MISSION-CRITICAL COMMUNICATIONS NETWORKS FOR POWER UTILITIES

NETWORK TRANSFORMATION WITH IP/MPLS FOR SYNCHROPHASOR APPLICATION

APPLICATION NOTE

Alcatel·Lucent

ABSTRACT

Momentous changes have occurred in how power utilities operate and how they deliver electricity to customers. Depending on the market, the changes have been driven by various needs: from simply making the power grid more reliable (avoiding blackouts), to coping better with the challenges of renewable energy and electric cars, to improving the quality of power (eliminating voltage surges and brownouts). Technological initiatives such as substation automation are pivotal to ensure that utilities' power grids are ready for the future.

One principal component of substation automation is installation of a synchrophasor application, which samples current, voltage and other parameters, then makes the data available for real-time and offline analysis by various applications. However, installation of a synchrophasor application requires a robust communications network for delivery of such mission-critical data.

Rising to this challenge, Alcatel-Lucent delivers a converged IP/MPLS-based communications network for power utilities using next-generation products and advanced management systems that can meet such stringent requirements. This document analyzes the network considerations and requirements when deploying a synchrophasor application and presents a blueprint design to show how an IP/MPLS-based network can enable successful deployment.

TABLE OF CONTENTS

INTRODUCTION

Investments in power utility projects have been fueled by initiatives dedicated to substation automation and smart grids. While most of the media attention has been on the effects of smart grids on consumers, substation automation is equally important. Its key component is a synchrophasor application to sample current, voltage and other parameters, then make the data available for real-time and offline analysis by various applications.

Due to the high sampling rate, synchrophasor applications are typically more bandwidth-intensive than supervisory control and data acquisition (SCADA) applications; this makes a robust communications network vital. In response, many power utilities have started transforming their SONET/SDH/PDH/TDM-based networks to converged IP/MPLS networks to carry monitoring, control and status data and also handle legacy traffic.

This converged network enables a power utility to maximize the cost-effectiveness and productivity of its network without jeopardizing reliability and also to deploy new devices and applications that can improve operational and workflow efficiency. A highly available IP/MPLS network is ideally suited to support both mission-critical operations and all other corporate communications requirements.

In addition, an Alcatel-Lucent IP/MPLS network meets these requirements and also allows power utilities to improve their efficiency by automating and simplifying operations management for communications services, thereby reducing the barrier to introducing IP/MPLS-based technologies and services.

SYNCHROPHASOR APPLICATIONS

A synchrophasor application, an indispensable part of substation automation, is a real-time application vital for reliable and stable operations of the bulk power systems. It can also play a key role in optimizing energy transit in interconnected bulk power systems. It does so by providing reliable and immediate feedback to the control center through probes called phasor measurement units (PMUs) installed at the substation. The PMUs stream real-time situational data over a robust WAN to a data collector called a phasor data concentrator (PDC).

The information in the data stream sent from each PMU includes the time of measurement, the amplitude and phase of the phasor, the frequency and the rate of change of frequency.

According to a NERC report, power utilities, armed with such precise, time-synchronized, power-grid-wide data, can improve grid stability and reliability for both real-time operations and offline planning applications as listed below[1].

Real-time operations applications

- Wide-area situational awareness
- Frequency stability monitoring and trending
- Power oscillation monitoring
- Voltage monitoring and trending

1 NERC, *Real-Time Application of Synchrophasors for Improving Reliability*, October 2010, http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf

- Alarming and setting system operating limits, event detection and avoidance
- Resource integration
- State estimation
- Dynamic line ratings and congestion management
- Outage restoration
- Operations planning

Planning and off-line applications

- Baselining power system performance
- Event analysis
- Static system model calibration and validation
- Dynamic system model calibration and validation
- Power plant model validation
- Load characterization
- Special protection schemes and islanding
- Primary frequency (governing) response

Successful deployment of a synchrophasor application is crucial to an efficient and robust grid that delivers an unceasing flow of electricity to users without faults or even brief interruption.

THE ALCATEL-LUCENT IP/MPLS NETWORK

Advantages

Many power utilities have started to consider deploying, or have already deployed, next-generation networks to support all their communications needs. However, not all next-generation solutions are appropriate for power utilities. To simultaneously support all mission-critical and non-mission-critical traffic of a power utility, an IP/MPLS-based communications network is needed.

Non-MPLS-based IP networks have grown significantly in recent years, but they often lack the necessary traffic management capability to support traffic that requires strict quality of service (QoS) for mission-critical operations. They also lack the flexibility to optimize the use of network resources and the capability to react to network events fast enough to guarantee end-to-end QoS per application.

By using an Alcatel-Lucent IP/MPLS, the power utility gets the best of both worlds — an IP network that has the robustness and predictability of a circuit-based network along with high capacity and support for packet-based traffic with high QoS. An IP/MPLS network enables the deployment of new IP/Ethernet applications and also supports existing TDM-based applications, allowing the power utility to improve services for both internal and external users. A power utility can continue to support existing TDM services and flexibly choose when to migrate them to IP.

With an IP/MPLS network, the power utility has a network with the following features:

- High scalability and robustness with full redundancy and rapid recovery mechanism such as MPLS Fast Reroute (FRR)
- A solution that addresses a wide range of QoS and service level agreement (SLA) requirements, from circuit emulation to best-effort Internet surfing

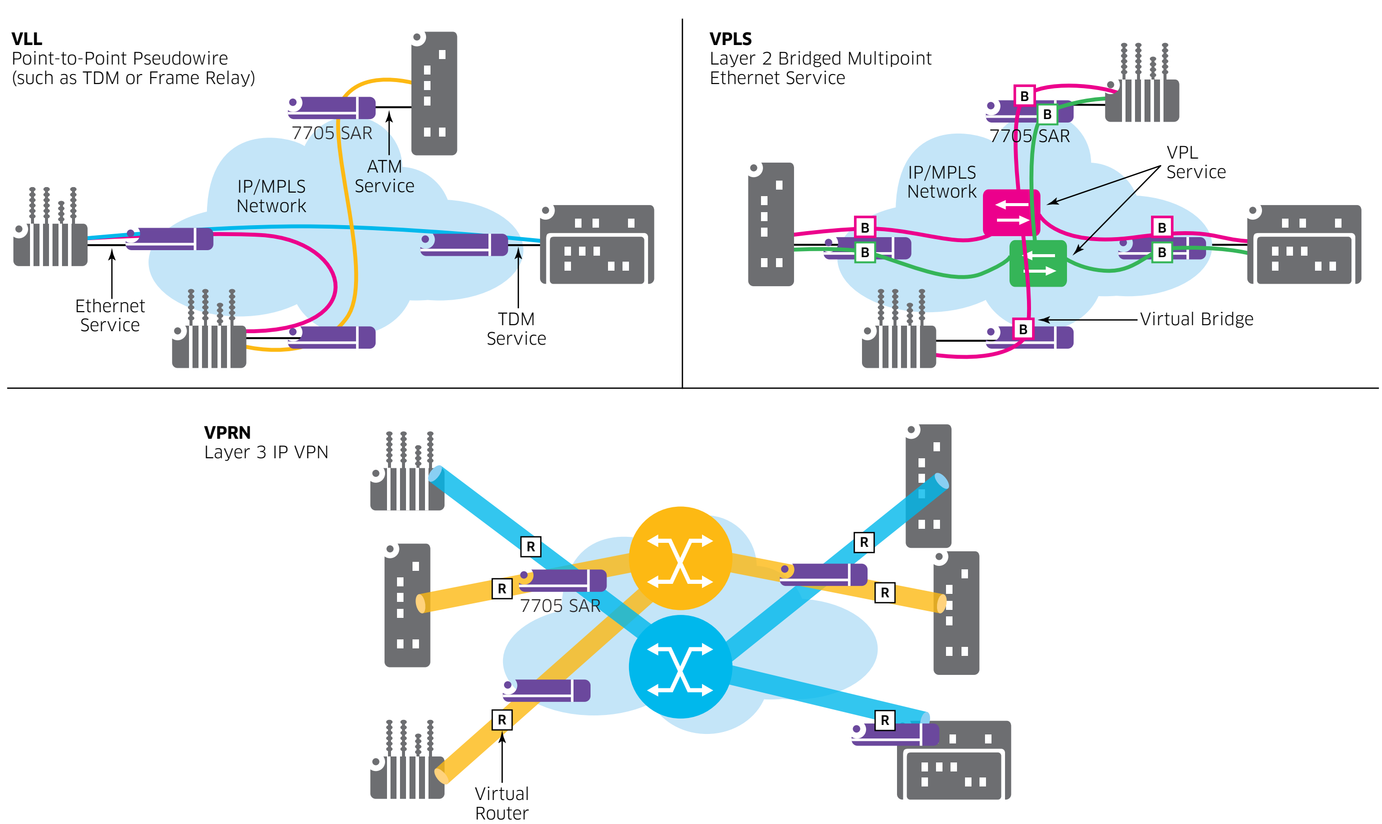
- Optimized bandwidth usage of all links and avoidance of common modes through traffic engineering
- An extensive operations, administration and maintenance (OAM) suite for performance monitoring, troubleshooting and maintenance at all protocol layers
- Advanced network and service management to simplify operations

Each application run on the network has its unique requirements for bandwidth, QoS and availability. An IP/MPLS network enables the power utility to set service parameters for each service and traffic type according to operational requirements. This includes multiple types of voice, video and data traffic. The network can also support low jitter and delay to handle all traffic types effectively and reliably in real time. In addition, the Alcatel-Lucent IP/MPLS network supports advanced capabilities, including non-stop routing, non-stop services and FRR, to maintain high network resiliency.

Many VPNS, one network

An Alcatel-Lucent IP/MPLS network provides for the virtual isolation of various traffic types on a single infrastructure supporting many Virtual Private Networks (VPNs) simultaneously. As shown in Figure 1, whether the network is a Virtual Leased Line (VLL) of various types, Virtual Private LAN Service (VPLS) or a Virtual Private Routed Network (VPRN), an Alcatel-Lucent IP/MPLS network allows the full separation of control and data traffic in each VPN from different applications or operations in the utility company. The results are a fully secured environment, effective infrastructure sharing and optimal bandwidth allocation. With this advanced capability, a power utility can also leverage the same IP/MPLS network infrastructure to carry their corporate business data.

Figure 1. Alcatel-Lucent IP/MPLS network



Alcatel-Lucent solution components overview

The Alcatel-Lucent IP/MPLS implementation provides a service-oriented approach that focuses on service scalability and quality as well as per-service OAM. With a service-aware infrastructure, the power utility has the ability to tailor services such as mission-critical applications so that it has the guaranteed bandwidth to meet peak requirements. The Alcatel-Lucent service routers support IP routing and switching, which enables the power utility to support real-time Layer 2 and Layer 3 applications.

The Alcatel-Lucent converged IP/MPLS network leverages multiple state-of-the-art technologies. The network extends IP/MPLS capabilities from the core to access and can include the following main components:

- Alcatel-Lucent 7750 Service Router (SR)
- Alcatel-Lucent 7705 Service Aggregation Router (SAR)
- Alcatel-Lucent 7450 Ethernet Services Switch (ESS)
- Alcatel-Lucent 7210 Service Access Switch (SAS)
- Alcatel-Lucent 9500 Microwave Packet Radio (MPR) providing packet microwave link connecting MPLS nodes
- Alcatel-Lucent 1830 Photonic Service Switch (PSS) as optical layer underlying the IP/MPLS network
- Alcatel-Lucent 5620 Service Aware Manager (SAM) for service and network management

KEY NETWORK CONSIDERATIONS FOR A SYNCHROPHASOR APPLICATION

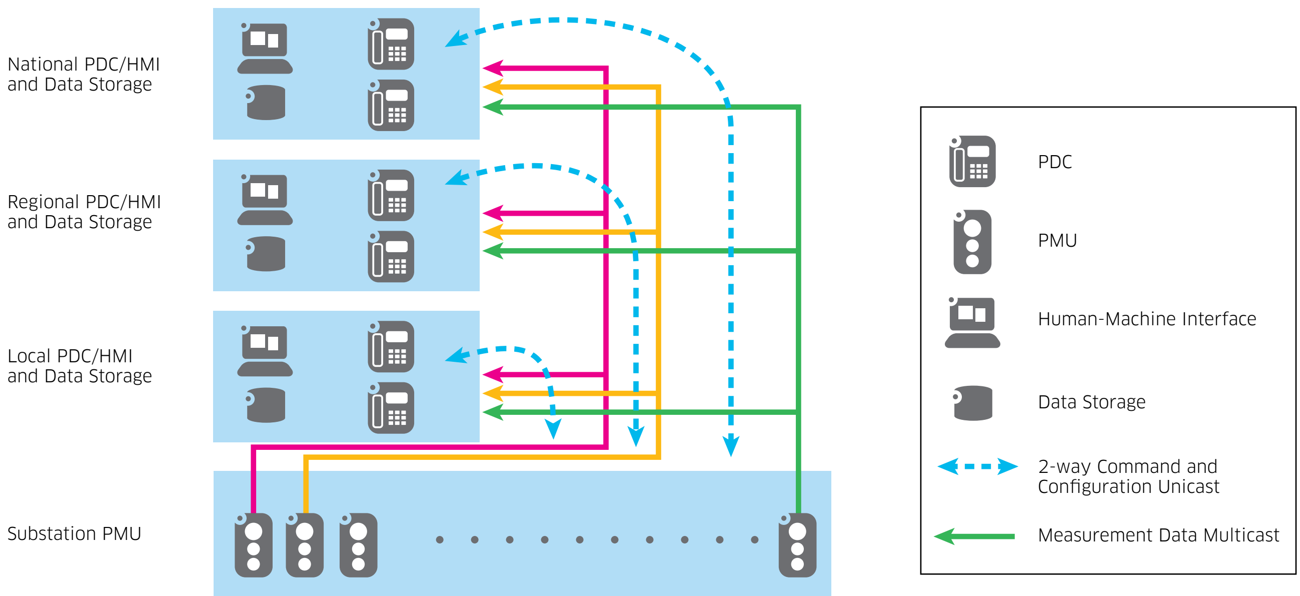
Understand the traffic flow

A synchrophasor application deployment consists of one or more PMUs deployed in substations and multiple PDCs in control centers at various levels (local, regional, national). Connected to the PDC is a data storage device that stores all measurement data and a human-machine interface (HMI) installed on a computer. The storage device and computer communicate with the PDC through an internal LAN in the control center, not through the IP/MPLS network.

The number of PMUs can range from a few hundred to tens of thousands transmitting data to a pair of active and backup PDCs. In a large national grid, there could be multiple levels of PDC pairs.

Figure 2 shows a reference deployment model with traffic communication flows.

Figure 2. Synchrophasor system reference deployment model



A few observations can be made about the reference deployment model.

Traffic flow pattern

Each individual PMU continually streams measurement data to a number of PDCs located in control centers at different levels for monitoring and analysis performed by different teams. For data redundancy protection, it is also common to find a pair of PDCs at each level, with each PMU streaming two flows of data packets, one for each of the PDCs. Due to the high number of PMUs, which can range from a few hundred to tens of thousands, this represents a correspondingly high number of multicast flows — from hundreds to potentially tens of thousands. Each multicast flow requires a separate multicast channel, which has its own multicast tree. For each channel, there are a handful of listeners (PDCs at various levels).

The multicast trees are static once the application is up and running. This is the opposite of a typical carrier IPTV application, where the multicast trees with up to tens of thousands of TV viewers are establishing and tearing down branches dynamically as viewers change channels.

Geographic sparsity of listeners

The handful of PDCs are typically located in the aggregation location of the network. This is the opposite of an IPTV multicast network, in which the listeners, TV viewers, are situated everywhere across various access domains.

The multicast traffic pattern is summarized in Table 1.

Table 1. Synchrophasor data multicast characteristics

TRAFFIC CHARACTERISTIC	DESCRIPTION
Number of flows/channels	Range from hundreds to tens of thousands because each deployed PMU uses two channels
Multicast tree branch	Fixed or static tree
Listeners' geographic sparsity	Unlike Internet applications, all listeners (PDCs) are located in the same geographical domain

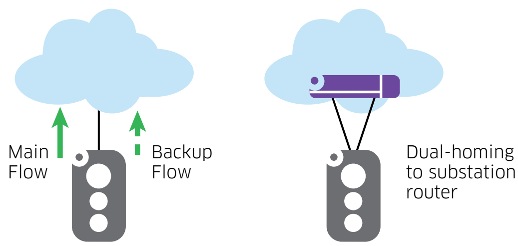
Redundancy protection

To ensure end-to-end reliable delivery and collection of measurement data, redundancy protection needs to be considered for the hosts: the PMU and PDC.

PMU protection

Figure 3 shows PMU protection.

Figure 3. Protection with redundant flow and secondary link



The PMU continually collects measurement data that can be as high as 50 frames per second in a 50-Hz power system or 60 frames per second in a 60-Hz power system.

To protect data frames from frame loss or corruption, two data frame flows of the same measurement result are sent separately to the PDCs. Also, the PMU is dual-homed to the network substation router to protect against link and port failure. Both of these protection mechanisms are shown in Figure 3.

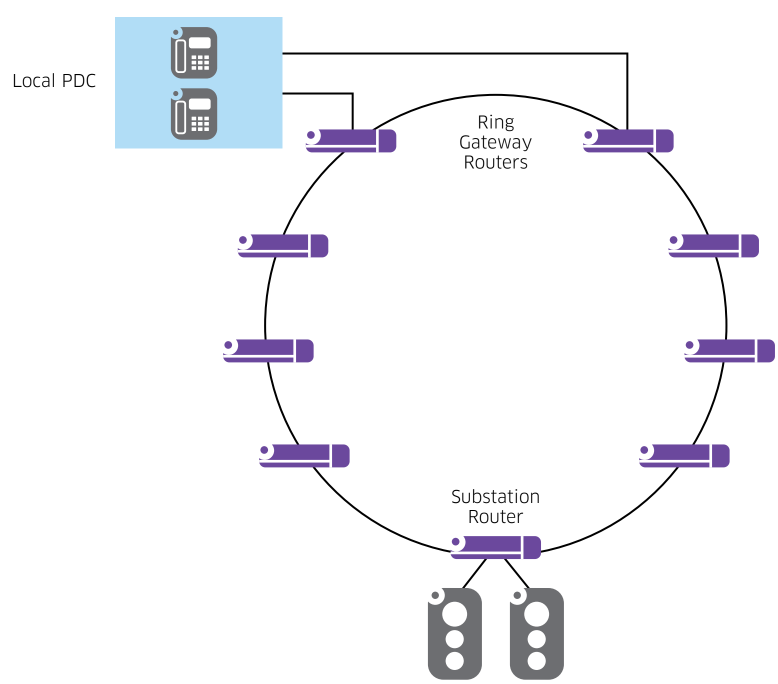
Due to the large number of PMUs in the networks, equipment protection with a second PMU for the same measurement point is usually not a practical measure.

Substation ring and protection

A network topology with dual-homing path diversity can provide protection for communications against substation router failure. A ring topology (see Figure 4), built with optical fiber, microwave or both, provides strong and resilient protection. In the event of a ring failure caused by a fiber cut, a high microwave link bit error rate condition or a transit router failure, traffic in the ring can recover by switching to the alternate ring direction.

Protection for the ring gateway router can be provided through a router with a dual control complex or through two routers (as shown in Figure 4). Either method provides total equipment redundancy, boosting reliability.

Figure 4. A substation router ring connecting to local PDC center

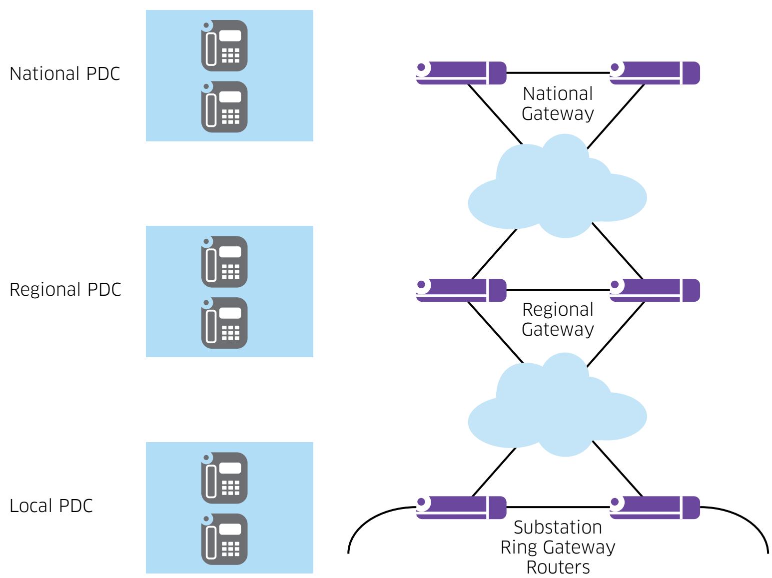


Local PDC protection

The PDC, a key component of a synchrophasor application, collects the measurement data and stores it in local storage. If a PDC fails or is undergoing maintenance, the data is lost. To avoid this situation, a PDC redundant pair providing equipment protection should be implemented to ensure that data collection is not interrupted.

For a large national grid, a synchrophasor application implementation design might be divided into a hierarchy, as shown in Figure 5.

Figure 5. A hierarchical synchrophasor application implementation



Protection at regional and national levels

The protection considerations at the regional and national levels are similar:

- Dual- or multi-homing into the network and dual gateway node protection are essential to protect the communication path for reliable data transmission.
- Dual PDCs are required for reliable data collection.

Multiservice backhaul

In addition to measurement data, data from applications such as CCTV, SCADA, teleprotection, VoIP, and on-site corporate intranet and Internet access all need to be backhauled to the central station.

Table 2 shows the typical applications and the corresponding physical interfaces and IP/MPLS services used to support them.

Table 2. Multiservice backhaul applications

APPLICATION	INTERFACE	SERVICE
Synchrophasor data	IP/Ethernet	VPLS or IP
VoIP, CCTV, intranet or Internet	IP/Ethernet	Ethernet VLL or IP
SCADA/teleprotection	Ethernet or TDM (E1/T1, E&M, serial, etc,)	Ethernet VLL, Ethernet VPLS or CES
Substation alarm monitoring	Dry contact	Dry contact port to SNMP alarm

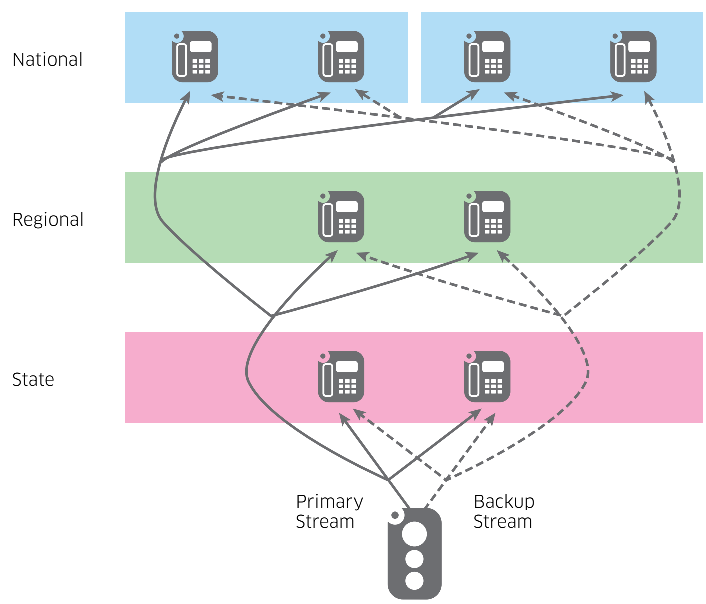
A BLUEPRINT NETWORK DESIGN FOR A SYNCHROPHASOR APPLICATION

This blueprint network design for a synchrophasor application is based on the Alcatel-Lucent 7705 SAR and the Alcatel-Lucent 7750 SR. The 7705 SAR is deployed as the substation router and, depending on the size of the aggregation site, either the 7705 SAR or the 7750 SR is used there.

Phasor data collection topology

This blueprint network design is divided into a hierarchical domain with state, regional and national levels (see Figure 6). There is one PDC pair at the control center at each level except the national level, which has two pairs: one pair at each national control center. Each PMU sends phasor data in two IP multicast streams (the solid and dotted lines in Figure 6) on two separate physical paths.

Figure 6. A high-level topology



There are eight multicast listeners in the network for each multicast stream.

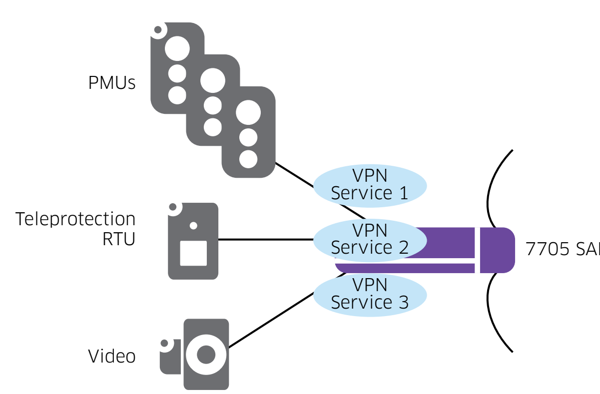
Physical network topology

At the state level, in each substation a router is used to aggregate traffic from various PMUs and other equipment (see Figure 7).

The 7705 SAR plays a critical role through the following functions:

- Provides L1, L2 and L3 VPN service for each piece of equipment/application in the substation, ranging from PMUs to teleprotection terminals to video
- Aggregates all data with the appropriate level of QoS
- Performs OAM demarcation to verify substation site connectivity and delay/jitter monitoring for time-sensitive applications
- Provides security, stopping unauthorized incoming and outgoing traffic

Figure 7. A substation router: Alcatel-Lucent 7705 SAR



The substation router feeds data into an access ring that has a dual-ring gateway. A ring topology is chosen because it provides high-level resiliency, which is central to a mission-critical network, with the least amount of connectivity required.

Depending on the terrain where substations are located, the connectivity between substation sites can be based on fiber, microwave or copper.

At the aggregation site where the state-level PDUs are located, there are two 7705 SARs as aggregation routers, which drop off phasor data as well as forwarding it upstream to the next level in the hierarchy, the regional level (see Figure 8). This process is repeated between the regional level and national level.

Figure 8. State and regional aggregation sites

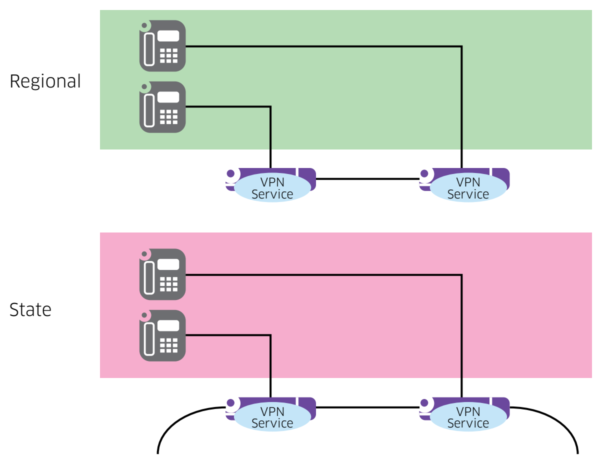
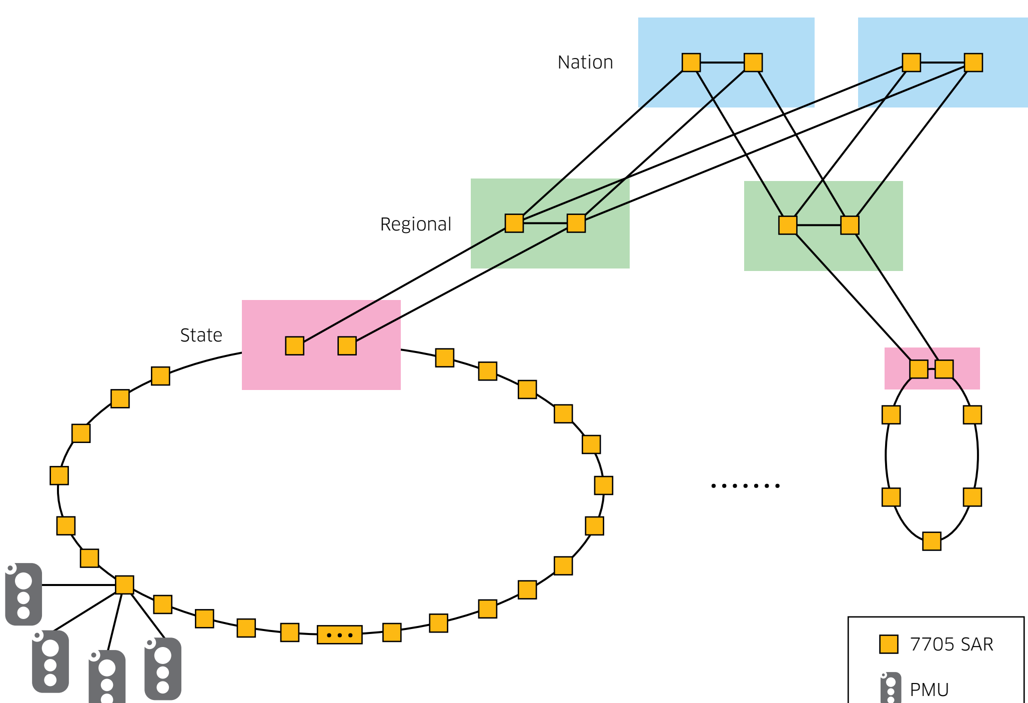


Figure 9 shows all the hierarchies combined together.

Figure 9. A complete physical network topology view



Multicast tree delivery mechanism

Two important multicast solutions are Layer-3 PIM-based IP multicast and Layer-2 hierarchical VPLS multicast. While both solutions have been deployed extensively, to make the best architecture decision a network operator must understand the attributes of their multicast application.

Table 3 compares the two solutions.

Table 3. A comparison of an L3-based and an L2-based solution

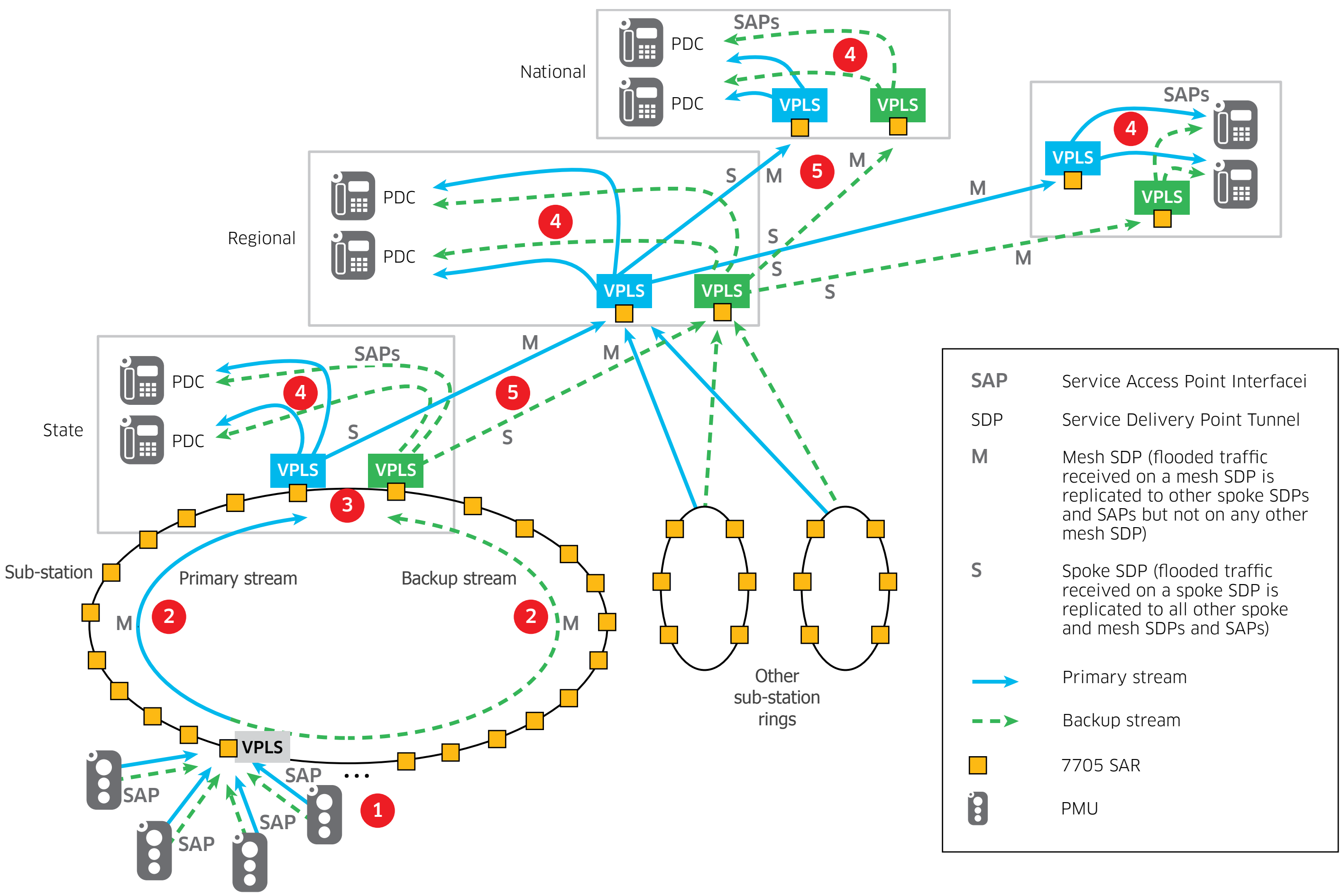
	IP-MULTICAST BASED	HIERARCHICAL VPLS
Control plane complexity	Need a separate PIM-based routing protocol	No new protocol required
Multicast tree buildout	Dynamic buildout as listeners join and leave; ideal for bulk delivery applications such as IPTV; need to maintain multicast state for each multicast tree in the network	Static buildout because PDCs are fixed, or “well-known,” and small in numbers; no need for multicast tree state maintenance in the network
Geographical spread of listeners	Randomly and sparsely scattered	Strategically concentrated at hierarchical hubs
Data replication	Optimized because tree is pruned by control plane	Equally well optimized because only PDC-connected interfaces are part of the hierarchical VPLS domain
Traffic engineering	None	Full support with RSVP-TE
Convergence	Convergence of routed multicast is typically slower than hierarchical VPLS multicast, particularly in a ring network	Based on MPLS resiliency mechanisms, FRR, secondary paths
Phasor System IPv6 migration	Requires IPv6 address provisioning in network	No new efforts are required because end equipment IP addressing is transparent to VPLS

Based on this comparison, for this blueprint design a hierarchical VPLS-based design is an optimal solution due to the reasons stated in the table.

A hierarchical VPLS design

The hierarchical design shown in Figure 10 provides full end-to-end protection with optimal data replication efficiency.

Figure 10. A synchrophasor communications network with hierarchical VPLS design



The following procedure describes the steps a packet goes through as it travels through the network. The numbers on Figure 10 correspond to the steps that follow.

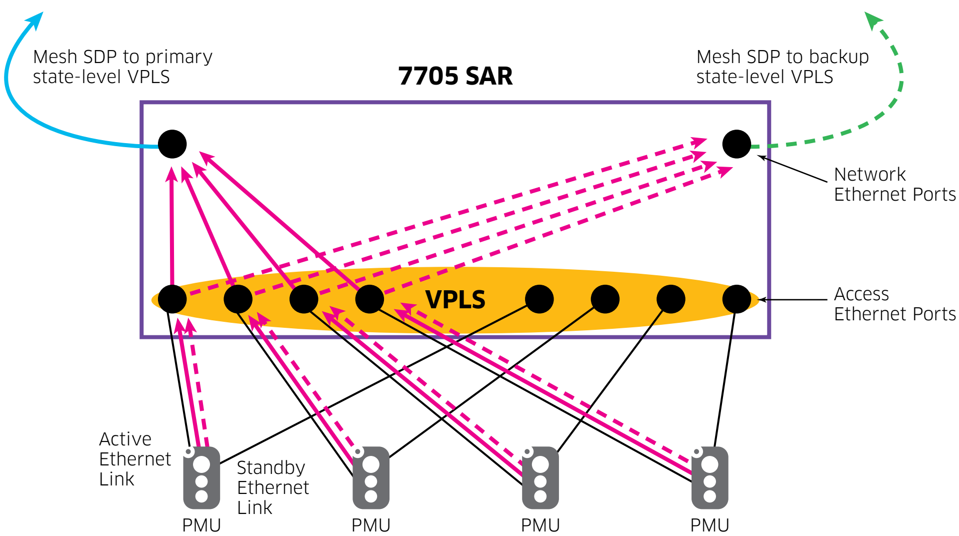
1. Each PMU has two Ethernet links (active and standby) to the 7705 SAR substation router with two PMU data streams (primary stream and backup stream) on the active Ethernet link. If the active link fails, the PMU sends traffic through the standby link.

   When there is more than one PMU per substation, each data stream from an individual PMU is carried in a unique IP multicast flow entering into the same VPLS in the substation router.

   Due to the nature of VPLS data plane behavior, the substation router then forwards the two streams from each PMU, one stream to the east and the other to the west. Each stream reaches one of the two ring gateway routers, located in the state-level control center, using a meshed-SDP over a labeled switched path (LSP) with MPLS protection for ring failure. A meshed-SDP is a network interface connecting two routers (for example, an access router and an aggregation router).

Figure 11 shows a detailed view of the VPLS using an active Ethernet link.

Figure 11. Detailed service view of a substation router



2. All the substation routers along the ring path shown in Figure 10 act as label switch routers (LSRs); they switch the traffic until it reaches the aggregation router (see Figure 12) before the next level of VPLS forwarding is performed.

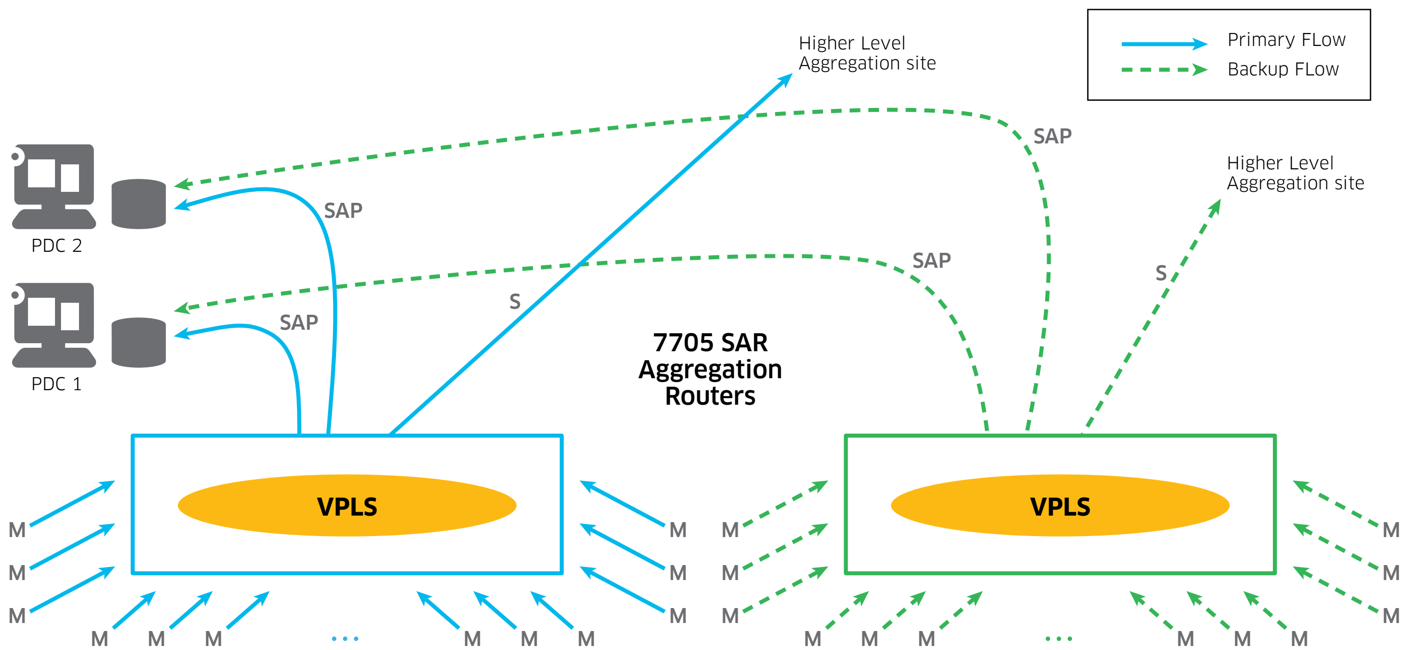
   If a failure is detected in the ring, the LSR performs FRR.

   In this design, each aggregation router is dedicated to process only one designated flow of the two from each PMU. The aggregation router pair can also provide equipment protection when one of the routers fails.

3. The gateway router forwards the received multicast streams from all substation routers in the ring onward to the higher domain aggregation router, without having to send the multicast streams downstream to other routers in same ring or in other rings, due to the forwarding characteristics of a meshed-SDP.

4. Each gateway router at the aggregation site has two SAP interfaces connected to the two PDCs in the state-level site. The router delivers the streams received from all PMUs to the PDCs. Each PDC receives two streams (a primary stream and a backup stream) from each aggregation router (see Figure 12).

Figure 12. Detailed service view of an aggregation router



5. Step 4 is repeated at the regional-level aggregation site and national-level site.

All the data forwarding described is taking advantage of the nature of VPLS (MAC learning) and forwarding behavior. Therefore, other than configuring the VPLS and the associated interfaces, no control plane protocol and extra configuration are required. Also, no traffic will be received or forwarded on interfaces that are not configured to be part of the VPLS, thereby providing inherent security protection from unauthorized traffic.

CONCLUSION

Since the advent of IP/MPLS technology in communications networks, it has proven to network operators and service providers worldwide its versatility and adaptability to new applications. From VPNs carrying critical and high-value data to Internet best-effort traffic, MPLS supports the most stringent applications, such as telecontrol and teleprotection, as well as best-effort applications such as Internet surfing.

This application note presented a blue-print design to illustrate how to deploy an IP/MPLS-based service to optimally transport synchrophasor application traffic. Network operators can leverage the strong service capabilities and flexibilities to tailor the design for different synchrophasor system vendors and network architectures.

ACRONYMS

CCTV	closed circuit television
CES	Circuit Emulation Service
FRR	Fast Reroute
HMI	Human Machine Interface
IP	Internet Protocol
IPTV	Internet Protocol television
LAN	Local Area Network
LSP	label switched path
LSR	label switched router
MAC	media access control
MPLS	multiprotocol label switching
NERC	North American Electric Reliability Corporation
OAM	Operations, administration and maintenance
PDC	phasor data concentrator
PDH	Plesiochronous Digital Hierarchy
PE	provider edge
PIM	Protocol Independent Multicast
PMU	Phase Measurement Unit
QoS	Quality of Service
RSVP-TE	Resource Reservation Protocol with Traffic Engineering
RTU	Remote Terminal Unit
SAP	Service Access Point
SDP	Service Delivery Point
SCADA	supervisory control and data acquisition
SDH	Synchronous Digital Hierarchy
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Networking
TDM	Time division multiplexing
VLL	virtual leased line
VPLS	Virtual Private LAN Service
VPN	Virtual Private Network
VPRN	Virtual Private Routed Network

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