 - Garland, Texas Fiber Optic and Substation Map

The city felt the ability to perform fiber splicing in house would be beneficial in the future when repairs had to be made to the fiber. This proved to be a good investment as Pat Polk, Substation Fiber Technician, was able to perform all required splicing, both during the installation and whenever problems arose. The longest single section installed today without a splice is 10,500 feet. The North loop was completed in June of 1997. The South loop would have been completed by 1998 had it not been for a six-month delay during the summer heat wave of that year.

The four-fiber-hot-standby (FFHS) loop approach was selected to minimize channel delays for rerouted HCB circuits. The maximum delay for "healed" circuits in the Garland system will be 800 µs, which is well within the tolerance of the HCB relay. The delay for an APM (two-fiber) system would have been greater than permissible for proper relay operation. Two independent rings of 11 and 13 nodes were installed in the North and South rings as shown in Figure 21. The rings are interconnected between Ben Davis and Wynn Joyce to provide a direct path for the HCB system between these two substations. To provide redundancy for this connection, traditional hot standby optics were utilized with the standby fibers routed the opposite direction around the rings. The interconnection also permits a single network management program to have visibility of the entire system. It is possible to view targets, configurations and make changes to any node in either ring with a PC connected to any other node in either ring. Cliff Parker, a PE from the city's engineering department, was tasked with configuring the time slot maps for the system. An example time slot map is shown in Figure 22. RS-232 circuits were added after the initial installation to carry the pilot channels for the backup SEL321 relays.

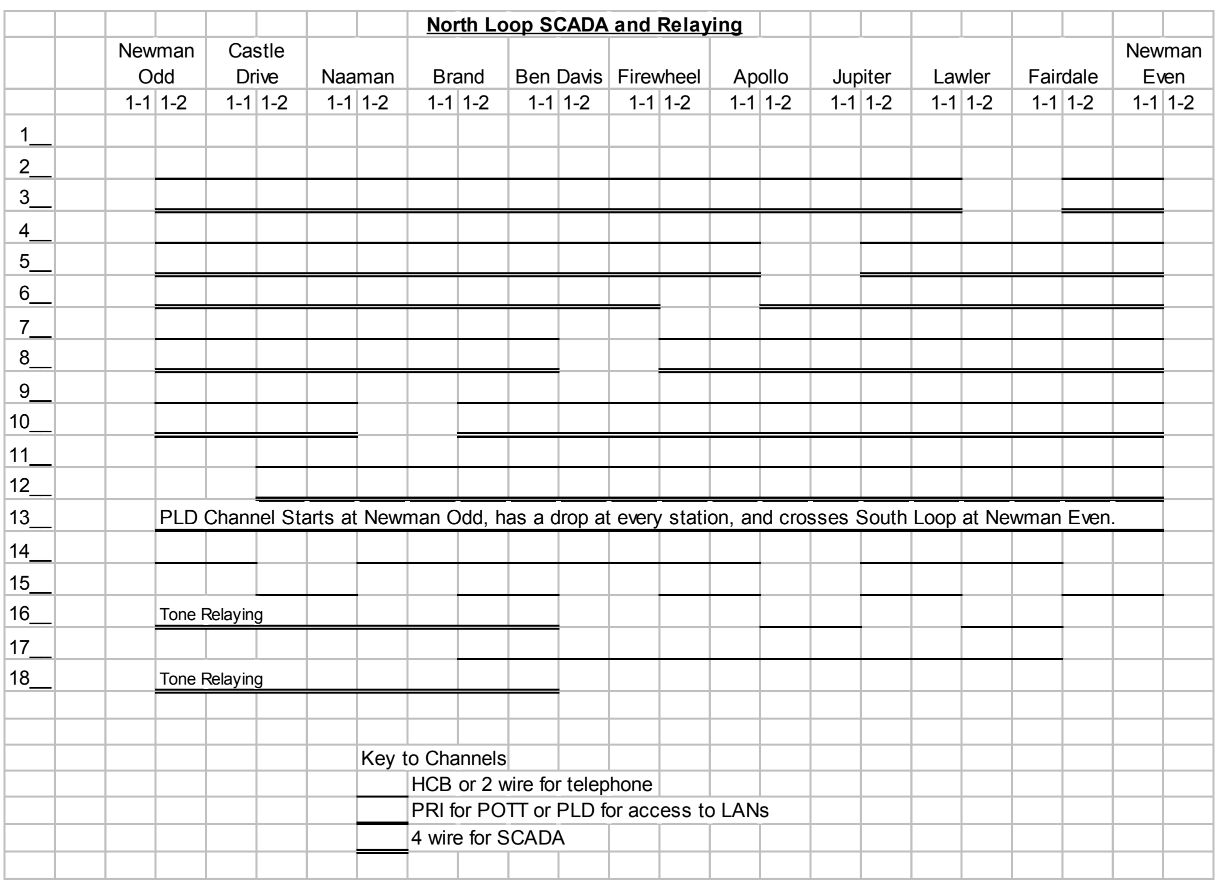

Figure 22 - Garland, Texas Channel Map

The cost of adding pilot communications for backup relaying was financially justifiable since the fiber system was already in place. A less desirable non-pilot backup scheme was the alternative had the fiber not been available.

The operating experience of the new system has been beyond all expectations. The project ran very smoothly due largely to a high level of joint support and cooperation between many individuals and particularly the distribution and substation departments. Doug Kendrick, T&D Coordinator, says, “they are still waiting for the first HCB misoperation.” The SCADA systems have operated as expected with no occurrences of RTUs going off line due to channel problems. Having a telephone in every substation was a bonus not available with the previous system, since the cost for leasing phone lines from the local Bell company was cost prohibitive. The fiber system simply adds extensions from the existing city switch to every substation and does not involve the phone company.

Ocala Electric Utility - Installation and History

In April of 1995 the Ocala Electric Utility (OEU) in Ocala, FL, located about one hour north of Orlando, FL, installed a FOCUS FFHS scheme between 16 of their substations. According to Pete Faulhaber, who provided the following information about his system, the primary reason for implementing the fiber system was to improve the reliability of the 16 HCB relay systems in use on the OEU network. Prior to 1995, the HCB/PM schemes averaged three correct operations and 5 incorrect operations each year due to failing or marginal pilot wires. Knowing that the condition of the pilot wires will greatly influence the reliability of the pilot wire scheme, it was decided to keep the relays in service but replace the wires with fiber.

SCADA information was being carried over a combination of leased and owned wire circuits which were not only costing money to lease and maintain but frequently received errors requiring retransmission of RTU data which slowed down the entire SCADA system. Telephone circuits to the substations were costing an additional $5,090.00 annually.

The selected fiber system was designed to carry all of the needed relay, telephone and SCADA channels to improve relay reliability and lower the OEU's operational costs by eliminating leased line charges and reducing maintenance hours.

Due to the location of the substations and previously planned FO cable routing, it was not possible to construct the network in one large ring and maintain the requirement that a single cable break would not sever the ring in more than one location. This would have created island systems and prevented self-healing. Even if it was possible to implement a one ring solution, a more reliable system would result if the system was separated into two or more smaller rings. This practice will also minimize the possibility of multiple failures severing a ring in two or more places.

For OEU, a two ring solution was a natural due to the existing fiber routes. One ring connected 4 stations while the other connected 17 stations of which two were common to both. Figure 23 depicts the geographical configuration of the system. The delay through the 15 nodes on the back side of the ring would have been too excessive for the pilot wire relays if a 2 fiber APM scheme was selected. The FFHS approach was a good choice to carry the required number of channels and keep delays during self-healing within acceptable tolerances. Figure 24 shows the final time slot allocation map for the completed system. Note the number of available spare channels which can be used as the system expands.

In addition to the HCB and 4 wire circuits for SCADA, OEU included a Party Line Exchange (PLE) system to provide telephone access to every site. The PLE system requires just one time slot for the entire network to provide dial-up telephone communications to every site. Unlike a traditional telephone system, the PLE permits just one conversation at a time within the network. This was determined to be acceptable since all of the locations included were normally unmanned. There is also an emergency break-in code to join an existing conversation if needed for emergencies or party line calls. One location in the ring is connected to an OEU PBX extension to provide communications to other phones outside the ring and vice-versa. The PLE system uses normal DTMF telephones to ring each station using a user selected three-digit number.

Several Direct Transfer Trip systems were also added using four function PRS digital interfaces to provide permissive and direct transfer trip channels for lines with directional comparison relays.

The overall results exceeded the cities expectations.

During the first three years, there were approximately 10 correct HCB operations and 0 false operations. This is compared to an expected 15 false and 9 correct operations within the same time period with the original system.

The data rate for the SCADA could not be increased due to a limitation within RTUs installed. The overall reliability was improved by reducing the frequency of errors in the data.

The PLE system has replaced 16 leased single line telephone circuits in the substations. This cost savings represents a 5.2 year pay back for the PLE feature. They have also added extra telephone extensions in locations where previously they could not justify the expense of a phone circuit.

The system has been required to switch to the self-healing mode just two times in it’s history which gives testimony to the reliability of both the fiber cable and multiplexers.

The first event was caused by a failure of the station battery and charger which dropped all DC power to the chassis. For this case, every channel terminated at the substation was lost until dc power was restored. All pass-through channels were correctly rerouted around the failed chassis.

The second event occurred when one cabinet containing the FOCUS multiplexers was being moved (while energized) to another part of the control house. A fiber jumper was accidentally broken which caused the system to switch to FFHS mode. Once the cable was replaced, the system returned to normal as expected.

According to Arnie Hersh (who was responsible for the system), OEU is very pleased with the results of their decision to install an integrated fiber system which included all their substation communication requirements. It has proven to be both reliable and virtually maintenance free.

This is another example where the protection engineer benefited by agreeing to share fibers with SCADA and telephone functions. The self-healing rings and inherent reliability of fiber optics resulted in a much improved system which he might not have been able to justify for relaying purposes alone.

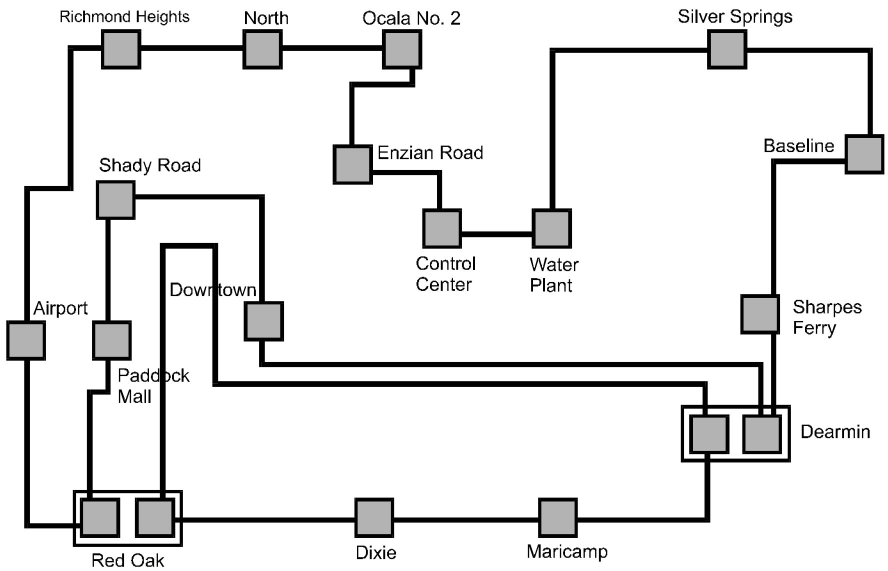

Figure 23 - OEU Fiber Optic and Substation Map

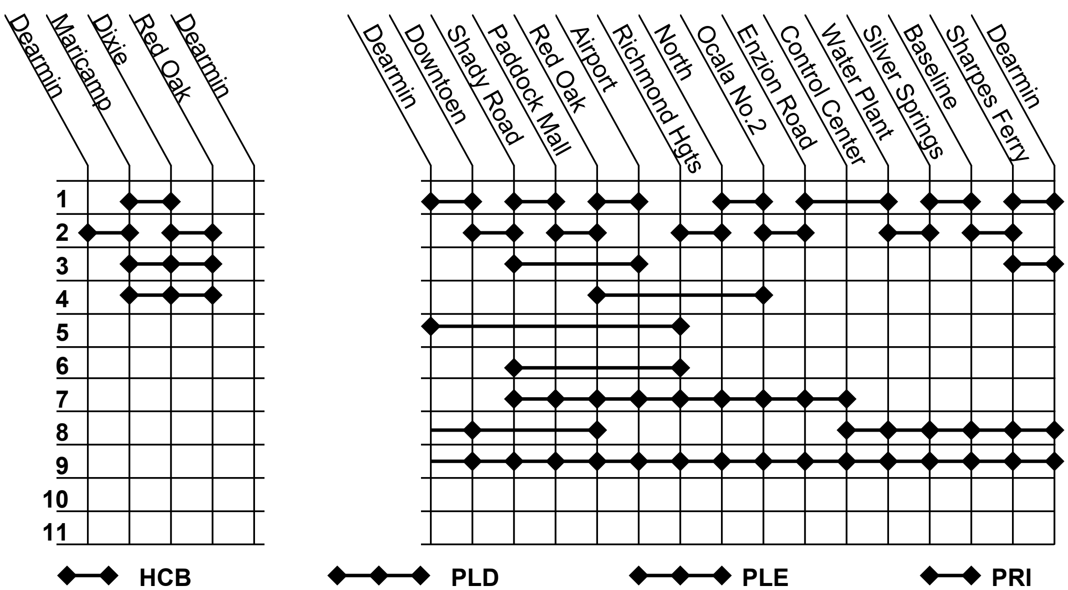

Figure 24 - OEU Channel Map

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