Pilot Protection Communication Channel Requirements

S. Ward T. Dahlin B. Ince
RFL Electronics Inc.
353 Powerville Rd.
Boonton, NJ 07005

Abstract

Pilot relaying has been applied for transmission line protection since the 30's. The well known communication channels (pilot wire or Power Line Carrier) are increasingly being replaced by digital channels. Dark fiber (dedicated fiber optic cable), multiplexed fiber optic systems (T1 and SONET) and 56 kbps phone lines (DDS – Digital Data Service) are now made available for pilot protection purposes. The new channels provide much higher data transfer rate but reliability and security performance criteria developed for the telecommunications industry are not easily translated to teleprotection applications. A number of new terms are introduced to the protection engineer and it might not be all that obvious what precautions need to be taken from a protective relaying point of view.

This paper discusses the requirements for the communication channel for common pilot schemes, direct transfer trip and current differential relaying. It addresses issues such as channel asymmetry and channel switching in T1 and SONET networks and the affect on pilot relaying performance. It also provides basic description of digital communication techniques and terminology that the relay engineer may encounter in his work.

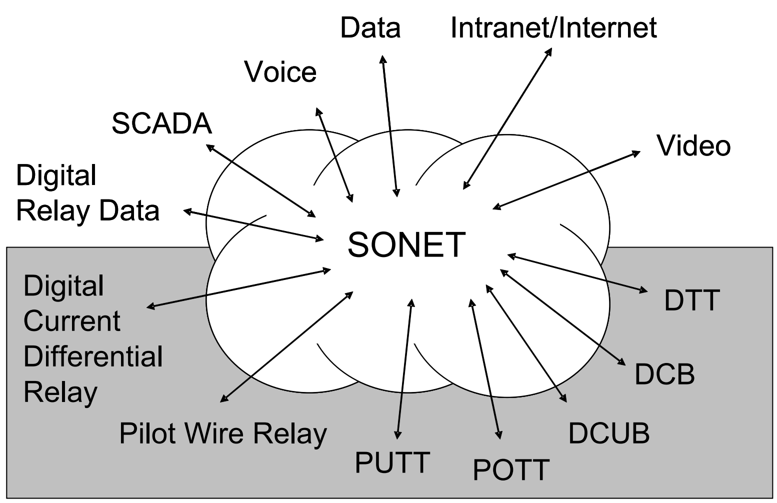

Figure 1 SONET data services

A glossary with telecom terms used in this paper is provided at the end of the paper. The number of new terms introduces made it impractical to include the description of each term in the text.

Telecommunications and Teleprotection

The demand for Information Technology and Telecommunications has grown exponentially over the last decade. Industries with critical infrastructure organizations, including electric utilities, are working to integrate their IT and telecom strategies in order to reduce costs, improve efficiency, and strengthen the information backbones within their corporations.

Teleprotection, or relaying, channels conventionally reside with the Utility Relaying group, as a relaying communications channel forms part of the Protection System. Relaying channels have traditionally been point-to-point connections but it seems logical, and cost effective, to use an existing digital communications network instead of installing or replacing a parallel dedicated relay communications channel. The relaying demands, at first glance, seem to easily fit into the telecommunications network that generally provides high redundancy and high bandwidth. However, due to a lack of understanding between the relaying group and the telecommunications group, the special requirements for teleprotection are not always clearly stated and, as a result, not fully considered in the communications network's design. At the same time, the relay engineer does not have a clear picture of how the relay's data is transported from the local relay to the remote, receiving relay. Consequently, any problems relating to the communications link can be hard to resolve due to lack of understanding of the entire teleprotection system, including both relays and communications.

Several working groups are active in this area. The new IEEE C37.94 "Standard for N times 64 kilobit per second Optical Fiber Interface between Tele-protection and Multiplexer Equipment" addresses connectivity between relays and multiplexers on an optical level. PSCC (Power System Communications Committee) as well as WECC have groups working on guides to provide communications system designers with basic performance criteria for communication circuits carrying protective relaying applications. The need for these guides was precipitated by the recognition of potential relay problems due to channel timing delays arising from the application of digital communications and switching technologies.

Digital Communication Channels

The types of media transporting relay data in digital form are:

- Dedicated optic fiber
- Multiplexed networks using 64 kbps interfaces
  - T1 Multiplexing
  - SONET
  - Digital Microwave and Radio Links
- CSU (Channel Service Unit) providing 56 kbps or 64 kbps service over copper phone lines

There is also Power Line Carrier available with the ability of transmitting up to 64 kbps but this bandwidth over a power line has not been sufficiently reliable to be used for other than SCADA or other non-critical data. Power Line Carrier, however, is still a popular media for conventional teleprotection such as Direct Transfer Trip and Pilot Distance Protection.

Dedicated Optical Fiber

A fiber optic pair available for exclusive use by the relays provides optimal performance for digital communications. Dedicated fiber gives a fast and error-free point-to-point connection. The main drawback is that a fiber cut will cause channel interruption for a long period of time, and many utilities lack expertise and equipment for replacing and splicing a damaged fiber cable. Of course, the installation and material costs for a dedicated fiber compared to conventional communication channels limits its availability for relaying.

Two optical fiber categories with distinctive operational attributes are multimode and single-mode fibers. The distance of the communication link generally dictates whether to use multi-mode or single-mode fiber.

Typical losses per km are:

- Multimode step index 3.0 dB @ 850 nm
- Multimode graded index 1 – 2 dB @ 1330 nm
- Single mode step index 0.35 db @ 1330 nm and 0.2 dB @ 1550 nm

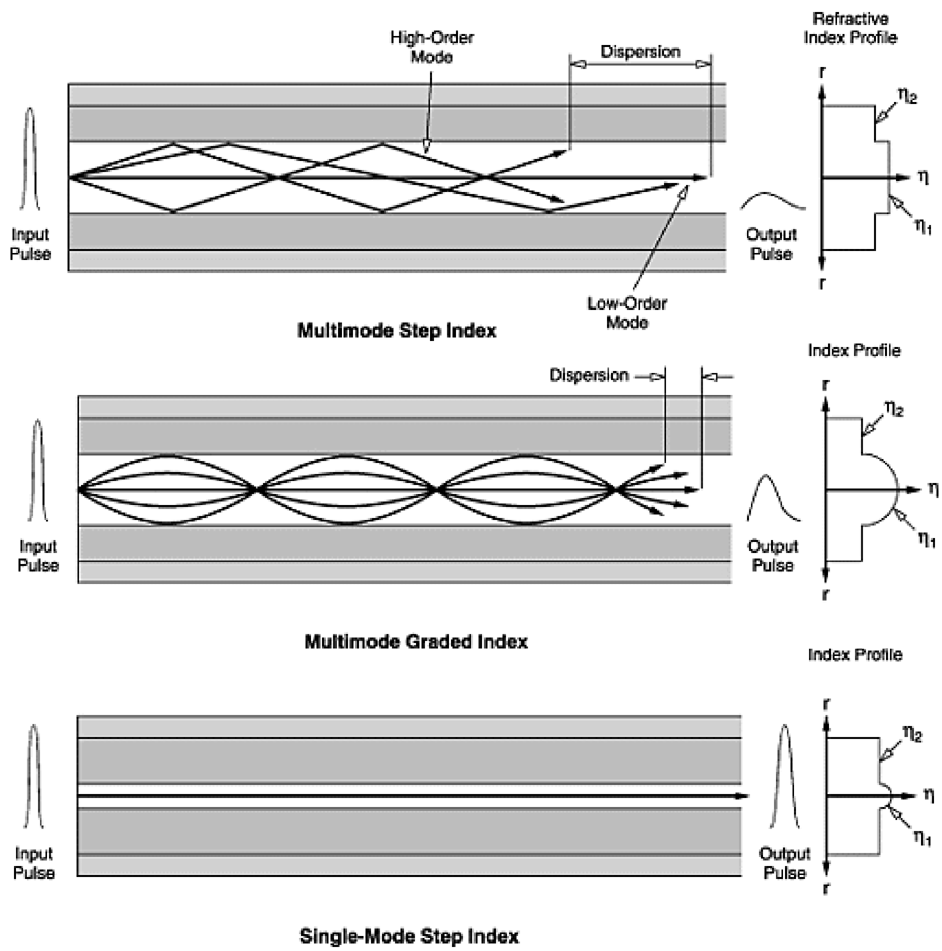

Figure 2 Optical Fibers

As shown above, two basic types of multimode fibers exist. The simpler and older type is a "step index" fiber that has higher losses than the "graded index" fiber. Multi-mode is used for shorter distances, up to about 10 miles. All inter-substation fiber optic connections are generally made with multimode mode fiber due to the lower cost. A typical example of an inter-substation connection is the C37.94 relay-to-multiplexer fiber interface that is limited to 2 km (1.25 miles).

For longer distances, single mode fiber is used, with LED or laser optical transmitters. Laser provides longer reach but is more expensive. The longest distances, 60 miles or longer, are achieved with single mode, 1550 nm fiber and laser optical transmitter. Relays and teleprotection devices often have a number of interfaces to choose from. To determine the required relay interface, an estimate should be made based on the actual installation, fiber loss and specified system gain, for example:

Optical Budget		
Optical Transmitter Power	-17 dBm	
Connector loss (2 dB per connector x 2)	-4 dB	
Splice loss (0.4 dB/splice x 4)	-1.2 dB	
Fiber loss 1310 nm singlemode (0.25 dB x 10 km)	-2.5 dB	
Receive signal Level	-24.7 dBm)	
Receiver Sensitivity	-40.0 dBm)	
System Margin	15.3 dB	(≥ 3 dB recommended)

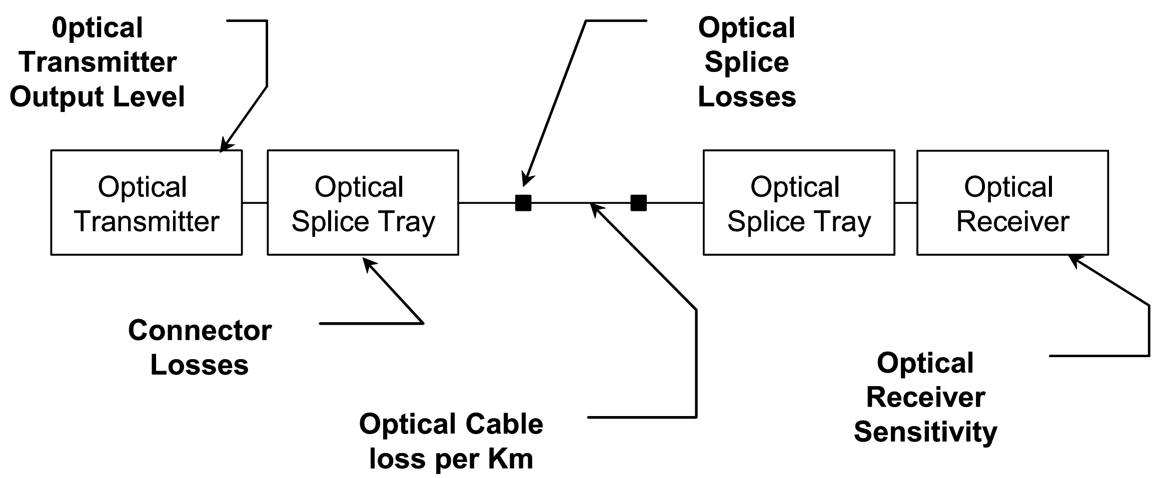

Figure 3 Losses in dedicated fiber applications

Note that some relay designs will not accept too high received signal level as this may over-drive the receiver circuitry. As the relay is not able to read the received signal, it will alarm for loss-of-channel. This might happen if a communications interface with high output level is used on a short fiber with too little attenuation, or during back-to-back bench testing. The remedy is to add an attenuator in the fiber circuit, or, if bench-testing, attenuate the circuit temporarily by loosening the fiber connector.

Dedicated fiber application for relaying is very straight-forward, but there might be a need to make sure that the fibers for the connection between the relay and the optical splice tray have the correct connectors ahead of time. The most common fiber connector is ST but some relays might require FC-PC connectors. An ST connector will then not work and if the splice tray uses ST connectors a special cable with FC-PC in one end and ST in the other is required. This modification is not easily done at site as special tools are needed to cut and fuse the fiber to the connector.

T1 Multiplexing

T1 is a term for a digital carrier facility used to transmit a DS-1 formatted digital signal at 1.544 megabits per second. T1 was developed by AT&T in 1957 and implemented in the early 1960’s to support long-haul pulse-code modulation (PCM) voice transmission. The primary innovation of T1 was to introduce “digitized” voice and to create a network fully capable of digitally representing what was, up until then, a fully analog telephone system.

Today T1 is used for a wide variety of voice and data applications. They are widely embedded in the network distribution architecture as a convenient means of reducing cable pair counts by carrying 24 voice channels in one 4-wire circuit. T1 multiplexers today are also used to provide DS0 “access” to higher order ‘transport’ multiplexers such as ‘SONET’.

T1 Frame

A T1 frame consists of 24 eight-bit words plus a framing bit. Each timeslot of the frame contains 8-bits of binary information. Each timeslot is called a Digital Signal Zero (DS0) which is sampled 8000 times per second. This sampling rate was chosen because it can adequately represent voice characteristics of a human speaker when using Pulse Code Modulation (PCM). Therefore, each DS0 contains 64kb/s (8k samples/sec x 8 bits/sample) of user information. Time Division Multiplexing (TDM) is used to combine 24 DS0’s into one T1 frame. Since there are 24 DS0's in a T1 frame, the effective data rate is 1.536 megabits per second. Also, each frame contains one framing bit, which is used primarily for frame synchronization. This bit adds an additional 8kb/s of overhead to the frame thereby primarily for frame synchronization. This bit adds an additional 8kb/s of overhead to the frame thereby increasing the information rate from 1.536 Mb/s to 1.544 Mb/s. This 1.544 Mb/s is commonly referred to as a Digital Signal One or DS1. Note that the word T1 and DS1 are used interchangeable, however this isn’t really accurate. A T1 refers to the digital transmission system, which happens to operate at DS1 rates.

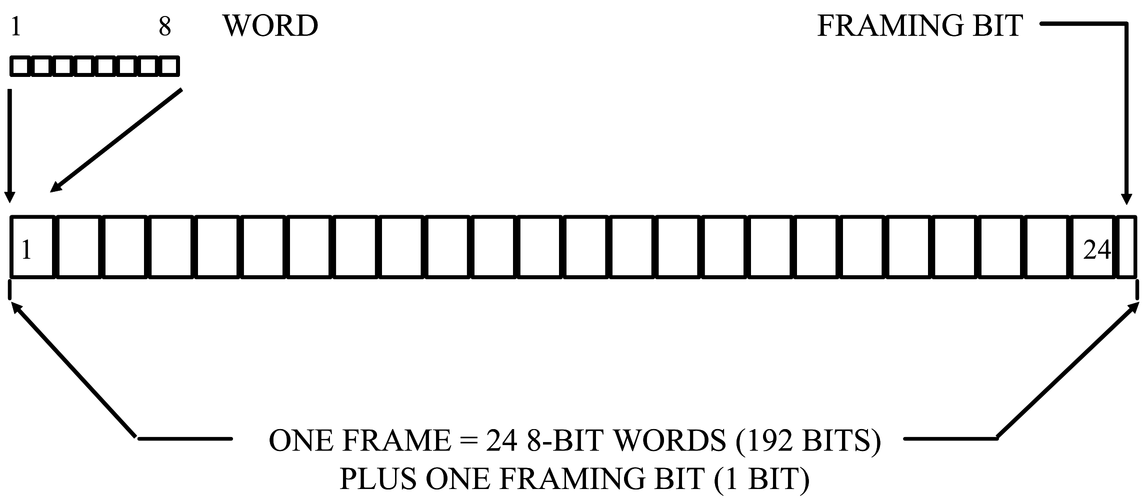

Figure 4 T1 frame

Framing

Framing is used on T1 circuits primarily to synchronize individual T1 frames without the need for external clocking devices. D1 framing was the first framing pattern to be used for transmission of T1 signals. Within a D1 frame, each timeslot contained seven-bits of digitized voice and one-bit used for signaling (call setup and routing). The framing bit identified the boundary between frames. As T1 networks developed, other framing and signaling methods needed to be developed. The SuperFrame (SF) or D4 framing was the first one introduced.

A SuperFrame consists of 12 individual T1 frames. The framing bit in every odd frame is used for terminal framing while the framing bit in every even frame is used for signaling framing. Terminal framing and signal framing are used to form a 12-digit word (100011011100). Notice that the even bits used to identify signaling frames are sequenced as X0X0X1X1X1X0. Signaling information is marked by the change in the bit pattern. Frame six transitioned to a one and frame twelve transitioned to a zero.

Thereby signaling information is contained within frames six and twelve of a SuperFrame. The sixth and twelfth frames are used the same in D1 framing. Only two of the 12 frames contain signaling information within each timeslot.

Today, most T1 facilities use a framing technique called Extended SuperFrame (ESF). ESF consists of 24 individual T1 frames. The 24 framing bits are classified into three different categories; alignment or terminal framing (2kbs), CRC (2kbs), and data link (4kbs). The terminal framing bits are used to identify frame boundaries and positions of other framing-bits. The CRC (cyclic redundancy check) is used to monitor the performance of the ESF and the data link is used to send performance information as well as other messages between multiplexers.

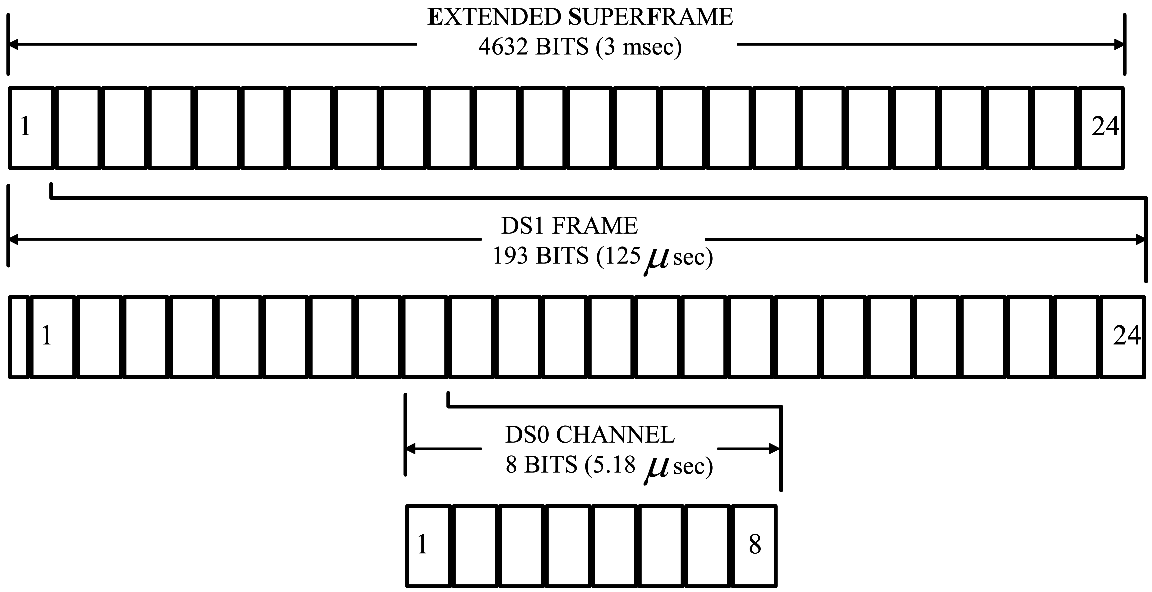

Figure 5 Extended Superframe

Line Coding

A T1 signal is transmitted on the link in a binary format (ones and zeros). This binary format is encoded onto the link using a technique known as alternate mark inversion (AMI). The format is alternating pulses (+3/-3 V) denoting a one and no-pulse denoting a zero. The benefit of this encoding is that it has a built-in method of error detection. Whenever consecutive pulses are detected of the same polarity, a bipolar-violation (BPV) is indicated. Therefore, we know that the frame experienced some type of error. A disadvantage to this encoding is the transmission of an all zero's pattern.

To correctly identify DS-1 input, the multiplexer must know when to sample the bipolar signal to determine whether a “0” or a “1” is being transmitted at any given time. To ensure proper sampling, the multiplexer relies on a timing method that uses the binary pulses (i.e., ones) to maintain synchronization with the network equipment that is transmitting the DS-1 signal.

Since pulses are critical to maintain power signal timing, all DS-1 signals are required to meet specific “one’s density standards”. These standards require that at least one pulse be transmitted within any eight-bit sequence (i.e., 12.5% ones density). Further, since long strings of consecutive zeros between digital values can also hinder signal timing, ones density standards prohibit the transmission of more than 15 zeros in succession.

Success in meeting ones density requirements can vary based on application. For example, since the size and content of the bit patterns that represent human speech are consistent, acceptable ones density in voice applications is a virtual certainty. But since digital data is highly variable in size and content, conformance to ones density standards cannot always be guaranteed. This technical problem is why a coding technique known as "*bipolar with 8-zero substitution*" (B8ZS) has gained in popularity.

B8ZS uses intentional bipolar-violations (BPVs) to break up long strings of zeros, allowing their transmission through the T1 link without violating the ones density standard. With B8ZS, network equipment replaces any string of eight consecutive zeros with two intentional BPVs before the DS1 signal is transmitted over the T1 link: the first BPV replaces the fourth zero, the second replaces the fifth and seventh zeros. Additionally, the eight-zero bit, which normally would be coded as a zero, is assigned a pulse value. Using this format, the DS1 signal can pass through the multiplexer on the T1 link with an acceptable level of pulse density. When the signal arrives at the receiving network equipment, the pattern is recognized as the B8ZS substitute for eight consecutive zeros; the equipment then replaces the international BPVs with their zero value.

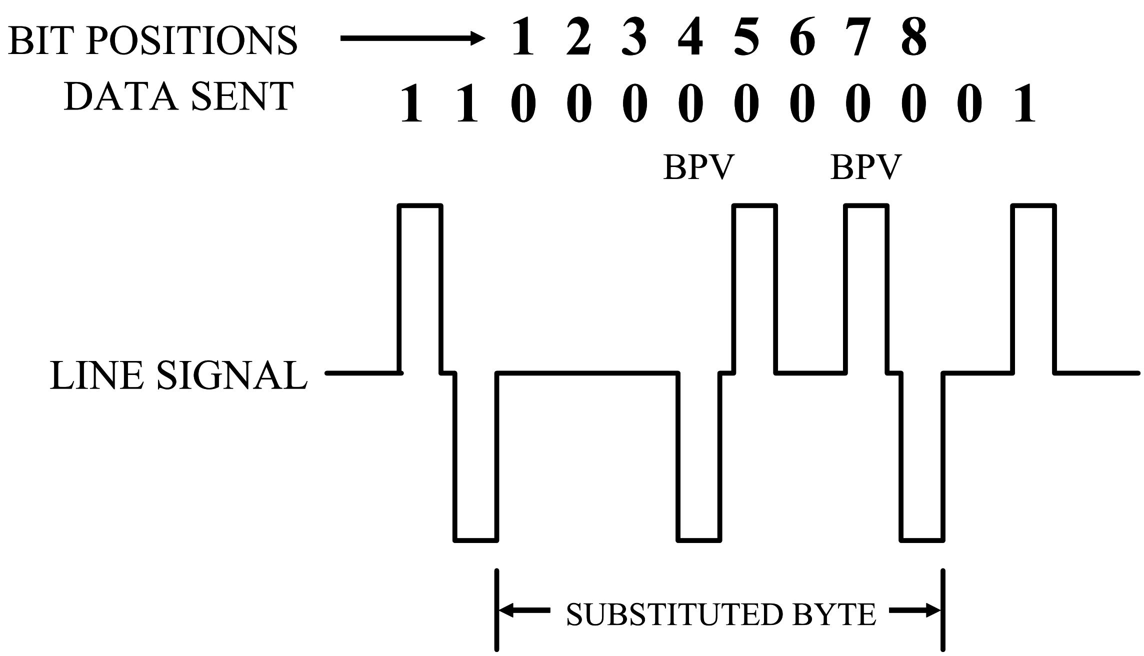

Figure 6 Bi-polar with 8-zero substitution (B8ZS)

Network Timing

T1 networks are designed to be primarily synchronous networks. That is, data clocked in at one point in the network has a fixed timing relationship to the point in the network at which the data is clocked out. Technically, this means that the speeds at both points are the same, and there is a fixed frequency relationship between the clocks which strobe the data in and out. This condition is usually referred to as "frequency locked".

The North American T1 network is derived from a series of a higher-order network multiplexer with unsynchronized clocks, using a technique called "pulse stuffing" to overcome clock inaccuracies and fluctuations. The use of unsynchronized clocks for higher-level TDM networks does not, however, preclude network-synchronized clocks for higher level T1 or DS1 signals. Synchronization of the network at the DS1 level is achieved by framing (D4 or ESF in North America) the data streams and frequency locking the node and network clocks. Loss of synchronization or unlocked clocks results in frame slips. A “frame slip” is a condition in which framing is momentarily lost, as well as network timing information, typically resulting in data loss.

T1 Multiplexer Reliability Concerns

Several considerations must be taken into account when selecting a multiplexer for a utility’s protection scheme. Some of those concerns are listed with an explanation of their importance.

- Reframe time
  “Reframe Time” is defined as: “The amount of time it takes a multiplexer to re-synchronize to the network should there be an interruption in the incoming signal.” This amount of time equates to an outage of system availability during that interruption. This is why this time should be kept to a minimum.
- Through-Channel Delay
  “Through-Channel Delay” is defined as: “The amount of delay time incurred by a channel passing through a drop-and-insert location.” Since many T-1 applications are multi-point, certain channels will typically pass through several locations before reaching their final destination. This amount of delay incurred may become prohibitive to certain relaying applications (current differential or blocking) should these delays not be kept to a minimum.
- Fallback Timing
  “Fallback Timing” is a necessity that guarantees system clock is available should there be a loss of the incoming clock source. This ensures the remainder of the system will continue to operate from that new clock source.
- DS0 Synchronization and De-synchronization delay in/out of T1 payload
  This is the amount of delay that it takes to input and extract the DS0 signal into and out of the T1. The longer the delay the greater the effect on the relaying circuit.

The ability to intermix voice and data and preserve the transmission characteristics of each is a primary requirement of T1 multiplexers. Voice transmission, for example, can tolerate a few bit errors and not affect the quality of the voice at the receiving end. Speed of delivery is important as any delay is noticeable in voice conversations. In telephone company channel banks, multiplexers data transmission is treated just the opposite. Error free transmission is a higher priority than speed of delivery. It is this practice that makes most Telco grade T-1 systems unusable for critical real-time applications such as current differential and phase comparison relaying.

SONET

SONET (Synchronous Optical NETwork) is the American National Standards standard for synchronous data transmission on optical media. The international equivalent of SONET is SDH, Synchronous Digital Hierarchy. Together they ensure that digital networks can interconnect internationally and that existing conventional transmission systems can take advantage of optical media through so called “tributary” interfaces. SONET features are:

- Application, service and protocol transparency. There is no service, protocol, nor application which cannot ride on the SONET backbone network.
- SONET is relatively inexpensive when compared to Asynchronous Transfer Mode (ATM) equipment for multimedia networks. Equipment costs can be as much as 60% less than an ATM equivalent product.
- An open systems optical architecture for Multi-Vendor Inter-working

One of the main drivers behind SONET is the Multi-Vendor interoperability. Earlier, standards existed for the electrical level only, and to connect to another manufacturer's equipment, back-to-back connected devices were required. With SONET establishing standards for the optical signal levels, a change of equipment can be made "mid-span', i.e. one vendor's multiplexer can be connected to the fiber network at one terminal and another vendor's multiplexer connects to the same fiber at the other end.

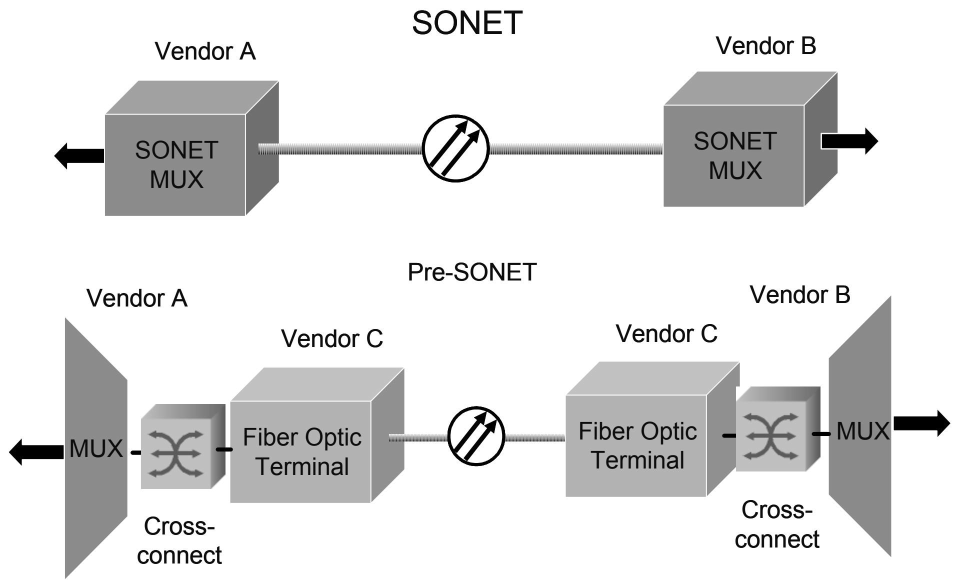

Figure 7 Multi-vendor interoperability

Some of the most common SONET (and SDH) applications include transport for all voice services, Internet access, frame relay access, ATM transport, cellular/PCS cell site transport, inter-office trunking, private backbone networks, metropolitan area networks and more. SONET operates today as the backbone for most, if not all, interoffice trunking as well as trans-national, and trans-continental communications.

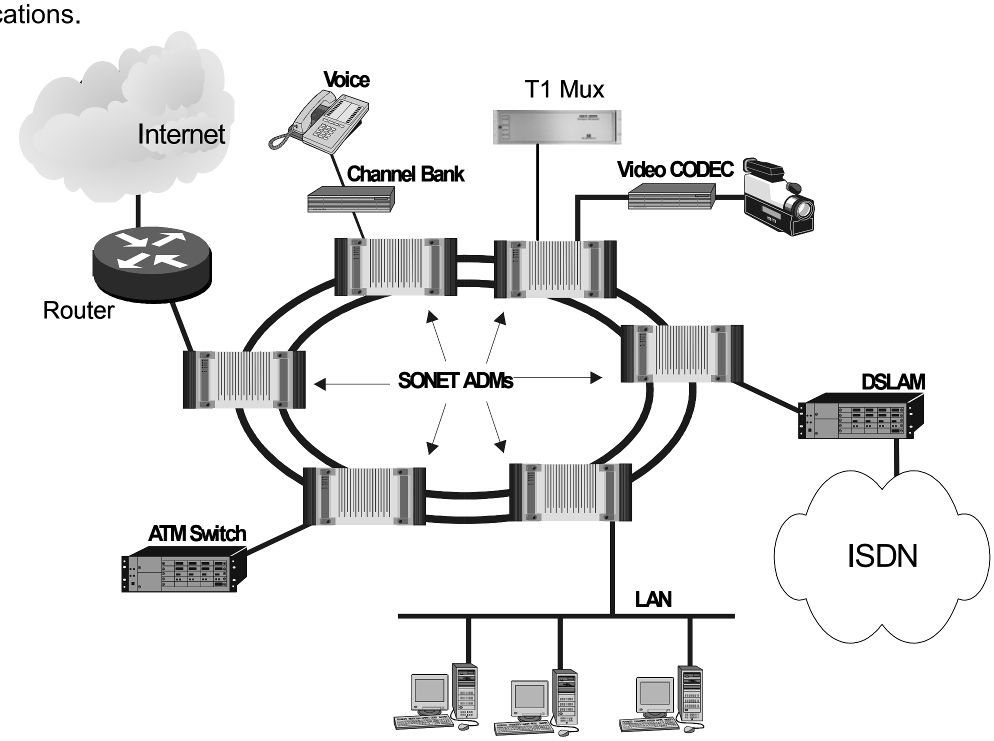

Figure 8 Telecommunications Network

Figure 9 illustrates the levels (bandwidths) in the SONET standard and how these relate to the North American Digital Hierarchy. STS-n is the Synchronous Transport Level where ‘n’ signifies the level (or bandwidth). STS is the electrical signal rate used within SONET prior to its optical conversion. OC-n is Optical Carrier Level where, again, ‘n’ is the bandwidth level. OC is the optical signal. DS stands for Digital Signal Level. DS-0 is one voice channel and occupies 64 kbps. DS-1, also called T1, is 24 DS-0’s or 1.544 Mbps.

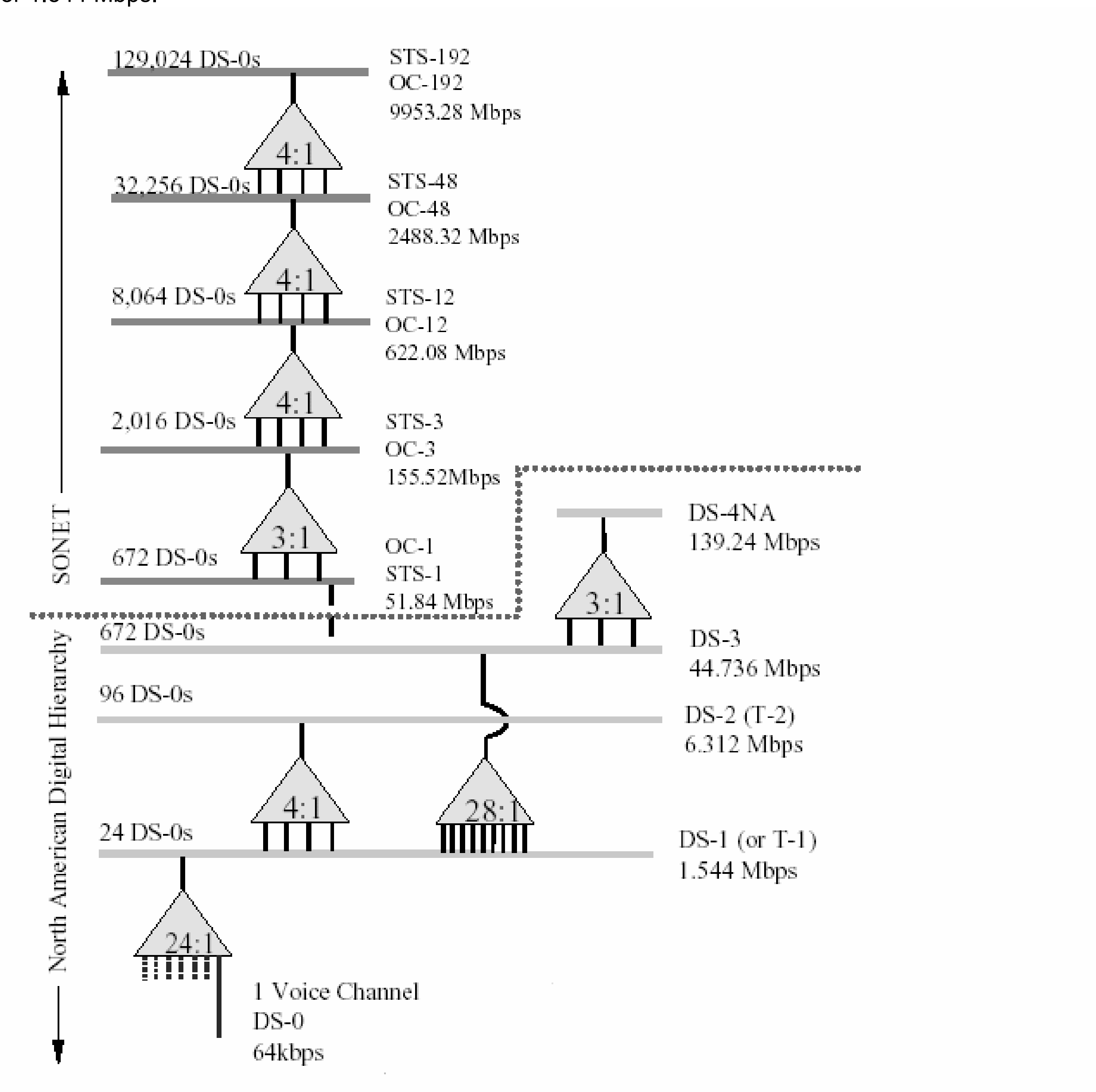

Figure 9 Digital and Optical Carrier Hierarchy Signals

Asynchronous and Synchronous Multiplexing

Transmission hierarchies in the past have been built using asynchronous multiplexing systems. SONET uses synchronous multiplexing. In asynchronous systems, each terminal in the network runs on its own clock. In digital transmission, clocking is one of the most important considerations. Clocking means using a series of repetitive pulses to keep the bit rate of data constant and to indicate where the ones and zeroes are located in a data stream.

Because these clocks are totally free-running and not synchronized, large variations occur in the clock rate and thus the signal bit rate. For example, a signal specified at 44.736 Mbps + 20 parts per million (ppm) can produce a variation of up to 1,789 bps between one incoming signal and another.

Asynchronous multiplexing uses multiple stages. Signals such as asynchronous DS-1's are multiplexed, and extra bits are added (bit-stuffing) to account for the variations of each individual stream and combined to form a DS-2 stream. Bit-stuffing is used again to multiplex up to DS-3.

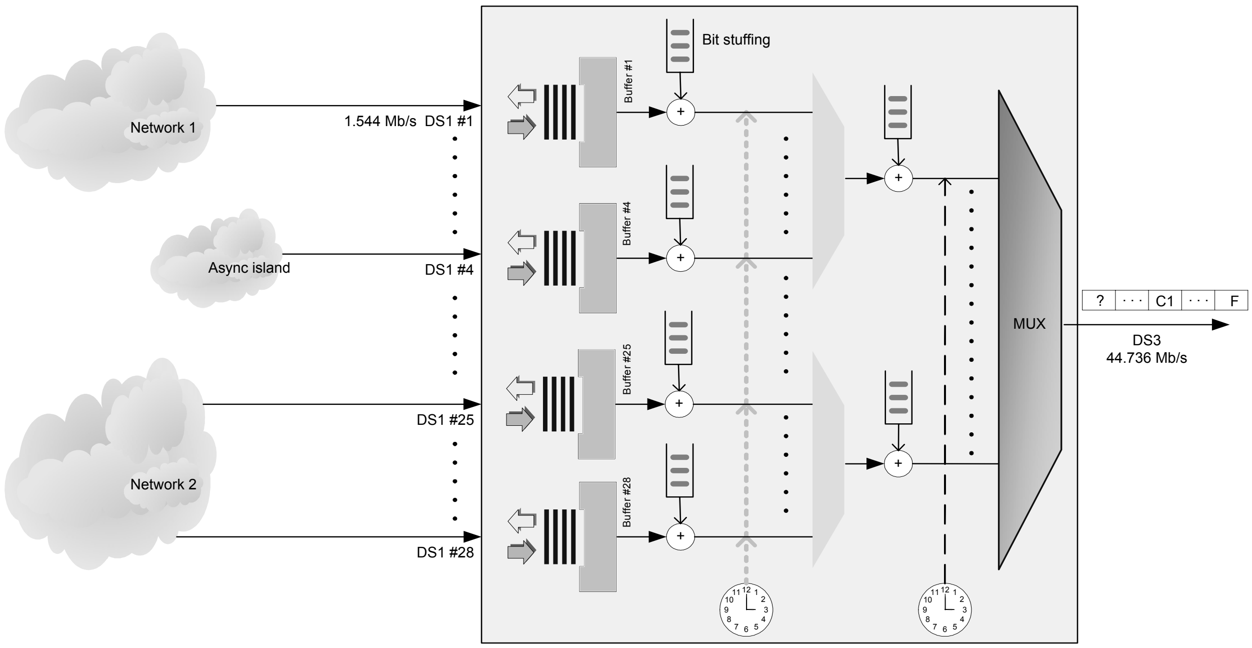

Figure 10 Asynchronous multiplexing and bit stuffing

The main problem with this procedure is that the lower, multiplexed levels, can not be accessed without de-multiplexing the entire signal. To add or drop a signal, the optical DS-3 needs to be converted to copper DS-3 and then de-multiplexed into individual DS-1 signals, and the required signal can be dropped. To add a signal, the reverse process has to take place.

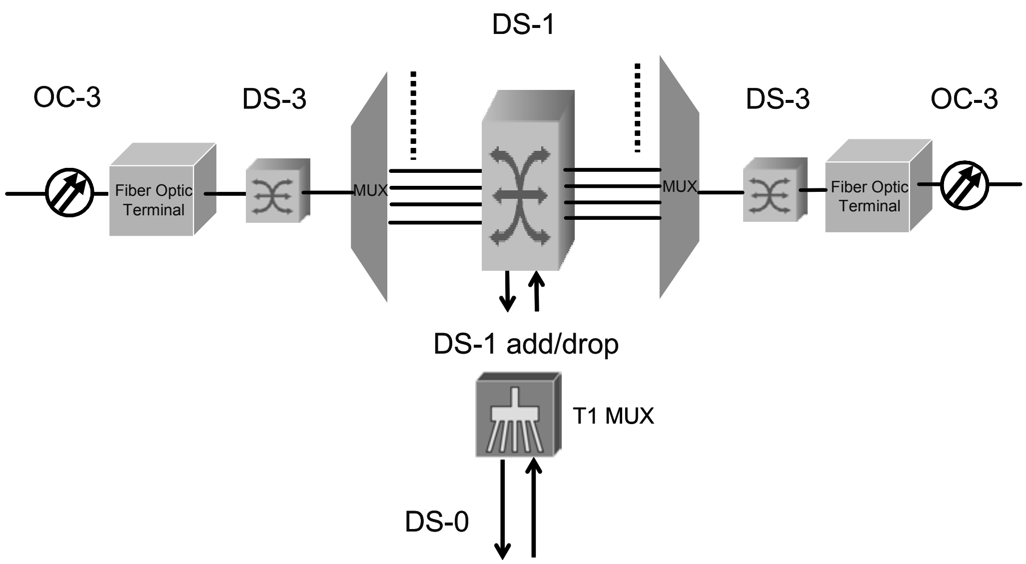

Figure 11 Multiplexing and de-multiplexing in an asynchronous system

In the synchronous SONET system, adding and dropping signals are much easier. The frequency of all clocks in the system will be the same (synchronous) or nearly the same (plesiochronous). Thus, the STS-1 rate remains at a nominal 51.84 Mbps, allowing many STS-1's to be stacked together without any bit stuffing. The multiplexing is done by byte interleaving. Figure 12 illustrates how three signals are multiplexed in an orderly manner.

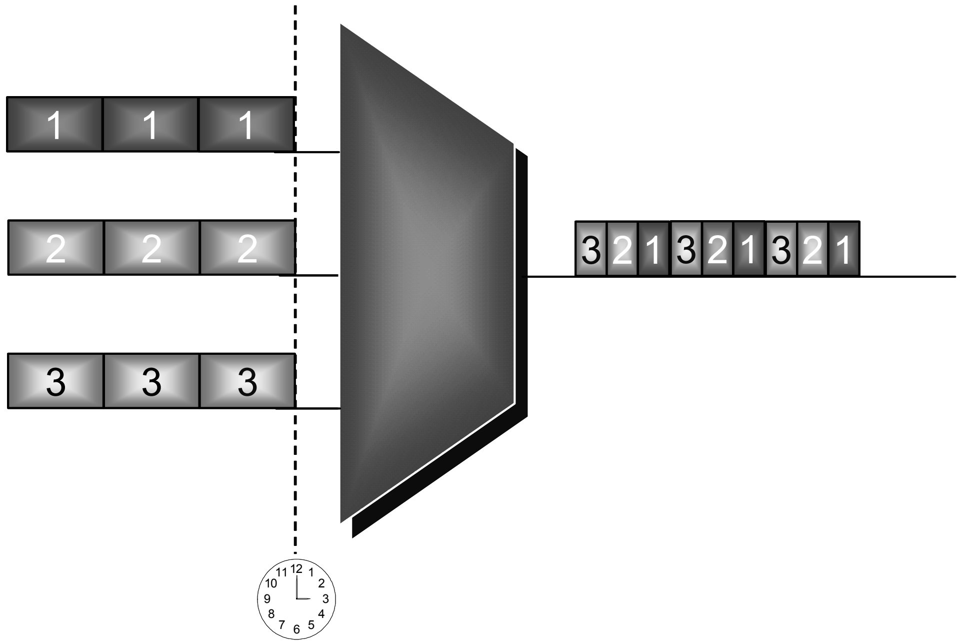

Figure 12 Byte interleaving

Byte interleaving makes adding and dropping signals easy as shown in Figure 13. One channel is dropped by just taking out the corresponding byte. Another signal can be added in the same way, occupying the byte freed by the dropped signal.

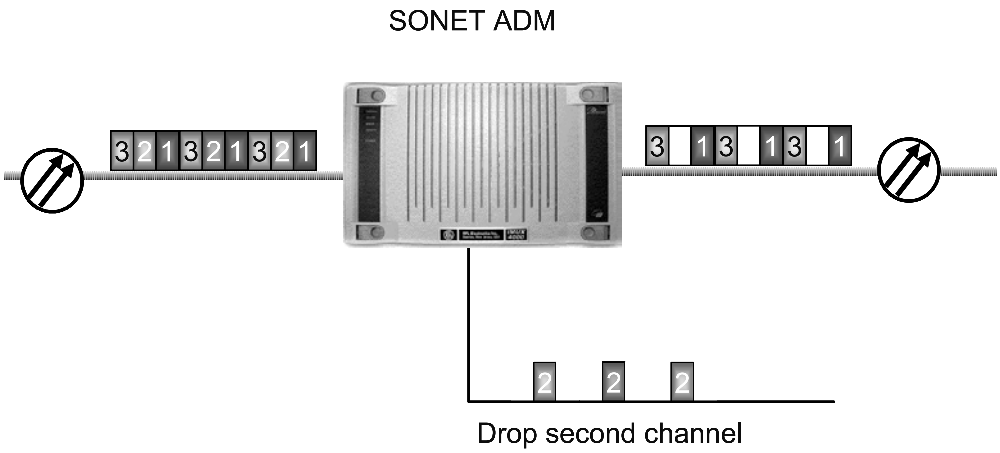

Figure 13 SONET Add/drop multiplexer

DS-1 is transported as VT1 on SONET. VT stands for Virtual Tributary. VT1 occupies 1.7 Mbps which includes the DS-1 1.544 Mbps and SONET overhead bits. Single-step multiplexing up to STS-1 requires no bit stuffing, and VT's are easily accessed.

SONET Network Components

A typical arrangement of equipment used to interface relaying to a SONET network is shown in Figure 14.

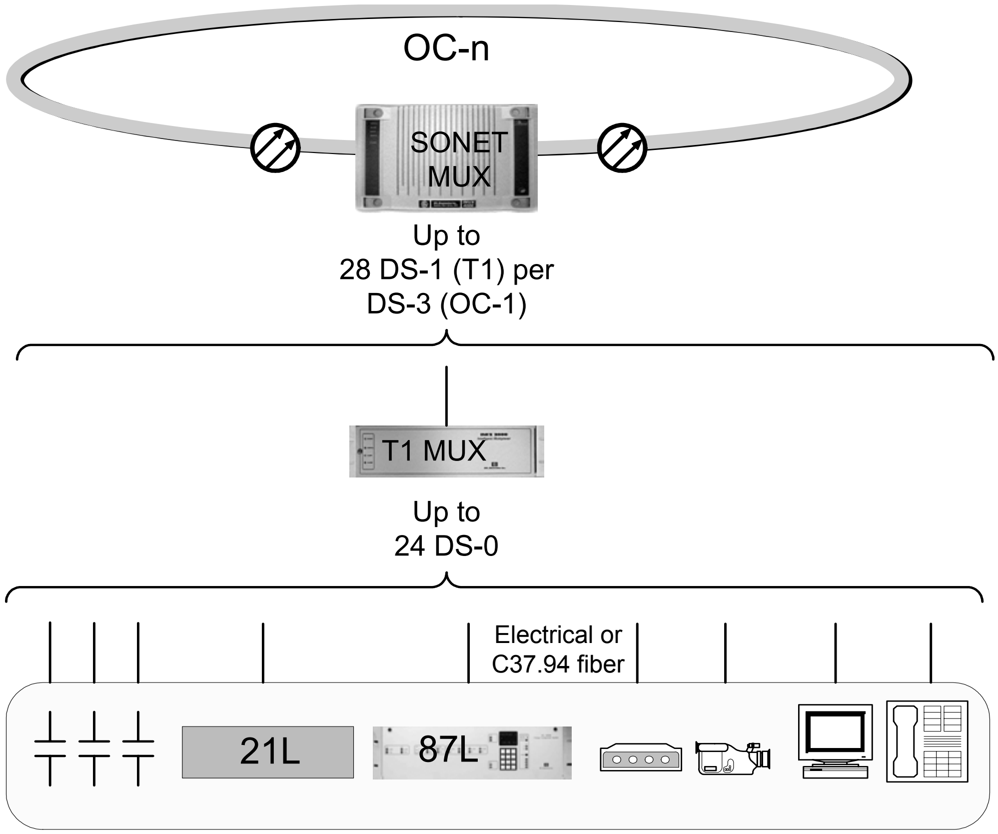

Figure 14 Network components

Typically, the substation devices are connected to a T1 multiplexer which in its turn connect to a SONET multiplexer. The T1 multiplexer provides various interfaces; synchronous 64 kbps for current differential relaying, RS-232 asynchronous data ports, contact interface inputs, and voice and data ports.

Note that the multiplexer needs to be equipped with an interface card, channel card, that is suitable for the type of data the application device, e.g. relay, delivers. Luckily, multiplexers are very flexible and channel cards can be added or exchanged in an existing installation as needed.

SONET Topology

Nodes, or terminals, in a SONET network are often arranged in rings to provide an alternate route or protected path in case of a fiber cut or failure of a node. Ring networks are less expensive than point - to - multipoint or star configured fiber optic networks since only two fibers (versus two for each location) are required to support all users or network elements on the ring. Traffic can be routed in either direction around the SONET ring. In case the primary path is cut, traffic is very quickly re-routed to the secondary path.

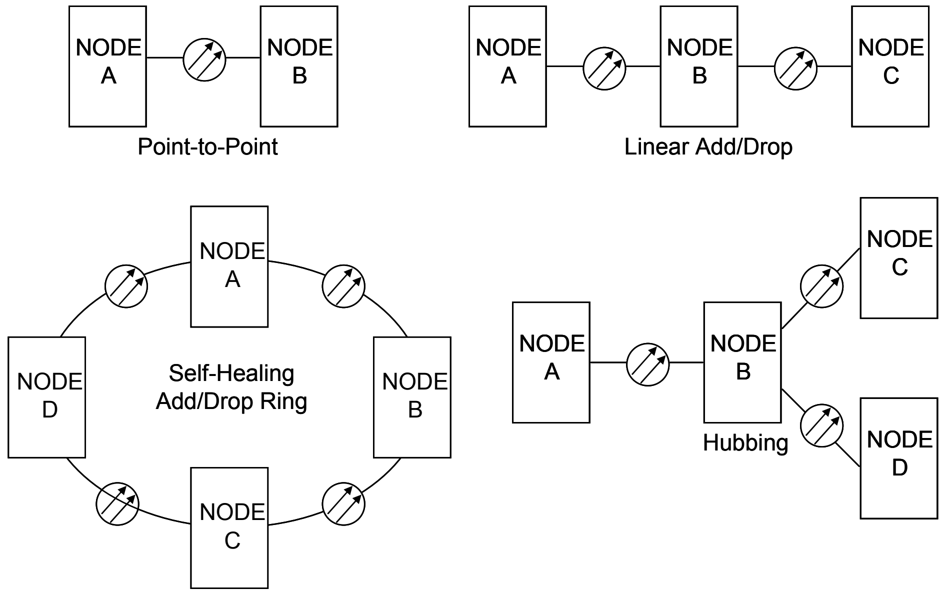

Figure 15 SONET ring topology

Often several topologies are combined in one network and interconnected. As the communications network does not take the same routing as the power system lines, two relays that are not physically distant might have a long communications link over the network. Delays imposed by each node the signal has to pass through need to be taken into account when checking possible channel delays. A ring delay calculation example is presented further down.

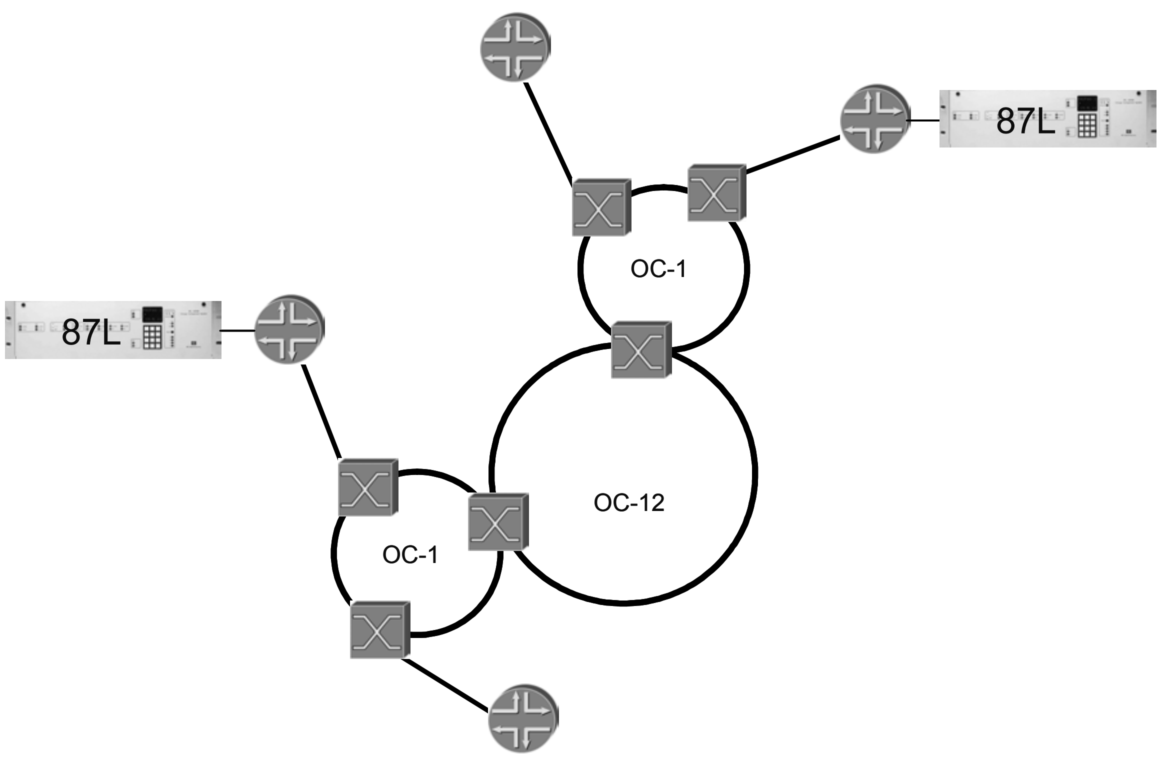

Figure 16 SONET network

CSU Channel Service Unit

Phone companies make leased digital phone lines accessible by use of CSU's. Typical data rates are 2400, 4800, 9600 and 56,000 bps. A CSU is typically provided as a demarcation point between the telephone company's communication equipment and the subscriber's terminal equipment. The CSU provides line conditioning and can be used to check the integrity of the communications link.

A CSU 56 kbps service should technically be suitable for use with relaying channels, but actual experience has not been promising. The CSU itself is not substation hardened and interference on the cable between the relay and the CSU, or the phone line itself, may cause loss-of-channel when there is a nearby fault. This is clearly undesirable for the protection system. Other problems have been very long end-to-end delay times (> 20 ms), asymmetrical delay and frequent channel interruptions due to CSU line conditioning commands that periodically interrupt the protection channel.

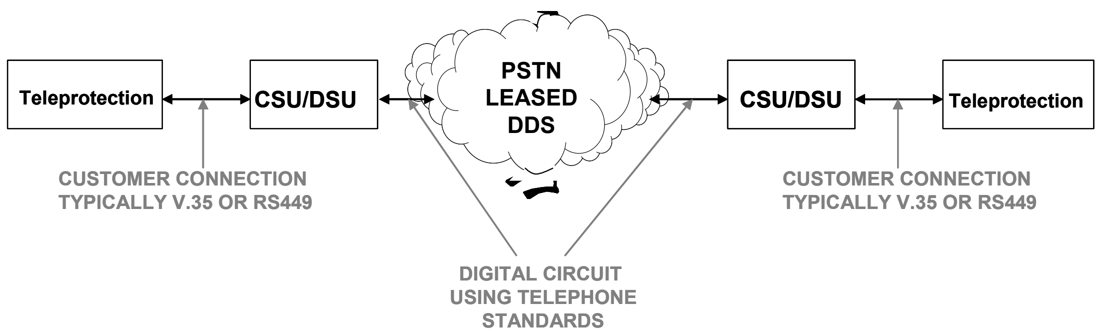

Figure 17 Typical Digital Data Service (DDS)

Microwave

Microwave is a high frequency radio signal that is transmitted though the atmosphere. Common frequency bands are 2 GHz, 4 GHz, 6 GHz, 10 GHz, 18 GHz, and 23 GHz. Transmitted signals at these frequencies require a direct line of site path, and accurate antenna alignment. The federal Communications Commission (FCC Parts 21, and 94) controls operation and frequency allocations.

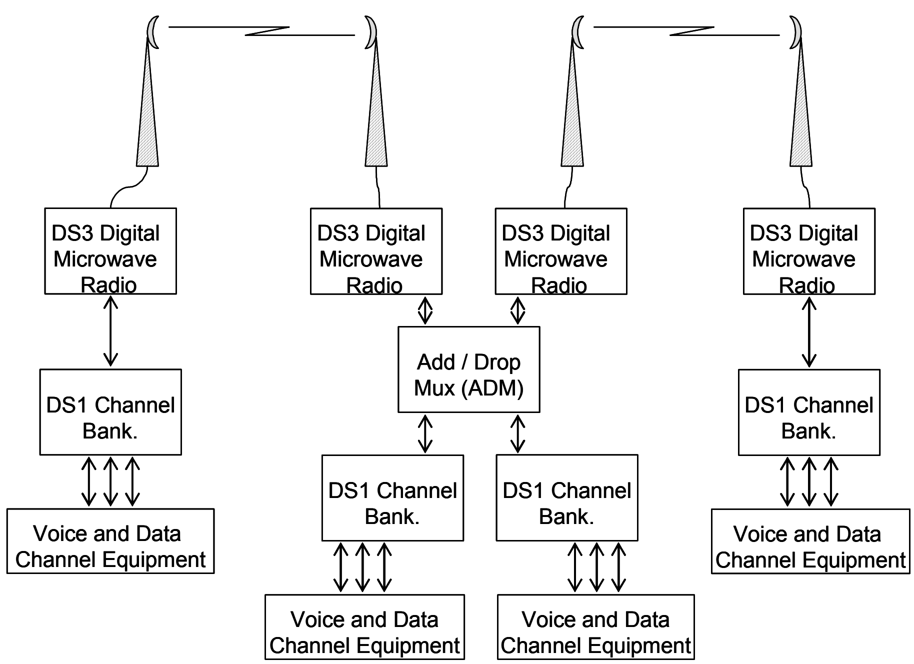

Figure 18 Typical digital microwave system

In digital microwave systems the data modems, required in an analog system, are replaced by digital channel banks. These channel banks can be combined to form a multiplexed system as shown in Figure 19. The channel banks convert analog voice, and data inputs into a digital format using Pulse Code Modulation (PCM). The digital channel bank combines 24 voice channels into a standard 1.544 Mbps DS-1 signal. The DS-1 level is further multiplexed into DS-3 before transmitted over the radio link.

Microwave losses

The microwave signal is vulnerable to losses in free space as the signal travels from the transmitter to the receiver antennas. These losses occur from weather conditions, and obstructions, in and around the signal path.

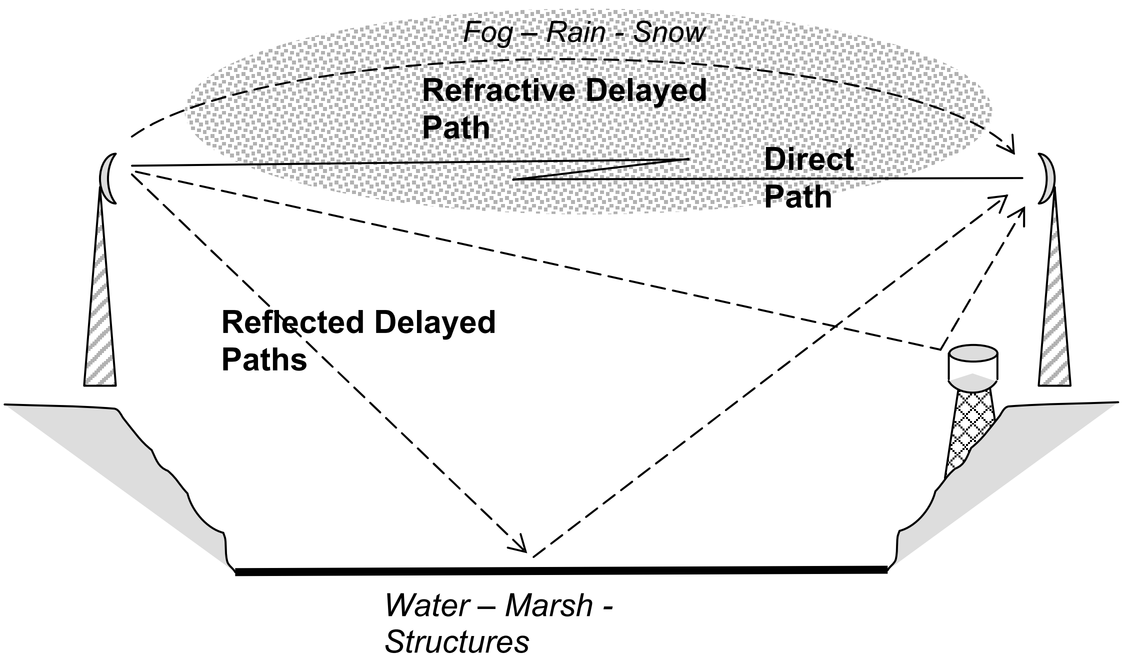

Figure 19 Microwave propagation and multi-path delay impairment

To compensate for signal fading, two different methods can be used; space diversity or frequency diversity.

Space diversity is the more common method and is obtained by adding a second receiving antenna at another height on the tower. Since signal cancellation is unlikely to occur simultaneously on both antennas, space diversity enhances system reliability.

Frequency diversity requires two transmitters and two receivers, running simultaneously. Since a cancellation is unlikely to occur at two different frequencies simultaneously, system reliability is enhanced. Because the additional equipment, and bandwidth required, frequency diversity is used only by government agencies.

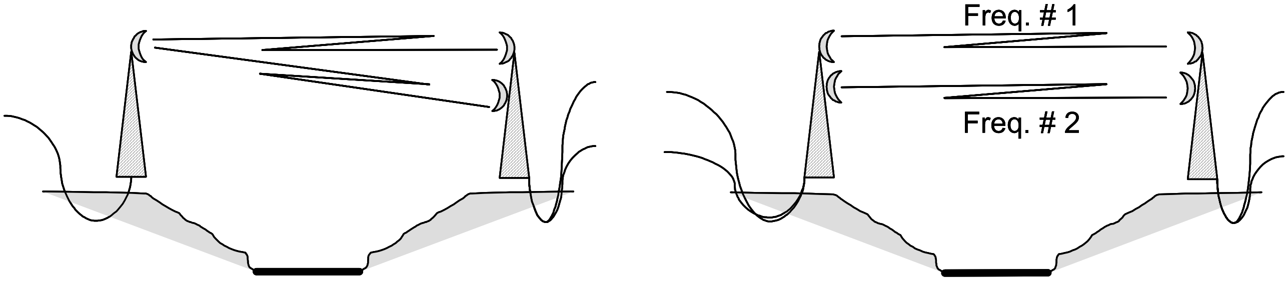

Figure 20 Space diversity (left) and Frequency diversity (right)

Digital microwave topologies

Digital microwave can be applied in SONET ring networks, either making up an entire ring of microwave stations or as a link in a fiber optic SONET ring.

When connected in a ring, a difference compared with a fiber network is that the ring is kept open to prevent system ringing. When any one of the other paths fails, communication is automatically established on back-up path between the two stand-by stations.

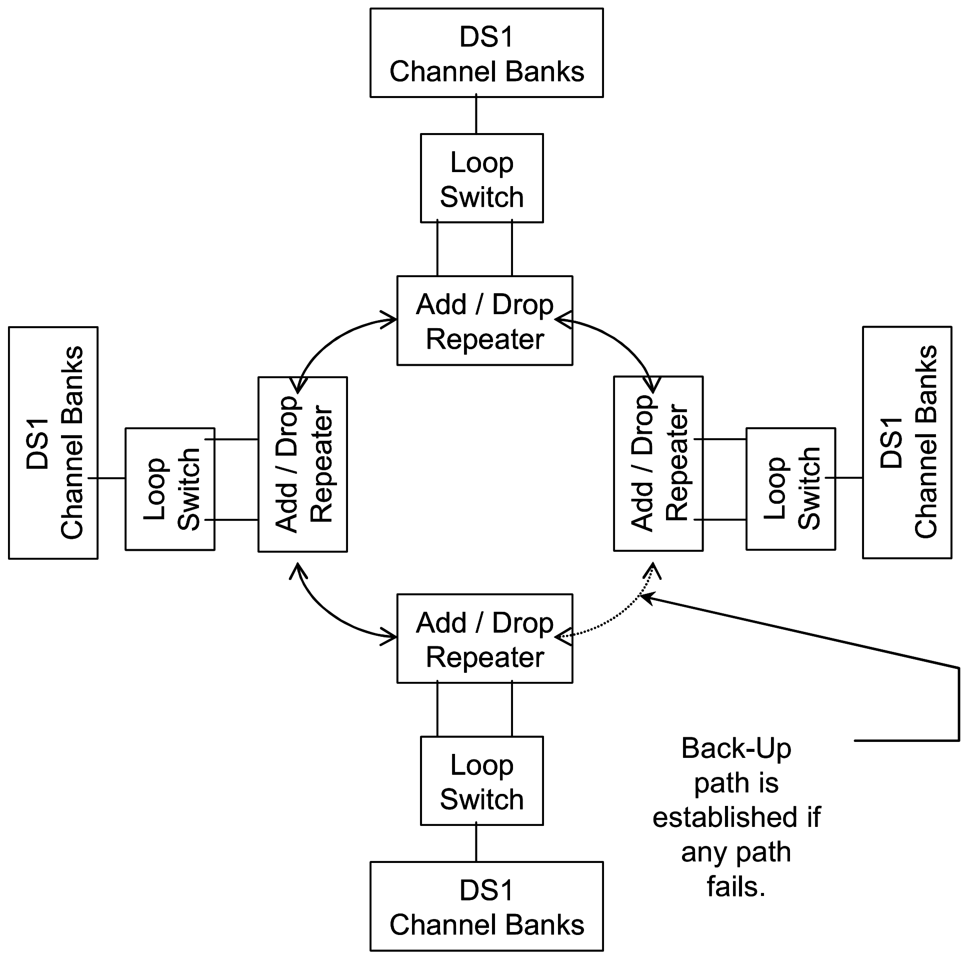

Figure 21 Microwave loop system

Digital Microwave Channel Performance

Channel delays on digital microwave are very short, typically 500 to 600 us, making them suitable for high speed relaying. Switching time allowed by SONET standards is 100 ms. After a signal fade, antenna switch, or lightning strike, the receivers must re-synchronize to the signal before they can demodulate, and process the information. A concern for relaying is fading during inclement weather conditions as this is when power system faults are most likely to occur.

Relaying over Digital Channels

The requirement of high speed data transfer for relaying is recognized by telecoms specifications. As shown in Figure 22, Protective Relay service requires the shortest Process Response Time of all power system communication services. It is also apparent from this Figure that protective relaying is just one of many services provided by the communications network, and most likely one of the smaller services with regards to amount of data transferred. It might therefore be difficult to justify optimization of the relaying channel in the same way as when a dedicated relay channel was used. Still, this should not be difficult to do, if the pilot relaying demands are fully understood.

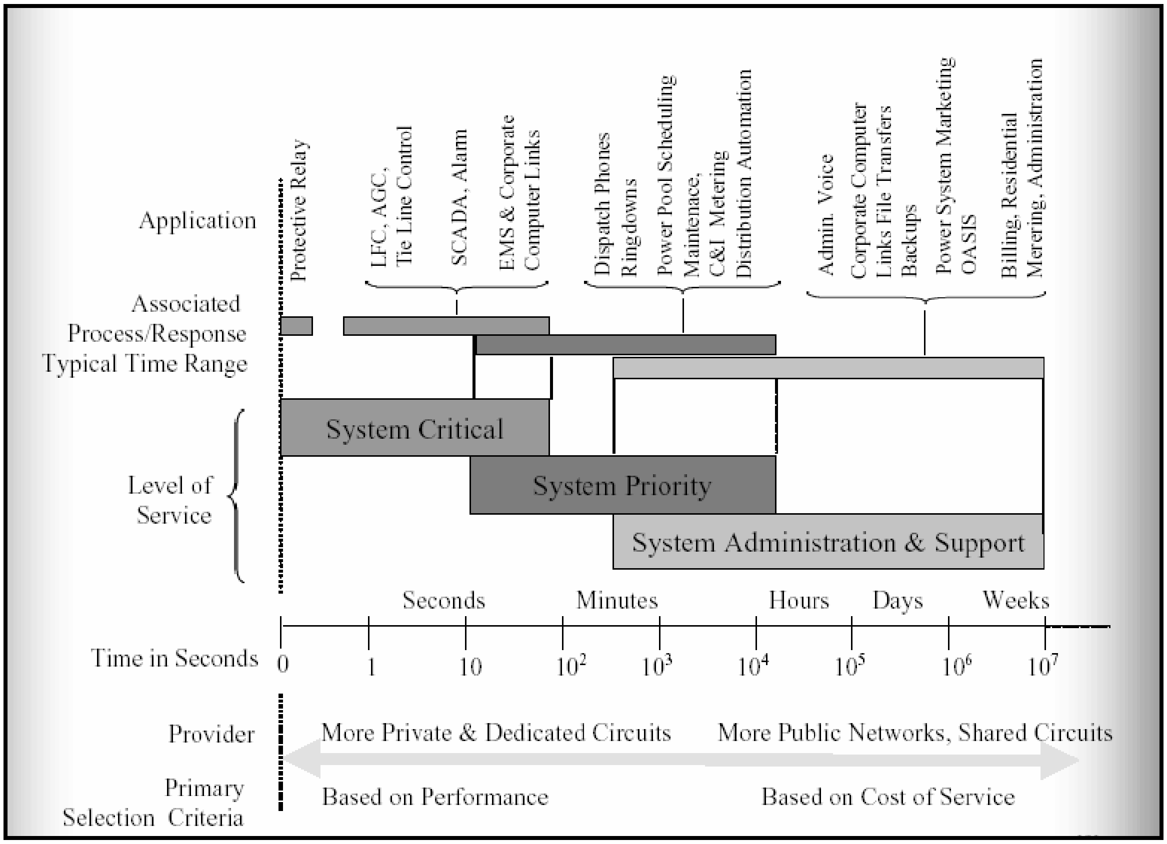

Figure 22 Power Systems Communications

In addition to high speed data transfer, protective relaying has very high requirements on reliability. Reliability comprises two contradictory components; dependability and security. Dependability and security can be defined as:

Dependability The facet of reliability that relates to the assurance that a relay or relay system will respond to faults or conditions within its intended zone of protection or operation. (The ability of the relay system to trip when it is supposed to trip.)

Security The facet of reliability that relates to the assurance that a relay or relay system will restrain from faults or conditions outside of its intended zone of protection or operation. (The ability of the relay system to refrain from tripping when not required to trip.)

When a digital communications system is used for teleprotection or pilot protection, the dependability and security of the communications network will have to be considered for overall protection system reliability.

A concern for relay communications over digital channels is timing issues:

- End-to-end delay
  - Variable delay
  - Excessive delay due to intermediate devices
- Asymmetry
  - Different transmit and receive delay paths
- Interruptions
  - Re-synchronization following a switching operation on the network

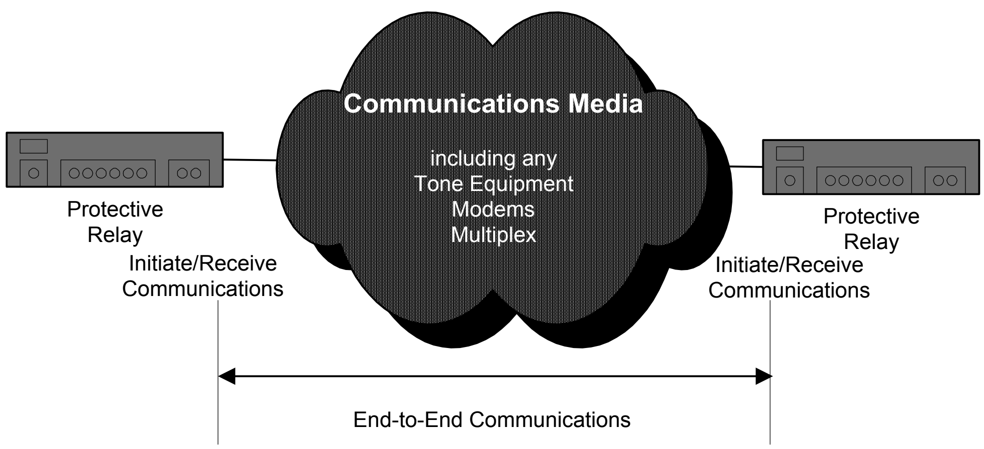

Figure 23 Pilot relay communication

SONET requirements are to detect signal failure within 10 ms and to switch over to a healthy channel in less than 50 ms. During the 10 ms fault detection interval, the multiplexer may deliver erroneous data to the receiving device. The relay securely needs to detect this and block its operation, and discard the faulty data.

The teleprotection standard IEC 60834-1 (1999) provides guidelines for dependability and security. The SONET standards define neither. However, SONET equipment manufacturers often specify availability which can be translated as (1 – dependability) x 100, expressed in percent.

The teleprotection requirements according to IEC 60834-1 are summarized in Table 1.

Scheme	**Dependability**	**Security**
Blocking (DCB)	$<10^{-3}$	$<10^{-3}$
Permissive underreach (PUTT)	$<10^{-2}$	$<10^{-4}$
Permissive overreach (POTT)	$<10^{-3}$	$<10^{-3}$
Intertripping (DTT)	$<10^{-4}$	$<10^{-6}$

Table 1

Translating dependability into availability, we find that the highest requirement, DTT, yields a requirement of $(1 - 10^{-4}) \times 100 = 99.99\%$. Typical SONET specifications state 99.999% availability which means that teleprotection standards are easily fulfilled.

However, in the case of the teleprotection residing in the relay, the combined availability needs to be considered. This is easiest done by adding unavailability time for the SONET system and the relay DS-0 interface. Unavailability could be calculated as

Unavailability (seconds/year) = (1 - availability) x 365 days x 24 hours x 60 minutes x 60 seconds

Unavailability for the typical SONET channel with 99.999% availability is

Unavailability = (1 – 0.99999) x 365 x 24 x 60 x 60 = 315.36 seconds/year

Assuming that the majority of SONET unavailability is due to switching, each with a duration of <60 ms (SONET standard), the number of switching operations per year are:

$$\#operations = \frac{315.36}{0.06} = 5236$$

It might be interesting to try to estimate the availability of a protection system over SONET based on the above numbers. Assuming that the relay needs to re-synchronize following each switching operation, the relay unavailability is 5236 x the re-sync time. A re-sync time of 10 seconds (including the 60 ms SONET switch time) will give a protection unavailability of 52360 seconds (14.5 hours) per year. If this is a line protection, both line relays needs to be operational for the pilot system. Assuming that the relay at the remote end is connected to a different network node, the unavailability due to SONET switching is independent in the two ends and the total unavailability for the pilot system is 2 x 14.5 hours, or 29 hours. This represents an availability of 99.667%. A relay with re-sync time of 40 ms (e.g. a total outage of 40 + 60 ms for each switching operation) will provide 99.997% availability.

It should be considered, however, that the communication channel is physically separated from the protected object, so what is the probability of a primary fault occurring when the relay is not functional? One way of estimating this is to consider the average number of faults on the line in question. For instance, if there is an average of 10 faults per year, the chance of a fault not being detected is the same as the fault occurring during the relay's unavailability period. The unavailability is (1-availbility). For the relay with 10 seconds re-sync time, this is 1 - 99.667% = 0.00333 and the probability is then:

Probability = 10 x 0.00333 = 0.0333

The probability 0.0333 can also be expressed as 1:30, i.e. there is one chance in thirty that this would happen. Again, considering 10 faults per year on the line, it would lead to the conclusion that one fault every three years would not be detected by this protection scheme. A corresponding exercise using 100 ms re-sync time yields a probability of 0.0003, or 1:3333, i.e. it would take on average 333 years before a fault was undetected due to unavailability.

The IEC 60834-1 teleprotection standard specifies maximum actual transmission times in the range 15 ms (DCB) to 40 ms (DTT). Digital channels should have no problems fulfilling these requirements, <u>as long as the number of any intermediate devices in the path is minimized.</u>

Service provided by 56 kbps CSU's might not meet this requirement as end-to-end delay is often not specified. Another digital circuit that might not work well is an ATM network, even if carried over SONET. The ATM access switch may cause excessive delays due to queuing and buffering.

Delay times for devices used in SONET networks are given in Table 2 and Table 3.

Typical DS-1 transmission times are:

	Channel Bank	Substation T1 multiplexer
Reframe time	<50 ms	<1 ms
Drop and Insert through time	125 to 250 us	<25 us
Data buffering at the DS-1 level	Included above	Included above
Data buffering at the DS-0 level	>1 ms	<375 us

Table 2

The SONET delay specifications are:

DS-1 synchronization delay	<100 us
DS-1 de-synchronization delay	<100 us
DS-1 through-path delay	<50 us
SONET ring switch transfer time	<50 ms (100 ms for digital microwave)
Signal failure detection time	<10 ms

Table 3

To establish the total channel delay from one relay terminal to the other, the delays for each possible node (drop and insert) between the locations and the signal delay through the fiber itself (8 us/mile) need to be considered, both for the main path and the back-up path.

A typical delay calculation is illustrated in Figure 24.

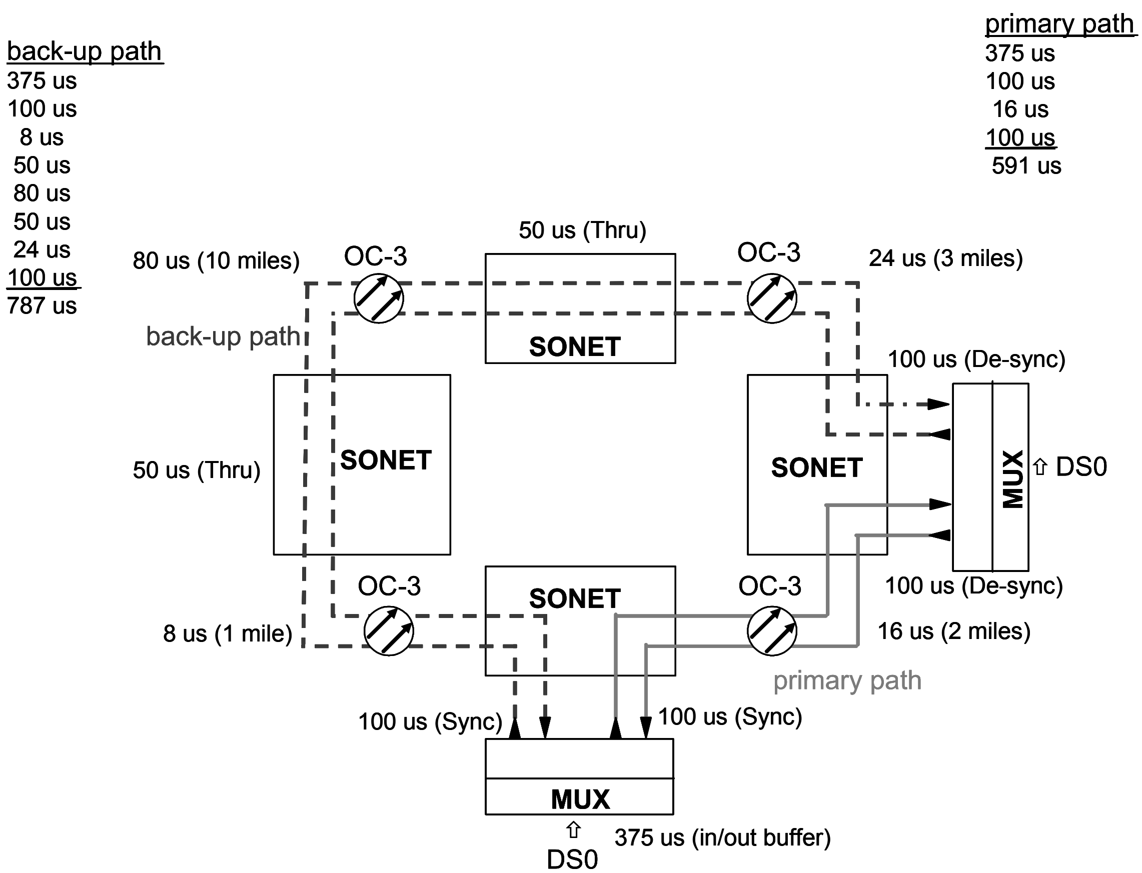

Figure 24 SONET delay calculations

Typical SONET ring delays are in the order of 1 – 2 ms and primary path delays are rarely longer than this. However, depending on the network's size, topology and distances, the alternate path might add several ms transmission time between relays. Still, even the worst case delay should not be a problem for a teleprotection or pilot relay scheme, with the exception of pilot wire relaying which can not accept longer delays than 1 or 2 ms.

More of a concern is if communications network switching result in unequal transmit and receive delays. A carefully designed network can avoid presenting such an asymmetric delay to the relays and an example is given in Appendix A. However, if there is a risk that the relays can be subjected to asymmetrical delays, the relay performance for this condition should be evaluated.

Change in delays following a path switch is handled by most modern relays as they automatically measure and adjust for actual channel delay. A pilot wire relay or other relays that do not have this ability will suffer degraded performance and might even misoperate as a result of the current from the remote relay being time shifted with respect to the local current.

Sources of Interference

Optical fibers are near to perfect as they are unaffected by electrical interference, ground potential rise or weather conditions. Only too long distances, causing too high attenuation, might cause excessive bit errors. However, very often a communications network is not all fiber optic; there might be metallic cable links or microwave links in the relay paths. The possible sources of noise in a digital communications network are:

- Noise on electrical wires
    - There could be copper links as part of the SONET system or as a spur connecting the relay to the network
    - The C37.94 standard for fiber connection between relay and multiplexer eliminates the possibility of electrical interference on metallic wires in the substation
    - When using CSU with a leased 56/64 kbps telephone line care needs to be taken to have galvanic isolation between the substation and the central office. Noise that may not corrupt signaling by audiotones might still interfere with a digital signal over the same channel, due to the digital signal's higher bit rate.
- Signal attenuation. Fiber attenuation too high for transmitted power available,
    - Repeaters are generally used for excessive distances
- Jitter and Wander. Jitter is defined as the short term variation of a digital signal's significant instants from their ideal positions in time. Simply, jitter is the time difference between when a pre-defined event should have occurred and when it actually did occur. Jitter may be caused by vibration or control voltage variations and is more of a problem in asynchronous communication where clocks are not synchronized. Wander is a long term variation.
    - Jitter and wander is minimized in SONET systems by use of "pointers" that adjust for minor clock differences. Should jitter or wander occur the effect on the data is what is called a "frame slip." A frame slip can occur due to overflow when a frame is dropped, or due to underflow, where a frame is repeated. The frame slip may cause a need for re-sync with a resulting 50 ms data interruption. The likelihood and frequency of this occurrence are depending on the network design and the components used but could be in the order of one slip per day to one slip per week.

- Atmospheric interference on microwave signal
    - Attenuation or loss-of-signal due to inclement weather. This is undesirable for relays as systems faults are more likely to occur during these conditions. Reliability can be improved by having two receivers using different paths or by using a ring topology with alternative routes around the ring.

Even though the risk of data corruption due to interference is much smaller in a digital communications system than over conventional media, each device using data for critical operation decisions has to be able to detect erroneous data.

Considerations for Teleprotection and Pilot Schemes

Based on the review above, it seems to be practical to use digital communication networks for protective relaying. Conventional pilot schemes were devised based on characteristics of the communication channel, utilizing its strength and compensating for any shortcomings. As the digital communication channel's characteristics may differ from the conventional media, there might be beneficial to look over pilot protection practices when a change from one media to the other is made.

Direct Transfer Trip

Direct Transfer Trip (DTT) is used whenever a trip signal needs to be transported to a remote location. Typical applications are transformer protection and breaker failure protection. DTT is also sometimes used together with Directional Comparison Blocking (DCB) schemes as the DCB will not automatically trip a weak end without sufficient fault current to operate the line relay at this end.

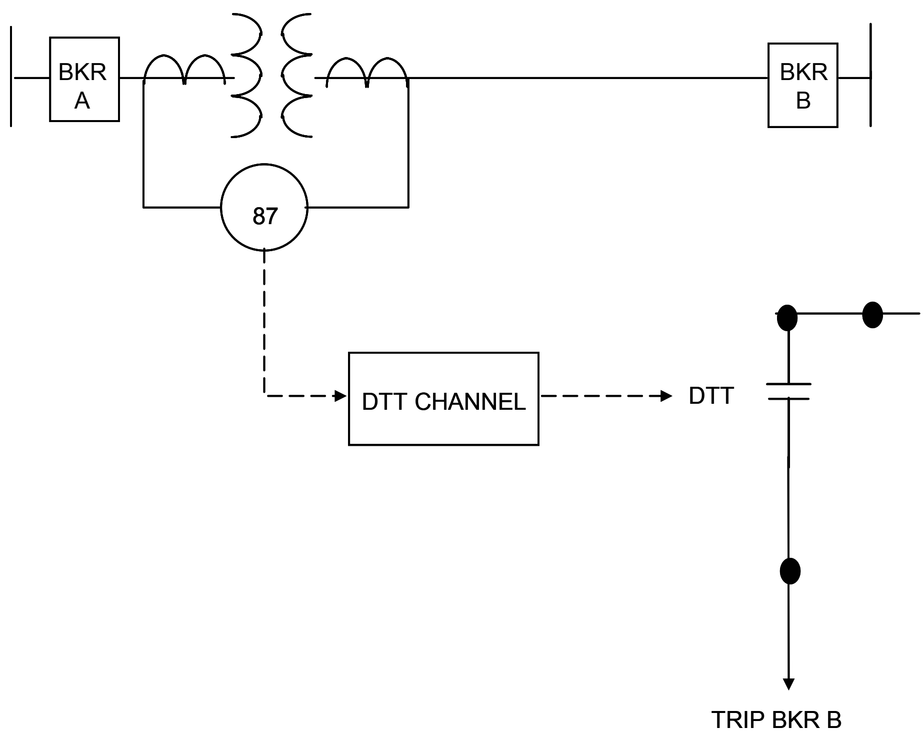

Figure 25 Direct Transfer Trip scheme

The DTT command is sent in one direction only, possibly to more than one remote location. In a traditional DTT scheme, the receiving end does not make any comparison with local conditions and gives a direct trip command to the breaker. Any false trip command over the communication link that is not detected by data error checking in the receiver will guarantee a false trip of the breaker. Consequently, the security requirements for DTT communications are very high with lesser demands on speed and dependability.

When used over conventional communication channels, security is generally increased by adding time delay. It has not yet been determined if the use of digital communication networks would allow shorter time delay without compromising security. SONET requirements do not specify security but SONET system design provides advanced error check capability. However, it should be remembered that SONET requirements call for <10 ms error detection time and during this time period, erroneous data may be delivered to the receiving device. Therefore, the receiving equipment must be able to make its own error checking to detect and discard the faulty data.

Digital channel delay times should not be an issue for DTT. The digital communications network end-to-end delay is shorter, or as short, as for a conventional communication media. Any asymmetrical delay is of no concern as there is no time coordination required between the two ends of the communication link.

Distance Relay Pilot Communication

In general, there should not be any problems applying traditional distance pilot schemes over a digital communications network. They are all less demanding than a DTT application with regards to security as a local conditional trip is made; the local relay has to make a decision about the system condition before it acts on a received communication signal (or, in the case of DCB, the lack-of-received signal).

Dependability, or rather any lack of dependability, will affect the pilot schemes in different ways. In case the communication signal is lost, the permissive schemes will suffer lack-of-operation while the blocking and unblocking schemes may overtrip for simultaneous external faults.

Typical SONET channel delays fall well within the range for conventional communication media. Minor asymmetric delays should not be of any concern to a conventional distance pilot scheme. The relays at the line ends are not synchronized with respect to each other and as long as channel delay falls within acceptable limits for the relay's pilot logic design, the scheme should work as intended. However, it is important to avoid any "intermediate" devices in the communication link that may add unspecified amount of delay. The use of a substation multiplexer with teleprotection interfaces is often practical.

Most distance relay pilot logic has been designed to suit conventional communication channel media and great care has been taken to coordinate the relay elements with the behavior of Power Line Carrier or Audiotone channels. There might be a need to review that this logic is not defeated by a channel that has different characteristics with respect to channel delay and channel reset times. Especially unblock, transient block or other channel related logic might be of concern.

On the other hand, a digital communication channel's advantages compared to conventional media might warrant a change of preferred pilot scheme. The traditional schemes were all designed to overcome shortcomings of the communications channel. For instance, with SONET ring topology providing channel redundancy and immunity to interference from line faults, perhaps a directional comparison unblocking (DCUB) is better suited than a directional comparison blocking scheme (DCB). DCB was designed for use with Power Line Carrier, and the risk of losing a communication signal at the time of a fault was overcome by requiring transmission on a non-faulted line only. A digital communications channel should not be affected by any power system fault and the benefit of the DCB scheme to handle such a condition is no longer as important. DCUB provides the advantages of a permissive scheme by not requiring any blocking timer coordination while at the same time offering a trip window for the 60 ms SONET switch time, should a fault occur simultaneously with SONET channel switching.

Directional Comparison Blocking (DCB)

DCB is operating on the principle to use a communication channel to block tripping for external faults while no signal transfer is required for internal faults. This scheme is typically applied with ON/OFF Power Line Carrier and has the advantage of not being affected by a possible loss-of-signal for faults internal to the line. Power Line Carrier transmission uses the power line itself and there is a risk of a transmitted signal being shorted or interrupted by a fault on the same conductor or line.

The DCB scheme with non-directional carrier start makes channel time coordination and distance element coordination easy while at the same time, tripping times are minimized for internal faults. The principle is based on that the non-directional element's operating time plus ON/OFF channel delay (2 – 4 ms) is shorter than the 21P (forward distance zone) operating time.

The distance relay needs only one directional pilot element, in the tripping direction. Another, non-directional, 21S, element is used to start carrier for all faults, sending a blocking signal to the remote end. In case the forward element operates, the carrier is stopped and the remote end is allowed to trip based on its forward operation and resetting of the received carrier blocking signal.

When applying a DCB scheme over a digital channel where longer channel delays than what is typical for an ON/OFF PLC can be expected, a channel coordination timer might be required.

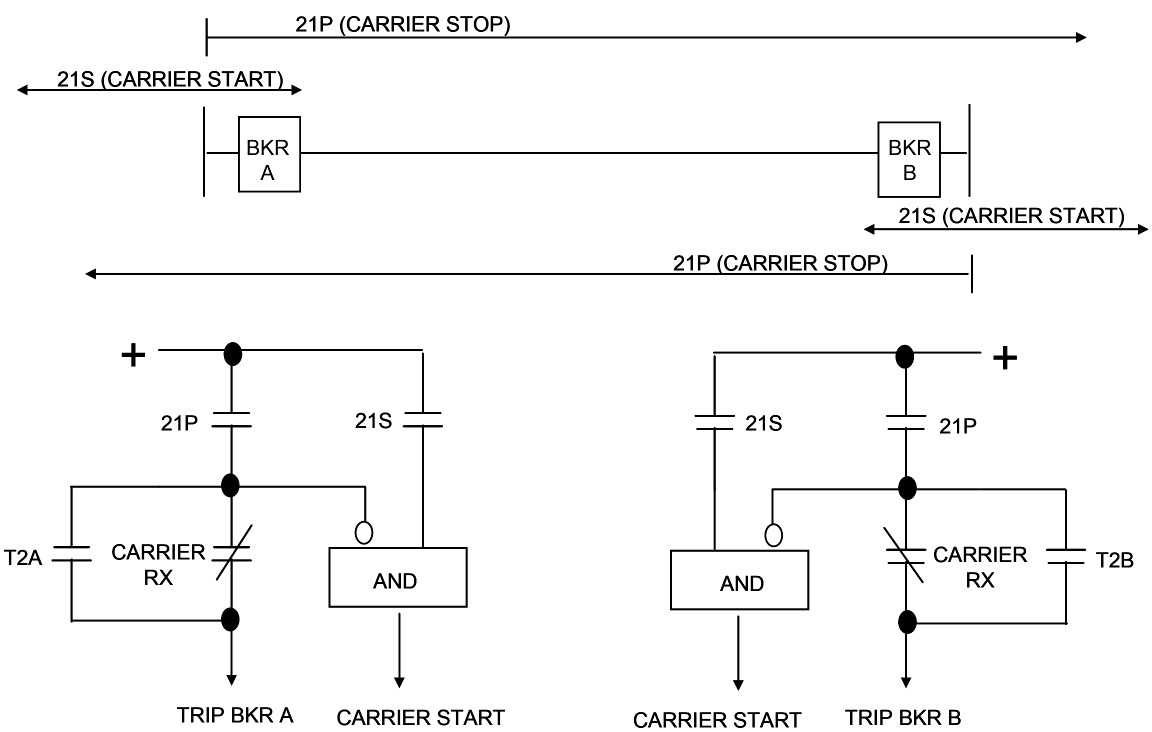

Figure 26 Directional Comparison Blocking with non-directional carrier start

A variation of the basic DCB scheme uses a reverse directional element to start and maintain a carrier block signal. The principle is otherwise similar to the previous scheme, except that a channel coordination timer is required, and a reverse distance zone is required. For a digital channel, the coordination timer should be adjusted to accommodate maximum expected channel delay.

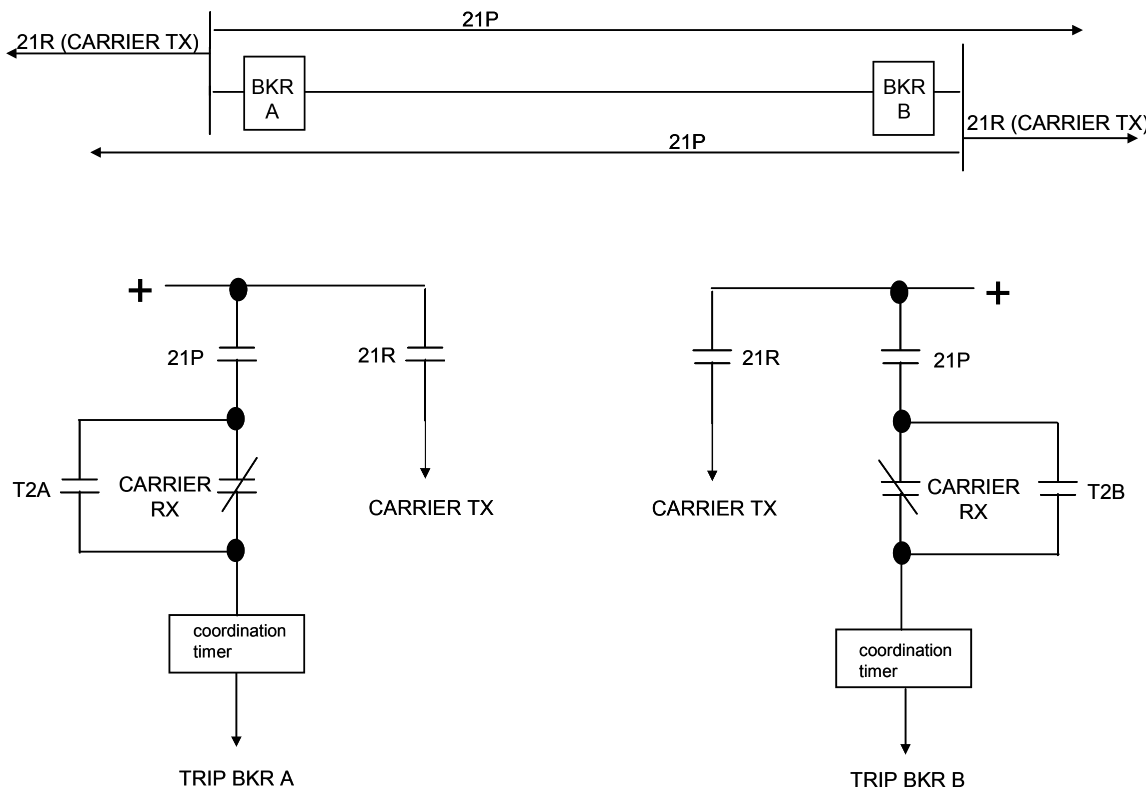

Figure 27 Directional Comparison Blocking with directional carrier TX

Directional Comparison Unblocking (DCUB)

The DCUB scheme was designed for Frequency Shift Power Line Carrier. The FSK carrier sends a continuous blocking signal. When a forward distance element detects a fault, the transmitted carrier frequency is shifted to a trip signal. The scheme is therefore a permissive principle; forward operation AND received permission are required for a trip. To accommodate for a risk of losing the carrier signal in the fault on the line, an unblock trip window is provided. If the receiver does not detect any signal, neither block frequency (GUARD), nor trip frequency, the relay is allowed to trip from its forward distance element for a period of 150 ms following loss-of-signal.

For a digital channel, the risk of losing the signal should be minimal. However, the DCUB scheme's ability of overriding a 60 ms SONET interruption makes it an attractive candidate for use on digital communication networks. As in other permissive schemes, channel delay is directly added to protection trip times. Excessive channel delays should affect only the operating time of the protection system, but might need to be considered for any built-in channel coordination logic, such as transient block logic for parallel line applications.

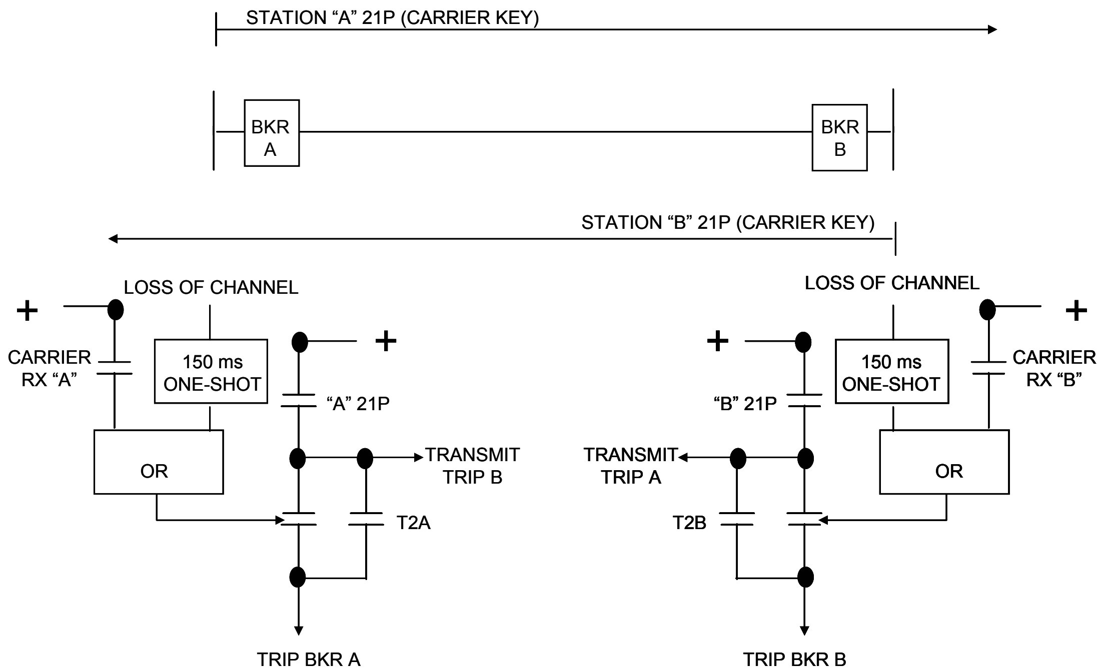

Figure 28 Directional Comparison Unblocking

Permissive Overreach Transfer Trip (POTT)

The traditional POTT scheme is similar to the DCUB scheme except that the "loss-of-guard" information is not used by the relay; only for communication channel failure alarm. This was a shortcoming when applied on conventional channels as the lack of a functioning communications link would disable the overreaching operation of the distance protection. However, when applied over a digital channel availability should not be an issue if conventional, synchronous communications with redundancy are used.

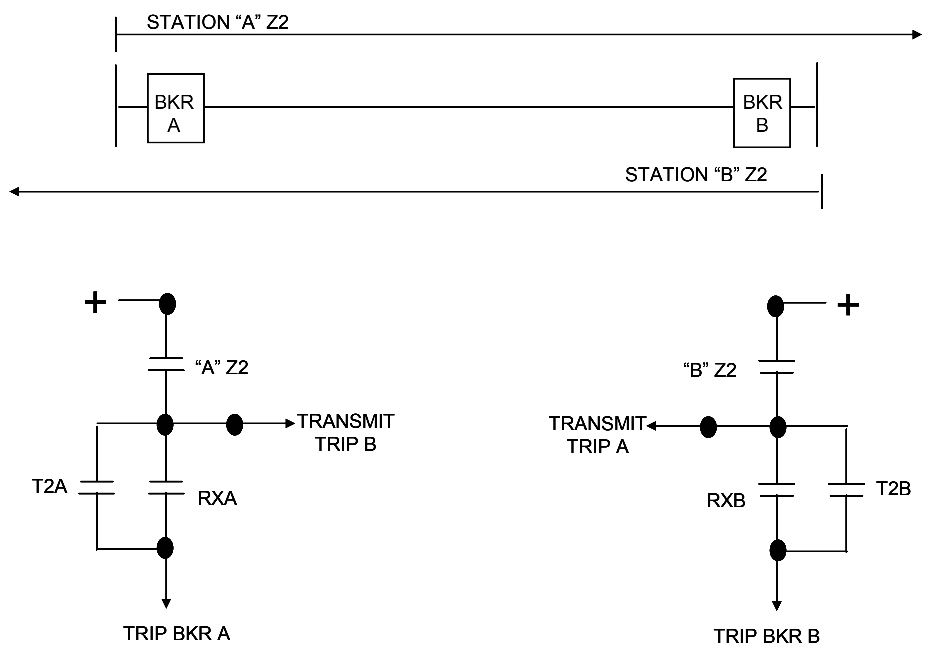

Figure 29 Permissive Overreach Transfer Trip (POTT)

Permissive Underreach Transfer Trip (PUTT)

The PUTT scheme is similar to POTT but sends a permissive trip signal for faults on the line only. The receiving end is then allowed to trip provided that its forward overreaching zone has also detected the fault. This provides higher security than POTT as no external faults will cause a permissive signal to be sent. The purpose of the scheme is to speed-up tripping for end zone faults that is outside zone 1 reach from one line end. The scheme was originally made for switched distance relays that only had one zone element, zone 1. On receipt of a permissive signal, the relay was allowed to switch to the longer zone 2 reach and make an immediate trip from this zone that covered the far line end.

The security provided by the PUTT scheme may be advantageous on parallel line applications as transient block logic is not required. It should be confirmed however that the two zone 1 elements cover the center of the line for all possible faults, considering that the reach might have been reduced to mutual coupling effects.

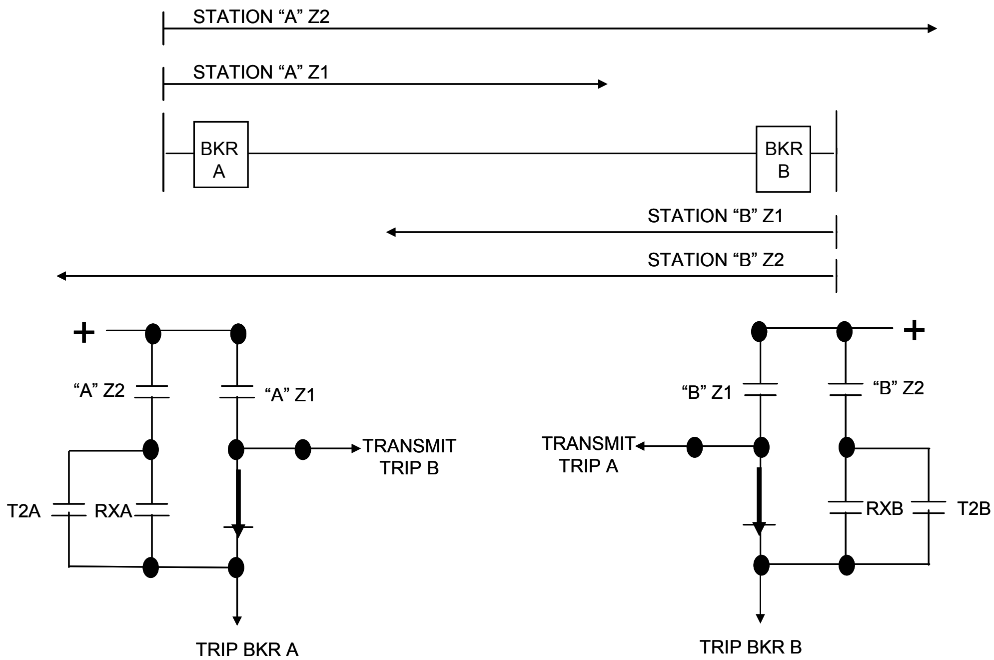

Figure 30 Permissive Underreach Transfer Trip (PUTT)

Current Differential Relaying

Pilot Wire Relays

Pilot wire relays were designed to use a metallic pilot wire as communication link. As the pilot wires are expensive to maintain and the lifetime of the pilot wire is shorter than the for the relay, it is tempting to substitute it with any of the digital pilot wire relay interfaces available on the market and use a digital channel. However, as the relay was not designed to take <u>any</u> channel delay into account, this is the most demanding application for digital communication networks. Not only is asymmetrical delay unacceptable, but end-to-end delay must be very short; less than 1 ms is desirable and more than 2 ms is prohibitive. The effect of channel delay on some typical electromechanical relays is shown in Figure 31. The curves show the measured operating current in multiples of pickup for increasing channel delays. Above 2 ms channel delay, all of the types shown risk misoperation.

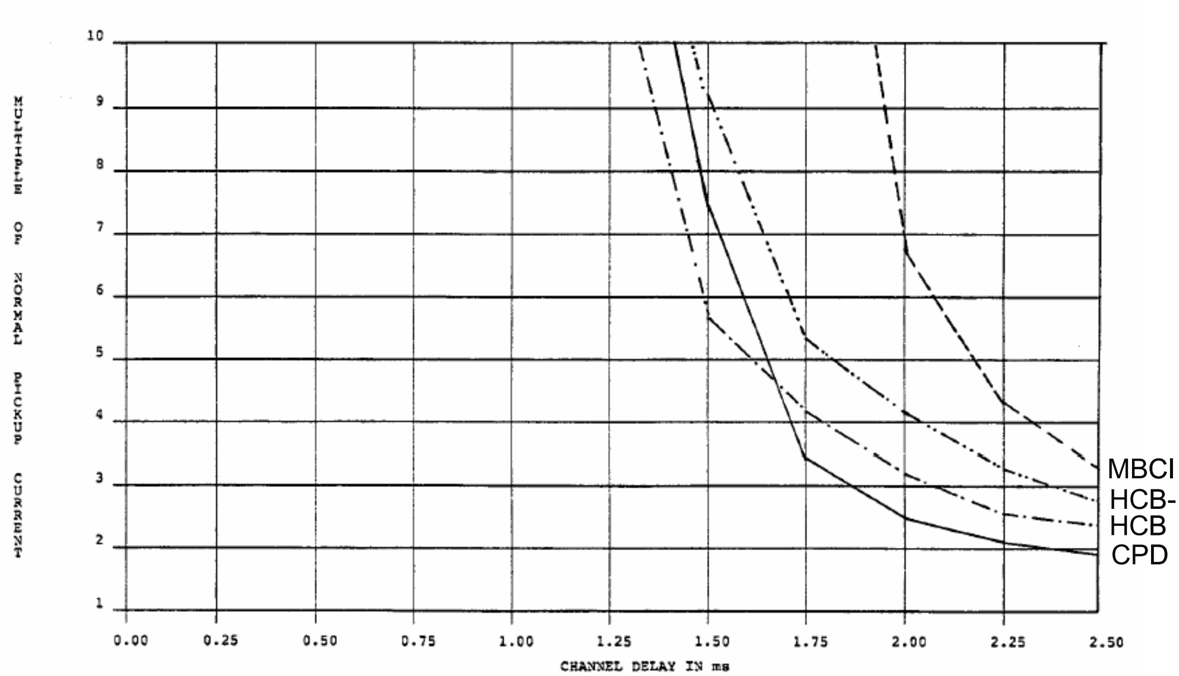

Figure 31 Pilot wire relay operating current as a function of channel delay at external faults

Typically, a SONET backbone can not fulfill this stringent delay requirement unless care is taken to limit the number of nodes between the two line ends. A communications network with multiplexers designed for teleprotection is preferred for this application. These multiplexers are optimized with regards to through-delay and can provide very short switch-over times. Any asymmetric channel delay is eliminated by the use of a Bi-directional Line Switched Ring (BLSR) topology rather than Unidirectional Path Switched Ring (UPSR) topology. These topologies and their differences are described in Appendix A.

Digital Current Differential Relays

Newer current differential relay designs provide a variety of communication interface options. In addition to the direct fiber interface (as used for dedicated fiber point-to-point applications) interfaces for multiplexed communication systems are available. For mulitplexer systems, RS-449 electrical interface or a C37.94 fiber interface is used. G.703, X.21 and V.35 interfaces might also be used for multiplex interfacing. Most relays today operate at 64 kbps over multiplexed systems even though higher data rates might be used over a direct fiber link.

The data format used to communicate current information from the relay in one line end to the relay in the remote end(s) is unique for each relay design, and sometimes unique for the actual relay firmware version. The C37.94 standard ensures that a relay can communicate though a multiplexer on optical level, but the actual data used by the relay is not standardized. Consequently, the relays need to be identical in all line ends.

The communication is synchronous, and referenced to the multiplexer clock (or to an internally generated clock source in the case of dedicated fiber). The synchronous communication provides continuous channel monitoring. Validation of received data has to be performed by the relay as the multiplexer is protocol transparent and pass exactly what is received through the system. The multiplexer will detect transmission errors but as the SONET requirements allow for a 10 ms detection time, the relay must detect invalid data during this period. In addition, it is of essence that the relay aligns received current data with local data. Any sudden change of channel delay time must be detected as the current comparison would otherwise be out-of-phase and could cause misoperation.

Current information is exchanged in a variety of ways; Fourier coefficients, phasors, current charge, or status of instantaneous current samples. Depending on what measuring method, and algorithm, is used various names are given to the protection; current differential, charge comparison, phase comparison or current comparison. They all operate on the same principle though; the difference in currents as measured in all line ends of the protected line section.

Current values can be sent on a per phase basis (phase segregated) or by a combined quantity (sequence measurement). Different methods require different amount of data to be sent. Also, the frequency of sending a data frame differs between designs, from one frame per 0.2 ms to one frame per half-cycle (8 ms) and the entire 64 kbps band does not necessarily has to be used for data; "idle" time can be inserted between data frames.

Most digital current differential relay designs have the ability of measuring and compensating for channel delay. Channel delay estimation is made by ping-pong measurement. The exact method and measurement frequency vary but the principle is similar. One end sends out a special message that is echoed back from the remote end. The loop time less the "turn-around" time divided by two is then the one-way delay. Using the references in Figure 32, channel delay is calculated as:

Channel delay = [t3 – t0 – (t2 – t1)]/2

With asymmetric delay, i.e. t3' – t2 ≠ t1 – t0, the calculated one way delay becomes:

Asymmetric channel delay = [t3' - t0 – (t2 – t1)]/2 and the error consequently is

Error = (t3' – t3)/2

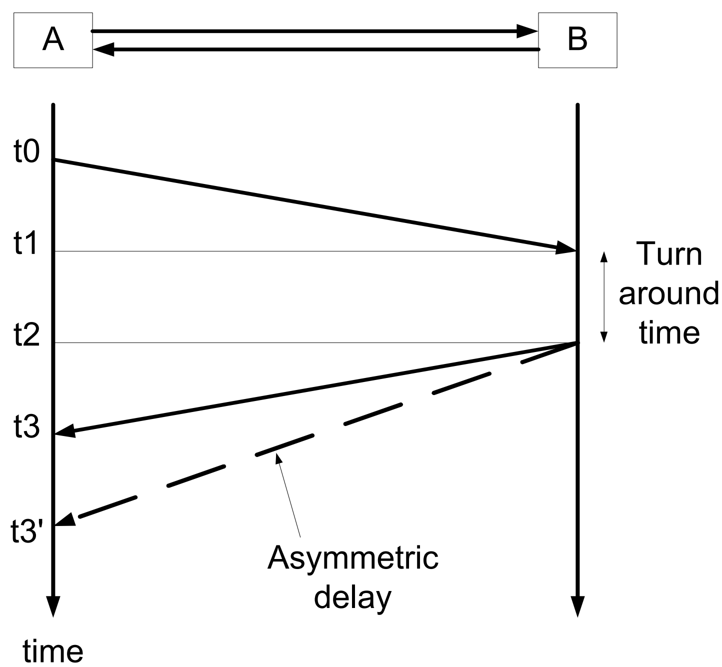

Figure 32 Ping-pong time delay measurement

Some current differential relays offer GPS clock synchronizing to eliminate the ping-pong error at asymmetrical channel delays. In these relays, a time-tag is part of the data frame so that the receiving relay can recognize that the actual one-way delay differs from the measured ping-pong delay, and compensate for it.

Channel delay measurement is used by the relays to align received current data from the remote end with memorized local current so that current is compared at the same instant in time. This is illustrated in Figure 33.

The calculated one way delay is used by the relay to align the received current information with local, stored current measurement that was made one channel time delay period previously. As long as measured channel delay equals actual channel delay, there is not error (except small inherent errors due to the finite sampling frequency, timer resolution, accuracy, etc.).

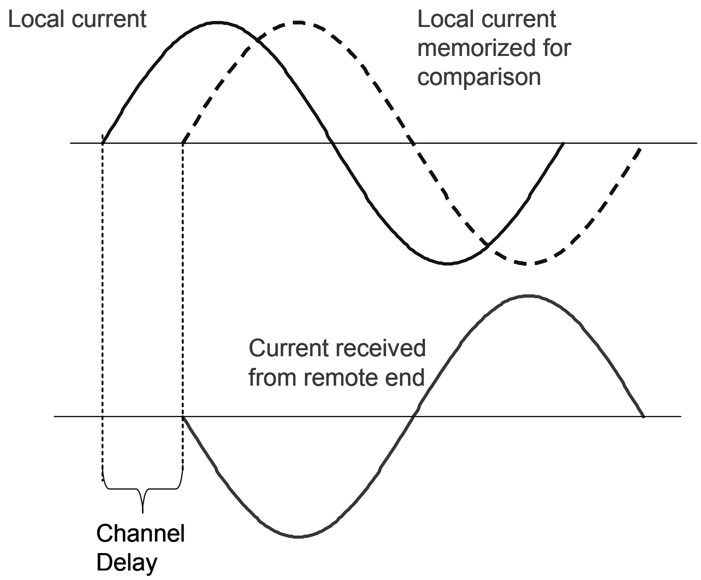

Figure 33 Channel delay compensation

When the actual delay deviates from measured delay, the error introduced to the relay will look like a differential current. As the currents in the two line ends are not compared at the same instant in time, a false difference will be produced. Different relay designs deal with this condition in different ways. In general, measuring principles based on the phase relationship between the currents in the line ends are more tolerant to channel delay errors than measuring principles based on amplitude comparison.

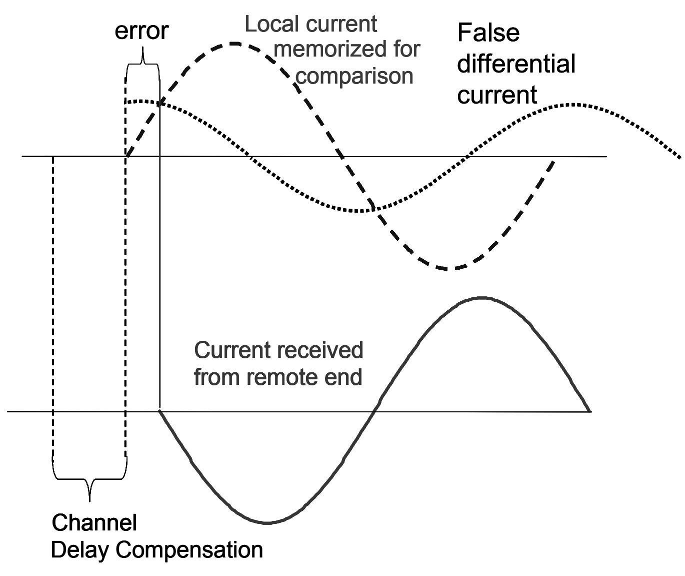

Figure 34 False differential current due to channel delay error

While GPS synchronizing bears the promise of an efficient method to handle asymmetrical delay, it may not be required for all current differential relays used in multiplexed communication networks. The possibility of asymmetric delay may be eliminated by proper network design so that both transmit and receive path are switched at the same time, as described in Appendix A. In addition, some current differential relay measuring principles can handle up to 4 ms delay error without affecting performance. Note that 4 ms one-way error equals 8 ms difference between transmit and receive path as the error is divided by 2 in the ping-pong measurement. Few, if any, existing SONET networks would manifest such a large difference.

Summary

Digital communications networks can provide reliable and interference-free relaying channels if some fundamental requirements are taken into account:

- The teleprotection and relay require exclusive use of the channel or channel-slot.
- Avoid any intermediate devices in the channel path between the relays that may introduce unacceptable delays. Make it as much of a point-to-point connection as possible.
- Routine network channel switching should be minimized. The 50 ms switch-over time does not cause interruption of voice traffic, where it will not even be noticeable. Data traffic will generally override such short interruptions as well by re-transmitting lost packages. These facts have influenced telecom procedures so there are often no restrictions on working on SONET equipment in service, causing channel switching. However, for a relay that relies on continuous real-time data, these routine interruptions cause re-synchronization with its associated loss-of-protection. They also result in frequent, unexplained, channel alarms in the relay event log.
- The effect of asymmetrical delay, if not eliminated in the communications network design, should be taken into account for relay scheme selection.

The table below summarizes requirements for teleprotection and pilot schemes discussed:

Teleprotection and Pilot Scheme Requirements			
Scheme	**Maximum Channel Delay (IEC)**	**Asymmetry**	**Dependability (IEC)**
DTT	< 40 ms	Yes	10^{-4}
DCB	< 15 ms	Scheme dependent. A few ms should pose no problem.	10^{-3}
POTT	< 20 ms	Scheme dependent. A few ms should pose no problem.	10^{-3}
PUTT	< 20 ms	Yes	10^{-2}
Pilot Wire	< 1 ms	No	-
Current Differential	< ~ 25 ms	Scheme dependent	Scheme dependent
SONET	~ 1 – 5 ms	Likely ~ 1 – 2 ms	~ 10^{-5}

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Glossary

ADM	Add/Drop Multiplexer. A multiplexer, such as a terminal multiplexer, capable of extracting and inserting lower-rate signals from a higher rate multiplexed signal without completely de-multiplexing the signal.
ATM	Asynchronous Transfer Mode. ATM is a high bandwidth, low-delay, connection-oriented, packet-like switching and multiplexing technique.
Backbone	The backbone of the network is the part that carries the heaviest traffic.
BLSR	Bi-directional Line Switched Ring topology. See Appendix A
Channel bank	A multiplexer. A device which puts many slow speed voice or data conversations onto one high-speed link. Typically the device that sits between a digital circuit – say a T-1- and a couple of dozen voice grade lines coming out of a PBX.
CODEC	Originally Coder/Decoder, but now also used by the PC industry for Compression/Decompression, i.e. an overall term for the technology used in digital video and stereo audio.
Cross-connect	To terminate and administer communication wires. For a relay engineer, this is similar to a terminal block.
CSU	Channel Service Unit. Also called CSU/DSU because it contains built-in Data Service Unit. A device to terminate a digital channel on a customer's premises. A CSU looks like a basic "modem," except it can pass data at higher speed and does not permit dial-up.
DDS	Digital Data Service. DDS is private line digital service, typically with data rates up to 56 kbps.
DSLAM	Digital Subscriber Line Access Multiplexer. A piece of technology at a telephone company's central office that provides phone and high speed Internet service to the customer.
DS-n	Digital Signal level. DS-0 is 64 kbps, DS-1 is the same as T1, 1.544 Mbps
ISDN	Integrated Services Digital Network. A high speed service (144 kbps or 1.544 Mbps) provided by the phone company.
IT	Information Technology. A fancy name for data processing. IT means all the equipment, processes, procedures and systems used to provide and support information systems, IT today includes control over data telecom, but typically not voice telecom.
LAN	Local Area Network. A geographically localized network consisting of both hardware and software. Devices on a LAN typically transmit data within buildings or between buildings located close to each other.
Packet switching	Sending data in packets through a network to some remote location. The packets may follow different physical paths and may experience varying levels of propagation delay, also known as latency. Additionally, they may encounter varying levels of delay as they are held in packet buffers awaiting the availability of a subsequent circuit.
PBX	Private Bank Exchange. A private telephone switching systems located on a customer's premises, providing pooled access to a group of access lines, typically by dialing '9' from an internal station set
PCM	Pulse Code Modulation. The most common method of encoding an analog voice signal into a digital bit stream.
PCS	Personal Communications Service. A new, lower powered, higher-frequency competitive technology to cellular.
Router	Central switching offices serving as interfaces between networks.
SDH	Synchronous Digital Hierarchy, the European equivalent of SONET.
SONET	Synchronous Optical Network.
T1	Trunk level 1. A digital transmission link with 1.544 Mbps signaling speed. T1 is a standard for digital transmission in North America.
Trunk	A communications channel linking a central office with a PBX or other switching equipment.
Trunking	Method employed to reduce the likelihood of traffic blockage owing to network congestion
UPSR	Uni-directional Path Switched Ring. See Appendix A.
VT-n	Virtual Tributary. Low-speed channel in SONET mux. Includes payload signal and associated SONET overhead bits. VT1= DS-1/1.544 Mbps, actually occupies 1.7 Mbps

Biography

Tom Dahlin
Tom has spent 23 years with RFL Electronics Inc. after graduating from Metropolitan Technical Institute. Tom has held numerous positions at RFL in Final Test, Customer Service, R & D Engineering, Systems Engineering and most recently in Sales as an Engineer and now Director of Sales. Tom spent many years working with Protective Relaying and teleprotection before changing his focus to telecommunications. Today, Tom spends most of his time designing SONET/SDH networks for Utility applications. Tom is an active member of the IEEE and resides on several working groups under the Power Systems Communications Committee including the "SONET and ATM Committee for Electric Utilities".

Solveig M. Ward
Solveig received her M.S.E.E. from the Royal Institute of Technology, Sweden in 1977. The same year she joined ABB Relays. She has held many positions in Marketing, Application, and Product Management. Assignments include a six-month period in Montreal, Canada and two years in Mexico. When Ms. Ward returned to Sweden, she was application responsible for the development of a numerical distance protection relay and in charge of marketing the product. After transferring to ABB in the US 1992, she was involved in numerical distance protection application design, and was Product Manager for ABB's line of current differential and phase comparison relays.
Solveig has written, co-authored and presented several technical papers at Protective Relaying Conferences. She is a member of IEEE and holds one patent, "High Speed Single Pole Trip Logic".
In June 2002, Solveig joined RFL Electronics Inc. as Director of Product Marketing

Bob Ince
Robert (Bob) Ince is a Senior Sales Engineer at RFL Electronics Inc. located in Boonton Township, New Jersey. Bob's prior positions during his 18 years at RFL include: Field Service Engineer and Customer Service Manager. Before joining RFL, Bob worked for Westinghouse Electric Corporation, at their Hillside, NJ, and Coral Springs, FL facilities. Positions held at Westinghouse included: Relay System Test Technician, System Test Trainer, and System Test Supervisor. Bob graduated from RETS Technical School in New Jersey, and served four years in the United States Air Force.

Appendix A

SONET Rings and Affects on Protective Relaying traffic

A major portion of SONET research was devoted to network resilience and survivability. For greater dependability, SONET rings offered automatic restoration for fiber cut or failures. Ring networks quickly became the preferred topology when deploying SONET equipment. SONET defines several types of rings; the most popular are discussed below.

GR-1400 2-Fiber **U**nidirectional **P**ath **S**witched **R**ing (**UPSR**)

A path is the logical connection between points where the information to be transported over SONET is assembled and disassembled or enters and exits the ring. Information entering the ring is bridged at the path (circuit) level and transmitted on both fibers opposite directions around the ring, as depicted in Figure 1. This scheme uses one direction around the ring as the primary signal path and the other direction as the protected path. Switching is based on the health of the path at the circuit level where it exits the ring, as depicted in Figure 2.

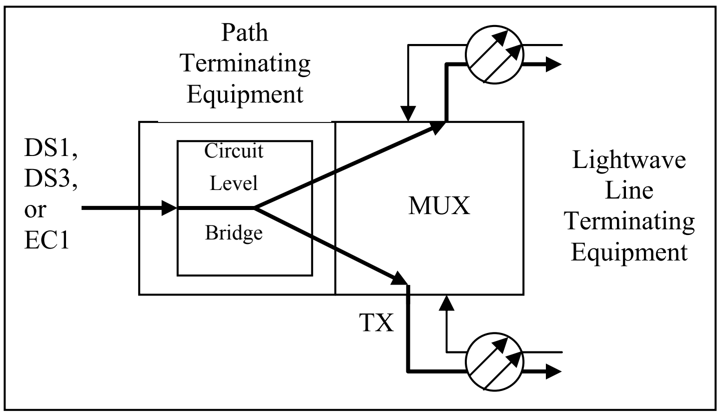

Figure 1. Path Terminating Equipment Circuit Level Bridge

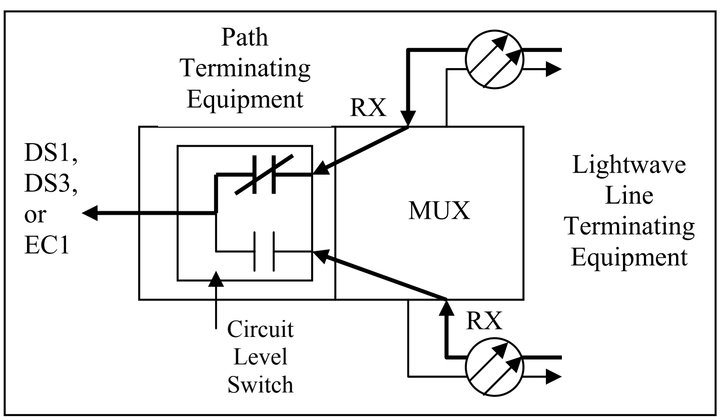

Figure 2. Path Terminating Equipment Circuit Level Switch

Figure 3 depicts a signal entering a UPSR topology at node A and dropping out the signal at node B. The primary service path is depicted as the shortest route between the nodes. If a failure occurs between Node A and B, switching to the protection route is done at the individual path (circuit) level at Node B, as depicted in figure 4.

Appendix A

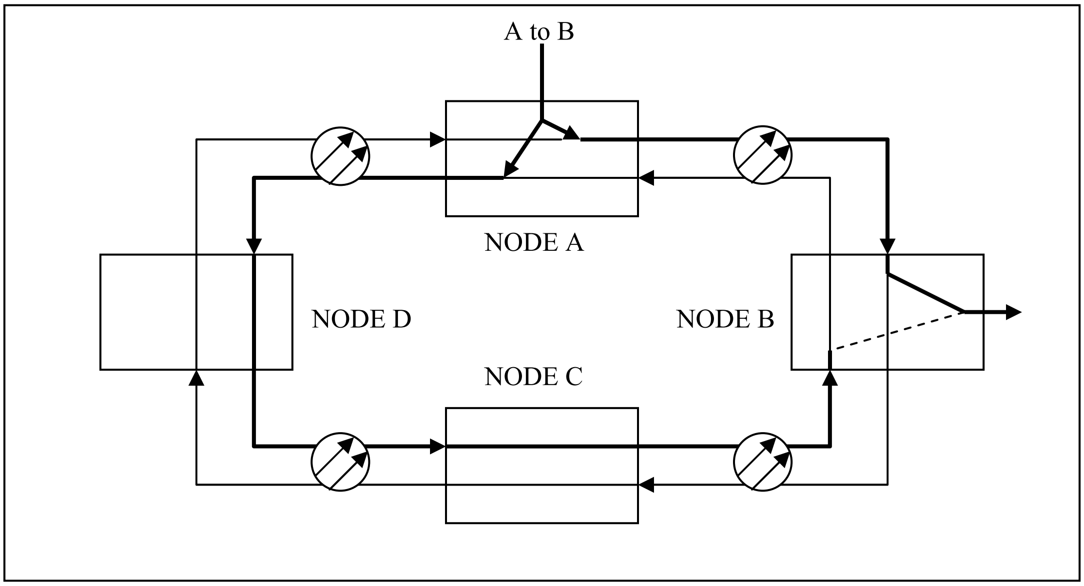

Figure 3. 2-Fiber Unidirectional Path Switched Ring

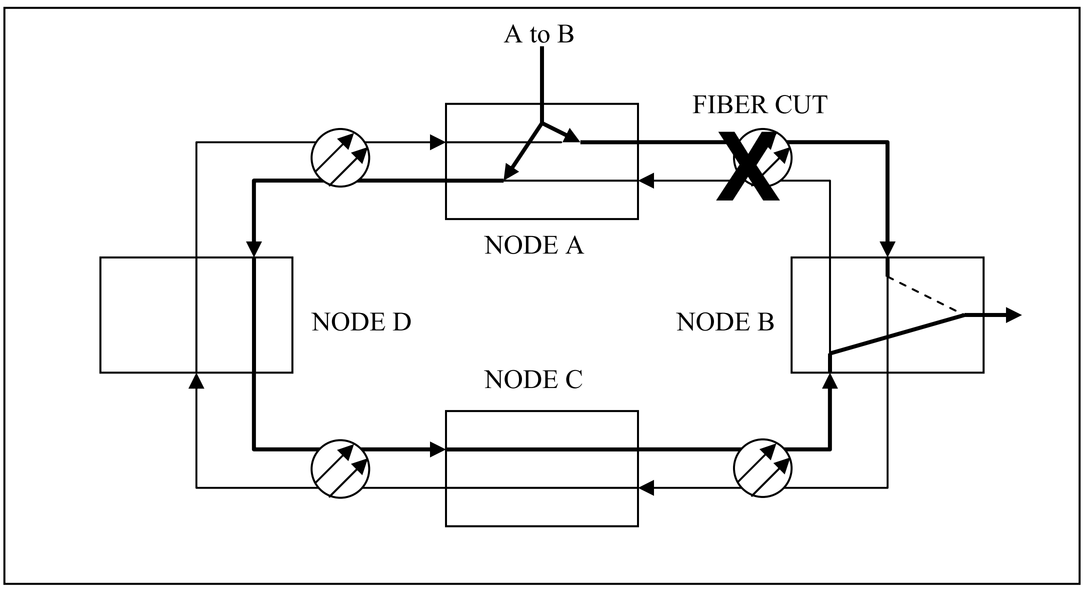

Figure 4. Protected traffic flow in 2-Fiber UPSR

In summary, the Service and Protection routes are based on a per signal (VT1.5 or STS-1) basis, where if only one VT1.5 or STS-1 fails, the protection path for only that service is selected. All other service paths remain unchanged. The advantage of the UPSR is that the switch threshold is tied directly to the quality of an individual customer's circuit. The UPSR topology is ideal for "Hubbing" or "Central Office" applications where most traffic terminates at one location.

Since each circuit is bridged to transmit both directions around the ring, one time slot is consumed all the way around the ring. Therefore the capacity of a UPSR is independent of the number of nodes and is directly related to the line rate. For example, an OC-1 is equal to or less than twenty-eight VT1.5's or one STS-1. An OC-3 capacity is equal to or less than eighty-four VT1.5's or three STS-1's, and so on. UPSR typically employs non-revertive switching. Since information is sent both ways around the ring, it did not make sense to disrupt the network a second time once the failure was repaired.

When applying some protective relaying over this type of ring topology, precautions need to be taken. Because most protective relaying is bi-directional in nature, consideration must be given to applications over a UPSR network. Since switching is determined at the individual path (circuit) level and switches at different nodes are independent from one another, it is possible for transmission from Node A to Node B to take a different route than transmission from Node B back to Node A, as depicted in figure 5. This can result in an unequal delay in transmit and receive paths of a bi-directional system. Some current differential and phase comparison systems cannot compensate for unequal channel delays between transmit and receive paths. These systems were designed with fixed equal delay compensation and asymmetrical delays could result in false operations or failure to trip.

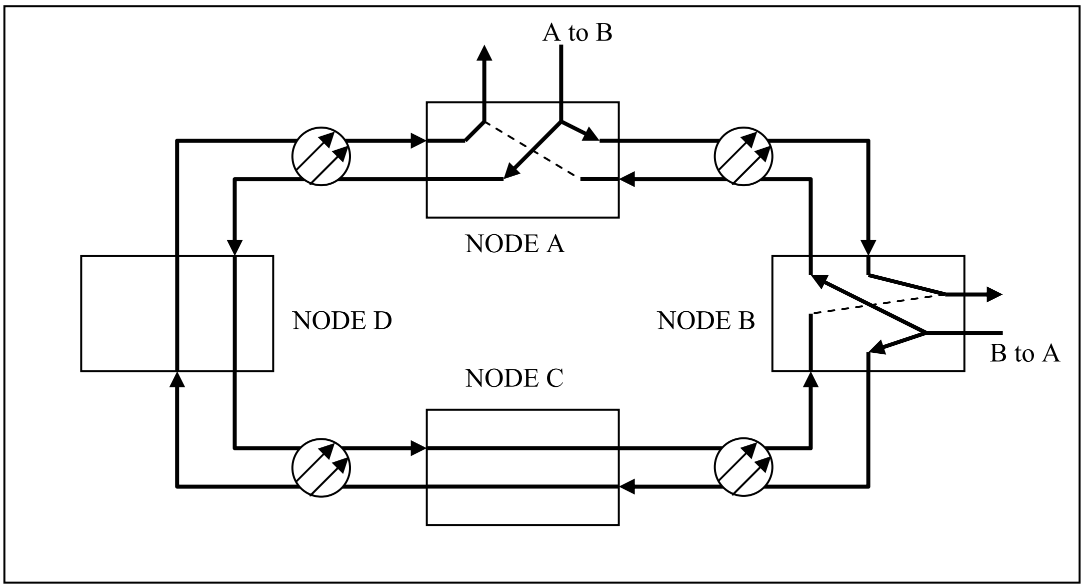

Figure 5. Example of unequal channel delay

GR-1230 2-Fiber **B**i-directional **L**ine **S**witched **R**ing (**BLSR**)

A SONET line layer is the connection or transmission span between any two node's optical line terminating equipment. The switching threshold is tied directly to the condition of the line. In a 2-fiber BLSR, half the bandwidth is reserved for Service and half the bandwidth is reserved for Protection. Both transmit and receive paths are mapped and switched as a pair thus eliminating any differential delay between transmit and receive paths. In a switched condition, delays around the ring may be greater in magnitude but the transmit and receive delays are symmetrical.

Figure 6 depicts a signal between nodes A and B. The primary or Service path is typically the shortest route between the nodes. The traffic from A to B travels on Service fiber 1, while the traffic from B to A travels on Service fiber 2. As mentioned earlier, half the bandwidth of each fiber is reserved for protection. If a failure occurs between nodes A and B, both nodes adjacent to the failure detect the problem and switch their traffic route onto the reserved Protection bandwidth the opposite way around the ring, as depicted in Figure 7.

In a BLSR, switching is typically revertive because all nodes around the ring share the protection bandwidth. If a second failure were to occur at a later time the protection bandwidth would be available for healing. The advantage of a BLSR is increased capacity for Interoffice applications. Since information is not sent both ways around the ring like a UPSR, timeslot or channel reuse is possible in an add/drop fashion around the ring.

Appendix A

When protective relaying is applied over this type of ring topology, precautions need to be taken. Although unequal transmit and receive channel delays are no longer a concern, one still has to consider the longer delays experienced when traffic is switched the opposite way around a ring. Some current differential, phase comparison systems and blocking schemes are very delay sensitive. These systems were designed with fixed delay compensation and long delays could result in false operations or failure to trip. This could limit the size of the ring network.

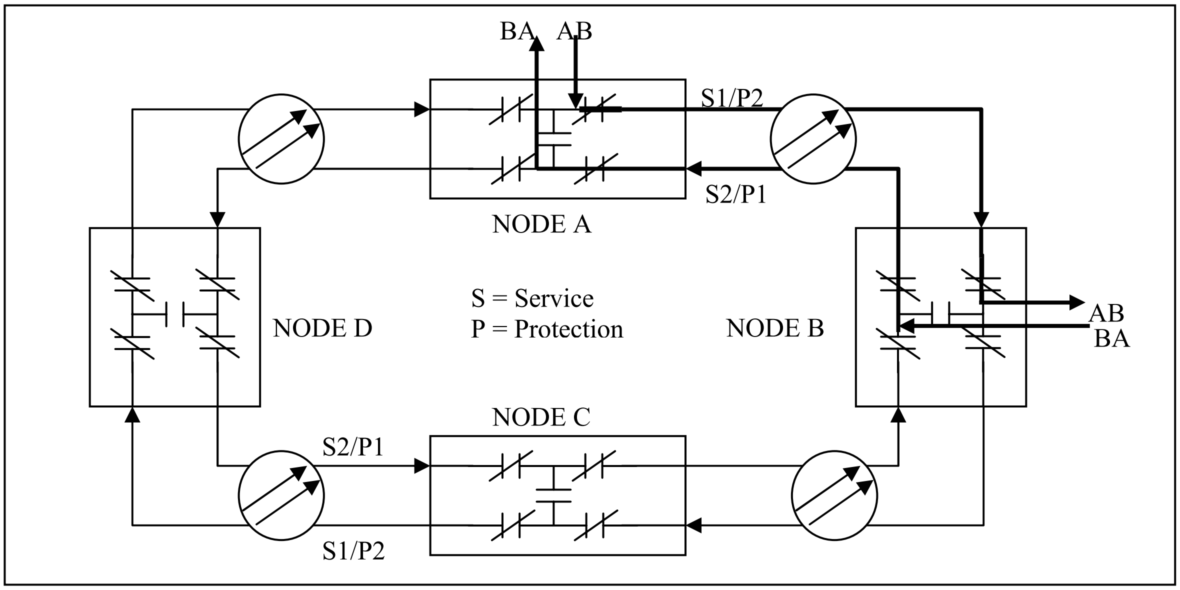

Figure 6. 2-Fiber Bi-directional Line Switched Ring

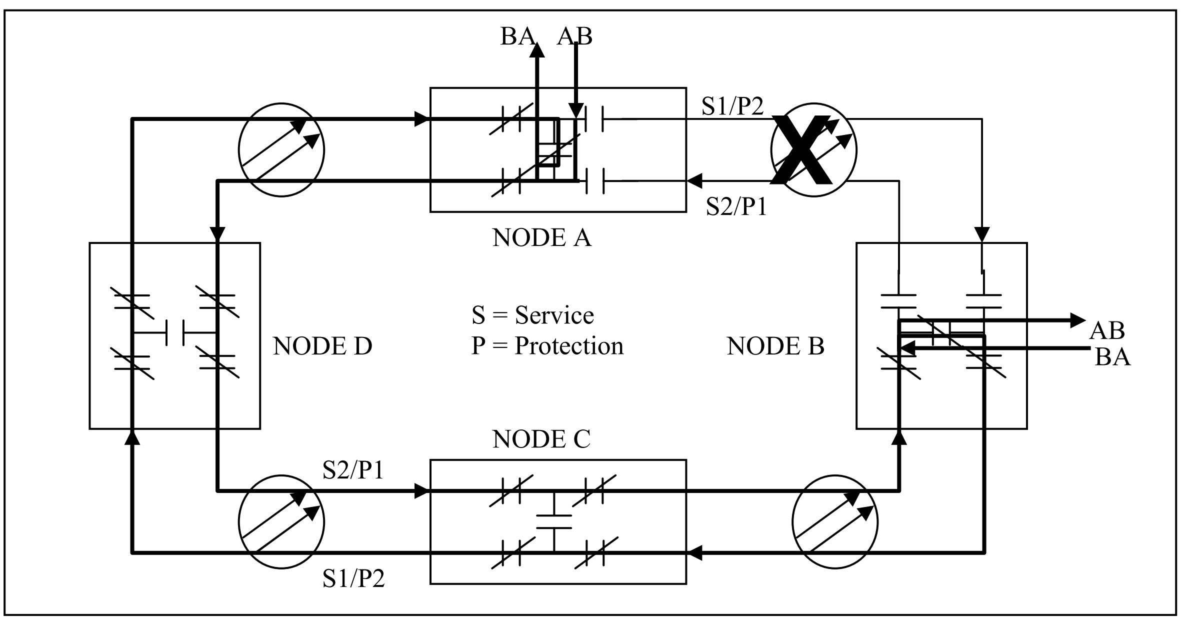

Figure 7. Protected traffic flow in 2-Fiber BLSR

Appendix A

Table 1 depicts a typical channel plan for an OC-1 payload using half the bandwidth for Service and the other half reserved for Protection. Table 2 depicts the reassigned channel plan for a fiber break between Node B and Node C.

OC-1	Node A		Node B		Node C		Node D	
VT1.5	West	East	West	East	West	East	West	East
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15	Reserved for Protection							
16	Reserved for Protection							
17	Reserved for Protection							
18	Reserved for Protection							
19	Reserved for Protection							
20	Reserved for Protection							
21	Reserved for Protection							
22	Reserved for Protection							
23	Reserved for Protection							
24	Reserved for Protection							
25	Reserved for Protection							
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28	Reserved for Protection							

Table 1. 2-Fiber BLSR OC-1 Channel plan under normal conditions.

Appendix A

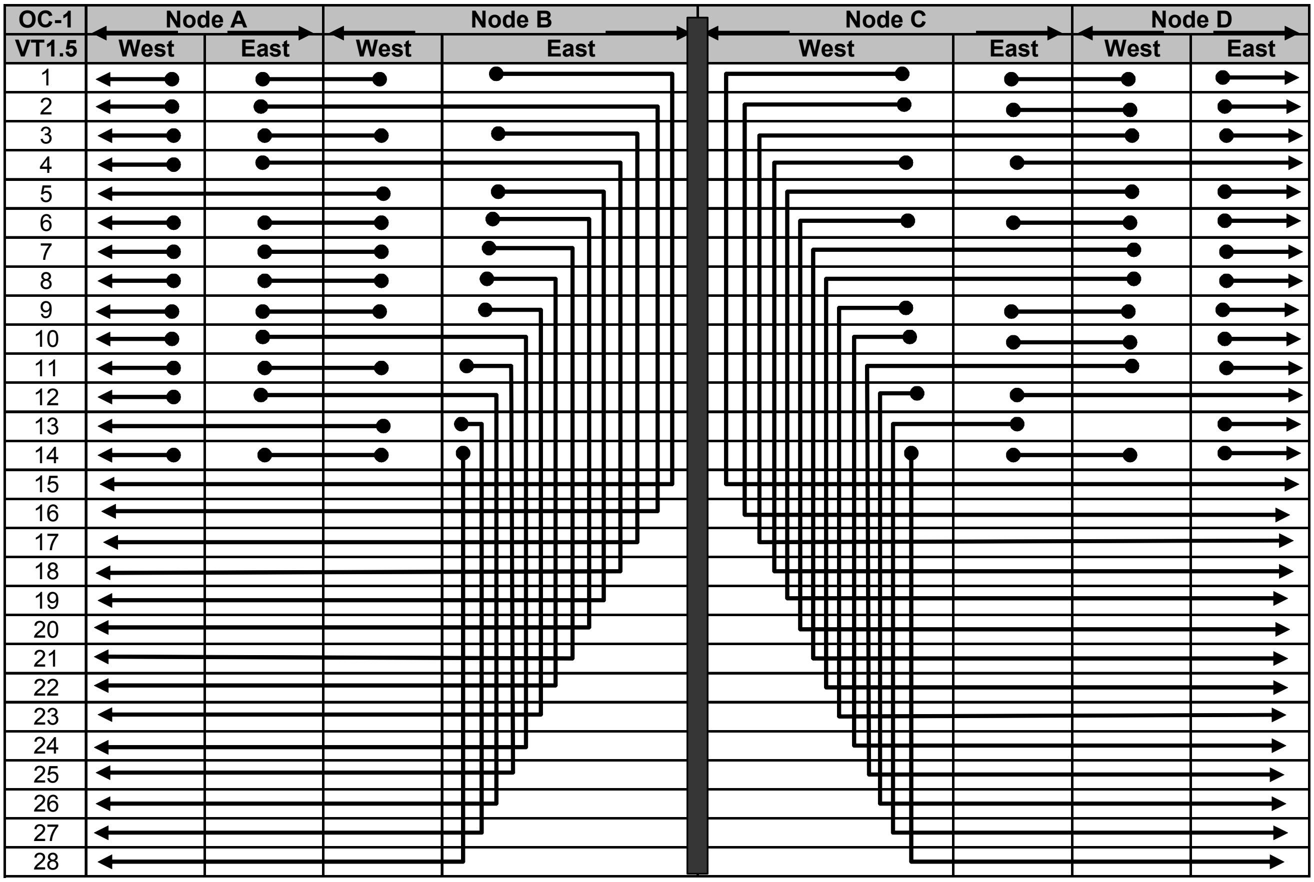

Table 2. 2-Fiber BLSR OC-1 Channel plan during fiber break between Nodes B and C.

<u>GR-1230 4-Fiber **B**i-directional **L**ine **S**witched **R**ing (**BLSR**)</u>

A 4-fiber BLSR is similar to a 2-fiber one but it uses a second pair of fibers around the ring for Protection. Since half the bandwidth is no longer used for protection, a 4-fiber BLSR can handle twice the capacity. However, a 4-fiber BLSR also requires twice the optical line terminating equipment, which results in higher cost to implement. Just like a 2-fiber BLSR, both transmit and receive paths are mapped and switched as a pair thus eliminating any differential delay between transmit and receive paths. In a switched condition, delays around the ring may be greater in magnitude but the transmit and receive delays are symmetrical.

SONET DELAY CHARACTERISTICS

In order to calculate the delay in a network the following SONET specifications need to be considered.

DS1 Synchronization Delay into SONET payload	< 100us
DS1 Desynchronization Delay out of SONET payload	< 100us
DS1 Pass-Through Delay	< 50us
Propagation Delay through Fiber	< 8us / mile
Propagation Delay through Radio	< 5us / mile

Appendix A

Since SONET standards only address DS1 as the smallest bandwidth low speed interface, an Engineer also needs to consider what type of multiplexer he uses for DS0 access onto the SONET transport.

SONET RESTORATION CHARACTERISTICS

Engineers may be concerned about the restoration time of their network. Restoration time is the amount of time that transpires once a failure is detected and until valid data is being output again. During this time period communications is lost. Keep in mind that restoration times on networks will only have a major impact on a protective relaying traffic if the communication equipment outage occurs precisely when the relay is trying to trip. The odds of that occurring are left to the Engineer to decide. In order to calculate the restoration time in a network the following SONET specifications need to be considered.

Time to sense a failure	< 10ms
Switch time	< 50ms

Again, since SONET standards only address DS1 as the smallest bandwidth low speed interface, the Engineer also needs to consider what type of DS1 multiplexer he uses for DS0 access onto the SONET transport. They should then look at the reframe time of the DS1 in order to calculate the total restoration delay. One should also consider any restoration times for the device being driven at the DS0 level. For example, some protective relays use channel addressing on switched digital networks to insure no miscommunications. These restoration times would need to be figured in the total equation.