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Redundant Passive Optical Network (PON) Transport for Grid Intelligence

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SUMMARY

ComEd has developed an industry first, redundant, Passive Optical Network (PON) solution to refresh the current operating management communications system for the power grid to improve access, increase speed of messaging, increase control management, and provide more robust security for various field communicating and edge computing devices. Communications infrastructure forms the foundation of enabling technologies and applications as it touches each functional area of the Smart Grid. Consequently, the communications infrastructure must provide a secure, tiered, robust, and deterministic converged communications architecture with adequate capacity to meet the current and foreseeable future capacity and performance requirements of the ComEd distribution devices portfolio.

In an effort to enhance the reliability and resiliency of the ComEd electric system, and to address the growing and changing needs of its customers, ComEd seeks to create a modern Smart Grid that uses advanced sensing, communications, and control technologies to generate and distribute electricity more effectively, economically, and securely. These improvements target innovative, yet utility industry proven, tools and technologies on the grid that will enhance flow from generation, transmission, and distribution to the end points of customer appliances and equipment.

This iteration of the Smart Grid network utilizes PON technology implemented in hardware suitable for deployment in field conditions and in or near the harsh substation environment, configured to be interconnected in multiple, redundant, self-healing backbone ring and tree communications infrastructures. PON has been evaluated to meet the requirements of a high speed, high bandwidth, low latency, secure, and scalable communication infrastructure for power Distribution Automation (DA), Voltage Optimization (VO), Advanced Metering Infrastructure (AMI), among other utility applications to benefit the resiliency and reliability of the electric grid. This technology integrates with the core communications network, which is the primary path to Operations Control Center (OCC), Network Operations Center (NOC), SCADA and other real-time systems. The PON infrastructure core is very robust with no

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single points of failure and is architected in a self-healing ring topology or point-to-point with backup circuit redundancy.

The PON technology is connected to the core network, in a communications hut/facility, at or near the substations, with distributed connectivity to 300+ communications huts/facilities, for the management of electrical power reclosers and other Electric Utility applications, in targeted communities or communication schemes. The design provides for required peer to peer communications together with operations control centers visibility for control of the automated power distribution networks. While this architecture is dependent on the physical fiber routing, the design must adhere to this fundamental requirement even if not deployed uniformly. To ensure that the backup fiber optic communications are available if needed, both primary and secondary fiber optic signal paths are to be deployed, monitored, and managed. The design contains redundant management and control of the power DA (and other) equipment such that in the event of a disaster which makes a communications hut facility completely inoperable, that another communications hut facility, at a different location, takes over the communications to the power DA (and other) equipment resources, maintaining system management and control. This differs from traditional PON deployments in that the dual feed into the device provides redundancy to geo-diverse OLTs for a more resilient network (eliminates the single point of failure).

KEYWORDS

PON - Passive Optical Network is the leading fiber access technology for delivering gigabit internet services to residential and business subscribers.

GPON - Gigabyte Passive Optical Network G.984 is a standard for passive optical networks.

EDRP – Expedited, Deterministic, Redundant, PON

OLT – The Optical Line Terminal is Common Aggregation Point

ONT – Optical Network Terminal – End Access Device

ONU – Optical Network Unit, synonymous with ONT

CPE – Customer Premise Equipment is a Layer 2 switch collocated with the end device that Communicates via fiber to other end devices.

Splitter - The fiber optic splitter, also referred to as optical splitter, is an integrated waveguide optical power distribution device.

PON Domain – Communication huts and downstream endpoint devices within a given backbone fiber ring.

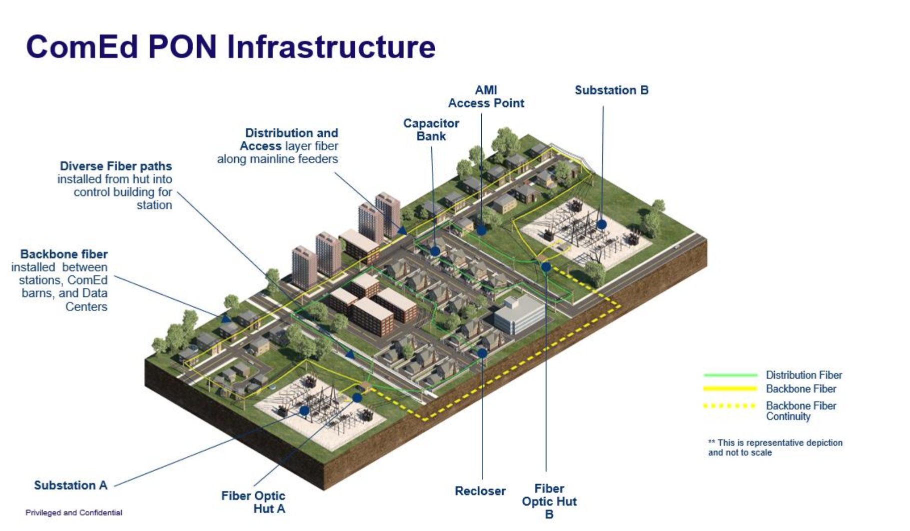
G.8031 ELPS – Ethernet Linear Protection Switching Defines the APS protocol and linear protection switching mechanisms for point-to-point VLAN-based ETH Sub Network Connection (SNC) in Ethernet transport networks.

Leaf-spine Architecture – Leaf-spine architecture is a network switch topology type that consists of two switching layers—a spine and leaf.

COMED EDRP DEPLOYMENT

An expedited, deterministic, redundant, PON (EDRP) as described herein, is a communications infrastructure configured to provide a secure tiered, robust, and deterministic converged communications architecture. The systems described provide infrastructure for power distribution automation (DA), voltage optimization (VO), advanced metering infrastructure (AMI), and other current, and future utility applications. A PON-enabled core communications network provides a primary path to network management devices, OCC devices, hut communication devices, and enables the required communication path to support SCADA, Generic Object Oriented Substation Events (GOOSE), Generic Substation State Events (GSSE) and advanced distribution protection schemes. The core of the PON network provides failover support between uplinks to the broader smart grid network (or data centers) via all geo-diverse telecommunications components (e.g., routers, optical line terminating (OLT), optical network terminals (ONT) devices, etc.). The maximum latency between end devices communicating over the network (reclosers, PMUs, etc.) should always be less than 10milliseconds to meet the communication requirements of advanced Utility applications. In addition, the failover time between primary and standby communication path occurs in less than 15milliseconds (less than one electric cycle at 60 Hz AC.) The system supports multiple configurations, such as tree configurations, linear configurations, ring (e.g., multi-ring, etc.) configurations, ring spur configurations, and/or the like. It will also support enterprise applications and communications for private networks and corporate network access. It also supports all industry-standard protocols and applications and operates in a deterministic manner that enables a clear understanding of latency, throughput, capacity, routing algorithms, peer-to-peer communications, data prioritization, encryption, and failover schemes. The PON core network is exceptionally reliable, with high availability for all components, and is self-healing due to its robust architecture which boasts no single points of failure. Figure 1 depicts an example deployment of 2 fiber optic communication huts housing the core PON network, distribution fiber paths connecting to field devices, as well as backbone fiber paths utilized for core network (or 'hut to hut' communications.)

Figure 1



The redundant PON network infrastructure contains redundant management and control of devices, such as power distribution automation (DA) equipment. In the event of a disaster that makes a component of the system, such as a communications hut/cabinet inoperable, another component, such as another communications hut/cabinet, at a different location, takes over the communications to the power distribution automation (DA) equipment, and/or any other device, component, equipment, and/or resource of the system to the communication system is always available. The system utilizes a multi-ring structure which contains primary and secondary fiber optic signal paths (e.g., via 1GE protected links, 10GE protected links, etc.) which are monitored and managed. This self-healing, two-fiber, path protection switched ring configuration includes at least two transmitter/receiver sets per location/node with at least one transmitter/receiver set for each direction in a ring. Each location/node of a ring includes one or more circuits of a plurality of circuits (and/or communication configurations) that interconnect and/or are in communication with the ring. Transmit and receive directions for each circuit of the plurality of circuits propagate over the same path around the ring. In the event of a single fiber failure (and/or any other problem/issue, etc.) that affects one direction of transmission only, both transmit and receive portions of selected circuits shall be able to switch simultaneously to minimize propagation delay differences between transmit and receive.

FIG. 2 shows a PON domain with uplinks to core data centers via existing substation network connectivity for utility infrastructure resiliency and provides an example of the ‘leaf-spine’ topology utilized for the PON core. In this example, huts 1 and 6 serve as the ‘spine’ of the PON core for all other huts in the network topology. The spine huts serve as the redundant aggregation points for all other huts within the PON domain. In addition, spine huts also serve as the communication path to the broader Smart-Grid, Data Center, and control system networks. For example, LEAF Hut-2 will include an optical line terminal (OLT) which connects to a passive optical splitter, and LEAF Hut-3 will include an optical line terminal (OLT) which also connects to a passive optical splitter. The OLTs will be common aggregation points for communications/services from field devices/assets, such as optical network terminals and end access devices. The OLTs provide redundancy and/or fail-over protection for each other. For example, if LEAF Hut-2 is impaired, inoperable, and/or malfunctioning, LEAF Hut-3 may take over communications and/or services provided/executed by LEAF Hut-2 and vice versa. Each LEAF hut will also have redundancy to both SPINE huts via direct fiber connections. This SPINE hut redundancy will provide an alternate path to the data centers if a SPINE hut were impaired, inoperable, or malfunctioning. For example, LEAF Hut-2 will communicate with SPINE Hut-6 if it loses communication with SPINE Hut-1. This topology ensures that no single point of failure will prevent the endpoint distribution field devices from reaching the core data centers.

Figure 2

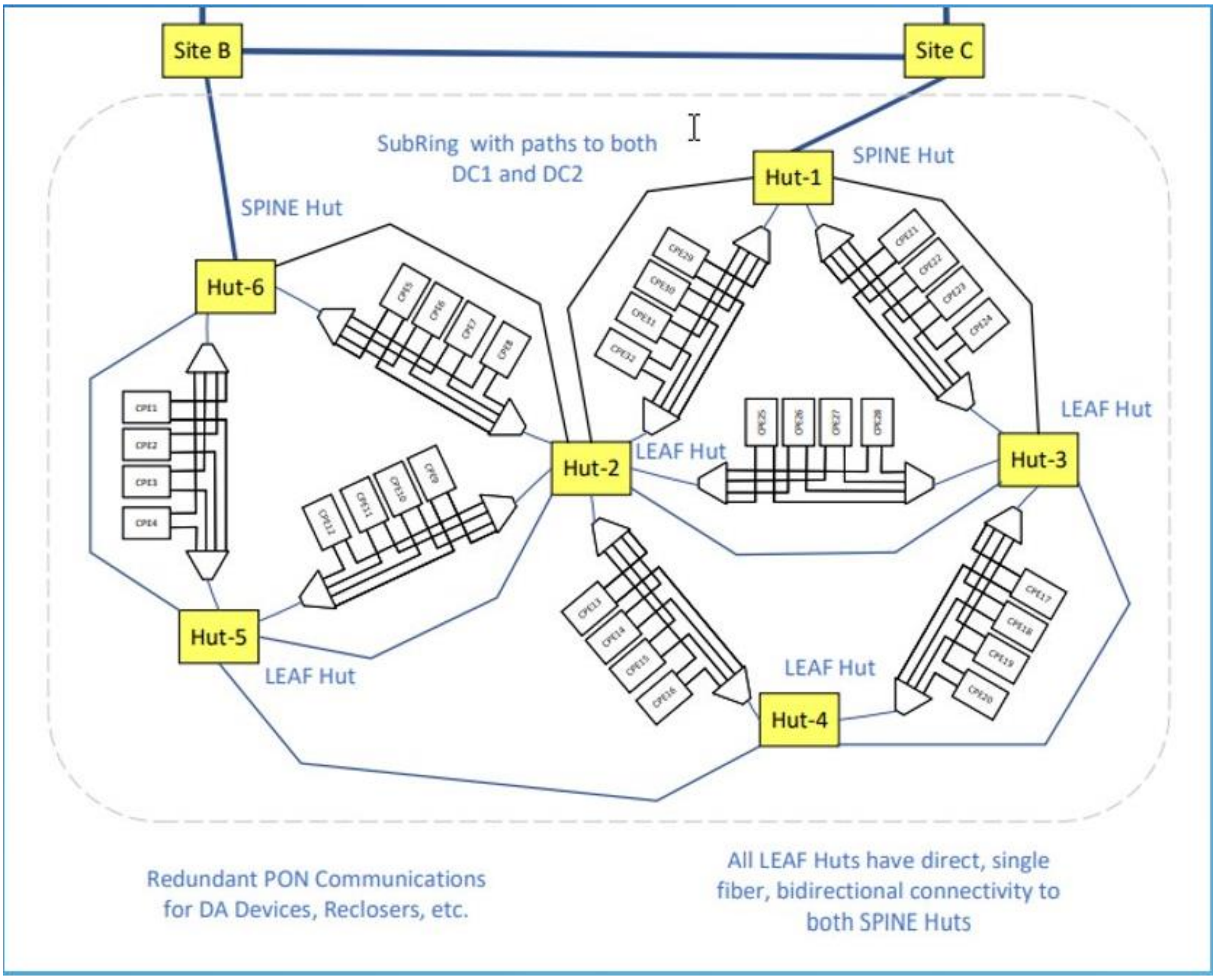


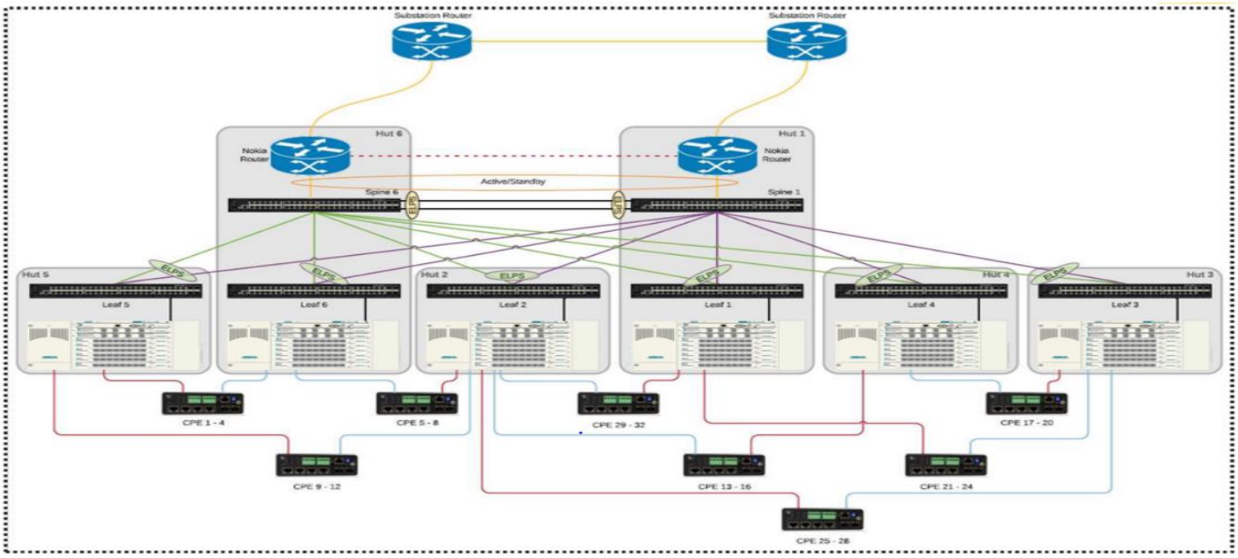
Figure 3 shows a more detailed example of components utilized within an EDRP network. The system may be used to support and scale up communications of increased amount traffic and backup data path(s) of distribution automation devices, after any network issue that redirects traffic to an alternate or protect path.

The primary backbone consists of a high-capacity fiber optic communication path which is configured to prevent any single point of failure and connects to all fiber optic huts within a given EDRP PON domain. This backbone fiber typically is routed in a ring configuration to each of the fiber optic huts within a geographical region to and provides geo-diverse redundant paths to/from each leaf hut to spines.

Smaller, regional rings will be routed along distribution feeder fiber paths to connect to the endpoint field devices (DA, VO, AMI, etc.) These regional or distribution fiber optic links will follow the electrical distribution feeders in order to maximize the number of devices to be connected and provide the required infrastructure for any future devices as well. By following the power distribution with fiber, we can target DA, VO, and AMI devices to benefit from the fast fail-over and control management among other benefits. The endpoint utility devices are connected to the network via a local PON CPE + dual ONTs with redundant fiber links which connect back to diverse Leaf Hut OLTs.

Each of the communication huts will be in communication with redundancy units within the PON domain. The OLT will include redundant passive optical splitters/combiners in communication with at least one other OLT. The splitters/combiners of each redundancy unit create fiber optic physical access for multiple ONT as depicted in the Intellirupter in figure 5. The ONTs and OLTs are configured for Gigabit Passive Optical Network (GPON) [3] bidirectional communications over single trunk fiber optical cables. Each PON CPE will have an active/working communications path and an inactive/protective communications path. If an ONT which serves as the active path experiences a fault, the secondary or protect path will resume the communications of the CPE with little no loss of telemetry.

Figure 3



PON CPE DEPLOYMENT EXAMPLE

PON CPEs may be located on utility poles, bollards, or pedestals along a distribution route throughout an area and/or region. The ONTs are installed within the CPE devices to provide two optical paths in/out of each device. Due to the small form factor of the CPEs and SFP-ONTs this makes it possible to retrofit existing DA, VO, and AMI devices and design a wide array of new devices which will create a more intelligent grid. For example, in figures 4 and 5 a PON CPE is located on a utility pole within the IntelliRupter communication module. The splitters/combiners of each redundancy unit create fiber optic physical access for multiple ONT as depicted in the Intellirupter in figure 5. ComEd Distribution Standards has worked with its various vendors to develop installation standards that incorporate the PON CPE device into existing device communication modules. Each CPE utilizes two redundant ONT's connecting back to two geo-diverse OLTs within the PON core.

Figure 4

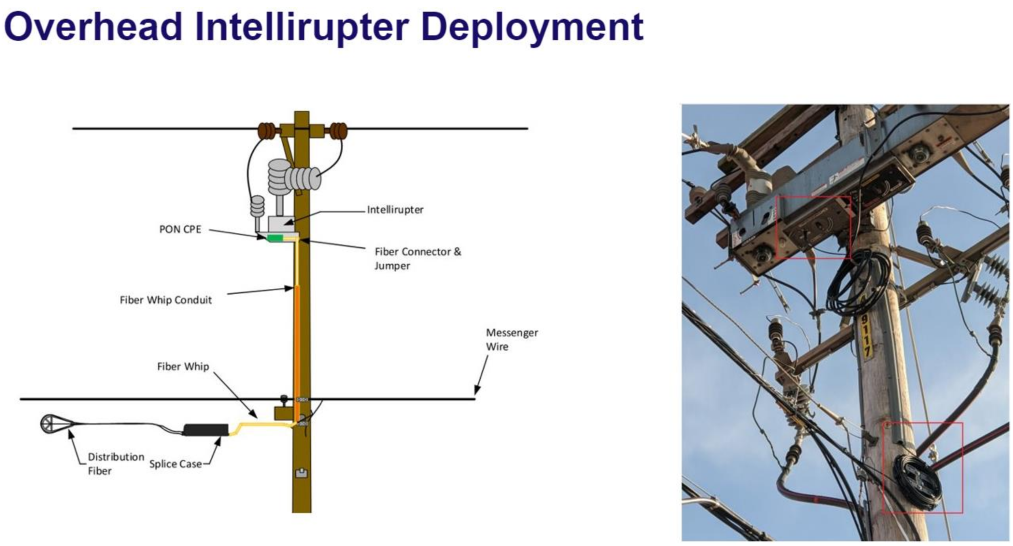
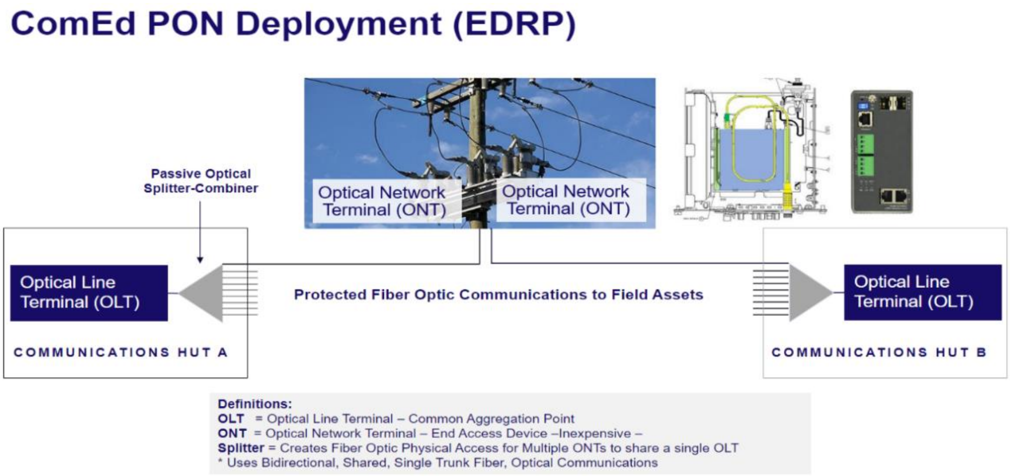


Figure 5



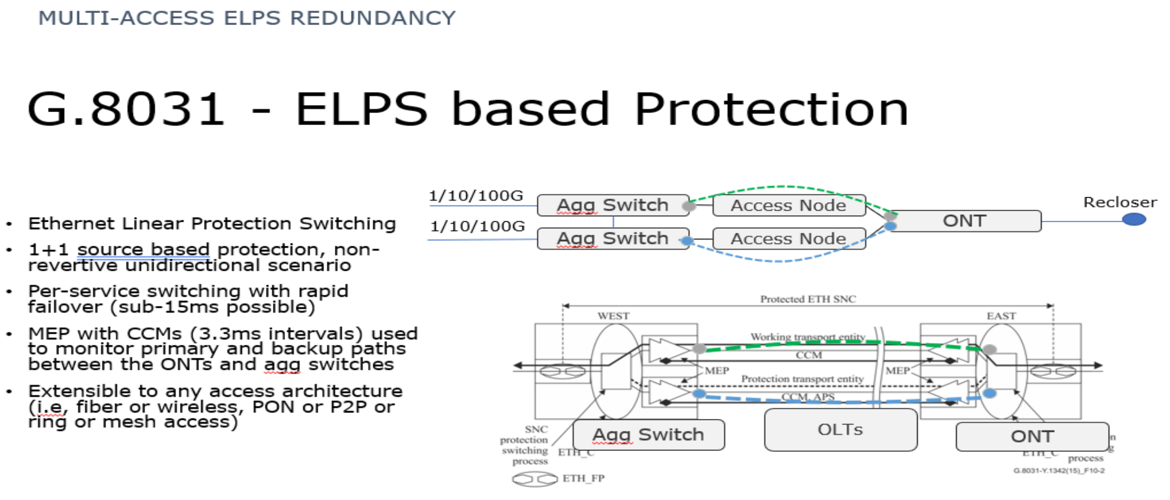
The CPE and ONTs have a small footprint with an ability to be configured with distribution automation devices and endpoint devices which is a key benefit as redundant PON can be retrofitted where existing radio devices are utilized. They have low power consumption and flexible control/configuration options. They are also temperature hardened (e.g., operating without failure or degradation throughout a temperature range of -40 to +70 degrees C (-40 to +158 degrees F) with a relative humidity of 5 to 90% non-condensing, etc.), lightweight, and easy to install (e.g., modular, etc.). No large external cabinet is required to install the ONTs, and no environmental controls are typically required to mitigate the temperatures within the devices irrespective of the outdoor climate and conditions.

They will include at least two diverse and/or redundant routing devices which are configured to behave as a single logical entity utilizing, for example, MC-LAG (Multi-Chassis Link Aggregation Group), VRRP [1] (Virtual Redundant Routing Protocol), and/or similar methodology. The network traffic is segregated into VLANs for each device group type (i.e., DA, AMI, VO, etc.).

EDRP FAST-FAILOVER VIA ELPS

The fast fail-over target failover time of 15milliseconds between primary and secondary communication paths is obtained via the use of ELPS [2] connections between both CPE and leaf switches as well as leaf to spine switches within the network. Each CPE is configured to with both primary and standby ELPS [2] connections to aggregation switches within the upstream leaf and/or spine huts. As shown in figure 6, the system is configured for active/Standby ELPS [2] connections and looks for continuity check messages (CCM) which are generated by the local CPE ONT closest to each communication hut. CCM messages are generated for each redundant link every 3.3milliseconds to ensure communication link or equipment failures are identified and failover to standby paths can occur within 15milliseconds. Uplinks between the spine switches to the redundant MPLS routers within the huts are configured with Multi-chassis LAG and dual links to ensure availability to the broader smart-grid network. The leaf LAG interface is configured for link-state awareness to shut down CCM's if no path to the main spine switches is determined/detected by monitoring physical links to the main spine switches. If a failure is detected, traffic is forced to the protection path. Local switching is performed within the OLTs for all peer-to-peer traffic. During a partial PON failure of the system, peer-to-peer traffic is switched by the leaf/spine switches. Non-peering traffic, however, exits the network at a spine switch.

Figure 6



CPE FAST-FAILOVER TEST DATA

Proof of concept for CPE fast-failover was performed in a lab environment where the architecture closely resembles ComEd's spine/leaf hut topology as shown in figure 7. The lab consisted of two spine switches, two leaf switches, two OLTs and 128 CPE. The testing methodology which was performed used the 128 simulated CPEs (ethernet switches) with 256 simulated links and a test set which could time failovers from a perceived fiber cut on the network between a VPLS and a simulated GOOSE VLAN. Fiber cut delay was introduced to allow for MAC learning timeout. The results were unremarkable, with no unexpected results. Over 17,000 trials were performed, and average CPE failover time was approximately 5.5milliseconds (see figure 8). 100% CPE failover was achieved within acceptable parameters (< 15milliseconds). All case results were as expected.

Figure 7

Lab PON Design

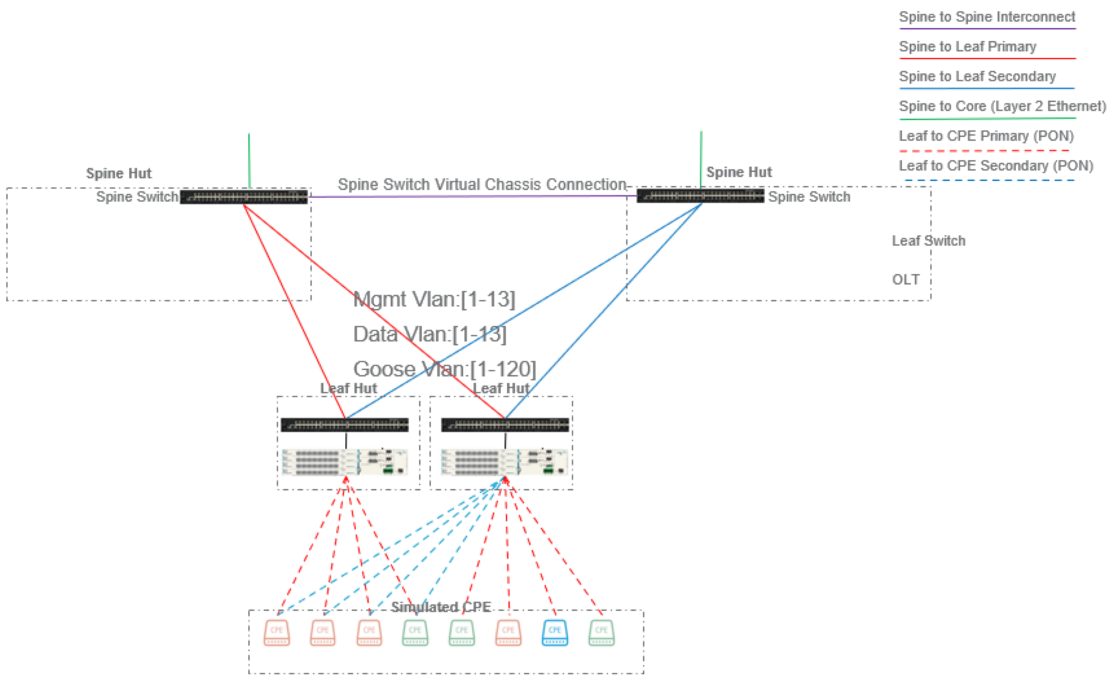


Figure 8

Sample Data Collected…

	CPE					
Trial	1	2	3	4	5	...128
1	5.431154	5.019111	5.059097	5.307957	5.811028	5.984282
2	5.78143	5.943355	5.843777	5.199343	5.33504	5.390121
3	5.573091	5.156515	5.812391	5.755843	5.830989	5.853106
4	5.959893	5.504321	5.474157	5.482327	5.486468	5.846503
5	5.698349	5.827256	5.819869	5.694911	5.5167	5.269226
6	5.485588	5.76693	5.994862	5.334869	5.138712	5.397937
7	5.712293	5.398836	5.605683	5.742782	5.574	5.572073
8	5.390877		5.505852	5.816922	5.091398	5.491222
9	5.509064	5.889237	5.091178	5.218493	5.28815	5.405855
10	5.244751	5.490153	5.177001	5.350989	5.672785	5.702926
11	5.166759	5.802641	5.379271	5.148923	5.05778	5.210337
12	5.443894	5.3062	5.618101	5.096329	5.479284	5.207599
13	5.738172	5.930981	5.086406	5.292661	5.36153	5.947931
14	5.478899	5.953385	5.412539	5.858689	5.411524	5.599528
15	5.888167	5.895621	5.746511	5.182607	5.922095	5.208927
16	5.114815	5.338952	5.992844	5.749411	5.999066	5.835092
... 17651	5.013845	5.530436	5.130334	5.994284	5.401455	5.215435
MIN	**5.000003**	**5.000058**	**5.000011**	**5.000041**	**5.000033**	**5.000046**
MAX	**5.99988**	**5.999988**	**5.999983**	**5.999995**	**5.999863**	**5.999976**
20	**5.49677**	**5.500419**	**5.497818**	**5.50092**	**5.501323**	**5.49871**

ComEd Advanced Communications Network Use Cases and Benefits

The PON Technology implemented PON has been evaluated to meet the requirements of a high speed, high bandwidth, low latency, secure, and scalable communication infrastructure for power several Use Cases that rely heavily on network availability, to benefit the resiliency and reliability of the electric grid. Providing two diverse feeds into a device provides redundancy to geo-diverse OLTs for a more resilient network (eliminates the single point of failure).

ComEd has developed several Distribution Automation (DA) Use Cases that specifically have a need for fast failover (< 1 cycle) of the network to support functionality. DA Reduced Team Restoration Times enable fiber connected DA to enhance teamed restoration activity to reliable immediate path completion. With Reduced Restoration Times, ComEd has also implemented Arc Flash Reduction/Falling Conductor Protection to decrease clearing time of overall arc flash energy and to rapidly deenergize conductors falling to ground.

ComEd has also leveraged the network to support MAIFI & Outage Reduction (Distribution and T&S). Dynamic Protection (Communication Enhanced Coordination), Feeder configuration and Switching overcomes some of the limitations with traditional TCC coordination. Feeder and station assets experience fewer cycles of fault current and less degradation to health and life. The faster reconfiguration of devices within milliseconds eliminates Sectionalizer device operations (with addition of fault interrupting devices on subtransmission).

While fast failover is developed to support Use Cases such as advanced protection schemes, a number of additional use cases take advantage of those same benefits such as small form factor, fast failover, and bandwidth. Some of these Use Cases include the backhaul of Access Points, Bulk Firmware Updates, Enhanced Substation Surveillance and Phase Measurement Units (PMUs).

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[2] ITU-T G.8031/Y.1342 (January 2015) “Ethernet Linear Protection Switching”

[3] ITU G.984.3 (October 2020) “Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification”