Combining TDM and Ethernet to Improve Network Performance for Mission-Critical Applications

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Published in
Wide-Area Protection and Control Systems: A Collection of Technical Papers Representing Modern Solutions, 2017

Previously presented at the
2nd Annual PAC World Americas Conference, September 2015

Originally presented at the
Power and Energy Automation Conference, March 2015

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***Abstract*—This paper shows how time-division multiplexing (TDM) and Ethernet communications can be integrated to operate together in a way that leverages the benefits of each technology. TDM communication still provides the best performance for real-time protection and control applications due to its fixed latency and deterministic characteristics. Ethernet communication is best suited for transporting traffic associated with applications such as supervisory control and data acquisition (SCADA), event reports, voice, video, and other information technology services due to its bandwidth efficiency and flexibility.**

The paper looks at the trend toward using Ethernet for all substation services and applications and evaluates the requirements of communications-assisted relay protection schemes. The paper shows how Ethernet and TDM can be combined in an integrated approach to provide a solution that improves upon the performance of native Ethernet and enables Ethernet to be optimized for mission-critical applications. Several application examples are discussed, with the first showing how services can be physically segregated to allow different engineering teams to work independently and ensure that changes made to noncritical circuits do not impact mission-critical services. The second application example focuses on how IEC 61850 traffic can be segregated on the network and how point-to-point Ethernet pipes can be built to carry Generic Object-Oriented Substation Event (GOOSE) messages and provide a better solution than relying on virtual local-area networks. The third application example reviews the network performance requirements for line current differential (87L) data exchange, discusses the challenges of using Ethernet for 87L data, and shows how Ethernet over TDM provides a high-performance solution. Finally, the paper considers future relay protection methods that will drive the need for lower-latency communications circuits.

I. Introduction

A typical electric utility substation contains a diverse range of applications and services that rely on data communications. These services consist of the following:

- Substation control, including local and remote substation control, and supervisory control and data acquisition (SCADA).
- Substation data analysis (event reports).
- Real-time protection and automation, including IEC 61850 Generic Object-Oriented Substation Event (GOOSE) with Sampled Values (SV) coming in the future, and also teleprotection.
- Metering and power quality monitoring.
- Wide-area monitoring and control schemes, including the use of synchrophasors.
- Security, including video surveillance, proximity alarms, and access control.
- Voice communications.
- Corporate local-area network (LAN) access.

These applications can be categorized into the following three classes: real-time data for protection and automation, including wide-area schemes; non-real-time data, including substation control, data analysis, metering, power quality monitoring, security, and corporate LAN access; and voice communications [1].

There is a clear trend within the industry to move toward using Ethernet for all of these applications and services with the goal of reducing capital costs and standardizing on common interfaces to simplify network design, maximize the technological lifespan of the used solutions, and reduce the cost of future upgrades, modifications, and replacements.

This paper examines the fundamentals of the real-time protection applications combined with the need to support other services within the substation to determine the performance requirements for the communications channel. The paper shows how Ethernet over time-division multiplexing (TDM) meets the communications channel requirements for Ethernet-based substation network implementations and looks at future relay protection technology based on traveling wave (TW) principles that will demand very low-latency communications solutions.

II. Power System Protection Fundamentals

Power system fault clearing is a fundamental aspect of the design and operation of a power transmission and distribution system. Faults can cause damage that requires expensive repairs or capital equipment replacement. Faults also cause severe operational disturbances. Severe disturbances can lead to the loss of power system stability and wide-area blackouts [2]. Power system protection schemes are designed to detect and clear faults with the goal of meeting the following objectives:

- Remove the faulty element from the rest of the system.
- Limit or prevent equipment damage.
- Prevent severe power swings or system instability.
- Minimize adverse effects on customer loads.
- Maintain power system transfer capability.

Communications-assisted relay protection schemes are used to share data between protection devices and implement methods that improve the selectivity, security, speed, and dependability of the protection schemes. If the communication fails, backup protection schemes ensure that power system faults are cleared, but they typically result in longer clearing times.

Today, digital channels are used for many protection schemes, such as line current differential (87L). There are 87L implementations that use direct point-to-point fiber links; however, it has become more common to use multiplexed channels within TDM systems, such as synchronous optical network (SONET) or synchronous digital hierarchy (SDH). Applications with direct fiber links are simple, fast, and reliable, but they underutilize bandwidth. The move toward multiplexed channels was driven by the need to make better use of fiber assets and provide alternate fiber paths for network healing in the event of fiber breaks. Wide-area networks (WANs) are used to carry the relay protection multiplexed channels in addition to other substation services and have become an integral and necessary part of modern power network protection systems. The next section discusses the different WAN technologies used by utility networks.

III. Communications Transport Technologies

A. Time-Division Multiplexing

TDM is a data communications method that interleaves multiple data streams over the same physical medium, giving each data stream a predefined, fixed-length time slot for using the physical medium. All data streams (subchannels) are allocated unique time slots on the physical medium.

Guaranteed bandwidth and data delivery times are key advantages of TDM over packet-based methods that have to consider if the physical medium is idle or busy at the moment of intended transmission (such as with Ethernet). The bandwidth in TDM networks is reserved for a configured subchannel regardless of whether the channel is actually sending new information or not, which leads to a less efficient use of the physical medium compared with packet-based methods. TDM systems are therefore naturally suited to support applications that stream data steadily rather than send data in irregular bursts.

The most common and lowest-order subchannel in TDM networks is referred to as a Digital Signal 0 (DS0) and represents a bit stream of 64 kbps. Historically, the DS0 channel stems from carrying digitized voice over a multiplexed medium. In traditional telephony, the audio signal is digitized at an 8 kHz sampling rate using 8-bit pulse-code modulation. The product of 8 bits per sample and 8,000 samples per second results in a data rate of 64 kbps. The 64 kbps data rate is the maximum bandwidth of a DS0 channel, but it can be divided into low-rate subchannels in some implementations, resulting in several lower-speed applications being sent over one 64 kbps time slot. For example, up to four 9.6 kbps EIA-232 circuits can be inserted into a single 64 kbps time slot by using a subrate multiplexing technique.

DS0 channels are typically assembled in groups, constituting a higher-order multiplexing known as a *T* carrier in SONET and T1 systems. The T1 frame carries 24 DS0 channels with an extra 8 kbps of framing information for synchronization and demultiplexing at the receiver, resulting in a transmission rate of 1.544 Mbps. In SDH and E1 systems, DS0 channels are aggregated into an *E* carrier. The E1 frame carries 32 DS0 channels.

The role of a multiplexer is to interleave or merge (multiplex) the lower-rate channels or circuits, such as DS0 channels, into a higher-order or transport level, such as T1 or E1. At the destination, the multiplexer disassembles or splits (demultiplexes) the higher-rate channel into subchannels or circuits. The multiplexer also provides the ability to cross-connect DS0 circuits between channels to allow circuits to transit data flexibly from source to destination ports using any available channel. This makes more efficient use of available bandwidth by using all available DS0s in the T1 frame instead of allocating a whole T1 frame for a single DS0.

SONET and SDH networks follow the general concept of multiplexing into higher data rates [3]. Table I shows the SONET digital hierarchy, and a similar structure exists for SDH. SONET networks carry synchronous transport signal (STS) frames. The basic STS frame is known as STS-1 and is equivalent to 28 T1 channels. When using fiber media, STS-1 is referred to as the optical carrier, or OC-1. OC-3 represents three times the OC-1; OC-12 represents twelve times the OC-1; and so on. The most popular OC rates progress in multiples of four: OC-3, OC-12, OC-48, and so on. In the SONET digital hierarchy, VT1.5 is a virtual tributary (VT) supporting 24 DS0 channels, which is equivalent to 1.5 Mbps.

Table I
SONET Digital Hierarchy

Level	Line Rate (Mbps)	Number of 64 kbps Channels	Number of DS1 Units
VT1.5	1.728	24	1
STS-1	51.84	672	28
OC-1	51.84	672	28
OC-3	155.52	2,016	84
OC-12	622.08	8,064	336
OC-48	2,488.32	32,256	1,344
OC-192	9,953.28	129,024	5,376

B. Packet-Based Technologies

Ethernet is one of the most widely implemented packet-based technologies. Unlike TDM, Ethernet does not use the concept of pre-allocated time slots to send data. Instead, all applications share the same physical medium. Contention resolution methods deal with the challenge of having multiple packets arrive at the same time while trying to access the shared physical medium. In this situation, data packets build up rapidly in the buffer. If the system is heavily loaded with many applications trying to send large amounts of data, it is impossible to buffer all the data, and therefore frames or packets are dropped. Higher-level protocols may deal with the detection of lost frames and may provide data retransmission.

Table II shows a comparison of two TDM-based systems (SONET and SDH) and Ethernet. When comparing TDM systems with Ethernet systems, TDM has traditionally been recognized as having the following advantages over Ethernet:

- Fixed latency.
- Determinism, in terms of latency and bandwidth use.
- The ability to dedicate bandwidth per application.
- In-band operation, administration, and maintenance (OAM).

TABLE II
COMPARISON OF TDM AND PACKET-BASED TECHNOLOGY

Attribute	TDM (SONET and SDH)	Packet (Ethernet)
Latency	Fixed	Variable
Determinism	Yes	No
Bandwidth	Dedicated	Shared
Multicast/broadcast	No	Yes
In-band OAM	Yes	No

Network management and OAM capability are incorporated into TDM-based systems through the allocation of in-band overhead data fields. This gives the technology the ability to reliably support management functions associated with running, maintaining, administering, and repairing the network without negatively impacting the performance of data services using the network. In particular, in-band OAM gives TDM-based systems the ability to rapidly recover from communications path failures, regardless of network size.

Ethernet does not inherently support in-band OAM; it requires additional protocol development to support these functions. These protocols access the shared physical medium in the same way as any other data service and are subject to the same variances in latency and lack of determinism. In contrast, Ethernet offers the following advantages over TDM-based systems:

- More efficient use of bandwidth for bursty traffic.
- Ubiquity of Ethernet as an interface.
- Ability to support multicast and broadcast traffic.

Ethernet has become a convergence protocol for many power system applications over the past 10 years, supporting an ever-increasing range of diverse services and applications. The connectionless approach of Ethernet means that packets are individually transported across the network without the concept of establishing an end-to-end connection between applications. This enables Ethernet to use bandwidth more efficiently. However, neither TDM-based systems nor Ethernet has remained the same since being introduced. TDM-based systems have evolved to provide support for running Ethernet services over TDM. Similarly, Ethernet has evolved to support virtual LANs (VLANs), class of service, and circuit emulation services to reduce latency and support circuit-based services.

There is a growing debate over the relative merits of packet-based systems versus TDM-based systems as more services and applications migrate toward Ethernet. The debate is particularly strong in the power utility industry due to the predominance of TDM systems, diversity of applications, age of equipment, and mission-critical aspects of the data services being run over the network. The introduction of Carrier Ethernet and multiprotocol label switching (MPLS) has added a new dimension to the packet-versus-TDM debate.

The goal of Carrier Ethernet was to address the shortcomings of standard Ethernet by providing the following features [4]:

- Standardized services. This supports and preserves existing LAN equipment to accommodate existing networking connectivity, including TDM services.
- Scalability. This supports business, information, communications, and entertainment applications with voice, video, and data while providing the ability to scale bandwidth from 1 Mbps to 40 Gbps and beyond in granular increments.
- Reliability. This supports the ability of the network to detect incidents and recover from them within 50 milliseconds without impacting users.
- Quality of service (QoS). This provides wide choice and granularity of bandwidth and quality of the service options, while also ensuring provisioning via service-level agreements that provide end-to-end performance based on committed information rate, frame loss, latency and jitter.
- Service management. This offers the ability to monitor, diagnose and centrally manage the network.

MPLS was developed to address the challenge of routing data through high-bandwidth core telecommunications networks. MPLS adds a small header to the standard Ethernet frame to allow for fast, easy, and efficient processing and routing of the packet [5]. MPLS was designed to carry different transport technologies, including TDM, Ethernet, frame relay, asynchronous transfer mode (ATM), and digital subscriber line (DSL).

Both Carrier Ethernet and MPLS offer improved performance over standard Ethernet by providing OAM mechanisms to enable faster network recovery after system element failures, bringing it closer to the recovery times of carrier grade TDM-based systems.

IV. EXAMPLES OF REAL-TIME MISSION-CRITICAL PROTECTION APPLICATIONS

This section focuses on the real-time mission-critical protection applications that are laggards in terms of making the move to using Ethernet, and it examines the performance attributes that Ethernet must meet in order to support the most challenging relay protection applications. The following subsections address the challenge of segregating real-time protection traffic from noncritical data, examine how to best support IEC 61850 over WANs, and discuss the requirements for supporting 87L relay schemes in an Ethernet-based network.

A. Application Example 1: Segregation of Critical and Noncritical Application Traffic

The typical substation supports a wide range of services and applications, and as discussed previously, these services include critical protection applications and other noncritical services. Fig. 1 shows a range of typical substation services that each require access to a WAN.

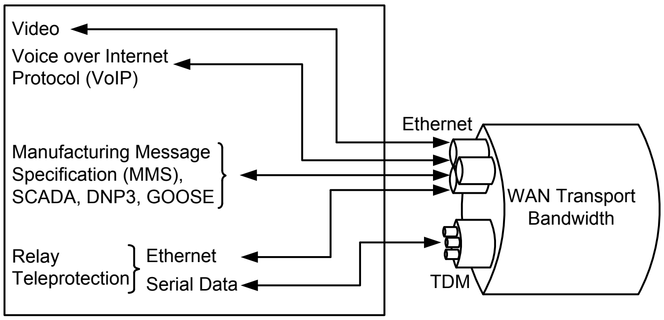

Fig. 1. Segregation of Data Services

Because all the data services shown in Fig. 1 share the same physical medium, there is a fundamental requirement to segregate each service to provide security and ensure that priority is given to the most critical services, such as relay teleprotection and GOOSE.

The WAN is a shared medium for transporting data between locations. Data segregation controls how bandwidth is allocated to different services, and it limits which network devices or ports have access to specific data. Data segregation is also important for network security. If the same physical WAN is shared between different organizations, it is essential that data traffic from one company cannot be accessed by another company on the same network. Similarly, in networks carrying data for critical systems, there are advantages to segregating protection traffic from noncritical traffic. This allows utilities to assign engineers and technicians responsible for noncritical systems to work independently from critical service teams and ensure that changes made to noncritical communications circuits do not impact critical data services. Data can be physically segregated using different fibers or electrical wires for different services or logically segregated using protocols within the shared fiber [6].

TDM provides security by segregating data into separate time slots and transporting the data to dedicated ports. The end service or application only sees data that are allocated to the timeslot.

In Ethernet, all data are transmitted over shared bandwidth. Ethernet supports the segregation of traffic through the use of VLANs. A VLAN is used to partition a single Open Systems Interconnection (OSI) Layer 2 network into separate virtual networks with distinct broadcast domains. Applications cannot communicate across VLANs, and data are kept within the boundary of each VLAN.

In the example services shown in Fig. 1, another advantage of traffic segregation is to prevent a high-bandwidth lower-priority service, such as video, from delaying higher-priority teleprotection or GOOSE services from sending data.

In an Ethernet-based network, even after using VLANs to segregate each data service and establishing priorities and QoS rules for each traffic type, it is still possible for the video service to negatively affect the latency and availability of the data channel for all other services due to head-of-line blocking. If the video service is using large frames, and one of the large video frames is currently egressing to the transport medium at the same time that high-priority critical traffic arrives, this high-priority critical traffic will be delayed until the currently egressing frame is finished. Jumbo frames (e.g., 9 KB in length) make this problem worse. With 100 Mbps Ethernet, a critical Ethernet frame would need to pause 740 microseconds for a full 9 KB jumbo frame. Faster Ethernet speeds reduce this problem. A critical Ethernet frame would only need to pause 74 microseconds for the same 9 KB jumbo frame at 1 Gigabit Ethernet (GigE) speed.

Fig. 2 shows how multiple independent Ethernet services can be mapped into a single higher-order SONET transport frame. Each independent Ethernet service is commonly referred to as an Ethernet pipe and is given dedicated reserved bandwidth. In the video head-of-line blocking example, a single reserved Ethernet pipe would be allocated to video traffic and other Ethernet pipes would be allocated to the other services such as GOOSE and teleprotection. In the same scenario where a high-priority GOOSE message arrives while a video frame is egressing, the GOOSE message would be allocated to its dedicated Ethernet pipe and clocked out immediately on the next TDM timeslot with no delay. Similarly, all other services would remain unaffected because they are given their own dedicated bandwidth.

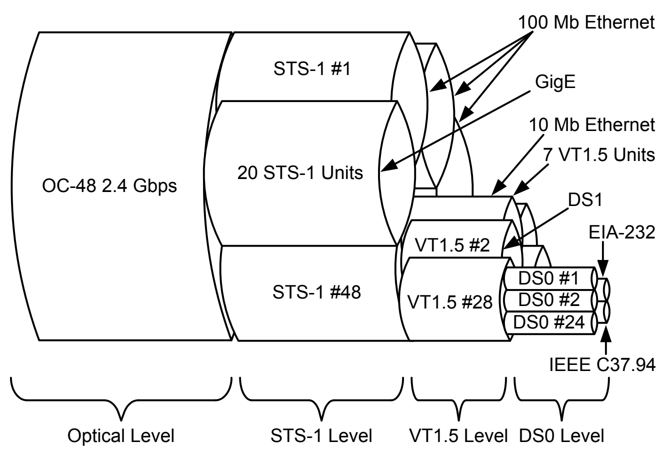

Fig. 2. Mapping Ethernet Into TDM Frames

Using Ethernet over SONET provides the following performance advantages over standard Ethernet:

- Deterministic and predictable latencies.
- Isolation of critical and noncritical services.

Ethernet pipes transported over SONET provide the equivalent of multiple discrete Ethernet networks sharing a single fiber-optic cable.

This inherent attribute of TDM is discussed further in the next section, where the ability to build dedicated Ethernet pipes provides an advantage for supporting IEC 61850.

B. Application Example 2: IEC 61850 Support

The IEC 61850 standard was developed to define standardized protocols and methods of communication for implementing substation automation and control functions, and it is based on Ethernet.

The IEC 61850 GOOSE object was developed for high-speed control messaging. GOOSE messages contain status, control, and measured values information. The performance requirement for GOOSE is an operation time of 4 milliseconds in the LAN. Many newer protective relays support GOOSE messaging. The main challenge when configuring communications networks to transport GOOSE traffic is that GOOSE messages are sent as Layer 2 broadcast messages between IEDs within a substation. The IEC 61850 standard also defines intersubstation GOOSE messages—also sent as Layer 2 broadcast messages—for communication between substations. This means if care is not taken to make appropriate use of VLANs to contain the broadcast domain for each IED, the network could become heavily loaded during a major power system disturbance and increase the latencies of GOOSE messages traveling across the network.

A significant benefit of Ethernet pipes is containment and isolation from other data traffic of Layer 2 broadcast intersubstation GOOSE messages. Pipes isolate intersubstation GOOSE messages from all other network traffic. Fig. 3 illustrates an application of two Ethernet pipes used to segregate corporate services from point-to-point GOOSE messaging used for control. For simplicity, only traffic between two substations is shown. The 10 Mbps pipe is a direct connection between Substations A and B. It should be noted that the backup path for this circuit is provided on an alternate path around the SONET ring.

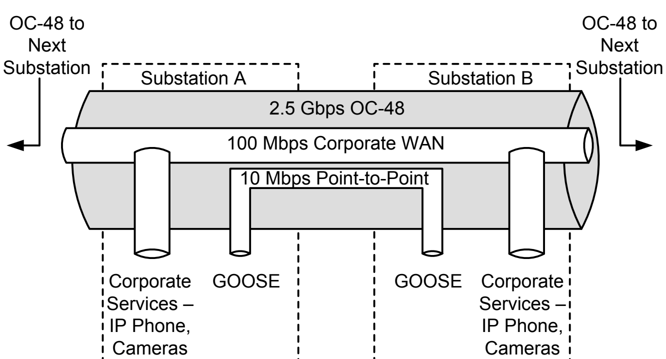

Fig. 3. Ethernet Pipes Provide Point-to-Point Service

C. Application Example 3: 87L Protection Channel Support

This section looks at the communications requirements for supporting the 87L protection channel, and it provides the details of a solution that meets the requirements. The 87L protection channel is one of the most demanding communications-assisted relay protection schemes to support from a communications perspective.

The principle of differential protection is based on Kirchhoff's current law: all branch currents flowing into a node sum to zero. If the sum of the currents entering a protected element is not zero, there must be an unmeasured current and thus an internal fault. The current differential principle has the highest potential for security (it sees the external fault current entering and leaving the zone) as well as the highest potential for dependability (it sees the total fault current). When applied to power lines, the principle performs well on multiterminal lines, very short and very long lines, and on series-compensated lines.

When used to protect transmission lines, 87L protection requires long-haul communications channels to exchange current data as well as a synchronization method to align currents measured at individual line terminals. Traditionally, the inherently distributed nature of 87L schemes and the high cost of communications channels imposed limits on the amount of data that could be exchanged between 87L relays, as well as limits on channel latency, maximum number of terminals in the scheme, and time synchronization. Historically, 87L schemes have been implemented using serial communication. The first schemes used direct point-to-point links with proprietary interfaces but later evolved into using multiplexed virtual channels within TDM-based systems [7].

The 87L protection relay consists of multiple protection functions linked by a communications channel, as shown in Fig. 4 [8].

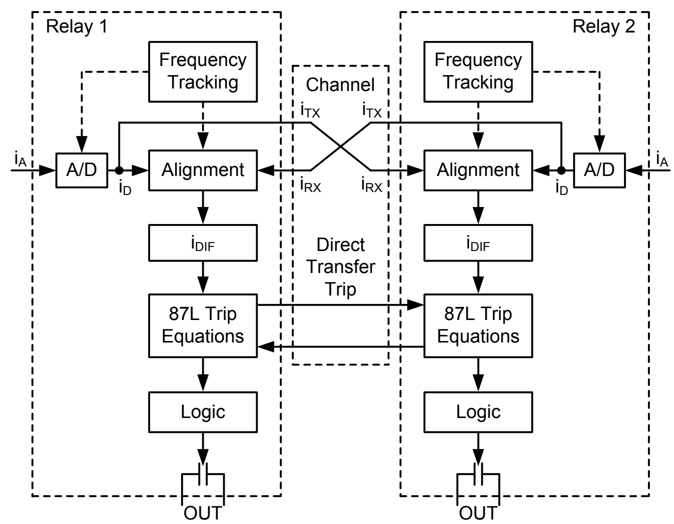

Fig. 4. Simplified Architecture of a Typical 87L System

The following are the key channel performance requirements for 87L applications:

- Availability: very high.
- Channel latency: 1 to 7 milliseconds [2].
- Bit errors: 10^{-3} to 10^{-6}.
- Channel asymmetry: less than 4 milliseconds [9].

It is important to understand that channel latency is specified as a port-to-port propagation time that includes the buffering and processing of any active communications devices included in the 87L channel. Similarly, asymmetry is specified as the difference between transmit and receive port-to-port propagation times including communications device buffering and processing.

87L protection requires time-synchronized measurements for the current differential calculation.

Wide-area communications required for supporting 87L protection channel applications are more challenging than other relay protection schemes due to the channel latency and asymmetry requirements. Wide-area transport is typically accomplished using TDM-based systems, Carrier Ethernet, or MPLS systems. Solutions typically use ring topologies that offer protected path switching, with duplicate or failover messages being sent in the counter rotating direction, allowing for fast failure recovery. Recovery times are typically in the vicinity of 50 milliseconds for Carrier Ethernet and MPLS and around 5 milliseconds for protection-grade TDM equipment. As discussed previously, modern TDM-based systems provide Ethernet transport, which can be allocated into configurable pipes with a guaranteed bandwidth. Pipes allow easy configuration of dedicated Layer 2 network segments optimized for critical applications such as 87L protection. Similar functionality can be achieved using MPLS, but this typically requires router configuration to establish dedicated Layer 2 tunnels or the use of higher-overhead User Datagram Protocol/Internet Protocol transport with Layer 3 addressing.

D. Application Example 4: Multiterminal 87L Protection Over Ethernet

For 87L applications with more than three terminals, Ethernet is an attractive means to connect the 87L relays to the network for the purpose of point-to-multipoint communications. Ethernet over TDM provides adequate performance for secure implementation of 87L schemes. Ethernet over TDM can be viewed as similar to provisioning DS0 channels over TDM to substitute for the direct fiber links between 87L relays.

Secure and dependable 87L application requires the deterministic delivery of current data between all the relays in the 87L scheme. In general, Ethernet cannot guarantee a true deterministic data transport [1]. The use of VLANs and priority tags can improve the quality of data transport in a general purpose utility Ethernet network, but this solution requires engineering and testing and may develop problems during the lifetime of the network as new devices and services are added.

The two network architectures for 87L applications over Ethernet described in the following subsections address the challenge of guaranteeing deterministic Ethernet.

1) Isolated Point-to-Point Ethernet Connectivity

An isolated Ethernet network performs well because it does not carry any other data and is not subject to any new traffic, new services, or new end devices. The system is shown in Fig. 5 and includes local Global Positioning System (GPS) time synchronization at each relay. The loss of time synchronization at any of the line terminals renders the 87L scheme out of service.

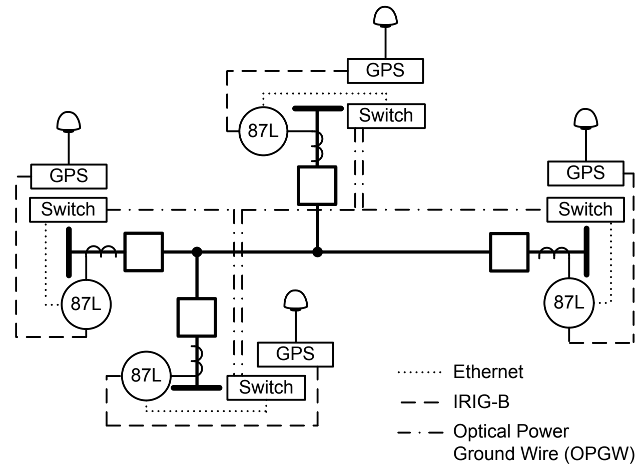

Fig. 5. Four-Terminal Application With 87L Over Ethernet Using an Isolated and Dedicated Ethernet Network

2) Ethernet Over TDM

As explained previously, Ethernet over TDM provides the equivalent of a physically isolated Ethernet network. This is a preferred architecture for using multiterminal 87L schemes over Ethernet.

Provisioning an Ethernet pipe of 1.5 Mbps or greater allows channel latency of below 2 milliseconds [7], which is adequate for the vast majority of applications. Fig. 6 illustrates the usage of Ethernet over TDM for the same four-terminal application in Fig. 5. With this scheme, it is possible to use the WAN to distribute a time reference to each relay device and address the issue related to the loss of GPS at any line terminal. Whereas the loss of GPS would normally render the 87L scheme out of service, in this case, the 87L would remain in service based on the network time provided by the TDM network. The network maintains highly accurate relative time even if the network drifts away from GPS time, and it is relative time accuracy that is required for 87L operation. This time distribution approach would require the network to communicate a relative time accuracy quality indicator to each relay device to maintain 87L operation in the event of degraded absolute time accuracy.

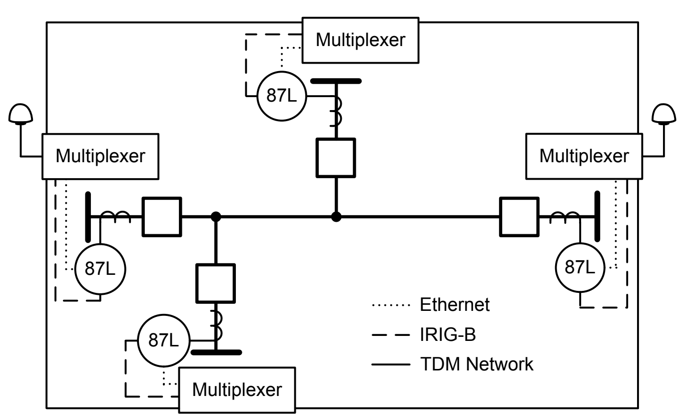

Fig. 6. Four-Terminal Application With 87L Over Ethernet Using a TDM Multiplexer-Based Network

V. Future Relay Technology Advancements

The faster relay protection schemes can operate, the greater the power system operational benefits, yielding the following advantages:

- Higher power transfer.
- Reduced equipment wear on generators and transformers.
- Improved safety.
- Reduced property damage.
- Improved power quality.

Present-day relays operate in 0.5 to 1.5 cycles (8 to 25 milliseconds), and present-day breakers operate in 2 cycles (33 milliseconds). There are newer relay technologies in development with the goal of providing ultra-high-speed fault clearing. These newer technologies are based on TW principles and promise operation times of less than 0.5 cycles (8 milliseconds). There are also new dc breaker technologies in development that are expected to achieve subcycle operation times of 16 milliseconds.

These advancements in relay and breaker technology have implications for the latency requirements of future communications circuits.

TW-based relay technologies rely on sensing the TW that propagates along the power line as a direct consequence of the fault. The wave propagates in both directions from the fault with a velocity close to the speed of light and is the first information that a protection device is able to receive about the fault event.

Fig. 7 illustrates the minimum operation time of a TW-based permissive overreaching transfer trip (POTT) protection scheme and shows that latency in the communications path will become an increasingly significant factor in determining the overall operation time of the relay.

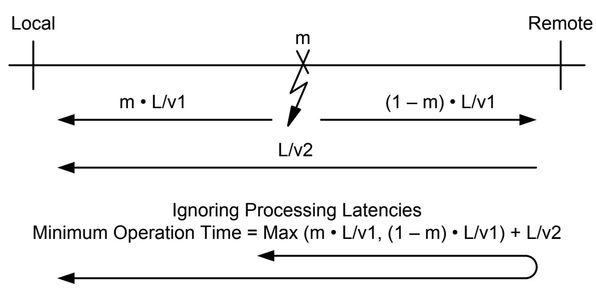

Fig. 7. Minimum Operation Time of TW-Based POTT Scheme

The TW-based POTT scheme is intended to operate once a single relay receives the first TW current information from both terminals.

Assuming a fault location of *m* per-unit on a line that has a length of *L*, the speed of a TW on the line is v1 (0.998 c, where *c* is the speed of light in vacuum) and the speed of light in fiber is v2 (0.6 c). With this information, the minimum operation time of the system can be determined. Fig. 7 demonstrates the following:

- The local terminal sees the first TW in m • L/v1.
- The remote terminal sees the first TW in (1 – m) • L/v1.
- The remote terminal sends the received TW to the local terminal in L/v2.

The fastest that the local TW POTT element can trip is Max (m • L/v1, (1 – m) • L/v1) + L/v2, with *m* being a per-unit distance to the fault from the local terminal. Assume v2 < v1, which is true for when the communications channel is fiber and the protection line is an overhead line.

For a transmission line length of 100 miles, we can calculate the limit on minimum achievable operation time. This ignores processing latencies within the relays and assumes a direct fiber communications path between relays with no buffering or packetization delays.

For a mid-span fault, the minimum trip time is Max (0.5 • L/v1, 0.5 • L/v1) + L/v2 = 0.5 • L/v1 + L/v2 = 1.2 milliseconds.

For a close-in fault, *m* = 0, and the fastest trip is L/v1 + L/v2 = 1.4 milliseconds.

For a remote fault, *m* = 1, and the fastest trip is L/v2 = 0.9 milliseconds.

Assuming that the estimated processing latencies for future TW relays are in the range of 0.1 to 0.2 milliseconds, the physical limit on minimum operation time would be 1 to 2 milliseconds.

With less than 0.25-cycle relays and 0.5-cycle breakers, the communications channel will become a considerable factor in overall system operation time. The choice of network communications technology will become more significant when implementing TW-based relay schemes. It will require protection and communications engineers to carefully assess the performance of their existing communications networks and understand the latencies and network healing times for different communications methods.

VI. Conclusion

Traffic latency, determinism, and network healing are the key performance attributes for substation WAN communications networks. As more applications migrate toward using Ethernet for communications, there has been a tendency to accept a tradeoff in determinism for improved bandwidth utilization.

Looking to the future, once faster relays and breakers become available, the reduction of communications latencies is expected to become a significant goal of utility communications systems.

This paper showed that running Ethernet over TDM provides the following performance advantages over standard Ethernet:

- Deterministic latencies.
- Faster network healing times.
- Native segregation of services via timeslots.

These attributes provide advantages for implementing IEC 61850 and 87L schemes. Looking to the future, new TW-based relay schemes will demand lower-latency communications services.

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VIII. Biographies

Ken Fodero is a sales development manager for the communications product lines at Schweitzer Engineering Laboratories, Inc. (SEL). Before coming to SEL, he was a product manager at Pulsar Technology for four years in Coral Springs, Florida. Prior to Pulsar Technology, Ken worked at RFL Electronics for 15 years, and his last position there was director of product planning. He is a senior member of IEEE and has authored and presented several papers on power system protection topics.

Paul Robertson is a senior marketing program manager for the communications product lines at Schweitzer Engineering Laboratories, Inc. (SEL). He has over 20 years of experience developing and marketing products for the telecommunications industry, spanning cellular wireless and wire line communications systems. Paul worked in various technical and marketing roles for Motorola, Hewlett-Packard, and Agilent Technologies before joining SEL. He has a BEng in electrical and electronic engineering from Strathclyde University and an MBA from Edinburgh Business School.

20150122 • TP6682-01