TÉCNICO LISBOA

Smart Grid Fundamentals

Smart Grid Applications

António Grilo

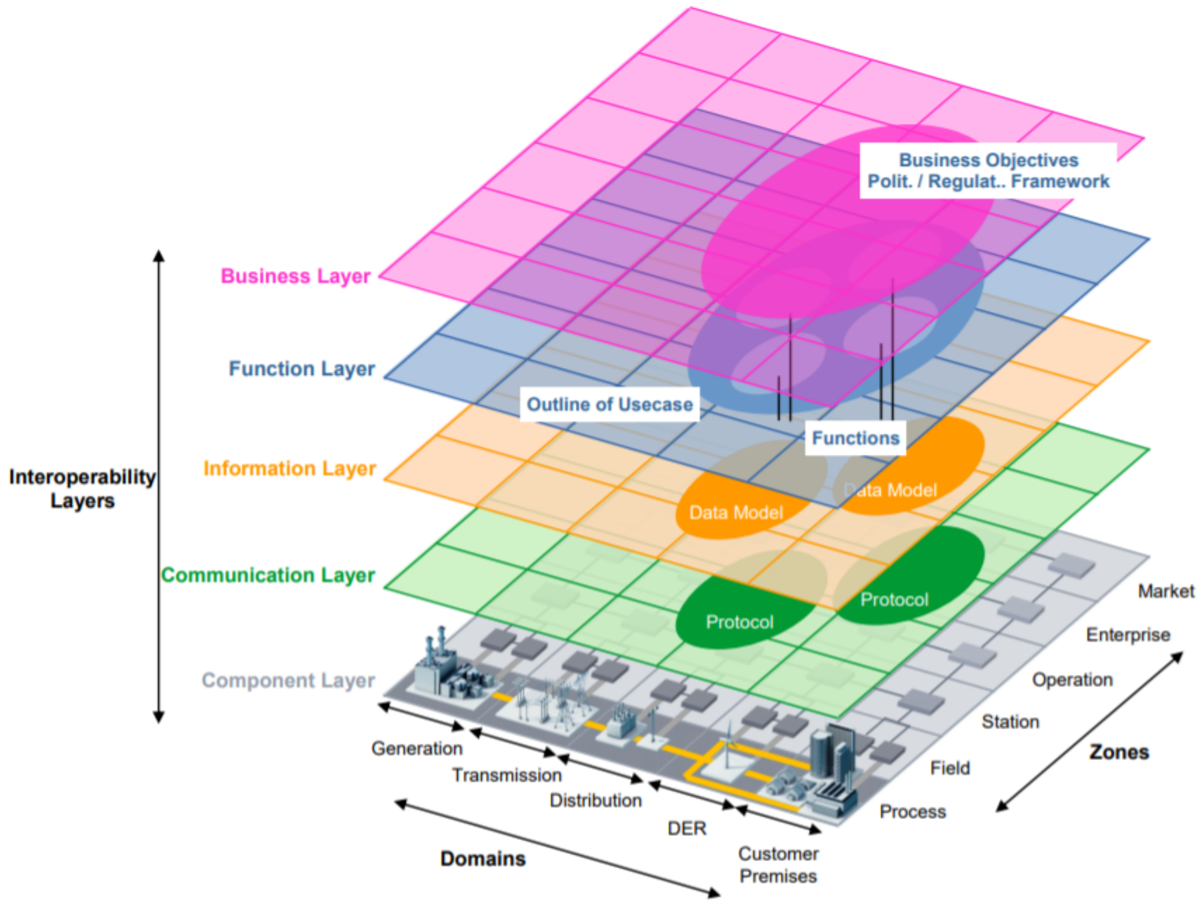
TÉCNICO LISBOA

Smart Grid Architecture Model (SGAM)

- It is a three dimensional model that is merging the dimension of:
  - Five **interoperability layers** (Business, Function, Information, Communication and Component)
  - Two dimensions of the Smart Grid Plane, i.e.:
    - **Zones** (representing the hierarchical levels of power system management: Process, Field, Station, Operation, Enterprise and Market)
    - **Domains** (covering the complete electrical energy conversion chain: Bulk Generation, Transmission, Distribution, DER and Customers Premises).

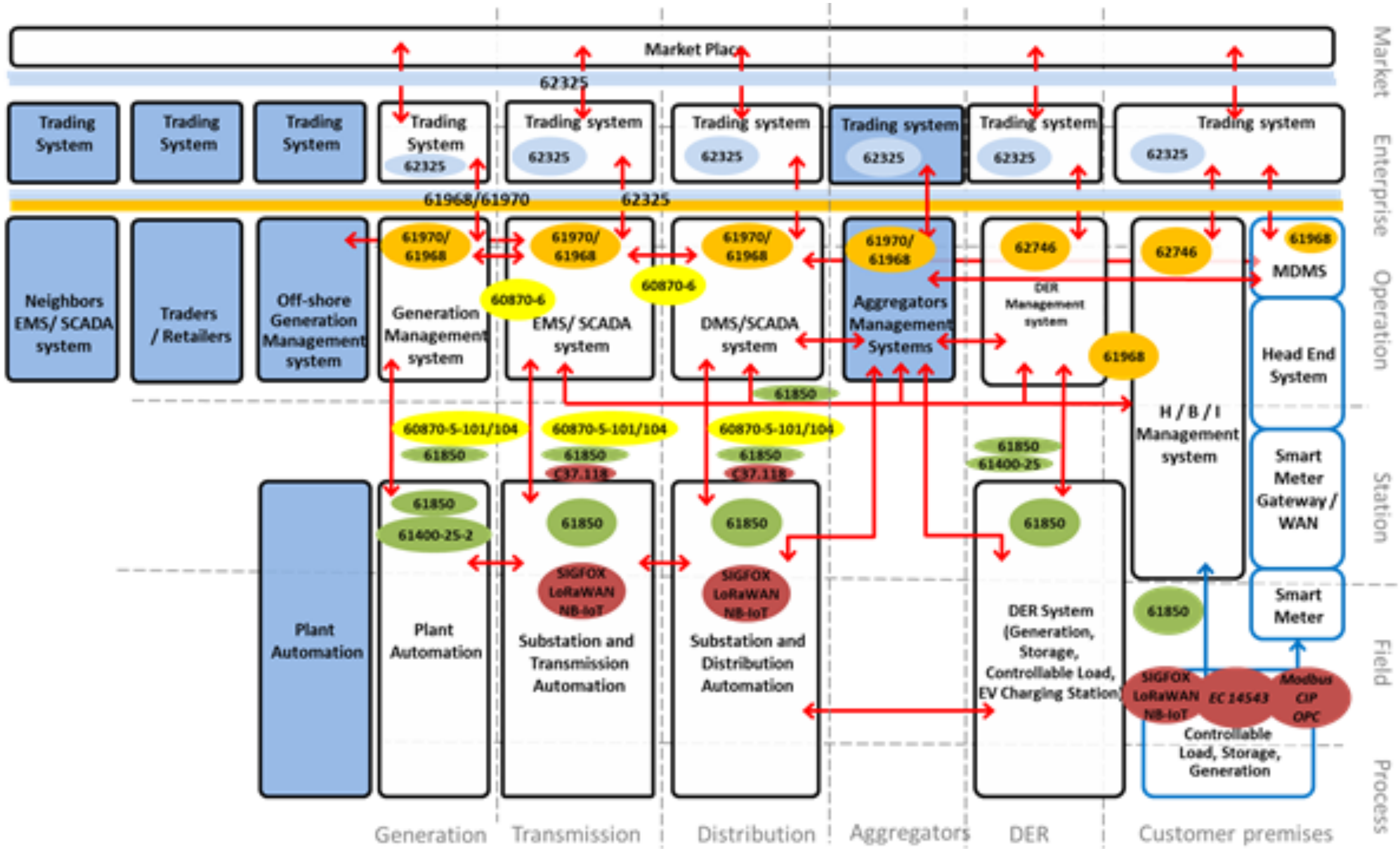
Smart Grid Architecture Model (SGAM)

- SGAM graphical representation:



Smart Grid Architecture Model (SGAM)

- Mapping of communication networks and protocols on SGAM communication layer:

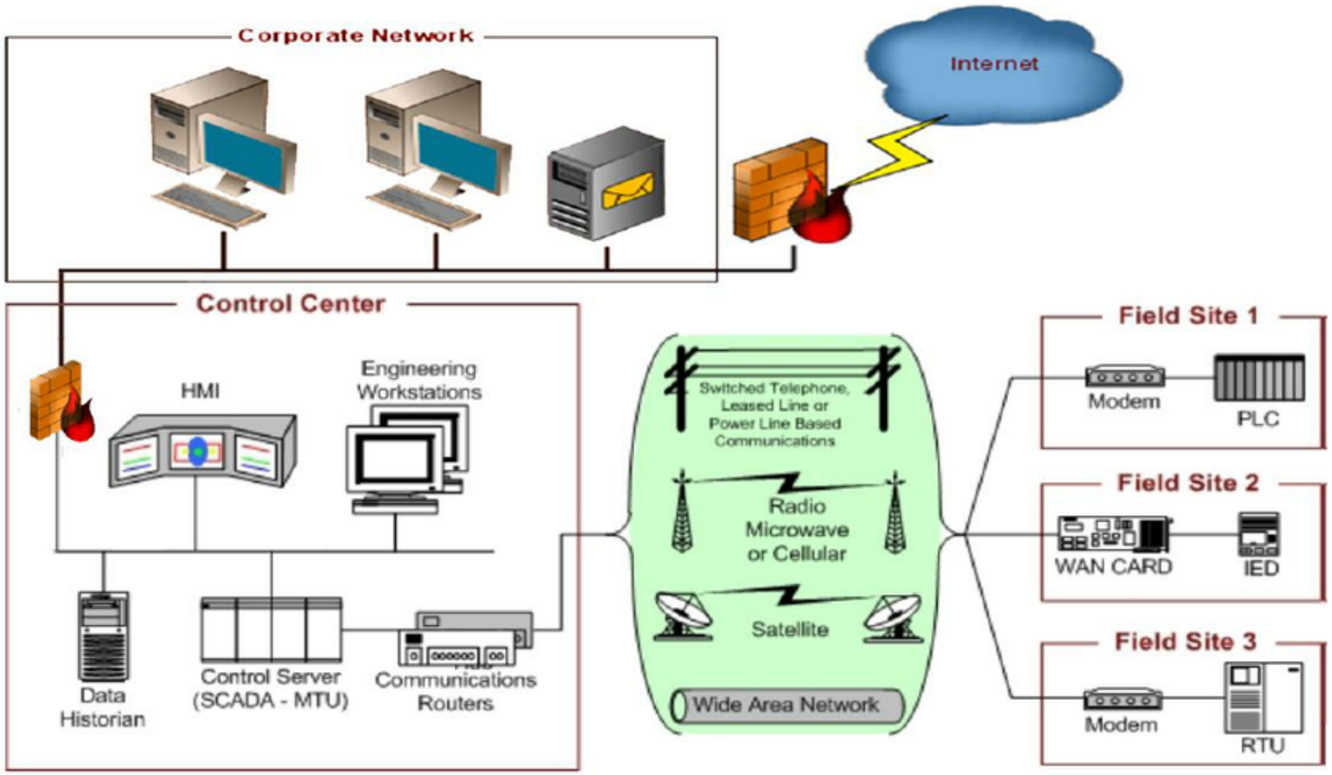


Supervisory control and data acquisition (SCADA)

- Functions:
  - Monitoring (or data acquisition):
    - Measurement and reporting of voltages, currents, power (W), and reactive power (VAR) and reporting on the status of different systems in the substation such as the circuit breakers and switches.
  - Control:
    - Control of substation operations such as tripping of circuit breakers and adjusting taps on voltage regulators.

Supervisory control and data acquisition (SCADA)

- SCADA System Architecture



A. Elhadi et al., "Generic Software Risk Management Framework for SCADA System", International Journal of Computer Applications (0975 – 8887), Volume 70– No.3, May 2013

Communication with Network Devices

- IEC 60870-5-104:
  - Network access for IEC 60870-5-101 using standard transport profiles.
  - Enables communication between data and control center and substation via a standard TCP/IP network.
  - Master/Slave interface at Application layer

7	Application Layer	IEC 60870-5-104 Companion Standard IEC 60870-5-5, IEC 60870-5-4	
6	Presentation Layer	n/a	
5	Session Layer	n/a	
4	Transport Layer	TCP (RFC 793)	
3	Network Layer	IP (RFC 791)	
2	Link Layer	PPP (RFC 1661 & RFC 1662)	Transmission of IP datagrams over Ethernet network (RFC 894)
1	Physical Layer	X.21	Ethernet (IEEE 802.3)

Communication with Network Devices

SCADA
Substation Automation
AMI
Distributed Automation
Distributed Generation
Distributed Storage
Electric Vehicle
Volt, VAR, Watt Control in DS
WASA&C
Energy Markets
ADR

- IEC 60870-5-104:

Supported Information Types	
Control Direction	Single Command Double Command Setpoint Regulating step command
Monitoring Direction	Single indication [1 Bit] with quality Single indication [1 Bit] with quality and time tag Double indication [2 bit] with quality Double indication [2 bit] with quality and time tag Measured scaled value with quality Measured scaled value with quality and time tag Measured normalized value with quality Measured normalized value with quality and time tag Measured floating point value with quality Measured floating point value with quality and time tag Bitpattern [32 bit] with quality Bitpattern [32 bit] with quality and time tag Counter value with quality Counter value with quality and time tag Step position value with quality Step position value with quality and time tag Event of protection equipment with quality and time tag

Communication with Network Devices

SCADA
Substation Automation
AMI
Distributed Automation
Distributed Generation
Distributed Storage
Electric Vehicle
Volt, VAR, Watt Control in DS
WASA&C
Energy Markets
ADR

- IEC 60870-5-104:

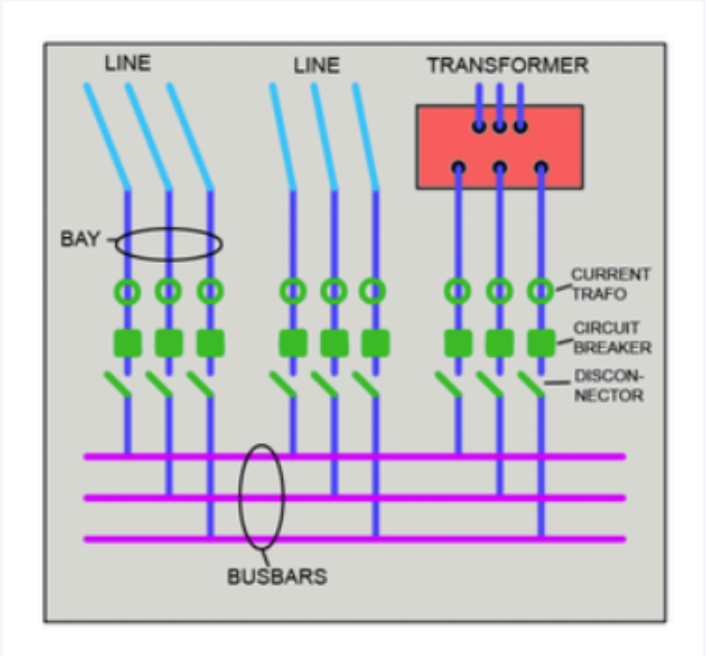
Protocol Features	
Application Layer	On-demand transmission (e. g. single indications, analogs, ...) Spontaneous transmission (e. g. single indications with time tag, ...) Direct command transmission (with select before operate) Clock synchronization File Transfer
Address Space	Common Address of ASDU: 1..65535 Information object address: 1..16777215

TÉCNICO LISBOA

Substation Automation

SCADA
Substation Automation
AMI
Distributed Automation
Distributed Generation
Distributed Storage
Electric Vehicle
Volt, VAR, Watt Control in DS
WASA&C
Energy Markets
ADR

- Typical substation has at least the following:



Gray: **Substation**
Cyan: **Power line**
Blue: **Bay**
Green: **Switches etc**
Purple: **Busbar assembly**
Red: **Transformer**

A bay is a power line within an electrical substation which connects a circuit (such as a power line or transformer) to a busbar. Each bay typically includes circuit breakers, disconnectors, instrument transformers and surge arresters.

https://wiki.openstreetmap.org/wiki/Tag:line%3Dbay

Substation Automation

- Refers to the combination of two modernization steps:
  - Deployment of microprocessor-based Intelligent Electronic Devices (IEDs) to replace conventional CTs, VTs, and RTUs and secondary equipment such as relays and bay controllers;
  - Development and deployment of new Distribution Management System (DMS) applications that take advantage of the enhanced monitoring and control functions provided by the IEDs.
- IEDs:
  - May support functions formerly supported by multiple conventional devices in the substation;
  - Multifunctional IEDs are more powerful and smaller in size than the devices they replace, reducing the costs associated with SCADA operations.

Substation Automation

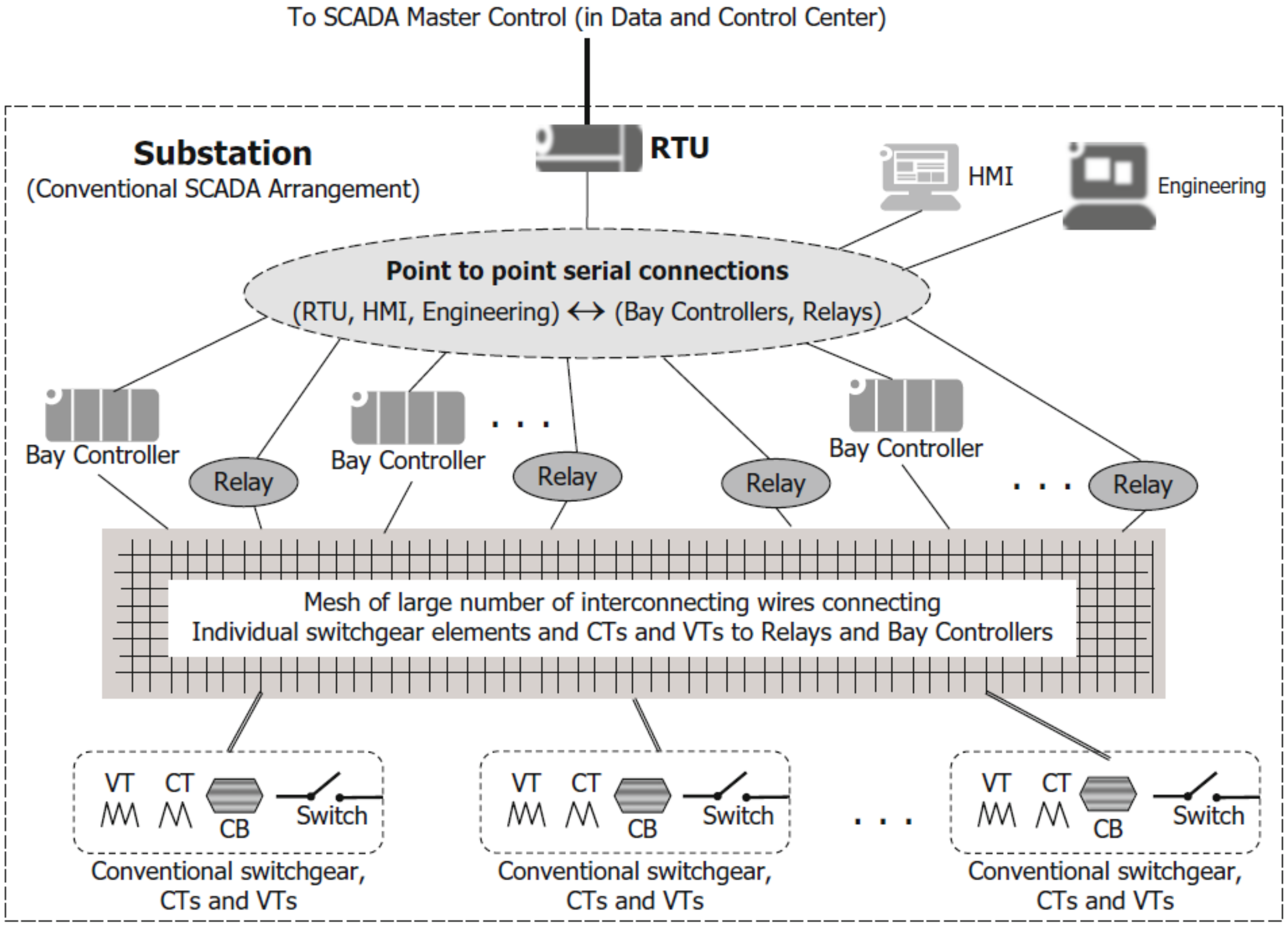


Fig. 4.2 Traditional SCADA schematics

Substation Automation

- IEC 61850 Substation Control Levels (w/o RTU) [IEC 61850-5]:

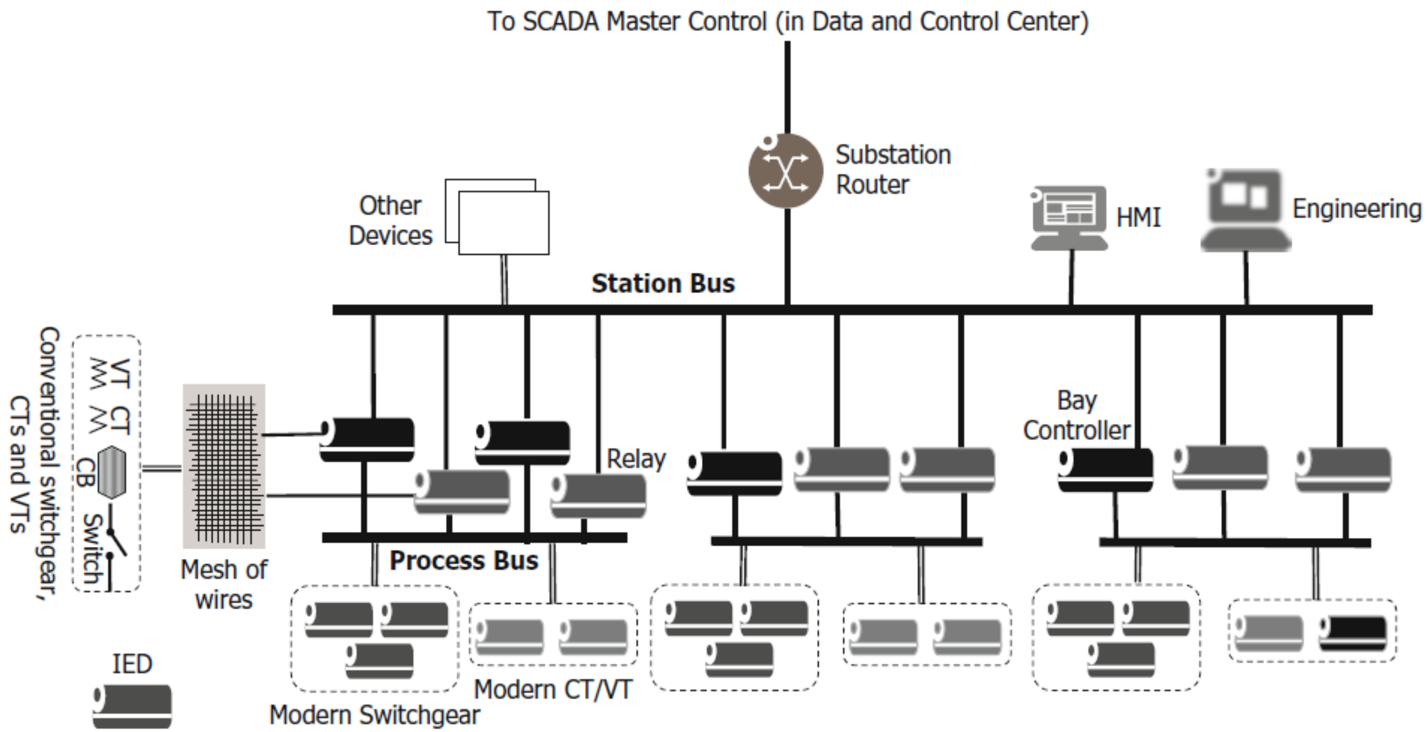


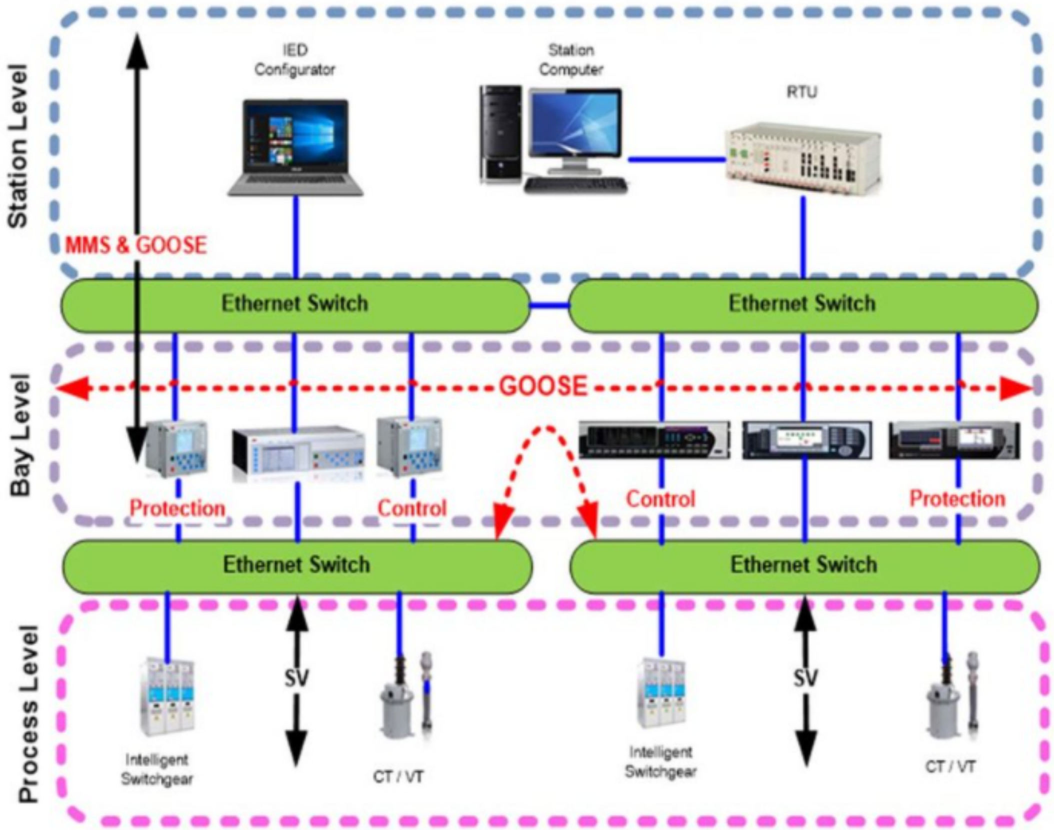
Fig. 4.3 Substation architecture with IEC 61850-7-1

Substation Automation

- IEC 61850:
  - Developed by the International Electrotechnical Commission (IEC) Technical Committee Number 57 Working Group 10 (TC57 WG10) and IEEE for Ethernet (IEEE 802.3)-based communication.
  - IEC 61850 is a 10-part comprehensive set of standards encompassing communication networks and systems in substations.
  - Abstracts the definition of the service and data items to be independent from the underlying protocols.
  - Maps the data to three different protocols, based on the application:
    - **Manufacturing Message Specification (MMS)** protocol: used for high-level control and automation functions.
    - **Generic Object Oriented Substation Event (GOOSE)**: used for real-time event notification (circuit breaker commands).
    - **Sampled Measured Values (SMV):** used for real-time quantity measurements (e.g., voltage, current).

Substation Automation

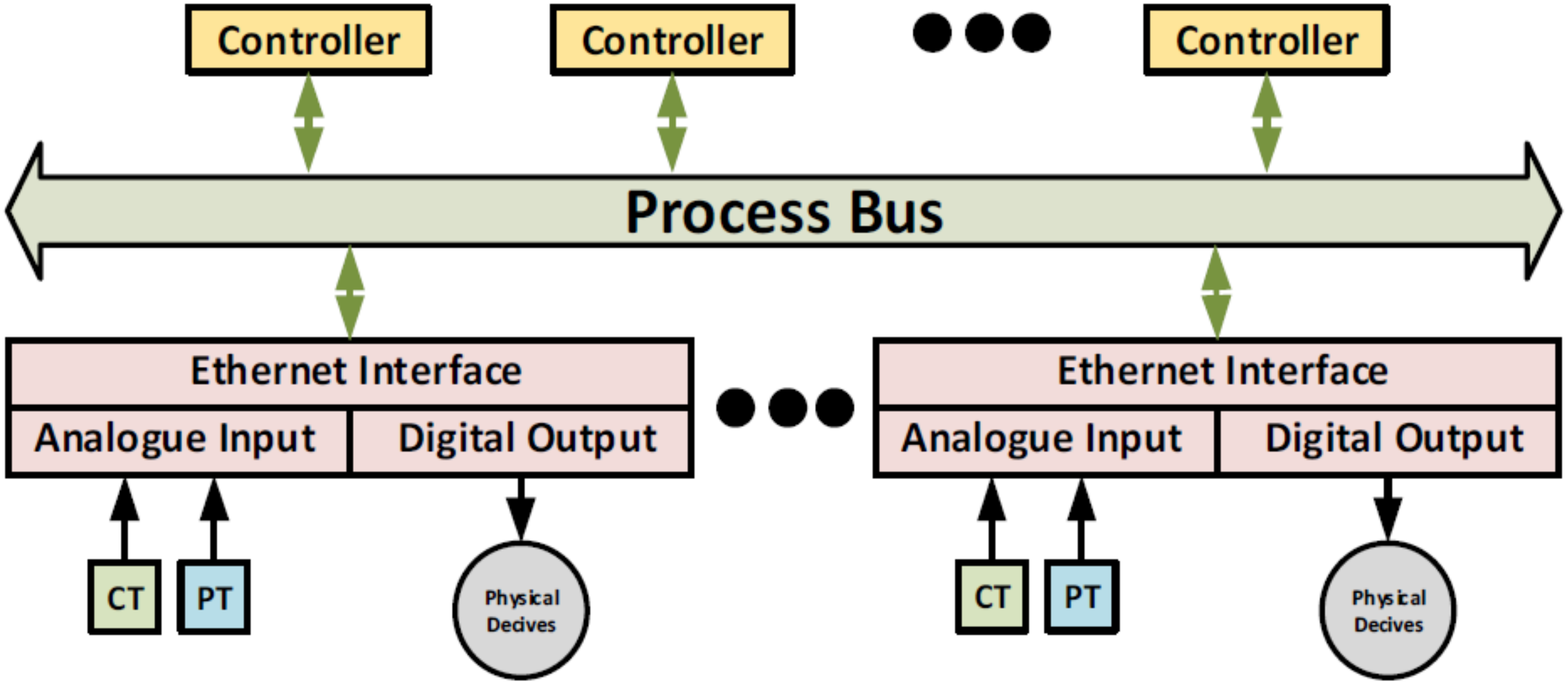
- IEC 61850 Substation Control Levels [IEC 61850-5]:



https://www.researchgate.net/figure/IEC-61850-Substation-Architecture_fig4_329613395

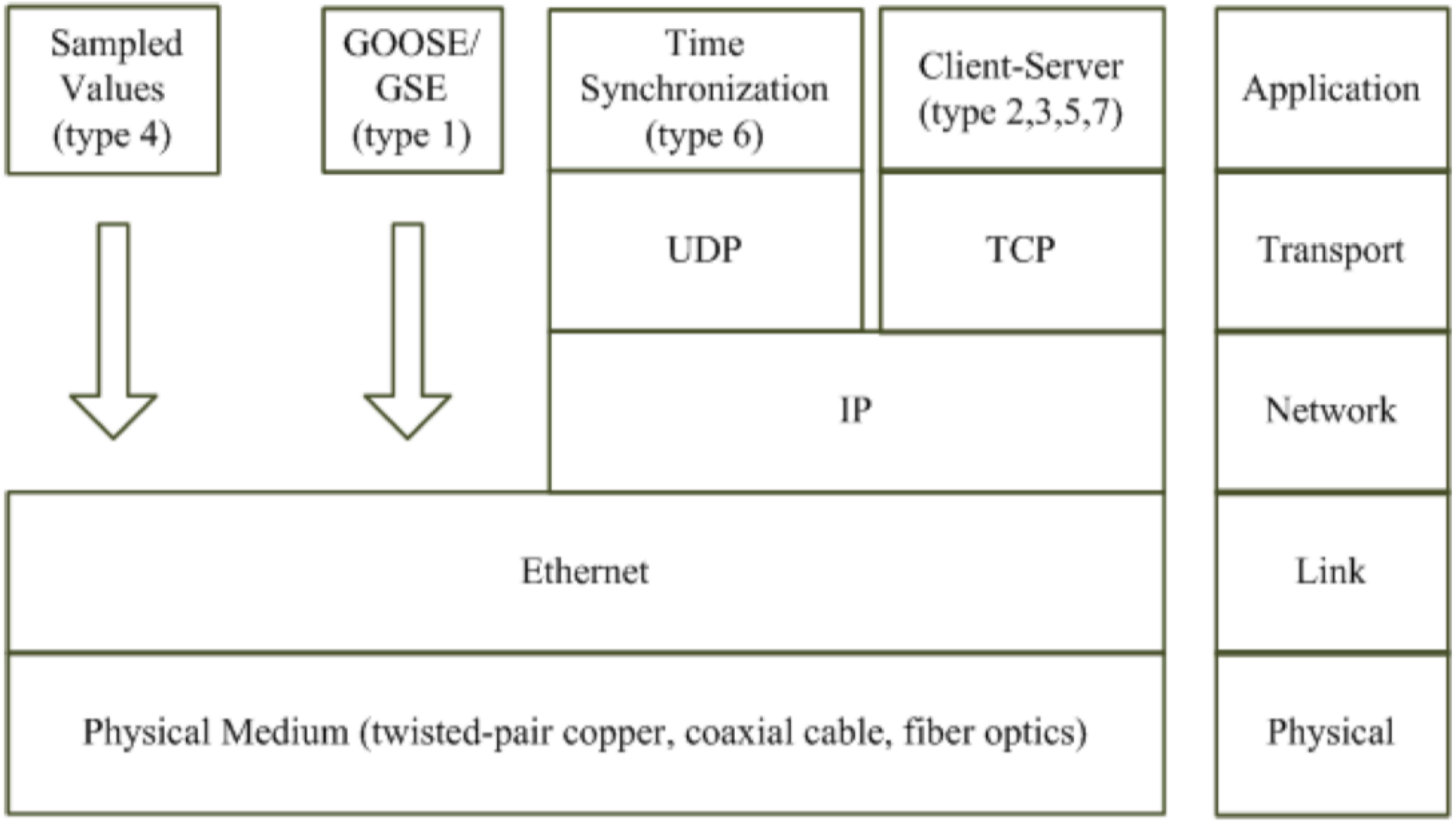
Substation Automation

- IEC 61850 Process bus:



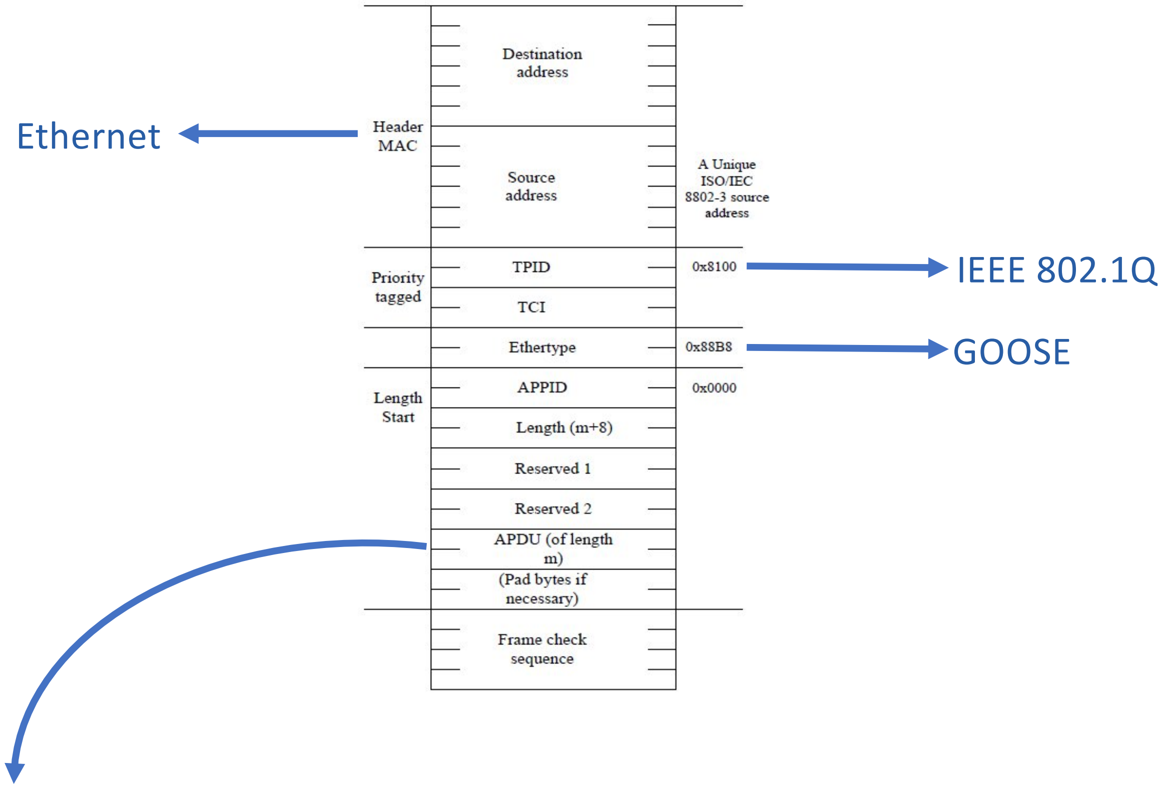
Substation Automation

- IEC 61850 Protocol Stack:



Substation Automation

- IEC 61850 GOOSE Message Format:



Tag (1 byte)	Length	Content	End of content (optional

Advanced Metering Infrastructure (AMI)

- AMI:
  - Monitoring of energy consumption, voltage, power, distribution of pricing information, and other consumer-centric functions in addition to billing the customers.
  - Encompasses:
    - Smart meters deployed at consumer locations.
    - Meter Data Management System (MDMS) located at the utility Data and Control Center (DCC).
    - Communication network elements interconnecting the above.
  - Uses the DLMS/COSEM protocol.

TÉCNICO LISBOA

Advanced Metering Infrastructure (AMI)

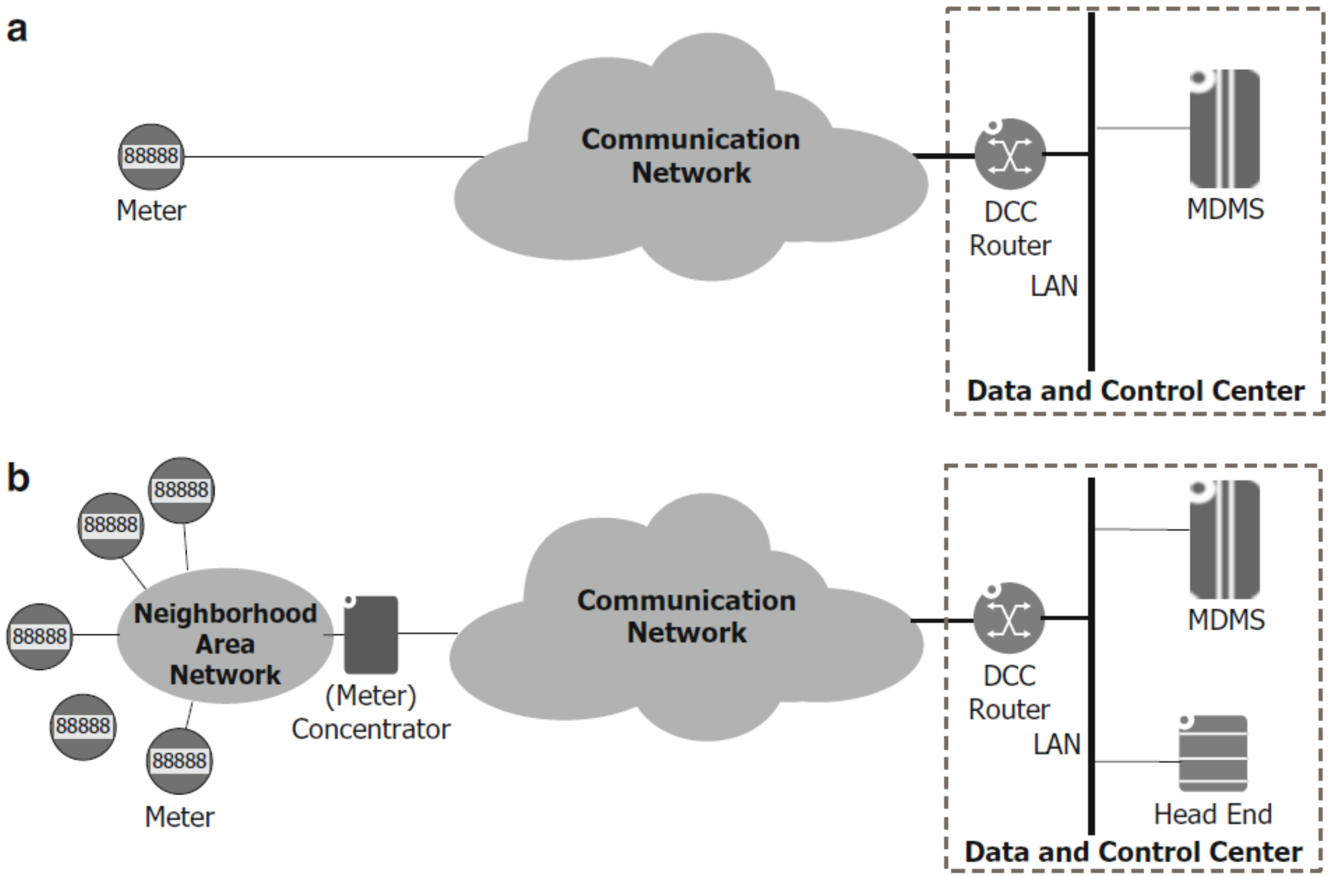


Fig. 5.1 Networking for AMI – two options. (**a**) Meters connects directly to utility MDMS. (**b**) Vendor-proprietary "AMI solution" connecting to the MDMS

Smart Metering Technologies

Table 2: Summary of some common communication technology in smart metering applications.

Technology		Data Rate	Frequency Bands	Range
Wireless				
Cellular	3G-4G	60–240 kbps	824–894 MHz, 1900 MHz	about 50 km
	GSM	≥ 14.4 kbps.	900–1800 MHz	1–10 km
	GPRS	≥ 170 kbps.	900–1800 MHz	1–10 km
IEEE 802.15 Group	ZigBee 6LoWPAN	20-250 kbps	868 MHz/915 MHz/2.4 GHz	10-1000m
	Bluetooth	721 kbps	2.4–2.4835 GHz	1-100m
IEEE 802.11 Group	Wi-Fi	≥ 54 Mbps.	2.4 GHz/5.8GHz	1-100m
	Enhanced Wi-Fi	≥ 54 Mbps.	2.4 GHz	1-100m
	IEEE 802.11 n	≥ 600 Mbps.	2.4 GHz	1-100m
IEEE 802.16	WiMAX	70 Mbps	1.8–3.65 GHz	50 km
Satellite	Satellite Internet	1 Mbps	1-40 GHz	100–6000 km
Wired				
NB-PLC	PRIME G3-PLC	up to 500 kbps	3–500 kHz	Several km
BB-PLC	HD-PLC	Up to several hundred Mbps	1.8–250 MHz	Several km
DSL	ADSL	800 kbps Upstream and 8Mbps Downstream	25 kHz-1 MHz	5 km
	HDSL	2 Mbps		3.6 km
	VHDSL	15-100 Mbps		1.5 km

F. Dahunsi et al., "Communication Network Simulation for Smart Metering Applications: A Review", in Journal of Innovative Science and Engineering (JISE) · March 2021

TÉCNICO LISBOA

DLMS/COSEM

- **Device Language Message Specification (DLMS):** a generalized concept for abstract modelling of communication entities. It is maintained by the DLMS User Association located in Switzerland and has been adopted by IEC as IEC 62056 series of standards.

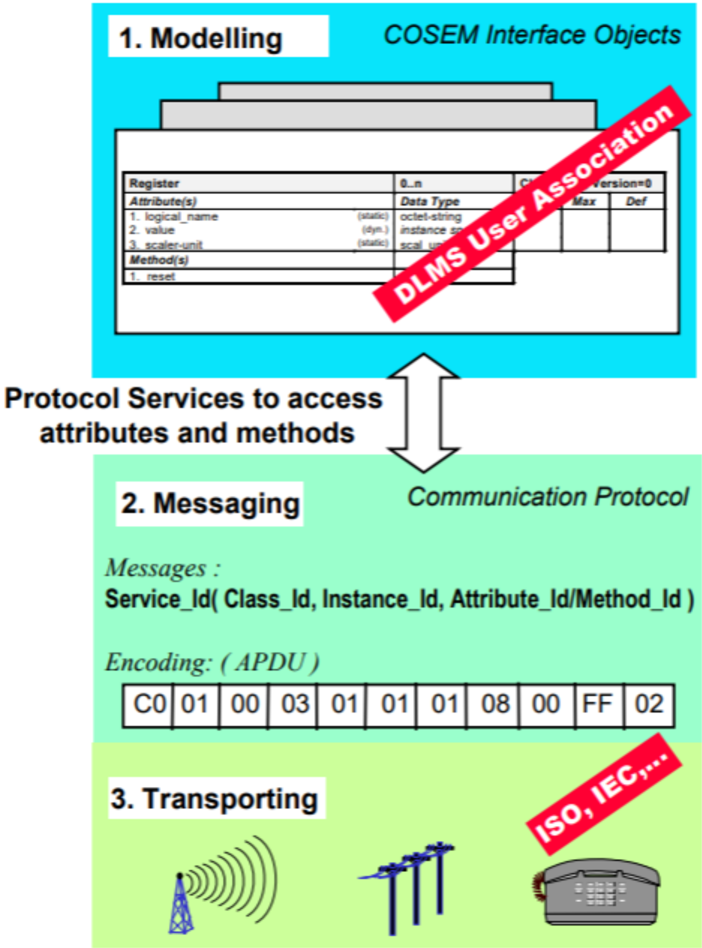
- **Companion Specification for Energy Metering (COSEM):** specifies the Interface Model and Communication Protocol for data exchange with energy meters and usable for all energy industry areas, including Electricity, Gas, water and Oil. It defines the Transport and Application Layers of the DLMS protocol.

DLMS/COSEM

- The DLMS/COSEM specification follows a three step approach:
  1. Modelling: Identification of the appropriate object codes (known as OBIS Codes) that identify the specific quantity and then choose the appropriate Interface Class that represents that quantity.
  2. Messaging: Mapping of available services to Protocol Data Units.
  3. Transportation: Transportation of messages through the communication channel.

TÉCNICO LISBOA

DLMS/COSEM



DLMS/COSEM

- Object Identification System (OBIS) names used for:
  - Identification of COSEM objects for communication.
  - Identification of COSEM object data for LCD display on meter.
- OBIS uses 6 value groups in a hierarchical structure:

A	Identifies the energy type measured, A=1 indicates Electricity meter
B	Identifies the measuring channels, Value=1..255
C	Identifies the physical quantity measured (C=32 Voltage, C=31 Line Current, etc.)
D	Identifies the processing methods (D=7 instantaneous, D=8 integrated over a period, etc.)
E	Identifies classification (E=1 Rate register 1, etc.)
F	Identifies historical values (F=101 History, F=255 not used, etc.)

Advanced Metering Infrastructure (AMI)

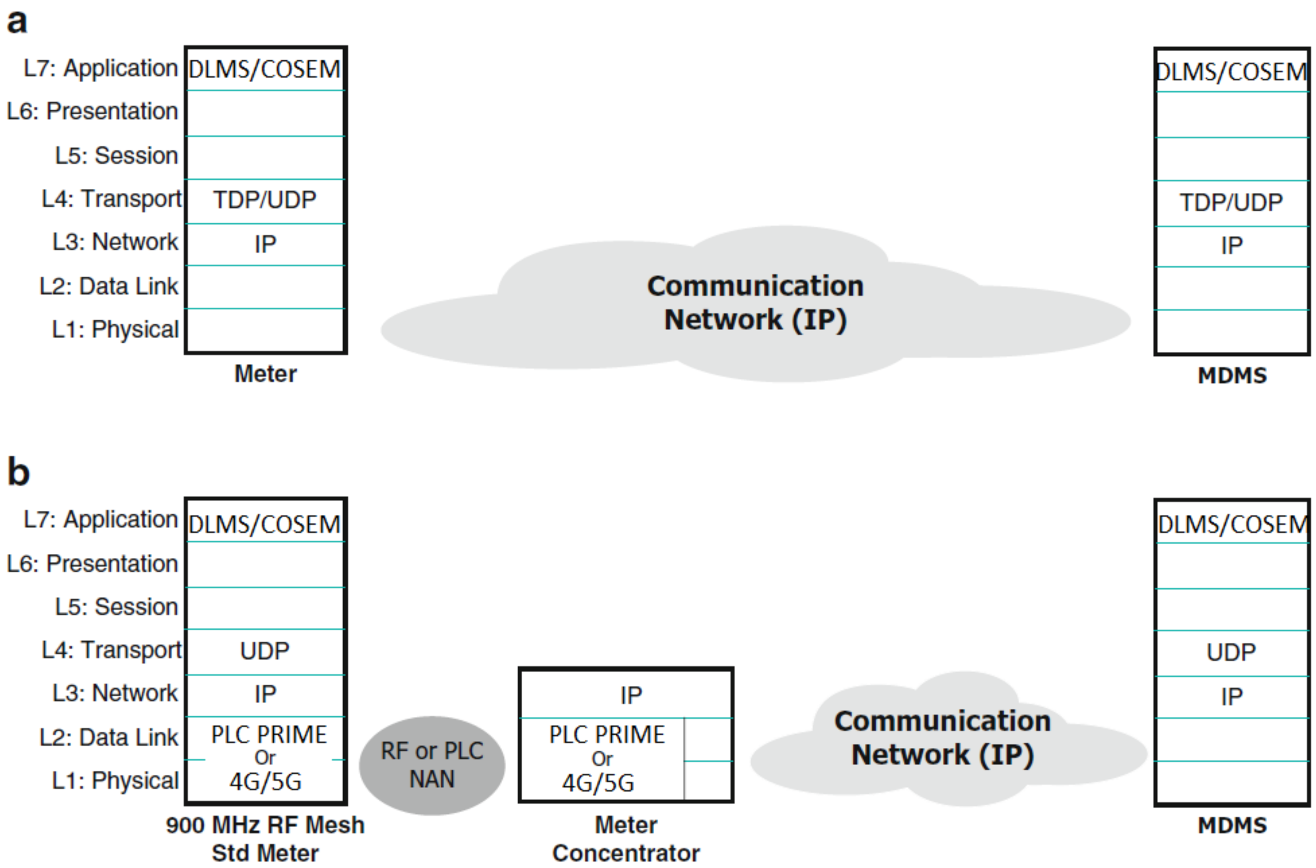


Fig. 5.3 Standards-based network for AMI. (**a**) Direct meter-MDMS connection. (**b**) Meter-MDMS connection through meter concentrator

Advanced Metering Infrastructure (AMI)

- Communication technologies for AMI:
  - Neighbothood Area Network (NAN)
    - Narrowband Power Line Communication (PLC), e.g. PLC PRIME
    - RF Mesh, e.g., IEEE 802.15.4
    - LoRaWAN
  - Wide Area Network (WAN)
    - GPRS
    - LTE/LTE-A
    - LTE-M
    - NB-IoT
    - 5G…

Advanced Metering Infrastructure (AMI)

SCADA
Substation Automation
AMI
Distributed Automation
Distributed Generation
Distributed Storage
Electric Vehicle
Volt, VAR, Watt Control in DS
WASA&C
Energy Markets
ADR

- Communication technologies for AMI:
  - Neighborhood Area Network (NAN)
    - Narrowband Power Line Communication (PLC), e.g. PLC PRIME
    - RF Mesh, e.g., IEEE 802.15.4
    - **LoRaWAN**
  - Wide Area Network (WAN)
    - GPRS
    - LTE/LTE-A
    - **LTE-M**
    - **NB-IoT**
    - 5G…

Distribution Automation (DA)

- DA in the strict sense:
  - Excludes AMI.
  - Excludes SCADA control of distribution substations.
- Device types monitored and/or controlled by DA:
  - Reclosers
  - Switches
  - Capacitor banks
  - Distribution transformers
- Each device is coupled with an IED.
  - Performs local monitoring and control.
  - Communicates with the DA master control at the DCC.
    - Directly or through concentrator at substation.
    - Same technologies a for AMI.

Distribution Automation (DA)

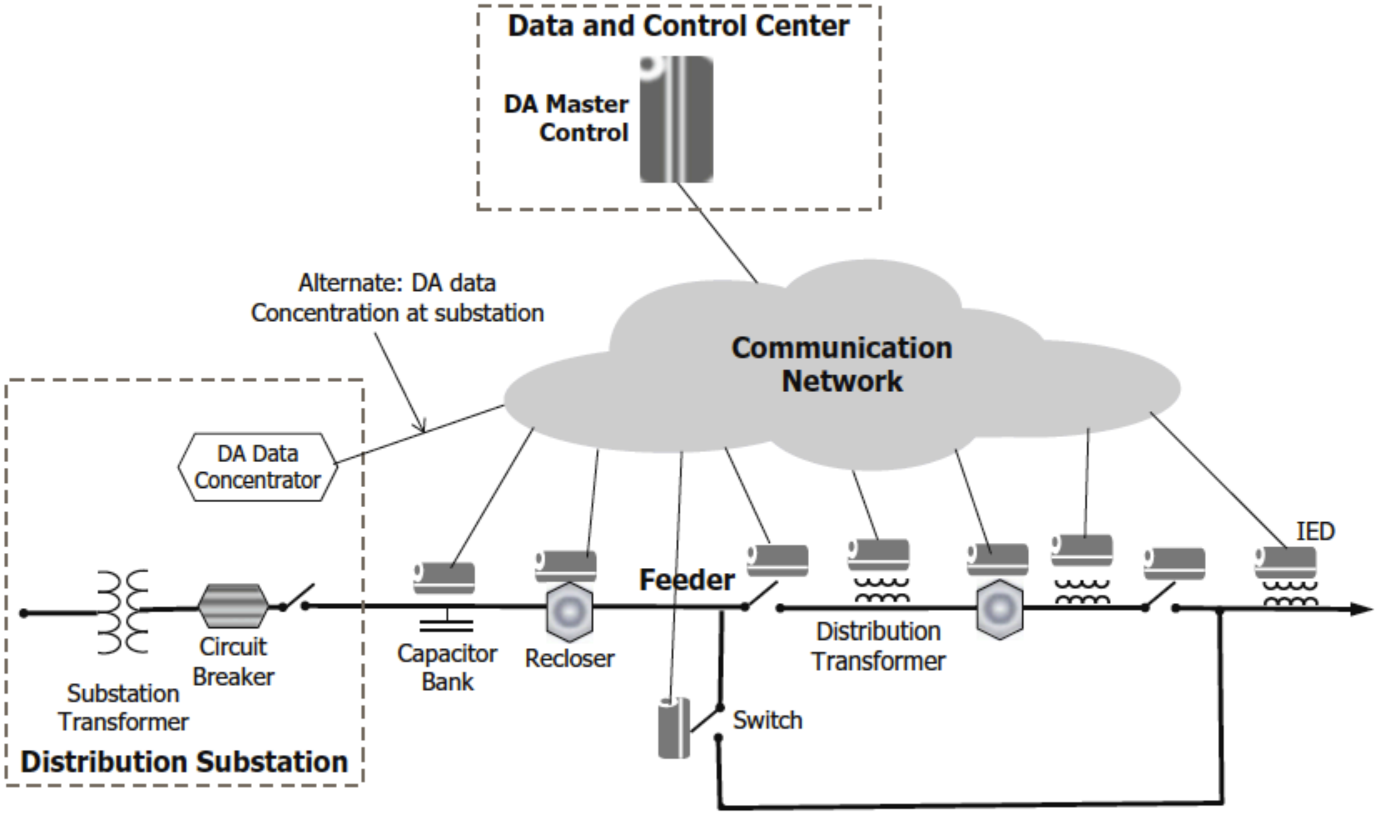


Fig. 5.4 Examples of feeder devices included in distribution automation

TÉCNICO LISBOA

Distributed Generation (DG)

- Power generations resources connected into the utility distribution system:
  - At consumer locations:
    - Tens to hunderds of kW;
    - Partly consumed locally;
    - Excess power made available to the grid.
    - Two metering options:
      - Single meter;
      - Two meters (drawn from the grid + supplied to the grid).
    - Pricing for the energy can vary based on the direction of the power flow as well as other considerations such as time of the day and pricing determined by the retail energy markets in the future.
  - Stand-alone DG plants:
    - Many MW;
    - The energy price may be set by the market (including the retail energy market) and/or in real time based on the utility need for demand response.

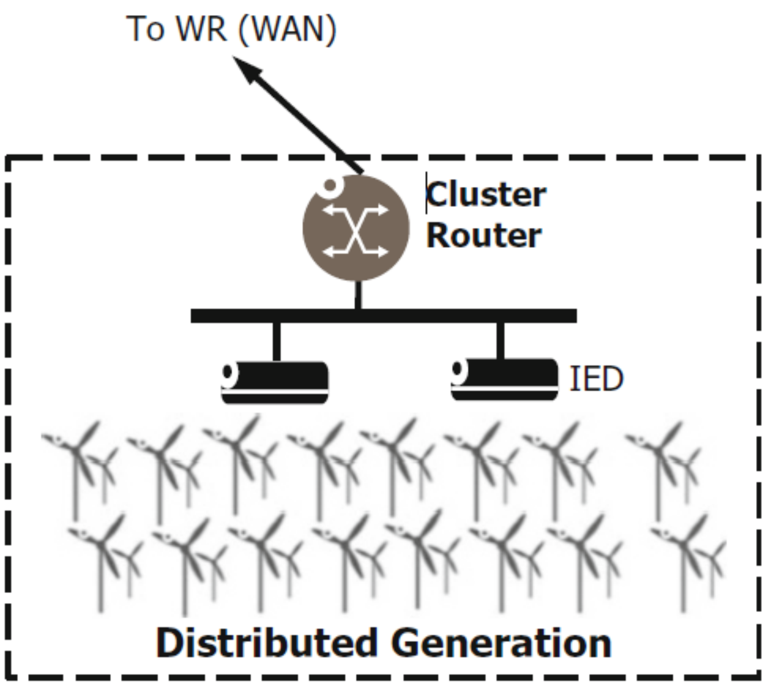
TÉCNICO LISBOA

Distributed Generation (DG)

- Functions:
  - Remote monitoring and control are needed to automatically disconnect (and reconnect) the DG–grid connection when necessary.
  - Electrical quantities are monitored and controlled so that they stay within their individual operation limits.
  - In the event of short circuits and ground faults, including scenarios in which the DG source feeds into the short circuits, the connection between the DG and the grid must be tripped. Therefore, relays and/or circuit breakers are deployed at DG–grid connection points.
  - System balancing is currently used to manage bulk energy sources. Ancillary services provide the necessary remedial measures for system balancing for bulk energy sources. These services include reactive power supply, voltage regulation, and frequency regulation.
  - "Intentional" controlled islanding in case of power outages.

Distributed Generation (DG)

- Communication between DCC and DG:
  - IEC 61850
  - Modbus / Modbus Sunspec
  - 60870-5-104

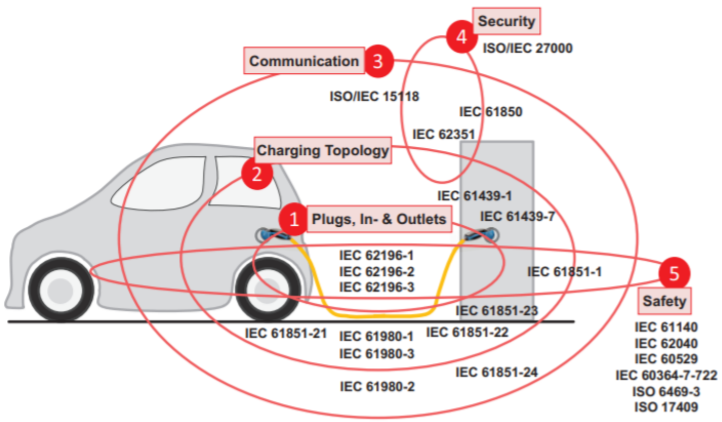


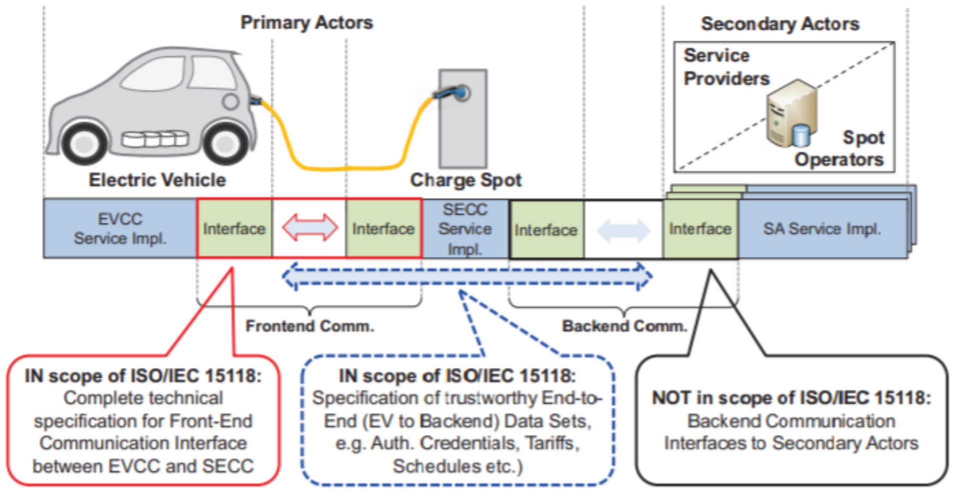
Distributed Storage (DS)

- DS refers to an electric energy storage device connected to the grid that is able to store electric energy received from the grid (charging) and deliver the stored energy to the grid (discharging) when necessary:
  - Batteries
  - Flywheels
  - Supercapacitors
  - Pumped hydro
- The communication networking requirements associated with managing the grid connection for storage are similar to those associated with managing DG.
- Communication protocols:
  - CAN bus (for local storage device management).
  - IEC 61850
  - Modbus / Modbus Sunspec
  - 60870-5-104

Electric Vehicle (EV)

- Frontend communication:
  - IEC 61851: IEC 61851-1 specifically defines a safety-related low level signalling process based on a Pulse Width Modulation (PWM) signal indicating various EV connection states, supported charge currents and communication means.
  - ISO/IEC 15118: defines a bidirectional, secure, IP-based communication protocol complementary to the low level signaling defined in IEC 61851-1.

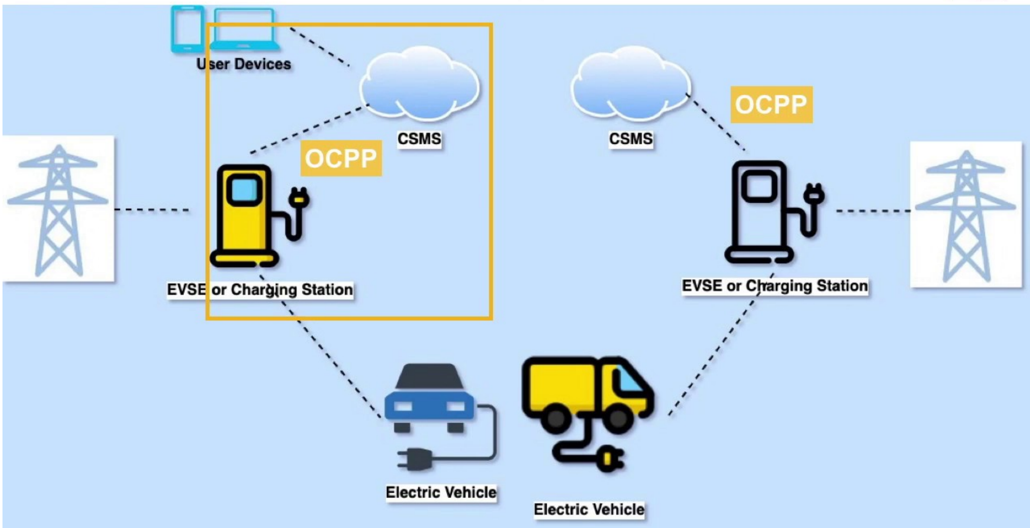




Electric Vehicle (EV)

- Communication with charging stations using Open Charge Point Protocol (OCPP), maintained by Open Charge Alliance.
  - Communication protocol that facilitates the exchange of information between an EV charger (Electric Vehicle Supply Equipment - EVSE) and its backend management system (Charging Station Management System - CSMS).
  - OCPP is an internationally adopted Open source standard.

Components of EV Charging Infrastructure



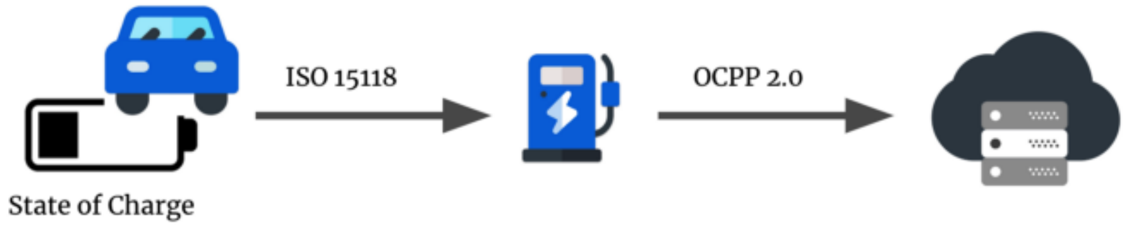
Electric Vehicle (EV)

- Examples of operations supported via the OCPP:
  - Start of charging operation, pre-authorisation is required to identify and allow the EV user to use the service.
  - Providing the charging session details to backend system, to calculate the charges.
  - User apps functionality to locate the charging stations and make reservations. Necessary data from charging session is transferred to CSMS.
  - Charging stations operators can the see real-time status of all charging equipment - e.g. which EVSEs are available, currently charging or suspended.
  - Remotely control the charging session - stop or start a charging event or change the status of a charger.
  - Upgrade firmware and configure the charging points. Read and repair errors logged by the EVSEs.

TÉCNICO LISBOA

Electric Vehicle (EV)

- End-to-end communication integrates frontend and backend protocols.



Volt, VAR, Watt Control in Distribution System

- The Volt, VAR, Watt Control (VVWC) function is responsible for ensuring that various electric quantities at different points in the utility grid remain within acceptable operational ranges.
  - Regulating Voltage (V) values;
  - Adapting the reactive power (VAR) for power factor regulation;
  - Controlling the overall power (W) delivered through the grid.
- The VVWC functions are required in both the transmission system and the distribution system.
- VVWC may collect measurements from a variety of sources including SCADA, DA, DG, DS, and AMI over the respective FAN connections.
- The VVWC function, in turn, sends control messages to the monitoring and control systems to regulate voltages, reactive power, and (active) power.

Volt, VAR, Watt Control in Distribution System

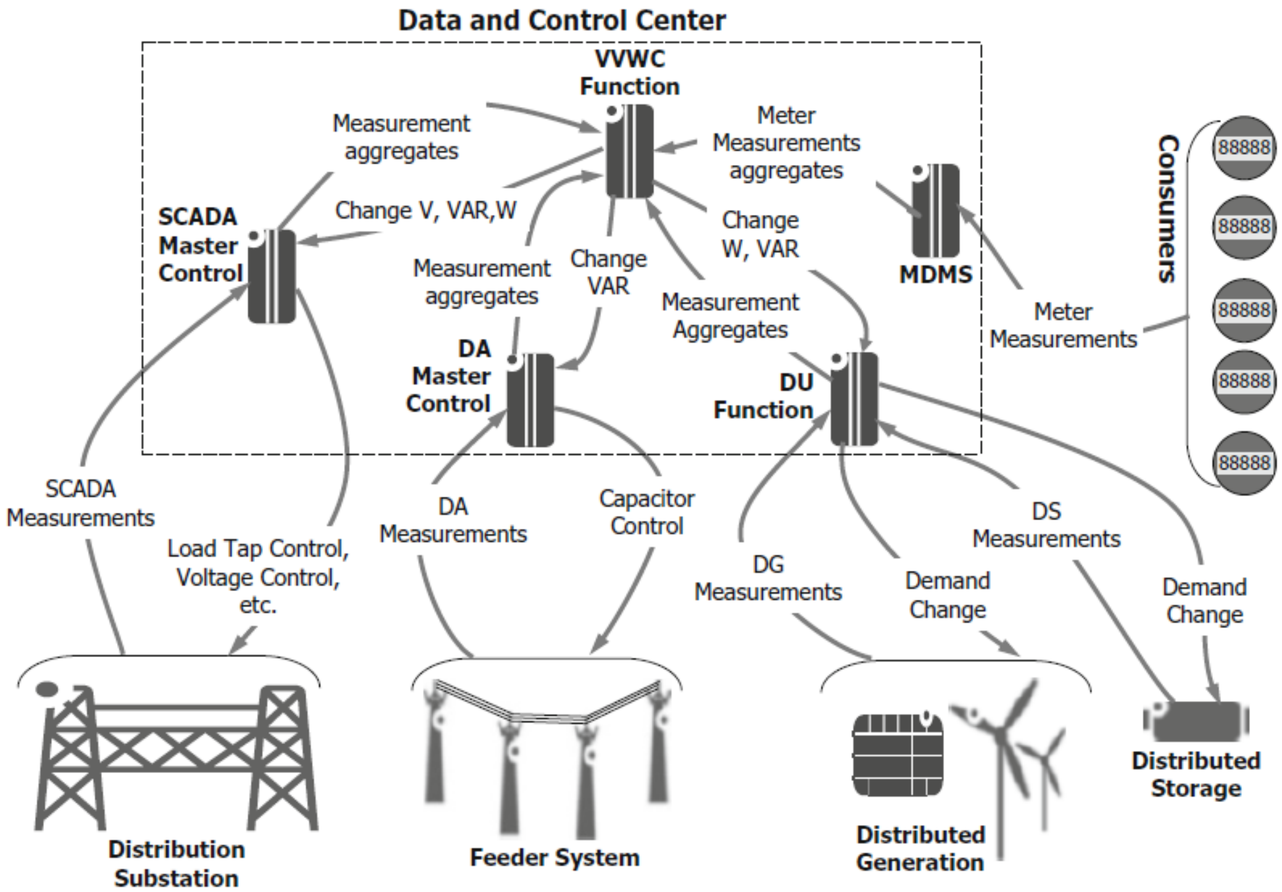


Fig. 6.14 Logical end-to-end connection for VVWC in utility distribution system

Wide Area Situational Awareness and Control

- The WASA&C system may be located at the regional authority.
  - The regional authority is responsible for WASA&C of the regional grid and for the interconnection of the utility grids in their service area.
  - Other monitoring centers may also play a role in management and control.
  - The WASA&C systems may use power system state estimates derived from PMU / synchrophasor measurements.
  - The WASA&C systems may send control signals to utility TMSs, where any control action (including protection) must be initiated.
  - In some cases, it may be necessary to send control signals to the bulk power generation source(s).

Wide Area Situational Awareness and Control

- Phasor Measurement Units (PMUs):
  - Measure phasor values (amplitudes and phase) of voltages and currents at extremely high frequency.
    - 50 or 60 times per second for power systems with line frequencies 50 and 60 Hz, respectively.
  - All measurements are time-stamped using a clock that is synchronized to the Global Positioning System (GPS).
  - With synchronized timestamping, PMUs are called **synchrophasors**.
  - Each phasor such as $V \angle\varphi$ is reported as a pair of two numbers $\sqrt{2V}$ and φ , or as its real and imaginary parts V1 and V2.
  - PMUs can be considered advanced IEDs.
- In the future, the Phasor Measurement Units (PMUs) may be deployed in the distribution system to better manage power quality, particularly with large-scale deployment of Distributed Generation.

Wide Area Situational Awareness and Control

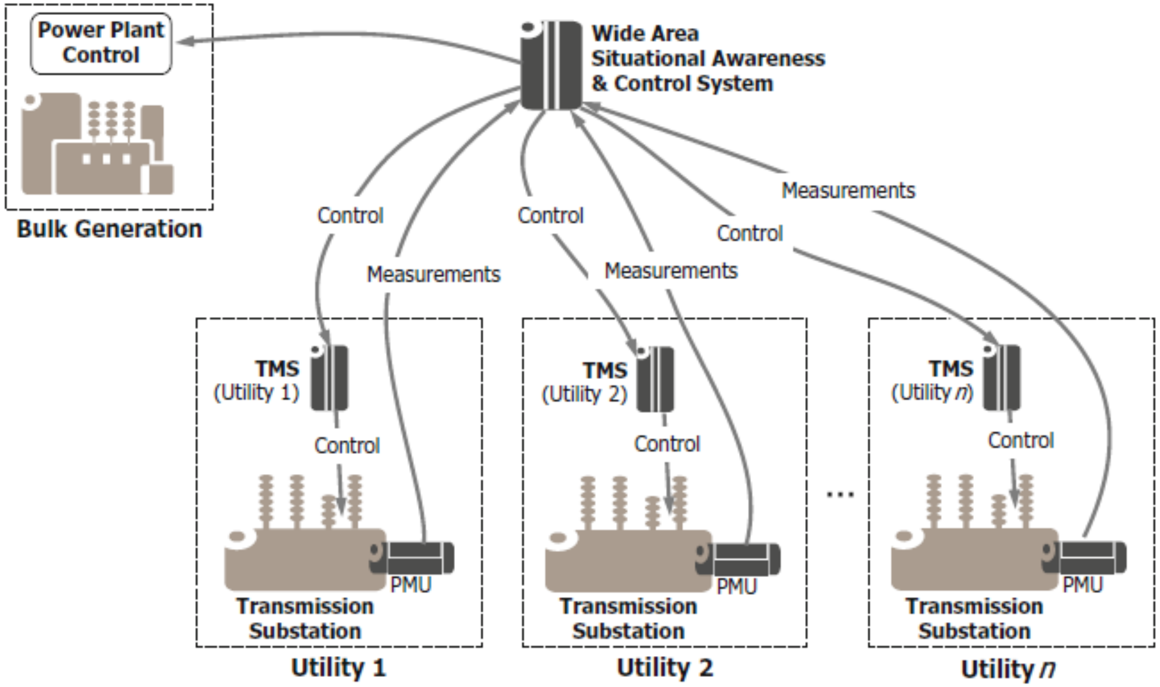


Fig. 6.15 Logical end-to-end connection for WASA&C

Energy Markets

- The IEC TC 57 (Power System Management and Associated Information Exchange) is currently developing the IEC CIM 62325 series of standards for the exchange of data required by deregulated energy markets.
  - IEC 62325-301 "CIM extensions for markets" standard, which is an abstract model that caters for the introduction of the objects required for the operation of electricity markets;
  - IEC 62325-450 "Profile and context modelling rules," the International Standard for the generation of profiles.
- WG 16 (Deregulated Energy Markets) is developing these standards as a framework for energy market communications encompassing two market styles: European style and North American style markets.
- The IEC 62325-351 "CIM European market model exchange profile" International Standard, and the IEC 62325-451-'X' set of standards, which are built on this CIM profile, are being maintained and further developed, notably for Europe's internal electricity market (IEM).
- The European style market profile (ESMP), as defined in IEC 62325-351, provides the core components for use in the IEC 62325-451-'X' standards, which target specific core business processes within Europe's internal electricity market, such as scheduling, settlement, capacity allocation and nomination, acknowledgement, etc.

Energy Markets

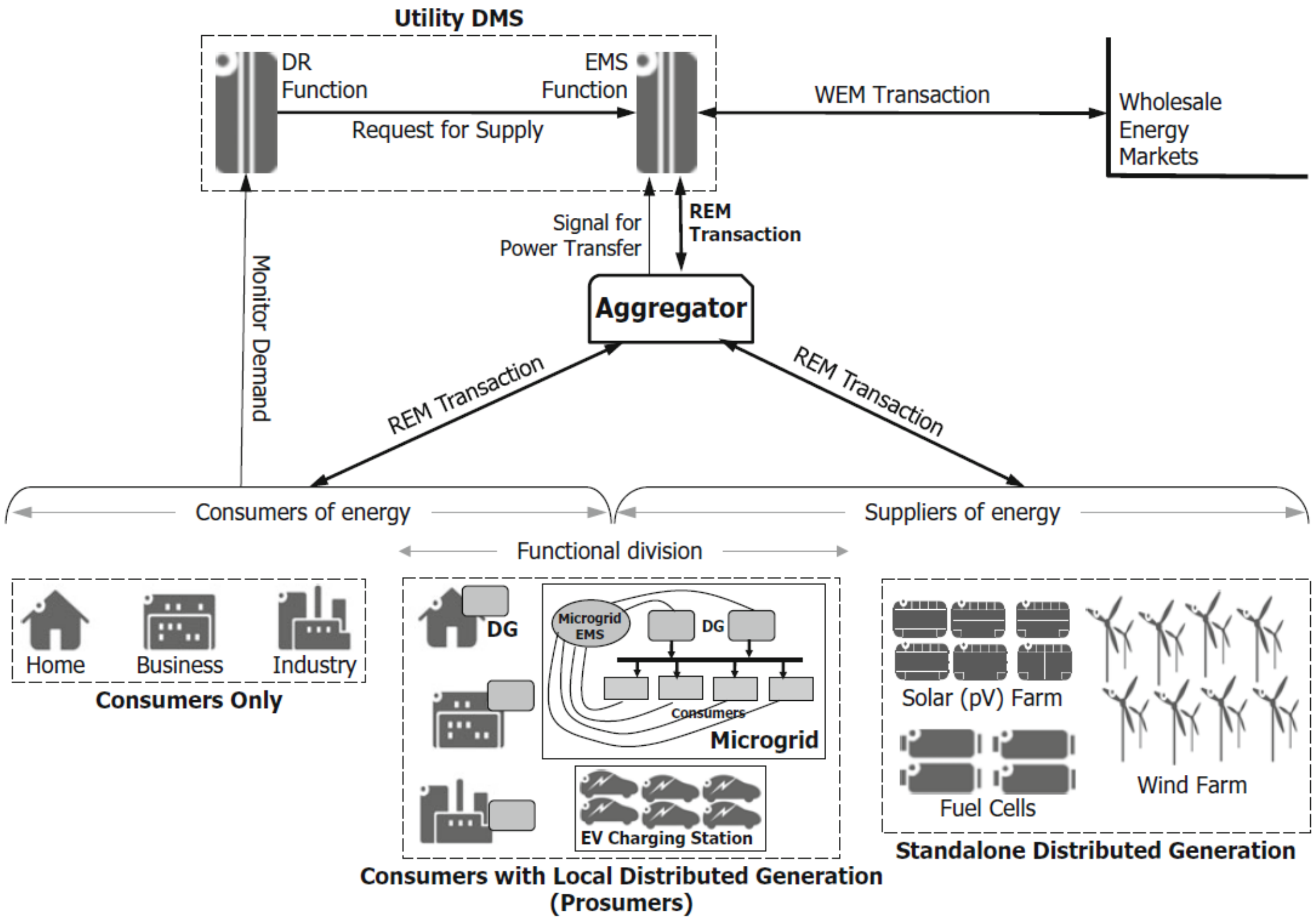


Fig. 5.7 Retail energy market concept

Automated Demand Response (ADR)

- When overall demand for energy exceeds supply, a utility may invoke demand response mechanisms.
- With the advent of home energy management systems (HEMS), DR can be automated with real-time communication between the utility EMS (UEMS) and HEMS over a communication network.

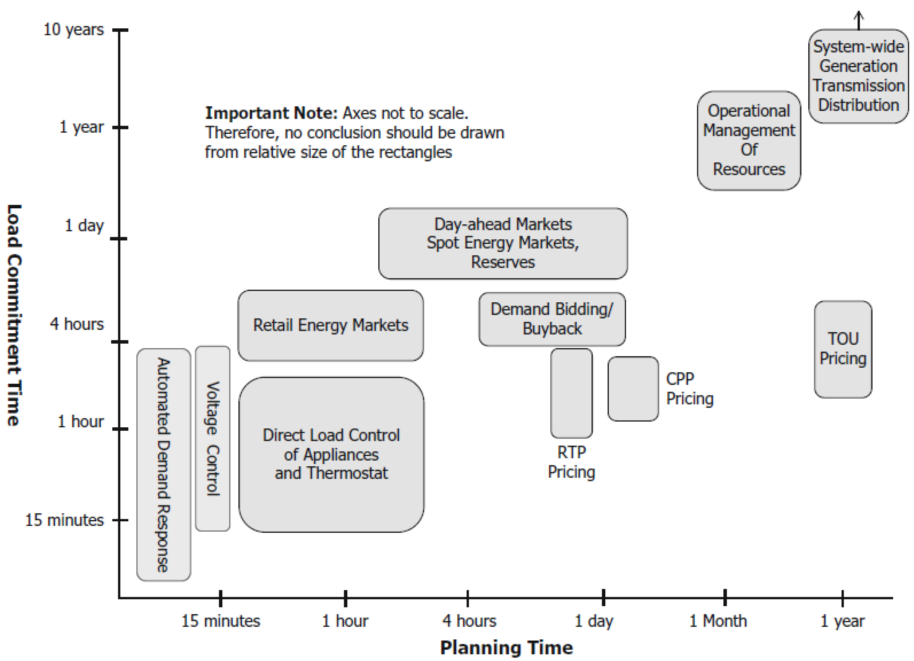


Fig. 5.8 Demand response methods

Automated Demand Response (ADR)

- The Open ADR Alliance has developed “OpenADR” standards.
  - Communication between the utility and the consumer.
  - OpenADR communication is based on IP connectivity between the two entities (e.g., HTTP).
  - OpenADR may be supported over the Internet if acceptable to the utility and the consumer.
- Two different connection options for supporting communication between the utility EMS and the consumer EMS:
  1. Connect to the UEMS over an IP connection from the home gateway:
     - If the Internet is used for communication, the utility may need to provide a security apparatus.
  2. Connect the smart meter into the HAN:
     - ADR signals between the two EMSs pass through the meter.
     - Meter vendors have provided interfaces such as Ethernet and ZigBee to connect meters to an HAN.
     - Due to security concerns, many utilities do not favor this option.
  3. The utility may outsource ADR management to a third-party energy management service.
     - The third party may relay the ADR signals to the consumer EMS (such as the HEMS) over the Internet.

Automated Demand Response (ADR)

- The consumer EMS must take appropriate action, shutting off or scheduling appliance operations and/or increasing the supply from the local DG.
- The EMS communicates with these local entities over the HAN or local LAN.
  - Note that the WAN, several FANs, possibly a NAN, possibly an extranet connection (through the Internet), and a HAN are used to achieve these logical connections.

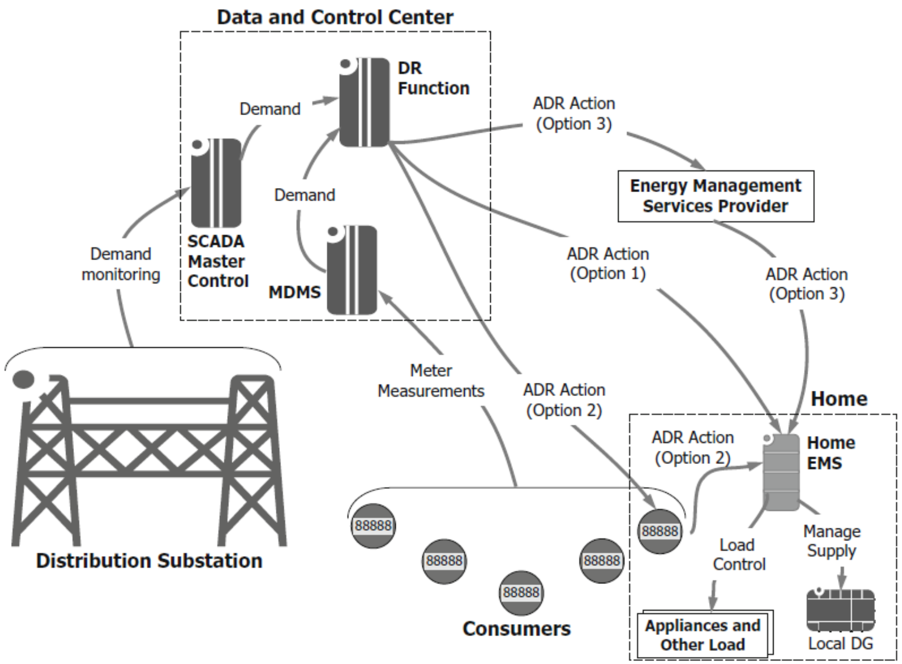


Fig. 6.13 Logical end-to-end connection for ADR