Solving the Inherent Problem of Transporting Serial Teleprotection Circuits Over MPLS

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Summary

In a growing power industry trend, utilities are moving away from using traditional synchronous optical network (SONET) and synchronous digital hierarchy (SDH) systems for wide-area network (WAN) communications. Information technology (IT) teams and equipment manufacturers are encouraging utilities to implement a different kind of technology that offers greater bandwidth efficiency: a packet-switched Ethernet network.

The technology migration comes with a challenge for utility communications engineers, who must now design packet-based pilot channels that still meet the strict performance and determinism requirements of protection applications. This paper describes a deterministic transport solution that provides guaranteed, low latency for critical traffic transported over packet-switched Ethernet networks. The solution is compatible with both Multiprotocol Label Switching (MPLS) and Carrier Ethernet systems.

This paper provides performance data for the solution from live network implementations, including data on latency, asymmetry, and packet delay variation (also known as "jitter"). These data demonstrate the ability of a deterministic packet-switched Ethernet network to support direct transfer trip (DTT) and line current differential protection performance across mixed transport network topologies.

Keywords

Carrier Ethernet, Multiprotocol Label Switching (MPLS), packet-switched Ethernet network, teleprotection, time-division multiplexing (TDM), wide-area network (WAN).

1. Introduction

Time-division multiplexing (TDM) was widely adopted by utilities across the power industry as the preferred technology for wide-area network (WAN) transport because it provided low-latency, deterministic, and minimal-asymmetry performance. However, the industry is increasingly turning to packet-switched Ethernet networks for all utility applications and services, including protection. The industry switch from TDM-based systems is driven by a widespread desire to converge information technology (IT) and operational technology (OT) networks and standardize on a common set of interfaces to reduce capital and operating expenses.

However, teleprotection interfaces such as IEEE C37.94, G.703, and MIRRORED BITS communications require a deterministic channel and reliable data transfer. The migration to packet-switched Ethernet network technologies such as Multiprotocol Label Switching (MPLS) and Carrier Ethernet has challenged utilities to engineer teleprotection services that provide the determinism and guaranteed performance required by protection applications.

This paper, a compilation of [1] and [2], describes a solution that addresses this challenge. A virtual synchronous network (VSN) can transport serial teleprotection channels (such as IEEE C37.94) over MPLS or Carrier Ethernet while maintaining TDM performance for relay protection applications.

2. Communications Channel Performance Requirements

Three key communications channel performance requirements for teleprotection are latency, asymmetry, and restoration time. Several standards specify communications channel performance requirements for electric power substation applications, including IEEE 1646 and IEC Technical Report (TR) 61850-90-12 [3] [4]. Table 1 summarizes protection circuit communications channel performance requirements derived from these two standards as well as relay manufacturer requirements.

Table 1 Communications Channel Performance Requirements for Protection Circuits

Scheme	Latency (ms)	Asymmetry (ms)	Restoration Time (ms)
Line current differential protection	5	<0.5	5
Pilot protection	8	5	5
Direct transfer trip (DTT)	10	5	5

The first key requirement is latency. IEEE 1646 and IEC TR 61850-90-12 define communications channel latency requirements for teleprotection schemes. For critical transmission lines, IEC TR 61850-90-12 specifies a latency of no longer than 5 milliseconds for line current differential communications circuits.

The second requirement is asymmetry. Line current differential schemes that use channel-based timing cannot operate with a channel asymmetry longer than a quarter power cycle (4 milliseconds). Depending on the specific line being protected, some applications require the differential element to be able to operate when the current deviates by 10 to 20 percent from the norm. For a scheme to achieve data-alignment accuracy of 1 electrical degree, which equates to a spurious differential current of less than 1 percent of the through current, the channel asymmetry must be 0.05 milliseconds or better. Many high-sensitivity, high-speed line current differential schemes are designed to trip when the fault current deviates by 10 percent from the norm, which requires a channel asymmetry of 0.5 milliseconds or less.

The final requirement is communications channel restoration time. Line current differential protection implementations are very sensitive to data loss. Some relays interpolate data when a single data packet is missing. However, the loss of successive data packets often forces a relay to limit the risk of a misoperation by blocking the differential protection element until the communications channel is restored and the relay receives a confidence window of data. Depending on how long the communications channel is lost, the relay may need to completely resynchronize, which blocks the differential element for a much longer period (a second or more). Achieving a restoration time of 5 milliseconds or less guarantees minimal impact to the line current differential protection function and ensures the highest level of protection for a critical power transmission system.

Packet-switched Ethernet network technologies such as MPLS and Carrier Ethernet have difficulty meeting the stringent communications channel requirements of line current differential relays.

3. Achieving TDM Performance Over Packet-Switched Ethernet Networks

The power industry has long relied on TDM communications technologies such as T1, SONET, and SDH to carry teleprotection traffic. TDM is an ideal solution for teleprotection because it is a synchronous system that uses a common clock to maintain network timing. It also dedicates bandwidth to each communications circuit. TDM provides deterministic, low-latency, and low-asymmetry communications circuits with guaranteed performance that is unaffected by other traffic on the network.

Packet-switched Ethernet network technologies such as MPLS and Carrier Ethernet are unable to offer the same guaranteed low latency and asymmetry performance as TDM for synchronous circuits. These technologies are asynchronous, using shared bandwidth to transport data efficiently and manage a wide range of data services with varying traffic loads. When a packet-switched Ethernet network transports synchronous serial circuits that require low latency, the system typically requires large jitter buffers and significant bandwidth. This increases latency and degrades asymmetry performance compared to TDM and makes the migration of serial teleprotection channels to Ethernet very difficult [5].

Even though the latest generation of line current differential relays offers an Ethernet teleprotection channel interface, this option only improves latency by removing the serial-to-packet conversion process. For MPLS and Carrier Ethernet networks carrying large numbers of protection circuits, the variation in queuing delays through network elements can still impact asymmetry. Priority-queuing methods are challenged when all traffic is classified as high-priority. Most significantly, even after an Ethernet teleprotection interface is adopted, both MPLS and Carrier Ethernet do not meet restoration time requirements: restoration times for MPLS are typically 50 ms or greater and Carrier Ethernet restoration times are typically about 20 ms.

VSN technology transports serial and Ethernet-based teleprotection channels over MPLS and Carrier Ethernet while maintaining TDM performance for protection applications. VSN technology maintains a synchronous network by using a TDM engine as the primary communications method. The TDM subsystem provides a synchronous interface for each teleprotection serial circuit. On top of the TDM subsystem, a packet-switched Ethernet network is implemented. To be more bandwidth-efficient, this system packetizes native SONET data at the VT1.5 or STS level (rather than DS0). The Ethernet packets are standard Layer 2 frames that contain the SONET data along with synchronization information and the network management system (NMS) channel.

To maintain the synchronous operation of the TDM engine, the TDM engine must transmit Ethernet packets at regular intervals. The packet-switched Ethernet network must also guarantee Ethernet packet delivery within an acceptable packet delay tolerance. The VSN implementation is shown in Figure 1. Its network requires much smaller jitter buffer sizes to manage the packet delay variation through the core network. Typical VSN implementations use a jitter buffer size of 200 microseconds.

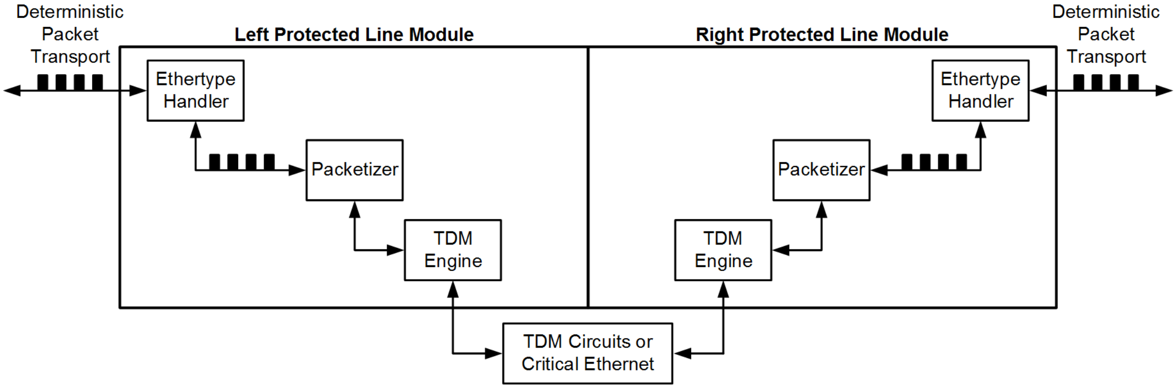

Figure 1 VSN Implementation

By maintaining the synchronous principle of TDM, VSN technology transports serial circuits with almost the same performance as a native SONET network. Although the end-to-end latency of VSN technology is increased by size of its jitter buffer, determinism is maintained and the asymmetry is very close to that of native SONET.

In a VSN implementation, fixed or static paths are provisioned across the core to create a ring topology, as shown in Figure 2. This topology has several 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 node device in less than 5 milliseconds.

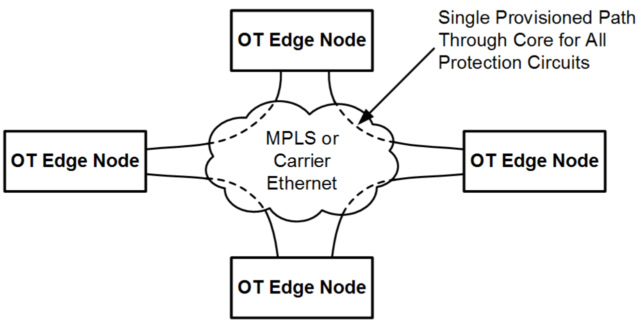

Figure 2 VSN Ring Topology Supported by Static Paths Through Core

4. Performance Test Results of VSN

The VSN technology performance testing was tested by a third-party consultant in the consultant's test facility. The consultant tested VSN implementations across MPLS and Carrier Ethernet core network equipment. Figure 3 shows the test network topology used.

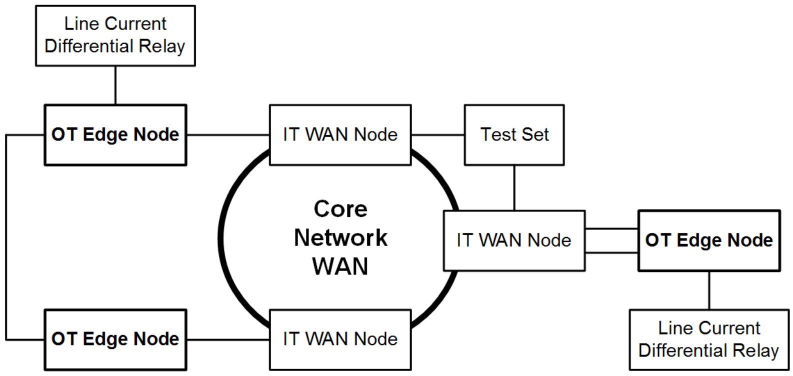

Figure 3 Performance Test Network Topology

The test configuration used a pair of line current differential relays with an IEEE C37.94 interface to establish a line current differential teleprotection circuit across a packet-switched Ethernet network. In Figure 3, the packet-switched Ethernet network is represented by the three IT WAN nodes. The OT edge nodes in the topology provide the VSN function, support the IEEE C37.94 interface to the relays, and provide an Ethernet transport interface to the core network. A test set provided a method for adding Ethernet traffic to the network; this allowed for testing under network load conditions. The two line current differential relays measured and reported channel performance statistics (latency, asymmetry, and packet loss). The consultant tested three core networks set up using equipment from different manufacturers.

For the Carrier Ethernet network test, the VSN traffic was given a Fixed Resolved Class of Service (F-RCoS) of zero and the traffic from the test set was given a F-RCoS of seven. For the MPLS network testing, the VSN was assigned a forwarding class of High 1 (H1) and the traffic from the test set was assigned a forwarding class of Expedited (EF).

The testing was performed first over Carrier Ethernet and then with MPLS equipment inserted in place of the IT WAN nodes shown in Figure 3. A series of five separate measurements was made during each test. The average latencies and asymmetries of each series are shown in Table 2.

Table 2 Communications Channel Performance Test Results

Parameter	**VSN Baseline Without Core Network (ms)**	**VSN and Carrier Ethernet Service (ms)**	**VSN and MPLS, Equipment Setup 1 (ms)**	**VSN and MPLS, Equipment Setup 2 (ms)**
Latency	0.05	0.5	0.5	0.4
Asymmetry	0	0.06	0.12	0.19

The individual VSN OT edge nodes used a variable-size jitter buffer adjusted with a packet delay variation setting to optimize latency through each IT core network. The jitter buffer was set at 50 microseconds for the Carrier Ethernet network and 200 microseconds for the two MPLS networks.

Network healing tests were also performed to measure the comparative performance of edge versus core network failovers. The network healing performance for VSN paths can be optimized by provisioning unprotected point-to-point tunnels through the core network. (These tunnels are illustrated as dotted lines in Figure 2.) Network healing is then performed by the VSN OT edge node devices rather than by the core network. Network healing test results are shown in Table 3.

Table 3 Network Healing Test Results

Failover Method	Technology	Failover (ms)
Core network	Carrier Ethernet	~20
	MPLS	~50
Edge network	VSN	<5

5. Achieving Low-Latency Teleprotection Over Leased Ethernet Circuits

Thousands of substation sites across North America rely on the predictable and guaranteed performance of analog leased phone lines to run critical power protection circuits. However, national carriers plan to discontinue support for analog-based circuits over the next few years to encourage the migration of power protection services to digital Ethernet-based circuits.

Extended field trials were performed by the utility Consumers Energy in Michigan, USA, to characterize the end-to-end latency performance of both a DTT scheme and a line current differential scheme over a leased Ethernet service. The results show that VSN can be used to improve the latency performance of a leased Ethernet circuit, exceed analog communications channel performance, and provide an economical migration path from analog to Ethernet, avoiding the need to upgrade utility end equipment.

Figure 4 shows the performance results for a DTT scheme running over a leased Ethernet circuit. The circuit ran between two substation sites located 19 miles apart. The channel performance was monitored over a period of five months, and in that period, only one 24-hour interval recorded an outage that could not be accounted for. This outage lasted for 2 minutes and 33 seconds. Consumers Energy is working with the carrier to determine the exact cause. At this time, they suspect that a firmware upgrade to core switches caused the outage.

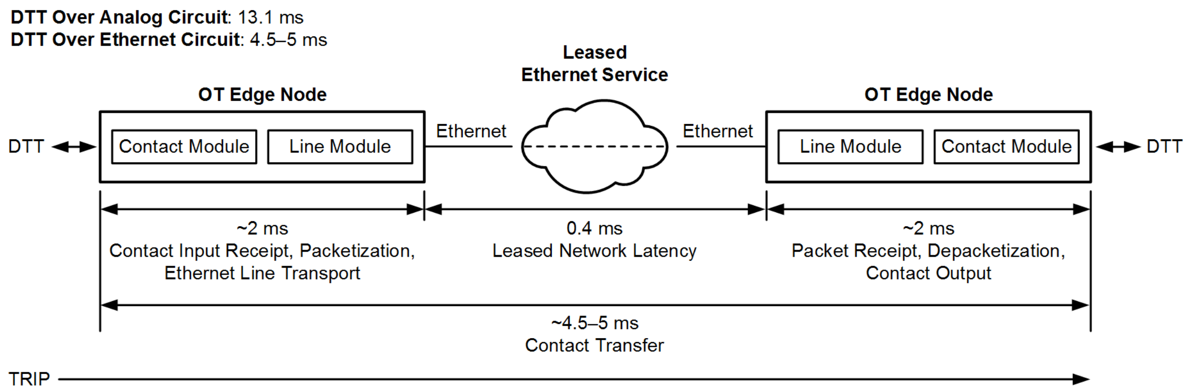

Figure 4 Live DTT Circuit Substation Results

From a communications-channel perspective, line current differential is the most challenging type of teleprotection scheme to support because of its tight latency and asymmetry requirements. For this reason, utilities have avoided using leased circuits to support such schemes. However, the channel performance of the OT edge node device during DTT testing, along with its interface capabilities, prompted Consumers Energy to consider using VSN technology to support a line current differential circuit over leased Ethernet.

To evaluate the long-term performance of the channel and the feasibility of the scheme, Consumers Energy installed a pair of protective relays and ran a live current differential protection channel across the leased Ethernet circuit. The protection relays measured the performance of the communications channel. Table 4 and Figure 5 show the results from a four-month trial.

Table 4 Line Current Differential Trial Performance Results

Parameter	**Line Current Differential Performance**
Round trip delay	2.3 ms
Transmit delay	1.2 ms
Receive delay	1.1 ms
Asymmetry	0.08 ms
Number of dropped packets	0 (except for 1 network outage)

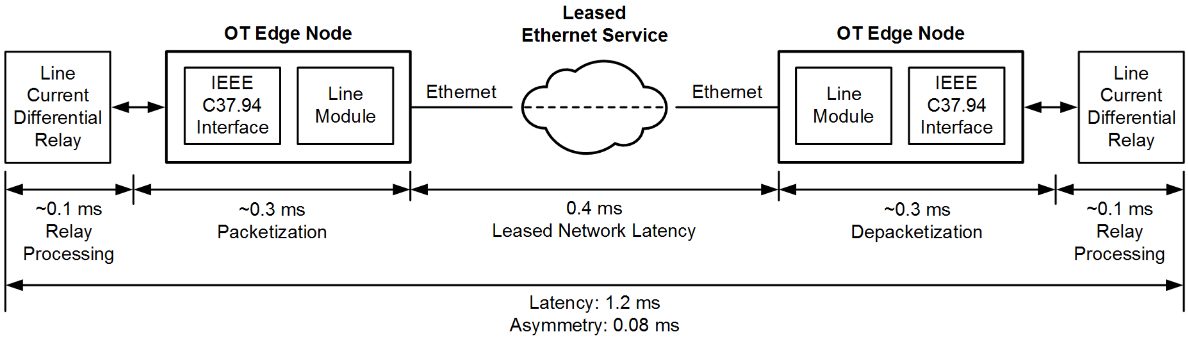

Figure 5 Live Line Current Differential Circuit Substation Results

The results from the live field testing are significant because they show measured DTT and line current differential scheme performance levels equivalent to the expected performance of a private fiber-optic network using TDM equipment. The implications for the power industry are far-reaching. These results illuminate opportunities for utilities to use leased Ethernet circuits in a wide variety of protection schemes, including line current differential protection schemes.

6. Conclusions

VSN technology can convey mission-critical protection and control system traffic over a packet-switched Ethernet network without impacting protection application or network performance. The communications channel performance attributes of this solution meet the requirements specified in IEEE 1646 and IEC TR 61850-90-12.

Because it is standard-agnostic, VSN technology is interoperable with packet-switched Ethernet network technologies, such as MPLS and Carrier Ethernet. Utilities can now migrate protection circuits from TDM-based to packet-based transport technology in an elegant manner, because with the VSN solution, OT network design, planning, and implementation are greatly simplified. This is especially true for complex networks that use equipment and transport technology from multiple manufacturers for substation edge and core network elements.

The VSN solution uses a simplified provisioning model that easily scales as the network topology changes and grows. Because the implementation uses point-to-point tunnels through the core network that have the highest quality of service setting below the NMS, critical circuit performance is maintained even as changes are made on the network. Therefore, each protection circuit does not need to be managed individually. Even though the VSN traffic has higher priority, the added delay for all other traffic is negligible (a maximum of 0.1 microseconds for each network link in a 10 GigE core network).

VSN technology offers the same performance benefits when applied to leased Ethernet network services. After a migration from leased analog to leased Carrier Ethernet circuits, VSN technology can serve as a suitable teleprotection channel solution for DTT and line current differential protection schemes.

In summary, VSN technology offers the following benefits: it guarantees protection channel performance for serial- and Ethernet-based relay teleprotection schemes over MPLS and Carrier Ethernet packet-switched networks; it bundles all substation circuits into a single static path, reducing the complexity associated with provisioning and managing separate paths for each packet-switched Ethernet network protection circuit; and it creates a demarcation between IT and OT that allows OT teams to manage all of the protection circuits.

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