Analysis of In-Service Line Current Differential Protection Circuits: Comparing SONET With Packet-Switched Network Performance

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***Abstract*—Many utilities are migrating their wide-area network infrastructure from time-division multiplexing (TDM) and synchronous optical network (SONET) to packet-based technologies based on multiprotocol label switching (MPLS) or Carrier Ethernet. This has created the challenge of engineering packet-based pilot channels to provide the determinism (guaranteed performance) required by protection applications. Line current differential protection schemes are the most stringent from a communication channel performance perspective. These schemes require low and deterministic latency, low asymmetry, and fast recovery from communication channel failures. To date, most studies on running line current differential protection over packet-based networks have been based on laboratory trials under simulated network conditions and focused mainly on measuring channel latency. However, the contribution of communication channel asymmetry is more significant with packet-switched networks and needs to be considered in addition to latency.**

This paper provides a wealth of performance data taken from Central Lincoln PUD in-service protection systems running line current differential schemes over a converged information technology/operational technology (IT/OT) packet network. The paper provides an in-depth analysis of the communication channel performance in the context of the alpha plane, a popular relay operating characteristic. The alpha plane is used by differential relays to detect internal line faults while maintaining security for line charging current, current transformer (CT) saturation, and channel asymmetry. Alpha plane analysis is used to compare the protection channel latency and asymmetry performance prior to migration (using Central Lincoln PUD's SONET network infrastructure) with the performance after migration (using their packet network implementation).

Central Lincoln PUD's network implementation uses a technology called virtual synchronous networking to address the performance limitations when relay teleprotection circuits are transported over packet systems. The live network performance results show that it is possible to achieve SONET-grade performance over a packet-based wide-area network.

I. INTRODUCTION

Today, most power system protection schemes use digital communication channels. Communications-assisted protection schemes facilitate data sharing between protection devices and make it possible to employ methods that improve dependability, selectivity, security, and speed. These communication-assisted schemes also enable the implementation of differential comparison schemes, such as line current differential (87L) protection. Many utilities use a combination of direct point-to-point fiber links and two multiplexed channels to provide high-availability communication to maintain relay teleprotection circuit function in the event of different failure scenarios on the power system.

Central Lincoln PUD is a publicly owned power utility, serving about 700 square miles of territory across portions of four counties, including 112 miles of Oregon's central coastline. After beginning operations in 1943, Central Lincoln PUD currently serves over 32,734 residential customers and approximately 5,625 commercial and industrial customers.

Central Lincoln PUD uses direct fiber and a multiplexed communication network to support their line current differential teleprotection channels. Like many utilities, Central Lincoln PUD has relied on a synchronous optical network (SONET) network to provide their network communication. However, they recently embarked on a network migration program to modernize their network infrastructure by moving away from SONET and implementing a converged information technology/operational technology (IT/OT) network based on Carrier Ethernet packet technology instead.

The migration to packet-based networking technologies such as multiprotocol label switching (MPLS) and Carrier Ethernet has created the challenge of engineering teleprotection services to provide the determinism and guaranteed performance required by protection applications

Central Lincoln PUD was halfway through their network rollout and had migrated about half of their protection circuits over to the new packet infrastructure. Since Central Lincoln PUD already had an operational SONET network, they were in a unique position to study the in-service performance of their line current differential schemes to compare the relative performance over direct fiber, SONET, and packet transport.

The data analysis was taken from live operational relays, providing for the first time an objective analysis of SONET versus packet transport technologies. It helped assess how different communication channel technologies affect the data being presented to and processed by the line current differential relay systems.

II. EXPLAINING LINE CURRENT DIFFERENTIAL

Line current differential protection leverages Kirchhoff's current law for protecting various line lengths and voltages. Simply put, it compares the current entering the line with the current leaving the line. For this current comparison, data from all ends of the protected line must be carefully aligned for 87L calculations. This alignment requires reliable deterministic communication to exchange data. Modern 87L schemes have improved beyond just a current comparison scheme and now include features, such as local and remote disturbance detection, watchdog counters, advanced time alignment and fallback methods, line charging current compensation, and increased security with external fault detection.

Digital 87L offers the benefits of sensitivity, security, and selectivity. These systems provide fast fault clearing for faults anywhere in the zone on the protected line. Fig. 1 shows a one-line diagram of a two-terminal line with a primary and backup communication channel.

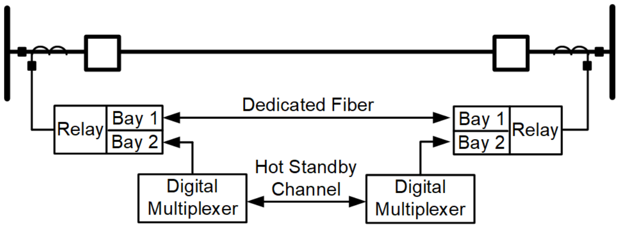


Fig. 1. Two-Terminal Digital 87L Application

87L systems are applicable to both long and short lines. They are a good solution for complicated applications, such as series-compensated lines, multiple-terminal lines, and lines with zero-sequence mutual coupling. They perform well for evolving faults, intercircuit and cross-country faults, internal faults with outfeed, current reversals, and power swings. Typical challenges for these systems include line charging current, in-line and tapped transformers, and current transformer (CT) saturation during external faults [1]. These systems require a reliable, high-capacity, low-latency communication channel and must reliably time-align currents samples at remote terminals in spite of channel noise, delays, and asymmetry [2].

Traditional current differential schemes use a percentage restraint characteristic. Operate, or differential, current is calculated as the magnitude of the sum of the terminal current phasors. Restraint current is a measure of the terminal current magnitudes. Depending on design, it could also be the sum of the terminal current magnitudes, the average of the terminal current magnitudes, and so on. The differential relay traditionally operates when the operate current exceeds a percentage of restraint, as determined by a slope setting. A limitation to this design is that sensitivity and security are inversely proportional. The slope-based characteristic increases security for higher restraint values by lowering sensitivity. Security can be increased by manipulating the restraint values and slope characteristics [3].

Reference [4] introduced the original concept of a digital 87L principle that used a restraint characteristic implemented in the alpha plane. The alpha plane is a current-ratio plane of the real and imaginary current components. Fig. 2 depicts the alpha plane representation of ideal through-current conditions. The magnitudes of I_L (current measured at local) and I_R (current measured at remote) are equal, and their phases are 180 degrees apart. Therefore, $I_R/I_L = 1\angle 180 = -1$ pu.

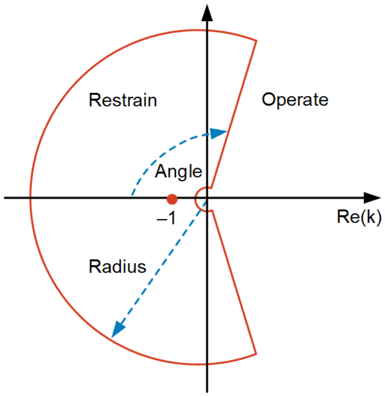


Fig. 2. Alpha Plane

The ratio of remote terminal current to local current is plotted on the alpha plane. Ratios that lie within the restraint region prevent the differential element from operating. This characteristic responds well to phase alignment errors by explicitly looking at the angle difference between the local and remote currents. Sensitivity is further controlled by a separate comparison of operate current versus a minimum sensitivity setting. Sensitivity is further enhanced by the presence of zero-sequence and negative-sequence elements, in addition to segregated phase elements [2].

The primary focus of this paper is to compare different communication mediums for 87L channels and their effects on the overall protection scheme. The data gathered from live transmission systems captures the overall effects from latency and asymmetry on the scheme.

Latency (i.e., channel delay) is an additive component in the 87L trip time calculations. Excessive latency slows down the 87L operation and may violate the critical clearing times. Typical requirements for 87L channel latency are in the range of 5 to 10 milliseconds. Reference [5] suggests specifying channels with latency below 5 milliseconds [6].

Latency is the time it takes to buffer and process any active communication devices that make up the 87L channel. In some networks, the worst-case latency is of interest, because it may change considerably, depending on the data traffic, failure modes, or network configuration changes [6].

87L schemes can align the remote and local currents using the channel alone (i.e., without the aid of any external time reference), but only if the channel is symmetrical. This means that the propagation times in the transmitting and receiving directions are equal. For these schemes, channel symmetry is a key channel characteristic.

In 87L schemes that align current without external time sources, asymmetry in the order of a quarter-power to half-power cycle, depending on the relay design, can render the scheme useless. As with the case of channel latency, the worst-case asymmetry is of interest [6].

III. COMMUNICATION NETWORK OVERVIEW

Central Lincoln PUD uses a combination of microwave and fiber for their wide-area network communication infrastructure.

Fig. 3 shows the communication medium used for their line current differential relays. The primary teleprotection channel (X) is carried over a direct fiber, and the secondary channel (Y) is transported over a communication network

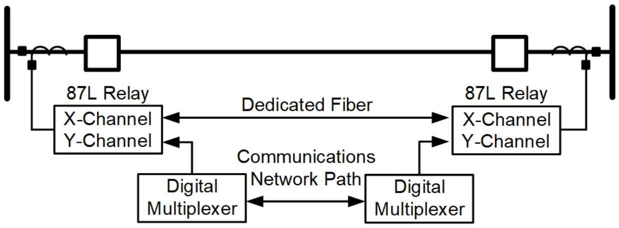


Fig. 3. 87L Relay Communication Paths Used for Teleprotection

A. Direct Fiber

Direct fiber uses a dedicated fiber-optic cable, or a pair of dedicated fibers (transmit and receive), to provide the medium for relays to communicate. Since no intermediate communication devices are used in the exchange, it can be considered an ideal communication path from a channel latency and asymmetry performance perspective. In this study, direct fiber provides an ideal reference to compare the performance of the communication networks.

B. SONET Network

Central Lincoln PUD has been using a SONET network to multiplex their secondary line current differential teleprotection circuits for many years. SONET infrastructure has provided Central Lincoln PUD with their wide-area network communications since 1995.

The utility industry has relied on time-division multiplexing (TDM) communication technologies, such as T1 and SONET, to provide the data communication that carry teleprotection traffic. TDM has traditionally provided an ideal solution for teleprotection circuits because of its synchronous architecture based on a common clock combined with a framing structure that dedicates timeslots to each circuit. This property ensures that each teleprotection circuit has a guaranteed fixed latency, regardless of other traffic on the network. TDM provides a deterministic, low-latency, and low-asymmetry communication circuit.

Most line current differential relays use a synchronous interface for the teleprotection channel communicates via a 64 kbps DS0. Central Lincoln PUD standardized on the synchronous EIA-422 interface, but other formats such as IEEE C37.94 and ITU-T G.703, are also commonly used.

C. Packet-Switched Network

In 2018, Central Lincoln PUD embarked on a network modernization study to evaluate a solution for their next-generation wide-area network (WAN). They made a decision to adopt a packet network transport solution based on Carrier Ethernet, and in 2019, they started to deploy the new packet network infrastructure. Central Lincoln PUD's goal was to implement a converged network model that uses a single network to carry IT/OT traffic. Teleprotection fits into the operational technology category, along with other services that are directly associated with the real-time operation of the power system.

There are challenges with implementing a converged IT/OT network model when delivering the performance needed for critical protection circuits. These challenges include the following:

- **Complexity**: Provisioning individual protection circuits with strict latency and asymmetry performance requirements across a packet core is complex.
- **Traffic prioritization**: Giving all critical circuits highest priority creates queuing delays in packet networks.
- **Teleprotection performance**: Packet networks don't deliver the same latency, asymmetry, and restoration performance as TDM networks, and these performance factors can change due to network loading over time.

To help address these performance challenges, Central Lincoln PUD adopted a technology called virtual synchronous networking (VSN) as a solution to support their OT traffic while still achieving their goal of implementing a converged network. VSN allows the OT traffic that includes relay teleprotection circuits to be segregated from the IT traffic.

In addition, VSN technology provides a way to transport serial teleprotection channels over Ethernet while maintaining TDM performance. This technology allows utilities to preserve channel performance for their protection applications after migrating from a T1 or SONET system to one using MPLS or Carrier Ethernet [4].

VSN technology maintains a synchronous network by maintaining a TDM subsystem. The TDM subsystem provides a synchronous interface for each teleprotection serial circuit. On top of the TDM subsystem, a packetization and Ethernet transport function is implemented. The implementation packetizes the native TDM data at the VT1.5 or synchronous transport signal (STS) level (rather than DS0) to be more bandwidth efficient. The Ethernet packets are standard Layer 2 frames that contain the TDM data along with synchronization information and the Network Management System (NMS) channel.

OT edge nodes are used to describe the substation hardened communication multiplexers that provide VSN functionality. OT edge nodes provide the access point for substation OT services, including teleprotection. OT edge nodes are co-located with the Carrier Ethernet devices, which provide the WAN transport backbone. Fixed or static paths are provisioned across the packet network to create a VSN ring (see Fig. 4).

This approach provides the following benefits:

- It bundles all substation circuits into a single static path, which reduces the complexity associated with provisioning and managing separate paths for each protection circuit on the IT network.
- It creates a demarcation between IT and OT, allowing the protection circuits to be managed by the OT team.
- It allows failover to be performed by the VSN OT edge device, which enables very fast failover (less than 5 milliseconds).

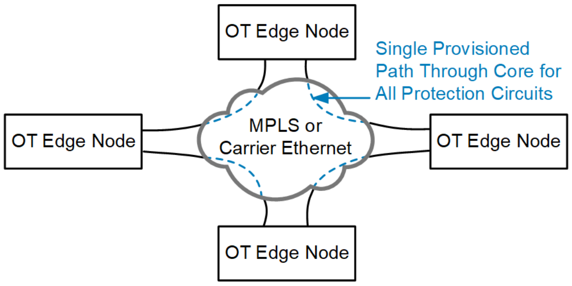


Fig. 4. VSN Ring Topology Supported by Static Paths Through Core

Fig. 5 shows the network diagram for Central Lincoln PUD's line current differential teleprotection circuit paths, where the X-channel is over direct fiber and the Y-channel is over the packet network.

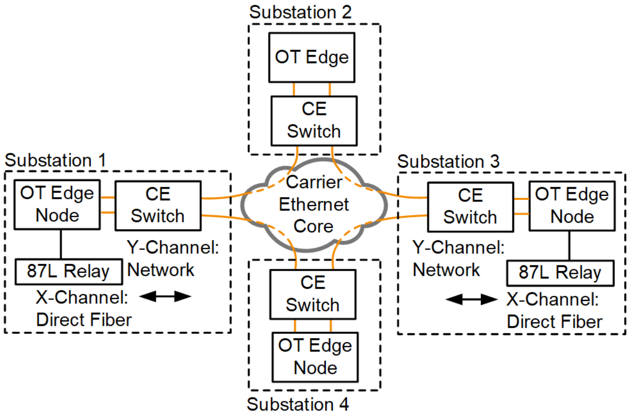


Fig. 5. Network Topology Showing 87L Teleprotection Circuit Paths.

Since Central Lincoln PUD utilized dedicated fiber for the primary channel on each relay, the study would be able to compare the network path against an ideal reference channel provided by direct fiber.

IV. OBJECTIVES AND METHODOLOGY OF THE STUDY

The objective of this case study is to evaluate the performance of two in-service line current differential channels simultaneously over a long period of time. Typically, the commissioning procedure for a line current differential relay verifies that all differential communication channels are available and relays are exchanging data as expected. The characteristics of each channel are verified to be within specific requirements determined by the user; availability, latency, asymmetry, and the received data match the expected values. However, the relays are expected to be in the field for years, but the commissioning procedure is at most a few days. What happens after the short commissioning procedure? The work Central Lincoln PUD did verifies that the performance of differential channels remains within tolerance over a long period of time.

The study directly compares a point-to-point fiber connection to either a packet-switched network or TDM/SONET network. Direct fiber acts as the control for this study because it can be assumed to be the best path of communicating differential data between relays. Therefore, the study evaluates the performance of the packet-switched or TDM/SONET network by comparing it to the direct point-to-point fiber channel.

V. METHODS OF DATA COLLECTION

We will discuss two methods that can be used when capturing data to conduct a study of the line current differential communication channels.

A. Relays With an Active Hot Standby Channel

The in-service relays used by Central Lincoln PUD for the study support two independent differential communication channels in the same relay. This paper refers to the channels as the X- and Y-channels. For the configuration of the relays used in this study, the X-channel was direct point-to-point fiber and the Y-channel was a networked communication path, either packet-switched or TDM/SONET.

The relays used by Central Lincoln PUD implement an active hot standby differential channel. The principle behind this concept is that the relay does the differential calculations twice every processing interval—once for the X-channel data and once for the Y-channel data—even though only one of the channels is actively being used by the relay differential protection algorithm. The active hot standby differential channel allows the relay to seamlessly switch between the X- and Y-channels, so that if anything were to cause the primary differential channel to drop out , the relay can instantaneously switch to the other available channel to perform line current differential protection. This transition from one channel to the other happens in the same processing interval. Event reports from this relay include both the X- and Y-channel data.

This paper uses the data from the event reports to analyze the performance of the differential channels. To acquire the necessary event reports for the analysis, the relay was programmed to trigger an event every hour for two weeks. The events were triggered and then immediately captured and stored. This resulted in hundreds of event reports for each two-terminal line being evaluated. It is important to note that this study had no impact on the availability of the protection of the relays involved. The value of using the event report as the mechanism of data collection is that it includes up to 1 second worth of differential data to be analyzed as opposed to a single processing interval of metering data, for example. When conducting a study of this nature, it is imperative to ensure there is enough data to make a conclusion about the performance of the differential channel.

B. *Relays Without an Active Hot Standby Channel*

This study can be replicated in relays that do not have an active hot standby channel as well. The setup requires that two separate relays at the same terminal be used. Each relay must be synchronized to a high-accuracy clock, because the time stamps in the event reports have to be used to compare the data from Relay 1 to Relay 2. For example, Relay 1 would have a direct point-to-point fiber connection and Relay 2 would have a networked communication connection. Event reports must then be triggered on both relays at approximately the same time, so that the event data in each relay overlaps. The two event reports could then be plotted together in event viewer software to evaluate the performance of each differential channel with respect to the other.

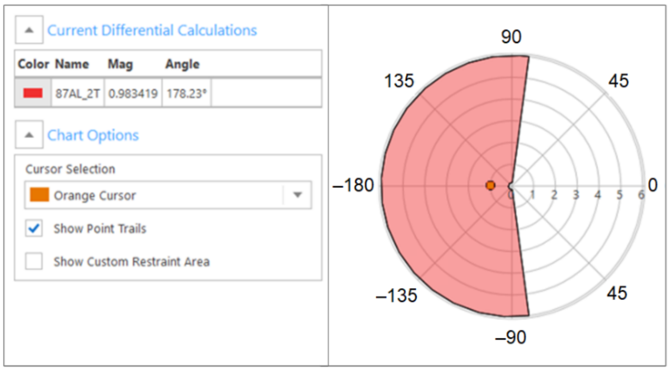
VI. DATA ANALYSIS

As mentioned previously, the relays that Central Lincoln PUD had in service on their system were equipped with an active hot standby channel. Therefore, the event reports captured for this study included both the X-channel (direct fiber) and Y-channel (networked communication) data from the remote terminal. However, the event report of the relay used the ping pong delay of the active differential communication channel to align the local differential current. The relay performed a differential calculation on the X- and Y-channel data, but the alpha plane data for the event report could only accurately be derived for the remote channel that was being used (X or Y). The reason was that the event report only included the local differential data once, when in reality, there were two versions of the local current because the communication delay was derived from the ping-pong calculation for the X- and Y-channels independently and may not be the same. For example, if the one-way channel delay for the X-channel was 1 millisecond and the Y-channel delay was 5 milliseconds, the local current had to be delayed by 1 millisecond to be aligned with the X-channel remote data, and the local current had to be delayed by 5 milliseconds for the Y-channel data. The event report did not include the data necessary to be able to determine the alpha plane for the channel that was standing by.

Since a direct comparison of alpha plane data for the X- and Y-channels could not be performed, data from the X- and Y-channels had to be combined to come up with a method to evaluate the performance of the networked communication channel, considering the following:

- The result of the alpha plane for the primary differential channel for load current (direct fiber in the case of Central Lincoln PUD) should be very near –1, as discussed previously. This revealed that the direct fiber channel was operating as expected and a relationship could be derived from it.
- Assuming the alpha plane data performed as expected, the analysis showed the angular relationship between the X-channel differential current and the Y-channel differential current. The expectation was that for two channels performing similarly, the angle between the similar X- and Y-channel phase currents should be the same throughout the event report. The expectation was that the Y-current would lag the X-current by approximately the same amount throughout each event report. The angular degree of separation should not only remain constant throughout the event, but also throughout the two weeks worth of data. It should be noted that the amount of separation is not of concern for this study. The performance of the channel was conducted by ensuring that the angular difference between the X- and Y-channels were not constantly increasing.

The data checks were simple. The alpha plane data could be derived from the information included in the event report. A plot of the alpha plane data for an event report was created by configuring the event viewer software to display the remote differential current from the active channel over the local differential current, as shown in Fig. 6. Some event viewer programs make this available without having to do a custom calculation.



▲ Current Differential Calculations

Color	Name	Mag	Angle
🟥	87AL_2T	0.983419	178.23°

▲ Chart Options

Cursor Selection

Orange Cursor ▾

☑ Show Point Trails

☐ Show Custom Restraint Area

Fig. 6. Alpha Plane Plot

The angular relationship between the X- and Y-channel data was derived through a custom calculation. A reference was assigned to the event data to simplify the equation used for the analysis. The equation then simply calculated the difference between the angle of the X-channel current to that of the similar phase of the Y-channel data. The equation was not necessary since it was simply using the phasor data. The phasor plot could have also been used, but it would only show a single data point of the event report, and a trend in the angular difference over the duration of the event would not be as easily identified. Then, the angular difference was plotted for the event report as shown in Fig. 7. In this example from Central Lincoln PUD's system, the A-phase local (IAL), A-phase X-channel remote (IAX), and A-phase Y-channel remote (IAY) data were compared. The B- and C-phase data were similar.

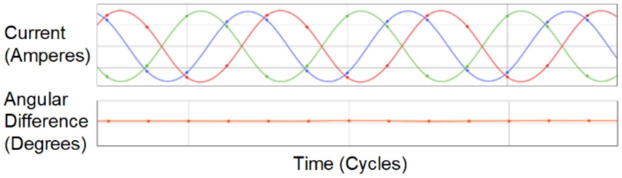


Fig. 7. Angular Difference Plot

The angular difference plot was flat over the time duration. This means that the phase relationship of the A-phase remote data that returned over the X-channel was stable compared to the data from the Y-channel. The flat angular difference plot indicated that the communication channel was performing identically to the direct fiber channel and there was no latency variation over time. Any latency variation would create a change in angular difference between the X- and Y-channels. Because we know the direct fiber channel is a perfect channel based on the physics of photons passing through a glass strand, any change in angular difference is due to latency changes on the communication network.

By capturing the angular difference over time, we can study the latency variation of the communication network and compare the relative performance of different networks.

The variance in angular difference between samples (i.e., the step change in measured angular difference between successive samples) correlates to the change in latency in the communication channel. By using the following relationship, where a 1 degree angular difference variation is equivalent to a 0.046-millisecond latency change for a 60 Hz system, we could derive an estimate of the maximum latency change exhibited on the channel to provide a numerical value to compare the performance of different communication networks. Identifying the largest step change could help make an approximation of the worst-case asymmetry of the channel compared to other channels measured.

In this study, we used this analysis method to compare the relative performance of SONET versus VSN over packet.

VII. TEST RESULTS

Testing was performed on four different relay schemes. Two of the relay pairs were using SONET for the Y-channel communication path, and the other two relays were using VSN over Carrier Ethernet. We will refer to each scheme as SONET Circuit 1, SONET Circuit 2, VSN Packet Circuit 1, and VSN Packet Circuit 2.

An event report was captured every hour from each relay over a two-week period. The data from each event report for each relay was combined into a single file to analyze trends over time.

Fig. 8 shows a sample data capture for a single day where the Y-channel is using the SONET network. The upper data plot shows the time capture with numbered hourly event reports. Because the analysis concatenates each event report into a single data set, there are discontinuities between the end of one event report and the start of the next. These discontinuities result in spikes in the angular difference plot. These should be ignored in the trend analysis of angular difference over time. In Fig. 8, the angular difference is stable over the 24-hour period with a very small variation from Hours 4 to 5, 21 to 22, and 22 to 23.

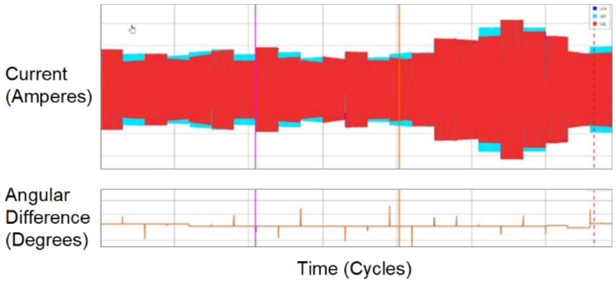


Fig. 8. Data Capture for a Single Day Showing Discontinuity Between Hourly Event Reports

A. *Latency Comparison*

By plotting the time view of the different network circuits versus fiber, a latency variation can be seen between SONET Circuit 1 and VSN Packet Circuit 2. Fig. 9 shows this in the phase difference between IAX and IAY. This phase difference is due to the latency difference in the network channel. VSN Packet Circuit 1 has lower latency than SONET Circuit 1. The relays were able to report channel latency for the Y-channel and are summarized as follows:

- Latency SONET Circuit 1: 6.2 milliseconds
- Latency SONET Circuit 2: 0.9 milliseconds
- Latency VSN Packet Circuit 1: 1.0 milliseconds
- Latency VSN Packet Circuit 2: 1.0 milliseconds

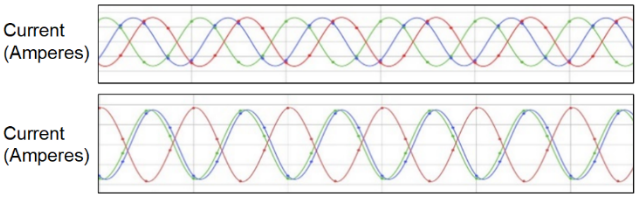


Fig. 9. Time Capture Showing Channel Latency of SONET Circuit 1 and VSN Packet Circuit 1

From the latency comparison, it can be concluded that VSN over packet provides a consistent latency, which is comparable to SONET. Fig. 10 shows the latency comparison between SONET Circuit 2 and VSN Packet Circuit 2. These circuits have similar latency.

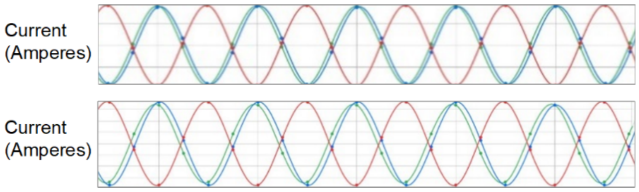


Fig. 10. Time Capture Showing Channel Latency of SONET Circuit 2 and VSN Packet Circuit 2

B. *Asymmetry Stability Over Time*

The goal of the study was to compare the latency and asymmetry stability over time of both SONET and VSN over packet compared to fiber. The following data shows the channel stability over a two-week period of the SONET and VSN circuits compared to direct fiber. As mentioned previously, the event reports were captured every hour and the angular difference was measured and plotted.

Each diagram shows the aggregated time capture of the event report data, the angular difference over time, the instantaneous phasor diagram of a single data point, and the alpha plane locus over time. The alpha plane was only plotted for the direct fiber channel. This is because the alpha plane data were only available for the active channel on the relay and not the standby channel. The alpha plane points are centered around the 1, 180 degree point, but the phase discontinuities between event reports cause spurious data points. Fig. 11 shows two data points that are in or close to the right-hand operate region of the alpha plane. These are due to phase discontinuity spikes, which can be ignored.

Fig. 11 shows the results for SONET Circuit 1. The angular difference variance results are summarized as follows:

- Minimum angular difference = 98 degrees
- Maximum angular difference = 137 degrees
- Angular difference variance = 39 degrees
- Maximum single variance step = 18 degrees
- Maximum estimated asymmetry = 0.8 milliseconds

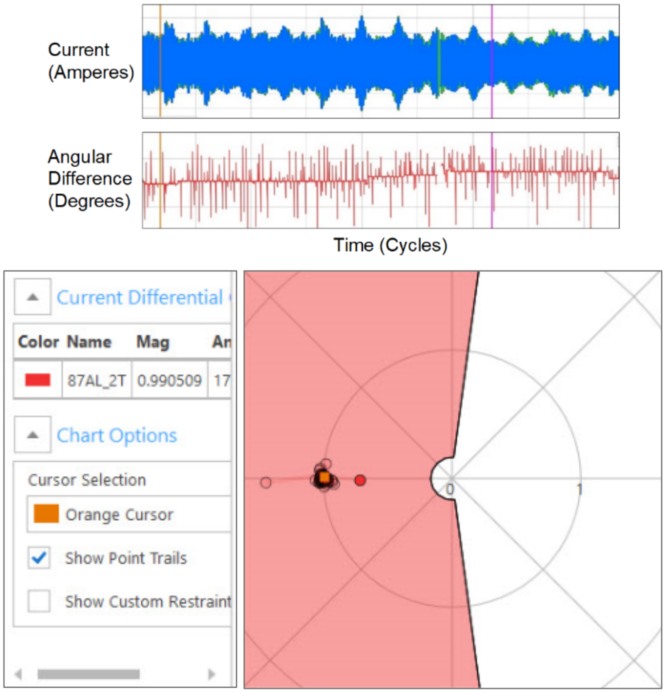


Fig. 11. SONET Circuit 1 Analysis Over a Two-Week Period

Fig. 12 shows the results for SONET Circuit 2. The angular difference variance results are summarized as follows.

- Minimum angular difference = 0.5 degrees
- Maximum angular difference = 25.5 degrees
- Angular difference variance = 25 degrees
- Maximum single variance step = 15 degrees
- Maximum estimated asymmetry = 0.7 milliseconds

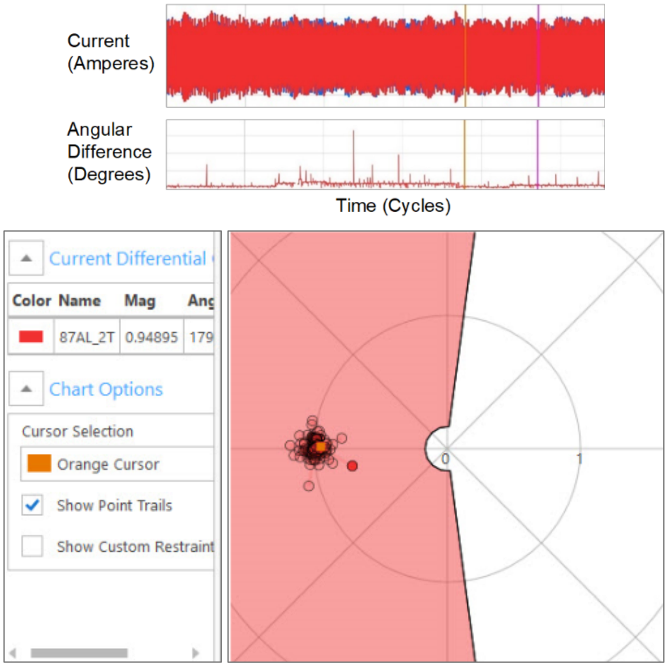


Fig. 12. SONET Circuit 2 Analysis Over a Two-Week Period

Fig. 13 shows the results for VSN over VSN Packet Circuit 1. The angular difference variance results are summarized as follows.

- Minimum angular difference = 10 degrees
- Maximum angular difference = 23 degrees
- Angular difference variance = 13 degrees
- Maximum single variance step = 13 degrees
- Maximum estimated latency step change = 0.6 milliseconds

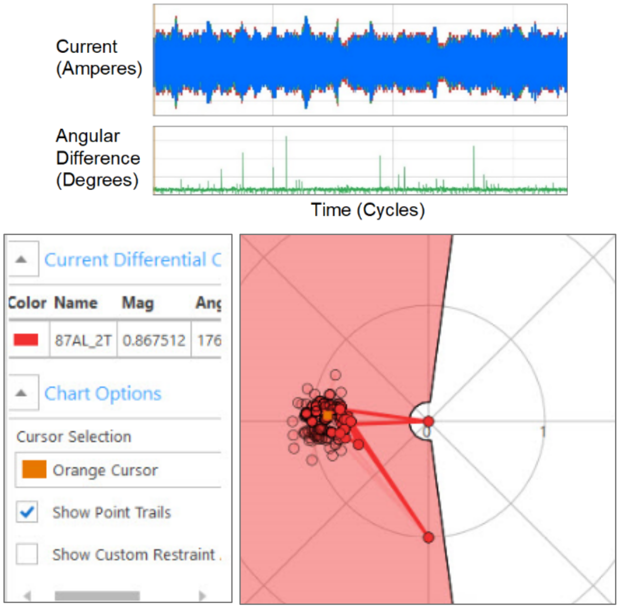


Fig. 13. VSN Over VSN Packet Circuit 1 Analysis Over Two-Week Period

Fig. 14 shows the results for VSN over VSN Packet Circuit 2. The angular difference variance results are summarized as follows.

- Minimum angular difference = 13 degrees
- Maximum angular difference = 26 degrees
- Angular difference variance = 13 degrees
- Maximum single variance step = 13 degrees
- Maximum estimated latency step change = 0.6 milliseconds

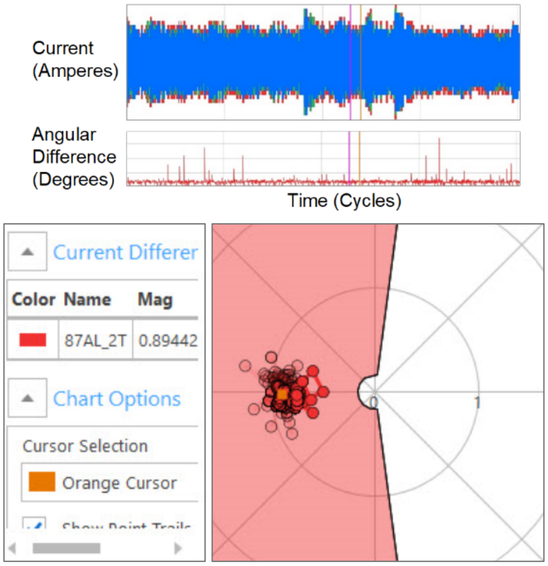


Fig. 14. VSN Over VSN Packet Circuit 2 Analysis Over a Two-Week Period

The OT edge nodes used for the VSN over packet network circuits were able to measure channel latency and asymmetry over the packet network from the reference point of the EIA-422 circuit used to communicate with the relay. It provides a single instance in time of the measured latency and asymmetry on each VSN packet circuit. The data are summarized as follows:

- Latency (primary path) VSN Packet Circuit 1: 0.175 milliseconds
- Latency (primary path) VSN Packet Circuit 2: 0.175 milliseconds
- Instantaneous Asymmetry VSN Packet Circuit 1: 0.009 milliseconds
- Instantaneous Asymmetry VSN Packet Circuit 2: 0.001 milliseconds

It is helpful to see the difference in values compared to the data captured from the relay event reports. There is additional overhead in the relay to process and transmit and receive data. An instantaneous measurement or series of measurements taken from the communication network interface are commonly used to provide an assessment of channel performance for relay circuits. This approach doesn't provide the depth of analysis needed to see the performance trend over time, and it doesn't show the view from the relay perspective on the data being used to measure the health of the power line being protected.

VIII. SUMMARY OF RESULTS

Table I summarizes the results of the study.

TABLE I
COMPARING SONET AND VSN OVER PACKET RESULTS

	SONET Circuit 1	**SONET Circuit 2**	**VSN Packet Circuit 1**	**VSN Packet Circuit 2**
Latency	6.2 ms	0.9 ms	1.0 ms	1.0 ms
Maximum angular variance	39°	25°	14°	13°
Maximum single variance step	18°	15°	13°	13°
Maximum estimated latency step change	0.8 ms	0.7 ms	0.6 ms	0.6 ms

IX. CONCLUSIONS

From studying the angular difference trend over time for each of the communication network circuits, we can observe that they all show a flat, stable trend over the two-week period and are similar to each other. SONET Circuit 1 shows slightly more change in angular difference over the analysis period: 39 degrees compared to 25 degrees for SONET Circuit 2 and 14 and 13 degrees for the VSN over packet circuits.

The more significant measure is the comparison of the maximum single step change in variance, which was very similar across all circuits tested. Again, SONET Circuit 1 had the largest step (18 degrees corresponding to an estimated 0.8-millisecond latency change). Both VSN packet circuits performed similarly with a 13-degree maximum step change that approximates to a 0.6-millisecond latency change. These data imply that the asymmetry of all channels was very similar with SONET Circuit 1, exhibiting slightly higher asymmetry than the other SONET channel and VSN over packet channels.

The key conclusion to draw from this study is that the VSN over packet method provides latency and asymmetry communication channel performance that is comparable to SONET. The stability performance over time with low latency and low asymmetry provides ideal characteristics for supporting line current differential protection. This is significant because the studies performed to date on native MPLS and Carrier Ethernet networks show a degradation in latency and asymmetry performance when compared to TDM/SONET. These results show that it is possible to maintain TDM/SONET performance over a packet network implementation and guarantee the same channel performance for critical protection circuits. This resolves many of the challenges associated with the migration to packet-based networks.

In addition, the analysis method provides a valuable analysis tool for studying the a communication channel over time to assess its suitability for supporting line current differential protection.

X. ACKNOWLEDGMENT

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XII. BIOGRAPHIES

Ron Beck is a network engineer for the Central Lincoln People's Utility District (Central Lincoln PUD) in Newport, Oregon. In this role, he is responsible for the design, engineering, and construction of the utility's telecommunication systems, local and wide-area networks, and cybersecurity systems. He was the primary architect of the communication infrastructure for Central Lincoln PUD's Smart Grid Investment Grant and Grid Modernization projects. He is presently serving on UTC's Board of Directors as the Past Chairman. He is a member of the InfraGard Oregon Alliance Chapter, is engaged with the National Cybersecurity Center of Excellence at NIST, and is an active member in several other industry advisory efforts.

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