Line Current Differential: Communication Channel Considerations

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Abstract: This paper briefly describes line current differential schemes, and focuses on their dependencies on communication channels. Dependencies on bit error rate and transmission latency are discussed. Effect of time synchronization accuracy on sensitivity of line current differential scheme is explained in details. Types of communication channels are discussed including dedicated, multiplexed and packet-based. Special attention is given to dedicated channel whose meaning has evolved with development of communication technologies from dedicated physical connection to dedicated bandwidth, etc. Examples of common and evolving communication technologies used for line current differential schemes are given, including the IEEE C37.94 N x 64Kbit/s and Multi-protocol Label Switching (MPLS). Known challenges with adoption of these technologies are also provided.

Key words: line current differential protection; dedicated, multiplexed and switched communication channel; availability; sample synchronization; latency; bit error rate.

I. Introduction

Line current differential protection became the de facto standard for many utilities. This protection cannot be possible without the use of a communication channel, as explained in details in many excellent books and papers [1],[2],[3]. The communication channel used for line current differential protection has to meet strenuous requirements to ensure that scheme's overall security and dependability requirements are met.

As typically protection engineers have not been focusing on understanding communications, power industry acknowledged this gap and responded by publishing various reports to educate the community on the use of communications for protection [4],[5],[6],[7]. The subject of dependencies of protections schemes on communications has been explored further in recent conference papers [8],[9],[10],[11].

Power community, being a conservative industry, very slowly and reluctantly embraces new technologies. Adoption of technologies whose expertise and responsibility lies in different departments within a company (e.g. protection and communication) becomes even more difficult. Understanding fundamentals and sharing experiences with the new technologies becomes essential. This paper responds to this need.

The paper focuses on communication channel for line current differential schemes and is organized as follows. Section II outlines necessary fundamentals of line protection and covers dependencies of line current differential protection on communication. Section III describes different communication channels used for line current differential protection today and explains the differences between dedicated, multiplexed and switched channel. In particular it clarifies the difference between Ethernet and MPLS-based switching, as the two are often confused. Section IV presents line current differential schemes implemented at EPCOR and AltaLink. Configurations using IEEE C37.94 over SONET channel and over MPLS channel are discussed. Field test results are presented. Conclusions follow.

II. Line current differential protection

This section covers necessary fundamentals of line protection, and dependencies of line current differential protection on the communication channel.

a. Line protection fundamentals

A transmission line, depending on its length, voltage level and operation criticality, can be protected by different protection schemes. Low to medium voltage distribution feeders are most often protected by simple overcurrent relays. Sub-transmission lines or lines where transient stability resulting from delayed

fault clearing is not a concern can be protected by step distance relays. Overcurrent and step distance protection schemes are the most simple and economic forms of line protection. They are non-unit protection schemes thus coordination with adjacent protective devices is required. For high voltage, heavily loaded transmission lines high-speed and simultaneous fault clearing (< 1.5 cycles) in multiple terminals are mandatory. Communication assisted pilot schemes, ranging from directional comparison, phase comparison, to the most sophisticated current differential based, should be applied to protect the power system from slipping out of phase and ultimately collapsing.

Line current differential protection (87L function) is most often applied as a unit protection scheme where the protected object, the transmission line, is fully enclosed in the protection zone defined by multiple current transformers located in geographically dispersed line terminals. No protection coordination with adjacent protective devices is required. The main difference of 87L function from other current differential protection schemes is that the equipment to be protected spans across a wide geographic territory as opposed to residing locally within a substation fence. This geographic separation requires a certain type of long-haul communication system in place for relays to exchange current measurement information with each other. The reliability of the communication channel is as crucial as the protective device itself to assure the same degree of operation dependability and security. Figure 1 shows a typical two-terminal line differential protection system.

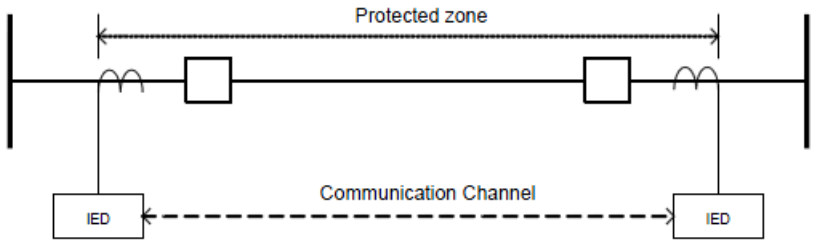

Figure 1. Line differential protection system.

Line current differential relaying is by nature very sensitive to internal faults and secure to external faults with properly selected current transformers. It is simpler to apply compared to overcurrent and distance schemes as no extensive knowledge of the power system beyond the protected line is required. Since it is a current based protection scheme, it is relatively immune and stable to most voltage induced transient phenomena such as power swings, voltage reversal in series compensated lines and capacitive voltage transformer transient measurement errors for short lines, to just name a few. On the other hand, line current differential protection requires a high-speed reliable communication channel between the relays forming the protection zone, which back in the “copper and analog” era was considered too expensive with only limited applications. Advances in digital communication technologies and the lower price of optical data transport led to the proliferation and maturation of line current differential relaying throughout electric utilities.

b. Analog line current differential systems

The older generation of current differential system used shielded 19 AWG twisted-pair pilot wires as the communication medium. The pilot wire system can be considered as the first true current differential protection system where both magnitude and phase information is communicated via the pilot wire and compared at each end of the line [3],[12]. The three phase current quantities were represented by a single phase voltage through a sequence filter. The sequence filter takes the three phase currents from the current transformers as sources, filters out the sequence components and calculates the filtered voltage. Then the resulting analog 50 or 60 Hz filtered output voltage signals are compared across the pilot wire. An example of a pilot wire relaying system is shown in Figure 2.

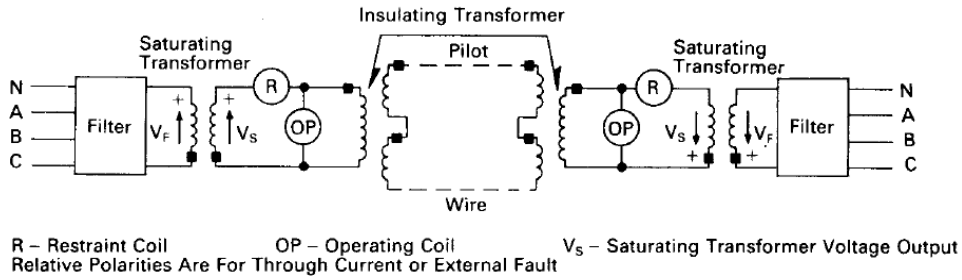

Figure 2. Pilot wire current differential system.

There are some limitations in this pilot wire current differential system. First, the pilot wire loop resistance and shunt capacitance cannot be excessively larger than the relay design values. A large loop resistance is comparable to an open pilot wire. An external fault may operate both relays. On the other hand, a large shunt capacitance is likely to short out the operating coil. The relay may not operate during an internal fault. Consequently, the pilot wire system is only applicable to short transmission lines as its dependability and security both degrade as the length of the line increases. Special DC voltage injection through the insulating transformer can be used to supervise the health of the pilot wire and alarm for any physical damages.

Other shortcomings to the pilot differential system include possible high voltage induction from the power line and station ground rise. Gaps or arresters need to be used to ensure personnel safety when operating the supervision equipment. Some utilities used leased telephone lines to operate this system. In return they lost control and management of the communication channel and suffered communication disruptions from unscheduled maintenance and malicious vandalism.

Digital communication system resolves the problem of harmful voltage induction and increases effective operating distance. A utility owned system not only enhances the reliability of the protection scheme but also addresses other communication needs due to its abundant and scalable bandwidth. The digital communication systems are the main focus of the paper.

c. Digital line current differential systems

For the last 20 years, microprocessor based numerical processing relays, also known as intelligent electronic devices (IED), have been introduced to the field of protective relaying. Since IED operation is based on software (firmware) computation and execution, they offer the advantages of lower cost, multiple protection functions, customizable logic schemes, station and remote communication features, sequence of events, oscillography and self-monitoring functionality [13]. An example of line current differential scheme with a multiplexed digital channel is shown on Figure 3.

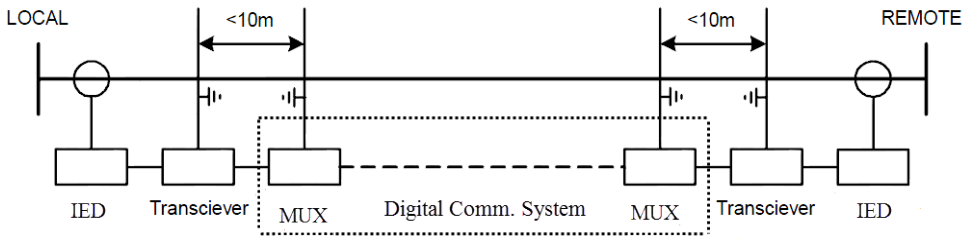

Figure 3. Line current differential protection system using a multiplexed digital communication channel.

Modern IEDs process analog signals from instrument transformers in more or less similar orders: by scaling down the analog signals to levels suitable for the relays, anti-alias filtering, sampling and digitizing the samples (A/D converter) and phasor estimation (e.g. Discrete Fourier Transform). The estimated fundamental phasors are then used in various protection algorithms such as differential calculations to generate the trip signals to operate the circuit breakers [13]. In line current differential

relays one extra step is taken after A/D processing: the quantized samples of local current measurement are transmitted to remote terminals through embedded communication interfaces via a digital communication system. Likewise the current samples received from the remote terminals are collected and passed to the phasor estimator along with locally measured current samples. One important consideration before the line differential algorithm processing is accurate time alignment and synchronization of samples measured at different terminals. Misalignment of data jeopardizes protection security.

There are in general two main 87L operating algorithms widely applied today: the biased (restrained) differential and the complex alpha plane. The biased differential scheme algorithm has also been commonly applied to protect the other substation apparatus. In the biased differential algorithm two quantities are calculated for each phase due to phase-segregated nature of line differential protection. The differential current is the vector sum of the fundamental current phasors at each terminal of the line, as defined by Kirchhoff's current law The biased current is calculated differently for different relay design, for example as:

$$I_{res} = ½ (|I_{local}| + |I_{remote}|) \text{ or}$$

$$I_{res} = \text{Max} (|I_{local}|, |I_{remote}|)$$

The relationship between the differential and bias current quantities, typically expressed in per unit of rated line current, can be expressed on a chart of linear lines with different slopes as in Figure 4. The region above the curve is the operating zone and the region below is the restrained zone. This basic mathematical property is the core design of the biased differential algorithm: the restraint current preserves relay security during heavy line loading or severe external faults by requiring higher operating current. The slopes and points of intersections between different curve sections are usually configurable to different system conditions.

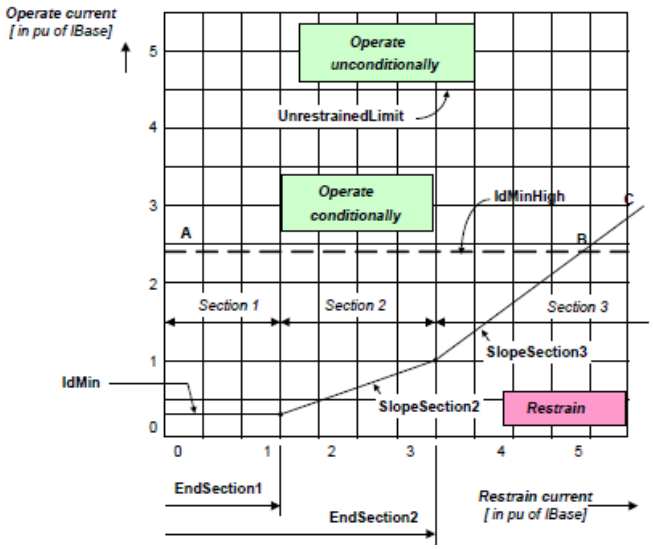

Figure 4. Differential relay operating characteristic.

The alpha plane algorithm is essentially the polar representation of the phase difference between the remote and local terminal current phasors. In homogeneous system conditions in which the system impedance on each side of the fault location is similar, no CT saturation and channel asymmetry, the phase difference for an internal fault will locate exactly on the positive real axis while an external fault will locate on the negative real axis. Those ideal conditions are of course fictitious in the real world. Line differential relays based on the alpha plan method typically come with settable parameters to enlarge the operating zone to account for measurement errors and the more realistic system conditions.

Although line differential schemes is relatively stable against system and voltage induced transient events, it is however sensitive to the capacitive charging current of the line. Modern line differential algorithms include special charging current compensation logic to offset or subtract the measured or calculated steady-state charging current from the differential current calculation to avoid desensitizing the protection especially in long transmission lines. Modern line current differential IEDs typically provide other features such as internal/external fault identification for added security to CT saturation, in-zone and tapped transformers protections and open CT detection. Redundant and backup protection functions such as distance, over-current and breaker failure functions are also commonly integrated.

d. Dependencies on communication channel

Line current differential protection cannot perform without a reliable communication channel. Modern 87L IEDs are equipped with digital transceiver modules intended to interface with the communication system that could be implemented as field swappable electronic circuit boards. In general, copper interfaces are mainly used for short-range connection, e.g. to the substation multiplexer. Optical interfaces can serve as either a short-range connection to the multiplexer or can also be applied as a direct long-range point-to-point channel between multiple 87L relays.

Certain communication channel requirements and dependencies must be fulfilled to ensure dependable and secure operation for an 87L protection system.

Availability

Legacy pilot-wire systems used leased telephone wires typically owned and maintained by telecommunication providers. The maintenance schedules might not be communicated effectively and accidental breakage or even criminal sabotage of the channels was not under the control of the operating utility. Channel availability and protection dependability greatly improve if the communication network were solely owned and operated by the utility. The other measure that can enhance channel availability is provision of a redundant channel, ideally with different communication technologies (e.g. direct fiber and SONET channels) and/or different routing (dual-ring SONET with different path). Data communication modules on a modern 87L IED can be configured as “hot-standby” in which the identical data received on the “redundant” module automatically substitutes data from the primary module when it fails. Loss of both communication channels due to damages to the transport media or delayed recovery and healing of a communication path after a fault may trigger the security algorithm in the 87L relay to block its operation.

Latency

Due to the geographical separation in 87L terminals data transmission between the relays inevitably suffers from transmission delay. Latency is the parameter indicating the delay incurred by the data packet to traverse from the sending to the receiving relay. To achieve high-speed operation especially for strategic transmission lines in critical operating conditions, the channel latency cannot be excessive. In essence, the current samples should be delivered in less than the data reporting interval, for example 5 ms. Maximum transmission delay, usually configurable as a relay setting, will ultimately lead to blocking of the 87L function. Modern protection grade telecommunication equipment can be configured and be selective to assure that the shortest path be taken by packets between two designated network nodes.

Samples synchronization and alignment

Local and remote current samples must be accurately aligned before being processed by the differential algorithm. A misalignment of 0.1 msec accounts for 4% of magnitude error in differential calculation and a 1 msec misalignment can produce up to 38% of magnitude error [15]. In general two time synchronization techniques for the purpose of current sample alignment are used in modern 87L IEDs: channel-based and external time based. In channel-based mode, also known as “echo”, the path latency, and clock offset between the relays is calculated from the time-tagged datagrams exchanged between the terminals during a complete round-trip journey. The derived clock offset is then used to interpolate the received sample and align with the local one before further processing. The channel-based method requires symmetric communication path between the relays for the calculation to be accurate, e.g. a

direct point-to-point channel such as a pair of single-mode optical fibers. Attention must be paid to multiplexed networks during their self-healing path switching and to IP-based networks with theirs inherent nondeterministic path and latency as transmit and receive paths become asymmetrical. Under such condition the calculated clock offset may contain errors, jeopardizing both dependability and security of the protection algorithm. Teleprotection grade multiplexers such as SONET nodes offer configurations to assign preferred path for teleprotection services before and after path switching and how the path is to be switched. Modern 87L IEDs by design can also tolerate up to a certain degree of path asymmetry without causing a security concern or provide the users with a setting to account for a known fixed path asymmetry in the communication system. For systems with unspecified path switching or significant path asymmetry, external time-based synchronization, typically in the form of an integrated GPS receiver is used. GPS modules synchronize the internal relay clocks down to 1 µs or 100 ns accuracy thus local and remote samples are aligned. Upon losing the GPS signals from either natural causes such as solar flare or malicious activities such as signal jamming, there are usually fallback provisions in place to dynamically switch to either channel-based synchronization, internal clock or to completely disable the 87L function.

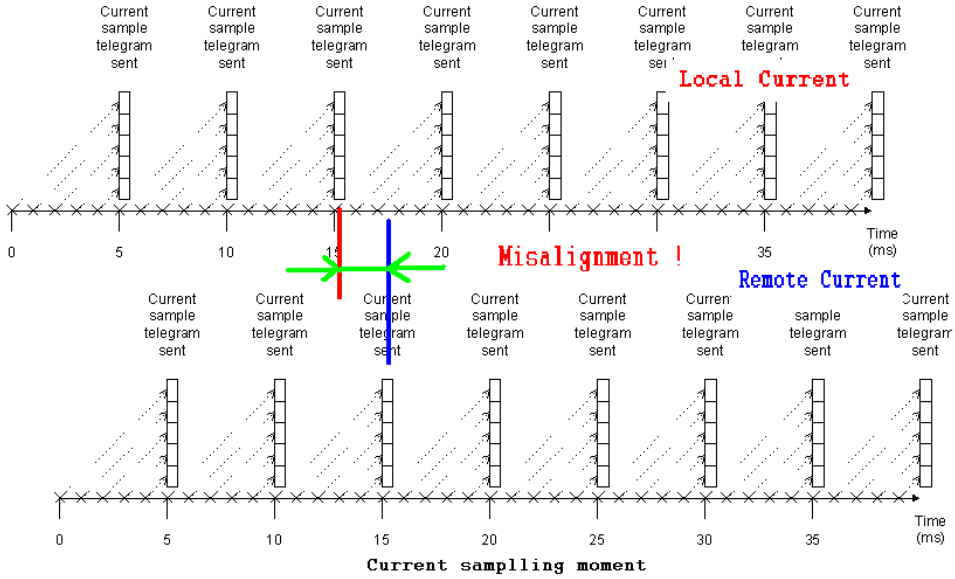

Figure 5. Samples synchronization and alignment.

Bit Error Rate

A properly designed and maintained communication system must possess a very low bit error rate (BER) to be suitable for 87L applications. Bit error is defined as the number of received bits in a data stream over a communication channel that has been altered due to noise, interference, attenuation and distortion. If the BER is excessive, unintended operation may occur, jeopardizing protection system security. In digital communication each data packet contains special bits intentionally transmitted so that bit errors can be detected at the receiving end with special error detection algorithms. Modern 87L IEDs can usually detect, alarm and display BER on the Human Machine Interface (HMI) screen as statistical information or simply with LEDs for the convenience of troubleshooting. Embedded data integrity measure in the communication module will discard the packets tainted with excessive BER to prevent mis-operations and disable 87L operation until the channel is healthy again. An acceptable BER for 87L application should be around 10^{-9} to 10^{-8} during normal conditions. Use of optic transport media whenever possible can reduce unwanted interference which in turn improves BER and protection dependability in harsh utility environments.

Typical digital communication parameters available in modern 87L IEDs related to communication channel dependencies are shown below.

- Terminal ID: vendor-specific address for each communication module to avoid wrongful delivery of data samples.
- Time synchronization mode: external time-based (GPS) or channel-based.
- GPS time-sync fallback mode: the fallback measure when GPS signal is lost. Options include blocking 87L or channel-based sync.
- Fixed Asymmetric Delay: known fixed asymmetric path delay to compensate for in channel-based mode.
- Latency: maximum one-way latency, beyond which 87L function is blocked.
- Maximum Clock Offset: maximum allowable clock offset between relays in different terminals with channel-based time sync mode, beyond which 87L function is blocked.

III. Types of communication channels

As discussed in previous section security and dependability requirements of the line current differential schemes place stringent requirements on digital communications channels used for these schemes, thus understanding and selection of an appropriate communication technology becomes crucial.

Digital communication channels used for line current differential schemes could be broadly divided into dedicated, multiplexed and switched. It should be noted that the meaning of the dedicated channel has evolved with developments of communication technologies. Dedicated bandwidth or dedicated frequency/wavelength in a multiplexed channel also operates as a dedicated resource, thus a multiplexed channel could be considered as a set of dedicated channels. Dedicated and switched channels, however, are inherently different, as switching (or routing for IP-based communications) relies on availability of channels and buffering resources. These challenges are addressed differently by different technologies.

This section describes various digital communication channels technologies used for line current differential protection.

a. Dedicated channel

Dedicated communication channels have been used in protective relaying over the years for simple status/command exchange between relays using binary input/output signals. In this case the communication media, a copper wire, is dedicated to a single connection and a single command. This communication is 100 % available and corresponds to a single bit of information (1 or 0) in digital communication terms.

If multiple commands are used, multiple combinations, e.g. 4 for a breaker protection or a teleprotection scheme, need to be communicated. To communicate 4 combinations 2 wires or 2 bits are needed (2^2=4). Single byte that comprises 8 bits can communicate 2^8=256 combinations. Transmitting these combinations every second corresponds to data rate of 256 bits per second (b/s). Older serial communication technologies support data transmission rates from 300 to 115,200 b/s. Modern communication technologies support data transmission rates in Gb/s, which opens new grounds and plethora of possible data usages and applications.

Note that all these bits are sent over a single “wire” or a physical communication media that could be copper, fiber or air. Copper media includes copper, also called galvanic, communication cables as well as power lines for power line carrier applications. Fiber media, also called glass, includes different types of fiber optic cables: multimode fiber (MMF) for shorter distances and single-mode fiber (SMF) for longer distances. Air includes different frequencies for wireless transmissions, e.g. 2.4GHz (for WiFi) and frequencies 1-30GHz (for microwave).

Data bits are grouped into bytes and combined into frames, packets or messages in accordance with a given communication protocol format. A protocol is essentially a set of pre-defined rules that allows communicating parties to understand each other. It usually attaches additional information to the frame, such as source and destination addresses, and data integrity checks that are similar to a mail envelope's "To" and "From" fields and a seal that proves that the content was not altered.

Traditional digital communication technology uses a 64 Kb/s channel as a building block, as originally this rate was defined for digitizing voice. A standard analog audio signal was traditionally sampled at 8 KHz and then encoded as an 8-bit stream using pulse-code modulation. The resulting data rate of the digitized channel is 8000 samples/sec × 8 bits/sample = 64 Kb/s.

While currently no standard protocol exists for direct relay-to-relay (or point-to-point) communications, 64Kb/s channel(s) are commonly used to carry required data between the relays. For line current differential protection this channel can be used to exchange current samples encoded as 8 or 16-bit values, clock information (timestamp) and various binary signals (trip, block, alarms). This data exchange is usually bi-directional with data transmitted and received at the same time, defined as the full-duplex operation mode. Different physical interfaces (fiber, copper) could be utilized, but due to longer distances typically SMF is used. An example of dedicated relay-to-relay communication is shown in Figure 1 and Figure 12.

Various methods, e.g. using IEEE C37.94-2002 frame format [16] or a fully proprietary protocol can be used to exchange information required for operation of line current differential schemes. Data transmissions are usually periodic and are based on local clocks. To properly identify transmitted data pre-defined start and stop identifiers can be used. These are common for asynchronous data transmissions which can start at any time.

The same relay can have direct connections to other relays and can act as a master in multi terminal line current differential scheme. Each connection could use a dedicated 64Kb/s channel, for example, one channel in the IEEE C37.94 data stream.

Some vendors extended the use of IEEE C37.94-2002 data format by adding relay-to-relay communication over SMF. A revision to IEEE C37.94-2002 has started to address inclusion of SMF and relay-to-relay communications.

A utility use case with relay-to-relay communication using IEEE C37.94 data format for line current differential protection is discussed later in this paper.

b. Multiplexed channel

As available data capacity (or communication bandwidth) increases rapidly, it becomes possible and logical to share available communication resources. Multiplexing performs this function. Multiplexing is the technology that allows multiple signals to share the same physical communication media. Common multiplexing techniques include

- frequency division multiplexing (FDM): channels use different frequency in analog carrier,
- time division multiplexing (TDM): channels use different time slots in digital carrier,
- wave division multiplexing (WDM): channels use different wavelengths in optical carrier.

As a dedicated physical resource (frequency, time or wavelength) is allocated for a single communication channel, a *multiplexed channel* can be considered as *a set of dedicated channels*, as long as allocated resources are fully available.

Analog systems and FDM technologies are not discussed in this paper. Common TDM and WDM technologies are covered below.

General principle of TDM communications is shown on Figure 6. Each data source is assigned a dedicated time slot for data transmissions. Time slots are grouped for transmission in a single data frame.

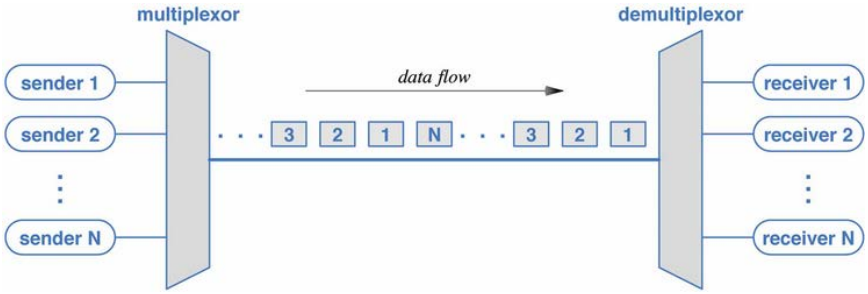

Figure 6. Data multiplexing principle

The base 64 Kb/s digital channel, discussed earlier, was named Digital Signal 0 (DS0) and became the fundamental building block of a digital multiplexing system called pleseochronous digital hierarchy (PDH). In North America 24 DS0 channels were combined into a DS1 channel (also called T1) at 1.544 Mb/s, while in Europe 32 DS0 channels formed an E1 signal at 2.048 Mb/s. PDH systems require accurate frequency synchronization to avoid data losses or slips, defined as loss or duplication of a complete data frame.

SONET/SDH

Further developments in communication technologies led to the introduction of European Synchronous Digital Hierarchy (SDH) and North American Synchronous Optical Network (SONET) that use precise frequency synchronization for high availability reliable high-speed data communications [17]. Operation principle of SONET/SDH networks can be visualized as a fast train, which never stops, is always on time and always has allocated space (containers) for those needing to travel (send data). Train capacity depends on the system used. SONET rates vary from Optical Carrier 1 (OC-1) at 51 Mb/s to multiples of OC-1 as in OC-3, OC-12, OC-48 and OC-192. Similarly, SDH rates vary from Synchronous Transport Module 1 (STM-1) at 155 Mb/s to STM-3, STM-12 and STM-48. Depending on the type and size of a "parcel", data can be placed into an appropriate Virtual Containers (VT), e.g. VT 1.5 can carry 1.544 Mb/s DS1 or 2.048Kb/s E1 channels.

The train uses "coaches" (frames) to carry data containers. Data can be "added" (multiplexed) and "dropped" (demultiplexed) at data source and destination locations, called nodes, thus SONET/SDH multiplexers are called an Add and Drop Multiplexers (ADM). Adding and dropping data requires data storage, which introduces delays. Bypassing data through a pass-through node allows passing data directly without multiplexing / demultiplexing delays. This mode is preferred for line current differential application as discussed in a utility use case in section IV.

The OC-1 frame consists of 810 bytes organized in 9 rows by 90 byte-wide columns. First three columns rows are the overhead that contains start of frame flag, information on data path and a data pointer. Remaining 87 columns are allocated for the data. Data pointer field indicates where the actual data starts inside the frame. The frame is transmitted synchronously during exactly 125 µs. Higher rates are obtained from multiple OC-1 frames simply by byte interleaving.

It should be noted that SONET/SDH systems are

- highly available (allocated data container is always available, regardless if there is a data to transmit)
- deterministic (synchronous and deterministic processing result in guaranteed delivery and known delays)

Typically, SONET/SDH systems use redundant ring or linear/flat ring configurations, offering 1+1 communication redundancy (also known as self-healing) and fast switching on a single path failure. If the communication system is used for time distribution, delay asymmetry shall be considered and minimized, especially when path fail over switching is performed.

As a physical communication media most commonly redundant SMF are used between SONET/SDH nodes, but microwave transmissions are also possible if needed for remote location. SMF cables with ST

or LC connectors are common. For ring configuration, 2 SMF strands are used in each direction for the total of 4 SMF strands, preferably on two path-diverse SMF cables. SONET/SDH application cards support a variety of user interfaces, including Ethernet, IEEE C37.94, etc.

IEEE C37.94

IEEE C37.94-2002 standard defines an Nx64 protocol for the interface between a relay and a multiplexer [16]. A base 64Kb/s channel is used and up to 12 channels can be supported in the same interface. The standard defines the use of MMF and ST connectors as communication media. Data format consists of a 256 bit-frame with a 16-bit header, 48-bit overhead data link between the multiplexer and the IED, and 192-bit data. The standard does not support addressing, which must be defined by the protection equipment or the multiplexer.

A utility use case with IEEE C37.94 over SONET communication channel for line current differential protection is discussed later in this paper.

Wave division multiplexing (WDM)

Wave-division multiplexing (WDM) is a technology that allows multiple optical signals (light wavelengths) to share the same optical media [20]. WDM conceptually is the same as FDM, but WDM uses light wavelength (a period) in an optical carrier, while FDM uses signal frequency in a radio carrier. WDM concept is also similar to having multiple conductors in a single electrical cable. Refer to Figure 7.

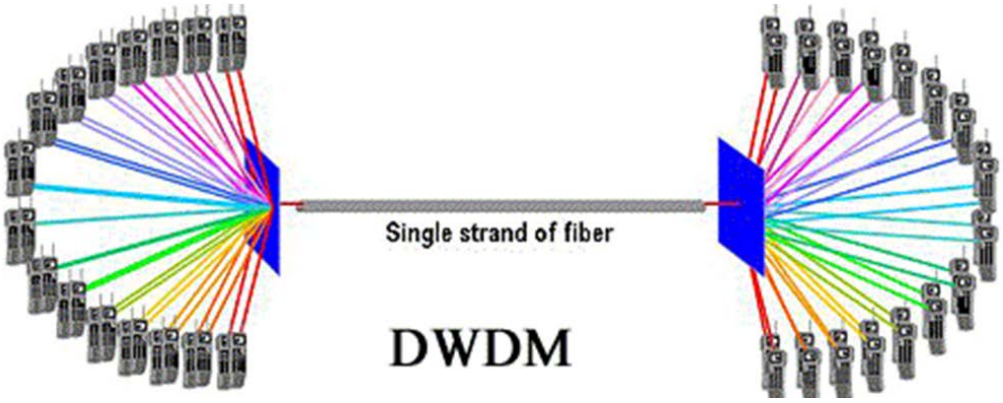

Figure 7. Principle of wave division multiplexing.

WDM systems are divided into coarse wave-division multiplexing (CWDM) and dense wave-division multiplexing (DWDM). CWDM systems provide up to 8 channels, while DWDM can provide 40 or 80 channels in the same fiber optic cable. Most WDM systems use SMF cables but some can also support MMF cables.

WDM is commonly used for SONET/SDH as well as Ethernet technologies. Interesting to note that Ethernet LX-4 10 Gb/s physical layer uses CWDM with 4 wavelengths near 1310 nm, each carrying a 3.125 Gb/s for total data rate of 10 Gb/s.

CWDM in contrast to DWDM uses increased channel spacing to allow less sophisticated and thus cheaper transceiver designs. New gigabit interface converters (GBIC) and small form factor pluggable (SFP) transceivers perform passive optical CWDM multiplexing. Addition of these devices allows upgrading existing legacy systems to CWDM.

Wave multiplexing principle can also be used to reduce number of cables, e.g. to use one wavelength for transmit and another for receive, thus requiring only one fiber strand in place of two, which are normally used in this case.

A utility use case with WDM communication channel for line current differential protection is discussed in this paper.

c. Switched

Switched communication channel is inherently different from multiplexed and dedicated channels as it connects (switches) a communication resource when such resource is available. This principle was used in old PBX-based telephone networks, whose capacity was calculated using queuing theory for a typical load. Such systems dropped about 20% of the calls when everybody wanted to talk at the same time. However, if a channel was allocated, it was fully available for the full length of the connection.

Modern communication systems integrate voice and data transmissions, and are based on datacom principles. Data is placed in one or multiple "containers" (frames, packets or messages), and each "container" is switched (or routed) separately. Identification is provided to assemble received data in the correct order.

Switching relies on availability of communication channels and internal buffers to achieve reliable data delivery. The more available these resources are the more reliable and deterministic data deliveries would be. Various mechanisms have been introduce to improve resource allocation, such as traffic prioritization, deterministic buffer allocation for high priority, rate limiting, virtual local area networks (VLANs), resource reservation protocol (RSVP), etc.

Differences between switching and routing should be noted. Switching originally came from telecom world, while routing came from datacom world. For decision making switching typically uses a single parameter (such as address or a label) and a local lookup table, while routing in addition uses system-wide information and protocols, e.g. Internet Protocol (IP) routing can use Open Shortest Path First (OSPF) protocol. Switching is faster and is typically implemented in hardware, without Central Processing Unit (CPU) intervention, while routing is typically implemented in software running on a CPU, thus is much slower. Modern systems perform switching and routing at different layers of Open Systems Interconnection (OSI) model, e.g. at Layer 2 for Ethernet switches, Layer 3 for IP, etc.

Ethernet

Ethernet operates at Layer 2 of OSI model. It uses specific frame structure and Media Access Control (MAC) addresses to forward frames [18]. MAC addresses are *globally unique* for a given hardware. They consist of 6 bytes (48 bits), refer to Fig x, and include 3 bytes of Organization Unique Identifier (OUI), assigned to the equipment vendor and 3 unique bytes assigned by the equipment vendor. As sometimes it is desired to send the same frame to all connected devices or a group of connected devices MAC addresses support broadcast ("one to all") and multicast ("one to many") modes. Unicast ("one to one") mode refers to communication between one source and one destination.

Although originally Ethernet was introduced as a "best effort technology", i.e. only best effort is made to deliver data, but in general data delivery is not guaranteed; multiple enhancements were made to provide an available and reliable Ethernet channel. These include full-duplex mode, advanced MAC table algorithms, priorities, buffer space reservation, rate limiting, etc. Data re-transmissions can also be used, as specified for IEC 61850 Generic Object Oriented Substation Event (GOOSE) messages.

As a physical interface, Ethernet uses copper, fiber optical cables and wireless transmissions (WiFi, WiMAX). The most common copper cable is unshielded twisted pair (UTP) CAT 5/6 with RJ45 connector. Both straight and crossover (that connect transmit conductors to receive terminals) cables can be used. Note that Ethernet switches perform automatic crossover function. Electrical Ethernet also is capable of automatically negotiating speed (10, 100 or 1000 Mb/s) and duplex mode. Ethernet fiber optic interfaces vary from MMF with ST connector for older 10Base-FL at 10 Mb/s to MMF and SMF with ST, SC and LC connectors for 100 Mb/s. Small Form Factor Pluggable (SFP) transceivers are also common. Auto-negotiation for speed and duplex is not supported over optical Ethernet cables.

Multiprotocol Label Switching (MPLS)

Multi-protocol Label Switching (MPLS) operates above data link layer (Layer 2) and below transport layer (Layer 3), and is often referred to as a Layer 2.5 of the OSI model [19]. It was initially introduced to provide a faster (than IP routing) switching, based on short (20-bit) labels. Thus MPLS switching can be performed by hardware via a fast local lookup and does not require CPU intervention.

MPLS devices include label switch routers (LSR) that perform switching only based on 20-bit MPLS labels and label edge routers (LER) that add / remove MPLS tags to / from the data packets. Labels and processing rules are distributed between LSRs using label distribution protocol (LDP). Label switching paths (LSP) are established by network operators to create an IP-based network or to route specific traffic over a specific path to meet requirements of a particular application, e.g. line current differential protection

MPLS header consists of 32 bits (4 bytes). As shown on Figure 8, it contains 3 experimental bits used for Quality of Service (QoS) / priority information. Time–to-live (TTL) indicates the number of retransmissions or network hops.

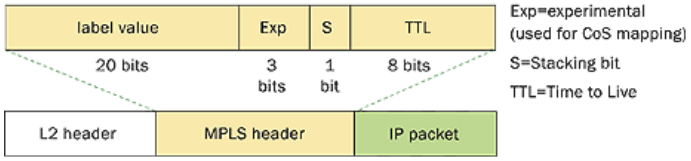

Figure 8. MPLS label format.

The strength of MPLS is fast data switching and extensive QoS support. It supports circuit emulation (C-pipe) connections that are similar to dedicated connections within an MPLS network. It also offers a fast reroute with times comparable to SONET/SDH (50ms). A utility case study with MPLS communication channel for line current differential protection is discussed in section IV.

IV. Utility case studies

This section contains utility case studies for line current differential application using different communication channels, namely IEEE C37.94 over SONET and MPLS.

a. Case study 1: Line Current Differential protection via IEEE C37.94 over SONET

EPCOR Distribution and Transmission's (EDTI) SONET provides reliable and deterministic communication between 27 substations that is used for SCADA, telephone and teleprotection (TPR) communication. Every substation that operates at >15kV has a SONET node that is, in almost every case, connected via two separate SMF cables. This adds to the reliability of the system by minimizing common-mode failure due to cable failure. All operational communication utilizes the SONET and there are no other types of communication schemes mixed-in. The SONET nodes are connected in two rings with two ties between the rings, see Figure 9. The connections as shown are logical connections and do not necessarily follow HV electrical connection. Depending on the physical route of the SMF cables, the connection between two adjacent SONET nodes may pass through several other nodes, i.e. SUB 6A and SUB 7A are adjacent nodes, but the physical optical connection is routed through SUB 5A.

Each node has a left (L) and right (R) connection from a L and R Optical-Level card, shown in Figure 11 (MUX level) that is fully independent of the other. Either the L or R units may lose signal or fail and its companion unit is capable of fully supporting the entire operation of that node. Communication always passes from L → R or R→ L. In the case where a failure of the Optical level card or cable failure, ring communication will change to linear communication, however even with N-1 and some N-2 or even N-3 conditions, communication will not be interrupted. Path switching takes no more that 50ms, a delay that has never been recorded to cause mis-operation. It is important to note that the duality, like on the Optical

Level cards, does not extend to the application cards that are the interface between the relays and the MUX of the SONET. If one of these cards fails, then the communication for that application is stopped.

There are no spur nodes in EDTI's system, all nodes are ring nodes that have two unique L and R connections. A spur node is a node that is connected to only one other node. All nodes in the SONET obtain their synchronizing signal from a dedicated GPS clock located at one of the sites (SUB 3B). This synchronization is used only for SONET purposes as each substation has its own IRIG-B clock generator that provides synchronization between same-site devices such as relays and Disturbance Fault Recorders (DFRs). If a group of SONET nodes becomes isolated, they self-time from the last and best quality time signal either one of them received before isolation. This is not ideal as the time signal will degrade, but it allows for communication to continue between these nodes until the original configuration is re-established.

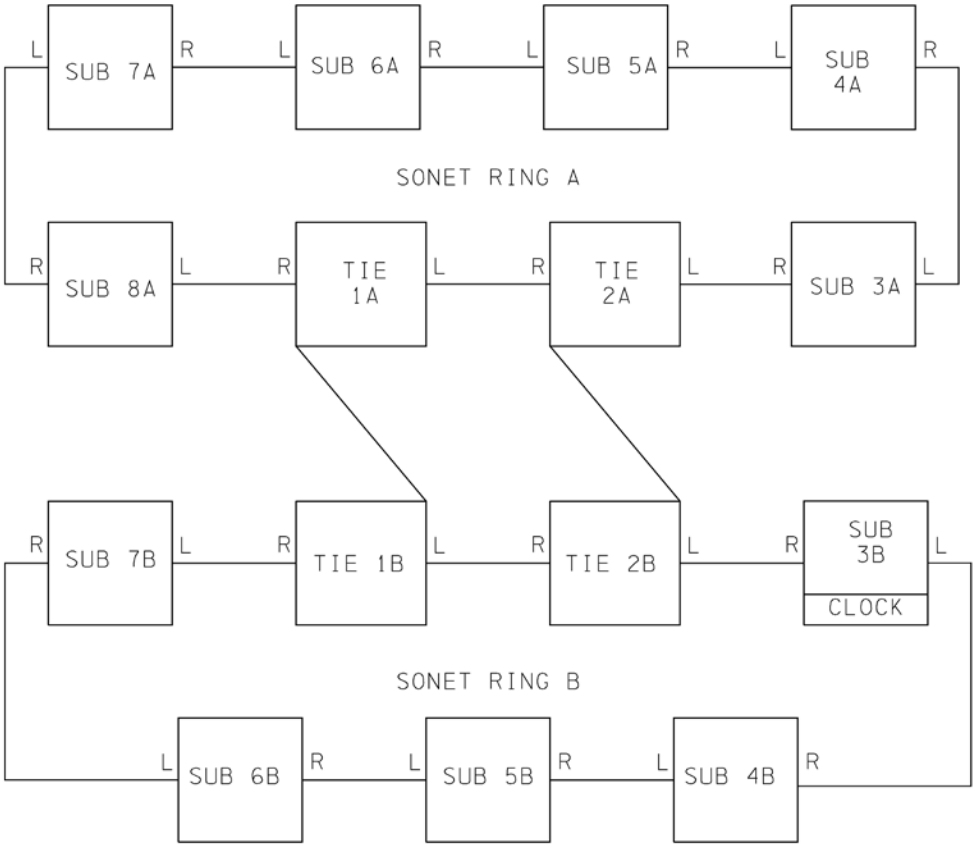

Figure 9. EDTI's SONET system.

The high availability, reliability and deterministic nature of SONET make it an excellent candidate for teleprotection communication, specifically peer-to-peer communication schemes.

EDTI's peer-to-peer communication is limited to three scheme types: G.703, RS232 and IEEE C37.94. The relay units at either end are without exception not only from the same manufacturer, but also the same model and the same firmware version. TPR schemes are inherently symmetrical and whatever is discussed at one node will be mirrored in the far-end node. Table 1 is a summary of the specific points to consider when setting-up various peer-to-peer communication schemes over SONET.

Table 1 – Application Summary

Communication protocol	Connection medium (connector type)	Settable parameters	Data speed
RS232 serial	Copper (wired to TB or DB9)	• Baud rate	4x9.6 kb/s = 38.4kb/s (asynchronous)
G.703	Copper (wired to TB)	• Circuit addressing * (RX & TX)	64kb/s (synchronous or pleseochronous)
IEEE C37.94	Copper (wired to TB), MMF or SMF (ST)	• Circuit addressing *(RX & TX)	64 - 768 kb/s

*this is internal to the SONET and ensures that the proper information gets to the right application card

TPR schemes typically have a "standard" VT1.5 (1.536 Mb/s) dedicated to communication for one HV line. A and B protection is on different DS0 channels within that VT1.5. A "standard" VT1.5 will only add/drop information at two sites and will pass through any nodes in between without adding delay. This is analogous to an express train travelling non-stop from Vancouver to New York and not stopping in any city along the way. The second type of VT is a "shared" VT that will stop at every node along the way, whether it has traffic for that node or not, like a train that stops at every station along the rails. This obviously adds much delay. To further decrease latency on "standard" VTs, the path with least number of hops, or shortest physical connection between sites may be specified by choosing the preferred side (L/R) for each node. To illustrate (refer to Figure 10): if SUB 7A and SUB 4A are connected with a 240kV line, the teleprotection will use a standard VT1.5 that will only access SUB 7A and SUB 4A nodes. The shortest path is to leave SUB 7A on the Right and enter SUB 4A on the Left. If this path is interrupted because SUB 6A node fails, then the traffic will automatically be re-routed to SUB 7A Left to SUB 4A Right, but will automatically revert to the preferred path once it is re-established.

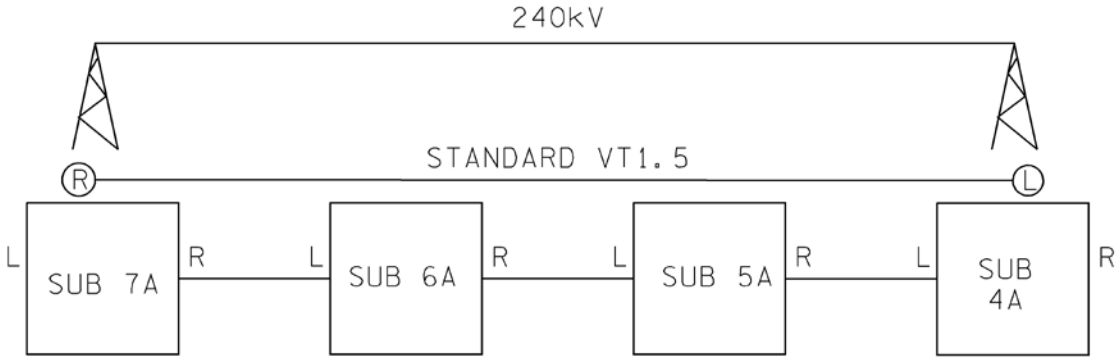

Figure 10. Standard VT.

Figure 11 shows a typical configuration for a SONET node with TPR schemes for two transmission lines, with A and B line protection schemes. The relays are multifunctional relays with both distance and differential capabilities. Note that each 240kV line has a separate standard VT and that each shelf is fed from dual power supplies.

Relay to multiplexer communication with IEEE C37.94 protocol, typically uses MMF connections since the relay and SONET node are usually located in the same building or the same substation yard. An SMF connection to the SONET application card would be used if distance between the two devices is greater than 2 km, otherwise there may be problems with overdriving the transceiver on the SONET application card. The connector on the application card may look the same for both MMF and SMF connections,

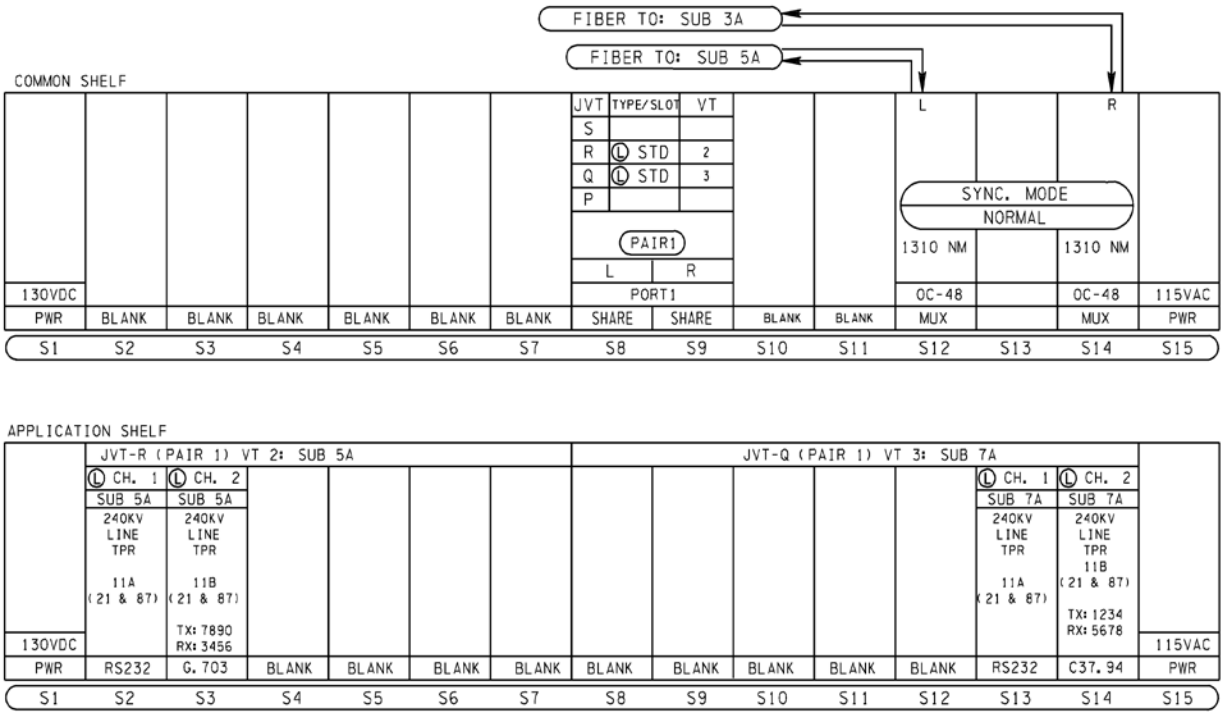

Figure 11. Typical SONET node.

However, the transceiver is not be interchangeable and has to be matched at both ends of the fiber cable. In the case of an SMF application, both the relay communication card and SONET application card would have to be equipped to handle SMF.

EDTI has not experienced many problems with the TPR schemes for line differential over SONET. If both ends are matched properly with the settings in Table 1, then the communication is almost seamless. Maintenance on SONET nodes has been performed several times, with one side (L/R) of the node in question put to 'sleep' forcing traffic to change directions, freeing the sleeping side for work. This practice has not caused mis-operation on the relays. As a precaution when relays are blocked for isolation, the connection to the SONET application card is sometimes removed to ensure no signals are passed. This is done on a case-specific basis and depends on line criticality and overall system prevailing conditions. Using SONET for line differential communication is still a relatively new application and as is expected, there exists some mistrust of its reliability when it comes to abnormal (i.e. relay blocked) operation. Future operations and understanding will hopefully change the prevailing feeling to one of trust.

Communication over dedicated SMF

An alternative to using SONET as a communication transport medium is a direct SMF connection between the line differential relays. EDTI's experience pertains only to such a connection using IEEE C37.94 and between two substations connected with minimal cable routing, see Figure 12. This type of connection does not provide redundancy in the case of a cable failure, but it does eliminate other possibilities of failure, for instance on the SONET equipment. Thus far, there have been no problems with the connection.

Line differential communication over SONET and dedicated fiber is quickly proving to be a reliable and versatile solution, at least in EDTI's experience.

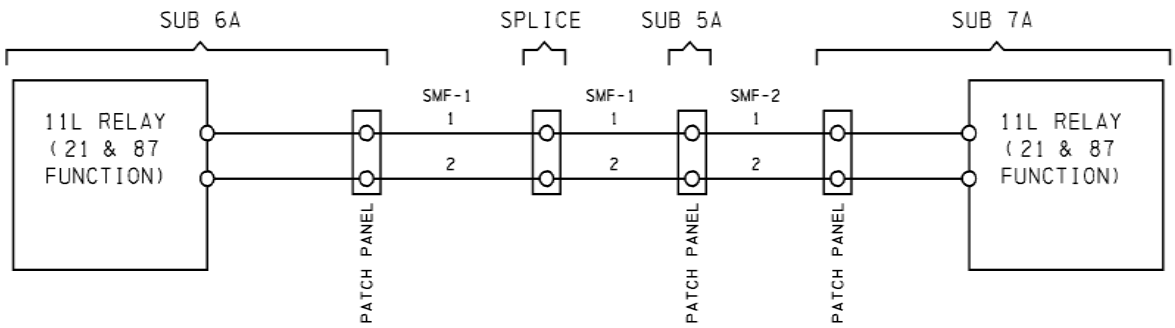

Figure 12. Direct SMF connection.

b. Case study 2: Line Current Differential Protection via RS232 and G.703 over MPLS

AltaLink's electricity transmission system covers more than half the geographic area of the province of Alberta and is comprised of over 12,000 km of transmission lines and more than 280 substations, refer to Figure 13. Most facilities are directly serviced by our microwave/VHF radio network supplemented by over 50 standalone telecom core radio sites, a small number without radio paths have satellite terminals and also an emerging fiber optic system in the form of optical ground wire (OPGW) is coming into service on new line builds or limited rebuilds.

For clarity, though MPLS has an immediate connotation of utilizing Ethernet technology and often the assumption is GOOSE messaging, IEC 61850, etc, the application outlined here is traditional Teleprotection schemes (TPR) utilizing discrete relay to relay communications, in that a unique data circuit connects each relay in the protection scheme via dedicated data interfaces such as RS232 or G.703 to the local substation MPLS switch. This functionality is not being done through general function protocols or in any 'addressable' fashion as is emerging in the digital substation realm.

MPLS in the AltaLink network is a transport technology that is replacing all of our legacy Asynchronous Transfer Mode (ATM) and Time-Division Multiplexing hardware; as it has been discontinued and is becoming unsupportable. The MPLS technology being integrated on our system has been in use for several years by telecommunication carriers, primarily for packet data traffic such as premise-premise data pipes, Internet Service Providers (ISP's) and to provide bulk traffic movement for their own service offerings such as wireless and digital television. As is typical in that industry the hardware originally was oriented to higher capacity backhaul such as 1/10/100 Gb/s optical interface over dedicated fiber or DWDM systems for long haul networks; however the network equipment has evolved to also utilize legacy transport that is typical in the electrical utility realm such as OC-3 microwave radio or fractional T1 VHF radio but the system capacity via these is more limited. Newer microwave radios are coming out with Ethernet interfaces and have new features such as dynamic throughput in the form of adaptive modulation rates to increase throughput in good conditions.

The AltaLink network had several hundred legacy TDM nodes at substations connected primarily by microwave radio in the 7 and 11 GHz bands, with the majority of substations served by one radio path. Some substation radio towers serve next hop radio paths as well but relatively few have diverse telecommunication links. The deployment of fiber optic connectivity is growing as OPGW is included on some new transmission line builds but the network of radio backhauls will continue to be the mainstay links. Few radio paths follow the lines between substations due to terrain and distance; most instead home into core radio sites or traverse via intermediate substations going back to the core telecommunications backbone.

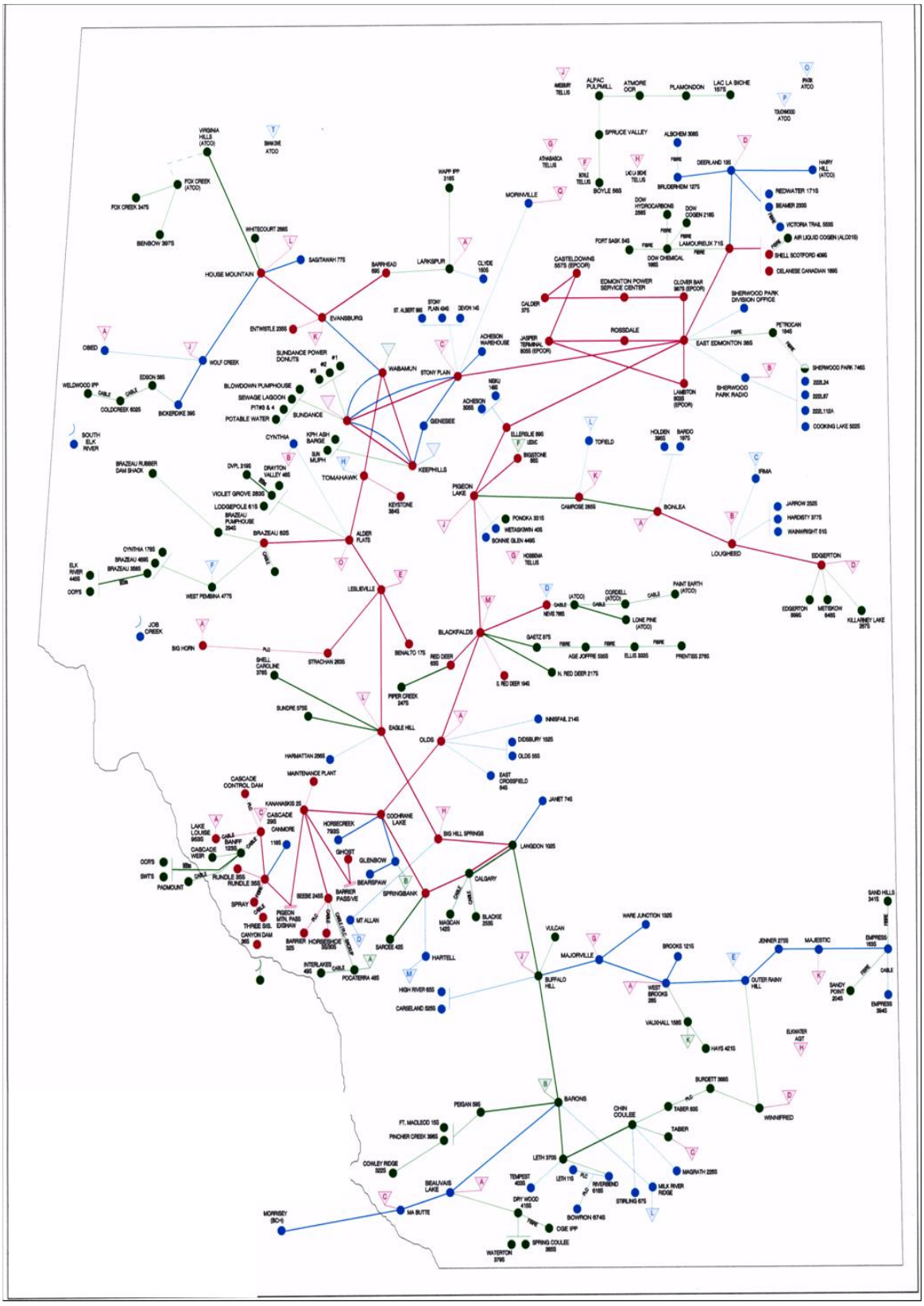

Figure 13. AltaLink network topology.

The transition to MPLS replacing the TDM/ATM network system means gradually migrating all of the several hundred teleprotection circuits connecting a wide variety of relays and RAS controllers. The existing direct relay TPR interfaces were primarily G.703, RS232 and RS422, with a few 'very legacy' analog tone systems relying on external interface equipment.

The circuit cutovers did not change the relay communications interface but rather the new MPLS nodes were equipped with the same type of interface ports as the TDM node being replaced, as shown in Figure 14, each relay still has a dedicated data connection directly to the substation MPLS node to tie to its associated remote relay at the line end.

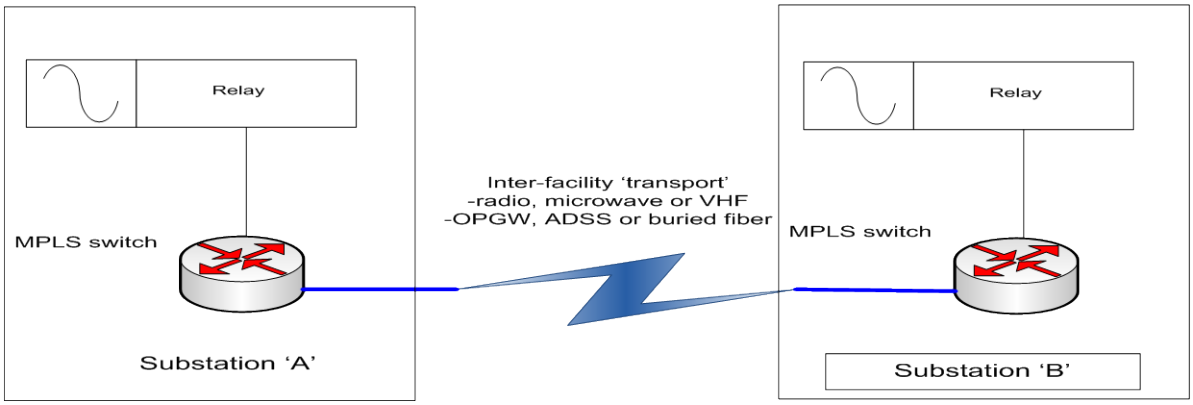

Figure 14. Principle of MPLS-based connection.

Conceptually the serial data stream arriving from the relay at the MPLS switch interface port are assembled into transport packets and assigned unique service labels, network nodes then don't have to examine actual data contents of packets traversing them as is the case in conventional Ethernet.

To accommodate the unique teleprotection application constraints for point to point connections between relays, specific provisioning is created on the MPLS system called a 'C-pipe' (Circuit Emulation), which creates a dedicated pathway based on substation end nodes and the circuit constraints of delay and throughput, plus any alternate routing of the circuit if possible and/or required.

Traffic management decisions in the switches are made based on that C-Pipe, in this way critical traffic associated with teleprotection, SCADA or Remedial Action Schemes (RAS) can be uniquely identified and handled. As the vast majority of our transport paths are point to point and singular up from substations to the core there are generally no 'decisions' in subsequent switches to be made as most often no alternate path is possible. In the cases where that is possible and deemed necessary then a 2nd 'strict' path is defined as an alternate route.

Also this provisioning keeps the teleprotection data circuits essentially isolated from other data traffic the MPLS node is handling from a given site such as the substation LAN (Ethernet), security monitoring and other corporate traffic such as VoIP telephone service and remote network access for staff on site. This type of traffic is provisioned as 'E-pipe', typically with unrestricted paths, as it does not have same dependencies of delay and availability. What is of significant benefit for MPLS technology over legacy is that any bandwidth capacity not being used at any given time can dynamically be servicing others, for example the remote retrieval of a relay Sequence of Events file is much faster than going through the legacy TDM network. Whereas in the TDM case every site telephone, LAN switch, etc had to be provisioned with stranded capacity at all times. MPLS offers the more efficient use of the 'bandwidth pool' and can handle mesh style networks if there are many possible paths.

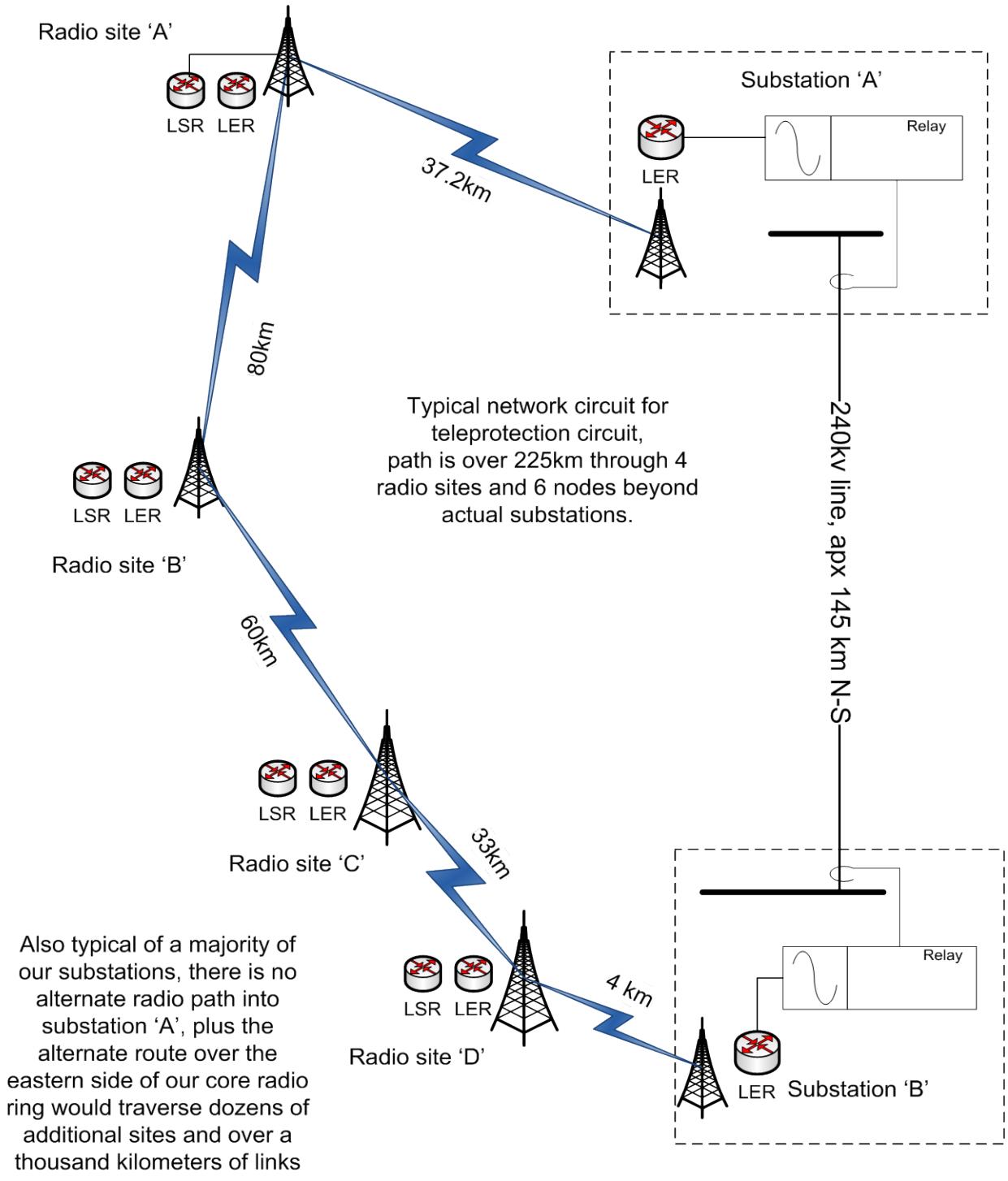

Figure 15. 240kV line from a mid-province substation to inside Calgary.

An example of 240kV line from a mid-province substation to inside Calgary is shown on Figure 15. Though the line itself is 145 km substation to substation, the teleprotection circuit path is over 225 km and traverses 4 additional radio sites, five microwave radios and six additional MPLS switches due to terrain and network design constraints, as backbone radio sites are sited to serve multiple substations and don’t follow lines.

Relay operation end to end previously was 18.8 msec on average; post cutover is 16.67 msec so has improved. Since the original transport was TDM at each site which was transported onto ATM through the backbone radio system, the uniform MPLS technology can improve on some circuit delays.

It should also be noted that for a new HVDC build now underway, the fiber optic path will be quite long and will require 3 intermediate repeater sites along the approx. 350 km path. This deployment will use DWDM technology for great capability but as well will only require optical amplification and dispersion compensation in-between, not Optical-Electric-Optical conversion, which also decreases circuit delay.

Future possible enhancements to the teleprotection supported schemes at AltaLink will include a possible transition to IEEE C37.94 optical interfaces on the relays. The MPLS equipment supports this but our legacy TDM did not. This will decrease the copper interfaces within substations and associated issues surrounding such.

V. Conclusions

This paper examined specifics of communication channels used for line current differential protection. It explained the differences between dedicated, multiplexed and switched channel, and presented line current differential use cases with use of IEEE C37.94 over SONET and RS232 / G. 703 over MPLS communication channels. Both schemes have been successfully deployed in Canadian utilities, and showed acceptable performance.

While developing a better understanding of interdependencies of protection and communications, it was noted that for protection, underlying concepts are generally straight forward, but relays' settings could be very complex; while for communications concepts could be quite elaborate but configurations relatively simple.

As line current differential schemes are not possible without communications, basic understanding of communications for protection engineers changes from "an asset" to "a must". Protection engineers should initially expect a steep learning curve, but would be rewarded by simple configurations, after grasping basic communication concepts.

Regardless of specific communication technology used for line current differential protection, the requirements of delay, data integrity, sample synchronization and system reliability remain to be of paramount concerns. With technological advancements new communication channels would inevitably be proposed for protection applications, thus open-minded position and continuous learning would constitute a more constructive attitude that value more than solid knowledge of a single communication technology.

Security and dependability requirements should always be met by the overall system, including any new communication technologies or concepts that appear, plus the provisioning and management of such technology should have rigid controls around changes and verification testing. The protection system engineering should be seen as a demanding client of any electrical utilities communication network. Protection and communication experts should be working together to achieve their top business and technological objectives, thus ensuring better understanding and coordination, which in turn lead to more reliable and available power systems.

References

[1] L. J. Blackburn and T. J. Domin, Protective Relaying: Principles and Applications, Third ed., CRC Press, 2007.

[2] W. A. Elmore, Protective Relaying: Theory and Applications, New York: Marcel Dekker, Inc., 2004.

[3] W. A. Elmore, Pilot Protective Relaying, Blue Ridge, Virginia: Marcel Dekker, Inc., 2000.

[4] IEEE PSRC Working Group H9 Report "Digital Communications for Relay Protection", http://www.pes-psrc.org/Reports/Digital communications for relaying (H9).pdf

[5] IEEE Power and Energy Society, "IEEE Guide for Power System Protective Relay Applications Over Digital Communication Channels, IEEE Std C37.236™-2013," 2013.

[6] KEMA, Inc., "Substation communications: Enabler of Automation. An Assessment of Communiaction Technologies Options and Opportunities for Substations Automation," United Telecom Council, 2006.

[7] Extract from CIGRE Publication "Protection using Telecommunications", Joint Working Group 34/35.11, August 2001.

[8] Bogdan Kasztenny, Normann Fischer, Ken Fodero, and Adrian Zvarych, Schweitzer Engineering Laboratories, Inc., "Communications and Data Synchronization for Line Current Differential Schemes," in *Western Protective Relay Conference*, Spokane, WA, 2011.

[9] Galina S. Antonova, Eduardo Colmenares, Ilija Jankovic, "Analysis of Protection Scheme Dependencies on Communications," in *Texas A&M Relay Conference*, Colleage Stations, TX, 2013.

[10] Galina S. Antonova, William Whitehead, Pedro Choconta "Integration of Substation and Distribution Communications", ABB Automation and Power World 2012, Houston, TX, USA.

[11] Bogdan Kasztenny, Gabriel Benmouyal, Hector J. Altuve, and Normann Fischer, "Tutorial on Operating Characteristics of Microprocessor-Based Multiterminal Line Current Differential Relays," in *Texas A&M Relay Conference*, College Stations, TX, 2013.

[12] Miriam P. Sanders "A Reliable Power-Line Carrier-based Relay System", Western Protective Relay Conference, October 2012, Spokane, WA, USA.

[13] IEEE PSRC Working Group I-01 Report "Understanding Microprocessor-Based Technology Applied to Relaying", 2009.

[14] Teleprotection Equipment NSD70D Operating Instructions 1KHW000371-EN, ABB Power Automation Ltd. Edition, July 2000.

[15] Application Examples. Communication set up for RED670 Differential Protection and 670 Binary Transfer in Telecommunication Networks, 1MRK 505 197-UEN Rev. D

[16] IEEE C37.94-2002 IEEE Standard for N times 64 Kilobit per Second Optical Fiber Interfaces between Teleprotection and Multiplexer Equipment.

[17] ANSI Standard T1.05-1996 (R2005) "Synchronous Optical Network (SONET) – Sub STS-1 Interface rates and Formats specification".

[18] IEEE 802.1Q-2011 IEEE Standard for Local and Metropolitan Area Networks – Media Access Control (MAC) Bridges and Virtual Bridged Local Area Networks.

[19] IETF RFC 5586 "MPLS Generic associated channel", June 2009.

[20] ITU-T G.694.2 "WDM applications: CWDM wavelength grid", December 2003.