Power Grid Architectures

As result of the standardization process in the Power Grid a critical standard was released the IEC 61850 that defines a set of Ethernet-based protocols to be used by power devices to exchange data, send commands, measure values and get synchronized

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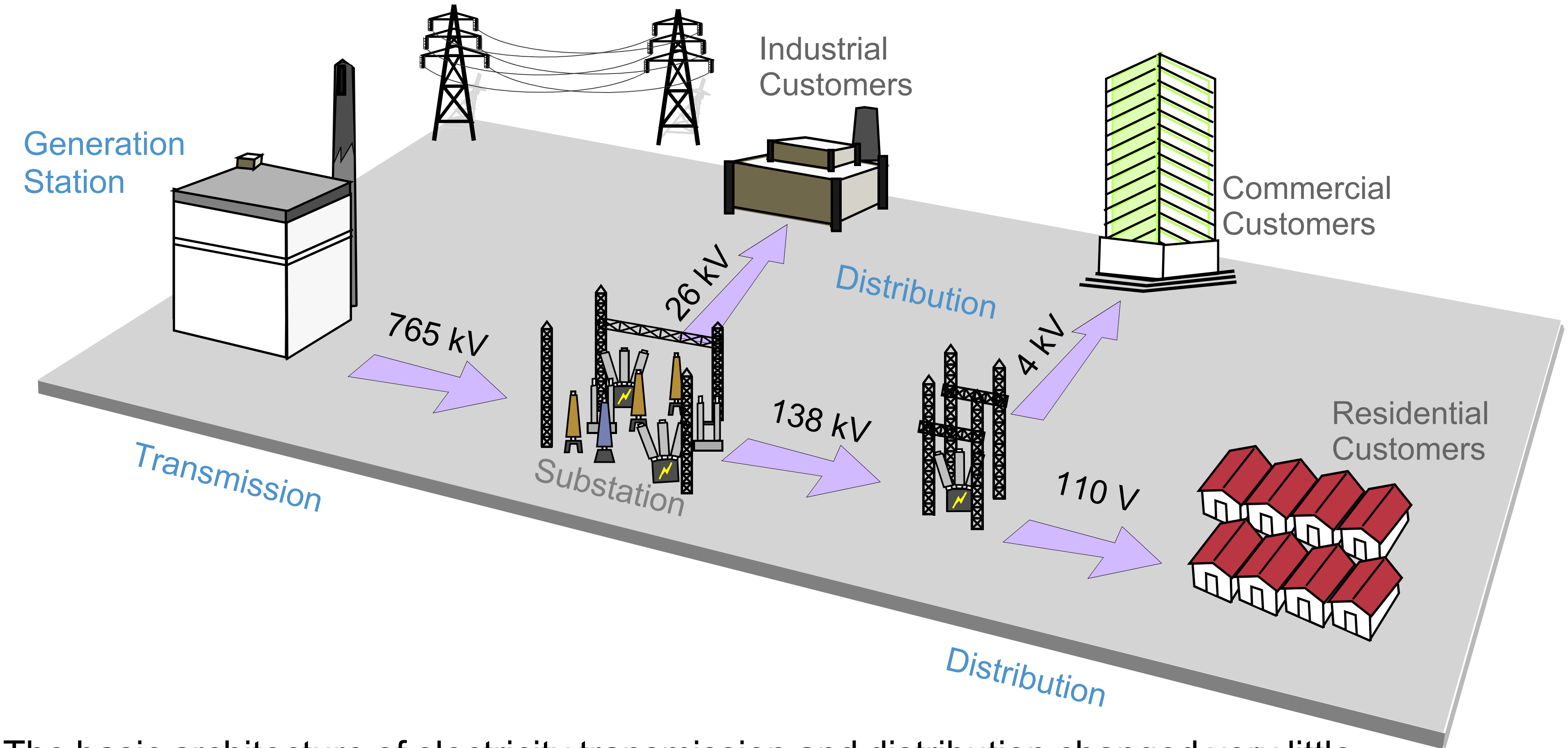
ABSTRACT

As result of the convergence process in the **Power Grid,** a new standard was released, the **IEC 61850**, that defines a set of Ethernet-based protocols.

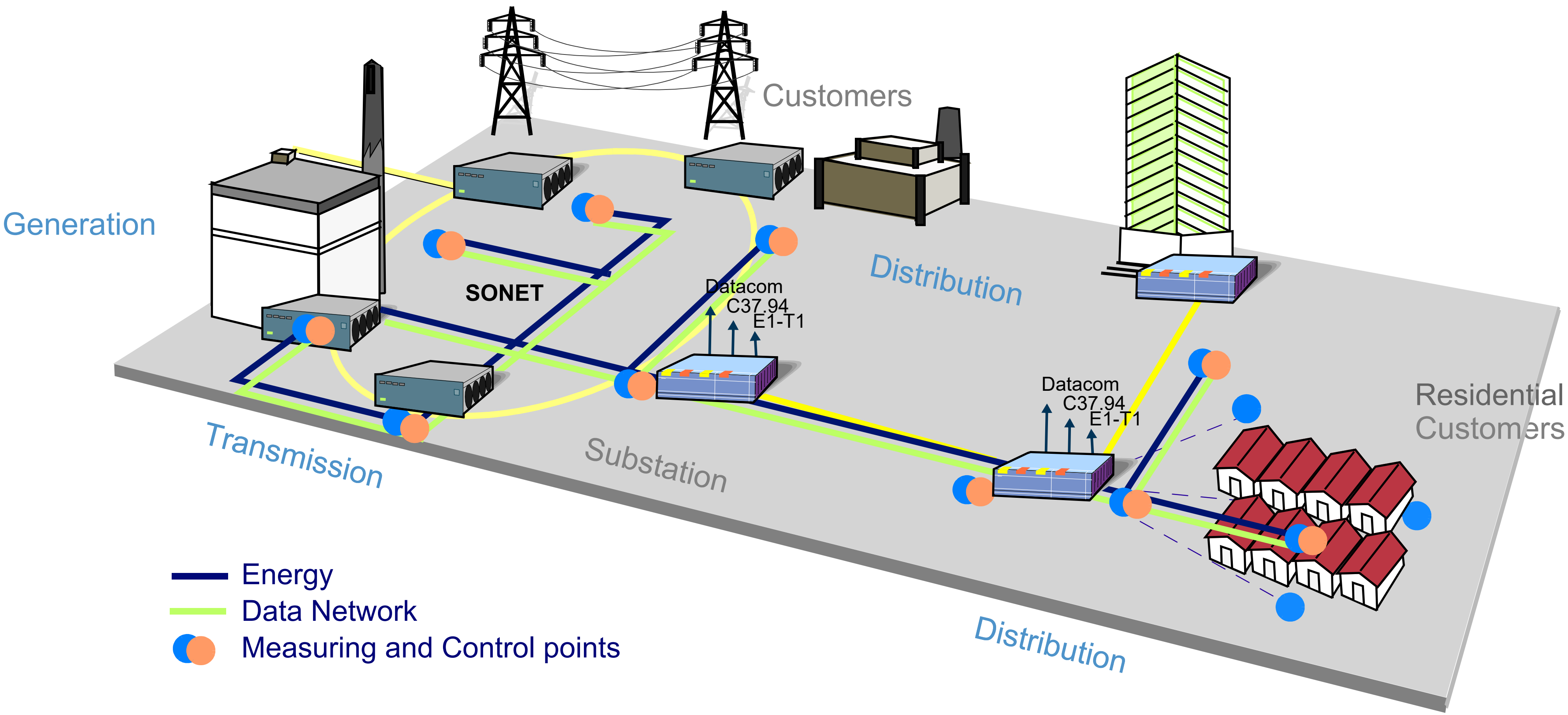
The IEC 61850 objective is to facilitate the interoperability (between devices and systems), ease of configuration (allocation of functions to devices), long term stability (layered, object-model based design), and reliability (lossless network architectures) to replace wire communications.

The Power Grid



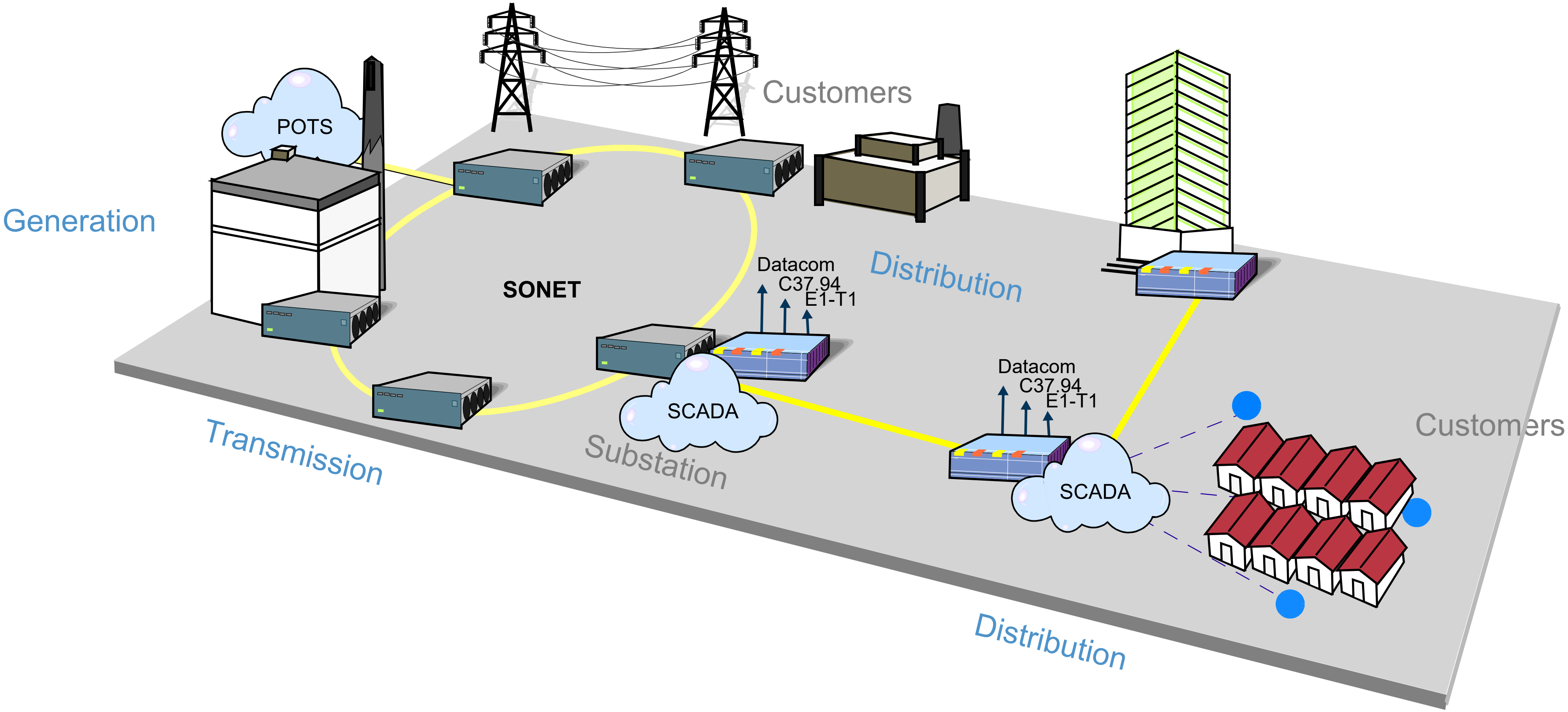
The basic architecture of electricity transmission and distribution changed very little during the first 100 years. However, in recent decades, the concept of **Smart Grid** emerged thanks to the massive use of digital technologies to increase efficiency, resilience and quality of the service.

The new **Smart Power Grid**



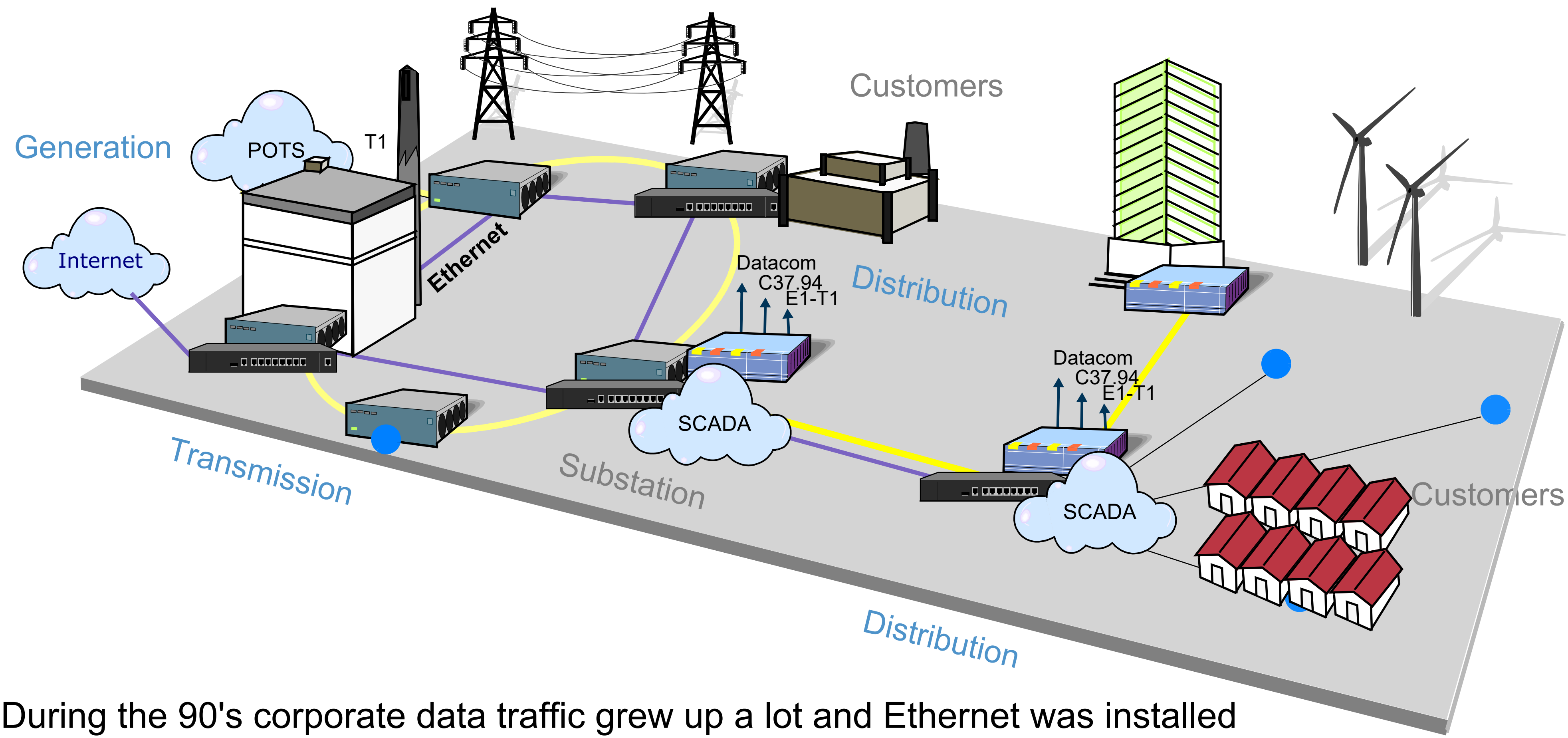
Smart Grid require a **Telecom Data Network** to communicate all the elements of the Power System, including Generation plants, Substations and Customers in order to increase the efficiency, resilience and quality of the power grid, while allowing advanced management.

Network evolution: **SONET/SDH**



At the 80's SONET was the first network to be deployed and it was a satisfactory solution for common applications such as SCADA, Telephony and Tele-protection because it is a predictable, symmetric, low latency, and fault tolerance architecture.

SONET/SDH + Ethernet

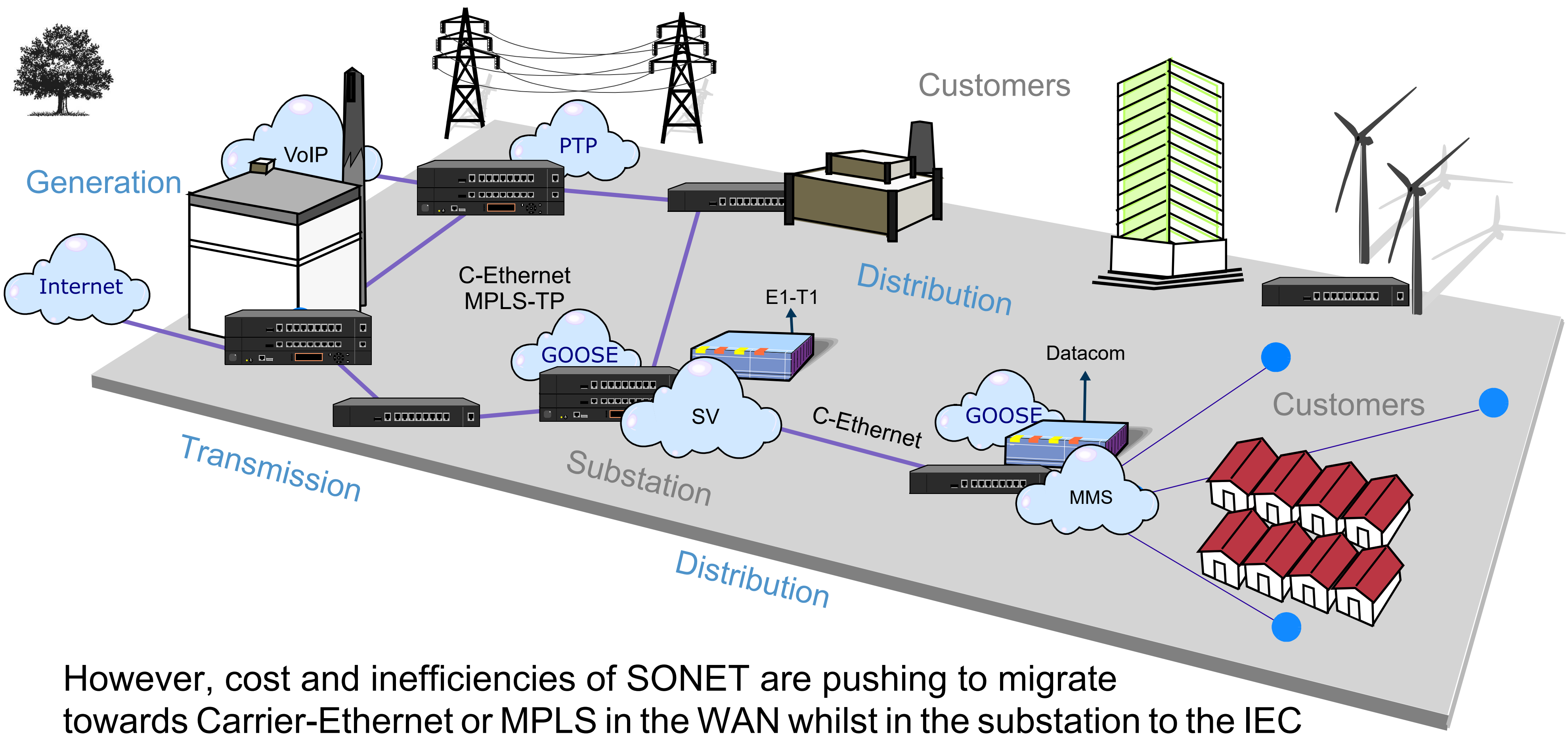


During the 90's corporate data traffic grew up a lot and Ethernet was installed everywhere to meet the demands of internet access, emails and enterprise data.

For many years, both networks were operational and interconnected:

- SONET to carry services such as T1/E1, Datacom (RS232), C37.94 and SCADA
- Ethernet to transport enterprise information such Internet, email, corporate files and new services

Ethernet + MPLS-TP



However, cost and inefficiencies of SONET are pushing to migrate towards Carrier-Ethernet or MPLS in the WAN whilst in the substation to the IEC 61850 in order to integrate all data traffic generated at the power grid under the Ethernet umbrella:

- IEC 61850: GOOSE, SV, MMS, PTP and SNTP protocols
- Carrier-Ethernet, MPLS and MPLS-TP to communicate substations
- Circuit Emulation to support legacy T1/E1, Datacom (RS232), C37.94

What is a **Substation**?

Located in between Generation and Consumers Substations manage key functions:

1. **Transforms**: Converting High to Lower Voltages
2. **Distribution**: Splitting power lines for sending the energy to the consumers
3. **Operation**: Configuring and supervising the electric system to the correct values
4. **Protection:** Detecting events and Isolating power elements and lines when faults occur
5. **Interconnection**: Linking circuits of varying voltages and different lines at the same voltage

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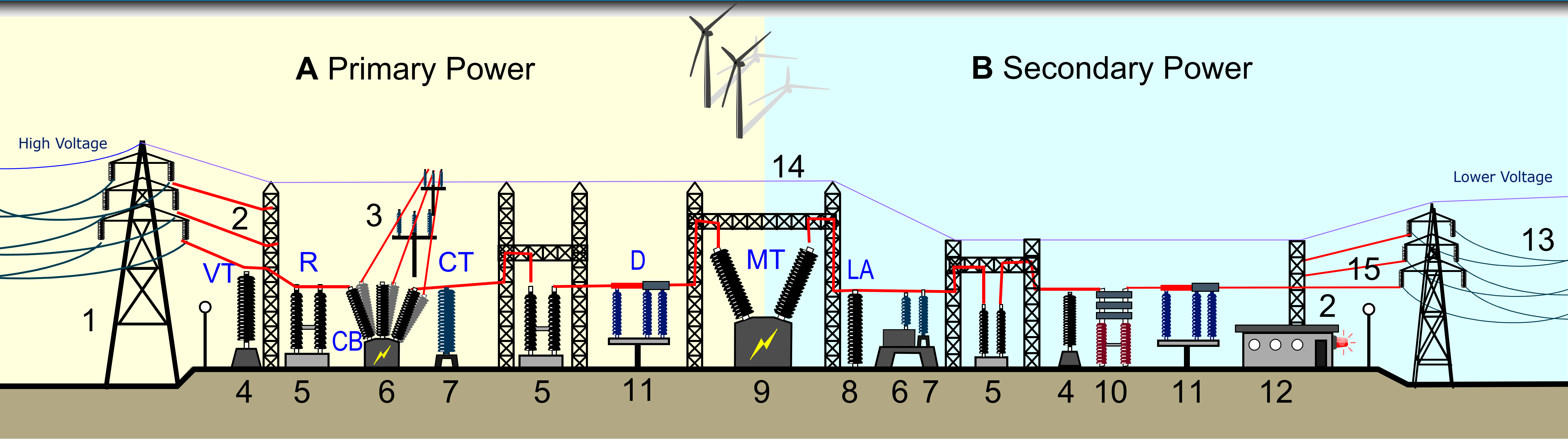
Components & **Systems** in a Substation



1.Primary Power (PP), 2.Feeder, 3. Busbar, 4.Voltage Transformer (VT), 5.Relay (R), 6.Circuit Breaker (CB), 7.Current Transformer (CT), 8.Lightning Arrester (LA), 9.Main Transformer (MT), 10. Capacitors (C), 11.Disconnector, 12.Control Shelter, 13.Secondary Lines, 14. Ground, 15. Overhead Lines

The **Primary Power** manages the high voltages lines coming from Generation while the secondary the lower voltages distributed to Industrial and residential consumers.

Main Transformer installed in between. **Disconnector** (D) isolates physically and visually the lines while **Lightning arrester** (LA) protects the power grid from electric storms. **Current** (CT) and **Voltage Transformers** (VT) are measuring devices to provide information to **Relays** (R) that process the inputs in real time. If a fault is detected (i.e. Current or Voltage changes, or a short-cut) then the Relay indicates the **Circuit Breaker** (CB) to close the line and disconnect the faulty section. **Capacitors** help to correct phase shifts and to improve the power factor.

IED (Intelligent End Device)

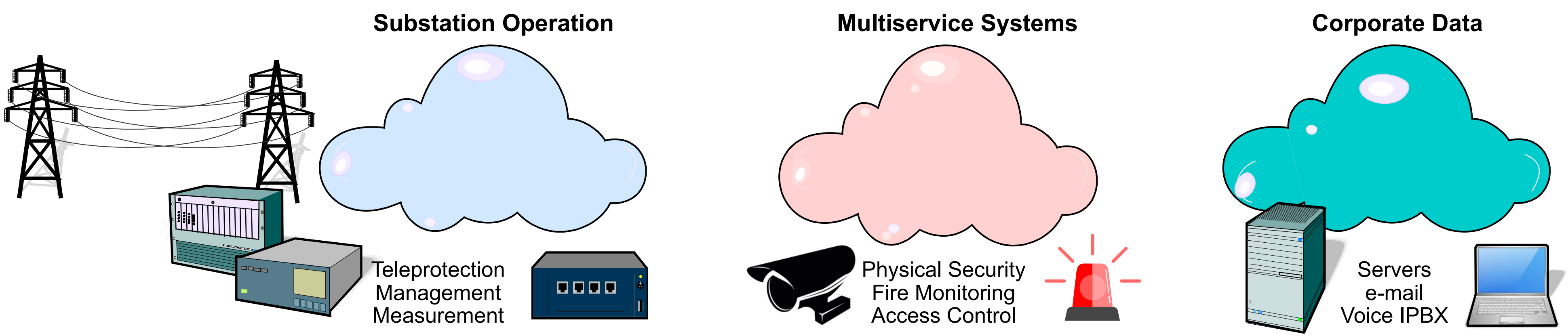
IEDs are a a key element in the substation and the result of the evolution of relays and other devices now equipped with microprocessor and advanced communications. There are several types of IED:

- **Protection Relays**: to protect lines, generators, motor, transformers, or feeders.
- **Bay Controllers**: to manage voltage regulators, logics in circuit breakers, event recording, etc.
- **Mergin Units** or **Metering Devices**: to data acquition and storage such as Voltage (V), Current (A), frequency (Hz), Power (MW), Energy (kWh), Harmonics (H), Temp (C), Tripping (t), etc.

IED can take decisions thanks to its capability to obtain and process information from the power grid. For instance in case of an event or a fault IEDs can automatically command circuit breakers to open or close for protection, IED can also reconfigure the network and provide service restoration in milliseconds.

Modern IEDs support IEC 61850 communication standards in order to assure vendor interoperability by means of universal protocols and data structures.

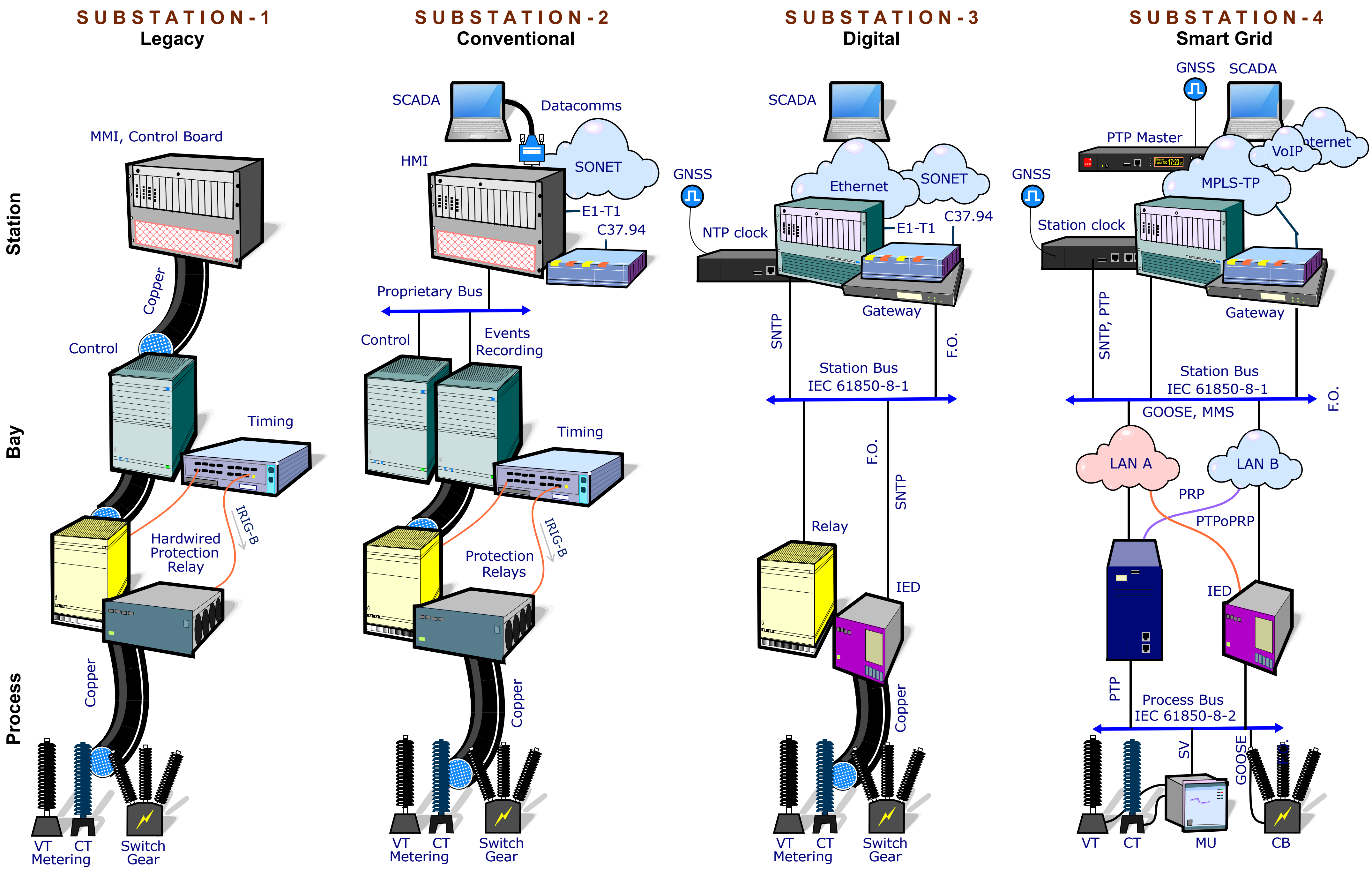
Communication needs in Substations



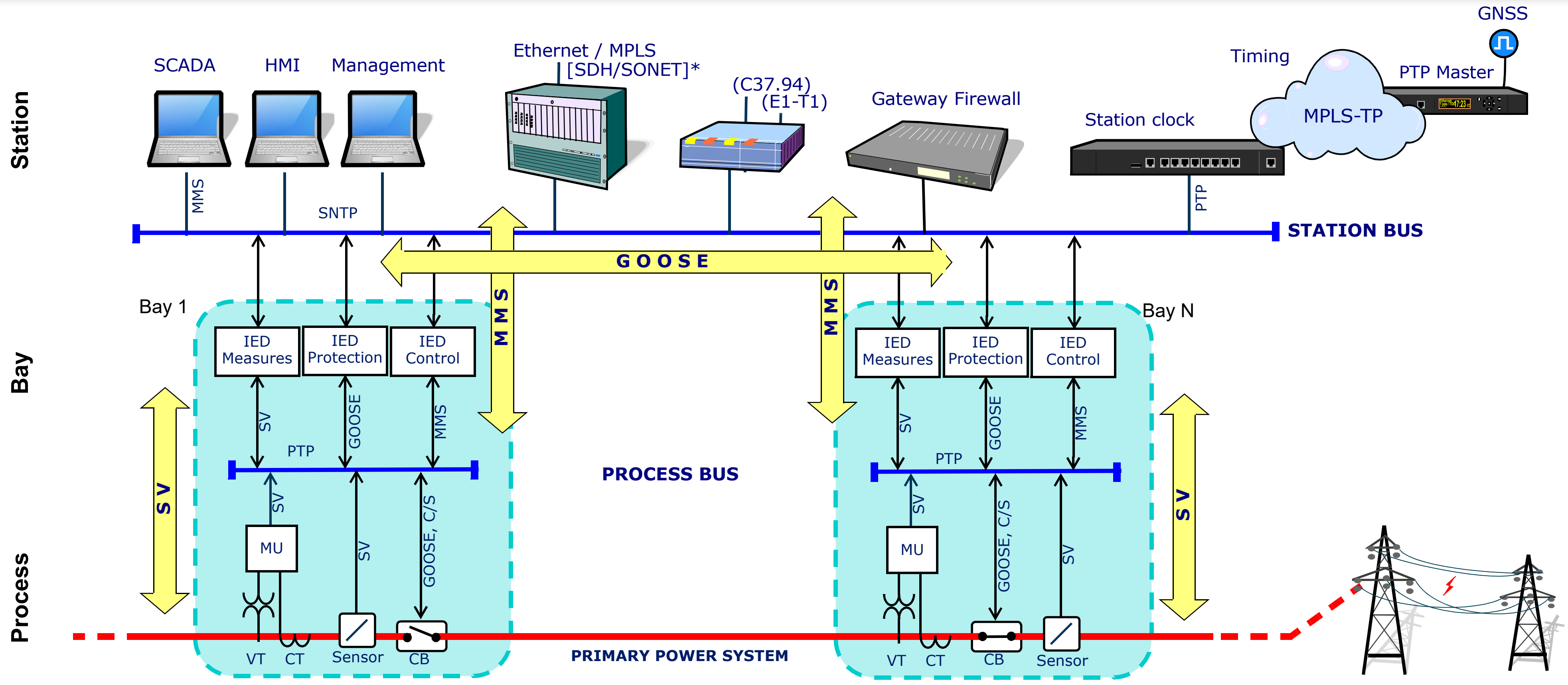
Communication infrastructures of a substation have three separate and differentiated networks:

- **Operation**: includes grid management and protection. It is deployed in the zone where critical utility monitoring and controlling infrastructure reside. It contains station and process buses as defined by IEC 61850 and other protocols such as C37.94, SCADA, Serial Datacom, E1/T1. Data have strict requirements for Latency, Symmetry and Redundancy.
- **Corporate**: for data traffic, LAN, email (no critic, no time sensitive) Ethernet connectivity (Wi-Fi), voice services, and general Ethernet connectivity for employees to access email, and Internet
- **Multi-service**: includes physical security components like Ethernet-connected badge readers, video surveillance cameras, local authentication, authorization, and accounting, and logging applications.

Substation **Evolution**



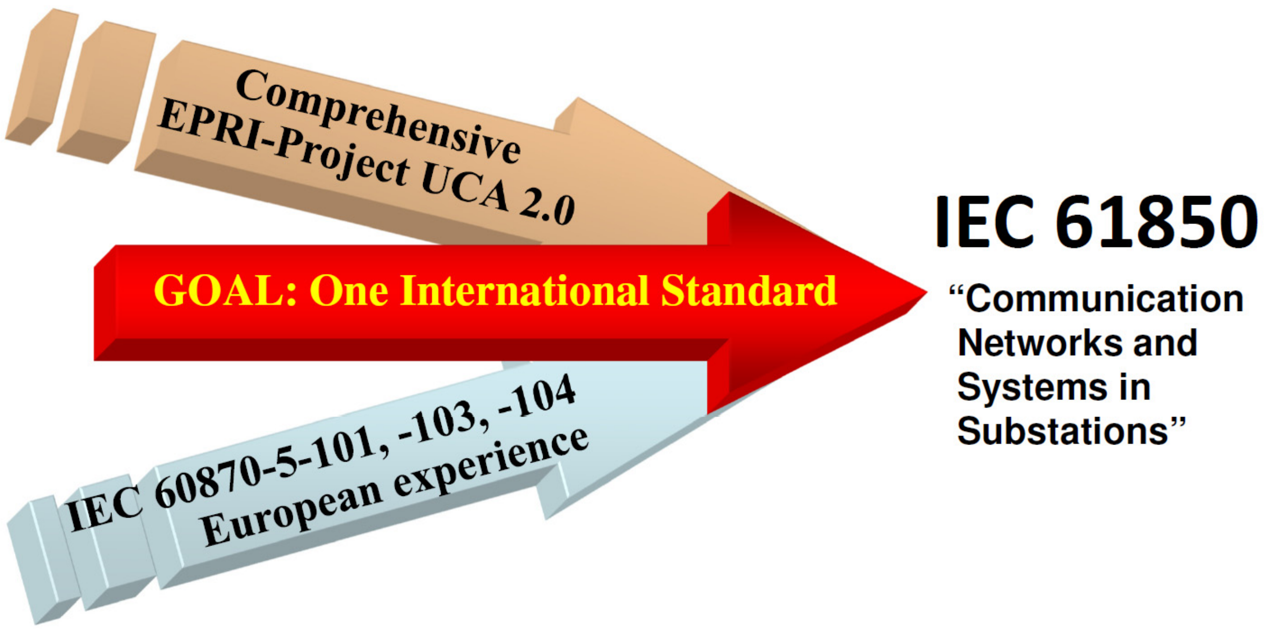
Smart Grid Substation **in detail**



The **Station bus** provides connectivity to individual bays, distributed controllers, gateways, management and human machine interfaces (HMIs). It may connect up to hundreds of Intelligent End Device (IEDs), often segmented physically or logically depending on their application.

Process bus, connects process equipment such as Current (CTs) and Voltage Transformers (VTs), Sensors, or Circuit Breakers to IED transporting data (such as voltage, current, status...) and operation commands (i.e. open/close circuit). The connection can be direct or by means of Merging Units (MU) that transform the analog measurements to digital data.

IEC 61850: Communication

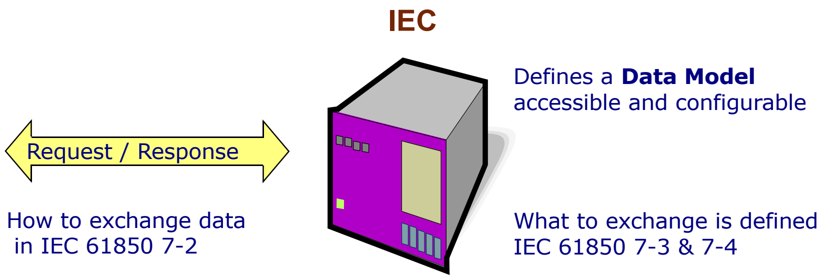


IEC 61850 then arises from the convergence of American and European standards.

It goes far beyond many others communications standards including:

- Communication between processes, defining what and how communicate
- Standardized and extensible object models
- Standardized configuration language
- Specification of the Conformity Tests from the first moment

Objectives



Interoperability between devices the substation

- By means of standardized data models and information exchange
- Use a known protocol
- Understand the information provided by other devices

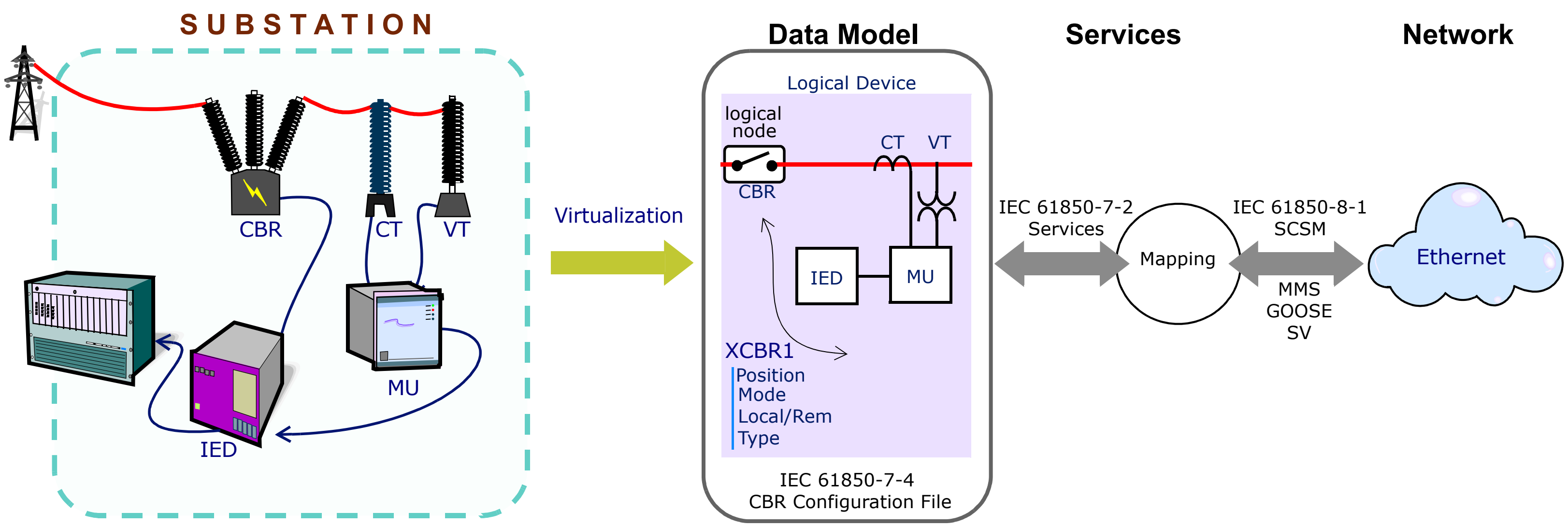
Simplify configuration and maintenance

- Self-descriptive devices
- Standardized configuration information

Integrated communication

- Acquisition of data directly on primary equipment (VT, CT, CB...)
- Reduction of wiring cost by means LAN vs. copper cables

The IEC 61850 structure

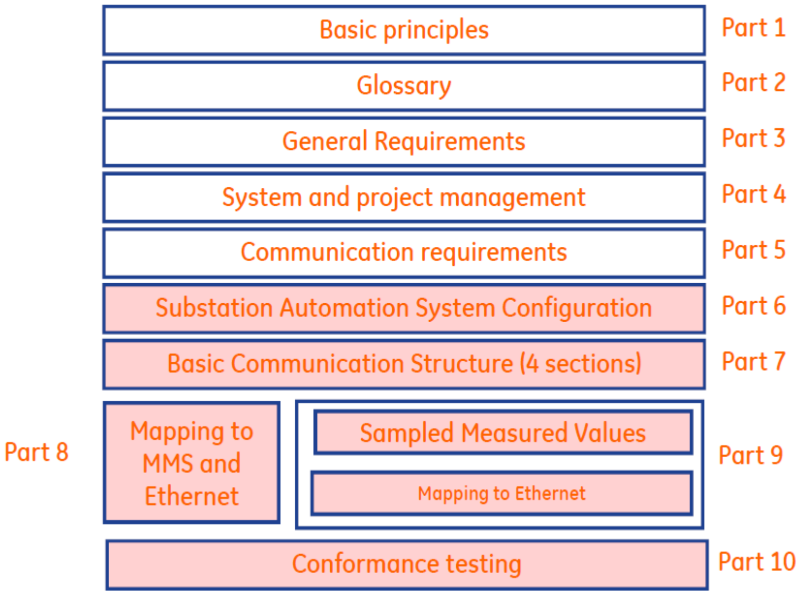


The Standard defines an information exchange mechanism:

1. **Information Models**: substation is virtualized using data structures ie. CBR status, measurements...
2. **Services**: how to use the information model ie. position of a Circuit Breaker
3. **Network**: standardized protocols to transport services and interchange information
4. **Configuration**: includes a complete description of each type of device

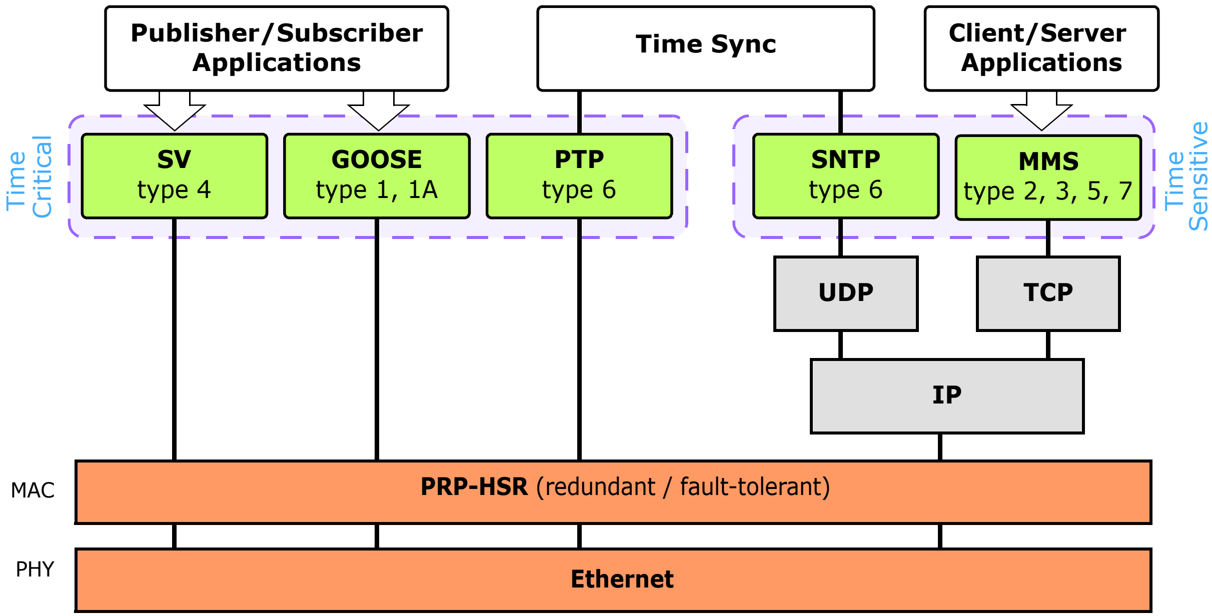
Complete functionality of the substation is modeled using logical nodes (LN) which are a virtual representation of real devices. Several LNs from different real devices build up a logical device (LD).

IEC 61850 structure



- IEC 61850-1: Introduction and overview
- IEC 61850-2: Glossary
- IEC 61850-3: General requirements
- IEC 61850-4: System and project management
- IEC 61850-5: Communication requirements
- IEC 61850-6: Configuration language in substations to IEDs
- IEC 61850-7: Basic communication structure for substation
  - 7-1: Principles and models
  - 7-2: Abstract communication service interface (ACSI)
  - 7-3: Common Data Classes
  - 7-4: Compatible logical node classes and data classes
- IEC 61850-8: Specific communication service mapping (SCSM)
  - 8-1: Mappings to MMS
- IEC 61850-9: SCSM
  - 9-1: Sampled values over serial unidirectional multidrop point-to-point link
  - 9-2: Sampled values over ISO/IEC 8802-3
- IEC 6185-10: Conformance testing

The **IEC 61850** model



The IEC 61850 is a set of standards and technical reports for interoperability (between devices and systems), ease of configuration (allocation of functions to devices), long term stability (layered, object-model based design), and reliability (lossless network architectures) to replace wire communications.

- **Ethernet-based Protocols**: Sampled Values (SV), Generic Object Oriented Substation Event (GOOSE), and Manufacturing Message Specification (MMS) that transport data and commands.
- **Time Synchronization**: Precision Time Protocol (PTP) and Simple Network Time Protocol (SNTP) that align in time the complete grid.
- **Lossless Architectures**: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) that build a fault-tolerant network to a single point of failure.
- **Substation Configuration Language** (SCL) specified by IEC 61850 for the configuration of substation includes representation of modeled data to have a complete interoperability

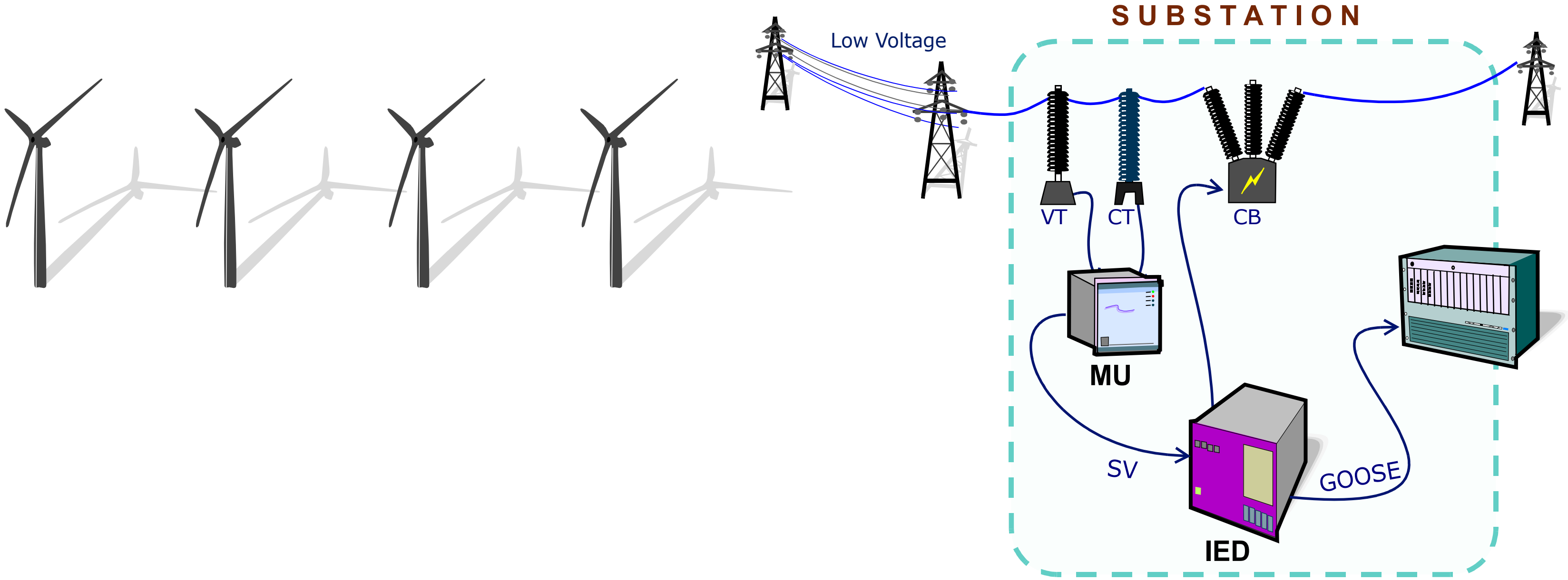
IEC 61850 formats & protocols

Substations are the building blocks for electric power grids. Substation automation refers to using data from intelligent electronic devices to enable stability, increase efficiency and maintain the system integrity. To make it possible a new standard was released, the IEC-61850 that facilitates the intensive use of ICT technologies and guarantees the interoperability between vendors, appliances and processes. The IEC-61850 defines a set of protocols and network architectures to synchronize, measure, exchange data, command and protect the grid.

Type	Message	Protocol	Layer	BWidth	Delay	Priority	Bus	Model	Application
1A	Trip	**GOOSE**	L2 - Multicast	Low	< 3 to 10ms	High	Process	Publisher	Protection
1B	Other	**GOOSE**	L2 - Multicast	Low	< 20 to 100ms	High	Process	Publisher	Protection
2	Medium Speed	**MMS**	L3 - IP/TCP	Low	< 100 ms	Medium Low	Process & Station	Client/Server	SCADA
3	Low Speed	**MMS**	L3 - IP/TCP	Low	< 500 ms	Medium Low	Process & Station	Client/Server	SCADA
4	Raw Data	**SV**	L2 - Multicast	High	< 3 to 10ms	High	Process	Publisher	Process Bus
5	File Transfer	**MMS**	IP/TCP/FTP	Medium	< 1000 ms	Low	Process & Station	Client/Server	Management
6	Timing	**PTP**	L2 - PTP	Low	Protection < 0,1 to 3ms Transformers ±1 to ±25us	Medium High	Process & Station	Unidirectional	Synchrophasors, IED
7	Command	**MMS**	L3 - IP	Low	< 500 ms	Medium Low	Station	Client/Server	SCADA

Power grid elements use IEC 61850-7-2 defines a basic set of services to exchange data, send commands and measure values that permit **the configuration, supervision, protection** and **control** the wide-area electrical network. Appliances such as IEDs of different vendors can now communicate each other with the help of common **protocol stacks** and **data structures.**

SV (Sampled Values)

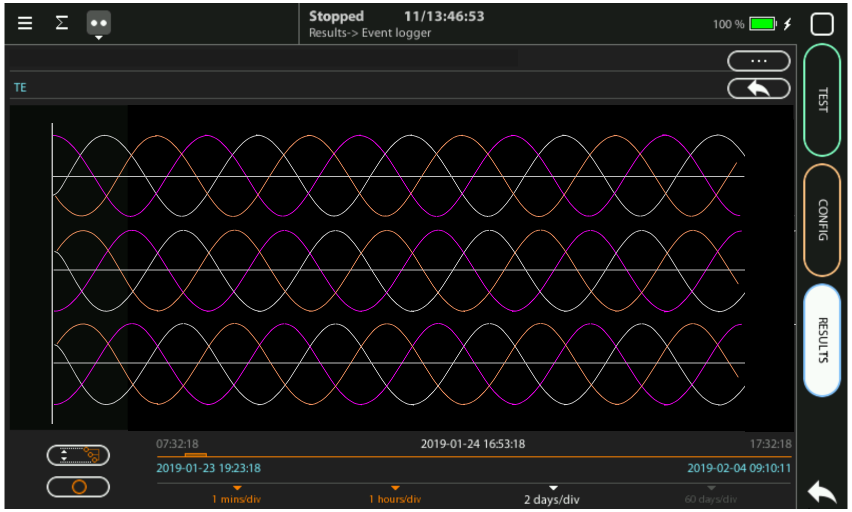


Sampled Values (SV) or **Sampled Measured Values** (SMV) is a protocol defined in IEC 61850-9-2 for the acquisition of raw data [8]. In particular, it facilitates the transfer of digitized samples of analog measurements. SV is time critical and can be streamed as unicast or multicast.

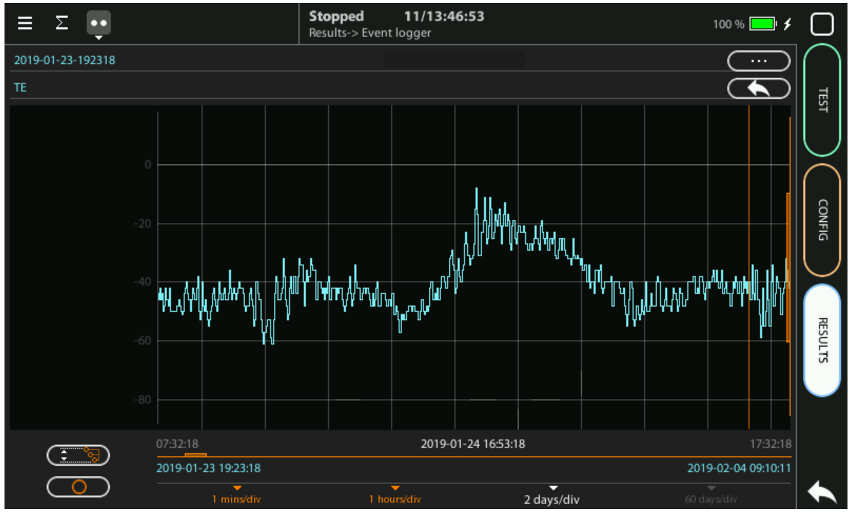
- SV are time critical messages, hence no acknowledgements are sent.
- SV is directly mapped, improving the time performance of data transfer. However, unlike in GOOSE, the same message is not retransmitted in SV.
- SV protocol continuously publishes data packets at a specific rate defined by the user.

SV (Sampled Values)

Voltage SV represented at Control Station



Phase Time Error extracted from captured SV



SV is used to transmit high speed streams of status, I/O signals and **values measured** by conventional or non-conventional current and voltage transformers:

- **Publisher/subscriber model**, for time critical transmitting unacknowledged data to subscribers
- The **Merging Units** (MU) converts analog to digital data before sending to the network
- SV simplifies substations using the process bus not need for specific wiring to make connections
- Used to send data about the Transformers deployed in the substations
- Transmission of Sampled Values from instrumental transformers: high amount of data to be sent in real-time and loss of data shall be detected
- Unlike GOOSE Messaging, which is event based, SV messaging is stream based

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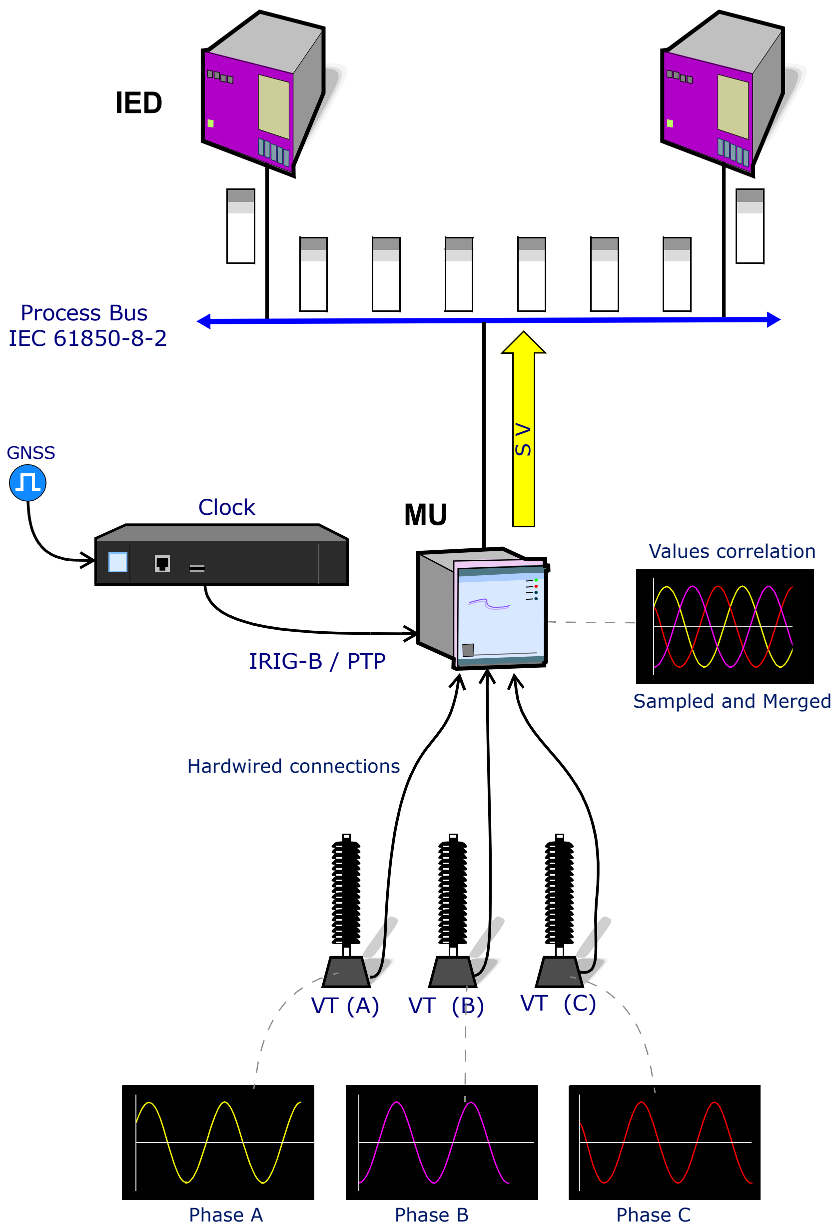
Merging Units (**MU**)

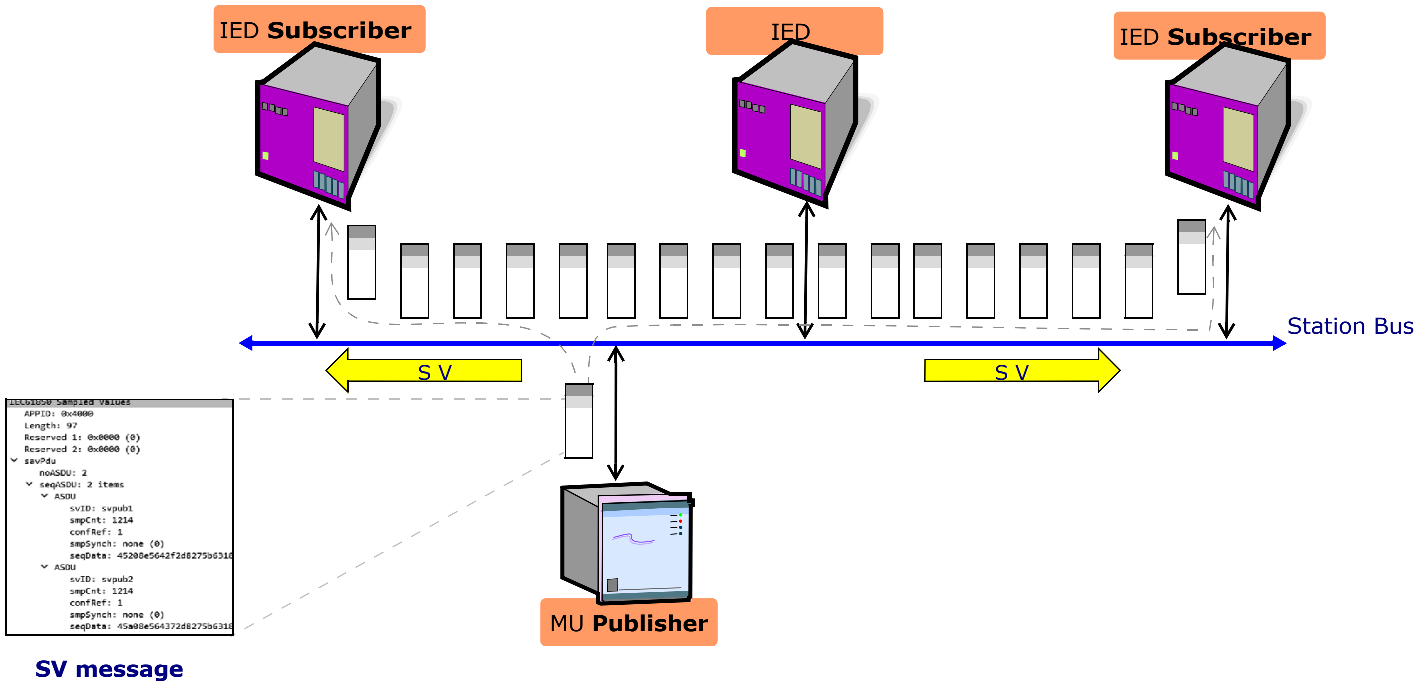


A **Merging Unit** (MU) is an IED that digitizes the analog measurements taken by current and voltage transformers. Afterwards the MU publishes the data as a stream at a predefined rate.

Protection and control IED interested in this information must be subscribed to receive this information.

- MUs combine and perform time correlation of voltages and currents of the three phases of a line.
- Connections from CT / VT to MU are usually hardwired.
- The data is published in the form of sampled values (SV) that can be used directly by bay IEC and controllers and/or protection relays that support this protocol.

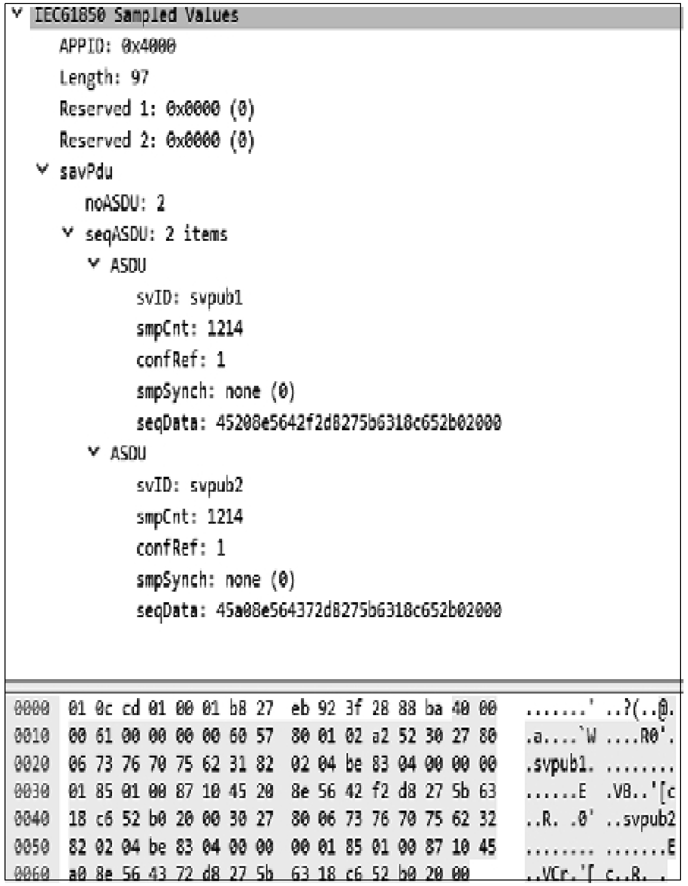
Publisher/Subscriber method



It is defined in the standard to provide a fast and cyclic transfer of samples.

- The Publisher must sample the entries with a specific sampling frequency. A time tag is added to the values, so that subscribers can verify the sequence of the values.
- SV is mapped **directly to Ethernet** to provide real-time communication
- Data is sent in multi-cast Ethernet frames to the **process bus**
- Point-to-Multipoint connection or Multicast-Application-Association (MCAA)
- The Publisher IED transmits a message that only the subscribers receive.The reaction of each receiver depends on its configuration and functionality

SV message **decoding**



Messages are a collection of values as members of a **Dataset**:

- **MsvCBRef** Multicast Sampled Value Control Block
- **DatSet** The name of the data set being sent
- **MsvID** System wide unique ID of the sending application
- **SmpCnt** The number of samples in the message
- **RefrTm** Time of the first sample
- **ConfRev** Configuration Revision of the MSV Control Block
- **SmpSynch** Samples are time are time synchronized (true/false)
- **SmpRate** Sample Rate
- **SmpMod** Sample Mode: samples/period, sampl/sec, sec/sampl.
- **Simulation** Simulated data (true/false)
- **Sample [1..n]** The sequence of samples (one data set per sample)

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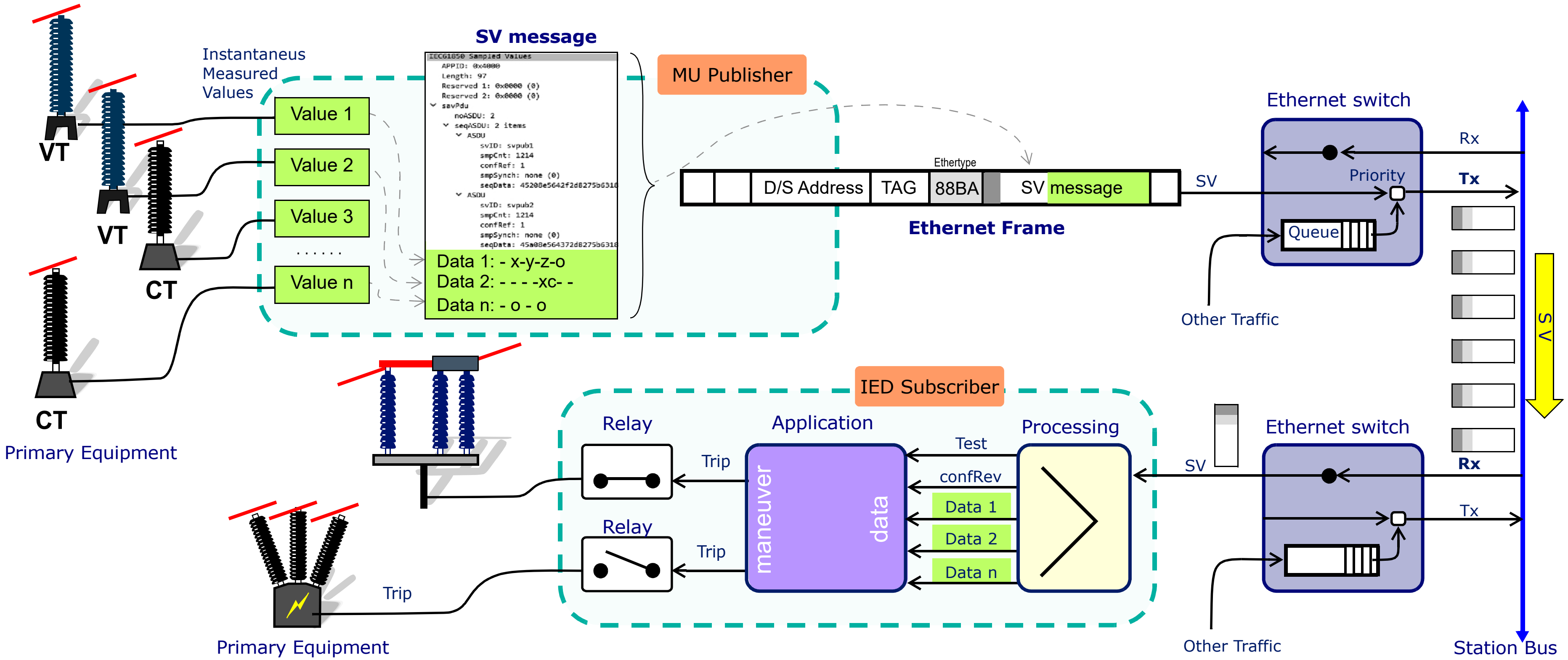
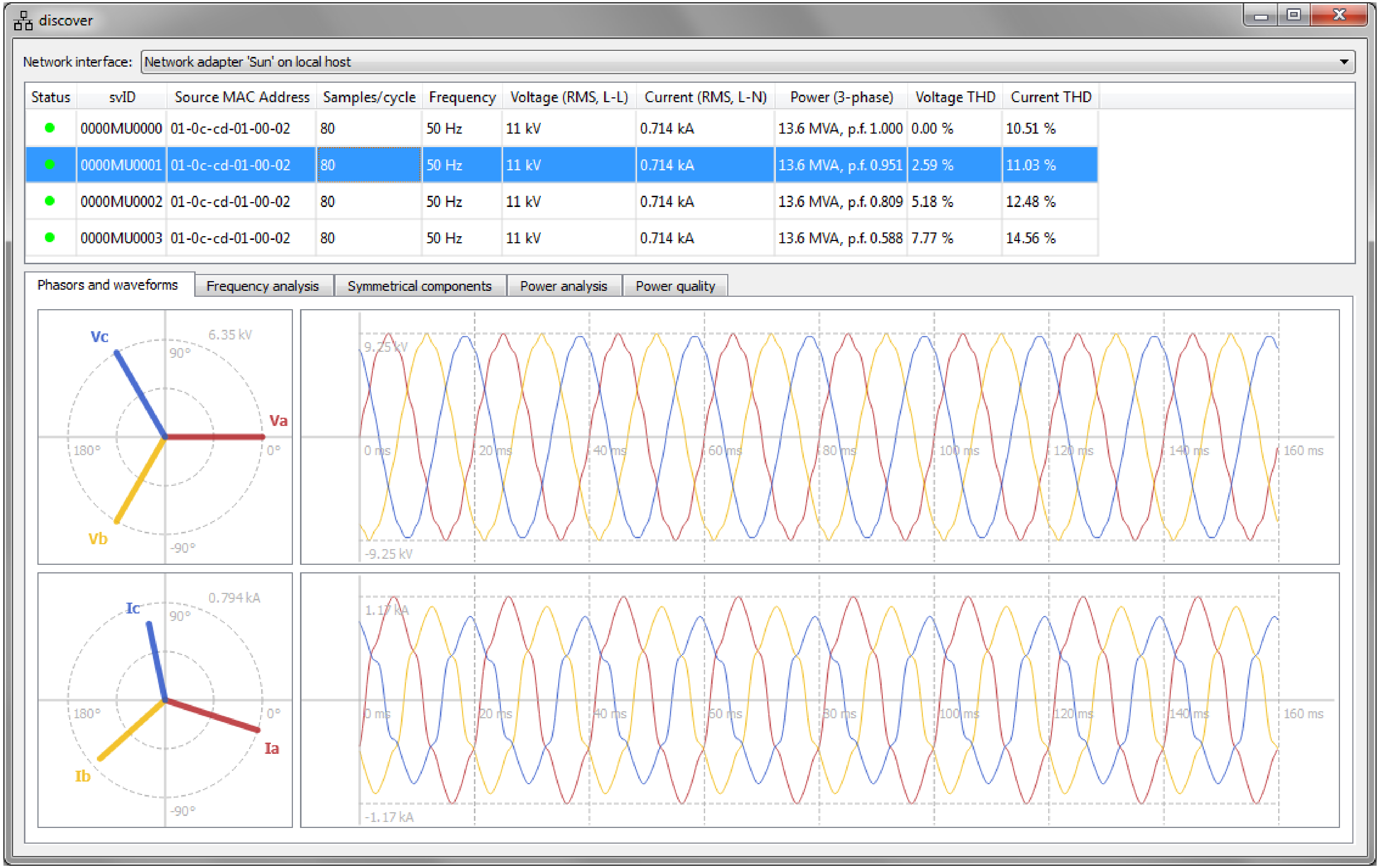
Publisher & Subscriber

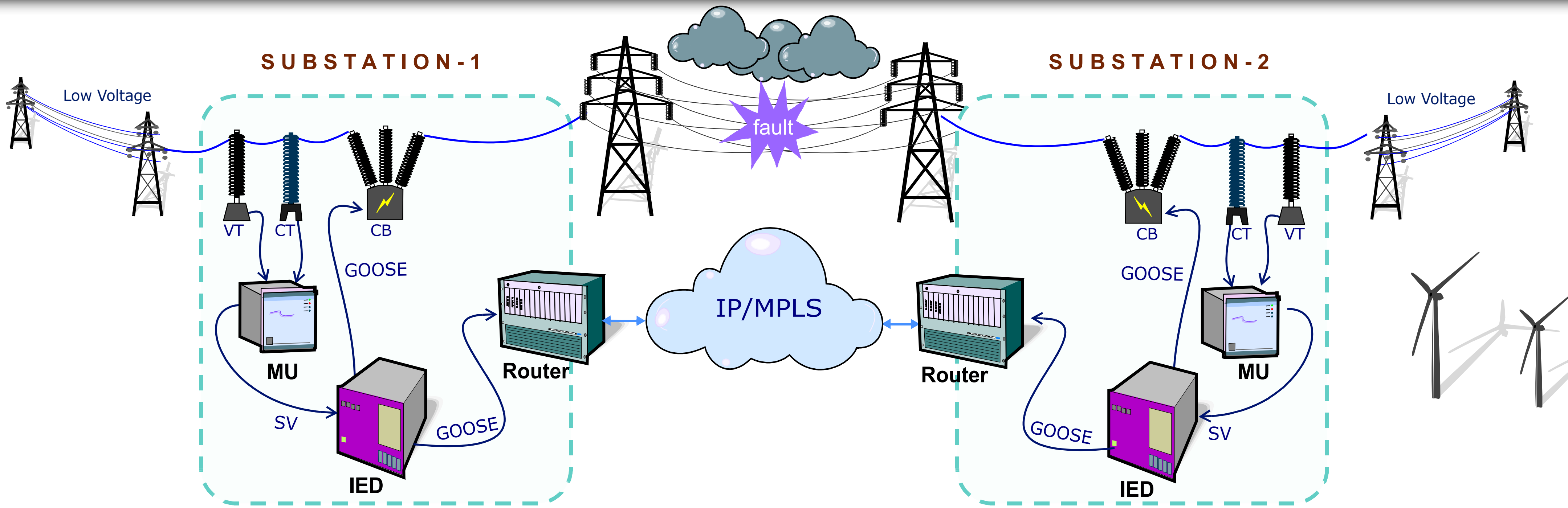


1. Merging Units digitalize the values and build the SV message mapped in Ethernet frames
2. Sampled Values (SV) supports distribution of time sampled data such as measurements, status, and other I/O signals over a separate “process bus”.
3. Unlike GOOSE Messaging, which is event based, SV messaging is stream based, each message contains one or more samples of data taken at a specified sample rate
4. Messages are sent constantly at a sufficient rate to communicate all the samples

SV **Graphic** representation



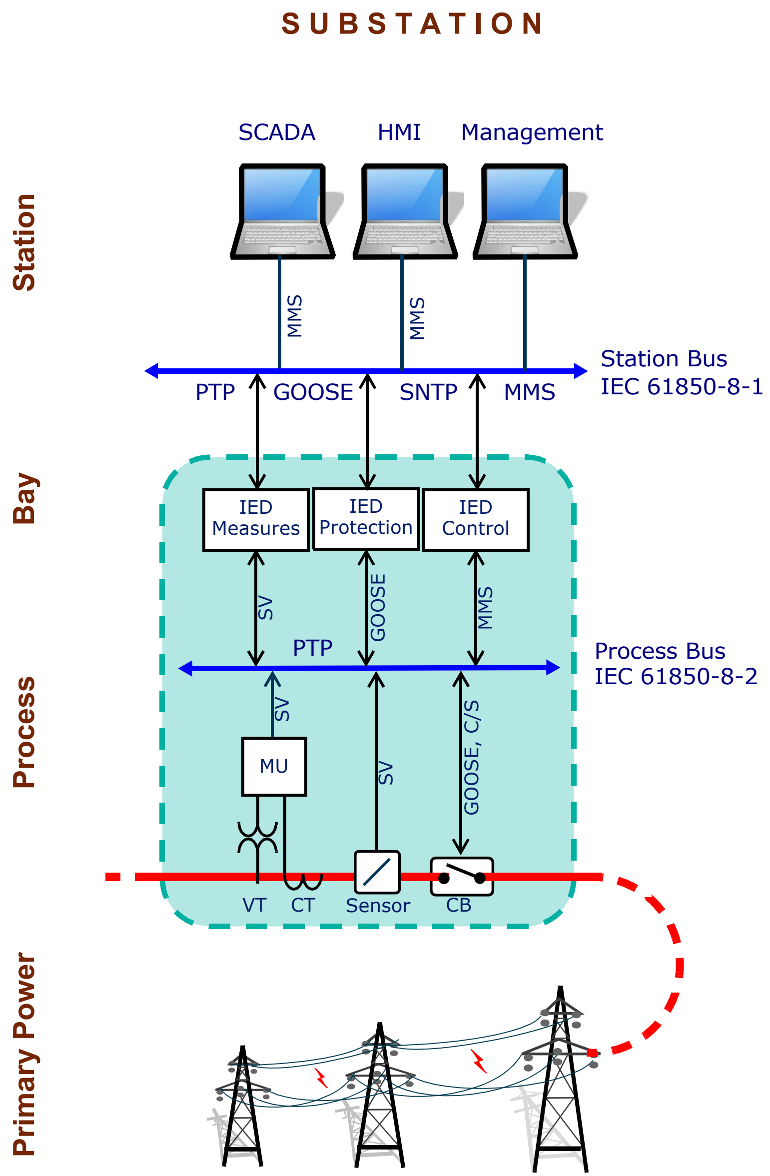
Sample: **Differential Protection**



Each protection IED analyses the SV data from MU and transmits GOOSE messages containing the trip status. The "smart" circuit breakers are responsible for subscribing to the appropriate relay trip GOOSE messages to actuate after the trip data attribute is set.

A virtual private LAN service (VPLS) has been configured to transport the Ethernet-layer SV and GOOSE data over the (emulated) wide-area IP/MPLS network. An "e-pipe" service would also be suitable for this application. It is also possible to encapsulate SV and GOOSE packets within routable layer-3 IP packets (IEC 61850-90-5) this is not necessary for a pure IP/MPLS network (which also has the benefit of constant latency due to the deterministic label-switched paths and packet prioritisation).

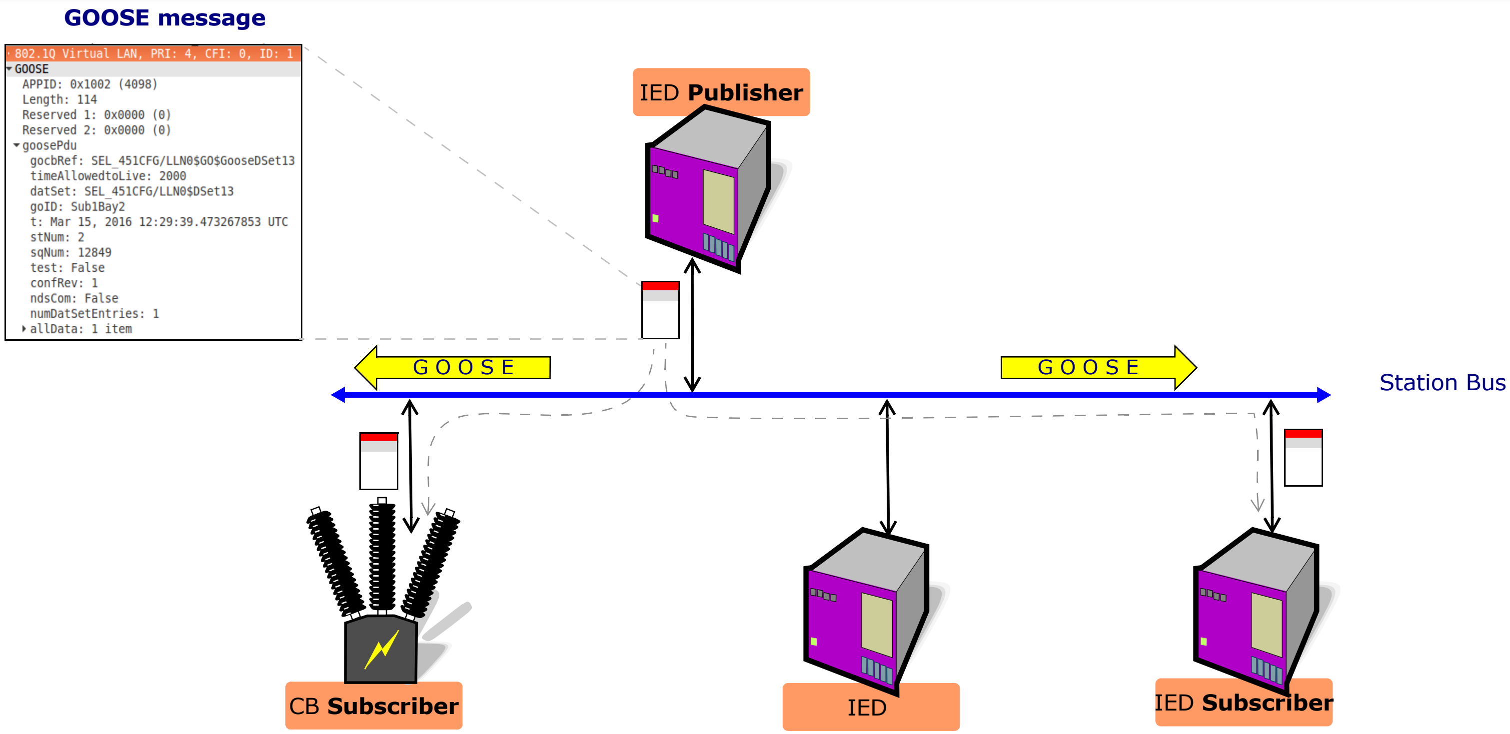
GOOSE (Generic Object Oriented Substation Event)



GOOSE is a messaging system used by IEDs and mission-critical applications to tell about substation substation events, such as commands, alarms, indications and measurements:

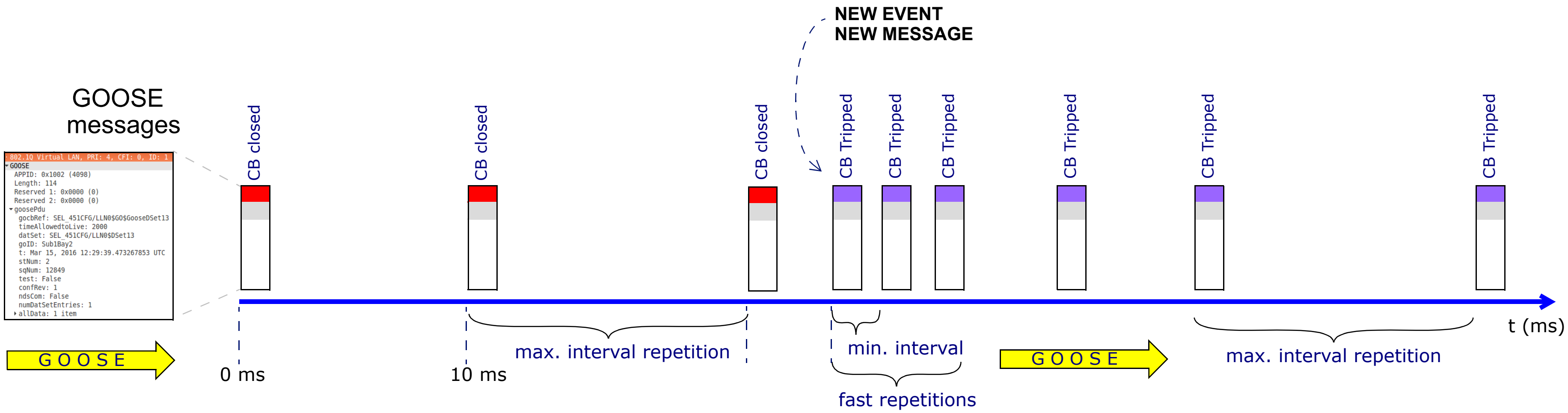
- Applications e.g. tripping of switchgear, starting of disturbance recorder, providing position indication for interlocking, and tele-protection.
- **L2 protocol**, GOOSE works in real-time ethernet context and used for fast / reliable distribution of data.
- **Publisher/Subscriber** method is used: *one* IED sends a message that can be read by *N* receivers. The reaction of each receiver depends on its functionality and configuration. For instance a message tells position of the Circuit Breaker (Open, Close, Intermediate)
- **No ACK** mechanism but messages are repeated cyclically during certain time, even if there are no changes. The idea to keep connected as a polling.
- **Simplifies wiring**, while the adoption of **fiber optic** unifies traffic reducing dramatically metallic cables.
- GOOSE is vendor **inter-operable** and **scalable.**

Publisher/Subscriber method



- GOOSE is mapped **directly to Ethernet** to provide real-time communication
- Point-to-Multipoint connection or Multicast-Application-Association (MCAA)
- This method provides efficient interchange of information between IED
- Tripping of Circuit Breakers: short information that needs to be sent without loss within msecs
- The Publisher IED transmits a message that only the subscribers receive.The reaction of each receiver depends on its configuration and functionality

Repetition mechanism



Since the GOOSE messages replace hard-wired signals used for protection and control applications IEC 61850 introduces mechanisms that ensure the delivery of the required information.

- DataSet values are coded as GOOSE messages and published
- At the beginning of a new nessage the repetition interval is very short just a few milliseconds
- Then the interval time increases until it reaches a value of a few seconds
- Max time interval (IEC 61850-8-1): **100ms < max interval < 60s**
- When any **DataAttribute** value changes Publisher transmits a new message
- The repetition mechanism allows continuous monitoring of the communications interface - something that is not possible in conventional hardwired systems.

GOOSE message **decoding**

Messages are a collection of values as members of a **Dataset**:

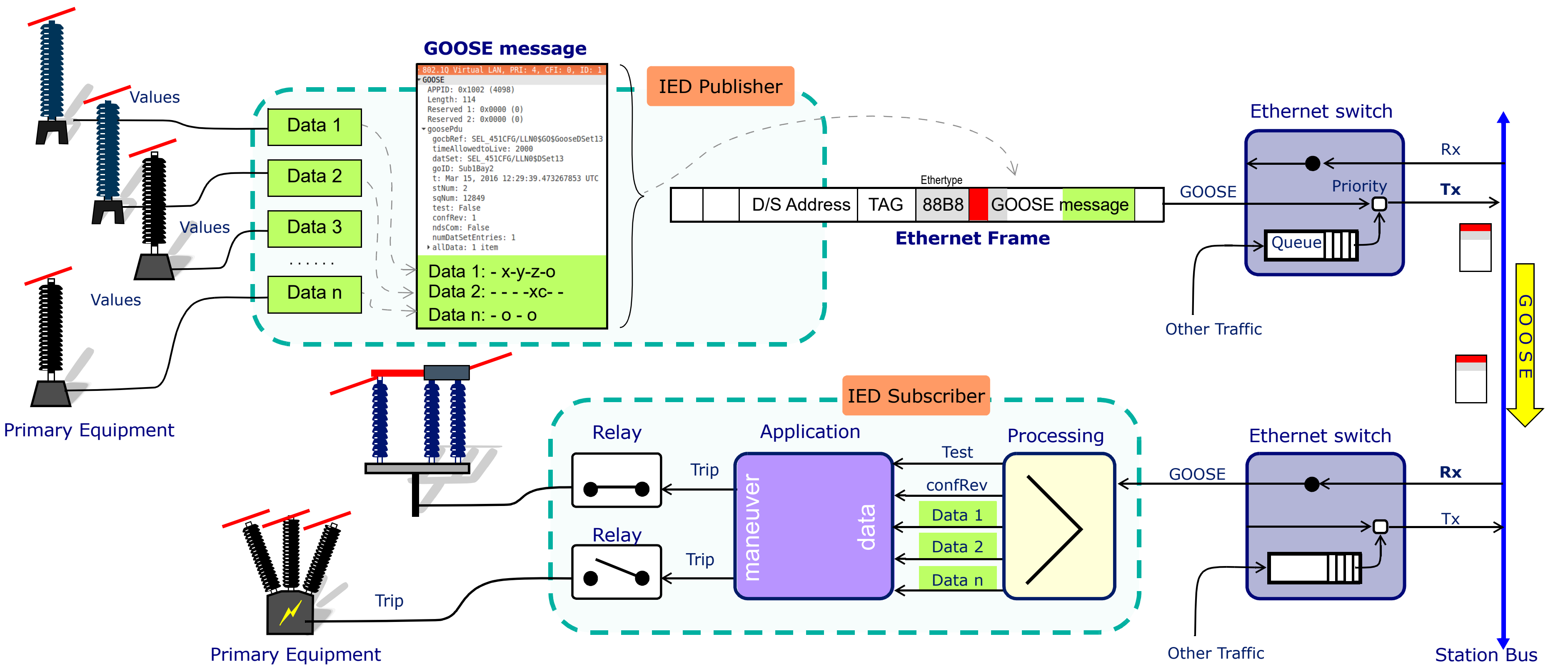
```
‣ 802.1Q Virtual LAN, PRI: 4, CFI: 0, ID: 1
▾ GOOSE
    APPID: 0x1002 (4098)
    Length: 114
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ▾ goosePdu
      gocbRef: SEL_451CFG/LLN0$GO$GooseDSet13
      timeAllowedtoLive: 2000
      datSet: SEL_451CFG/LLN0$DSet13
      goID: Sub1Bay2
      t: Mar 15, 2016 12:29:39.473267853 UTC
      stNum: 2
      sqNum: 12849
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 1
    ▸ allData: 1 item
```

- **gocbRef** address of the information
- **timeAllowedtoLive** max time to the next retransmission
- **datSet** description of the information contents
- **goID** identifier of the message
- **t** actual time
- **stNum** state number is a message counter
- **sqNum** sequence number of repetitions
- **test** tells if the message is just a test not a true value
- **confRev** compatibility verification
- **ndsCom** tells about the configuration
- **numDataSetEntries** number of DataSet entries
- **allData** data of the GOOSE message

NOTES:

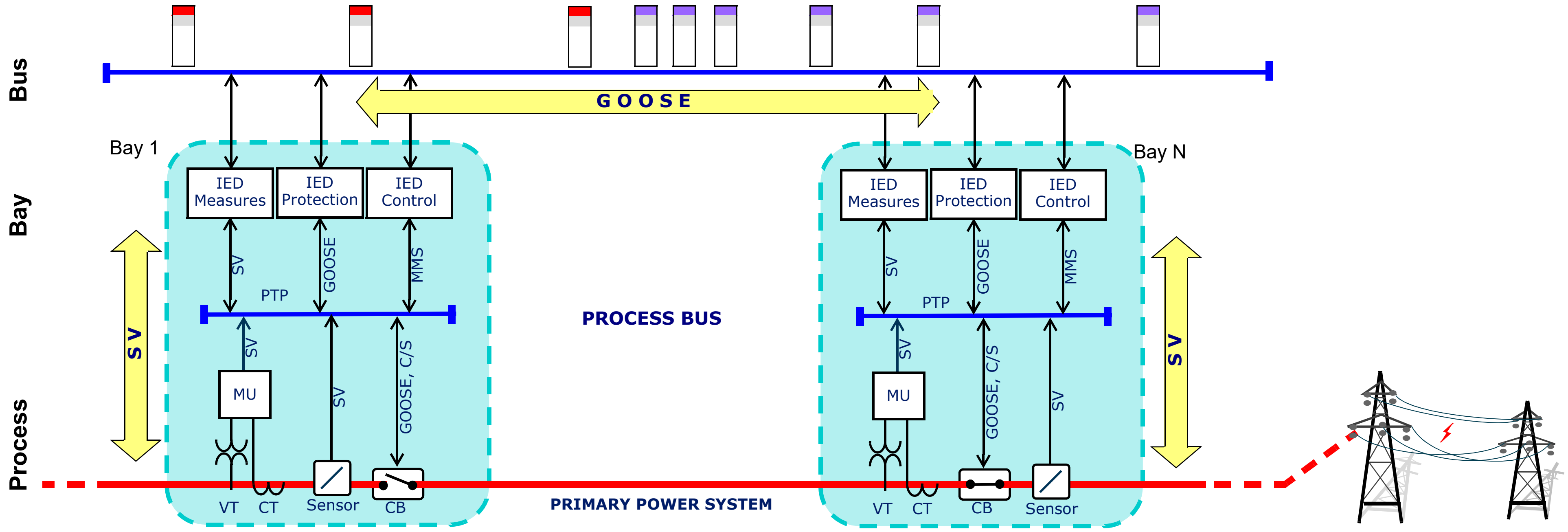
1.. if **timeAllowedtoLive** is greater subscribers can assume a communications failure
2.. **StNum + SqNum** can be used to detect intrusion (cybersecurity without encryption)
3.. if **test** = **true** indicates that the message is used only for test and simulations

Publisher & Subscriber



1. The IED publisher writes the values in a transmission buffer and multicast it over the substation local area network to the different subscribers sends the message without requirements and confirmation.
2. The prioritization of GOOSE over other traffic, requires switches supporting Priority in TAG field.
3. The Subscriber receives then process the messages. The reaction of IED Subscriber will depend on its configuration and functionality.

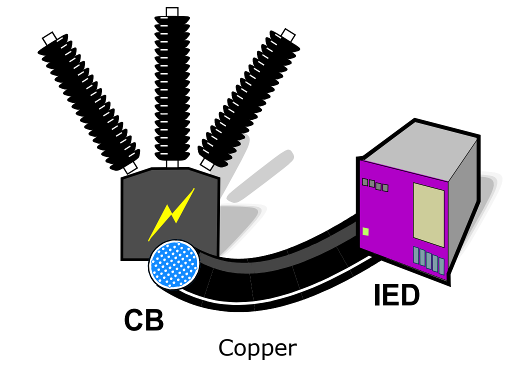
Heartbeat



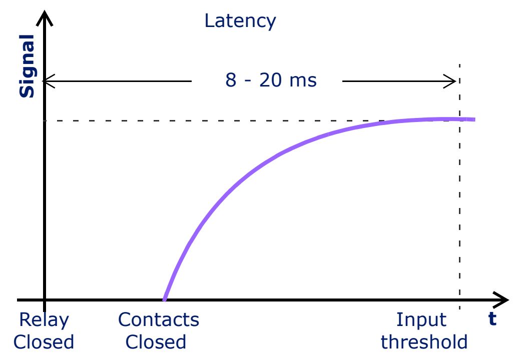
During normal operating conditions IED broadcast and retransmits GOOSE messages cyclically, this is the **heartbeat** of the substation. The health of the GOOSE messages are monitored closely to assure on-time delivery. A missing message is an indication for the **Subscribers** that the communication from the **Publisher** has become disturbed.

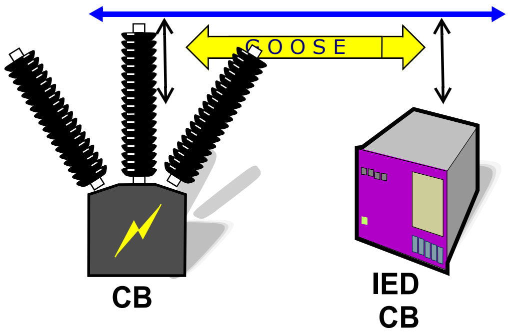
GOOSE messages are repeated to account for possible lost datagrams due to congestion or failure scenarios. IEC 61850 architecture prioritizes GOOSE and SV traffic to grantee high-speed avoiding degradations of layer 3 traffic which is used for normal Ethernet LAN traffic.

GOOSE vs. Hardwired

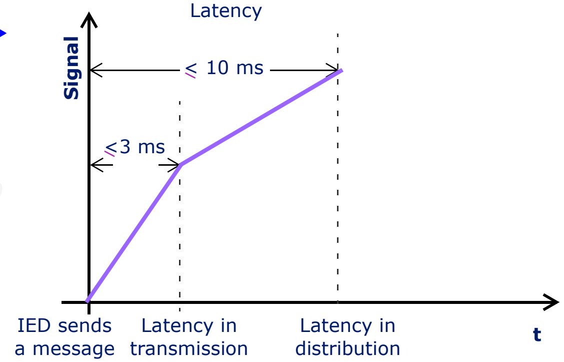


Hardwired Performance





GOOSE Performance

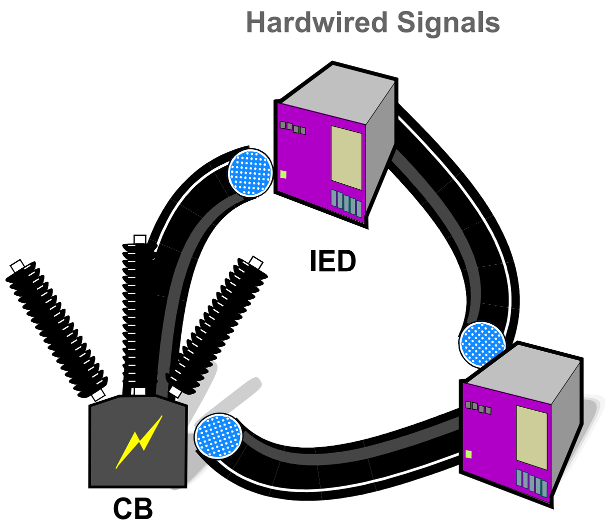


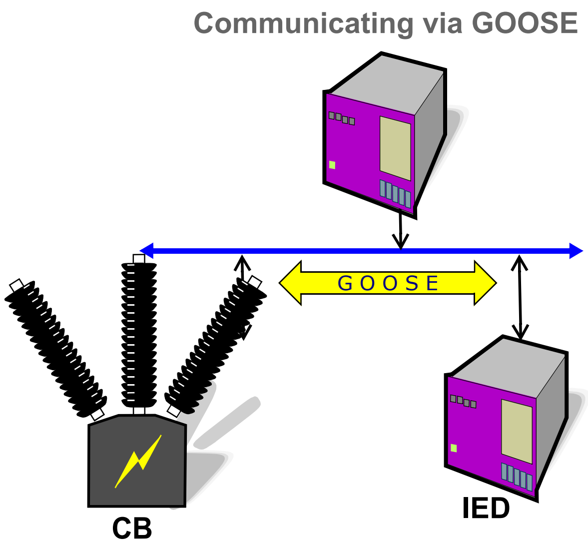
The performance of hardwired solutions is based on relays that in the worst scenario the IED transfer time can be 3/4 of cycle (15ms) that is improved with GOOSE alternative below to 3 ms.

When a GOOSE message is generated by IED (IEC 61850 server), it uses a layer 2 multi-cast transmission to send the event on the network. The receiving devices, known as a subscriber, subscribe to the multicast address of the message to be able to quickly filter the information and execute the needed task(s).

The requirements for a GOOSE message are stringent - no more than 4 ms to elapse from the time an event occurs to the time the message is received protection and control applications

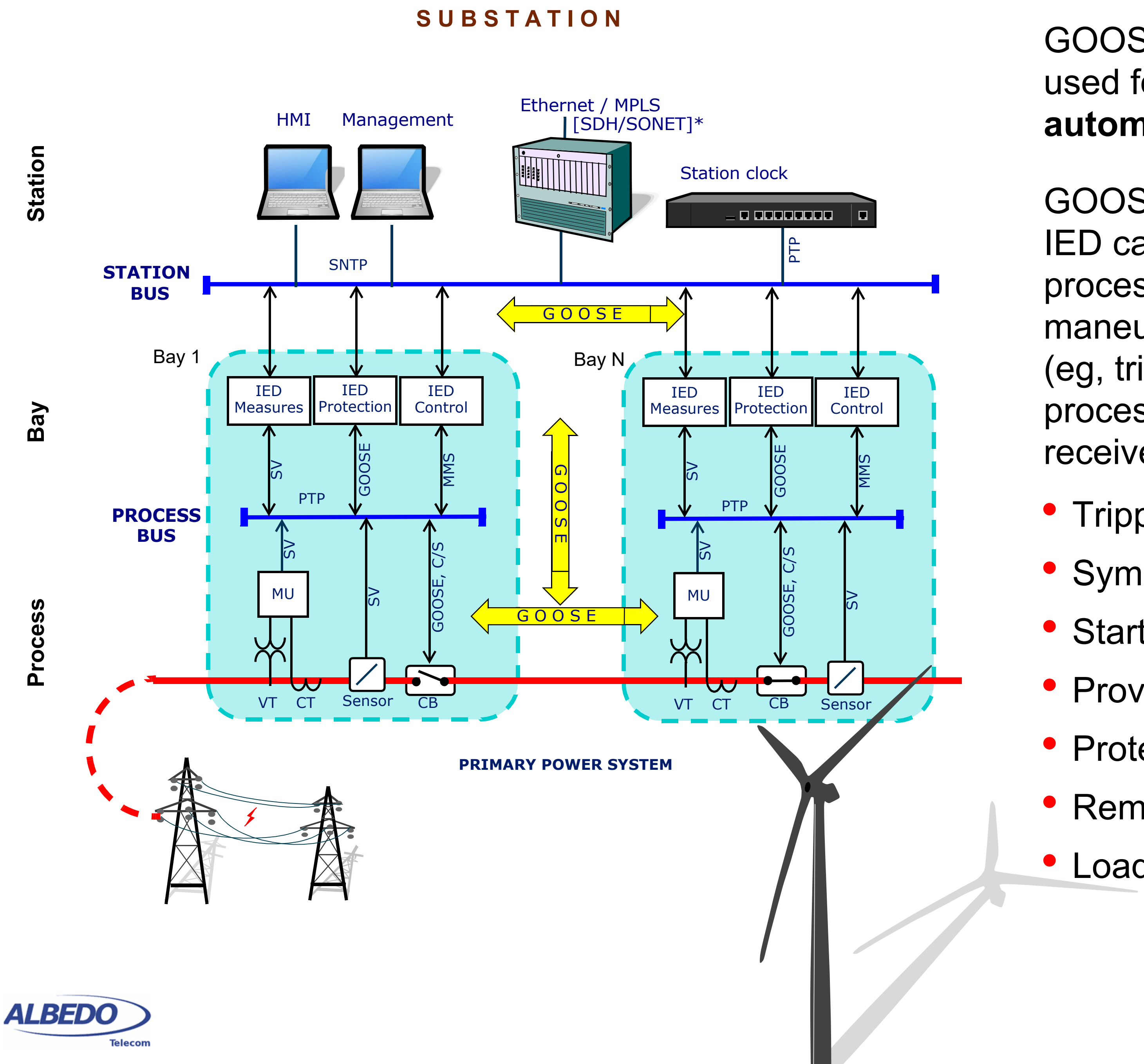
Goose **Benefits**





1. **Installation Costs**: due to the replacement of thousands individual control copper cables with a limited number of fiber optic cables from the terminal blocks to the relay terminals with a single pair of fiber.
2. **Testing cost:** It makes easier the testing of all hardwired interfaces vs. Ethernet GOOSE messages.
3. **Flexibility**: using GOOSE messages and virtual signals of the SCL configuration language can be achieved without the need for physical presence in the substation.
4. **Multipoint:** a single message can reach multiple subscribers then simplifies the interconnection particularly when several IED are involved for instance in a protection operation.
5. **Interoperability** the use of standard improves the reliability on the subscription of both IEDs on each side of several manufacturers.
6. **Reduced Maintenance** hard wired connections cannot be monitored then verification of all interfaces between individual components of the protection and control system is expensive.
7. **Remote Testing** protection systems in a digital substation allows the testing to be performed remotely by means of GOOSE and SV messages.

Applications

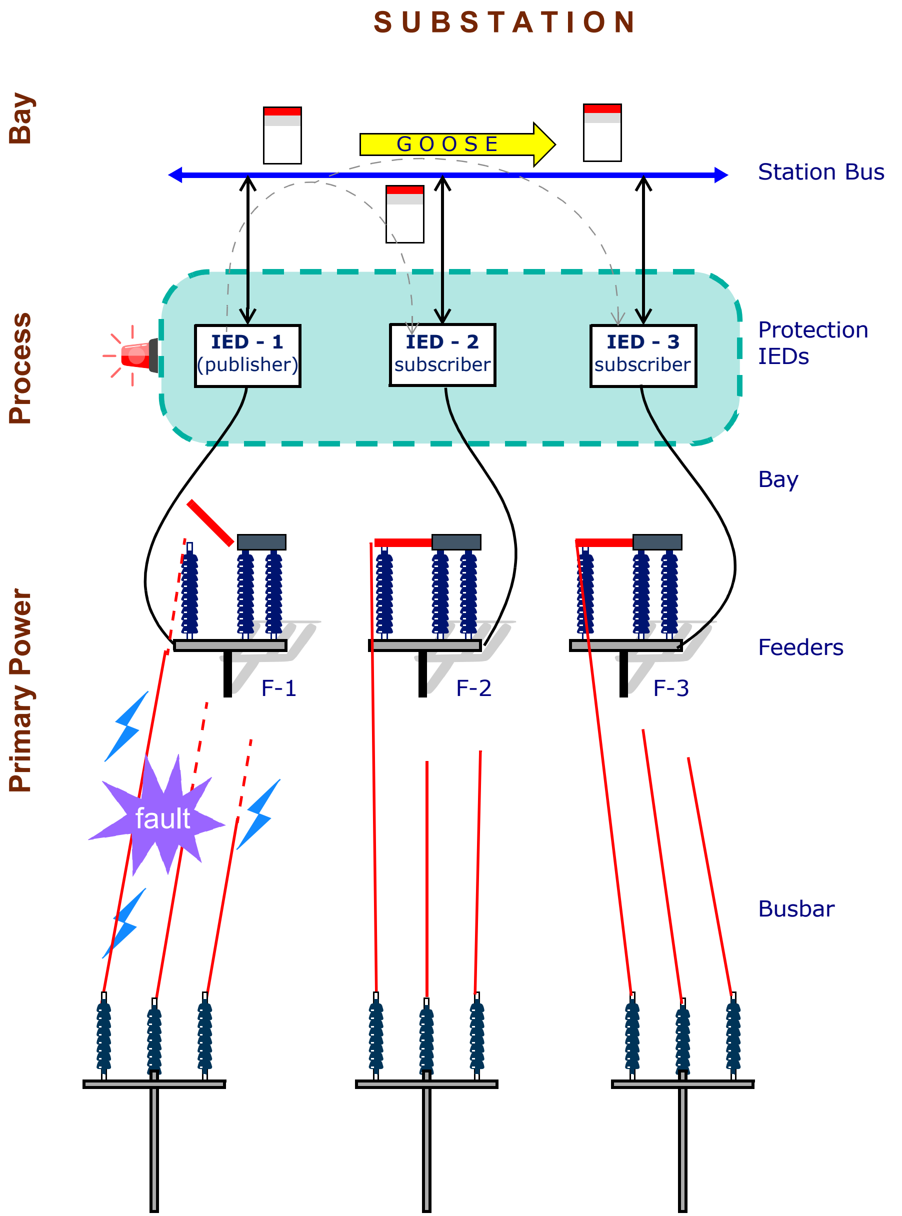


GOOSE most often applications is used for **protection, control and automation** of electric systems.

GOOSE messages subscribed by an IED can be used for internal data processing (eg, blocking logic) or to maneuver an output to the application (eg, trip order). The management and processing of GOOSE messages received are not part of the standard:

- Tripping of switchgear
- Sympathetic Trip Logic
- Starting of disturbance recorder
- Providing position indication
- Protection applications
- Remote Testing
- Load Shedding

Sample: **Sympathetic Trip Logic**



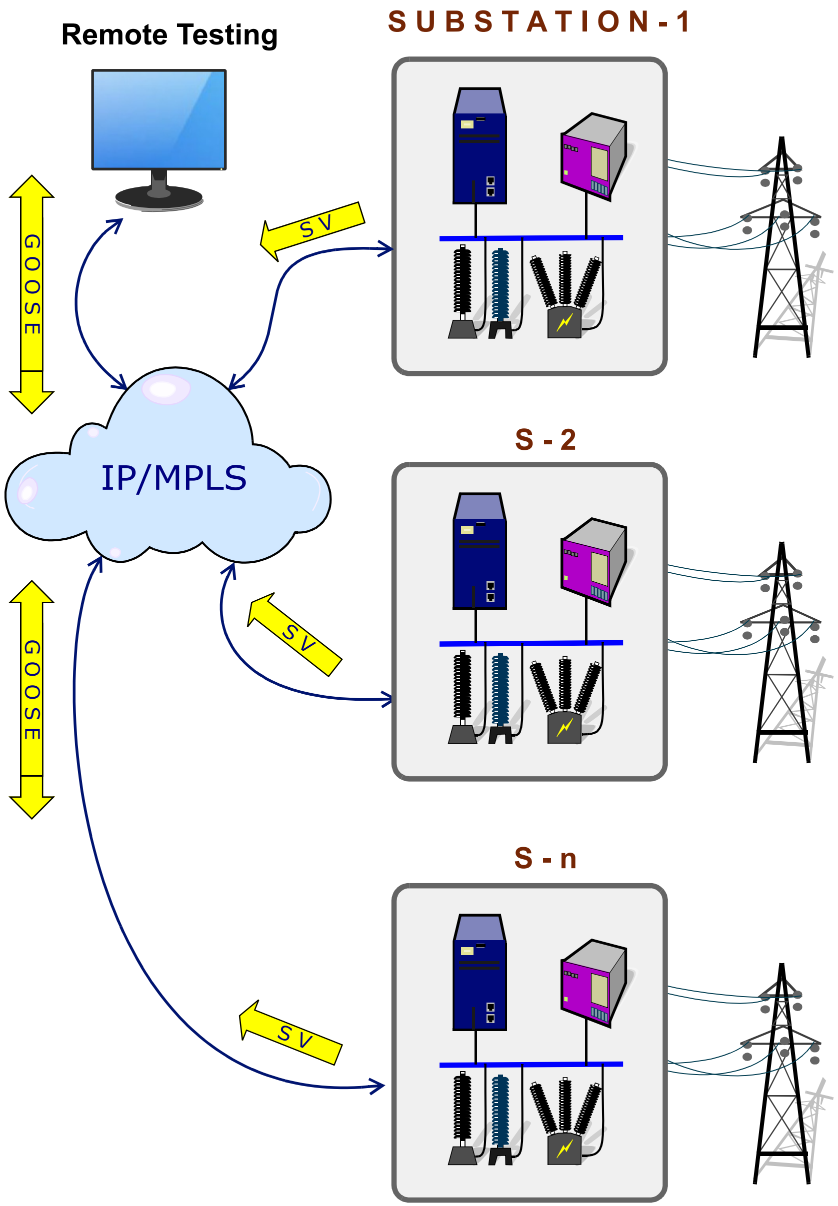
A fault causes a voltage drop on a feeder and, after the clearing of the fault, results in an inrush condition (a sudden arrival of energy) which may lead to a undesired operation of protection on the healthy feeders.

The IED-1 that protects Feeder-1, detects a fault and sends a GOOSE message to inform about an inrush condition will occur as a result of the voltage recovery after fixing the fault. Then the other IEDs protecting Feeder-2 and Feeder-3 adapt its settings expecting the coming inrush. They have two options:

1. Block the sensitive overcurrent setting
2. Reduce the sensitivity by increasing the pickup setting for the duration of the inrush

The benefit of using GOOSE messages is that doesn't need large number of wires between the inputs and outputs of all feeder IEDs, only need to publish/ subscribe to messages from the adjacent IEDs.

Sample: **Remote Testing**

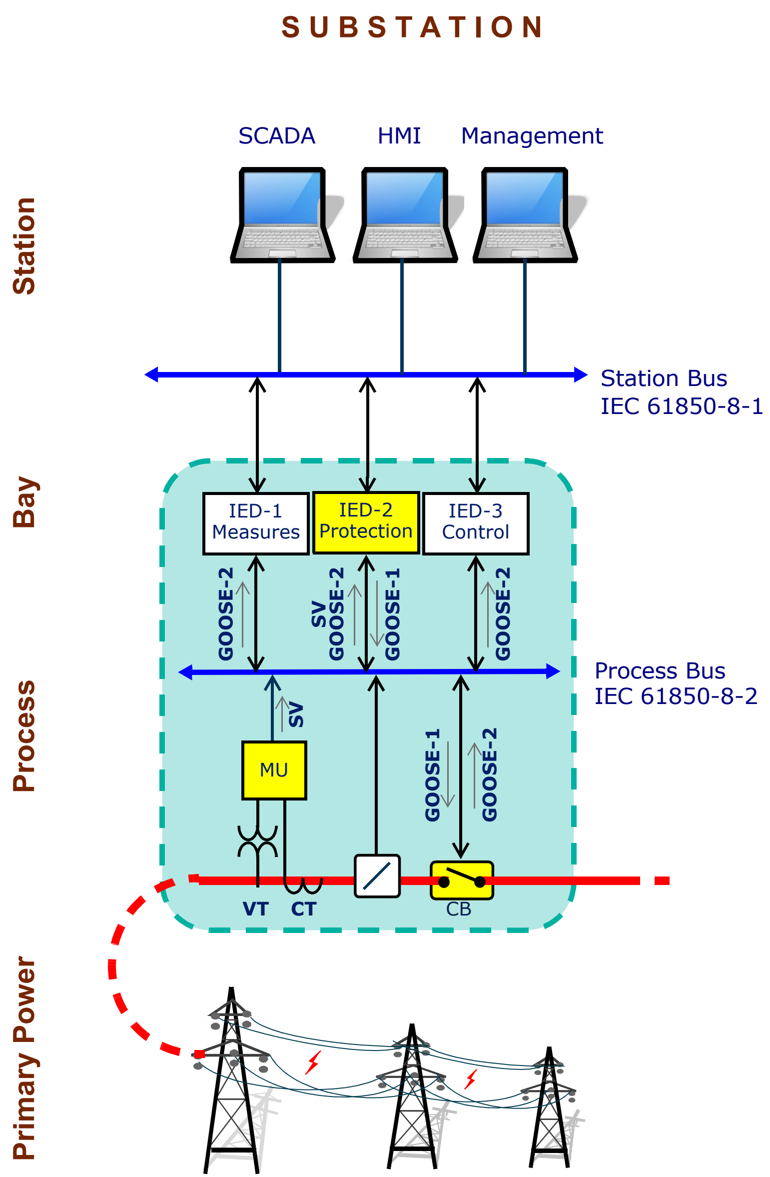


Since IEC 61850 Edition 2 – the **Simulation bit** in the GOOSE message and the different modes of the tested function elements play a critical role in the verification of Utility systems including the ability to **remotely test** a subset of functions and their elements while keeping the rest of **the system in service**.

Simulation is a parameter that indicates that the GOOSE message is used for test purposes (if TRUE) in this case values of the message have been issued just for simulation and shall not be used for operational purposes. The GOOSE subscriber will report the value of the simulated message to its application instead depending on the setting of the receiving IED.

Maintenance testing in cases such as IED mal-operation require its testing before putting it back in operation. In the past it required sending a testing crew to the substation to perform the testing which is an expensive process. The use of **protection systems** allows the testing to be performed remotely in this case SV and GOOSE is required for the end-to-end testing.

Sample: **SV & GOOSE**



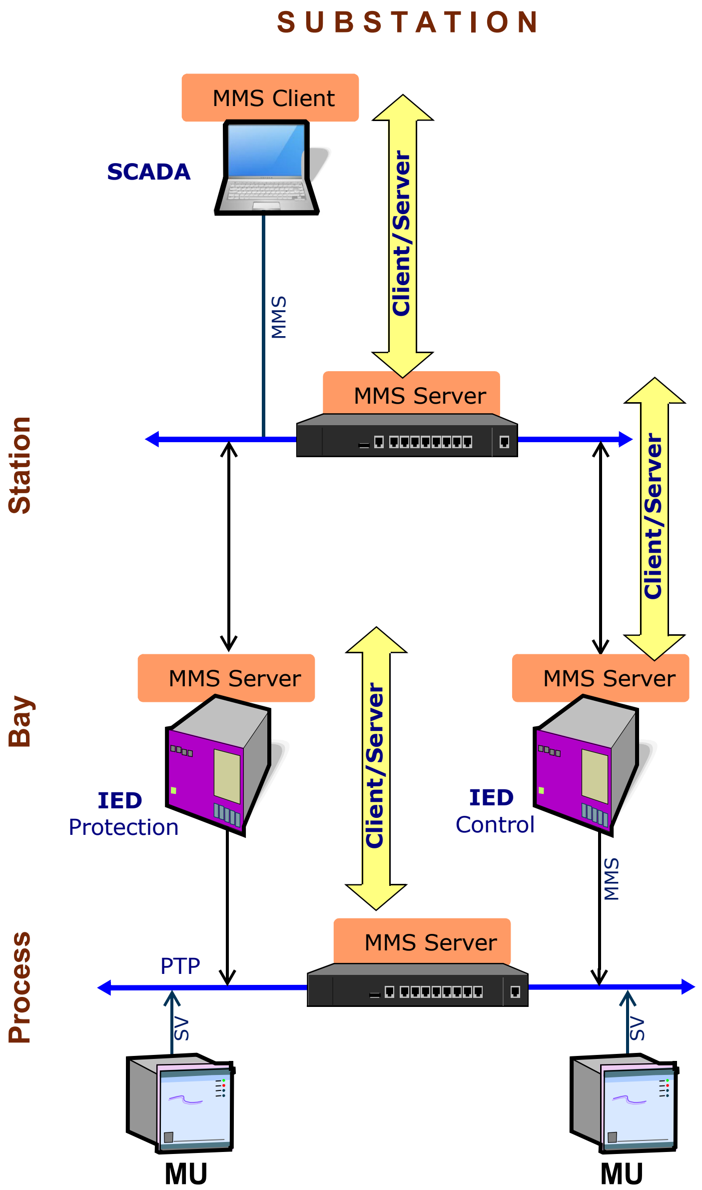
A **Merging Unit** (MU) accepts multiple analogue current and voltage samples coming from the VT and CT current and voltage transformers which are connected directly to the power line.

MU act as an analogue-to-digital-converter converting the samples into digital format and encapsulating them along with meta-data to put these measurements in context as SV packets, and sends them over the Process Bus to IED-2 that extracts the samples and measures to detect evidence of a fault.

If the outcome of the examination is positive, it issues a Trip order encapsulated as **GOOSE message-1** to the **Circuit Breaker** (CB) which then trips the appropriate switchgear and isolates the fault.

Afterwards, CB advises other IED of the action by issuing a **GOOSE message-2**. The exchange of time-critical messages described above is based on the publisher/ subscriber messaging model in which one or more IED subscribe to the publisher stating that they want to be notified of a particular event (in this case, to act as sinks for SV or GOOSE packets).

MMS (Manufacturing Messaging Specification)



MMS is used by the applications to **transfer data** between substation levels, communicating IEDs and SCADA systems to move the information such as device status, obtain reports, data acquisition in order to monitor and get control.

MMS uses **Client-Server method** to interchange no-critical information. The communication is done through a direct connection by means of commands and messages covering large geographical areas.

An IED acts as a **MMS server** and then transmits data the local station control system is then a connected client. The information contained in the "data set" of the IED (i.e. values of actions, triggers, position feedback, etc.) is transferred in a report to the **MMS client** in this case the SCADA system whenever a trigger condition is met for example a data change.

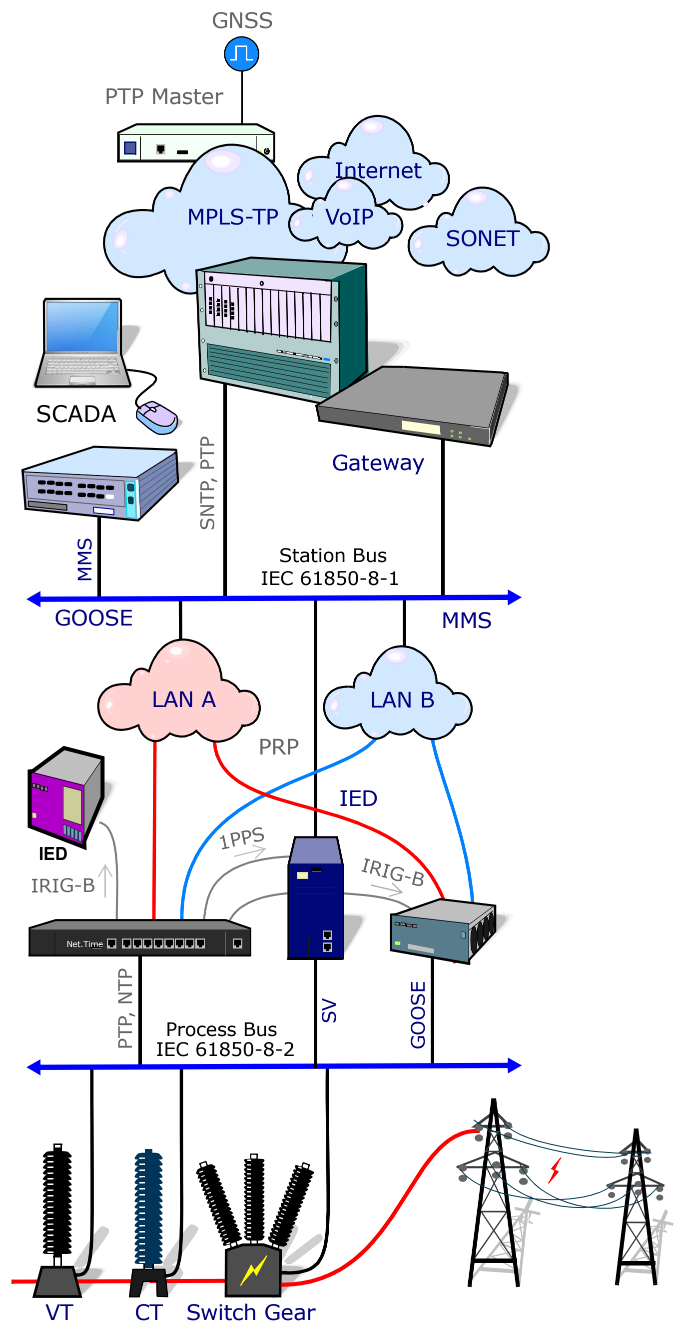
The communication with SCADA is based on TCP / IP.

Substation Automation & **Timing**

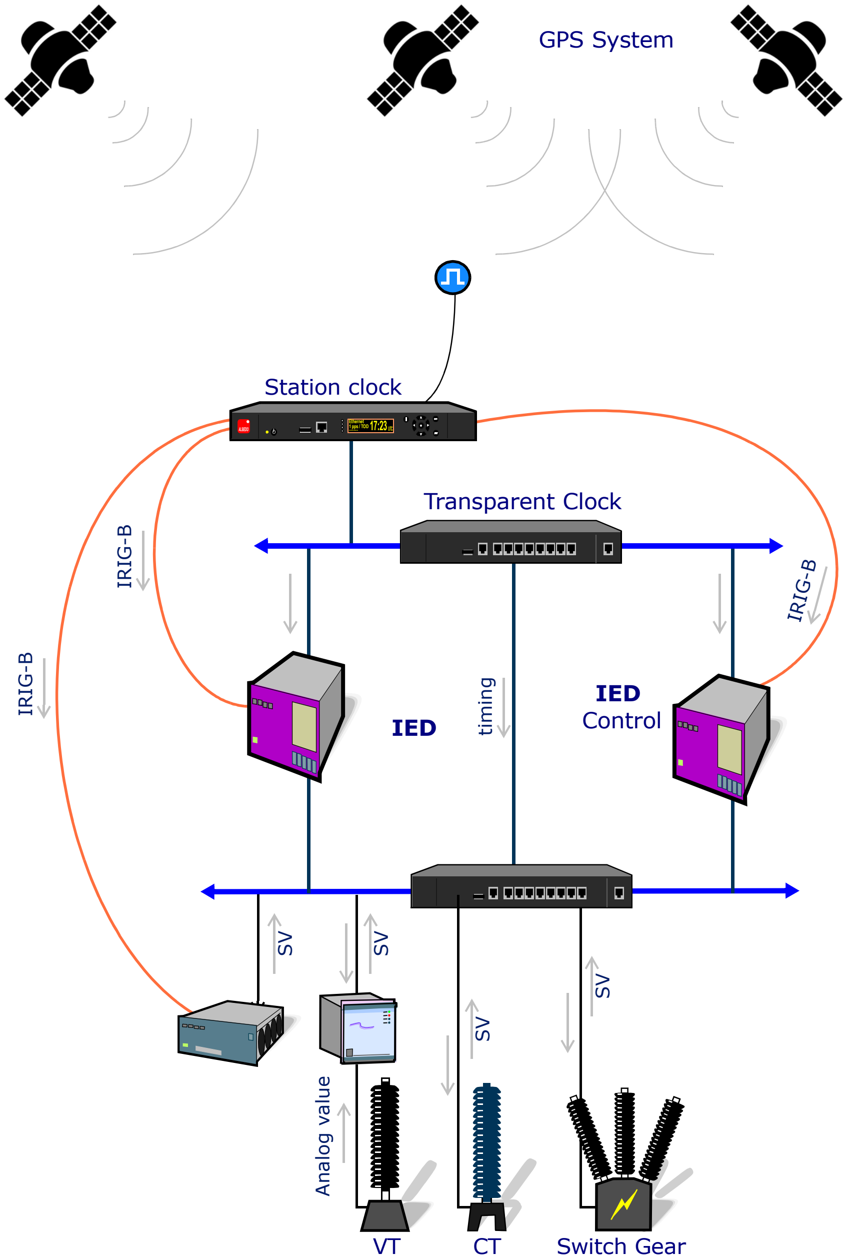
Time **synchronization** is used to precisely adjust internal clocks in IEDs, merge units (MUs), protection/control units, Ethernet switches and processes. It helps to achieve accurate control and precise global analysis of network response and when, where and why any faults have occurred and to generate the correct response. The following applications require time synchronization:

- IEC 61850 protocols like SV, GOOSE and MMS
- Real-time data acquisition from IEDs, RTUs and MUs
- Management applications such as SCADA
- Protection process and devices Relays, Switchgears
- Events recording for fault and performance analysis

Alternatives for timing include SNTP and PTP (both part of the IED 61850 standard) but also is common the use of Synchronous Ethernet, T1/E1, 1PPS and IRIG-B



The **GPS** / GNSS alternative

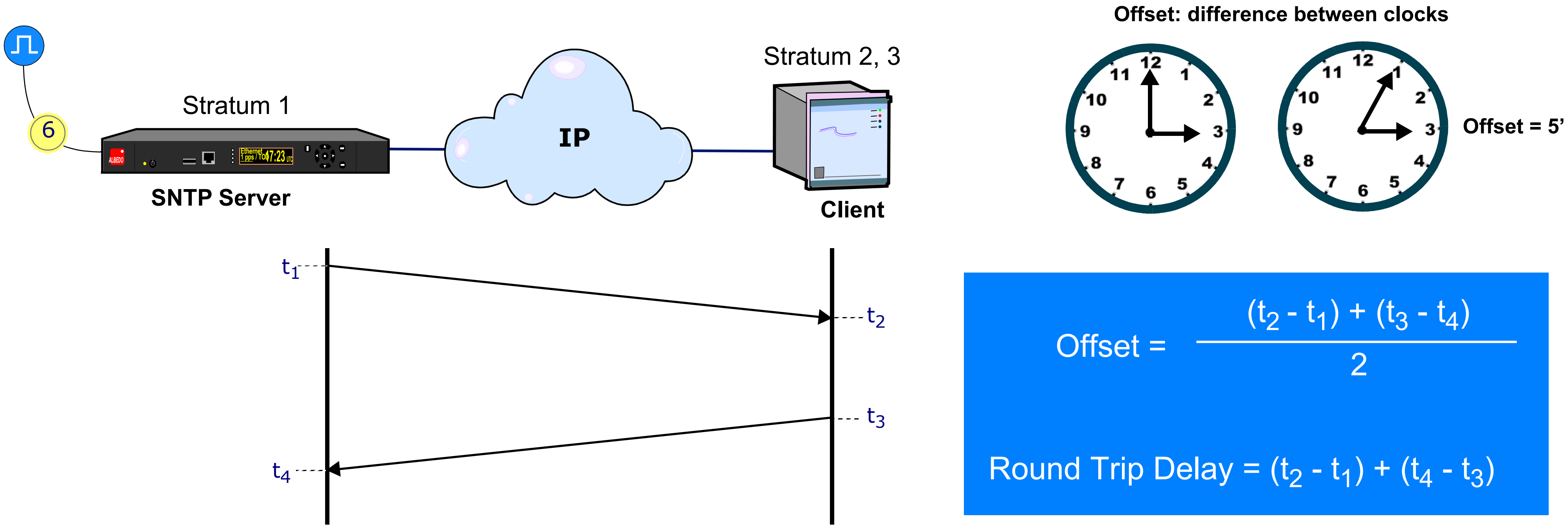


Many Utilities acquire timing from GNSS and the station clock converts signal into a 1-pps or IRIG-B code, which are then distributed by dedicated links to all the IEDs in a substation. However, important to say that this system has some **weaknesses** (*) being **vulnerable** to human and natural disruptions that may perturb normal operations by raising false alarms, delaying actions, and lowering system efficiency.

GPS is a good back-up, nevertheless modern substations should avoid the use of GPS as primary time reference for critical applications because time integrity cannot be assured. The alternative is PTP because it also provides frequency and phase timing and it has the required security to deliver synchronization in a reliable way for applications such as automation, wide-area monitoring, protection, and real-time control.

(*) Problems are produced by interferences and installation faults cause significant concerns about the reliability of satellite timing. Common issues include storms, satellite decommissioning, poor antenna installations, receiver failures, terrestrial or spacial interferences, and malicious spoofing that may send false timing to receivers that in some extreme cases, this could cause operational problems for the electric grid.

SNTP (Network Time Protocol)



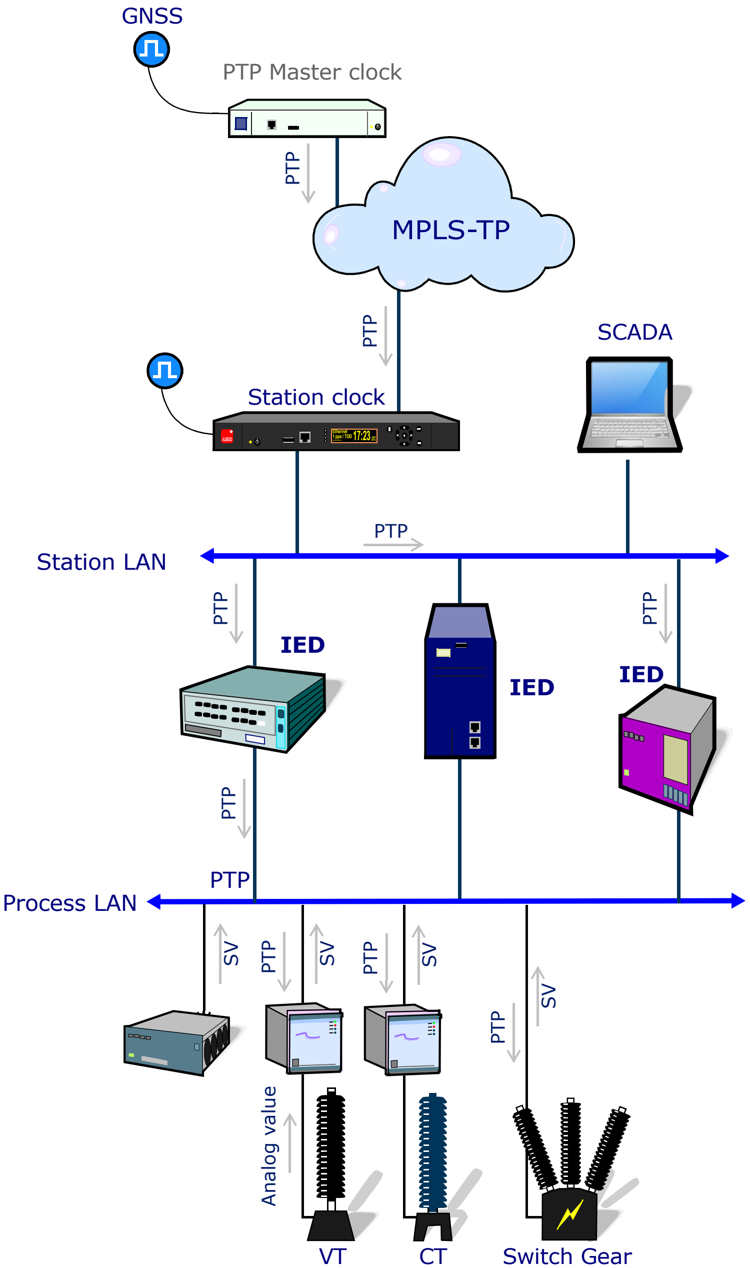
$$\text{Offset} = \frac{(t_2 - t_1) + (t_3 - t_4)}{2}$$

$$\text{Round Trip Delay} = (t_2 - t_1) + (t_4 - t_3)$$

SNTP is part of the IEC 61850 standard (a simplified version of NTP) which can provide a milisecs range of precision, is good enough for the station bus to synchronize SCADA and Ethernet switches but is not for the Process Bus with GOOSE and SV messages and devices that require an accuracy of microsecs.

- Network Time Protocol (NTP) is an Internet protocol for synchronizing the clocks of computer systems over packet network with variable latency.
- The clock frequency is then adjusted to reduce the offset gradually, creating
- Precision 1 - 10 ms. in Internet, (0,5 - 1 ms for LAN ideal conditions)

PTP in the Substation



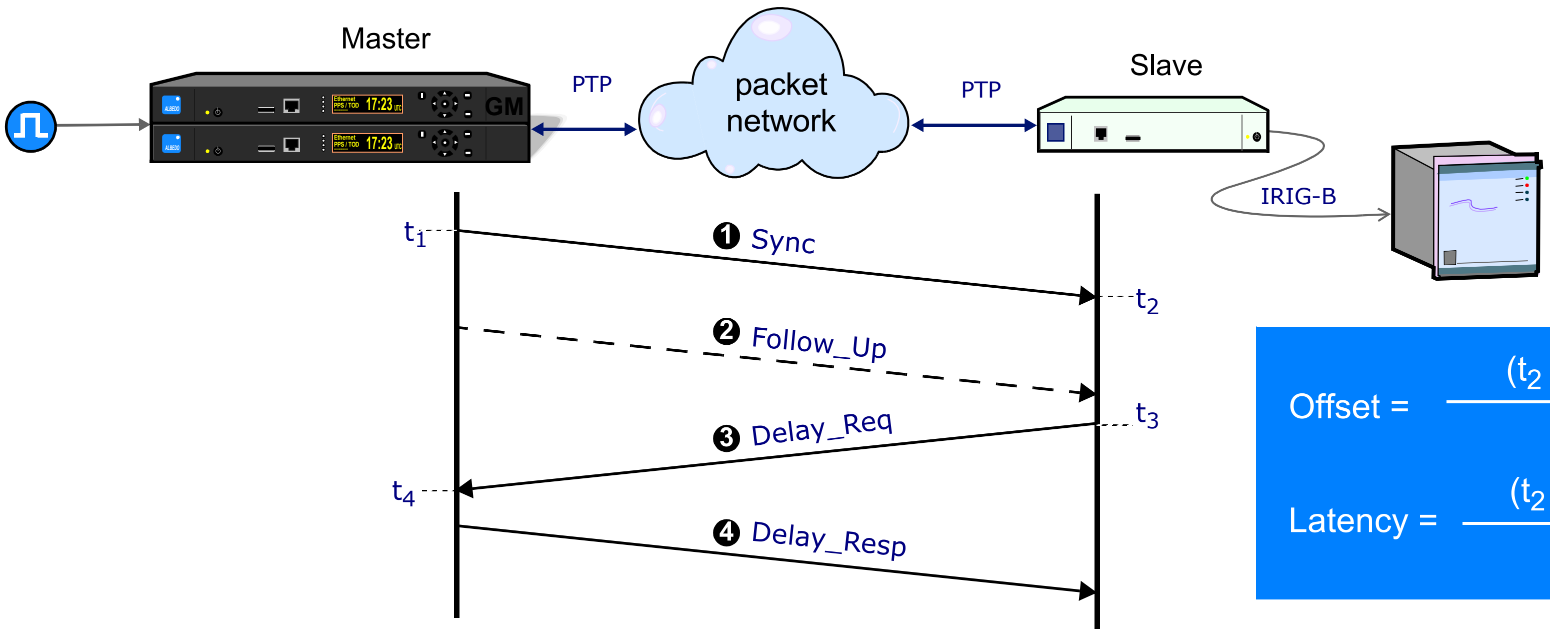
IEDs require accurate synchronization, unfortunately SNTP does not satisfy the needs of all applications.

Precision Time Protocol (IEEE 1588) with **Power Profile** defined in IEEE C37.238 address the requirements of the power industry in terms of accuracy, continuous operation (24/7) and deterministic failure behavior.

Application	Accuracy	Timing
PMU	1 µs	Absolute
Protection	1 µs	Relative
SV	1 µs	Relative
SCADA	1 ms	Absolute

Phasor Measurement Units (PMU) are not part of the IEC 61580 but the C37.1188 standard. PMUs are deployed across the grid for analyzing the quality of the power service by measuring magnitudes such as phase angle, line voltage and current waveforms in real-time. Values are collected at 30 to 120 samples/s, time-stamped with UTC and sent to data servers. Information is processed comparing many different points to know the situation, to load balance and to prevent faults. Synchrophasors have indeed timing needs due to high-frequency reporting, the wide geographic distribution and the large number of PMUs.

PTP - Precision Time Protocol (IEEE 1588)



$$\text{Offset} = \frac{(t_2 - t_1) - (t_4 - t_3)}{2}$$

$$\text{Latency} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$$

It is a cost-efficient solution and can be applied on the basis of the existing Ethernet network in a substation. PTP (IEEE 1588) applies master/slave time synchronization mechanisms and supports hardware time stamps. The basic parameters of Latency / Offset are computed from the $t_{1...4}$ stamps.

- Grandmaster sends a series of messages with date and time to client-clocks
- Client-clocks compensate the delays and get synchronized with the Master
- Frequency is then recovered with a precise time-of-d
- PTP prevents error accumulation in cascaded topologies, fault tolerance and enhances the flexibility and PTP can use an existing Ethernet reducing cabling costs and requires just a few resources.

IRIG-B signals

IRIG - Xabc

Rate
- A: 1000 PPS
- **> IRIG-B: 100 PPS <**
- D: 1 PPM
- E: 10 PPS
- G: 10000 PPS
- H: 1 PPS

Modulation
- 0: Unmodulated DCLS
- 1: AM (Amplitude Modulated)
- 2: Manchester Modulated

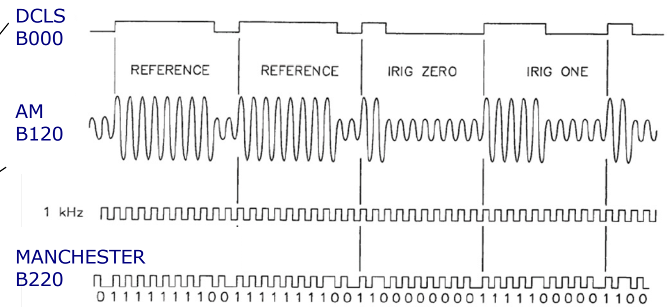
Carrier
- 0: No carrier (DCLS)
- 1: 100 Hz
- 2: 1 kHz
- 3: 10 kHz
- 4: 100 kHz
- 5: 1 MHz

Coding
- 0: BCD, CF, SBS
- 1: BCD, CF
- 2: BCD
- 3: BCD, SBS
- 4, 5, 6, 7: others

BCD	
0000	= 0
0001	= 1
0010	= 2
0011	= 3
0100	= 4
0101	= 5
0110	= 6
0111	= 7
1000	= 8
1001	= 9

BCD - Binary Coded Decimal, coding of time (HH,MM,SS,DDD)
SBS - Straight Binary Second of day (0....86400)
CF - Control Functions depending on the user application

IRIG SAMPLES: B000, B120, B220



IRIG-B sends a timing signal every second at 100 pulse/sec rate therefore the 100 is the number of bits of each frame. IRIG-B info includes Year, Day of the year, Hour, Min and Sec.

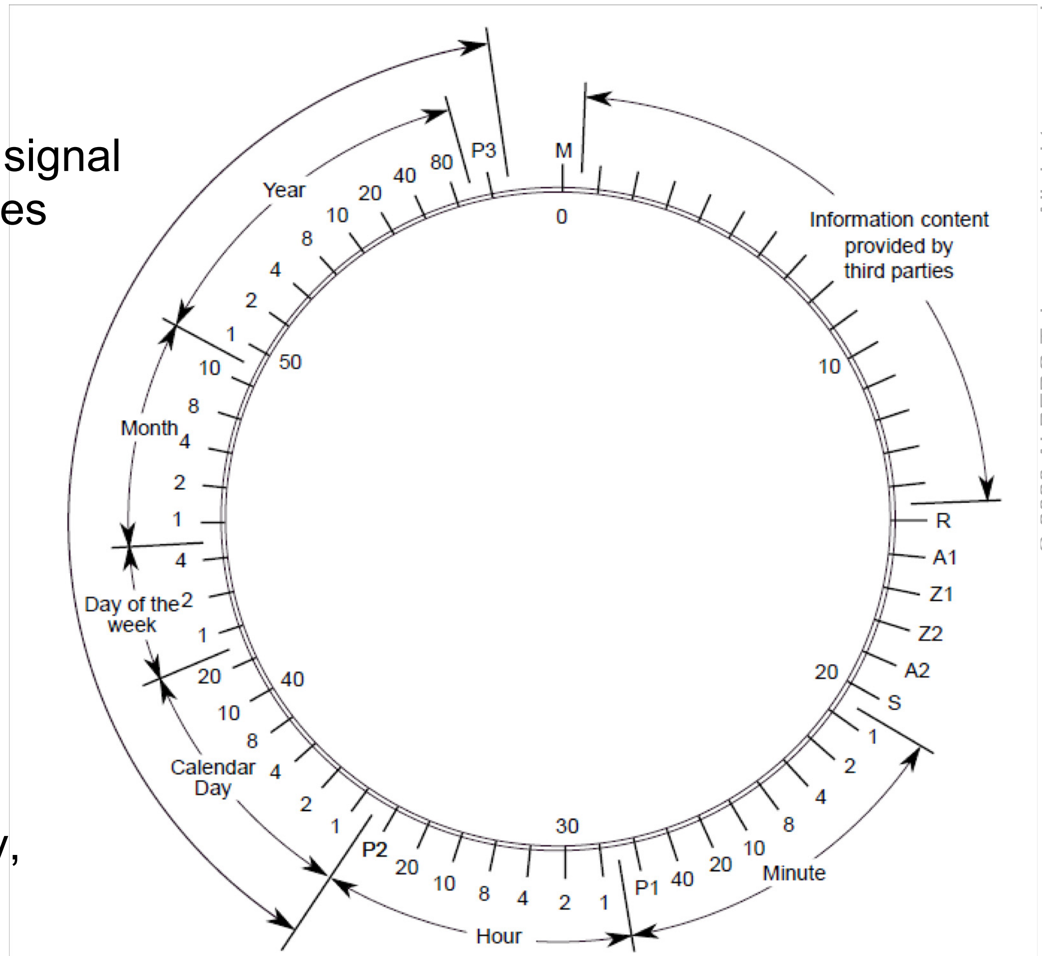
Unmodulated DCLS IRIG-B offers several transmission alternatives

- TTL-level signal over coaxial cable or shielded twisted-pair cable
- Multi-point distribution using 24 Vdc for signal and control power
- RS-485 differential signal over shielded twisted-pair cable
- RS-232 signal over shielded cable (short distances only)
- Optical fiber

DCF77

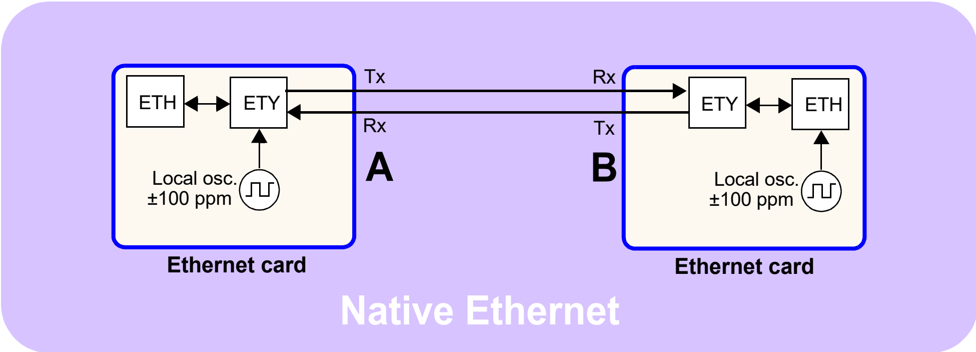
Originally DCF77 is a German long-wave time signal and standard-frequency radio station that carries an amplitude-modulated data signal repeated every minute.

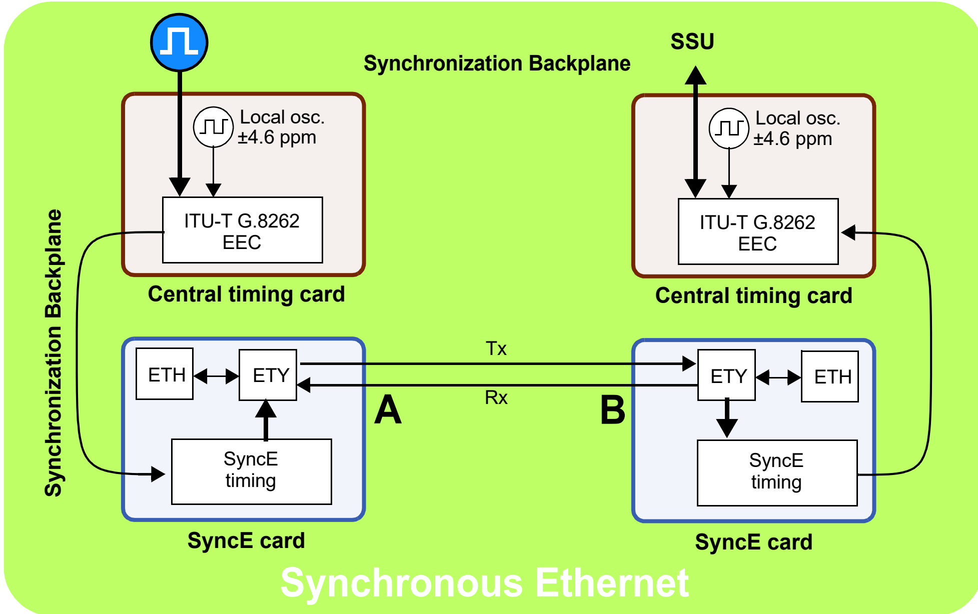
- M: Start
- R: service request to the DCF77 system
- A1: forthcoming change CET to/from CEST
- Z1, Z2: time zone indication
- A2: Leap second warning bit
- Pi: parity bits
- S: Start of time information minute, hour, day, week day, months, year



A lot of substations generate the DCF77 signal synchronized with GNSS (or the time reference used in the node). The accuracy of DCF77 is good enough for SCADA and wall clocks and is still used.

Synchronous Ethernet (SyncE)





SyncE is not part of the IEC 61850 but is being used in the Power industry

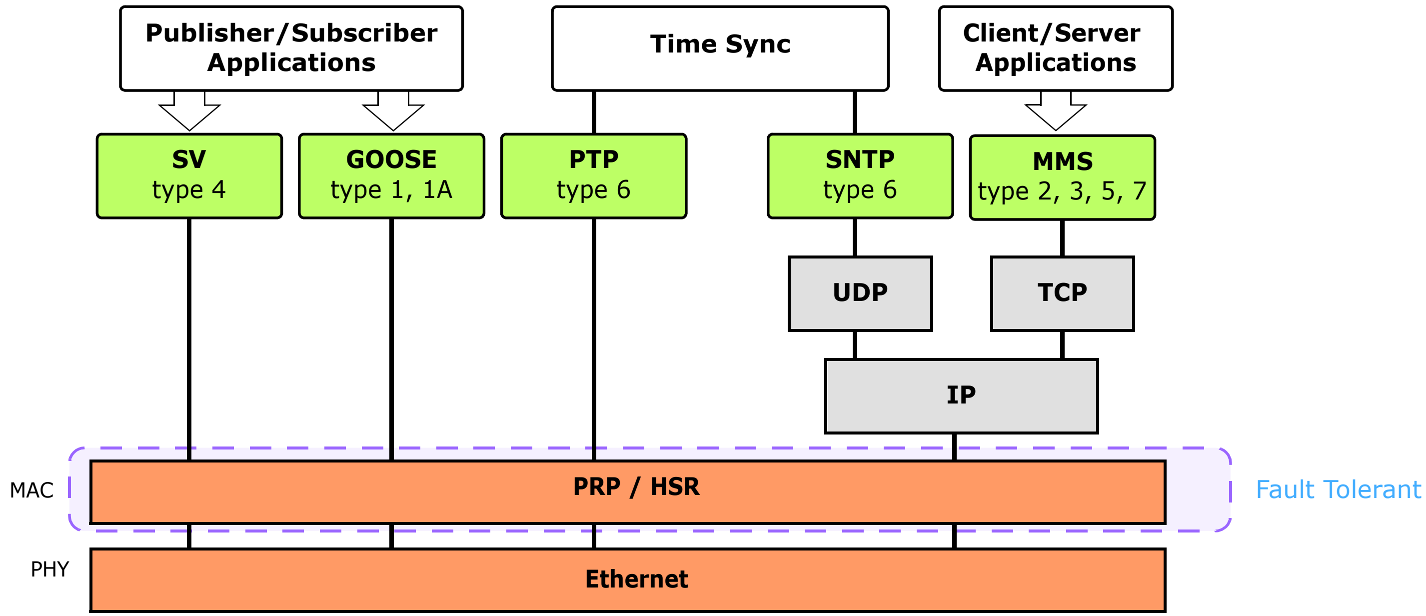
1. PHY Ethernet

- Rx gets synchronized using the input line [Tx (port B) >>> Rx (port A)]
- BUT there is no time relation between the Rx and Tx of the same Port

2. **SyncE PHY** (physical layer)

- Rx gets synchronized using the recovered clock
- Tx uses a traceable reference clock

IEC61850 **Fault Tolerant** architectures



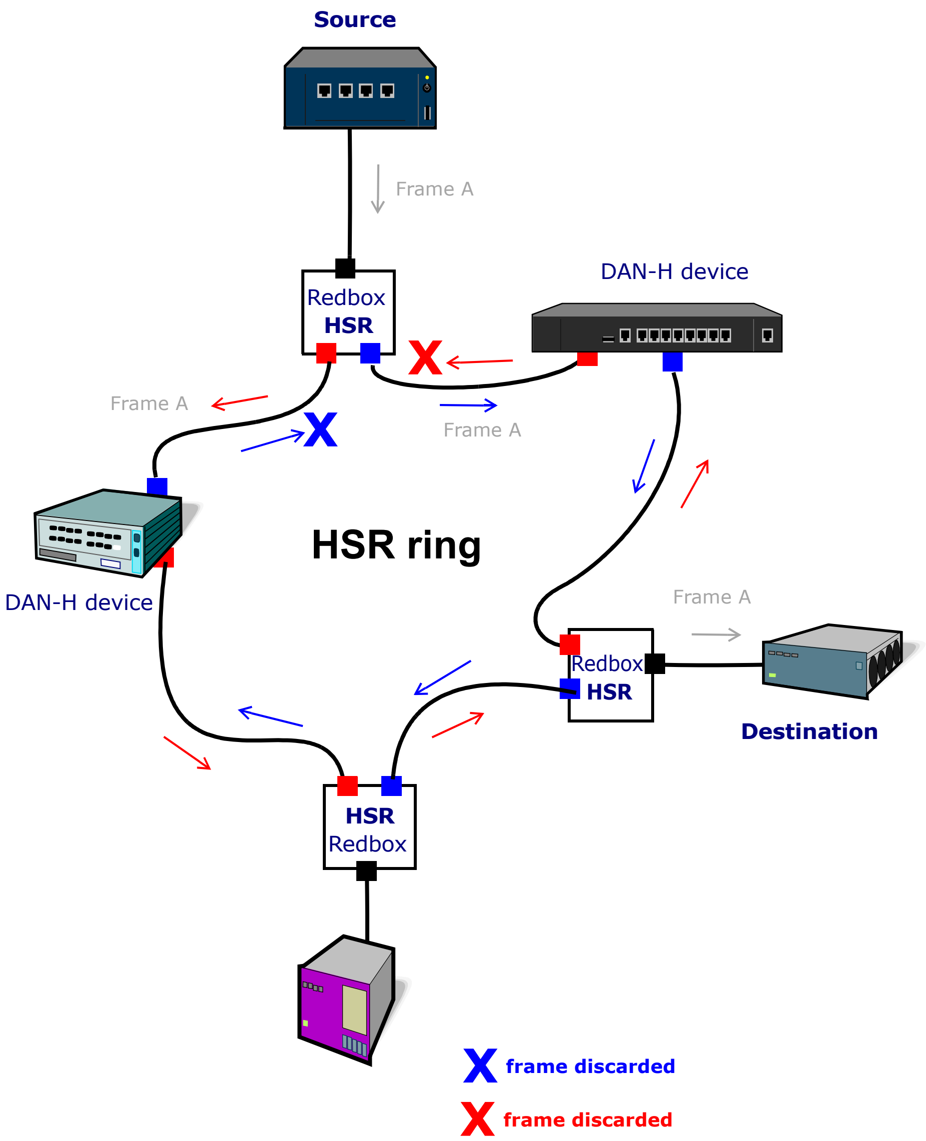
Network redundancy is crucial for maintaining **high network availability**, and many redundancy technologies can provide millisecond-level recovery. However, some mission-critical and time-sensitive applications **cannot tolerate** even **a millisecond** of network interruption without severely affecting operations or jeopardizing the safety of on-site personnel.

Lossless Architectures in the IEC 61850 to build a fault-tolerant network to a single point of failure:

- **HSR:** High-availability Seamless Redundancy.
- **PRP:** Parallel Redundancy Protocol

ALBEDO Telecom

High-availability Seamless Redundancy (HSR)

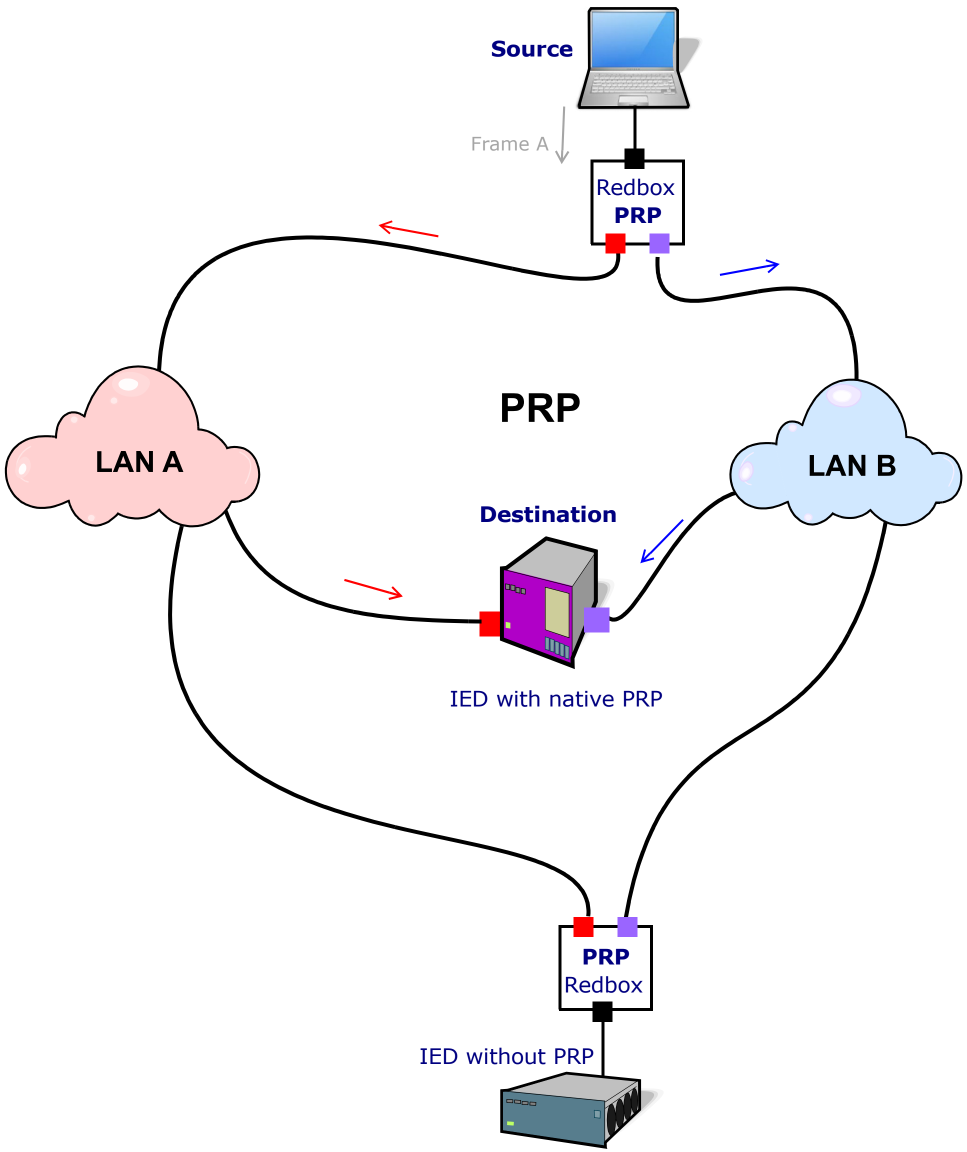


High-availability Seamless Redundancy (**HSR**) provide **seamless failover** from a single point of failure. HSR is designed primarily for ring topologies.

In HSR sll devices are connected to the network in a ring configuration. A source device publishes identical frames, the “A” frame and the “B” frame, in opposite directions out of the two ports. A destination device receives two identical frames on each port within a certain interval. The device uses the first frame received, and discards the second frame. If a network link fails, only one frame is received, and this frame is used, so zero recovery time is achieved. The nodes support the IEEE 802.1D bridge functionality and forward frames from one port to the other, except if the node has already sent the same frame in that same direction.

Based on these two seamless redundancy protocols, a redundancy box (**Redbox**) can quickly activate non-HSR devices connected to HSR with zero switch-over time.

PRP - Parallel Redundancy Protocol

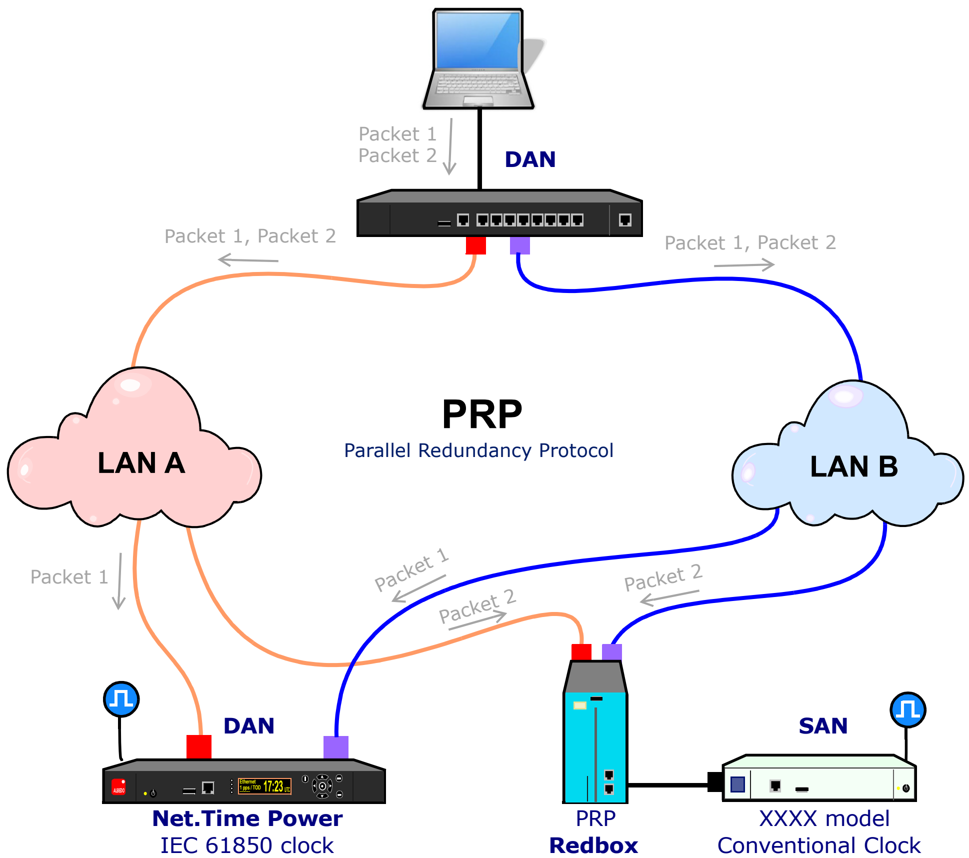


Network redundancy is crucial for maintaining **high network availability**, and many redundancy technologies can provide millisecond-level recovery. However, some mission-critical and time-sensitive applications **cannot tolerate** even **a millisecond** of network interruption without severely affecting operations or jeopardizing the safety of on-site personnel.

Parallel Redundancy Protocol (**PRP**) provide **seamless fail-over** from a single point of failure. PRP realizes active network redundancy by packet duplication over two independent networks that operate in parallel.

Based on these two seamless redundancy protocols, a redundancy box (**Redbox**) can quickly activate non-HSR or non-PRP devices connected to HSR or PRP networks with zero switch-over time.

DAN (double) - **SAN** (single)



PRP is based on the use of two independent networks. The sender **must send each packet twice** (to LAN A and LAN B) through two separate ports.

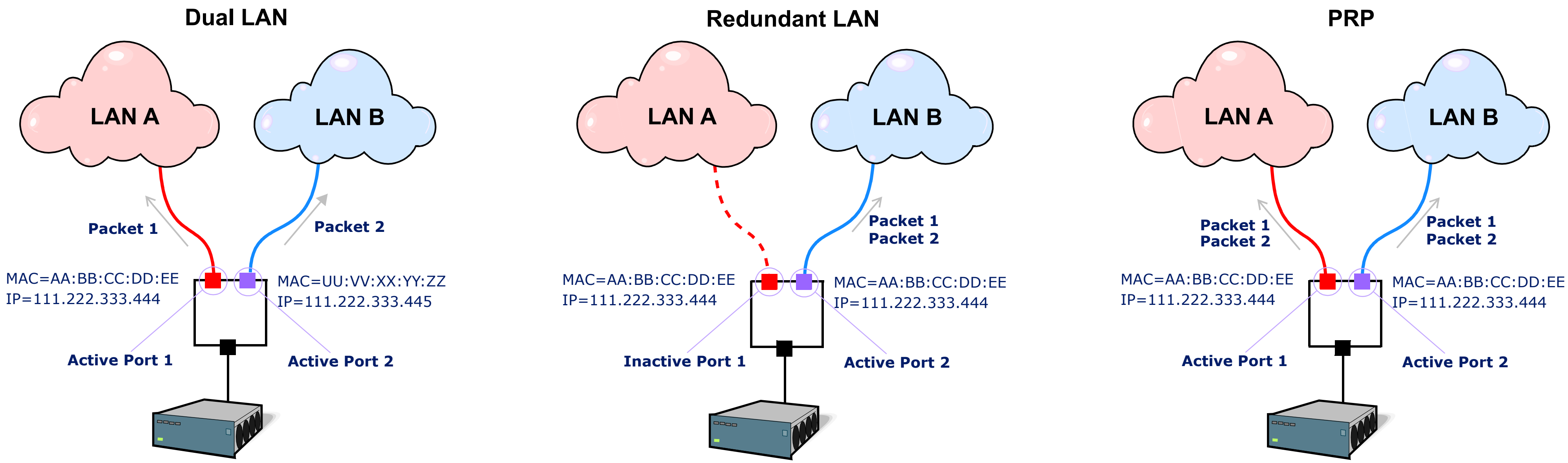
The latency of both networks should be similar, if they were very disparate packets would always arrive first through the same network and wait for the second.

We can find two types of devices:

- **DAN** (Double Attached Node) if has PRP support is integrated, then can be attached directly
- **SAN** (Single Attached Node) conventional device without PRP support then a Redundancy Box (redbox) is required to be connected.

PRP is encapsulated in IP/MAC then it can use conventional networks so LAN A and LAN B can transport any traffic, PRP and non-PRP, and this a nice advantage compared with HSR.

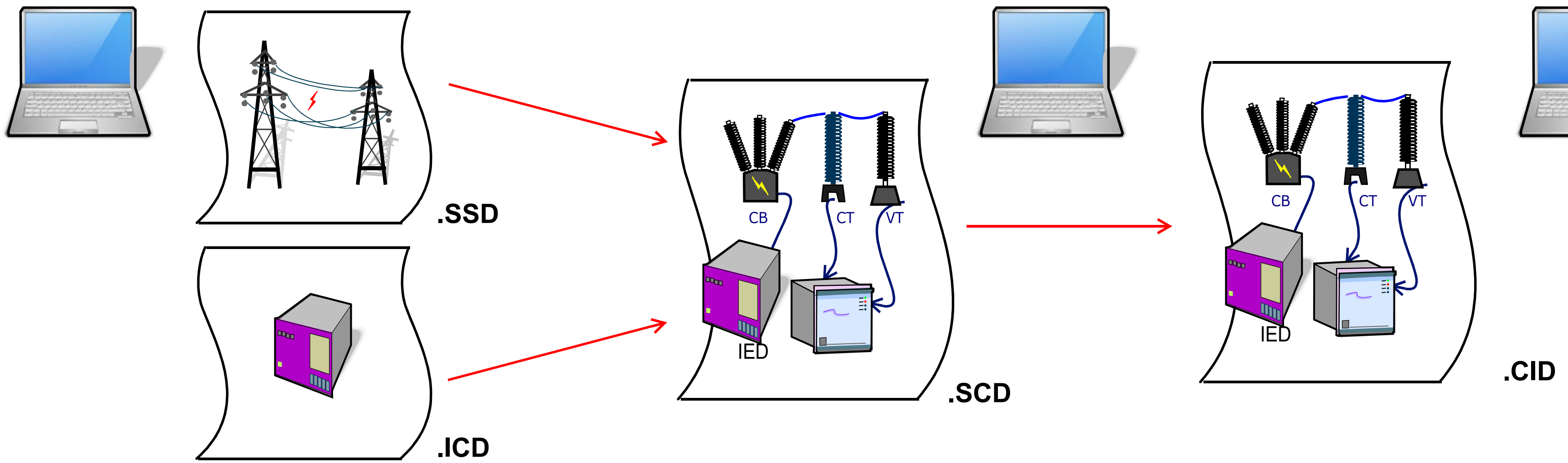
Dual LAN, Redundant LAN & **PRP**



PRP is based on the use of two independent networks: LAN A & LAN B

- Exactly the same frame (MAC & IP) is sent twice through two networks
- Latency in each LAN should be similar but not equal (if were very different we would always get the frame through the same network)
- PRP is encapsulated in MAC frames, then it is transparent, then PRP and no-PRP devices can communicate each other.

SCL: Engineering & Information structures

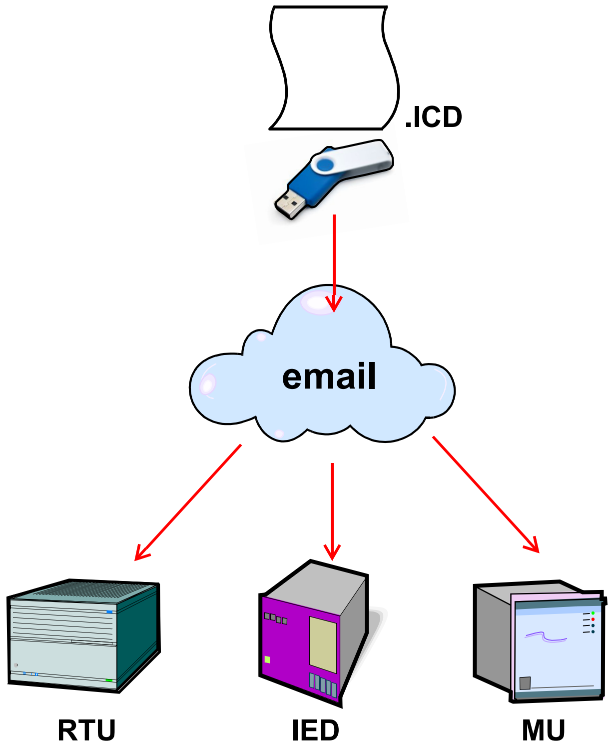


The **Substation Configuration Language** (SCL) specified by IEC 61850 for the configuration of substation includes representation of modeled data to have a complete interoperability:

- **Logical Node**: the smallest part of a function that can exchange data. For instance a XCBR has a the data structure called POS that tell its position (closed, open, intermediate). It has several attributes that belong to a function class. The all manufactures must implement this function.
- **Logical Device**: group of logical nodes. For instance we can group PIOC (instantaneous current) with PIOTC (Time Current) and the a logical IED groups several logical devices.
- **ECL language**: the SSD substation description.
- **ICD capabilities**: description of the substation as the addition of all IED.
- **SCD**: Substation Configuration Description is the combination of the SSD and ICD defining also all the relations between IED.
- **CID**: individual configuration of each IED that can be transfer to individual IED.

SCL facilities

SCL allows to perform the IEC 61850 engineering using standard tools topics include importing and exporting SCL file formats, the IED modification capabilities described in the standard and the communication and data flow configuration.



- SCL is the basis for the success of Plug & Play to simulate configurations
- SCL provides a common object and description
- SCL allows configurations set up and distribution via e-mail

IEC-61850 **benefits**

IEC - 61850

IEC 61850 facilitates configuration and testing of substations by means of data modeling, reporting schemes and commands in order to simplify interconnections between IEDs:

- Reduces dependence on propietary protocols
- Improves the of integration
- Reduces construction cost by eliminating most copper wiring
- Provides flexible programmable protection schemes
- Communication networks versus of hard-wired connections
- Sets an advanced management capability
- Based on High-speed, peer-to-peer communications
- Reduces construction and commissioning time and costs

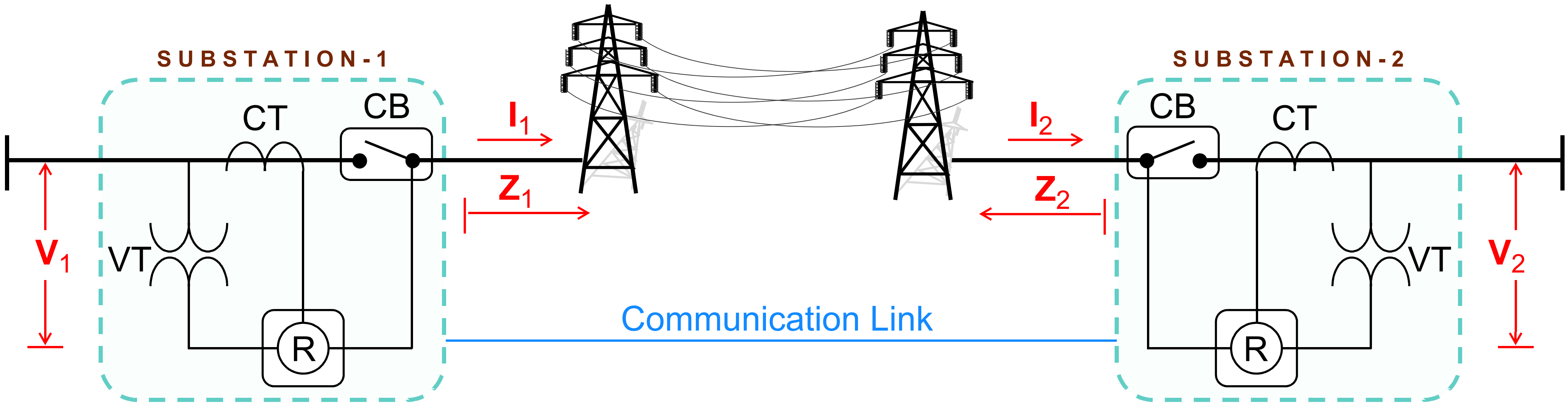
Protection schemes

A secure and uninterrupted supply of electricity is only possible with the help of comprehensive protection and control functions which ensure the reliable operation of the power system. Protection schemes have the objective of keeping the Power System **stable and isolated** from natural events (storms, earth-quakes, animals, winds), equipment failure, mis-operation... that may damage power grid elements:

- Power Generators
- Transformers in Plants and Substations
- Capacitors
- Power Lines (transmission & distribution)

Each component has its **particular way of protection** (fuse, differential, relay, disconnection...)

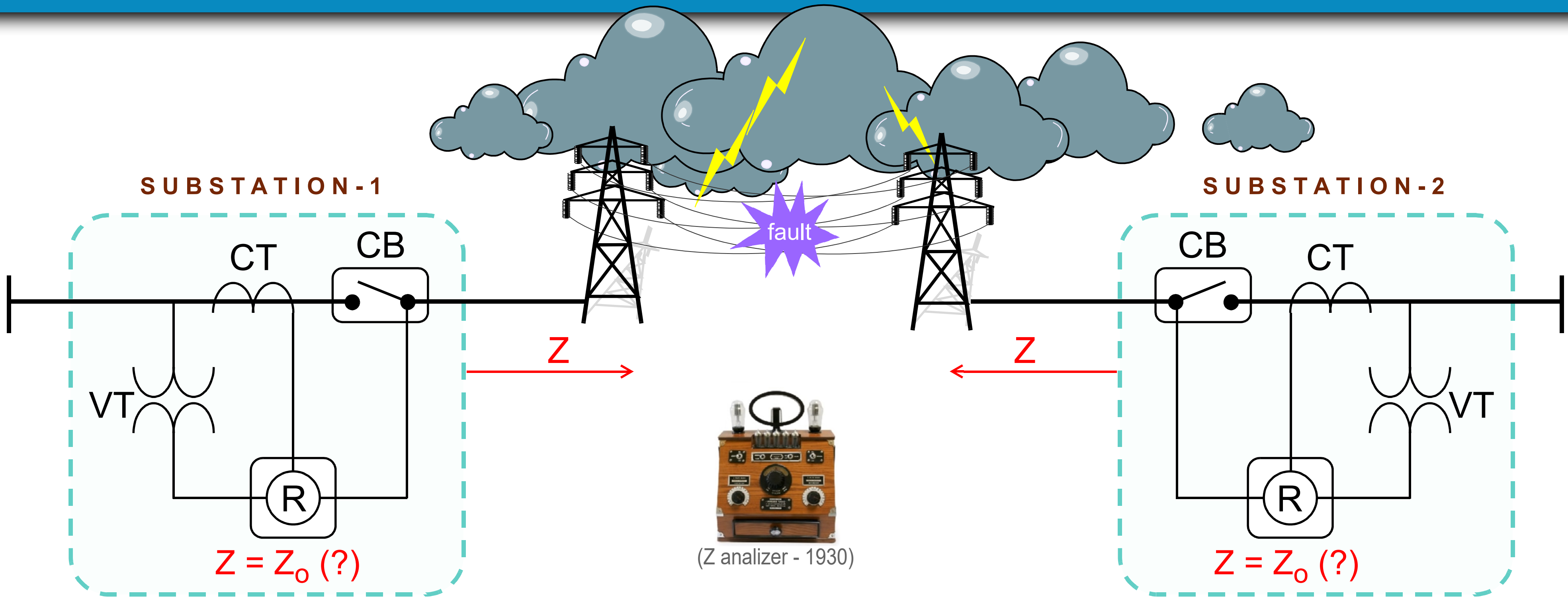
Line Protection



There are several line Protection schemes based on the measurement of electric values:

1. <u>Stand-alone schemes</u>:
   - **Overcurrent**: Relay responds to overcurrent condition read on CTs indicates tripping to CB
   - **Directional Overcurrent**: Relay responds to overcurrent condition in the forward direction only
   - **Impedance**: Relay responds to Z_i changes measured at CT and VT
2. <u>With communication link between Switchgears</u>:
   - **DCB** (Directional Comparison Blocking): CB tripping is allowed unless a block signal is received
   - **POTT** (Permissive Overreaching Transfer Trip): CB tripping is allowed only if a signal is received
   - **Line Current Differential**: current at I_1 is compared with the going I_2

Legacy Line Protection based on **Impedance**

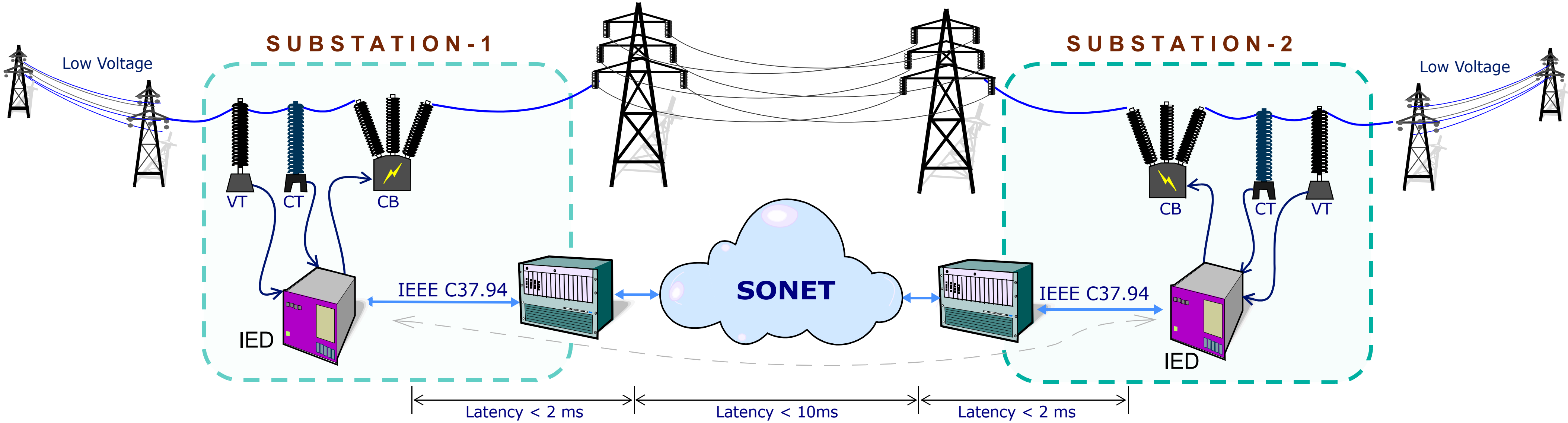


Impedance **Z = V / I** that is obtained measuring Voltage (V) at VT and Current (I) at CT.

$\mathbf{Z_o}$ is the initial set up of the line, then protection responds when actual $\mathbf{Z \neq Z_o}$ assuming then that there is a fault and the relay signals to the circuit breaker (CB) to cut the line and isolating the fault.

Incoming lines have a circuit breaker used as a protection device to interrupt fault currents automatically, and may be used to switch loads on/off, or to cut off a line when power is flowing in the 'wrong' direction. When a large fault current flows through the circuit breaker, this is detected through CT/VT transformers that are used to trip the CB resulting in a disconnection of the load from the feeding point to isolate the fault from the rest of the system and continue operating with minimal impact. Both switches and circuit breakers may be operated locally (within the substation) or remotely from a supervisory control center.

state-of-the-art: **C37.94** teleprotection

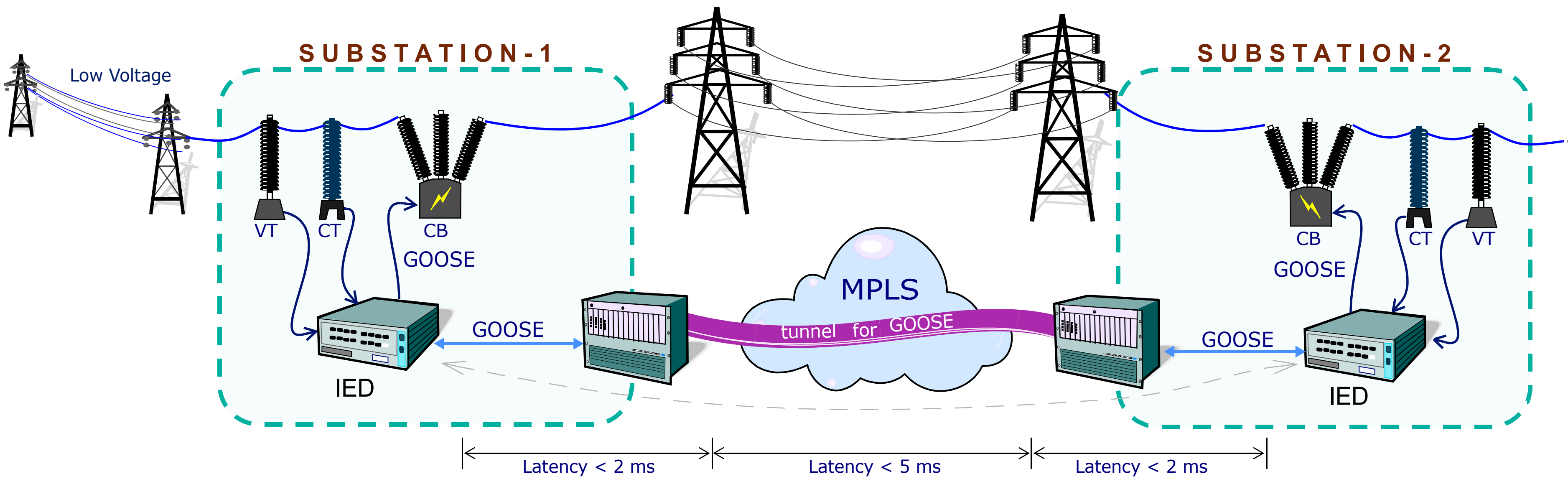


Tele-protection: protection schemes aided by tele-communications

Tele-protection relays on communicate between substations to isolate faults of the electrical plant. The reliability of the links is critical and must be resilient to the effects encountered in high voltage areas such as high frequency induction and ground potential rise.

The IEEE C37.94 is a TDM standard defines a Nx64 Kbps (N = 1…12) multi-mode optical fiber interface between tele-protection and digital multiplexer equipment, for distances of up to 2km. Allowing protection relays with C37.94 compliant interfaces to be directly connected to the unit.

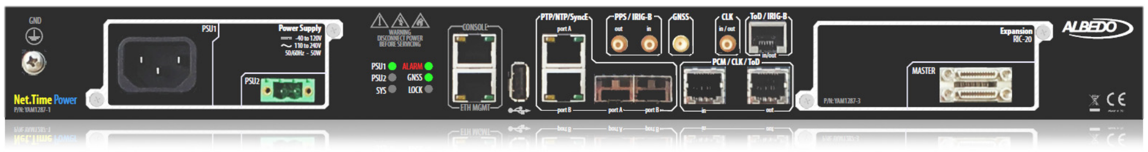
GOOSE is state-of-the-art teleprotection



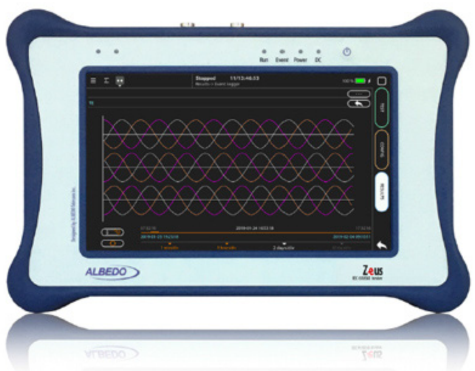
GOOSE is a Layer 2 protocol (not routable) used by IEDs send messages inside the substation LANs, nevertheless using MLPS it can be extended to remote substations and Tele-protection. MPLS facilitates GOOSE traffic through the WAN extending the LAN thus IEDs can exchange information with remote devices at remote substations:

- MPLS means good performance particularly on latencies that are critical for GOOSE
- GOOSE/MPLS architecture it is very scalable and inter-connectable with devices from different vendors.

ALBEDO **portfolio** for Utilities & the IEC 61850 **Power Substation** by **Layers**



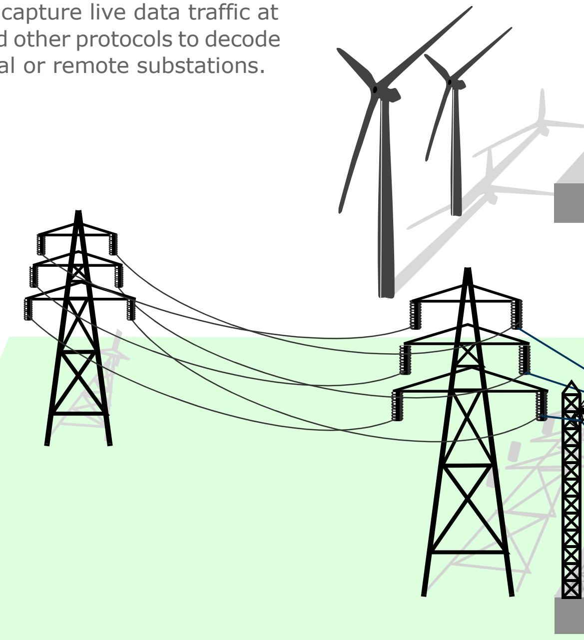
Net.Time Power is a synchronization node, compliant with IEC 61850, that supports PTP over PRP and multiple clock options such as NTP, SyncE, 1PPS, ToD, IRIG-B, etc. to satisfy all timing needs in substations. It also includes Power and Telecom PTP profiles and Rubidium oscillator. Net.Time simplifies the provision of timing facilitating the integration of the installed plant for perfect control, protection and data acquisition.

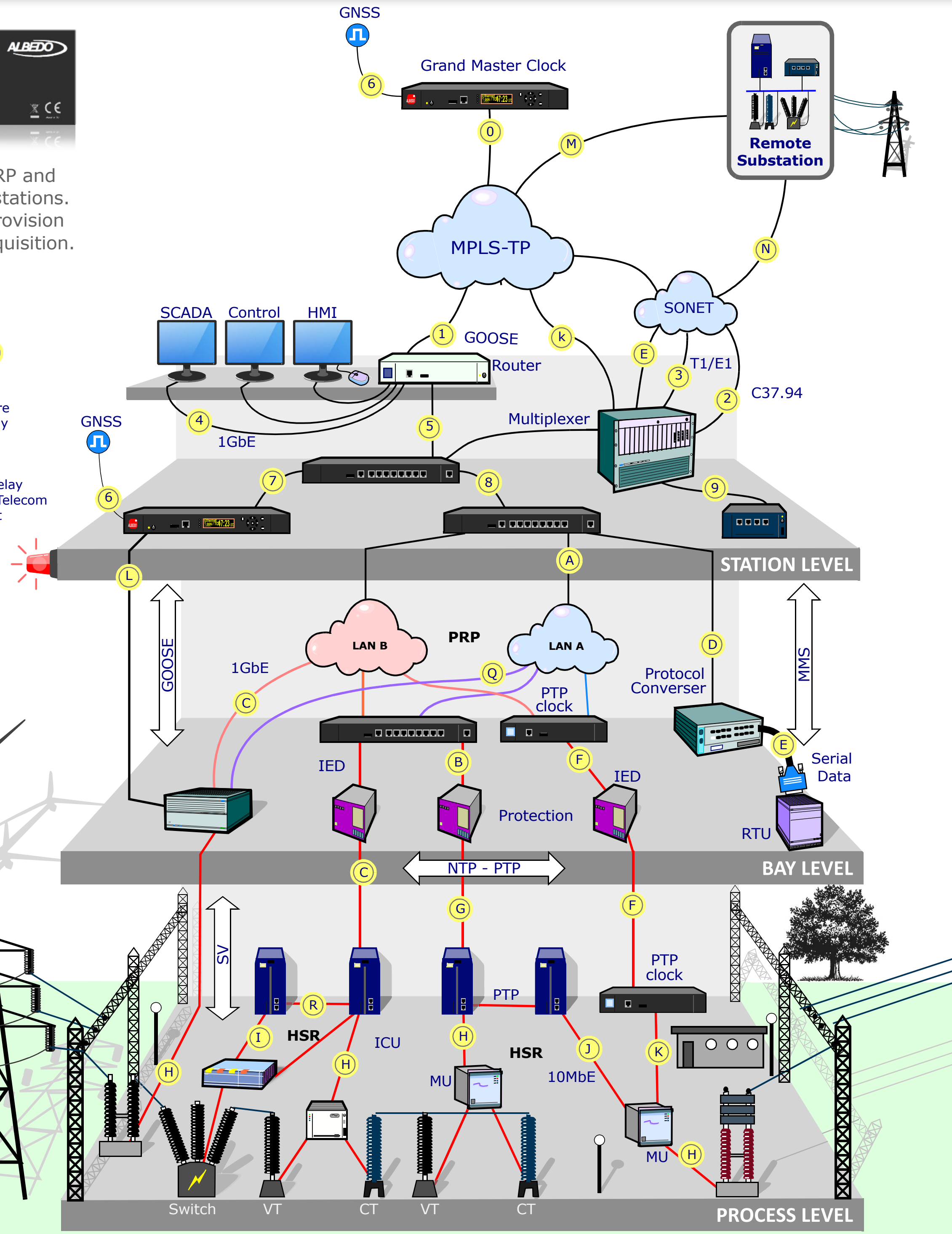


Test & Monitoring points

1 - GOOSE delay	E - RS-232
2 - C37.94	F - SyncE
3 - E1/T1	G - Codir (G703)
4 - GbE	H - SV capture
5 - MMS	I - GOOSE capture
6 - GNSS	J - One Way Delay
7 - 1PPS	k -100BASE-T
8 - Eth/IP	L - IRIG-B
9 - MPLS	M - GbE
A - PTP	N - Round Trip Delay
B - NTP	O - PTP Power / Telecom
C - GOOSE	Q - GOOSE offset
D - PTP wander	R - PTP wander

Zeus provides deep insights to design, install, maintain, troubleshoot and engineer communications infrastructures of the Smart Grid. The unit is able to test Ethernet/IP, PTP, GbE, IRIG-B, T1/E1, G703, C37.94 and GOOSE, SV and MMS protocols. One-way-delay tests, assisted by GPS, is possible at all interfaces. Zeus has a set of programmable filters to capture live data traffic at wire-speed. You can now analyze GOOSE, SV, MMS and other protocols to decode and save in PCAP format or calculate delays from local or remote substations.





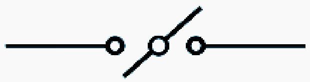
NetStorm can simulate the packet network dynamics by means of controlled packet delay, loss, error and duplication. It is fundamental to test the impact of these impairments that have such a strong impact on the Quality of Experience of devices, nodes, protocols and applications such as VoIP, IPTV, VoD, FTP, and critical data.

Symbols

Busbars

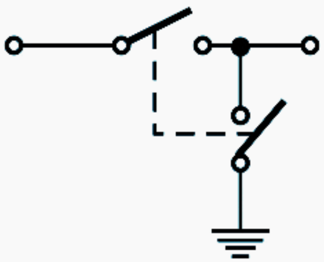
Single-break isolating-switch

Double-break isolating-switch

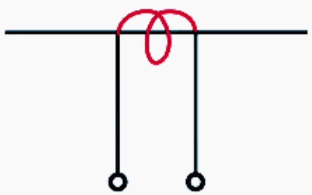


On-load isolating switch

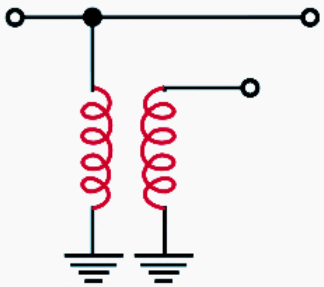
Isolating switch with earth blade



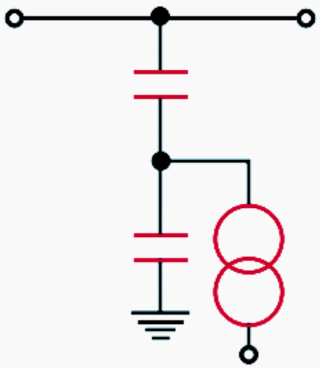
Current transformer (CT)



Potential (voltage) transformer (PT or VT)

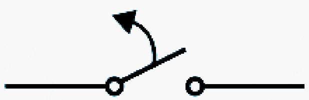


Capacitive voltage transformer (CVT)



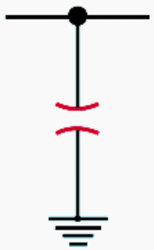
Oil circuit breaker

Air circuit breaker with overcurrent tripping device

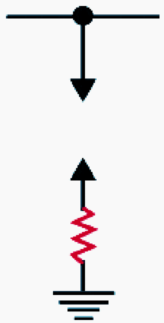


Air-blast circuit breaker

Lightning arrester (active cap)

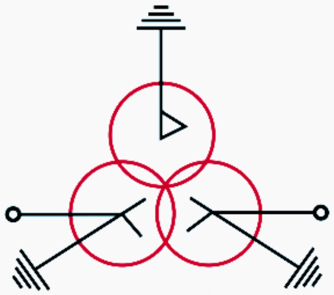


Lightning arrester (valve type)

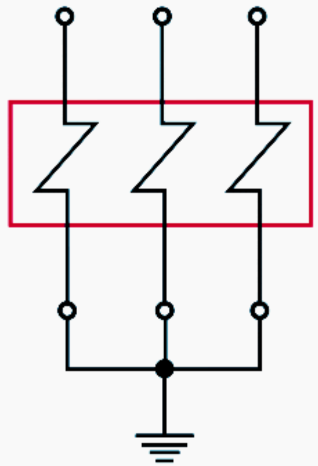


Arcing horn

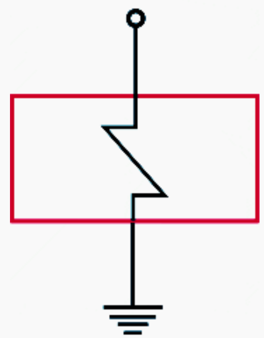
Three-phase transformer



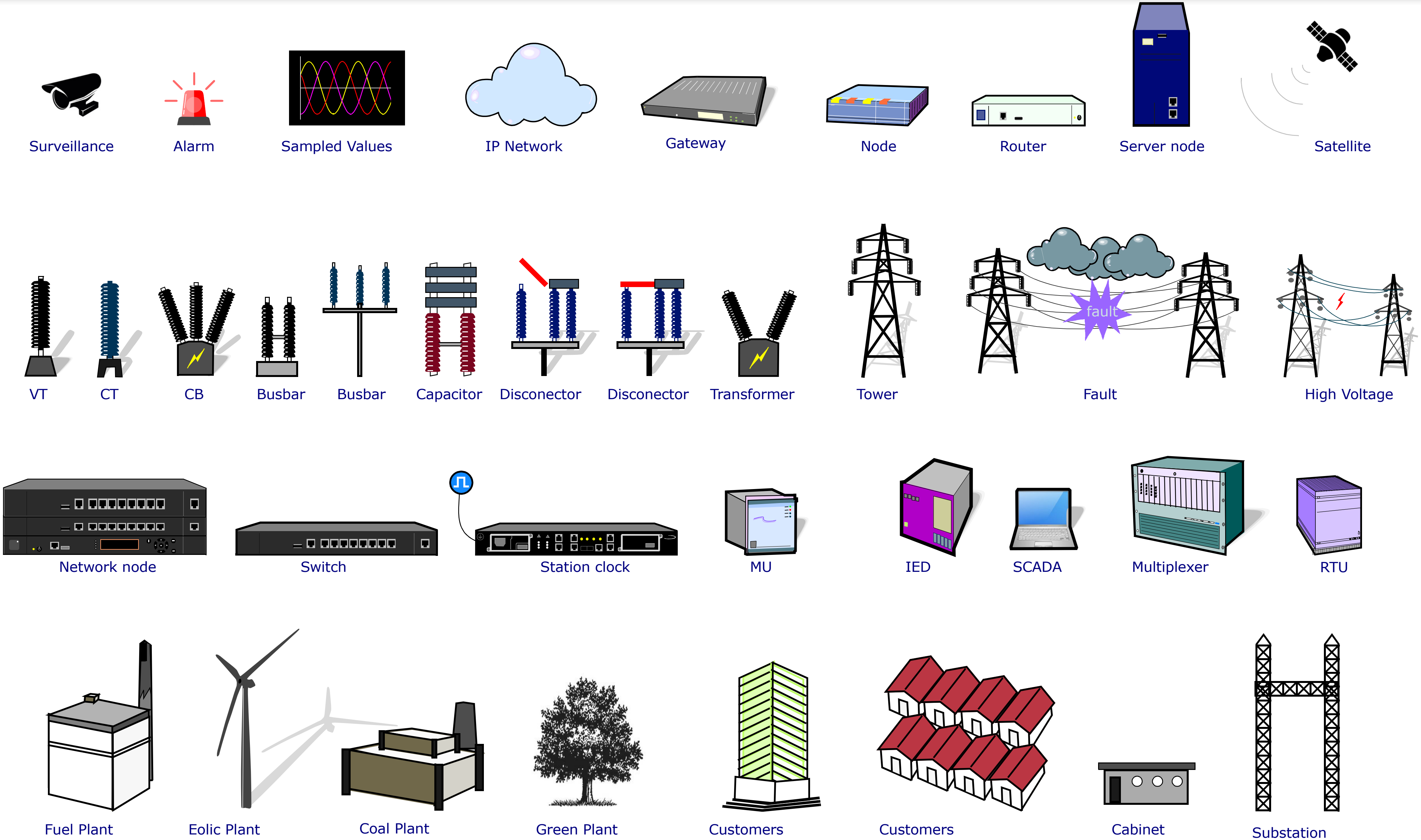
Overcurrent relay



Earth fault relay



Icons


Surveillance
Alarm
Sampled Values
IP Network
Gateway
Node
Router
Server node
Satellite
VT
CT
CB
Busbar
Busbar
Capacitor
Disconector
Disconector
Transformer
Tower
fault
Fault
High Voltage
Network node
Switch
Station clock
MU
IED
SCADA
Multiplexer
RTU
Fuel Plant
Eolic Plant
Coal Plant
Green Plant
Customers
Customers
Cabinet
Substation

AAA: Authentication, Authorization, and Accounting
ACL: Access Control List
AP: Access Point
Busbar: Metallic strip or bar, typically housed inside switchgear, panel boards, and busway enclosures for local high current power distribution
C37.94: TDM interface devoted for teleprotection
CB: Circuit Breaker designed to close or open electrical circuit under normal or abnormal conditions. It operates on relays command.
CBWFQ: Class-Based Weighted Fair Queuing
CG: Connected Grid
CID: Individual configuration of each IED
CIP: Critical Infrastructure Protection
CLI: Command-Line Interface
CorpSS: Corporate Substation
CT: Current Transformer, used for measurement of current, if too high to apply directly to measuring instruments, a CT produces a proportional current which can be measured and recorded, CT are used in metering and protective relays
DAN: Doubly Attached Nodes implementing HSR or PRP
DAU: Data Acquisition Unit
Disconnector: isolates physically and visually the lines
DMZ: Demilitarized Zone
DCB: Directional Comparison Blocking
DCS: distributed control systems
DSC: Differentiated Services Code Point
ESP: Electronic Security Perimeter
Feeder: Transmits power to the distribution points
GM: Grandmaster
GNSS: Global Navigation Satellite System
GOOSE: Generic Object-Oriented Substation Events is a control model defined as per IEC 61850 which provides a fast and reliable mechanism of transferring event data over entire electrical substation networks. When implemented, this model ensures the same event message is received by multiple physical devices using multicast or broadcast services
HMI: Human Machine Interface
HQoS: Hierarchical Quality of Service
HSR: High-Availability Seamless Redundancy
IA: Industrial Automation
ICS: Industrial control systems
ICU: Intelligent Control Unit
IEC: International Electrotechnical Commission
IEC 61850: Standard defining communication protocols for intelligent electronic devices at electrical substations
IED: Intelligent End Device, microprocessor-based controllers of power system equipment, such as circuit breakers, transformers and capacitor banks to enable advanced power automation.
IRIG: Inter-Range Instrumentation Group
ISE: Identity Services Engine
L3VPN: Layer 3 Virtual Private Network
LA: Lightning Arrester protects the power grid from electric storms
MQC: Modular QoS Command-Line Interface
MMS: Manufacturing Message Specification, messaging system for exchanging real-time data and supervisory control information. Allows client such as SCADA, an OPC server or a gateway to access all IED objects
MPLS: Multi-protocol Label Switching
MU: Merging Unit connected to the process bus converts analog data(ie. volts, currect...) into digital information
NERC: North American Electric Reliability Corporation
NIST: National Institute of Standards and Technology
NMS: Network Management System
OAM: Operations and Maintenance
PCP: Priority Code Point
PIOC: Instantaneous overcorrent Protection
PLC: Programmable Logic Controller
PMU: Phasor Measurement Unit
POTT: Permissive Overreaching Transfer Trip
PP: Primary Power
Process Bus: Connects primary units and control equipment to the IEDs
PRP: Parallel Redundancy Protocol
PT: see VT
PTP: Precision Time Protocol
RedBox: Redundancy Box
Relay: is automatic device which senses an abnormal condition of electrical circuit and closes its contacts and complete the circuit breaker trip.
REP: Resilient Ethernet Protocol
RCT: Redundancy Control Trailer
RTU: Remote Terminal Unit
SA: Substation Automation
SAN: Singly-Attached Node
Secondary Lines: lower voltage side at the substation
SCADA: Supervisory Control And Data Acquisition, transmits and receives data from events of controls, measuring, safety and monitoring. Power system elements can be controlled remotely over. Remote switching, telemetering of grids showing voltage, current, power, direction, consumption in kWh, synchronization.
SCD: Substation Configuration Description
SCL: Substation Configuration Language
SNTP: Simple Network Time Protocol
Station Bus: Connects the entire substation and helps provide connectivity between central management and individual bays
STP: Spanning Tree Protocol
SV: Sampled Values, is a method to read instantaneous values such as currents, voltages, impedances, etc. from CTs, VTs or digital I/O and then transmitted to make them are available for those IED subscribed.
Switchgear: combination of switches, fuses or CB to control, protect and isolate electrical equipment
SyncE: Synchronous Ethernet
TLV: Type, Length, Value
VT: Voltage Transformer (see CT)Potential Transformer, gives the reference voltage to the Relay for Over-voltage or Under-voltage Protection
UCA IuG: Utility Communications Architecture International Users Group
VDAN: Virtual Dual Attached Node

That's all

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