

Sharing Direct Fiber Channels Between Protection and Enterprise Applications Using Wavelength Division Multiplexing

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Sharing Direct Fiber Channels Between Protection and Enterprise Applications Using Wavelength Division Multiplexing

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Abstract—Protection system communications are increasing in importance because they enable optimal operation of power systems. Because of the high cost of communications systems in the past, protection systems had to be optimized to use minimum bandwidth and were often forced to rely on a single bit of information. A synchronous 64 kbps channel reserved exclusively for the most critical transmission lines was seen as the best-case scenario.

Communications system developments over the last three decades have opened a deluge of information, with a single optical fiber now capable of carrying multiple terabits of data simultaneously. Modern protection systems face a totally different problem. Communications bandwidth is almost unlimited, but the channel must be shared with other users and may present multiple challenges, such as channel asymmetry, variable latency, path reconfiguration due to automated failure recovery, packet-based transport, and the need for system-wide time synchronization.

This paper reports on an experimental investigation that uses coarse or dense wavelength division multiplexing (CWDM, DWDM) for applications in high-speed traveling-wave protection. The investigation was performed using the latest generation of carrier-grade optical transport network (OTN) equipment. The paper documents the performance, opportunities, and pitfalls associated with this application and outlines practical strategies for the seamless integration of protection systems with the latest generation of OTN technologies.

I. INTRODUCTION

Power system protection typically operates autonomously with communications-based schemes historically reserved only to protect the most critical transmission lines. Communications bandwidth and the cost associated with providing it has for many decades forced power system protection engineers to design exceptionally ingenious communications schemes that economized on communications resources.

Communications-based protection scheme deployments started with analog pilot wire schemes in which the current transformer secondary signals were used to drive several kilometers of dedicated pilot wire. Pilot wire schemes evolved rapidly, spanning ever-increasing distances. This often required reducing the communicated signal to a single bit transmitted using an amplitude modulated power line carrier coupled to the same transmission line. Protection relied on the distance and/or directional elements with permissive and/or blocking schemes matched to the available communications channel. Directional schemes such as permissive overreaching transfer trip (POTT) or directional comparison blocking (DCB) later evolved into

various types of phase comparison and eventually to full segregated phase differential schemes (ANSI device #87; see Fig. 1) using a variety of media that included wireless communications, leased voice circuits, and so on. Analog voice circuits were eventually digitized, carried over optical fibers, and combined with large numbers of unrelated telephone channels using time-division multiplexing (TDM). Digital telephone communications eventually peaked with the development of the synchronous optical network (SONET) and synchronous digital hierarchy (SDH) systems. The Internet-driven data deluge followed, forcing the communications systems to carry ever-increasing amounts of packet-based network traffic supplied by Ethernet and multiprotocol label switching (MPLS). Packet-based networks opened new interoperability challenges while simultaneously creating new opportunities to improve overall quality of service [1].

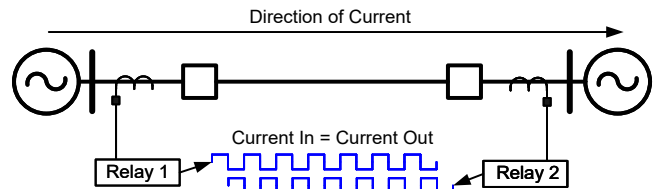


Fig. 1. Differential line protection example (87L)

Due to their critical nature, relay communications typically lag behind the mainstream communications, opting to use the most reliable and dependable technology available at any given time.

Protective relays slowly converged on a synchronous 64 kbps interface that can be easily transported using voice-grade network channels. Use of the 64 kbps interface was further strengthened with the introduction of the IEEE C37.92 standard, which defined a direct optical interface between protective relays and communications multiplexers. IEEE C37.92 allows for a single fiber pair to carry twelve channels, resulting in a total capacity of 768 kbps. Although appealing, increased capacity is seldom used, with the latest generation of protection devices starting to use more than one channel. A similar situation exists on the Ethernet interface side, with the latest generation of devices also starting to use this channel.

The latest generation of ultra-high-speed (UHS) transmission line protective relays has recently raised the bar by introducing time-domain protection elements, traveling-

wave fault location, high-resolution event recording, time-coherent MHz-level sampling, and current traveling-wave differential protection. The current traveling-wave differential element (TW87) uses real-time exchange of 1 MHz sample data between the two terminals of the line [2]. Communication is established through a dedicated fiber-optic channel, which includes time synchronization designed to ensure nanosecond-accurate time synchronization (<25 ns) between the two relays.

Without diving into a discussion about whether a dedicated TW87 fiber-optic channel is economically justified or technically feasible, it is sufficient to note that the sustained data bandwidth consumed by continuously transmitting 6 analog measurements (3 voltages and 3 currents) sampled one million times per second is on the order of 145 Mbps. Data are transported using a 1 G Ethernet channel with small form-factor pluggable (SFP) transceivers (see Fig. 2), allowing the user to match the required transmission distance and control the associated light wavelength.



Fig. 2. SFP transceiver installation example

As practicing engineers will immediately note, requesting a dedicated dark fiber channel for a single protection service is guaranteed to cause a major uprising in any system communications department. The uprising and/or outrage is fully justified, and as the authors can confirm, is a great conversation starter and creates a valuable opportunity for better cooperation and understanding between protection and communications system engineers.

This paper presents the results of a UHS protection relay test using a dedicated fiber-optic communications channel. The testing was conducted at the Pacific Gas and Electric (PG&E) High Performance Communications Technology Laboratory located in San Ramon, California. The test was performed using the PG&E optical transport network (OTN) system, which carried the required relay payload with ease.

The paper also raises several questions about the design of future protection systems, revolving around the realization that modern fiber-optic communications systems have managed to exceed the communications bandwidth typically requested by present day protective relay designs by as much as 5 to possibly 9 orders of magnitude.

II. DEDICATED COMMUNICATIONS CHANNEL REQUIREMENTS

A current-generation UHS transmission line relay instruction manual describes the TW87 communications link as a “dedicated, private point-to-point fiber connection” between

two relays without going into specific details. A more specific list of the TW87 requirements is summarized as follows:

- 1 Gbps Ethernet physical layer
- Industry-standard SFP module-based fiber interface
- Individual frame jitter that is below 25 ns
- Link asymmetry that is below 100 ns
- Low latency
- Constant link delay (no protected path switching)
- No third-party traffic

Travel time jitter and link asymmetry requirements are the most difficult specifications to meet but are essential for the UHS relay’s ability to maintain common time and synchronize individual samples down to the nanosecond level with hundreds of miles separating the two UHS relays. Synchronization could in theory be accomplished using two sources of time, supplied independently to the individual relays.

Although simple, the independent clock approach does not satisfy the key requirement that UHS relay designers wanted to achieve namely, “the relay protection functions shall be insensitive to external sources of time and any conceivable failure modes associated with those sources.” To meet this requirement, relays rely on an internal time source (highly accurate, temperature compensated crystal oscillator). External sources (when present) are strictly monitored, and if acceptable, are used to slowly adjust the 1 MHz sampling instant by, at most, $\pm 0.5 \mu\text{s}$. All other time related functions use a specially designed “time offset translation” algorithm to convert the continuously advancing relay time to the UTC timescale provided by the external time source.

When TW87 is enabled, a dedicated communications link allows the two UHS relays to form a strong synchronization bond. A ping-pong message exchange is used to continuously measure the fiber-optic link delay and the sampling clock phase difference between the two relays. To maintain synchronization, it is essential that the fiber-optic communications link between the relays be able to provide a constant Ethernet frame transport delay.

While not a primary requirement, the TW87 scheme channel latency is expected to be minimal and in line with the UHS relay’s operating speed. This translates to an expectation that the latency be comparable to the physical fiber delay necessary to span the protected transmission line. Low latency is important because the propagating speed of light through a single-mode fiber is approximately 60 percent of the propagation speed of the traveling wave on the transmission line. Optically communicated signals are, therefore, guaranteed to arrive later than their power system counterparts. Excess channel delay, therefore, directly affects the operating time of the TW87 element.

Fortunately, the UHS relay is typically used to protect long high voltage (HV), extra-high voltage (EHV), and ultra-high voltage (UHV) transmission lines (typically over 100 km in length). A disturbance on a power system launches traveling waves that propagate in the transmission line at approximately 300 km per millisecond. This results in an end-to-end travel time close to 1 ms. This leaves some time for digital processing, which at speeds of 1 Gbps typically takes less than 100 μs .

Using the outlined point-to-point link requirements, a list of communications technologies that can be used to establish the link is shown in Table I.

TABLE I
POINT-TO-POINT COMMUNICATIONS LINK OPTIONS

Transport Technology	Acceptability	Comment
Single-mode fiber pair	Yes	Difficult to justify for sole use by protection
CWDM	Yes	
DWDM	Yes	
OTN	Yes	
SONET	No	Jitter
Ethernet	No	Jitter
MPLS	No	Jitter
SDN-based Ethernet	Sometimes	Affected by device construction and network setup

Using a pair of single-mode fibers is the simplest solution. A pair of fibers is required because normally one fiber is required for data transmission and the other fiber is required for data reception. There are special SFP modules that support bidirectional single-fiber transmission, but they are generally less common and more expensive.

The use of wavelength division multiplexing (WDM) is much more common in the industry. In WDM, tightly controlled wavelengths of light (colors) are used to transport multiple communications links over the same fiber. WDM applications require good quality filter banks that are capable of separating different wavelengths. Furthermore, they also require frequency stabilized lasers that are capable of maintaining the designated wavelength across a wide operating temperature range. Simpler systems use CWDM with up to 16 channels available in the 1,310 nm and the 1,550 nm bands. More advanced systems use DWDM with 44 or 88 discrete channels allocated in the 1,550 nm band. This band has the lowest attenuation and leverages the availability of Erbium-doped fiber amplifiers (EDFAs), thus supporting long-distance transmission. Applications using any of the three intended technologies are shown in Fig. 3.

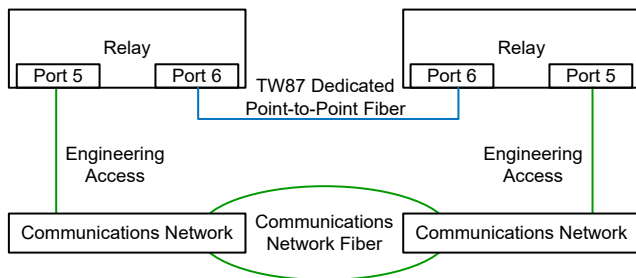


Fig. 3. Intended relay application (two systems shown side by side)

OTN is the latest generation of communications technologies intended primarily for metro aggregation and long-distance core networks. OTN provides a transparent digital wrapper intended for the end-to-end transport of lower-

speed network technologies, such as SONET, Carrier Ethernet, MPLS, storage area networks, and so on, and it is currently a preferred access method for large data centers. OTN provides transparent timing, meaning the transmission jitter is so low ($\ll 25$ ns) that it can support the stringent synchronization needs of SONET and synchronous Ethernet technologies.

SONET, SDH, Ethernet, and MPLS cannot currently be used to meet the TW87 link requirements. Software-defined networking (SDN) can in some cases be configured to provide sufficiently low jitter; but this performance remains manufacturer-specific and design-dependent. An additional discussion about this topic is provided in Section V.

III. OPTICAL COMMUNICATIONS NETWORK AT PG&E

PG&E is an investor-owned electric utility company serving over 5.4 million electric and 4.3 million gas customers. Headquartered in San Francisco, California, PG&E serves a territory of over 70,000 square miles in northern and central California. In addition to its extensive electric and gas networks, PG&E also operates a large optical network linking virtually all major HV substations in its territory. PG&E's network uses high-quality single-mode fibers typically deployed along the EHV transmission line right of way using optical ground wire (OPGW) technology. As a result, PG&E is uniquely positioned to bring high-quality communications services to rural parts of the state.

PG&E's communications network uses state-of-the-art OTN technology [3] with 61 nodes already in service. Ten additional nodes are in the works at the northern edge of the service territory, promising full network coverage in the near future. It is interesting to note that PG&E's utility neighbor to the north, Bonneville Power Administration (BPA), is in the process of commissioning a similar OTN system. This development is quite natural given that BPA has a long tradition of operating a fiber-optic backbone. The original fiber-optic backbone network was put in place during the Columbia River Basin hydroelectric power plant development and was expanded to accommodate the large number of major data centers presently lining the banks of the Columbia River. PG&E's neighbor to the south, Southern California Edison, operates a similar fiber-optic network with a long history of offering fiber-optic services on the open market.

IV. OTN TECHNOLOGY PRIMER

OTN is a tightly coupled set of technologies aimed at providing a transparent, multiservice transport for a wide variety of packet- and TDM-based technologies. OTN scales well beyond the 100 Gbps per transported tributary and includes a framework for efficient wavelength division control, reconfigurable optical add drop multiplexing (ROADM), optical amplification, centralized network management, and all optical long-haul transport capabilities. OTN is highly configurable and works hand in hand with the latest generation of SDN.

By being an optical transport technology, OTN should be seen as a large number of centrally managed point-to-point links that can be established and destroyed at will. DWDM and

the advanced modulation schemes in use today allow the OTN technology to approach the presently known theoretical limits of the capacity of single-mode fiber, as shown in Table II.

TABLE II
SINGLE-MODE OPTICAL FIBER CAPACITY AS A FUNCTION OF DISTANCE

Capacity (Tbps)	Modulation	Typical Distance (km)
4 to 7	PM-BPSK	5,000
8 to 15	PM-QPSK	3,000
12 to 21	PM-8QAM	1,200
16 to 27	PM-16QAM	500

The optical fiber capacities provided in Table II assume the use of DWDM with 88 or more individual wavelengths. Each wavelength is modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), or quadrature amplitude modulation with a constellation of 8, 16, or more symbols (8QAM, 16QAM). For modulation rates above 40 Gbps per wavelength, it is customary to use polarization multiplexing (PM). Additional capacity increase is achieved by abandoning the standard DWDM channel grid (44/88 channels with fixed 100/50 GHz spacing) in favor of tighter spacing, which is achievable with continuously tunable lasers. As of August 2017, commercial OTN systems have reached transmission speeds of 400 Gbps per wavelength and a maximum capacity of 48 Tb per fiber. At these speeds, technology is approaching the Shannon’s capacity limit for a single fiber, meaning additional gains are likely to require careful tradeoff between the data rate, spectral efficiency, and optical path reach.

Use of multiple wavelengths provides guaranteed (physical) separation of traffic between different streams, while the high transmission speeds make it possible to transparently encapsulate legacy rates and services (such as MPLS or SONET/SDH). OTN transport has standardized the following rates, as shown in Table III (applied per DWDM wavelength).

TABLE III
STANDARDIZED OTN RATES

Signal	Approximate Data Rate
ODU0	1.244 Gbps
ODU1	2.498 Gbps
ODU2	10.037 Gbps
ODU3	40.319 Gbps
ODU4	104.79 Gbps
ODUflex	Any configured rate

Rates are carefully selected to allow easy mapping of various legacy channels, for example, Gigabit Ethernet or OC48 (2.48 Gbps) SONET services. Slightly larger data rates make it possible to transparently transfer channel timing, while at the same time supporting frequency tolerance range and clock jitter mask requirements.

Although supporting lower rates (such as ODU0), OTN gets in the zone at 10 Gbps or above. For example, at those rates, the ODU2 10.037 Gbps channel can be used to multiplex together

one Gigabit Ethernet LAN tributary, one OC48 (2.48 Gbps) SONET channel, and 5 MPLS channels supplied using 1 Gbps Ethernet ports. All of these tributaries are transported in effect “one bit at a time” (in a round robin fashion, sending one, two, or more bits from each channel, depending on the rate of the tributary). Actually rate management is more complex, with multiple options available to the network engineer, but it is important to note that fine granularity (bit by bit) of such multiplexing allows OTN to deliver fully transparent links that make it possible for the subtended systems to retain their time and frequency synchronization services.

OTN systems use forward error correction, which results in slightly higher rates by the time fully multiplexed electrical signals are delivered to their corresponding modulators and/or WDM channels. Forward error correction provides an additional layer of robustness, allowing the optical transport specialist to monitor the bit error rates (BER) for each wavelength and proactively adjust the system parameters before the errors become visible to the downstream customers. The summary above barely scratches the surface of OTN network capabilities. For additional details, interested readers are directed to [3] and the easily accessible information on the Internet.

V. SAN RAMON LABORATORY TEST

In order to verify the PG&E network’s ability to transport the UHS relays’ TW87 messages, a live equipment test was conducted at the San Ramon Communications Systems Test Laboratory. Initial conversations among the engineers involved in the project indicated a high level of confidence on the side of the PG&E communications team, caution on the side of the PG&E protection team, and major reservations on the side of the relay design team.

The teams agreed to conduct two independent tests. The first test would use DWDM-capable SFPs plugged directly into the relays. The selected wavelength would then be brought directly into the PG&E OTN platform optical plane using the “alien wavelength” interface module. This approach guaranteed that the UHS relay would have direct access to the optical fiber for the given wavelength. The OTN system hardware used for the test is shown in Fig. 4.

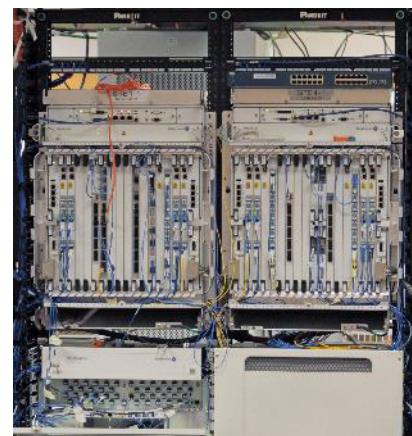


Fig. 4. OTN system used during the test

An alien wavelength card is normally intended for premium level service and used when the traffic from a neighboring carrier needs to traverse the network or when unknown extremely high capacity modulation schemes need to be transported through an existing system. Allocating an entire alien wavelength to a single gigabit channel in effect means committing a resource with a 100+ Gbps theoretical capacity. In the PG&E network case, resource allocation is slightly less critical because the individual wavelengths are typically modulated at 10 Gbps. The alien wavelength approach still provides much greater efficiency than using a dedicated dark fiber pair (15+ Terabit resource).

An alien wavelength interface card provides several functions that are crucial for successful OTN network functionality. To begin with, the alien wavelength interface card balances the incoming and outgoing light levels, ensuring that the optical amplifiers are properly loaded. Injecting an uncontrolled light level or inappropriate wavelength could jeopardize neighboring channels, putting a high level of scrutiny on the device using the wavelength (the UHS protective relay). Other important functions of the alien wavelength interface card are to apply the operations, administration, and management modulation on the alien wavelength signal. This modulation allows the wavelength to

be tracked end-to-end throughout the entire OTN network, which is very important in the day-to-day operation of the network. A detailed diagram showing the alien wavelength test setup is shown in Fig. 5.

A second test involved the use of ODU2 multiplexing. In this test, a 1 Gbps link is used by the UHS relays, thereby, becoming a simple tributary to the ODU2 (10 Gbps) stream, with additional services, including PG&E SONET and MPLS networks being multiplexed in at the same time. The OTN multiplexing approach provides the best bandwidth utilization with a 1 Gbps link being provisioned to consume a 1 Gbps resource. The utilization is still below ideal. As mentioned, the sustained link rate is only 145 Mbps, but it is orders of magnitude better than when using dedicated dark fiber. A detailed diagram showing the alien wavelength test setup is provided in Fig. 6.

The results for the two tests are shown in Table IV.

TABLE IV
OTN TEST RESULTS

Test	Error Correction	Measured Latency (μ s)	Measured Jitter (ns)
Alien wavelength	None	1.6	<8
ODU2 tributary	EFEC	60.8	<8

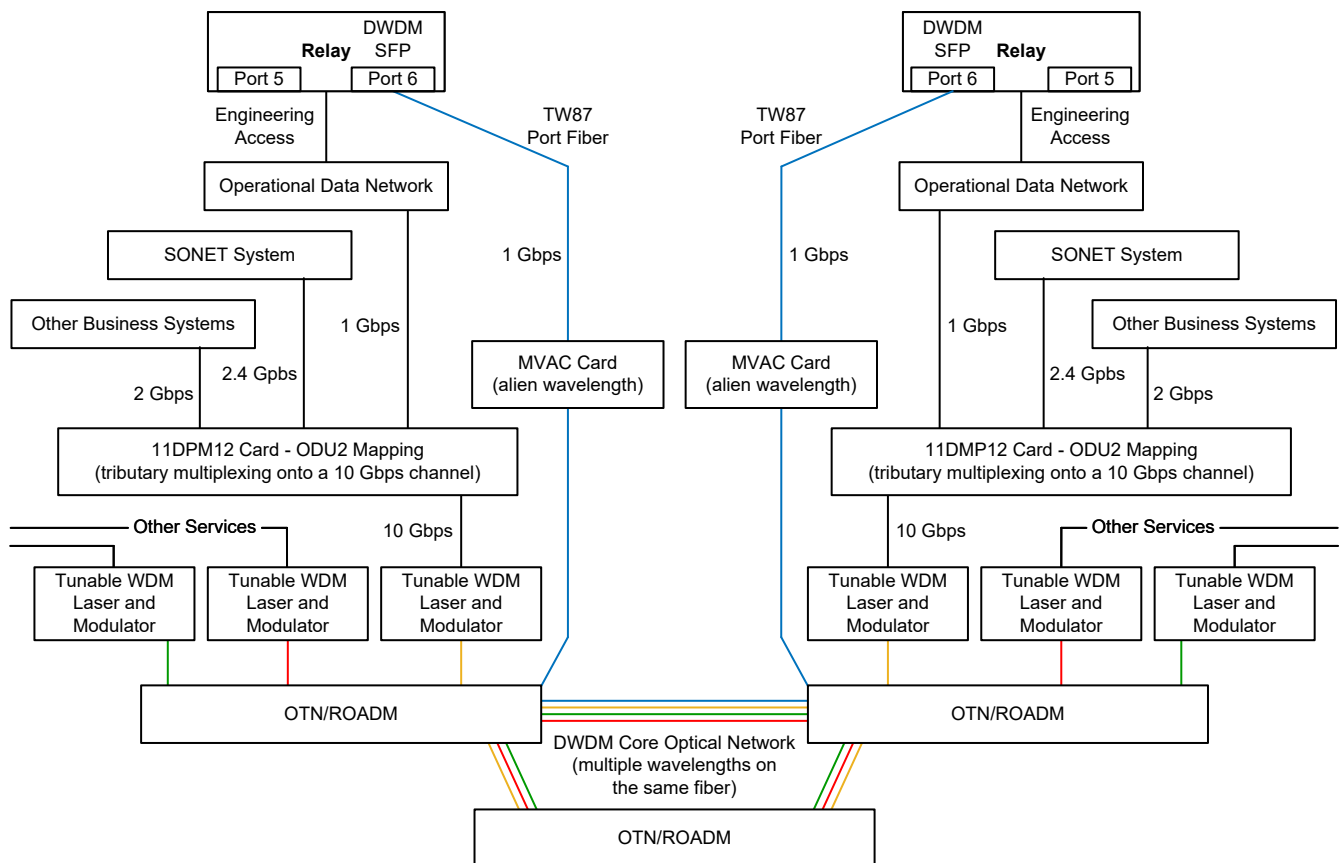


Fig. 5. Alien wavelength test setup

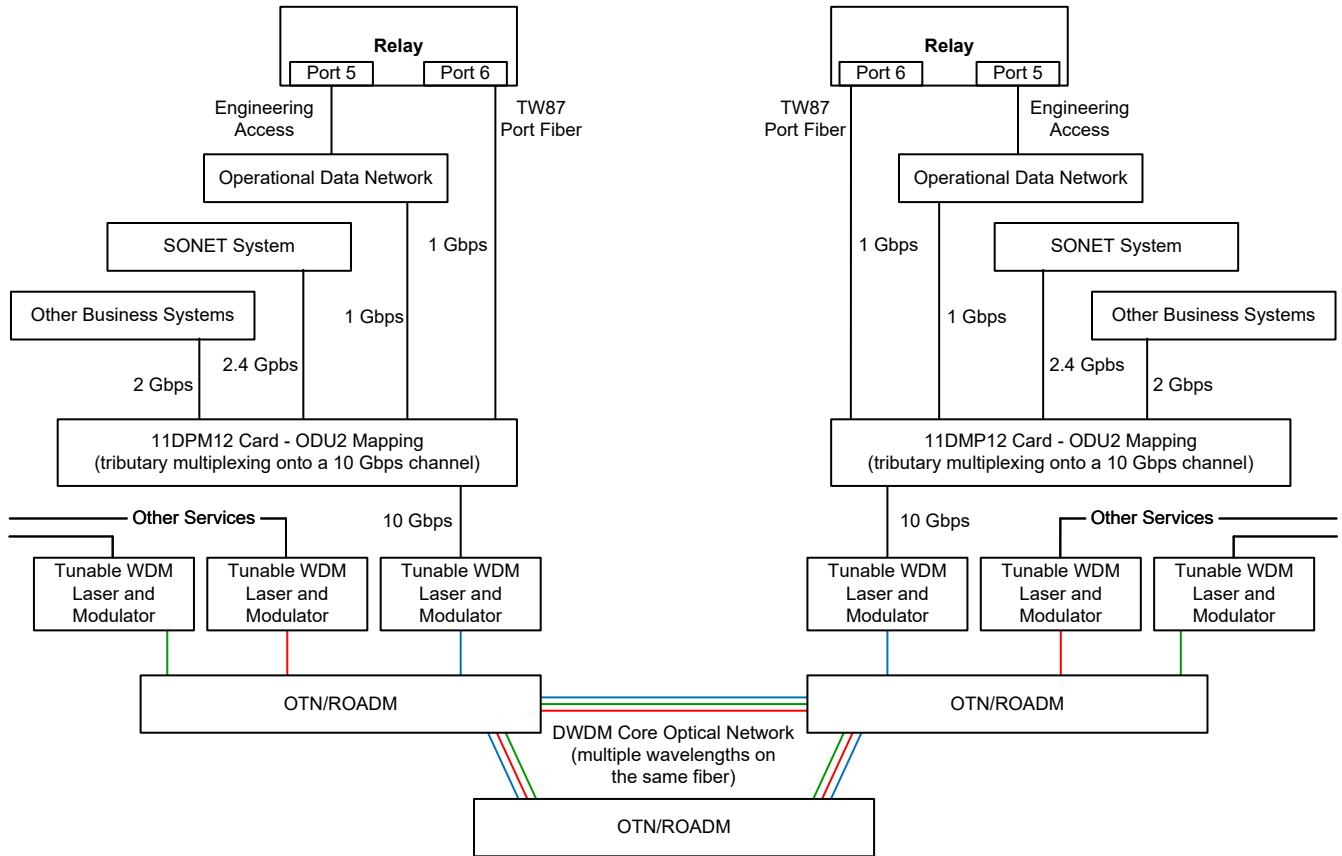


Fig. 6. ODU2 multiplexing test setup

As the results show, the UHS relay link was successfully established in both cases. The alien wavelength test provided the measurement of the actual fiber length connecting two OTN systems in the lab. The jitter measurement shows that there was no detectable jitter, with the actual values being below the UHS relay's 8 ns measurement limit. The ODU2 multiplexing test shows additional latency caused by the FEC system. This additional latency was expected and fully controlled by the OTN network engineer.

Available settings and the associated end-to-end delays are shown in Table V. The exact meaning of the various options (RS FES, EFEC, and so on) is beyond the scope of this paper, but can be found in [3]. What matters is the close agreement between the expected and the measured results of the test.

TABLE V
FEC AND ASSOCIATED TRANSPORT LATENCY

Line-Side FEC	Tributary Rate (GHz)	Line Rate (GHz)	Latency (μ s)
None	1.25	10.709	17
RS FEC	1.25	10.709	23.5
EFEC	1.25	10.709	59
EFEC2	1.25	10.709	157

VI. RELAY DESIGN OPPORTUNITIES

As explained in the introduction and clearly demonstrated during the test, modern utility communications systems are

more than capable of satisfying protection system data bandwidth needs. Difficulties emerge once the protection devices need low latency and highly symmetric channels required for channel-based synchronization.

Guaranteed quality of service is also required, with path protection switching often violating the above mentioned requirements. The situation becomes more complex with the use of modern packet-based (Ethernet) communications systems that offer very high bandwidth but cannot guarantee the exact packet delivery time (variable latency).

Faced with the continuously evolving communications capabilities, protection device designers are challenged to use the latest Ethernet protocols, while at the same time having to support the old 64 kbps synchronous interfaces. Low-speed interfaces of this kind are unable to transport the full bandwidth signals normally used by the relay. As an example, a line differential protection application needs to communicate a three-phase set of line currents. Assuming no compression and 16-bit resolution for each sample, it is easy to see that the maximum sample rate that can be supported by the 64 kbps interface is on the order of $64,000 / 3 / 16 = 1,333$ samples per second (sps). This number is calculated without taking into account the overhead required to address error protection, channel-based time synchronization, and other essential functions and/or requirements. The resulting sample exchange rate is typically reduced to the 800–1,000 sps level with dynamic range compression required to reduce the payload to 12 bits per sample. An alternate approach for fitting into a

64 kbps channel includes phasor-based differential protection elements, which benefit from the fact that the precomputed phasors need to be sent less often, however, this limits the protection applications for this device. The bandwidth reduction approach works well but results in a number of corner cases and compromises that must be explicitly addressed during the relay design phase. Achieving the protection scheme speed becomes more difficult with a bandwidth reduction approach. This then requires extra effort and ingenuity in order to make such a device competitive. Compromises can be eliminated by simply using higher bandwidth. With the synchronous multiplexer interface, the easiest approach is to standardize on the IEEE C37.94 fiber-optic interface, which is capable of transporting twelve 64 kbps channels. The resulting 768 kbps bandwidth can easily support sample rates in excess of 10 kHz, making it possible to exchange the relay samples in their native format (without the need for sample rate reduction).

Even higher performance can be achieved using the Ethernet communications commonly found in all modern relays. Ethernet communications are especially convenient in multiterminal applications in which a single relay needs to exchange data with multiple peers (more than two). In order to support mission-critical protection applications, an Ethernet network must be purposefully engineered and capable of providing guaranteed quality of service. General-purpose Ethernet networks are inadequate for this purpose. Instead, fully configured networks must be used instead with key technologies, including SDN, Ethernet pipe transport over SONET, and time-sensitive networking (TSN).

Packet-based networks are typically associated with queuing delays and an inability to control transport delay variations. As long as the total latency is low enough to meet the protection system requirements, these problems can be solved by adding a network-based time synchronization service, such as the Precision Time Protocol (PTP), also known as IEEE 1588, or one of its profiles (IEC 61850-9-3 or C37.238).

Use of an external time synchronization service directly contradicts the previously stated design directive that protective relay operation shall not be affected by the externally supplied time synchronization source. The external clock independence requirement appears to be an unsurmountable obstacle, promising to disqualify all packet-based protection schemes. The problem becomes more manageable if the time synchronization is performed over the same physical interface used to communicate the required differential element data. In the case of Ethernet, everything works as long as the Ethernet network can guarantee that the same time-synchronization signal will be delivered to all devices that can communicate with each other. Simply put, the loss of the time-synchronization signal is not a problem as long as the communications capabilities are lost at the same time.

The above discussion means that time synchronization must become a guaranteed core network service. Exact traceability of the network time source and its relationship to UTC are less important, as long as the same time is being distributed throughout the entire network. PTP-based clock synchronization can offer submicrosecond accuracy levels.

Less-critical applications may also use Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP), which offer millisecond-accuracy levels.

The exact method for distributing time throughout the network core is less important. It can be proprietary or standards-based as long as the time distribution is fully protected and unconditionally cybersecure. Synchronization can be accomplished using standard communications links between network devices or performed out of band using dedicated control channels. One such system based on SONET transport is described in [4]. SONET is especially convenient for this use because the key network nodes cannot operate without establishing a strict synchronous connection with the neighboring nodes. Using a common clock makes it relatively easy for the individual nodes to establish a common time reference. Once present in the transport core, the clock signal can very easily be distributed to the attached devices. Time distribution is simple, very reliable, and guaranteed by design because the core communications cannot be established without synchronizing the nodes. The system described in [4] represents a great time distribution service example demonstrating the level of performance that needs to be provided by any network core. The exact implementation is less important but applies equally well to the large OTN network core and the edge network emanating from that core (Ethernet, MPLS, and so on).

When considering OTN and maximum capacity limits for a single-mode optical fiber, it is important to note that power system protection and control (P&C) applications do not generate enough traffic to fully load or justify the OTN system. Present day P&C needs are easily met with a single OTN wavelength. Remaining OTN capacity can be leased or used for other purposes.

OTN is a physical layer (layer 1) technology that provides centrally managed point-to-point connectivity. It is used to transport network traffic but does not provide higher-layer bridging and routing services by itself. Higher-layer services are addressed at the OTN tributary level by using well-established technologies such as SDN, SONET, SDH, and MPLS.

VII. CONCLUSION

While every electric power utility cannot be expected to switch to OTN technology in the near future, the PG&E and BPA examples can be seen as forerunners of things to come over the next decade. The authors are very excited about the potential of OTN technology and future optical technology advancements.

Relay design engineers are finally finding themselves in an environment with virtually no bandwidth constraints, making it possible to exchange the optimal amount of data required for a given protection application. This also means much greater penetration of differential protection schemes, with virtually all key resources protected using some type of optical communications. This paper explains the importance of the network-based time distribution service and its need to become a guaranteed part of the core network design.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES

- [1] K. Fodero, C. Huntley, and P. Robertson, "Deterministic Communications for Protection Applications Over Packet-Based Wide-Area Networks," proceedings of PAC World Americas Conference, Raleigh, NC, August 2017.
- [2] E. O. Schweitzer, III, B. Kasztenny, A. Guzman, V. Skendzic, and M. V. Mynam, "Speed of Line Protection – Can We Break Free of Phasor Limitations?" proceedings of the 41st Annual Western Protective Relay Conference, Spokane, WA, October 2014.
- [3] Alcatel-Lucent 1830 Photonic Service Switch, Product Information and Planning Guide, Issue 4, February 2015.
- [4] K. Fodero, C. Huntley, and D. Whitehead, "Secure Wide-Area Time Synchronization," proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

X. BIOGRAPHIES

Jonathan Sykes is a Senior Manager of System Protection at PG&E, headquartered in San Francisco. Jonathan received his academic training from the University of Arizona in 1982 and worked at Salt River Project, in Phoenix, for more than 25 years before joining PG&E in 2009. He is a Professionally Licensed Electrical Engineer and Senior member of IEEE. Jonathan has helped pave the path to introduction of technology where grid modernization and system reliability reach equilibrium for more than 16 million customers in Northern California. Jonathan believes that knowledge needs to be shared and success is a result of collaboration. In the early 1990s, Jonathan led a team to provide the first integrated protective relay/RTU/SCADA systems in Arizona. In the early 2000s, his team implemented one of the first wide-area GOOSE systems in the world and his PG&E team is now cosponsoring the next-generation, routable GOOSE (R-GOOSE). Today, Jonathan's teams are developing new techniques and processes as the grid changes to inverter-based renewable power production. This requires his team to be engaged in emerging technologies such as synchrophasors, traveling wave, and artificial intelligence applications. His team also developed new concepts in the area of asset life cycle management. Jonathan leads a strong team of internationally recognized experts, Fellows of IEEE, and distinguished lecturers, with extensive knowledge in system protection and advanced power system dynamics.

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Kevin Fennelly is a ROADM/DWDM Product Specialist at PG&E, headquartered in San Francisco. Kevin has earned both a BSEE (1994) and MSEE (1997, Communications) from Loyola Marymount University in Los Angeles. He joined PG&E in 2013 and has more than 20 years of experience in communications systems design, operations, and management. Kevin oversees all of the evolution, growth, development, and management of PG&E's expansive optical transport network.

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