Building the digital substation communication foundation

A key pillar of sustainable grids

White paper

Contents

Executive summary

Carbon reduction and the falling price of renewables is causing the utility landscape to change and innovate more quickly than ever before. The challenge from a reliability standpoint is how to integrate these new technologies while maintaining stability and balance in the grid. Digital technologies will play a key role in making this possible, responding to problems of intermittency and the distribution of energy resources, all the while ensuring greater agility, oversight and resilience.

The digital substation is a key part of the new utility landscape. In this paper, we look at the communications foundation that will enable the digitalization of substations and what network characteristics the communications infrastructure must meet. We present Nokia's digital substation communications system blueprint.

Digital substations

A confluence of energy technology innovations and government sustainability policy is transforming how electricity is generated and consumed. The continued drop in the cost of renewable energy and energy storage has propelled renewables to the fastest growing source of new generation capacity. At the same time, governments and citizens have committed to achieving carbon neutrality by 2050, which will require the electrification of many machines and processes now powered by fossil fuels. These developments will place immense strain on electric grids in the coming decades. Utilities are faced with the monumental challenge of transforming the grid infrastructure and operations to deliver more carbon-free energy with higher efficiency while maintaining stability and quality. Digital technologies will play a critical role in meeting this challenge.

One of the principal changes required is the advent of the “digital substation” for better protection, control, oversight and operation of the grid. With digital substations, substation automation will be powered by microprocessor-based intelligent electronic devices (IEDs) such as digital protection relays and programmable logic controllers to control devices such as load tap changers, circuit breakers and reclosers. They communicate with digital devices like merging units (MUs) in the switchyard to collect operating information from transformers. They also exchange control and command messages with other IEDs in another bay or substation or with energy/distribution management systems (EMS/DMS) in the control center. They will enable wide-area situational awareness, fault and outage prevention management, and operational optimization. They perform traditional grid operations at a lower cost, using less space compared to their electromechanical precursors, while serving as a platform for emerging innovative grid automation applications.

Digital architecture

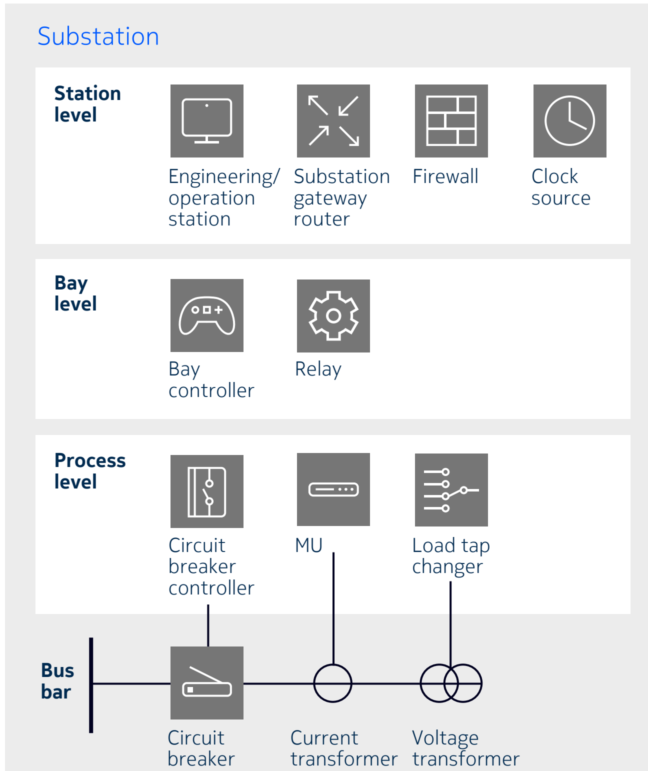
The IEC Technical Committee 57 has authored IEC 61850, a suite of standards defining a three-level digital substation architecture (see figure1):

Process level: The bottom level for primary power system equipment including instrument transformers and circuit breakers in the switchyard. Instead of sending analog transformer data (e.g., voltage and current) or breaker status information (open/close) to the bay level secondary equipment over many pairs of copper wire, as in today’s substations, a merging unit (MU) is used to convert analog measurement into sampled digital values , transmitting all data, together with breaker condition information, to the bay level IEDs over optical fiber.

Bay level: The middle level for secondary equipment and IEDs including protective relays, bay controller and fault recorder in the control house, where they monitor and control primary equipment at the process level. A substation would have a number of bays.

Station level: The top level for the station computer, engineering stations and operation stations for the bay level IEDs providing a central data base, HMI (or human machine interface), and gateway functionality for the entire substation. There is also a clock source, such as a GNSS receiver, and a gateway router paired with a firewall for secure external communications to the substation.

Figure 1. The three levels of a digital substation



Communications network architecture

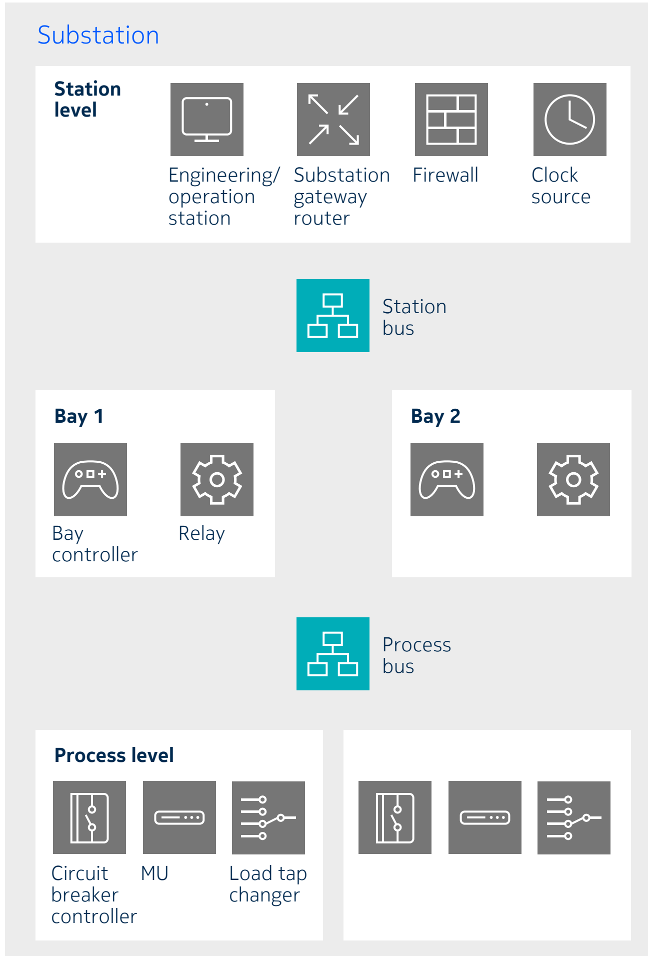
With grid intelligence distributed among the IEDs in a digital substation, communication between the three levels is required. The IEC 61850 standard suite defines an open communication network architecture linking the three levels together. This open architecture benefits power utilities in the following way:

- Interoperability among electrical equipment vendors, enabling a multivendor environment and fostering and accelerating grid innovations
- Consolidation of multiple networks into one converged network, both inside and outside the substation
- Deployment of a cost-effective, fiber-based optical Ethernet network replacing tons of copper wire at the process level for significant cost saving (material and installation), improved safety and abundant bandwidth for new innovations.

The architecture consists of a process bus[1] and a station bus (see figure 2). The process bus connects merging units and circuit breaker at the process level to the IEDs (relay and bay controller) at the bay level. It carries raw grid information (voltage and current samples and breaker status) to the IEDs to process for control and protection decisions, control/command messages and IEEE1588v2 time synchronization information. The station bus connects the substation central management and resources at the station level to individual bays. It also connects bays to each other and to the substation router for communication to a bay in another substation, operations center and data center.

1 Bus is a broadcast domain that is equivalent to an Ethernet broadcast domain in a VLAN or an untagged LAN

Figure 2. Digital substation network architecture

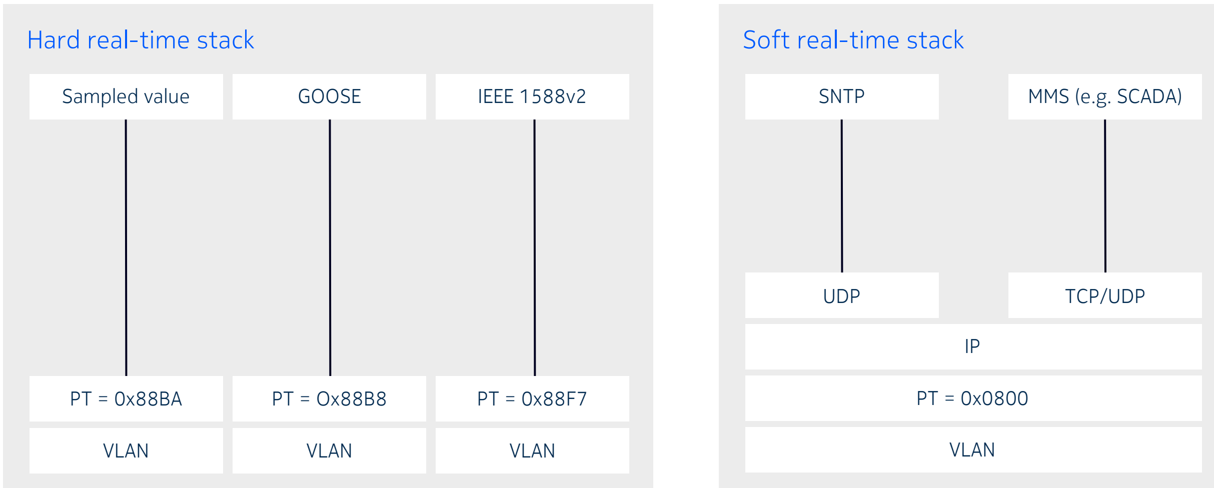


To facilitate a multivendor environment, the IEC 61850 suite also defines the communication protocol stack (see figure 3). There are two types of stacks:

Hard real-time stack: contains delay-sensitive traffic and requires real-time processing; examples are Sampled Value (SV) protocol for digitized current and voltage measurements, Generic Object Oriented Substation Events (GOOSE) protocol for teleprotection and other substation automation application, as well as IEEE1588v2 messages carrying time synchronization information.

Soft real-time stack: contains traffic that requires reliable delivery but is not as delay-sensitive; examples are Manufacturing Message Specification (MMS)-based applications such as SCADA using DNP3 or IEC 60870-5-104, synchrophasor and general management.

Figure 3. IEC 61850 protocol stacks



PT: Protocol type

A digital substation does not operate as an island. Through the router at the station level, acting as the communication gateway to the wide area network (WAN), IEDs can communicate with other IEDs in other substations for applications such as interlocking and teleprotection, as well as DMS and EMS residing in the control center and data center for grid-wide control, monitoring and optimization.

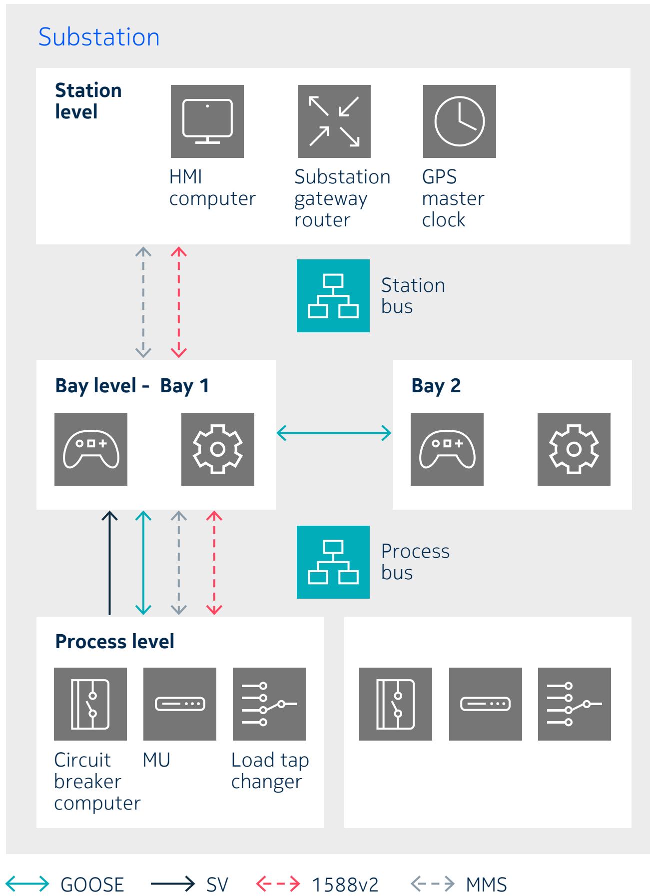
The rest of this paper will focus on the digital substation network and its internetworking with the WAN.

Network requirements

As explained, the network consists of two domains, one for the process bus and one for the station bus. It is important to identify and understand the IEC61850 traffic flows and their scopes in each domain (see figure 4):

- **Process bus traffic** comprises SV, GOOSE, MMS and IEEE 1588v2 traffic between bay level IEDs and IEDS at the process level within the same bay. They have different quality of service (QoS) requirements: SV and GOOSE are delay sensitive, IEEE 1588v2 is delay and jitter sensitive while MMS mainly requires reliable delivery.
- **Station bus traffic** comprises GOOSE traffic between IEDs belonging to the same bay or to different bays in the same or two substations, as well as MMS and 1588v2 traffic between IEDs and station-level equipment.

Figure 4. Digital substation traffic flow



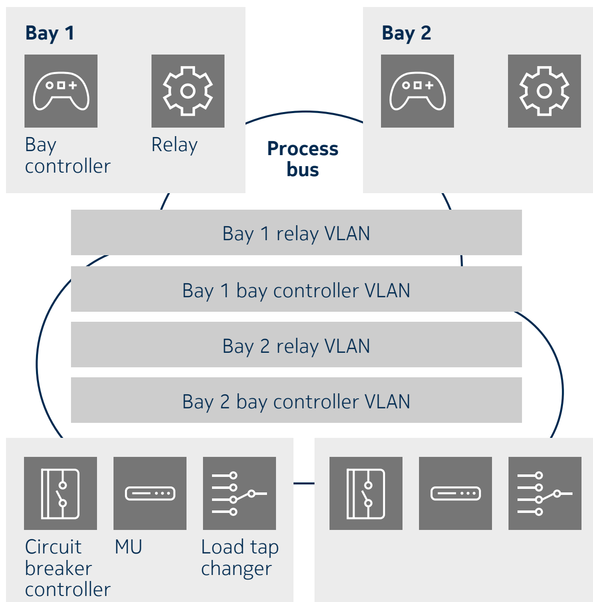
Digital substation operation requires IED traffic to flow reliably all the time while constantly meeting QoS objectives for each application. Therefore, the substation network needs to meet a range of communication needs:

- Multiservice
- Resiliency
- QoS
- Cybersecurity
- Synchronization
- WAN internetworking

Multiservice

With many grid applications deployed in a digital substation, the network needs to support multiservice with network segmentation. For example, a protective relay in a bay communicates with its set of MUs in its virtual network segment. Similarly, a bay controller exchanges GOOSE messages with a load tap changer controller in a different segment. (see figure 5). This network segmentation approach limits the size of a broadcast domain as each IED can only communicate with other IEDs in the same application domain. This approach eliminates broadcast storms, resulting in a stable network.

Figure 5. Process bus with multiservice support



Resiliency

Robust resiliency is essential since the network carries safety-critical traffic. An Ethernet ring topology employing Ethernet Ring Protection Switching (ITU-T G.8032v2, abbreviated as G.8032 hereafter) provides network layer protection for link or node failure. During normal operation, one of the ring segments is declared to be the ring protection link (RPL) with its ports blocked to eliminate a bridging loop. Consequently, traffic will flow in the other direction. When a failure is detected somewhere in the ring, the designated RPL ports will be unblocked so that affected traffic can flow in the other ring direction to restore connectivity.

To complement network layer protection, IEC61850 standardizes application layer protection schemes: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). Implemented on IED Ethernet modules, PRP rides transparently on the process bus with G.8032, providing multi-layer protection switching (cf. figure. 6a). In the case of HSR, the IEDs themselves form the process bus (Fig. 6b). Therefore, there is no need of Ethernet switches in the process bus.

Figure 6a. PRP transparently over process bus

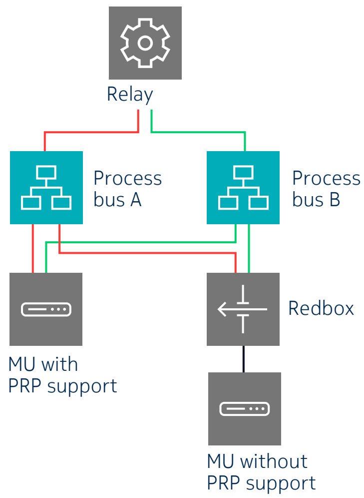
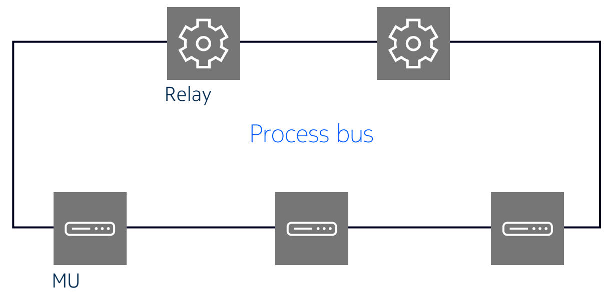


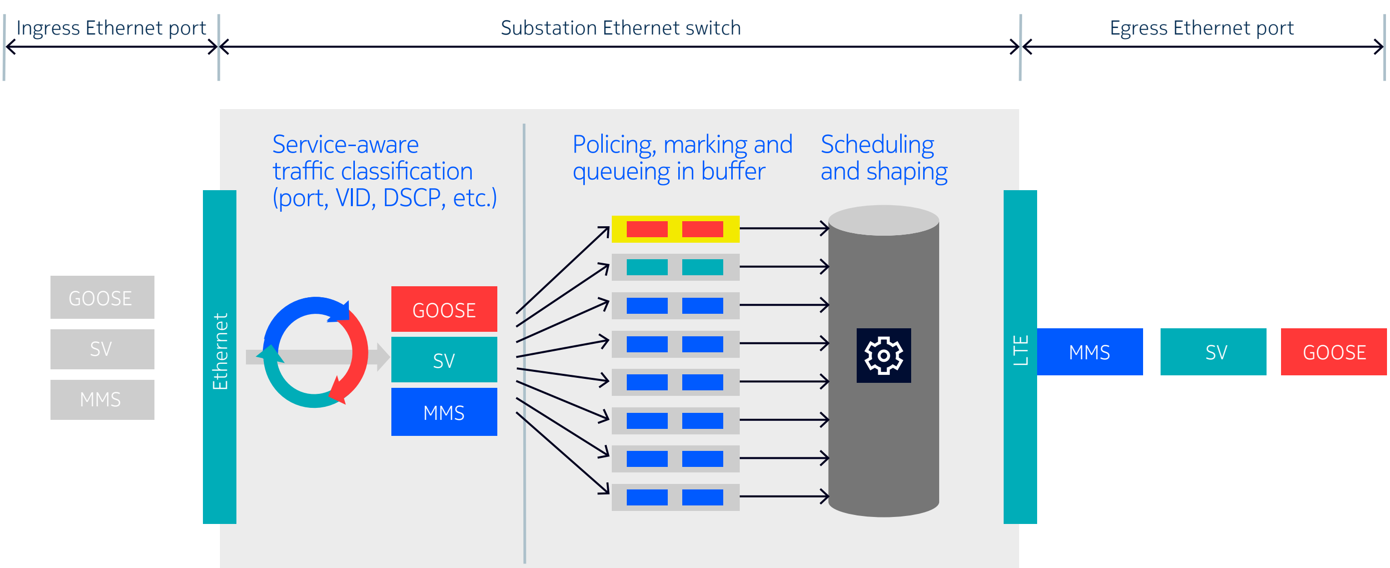
Figure 6b. HSR forms process bus



QoS

Applications like GOOSE are delay-sensitive and operate in real time. Therefore, the network must be able to constantly deliver the GOOSE traffic within the delay budget. Each Ethernet switch needs to classify it as a high priority forwarding class above other applications and transmit them ahead of others at both ingress and egress ethernet interfaces (see figure 7).

Figure 7. QoS in substation networking



Synchronization

As utilities digitize their substations using automation applications, they need to co-ordinate IED activities to synchronize grid data measurement and schedule resources among substations and the control center. An accurate, reliable common grid-wide time reference becomes critical. The ideal time synchronization source is GNSS. It is not practical, however, to equip every substation to have its own GNSS receiver. Also, GNSS signals are susceptible to natural, accidental and intentional interferences. Therefore, it is necessary to adopt a comprehensive synchronization scheme by using the network to distribute time synchronization as a backup for GNSS-enabled substations and the primary synchronization source for substations without GNSS receiver.

Cybersecurity

The power grid is critical infrastructure and a high-profile target for cyberattacks. As cyberattacks evolve, a multi-layer cyber-defense framework is necessary. The substation network can play an integral role in safeguarding the IEDs, complementing other defense components such as a firewall forming a security perimeter separating the WAN from the substation network.

WAN internetworking

IEC61850 was first conceived as the communication standard for use in information exchange between IEDs inside a substation (intra-substation communication). However, grid applications can span between substations and even extend into control and data centers (see table 1). Therefore, the substation network needs to extend connectivity to other locations.

Table1. Common inter-substation and substation-control center/data center applications

Inter-substation	**Substation-to-control center/data center**
Teleprotection (distance and current differential) with GOOSE	Synchrophasor
Interlocking	SCADA/Telecontrol
Remedial action schemes (RAS)	Power quality
Synchrophasor	Disturbance/fault recording

Consequently, it is important that the substation network can internetwork with the WAN, extending connectivity to another substation or the control and data centers (see figure 8).

Figure 8. WAN internetworking

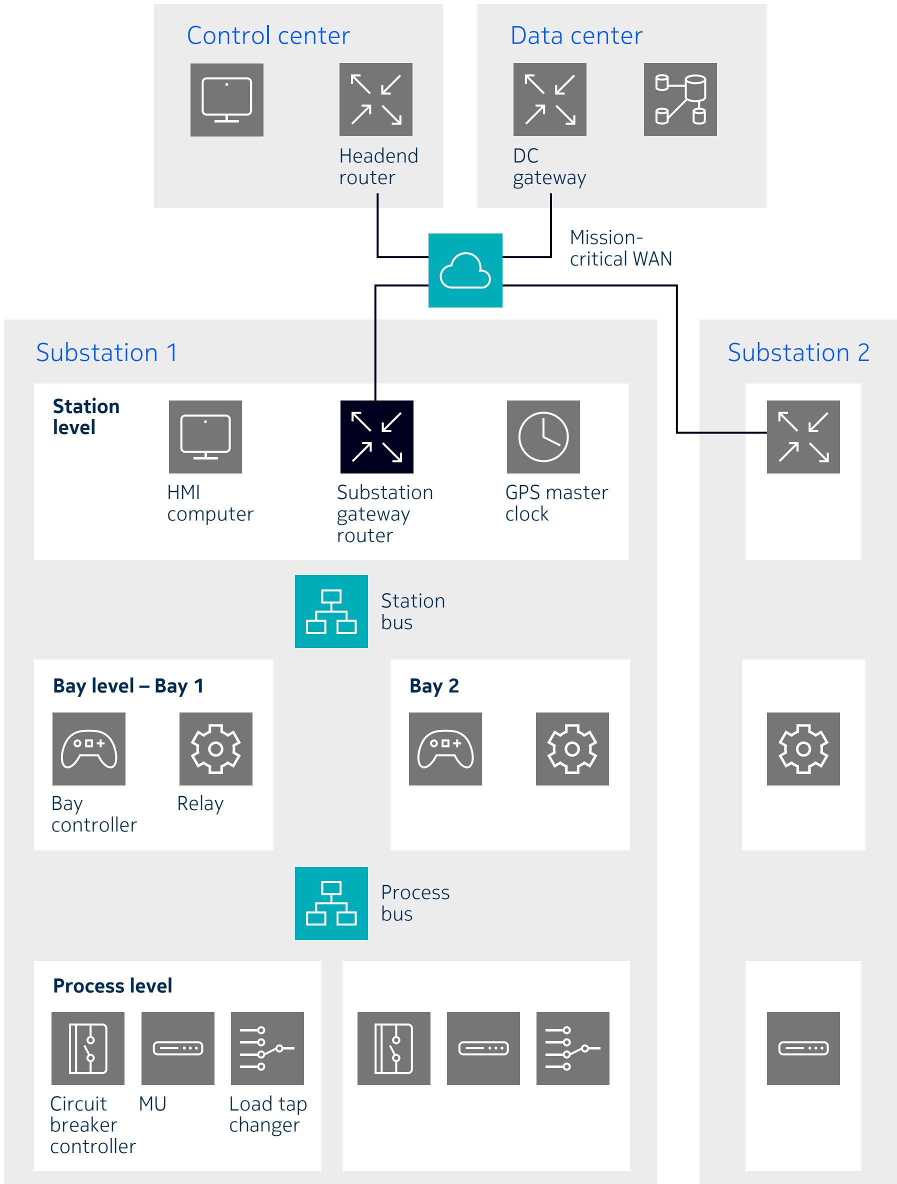
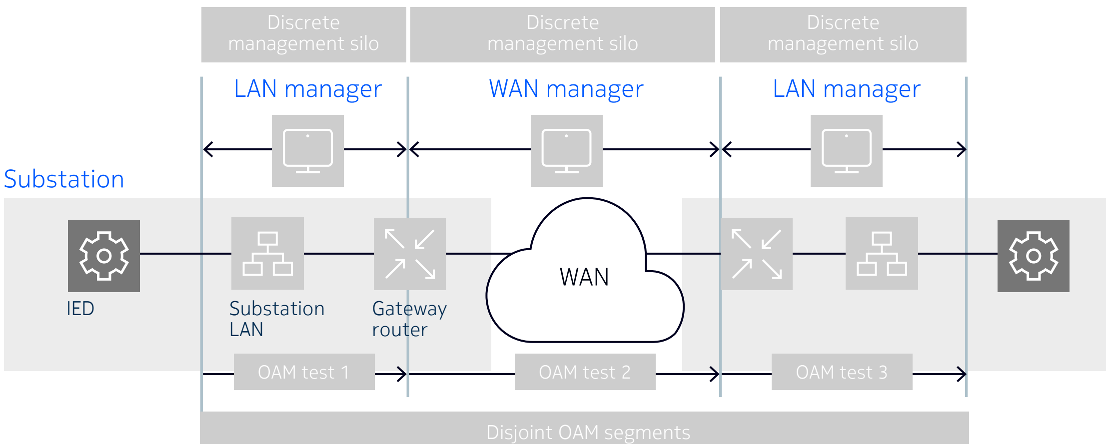


Figure 8 illustrates the example of provisioning and managing a communication path between two protective relays in two substations exchanging GOOSE messages through the WAN. With today's paradigm, utilities need to work with three disjoint network managers (one in each substation and the WAN domain). This is labor-intensive and prone to errors. Moreover, network maintenance and OAM works are also disjointedly performed on a segment-by-segment basis (see figure 9). As the number of such cross-domain IED connections scale up, managing them becomes a challenge. A new paradigm with a cross-domain end-to-end network management capability and seamless interworking becomes necessary.

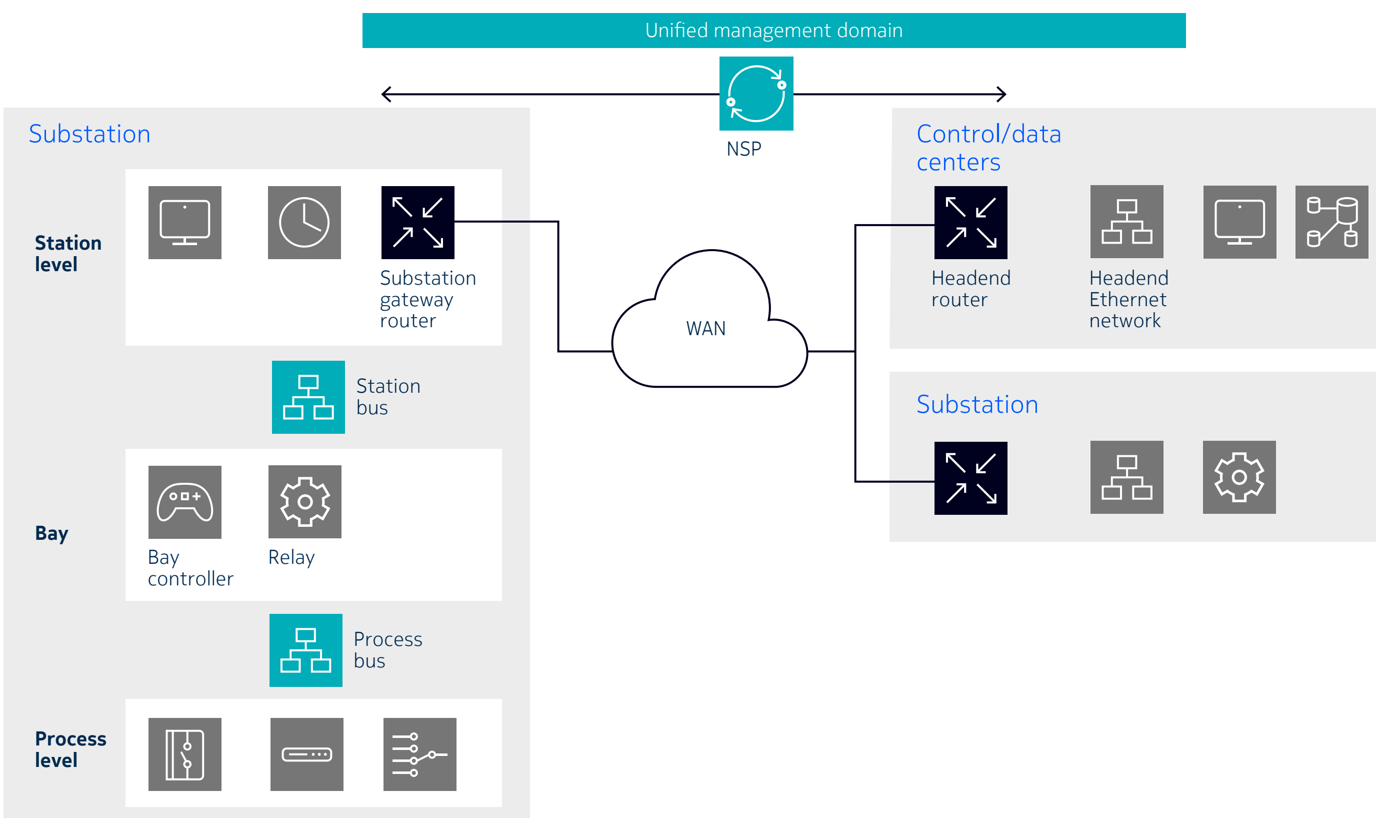
Figure 9. Disjoint utility network domains today



The Nokia digital substation network blueprint

Responding to the digital substation communication challenge, Nokia has introduced a converged digital substation network blueprint with managed WAN internetworking capabilities (see figure 10).

Figure 10. The Nokia digital substation networking blueprint



The blueprint is made of:

- 7210 Service Aggregation Switch (SAS) – a family of Ethernet service platforms that include ruggedized variants for substation networks
- 7705 Service Aggregation Router (SAR) – a family of IP/MPLS service platforms designed for substation router connecting to the WAN
- 7750 Service Router (SR) – a family of IP/MPLS service platforms for head end and data center gateway router terminating traffic from substations
- Network Service Platform (NSP) – a network and service manager for communications services in the substation network and the WAN.

The 7210 SAS forms the substation network for both the process bus and the station bus, fulfilling the intra-substation networking requirements as listed in table 2:

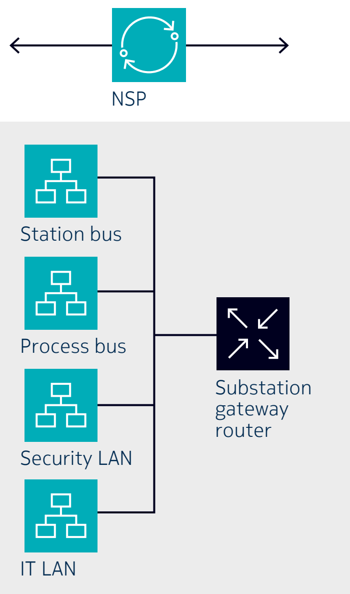
Table 2. 7210 SAS capabilities for substation networking

Substation networking requirement	7210 SAS capabilities
Multiservice	Network segmentation with VLAN networking (VPLS or Ethernet pseudowire, also known as virtual leased line)
Resiliency	G.8032 ERPS Link aggregation group (LAG) Interoperable with PRP/HSRP on IED and red box
QoS	Flexible priority-based queuing and scheduling
Synchronization	IEEE1588v2 boundary clock (BC)/transparent clock (TC)
Cybersecurity	MACsec IEEE 802.1X access port authentication Syslog Ethernet port closed by default VLAN segregation

Besides IEDs and other grid devices, there are security systems such as CCTV and access control, as well as IT systems for voice and data corporate service inside a substation. Ruggedized 7210 SAS variants have a high PoE (power over Ethernet) port density and large power capacity. Therefore, they are ideal to form separate security and IT network domains to connect and power many CCTV cameras and VoIP phones using PoE technology (PoE, PoE+, PoE++/HPoE) in every substation[2], all managed by the NSP. With 10GE interfaces, it brings abundant bandwidth for future automation applications (see figure 11).

2 Pan-tilt-zoom (PTZ) cameras with heaters and blowers; and VoIP phones with camera need more than 15W or even 60W of power. They can benefit from PoE+, PoE++ and HPoE support on the switches

Figure 11. NSP managing a multi-domain substation network

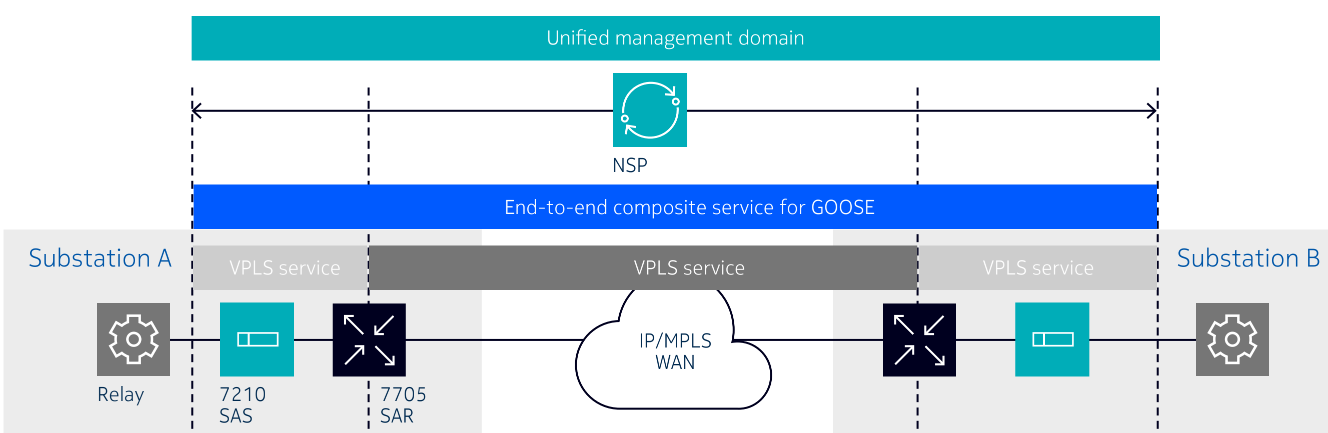


Seamless WAN internetworking

As discussed earlier in the Digital Substation Networking Requirements section, the current multi-domain network management paradigm is not adequate as it does not manage inter-substation and substation-to-operation center or data center connectivity with ease and at scale. The Nokia blueprint, with 7705 SAR as the substation gateway router and NSP as the end-to-end cross-domain manager, overcomes this challenge by bringing seamless WAN interworking at both the networking and management layers.

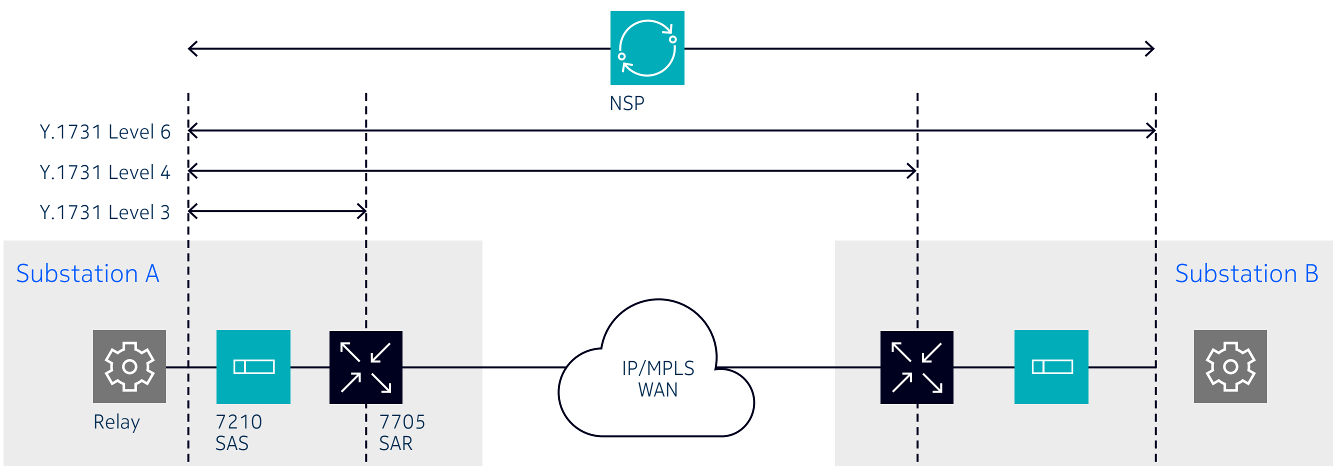
For example, a relay in substation A needs to exchange GOOSE messages with another relay in substation B over the WAN. The NSP can provision a composite service comprising a VLAN service on the 7210 SAS in the process bus on each side and a VPLS service (an Ethernet switching broadcast domain) across the WAN on a 7705 SAR in the WAN. This composite service oversees the entire communication path through the three network domains, enabling a unified management view (see figure 12).

Figure 12. NSP composite service for end-to-end cross-domain GOOSE communications



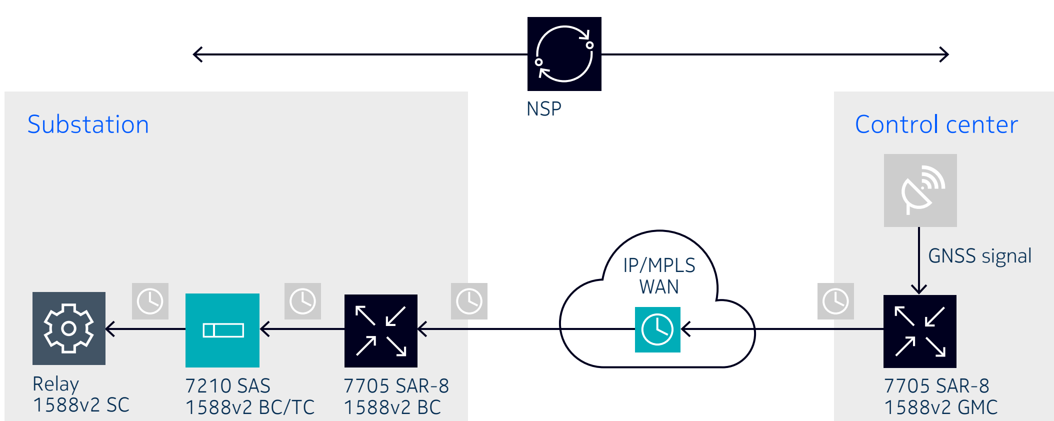
In addition, the NSP also provides end-to-end service assurance for GOOSE communications. It harnesses the power of ITU-T Y.1731 Ethernet OAM to continually monitor and measure the performance of the end-to-end path by leveraging the continuity check and delay measurement OAM capabilities. It ensures the end-to-end path is always up and can meet the required delay budget. While Y.1731 supports the concepts of OAM level (from 1–7) for segment-based OAM, configuring such OAM tests using today's paradigm requires considerable technical skills. With the end-to-end composite service view, the NSP can configure and launch OAM tests and measurements at different levels on an end-to-end and segment-by-segment basis without deep Y.1731 knowledge (se figure 13). The NSP can also periodically carry out the OAM tests for service assurance. When the continuity check test breaks or the delay measurement exceeds the threshold, the NSP will raise an alarm to notify operators.

Figure 13. NSP-managed multi-level multi-segment OAM



Accurate time synchronization is important for reliable relay operations to avoid false trips. With the NSP as the synchronization manager, the Nokia blueprint brings accurate timing across the WAN to every substation with IEEE1588v2 (cf. figure 14)[3].

Figure 14. The NSP oversees end-to-end 1588v2 peering relationship



3 Download application note: Providing accurate time synchronization for substation automation with IEEE1588v2

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Conclusion

The utility landscape is undergoing a monumental shift. Rising to the challenge of carbon reduction while maintaining a stable, balanced and reliable grid, utilities are transforming their operations to become digital, resilient and sustainable. This paper explains how the Nokia substation networking blueprint can become the digital substation communication foundation, not only inside the substation, but also with other substations, and with control and data centers.

With a broad communications product portfolio spanning IP/MPLS, data center fabric, 4G/LTE and 5G to packet microwave and packet optical transport, Nokia has the unique capability and flexibility to help utilities transform their networks for the highest reliability and cybersecurity. Our product portfolio is complemented by a full suite of professional services, including audit, design and engineering practices. To learn more about Nokia for utilities, visit our Power Utilities web page.

Abbreviations

7210 SAS	Nokia 7210 Service Aggregation Switch
7705 SAR	Nokia 7705 Service Aggregation Router
BC	Boundary clock
CB	Circuit breaker
DMS	Distribution management system
DWDM	Dense wavelength division multiplexing
EMS	Energy management system
FDIR	Fault detection, isolation and recovery
FERC	Federal Energy Regulatory Commission
FLISR	Fault location, isolation and service restoration
FRR	Fast reroute
GE	Gigabit Ethernet
GNSS	Global Navigation System
GOOSE	Generic object-oriented substation events
GPS	Geo-positioning system
HMI	Human-machine interface
HSR	High-availability seamless redundancy
IEC	International Electrotechnical Commission
IED	Intelligent electronic device
IP	Internet protocol
LAG	Link aggregation group
LAN	Local area network

LTE	Long-term evolution
MMS	Manufacturing message specification
MPLS	Multiprotocol label switching
MU	Merging unit
NSP	Network Services Platform
OAM	Operations, administration and maintenance
PRP	Parallel Redundancy Protocol
PT	Protocol type
QoS	Quality of service
RPL	Ring Protection Link
TC	Transparent clock
VAR	Volt-ampere reactive
VLAN	Virtual LAN
VPLS	Virtual private LAN service
VPN	Virtual private network
VVO	Volt-VAR optimization
WAM	Wide area measurement
WAN	Wide area network

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As a B2B technology innovation leader, we are pioneering the future where networks meet cloud to realize the full potential of digital in every industry.

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