Sensor networks for industrial applications

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Research activity on electronic systems for sensors and industrial automation.

- Industrial Communications
- Synchronization
- Smart sensors and wireless sensors
- Instrumentation and electronic nose

Main technologies and standards:
IEEE1588, Profinet, WirelessHART, Software Defined Radio, IEC61850

eSSS
embedded Systems and Smart Sensors

OUTLINE

- Sensors and Smart sensors for industrial applications
- The "real-time" constrain
- Trend of sensor networks for industry:
  from fieldbuses to the Real Time Ethernet
- Wireless sensor networks for industrial applications
- Challenges: Software defined radio
- New trends: Smart grids and Internet of things under the industrial point of view

AUTOMATION

Courtesy of Prof. Dr. H. Kirrmann, EPFL

5 { Planning, Statistics, Finances

4 { Production planning, orders, purchase

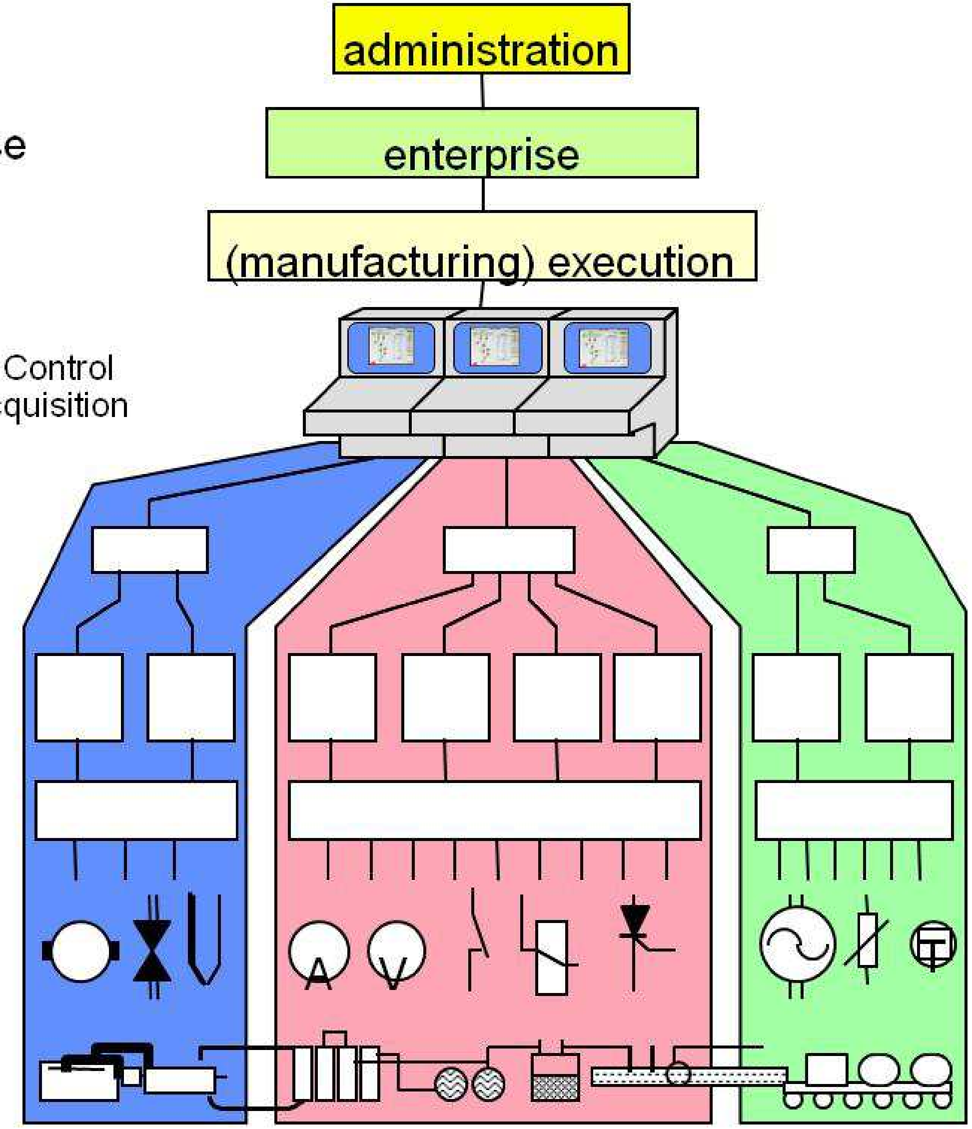
3 { Workflow, order tracking, resources

2 { Supervisory

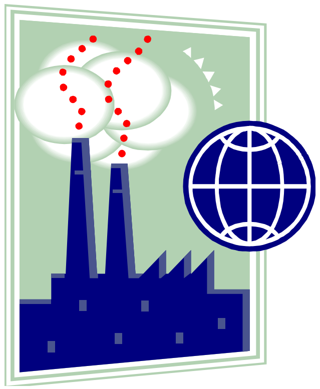
1 { Group control (Area)
Unit control (Cella)
Field
Sensors
& actuators

0 { Primary technology

SCADA =
Supervisory Control
And Data Acquisition



SENSORS AND ACTUATORS AT THE FIELD LEVEL



Society

Enterprise

Trends & History = Brain

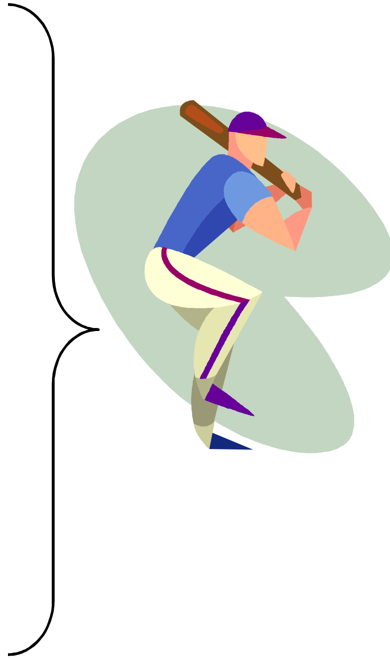
Display and react = Cortex

Communication networks = neural, spine

controller = ganglions

Sensors & Actors = Sense cells & muscles

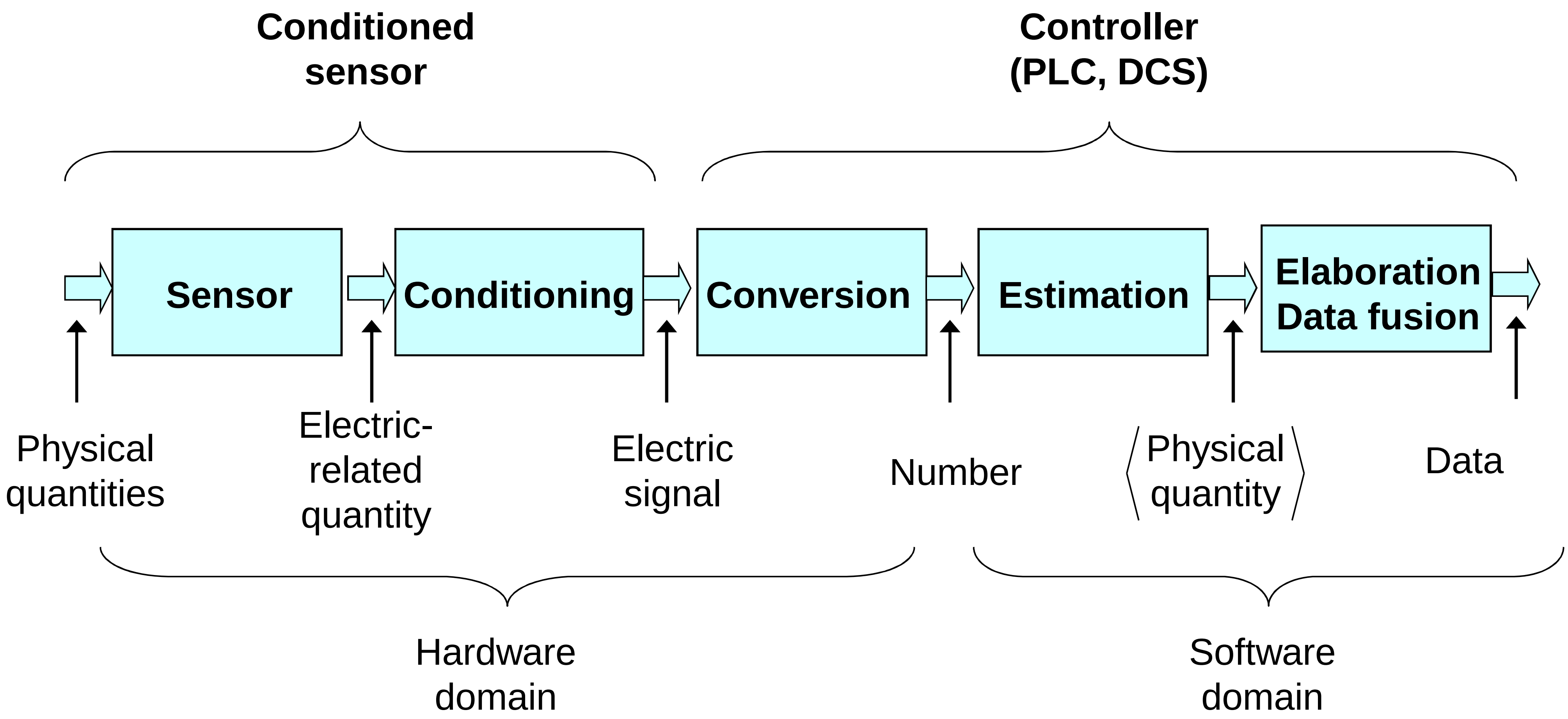
Automation = the neural system



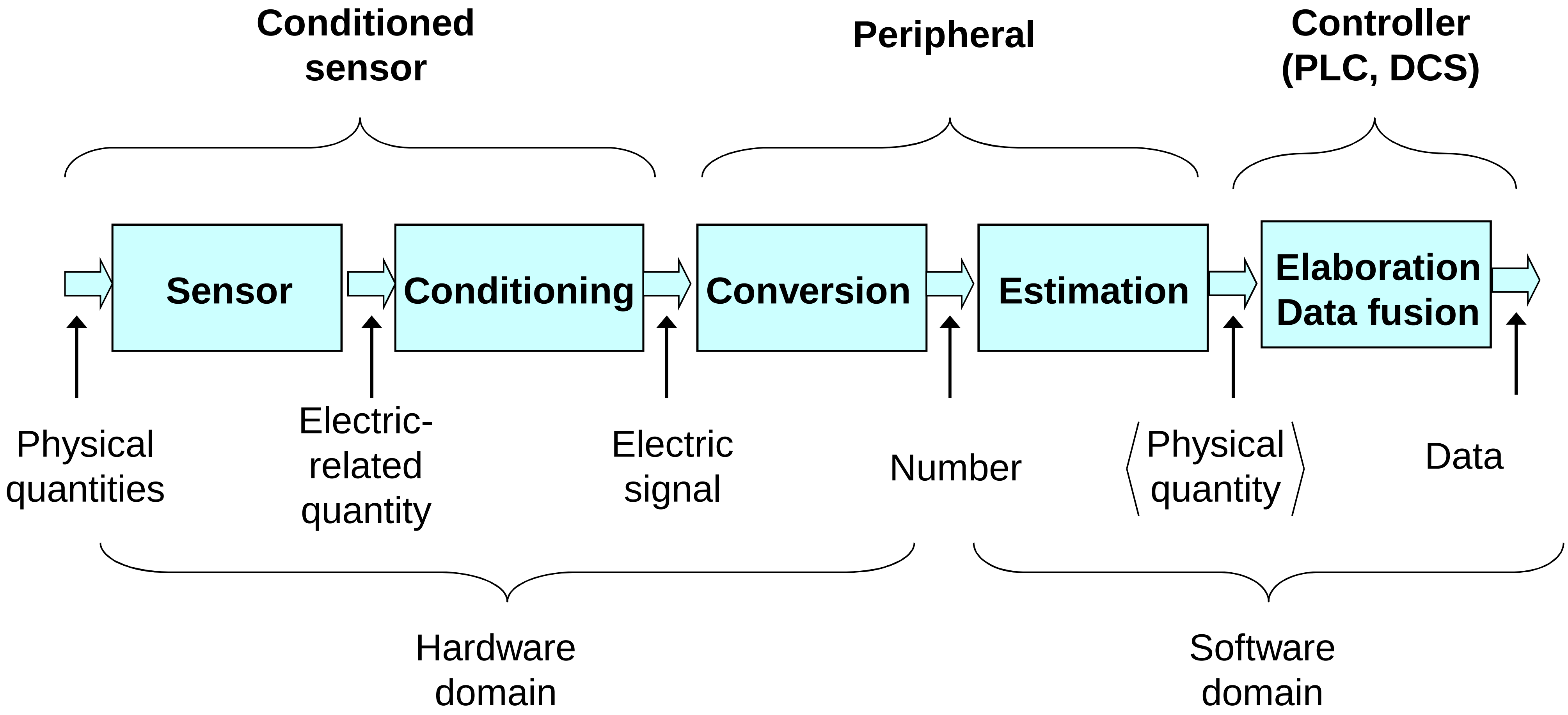
physical plant = skeleton

Courtesy of Prof. Dr. H. Kirrmann, EPFL

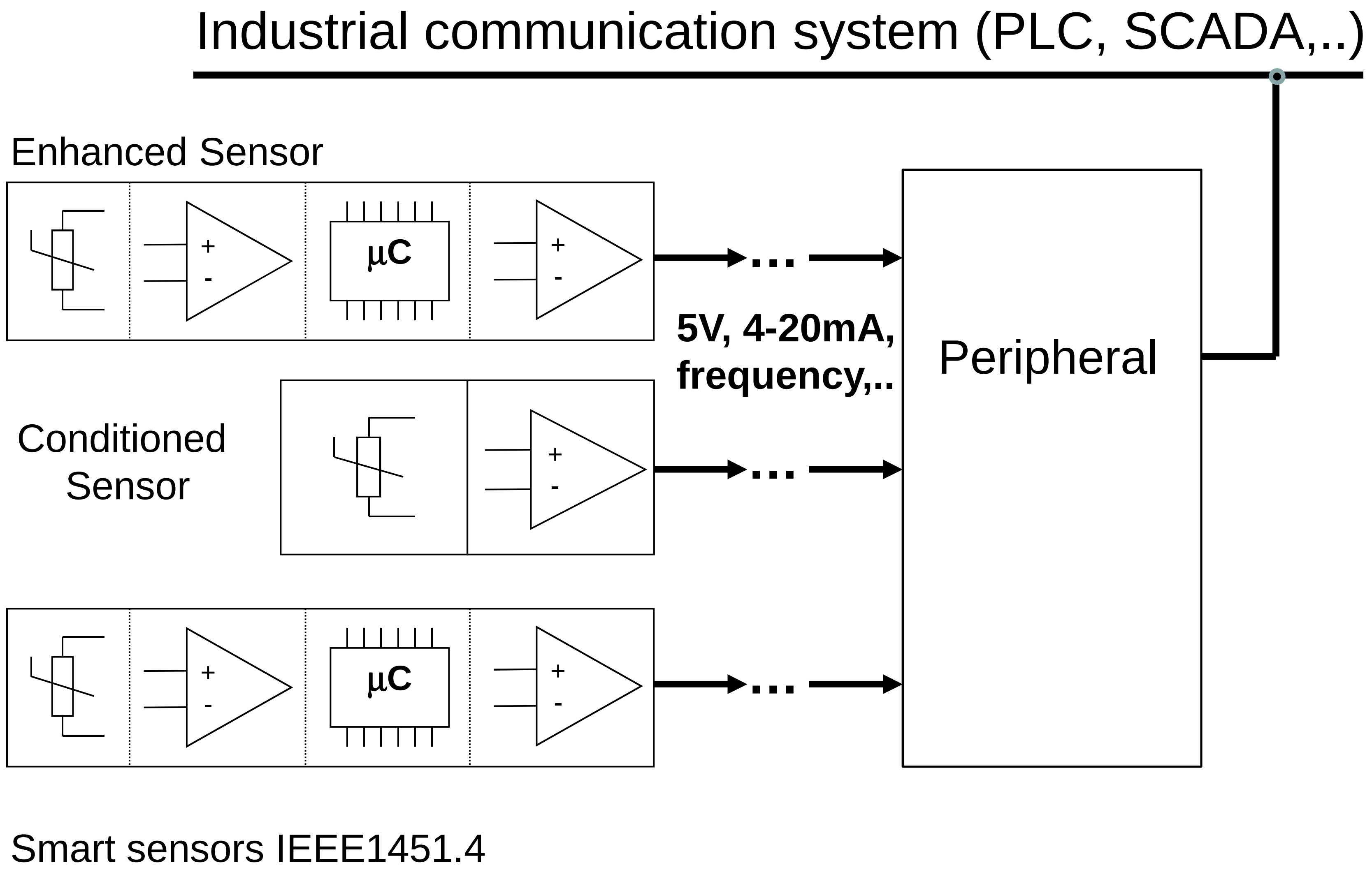
SENSORS AND CONTROLLERS



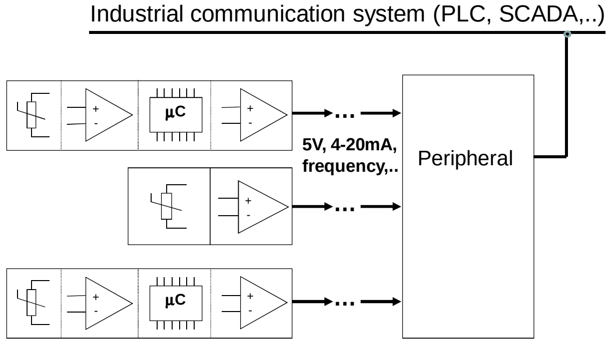
SENSORS, PERIPHERALS AND CONTROLLERS



SENSORS ARE NORMALLY INTERFACED TO CONTROLLERS



WHAT'S "WRONG"?

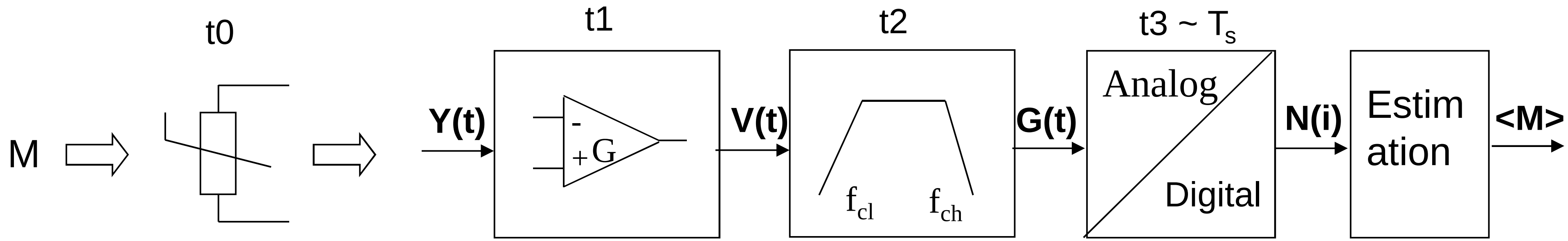


Information is reckoned by inverting the sensor characteristic (typically linear)

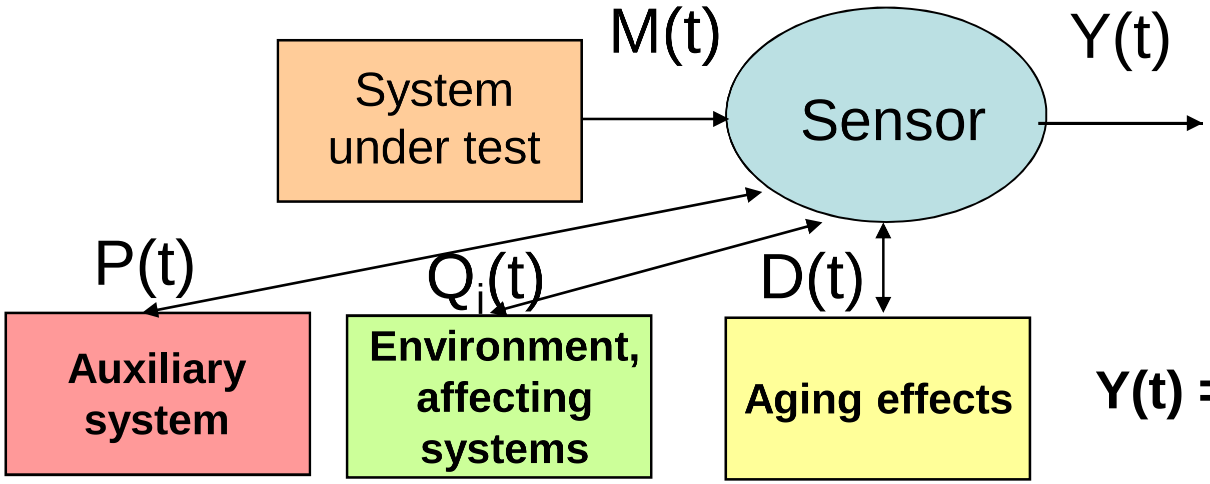
- No diagnostics (1 information = 1 wire)
- Heavy programming of peripheral (from the analog signal to the information in the correct measurement units)
- A sensor change implies reprogramming of the peripheral
- The high level system cannot identify sensors
- IEEE1451.4 suggests to download in the peripheral the sensor data sheet
- Some providers suggests to use an OPC server instead of the peripheral

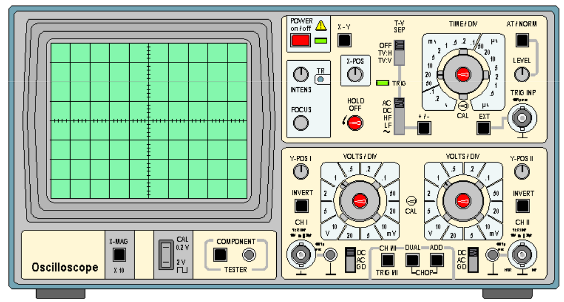
… programming and re-programming is a cost!

UNDERSTANDING “ESTIMATION”



$Y(t)=f(M(t),P(t),D(t),Q_0(t),Q_1(t),..)$ $G(t) \sim V(t-t2)=G_1 \cdot Y(t-t1-t2)+G_0$ $N(i)=g(G(i \cdot T_s-t3))$



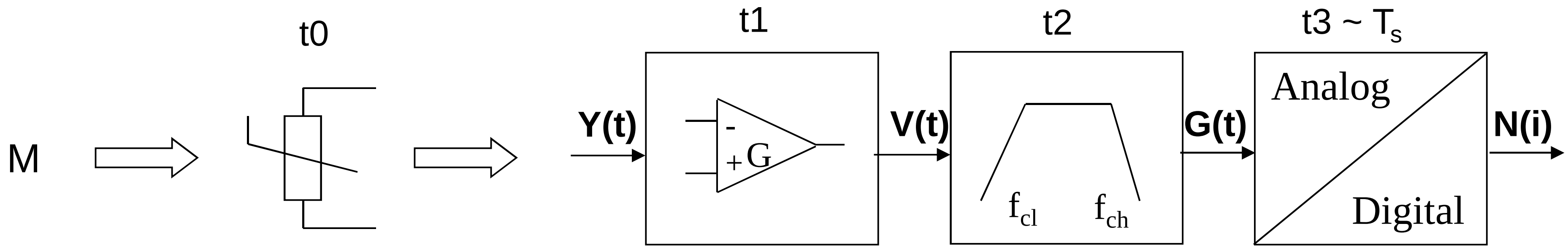


$Y(t) = f(M(t),P(t),D(t),Q_0(t),Q_1(t),..)$

Conditioning is normally a linear transformation (gain, offset) and a band-pass filter

Analog2Digital Conversion (B bit, Vrefh) is a linear transformation $N=int(2^B G/Vrefh)$

UNDERSTANDING “ESTIMATION”



$Y(t)=f(M(t),P(t),D(t),Q_0(t),Q_1(t),..)$ $G(t)\sim V(t-t2)=G_1\cdot Y(t-t1-t2)+G_0$ $N(i)=g(G(i\cdot T_s-t3))$

- The numeric sequence N(i) depends on measurand M. If $Y(t) = m\cdot M(t)+q$ then

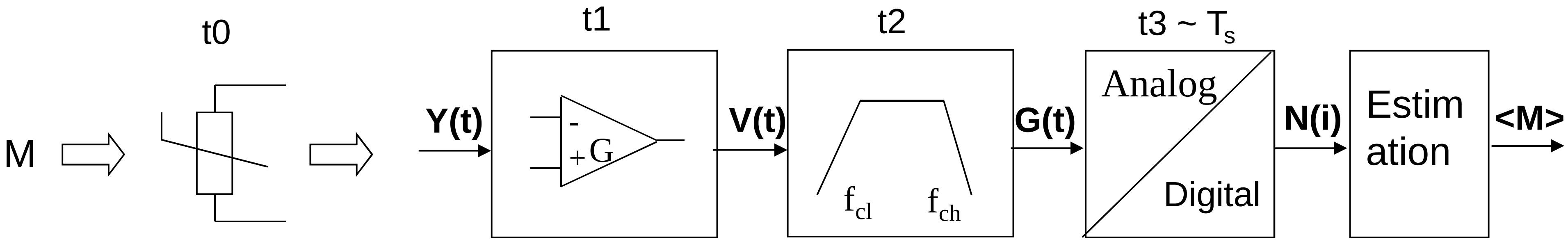
$$N(i)=Integer\left[2^B\frac{G(i\cdot T_s-t_3)}{V_{refh}}\right]=Int\left[2^B\frac{G_1\cdot Y(i\cdot T_s-t_1-t_2-t_3)+G_0}{V_{refh}}\right]=Int\left[2^B\frac{G_1\cdot f(M(i\cdot T_s\overbrace{-t_0-t_1-t_2-t_3}^{t_d}))+G_0}{V_{refh}}\right]$$

$$N(i)=Int\left[2^B\frac{G_1\cdot m\cdot M(i\cdot T_s-t_d)+G_1\cdot q+G_0}{V_{refh}}\right]=Int\left[\frac{2^B\cdot G_1\cdot m}{V_{refh}}M(i\cdot T_s-t_d)+\frac{2^B(G_1\cdot q+G_0)}{V_{refh}}\right]$$

$$N(i)=Int\left[\alpha\cdot M(i\cdot T_s-t_d)+\beta\right]$$

- **Quantization effect (value and time)**

UNDERSTANDING “ESTIMATION”



Y(t)=f(M(t),P(t),D(t),Q_0(t),Q_1(t),..) G(t)~V(t-t2)=G_1·Y(t-t1-t2)+G_0 N(i)=g(G(i·T_s-t3))

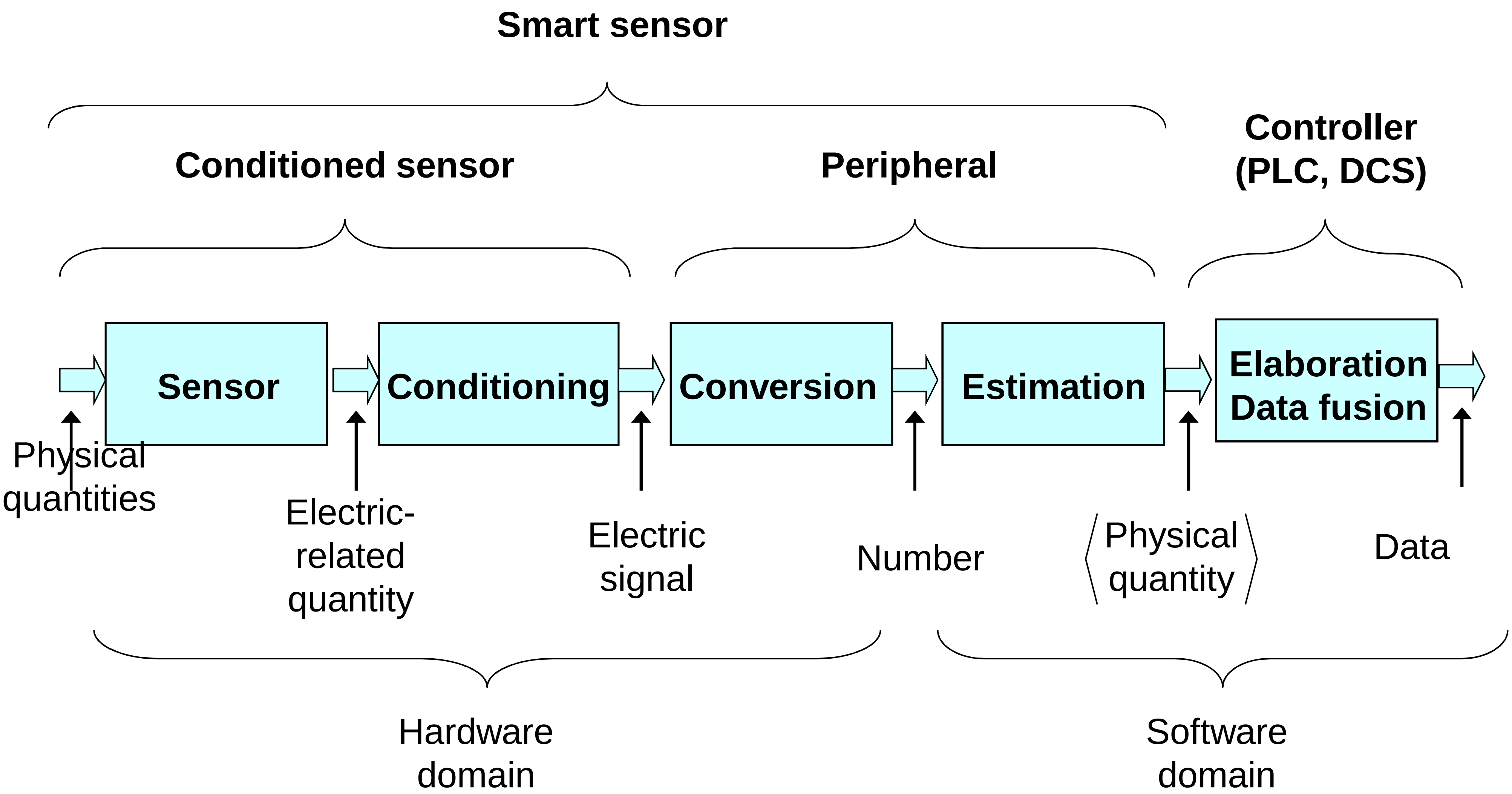
$$N(i) = Int\left[\frac{2^B \cdot G_1 \cdot m}{V_{refh}} M(i \cdot T_s - t_d) + \frac{2^B (G_1 \cdot q + G_0)}{V_{refh}}\right] = Int[\alpha \cdot M(i \cdot T_s - t_d) + \beta]$$

- The estimation of M is obtained by inverse conversion

$$< M(i \cdot T_s - t_d) >= \left[N(i) - \frac{2^B (G_1 \cdot q + G_0)}{V_{refh}}\right] \frac{V_{refh}}{2^B \cdot G_1 \cdot m} = [N(i) - \beta] \frac{1}{\alpha}$$

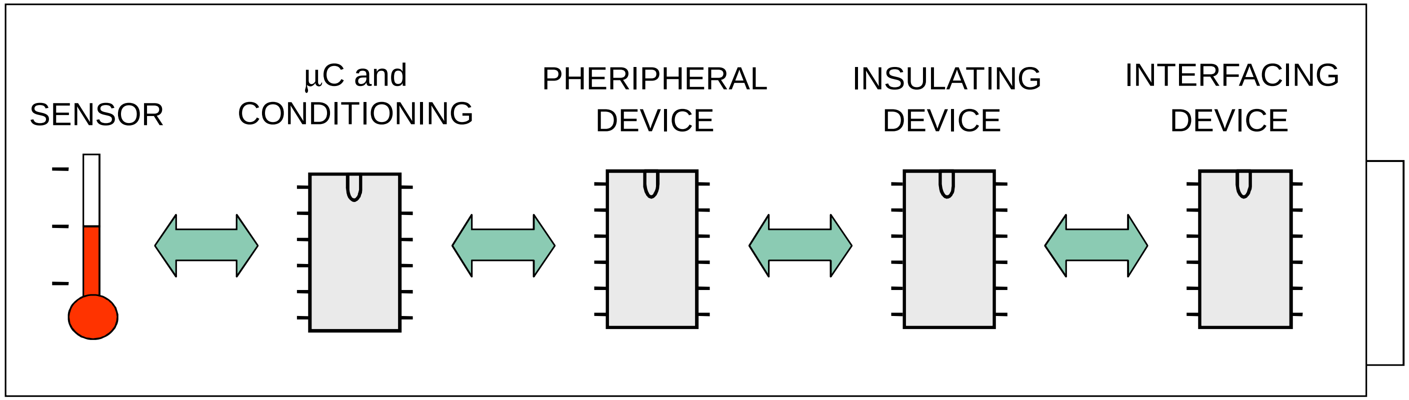
- … or by calibration (β and 1/α can be estimated by LMS calibration $\{N,M\}_i$)
- Noise (finite arithmetic) and delays due to estimation can be normally neglected

SENSORS AND SMART SENSORS



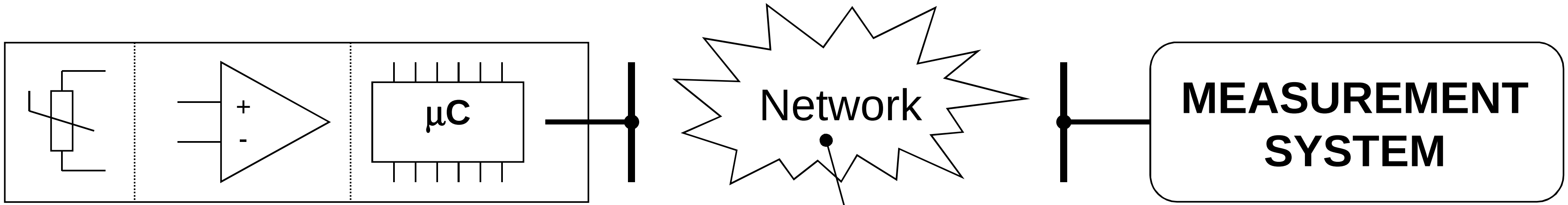
SMART SENSORS

The power/flexibility of DIGITAL TRANSMISSION = more information on 1 wire



SMART SENSOR

- Industrialized Units
- Qualified data
- Diagnostics
- “Plug&play”

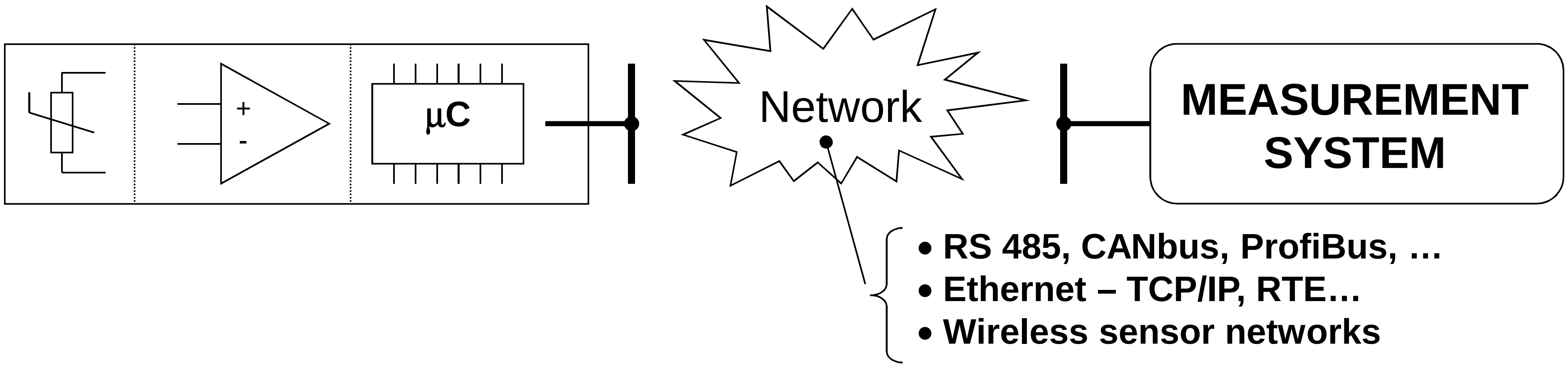


- **Fieldbus, USB, Ethernet, TCP/IP, …**
- **Wireless sensor networks**

IEEE1451 “Smart sensors”

The measurement quality is managed by the sensor (“a priori”, data sheet)

SMART SENSORS: A REAL SUCCESS?



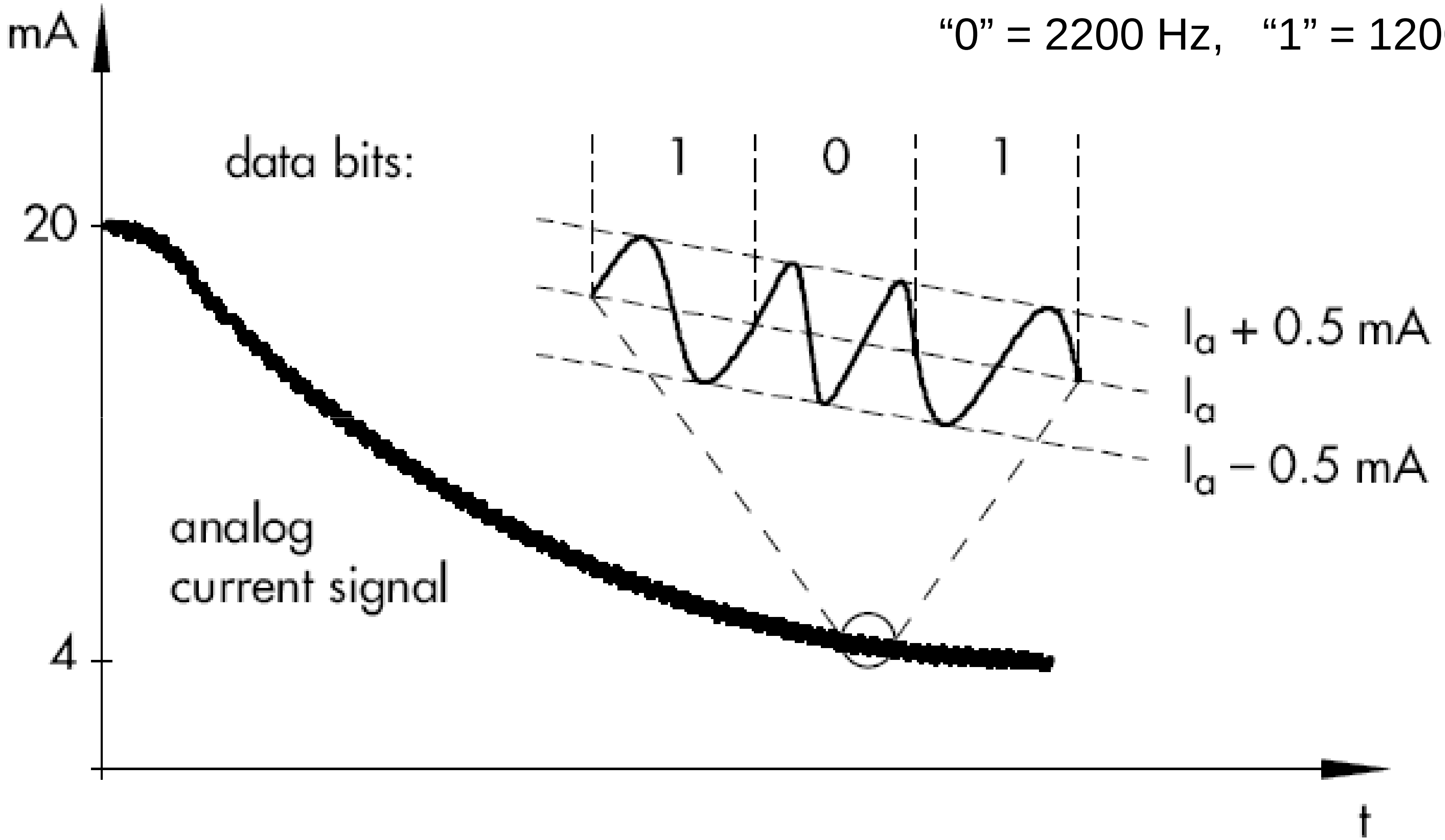
- Too many different communication networks
- Even if the network has been defined, managing a smart sensor is not so simple
- For this reason “smart sensors” are still not so widespread

REQUIRED SMARTNESS FOR INDUSTRIAL SENSORS

- Many sensors are very simple and only one information is useful during normal operating conditions
- Normal operating conditions come after a “warm-up” time
- “warm-up” is very important during commissioning or after a fault or a device replacement
- “warm-up” should include:
  - Identification of device
  - Computation of coefficients needed by estimation
  - Self-diagnostic of device
- In many cases “warm-up” requires a smart sensor while “normal operating conditions” not

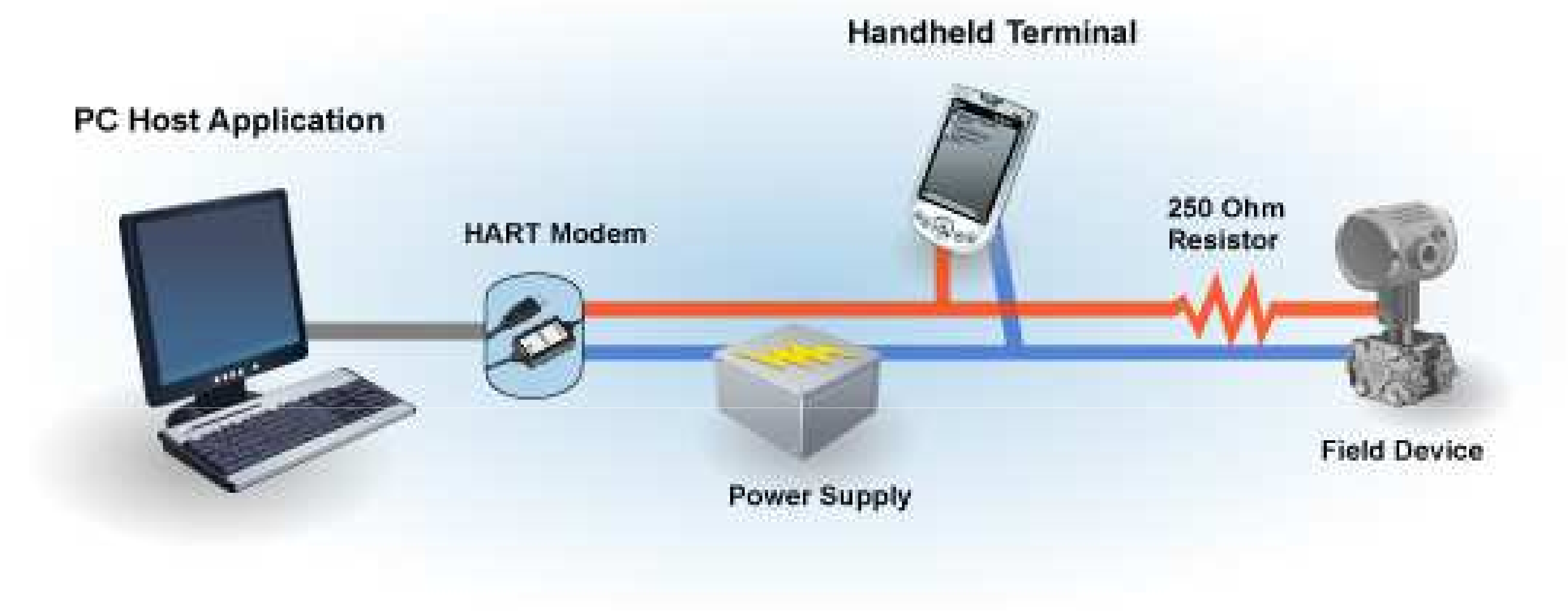
HART: MIXING OF TRADITIONAL AND SMART SENSOR

"0" = 2200 Hz,   "1" = 1200 Hz



Digital modulation can be easily filtered by a low-pass filter (slow process)

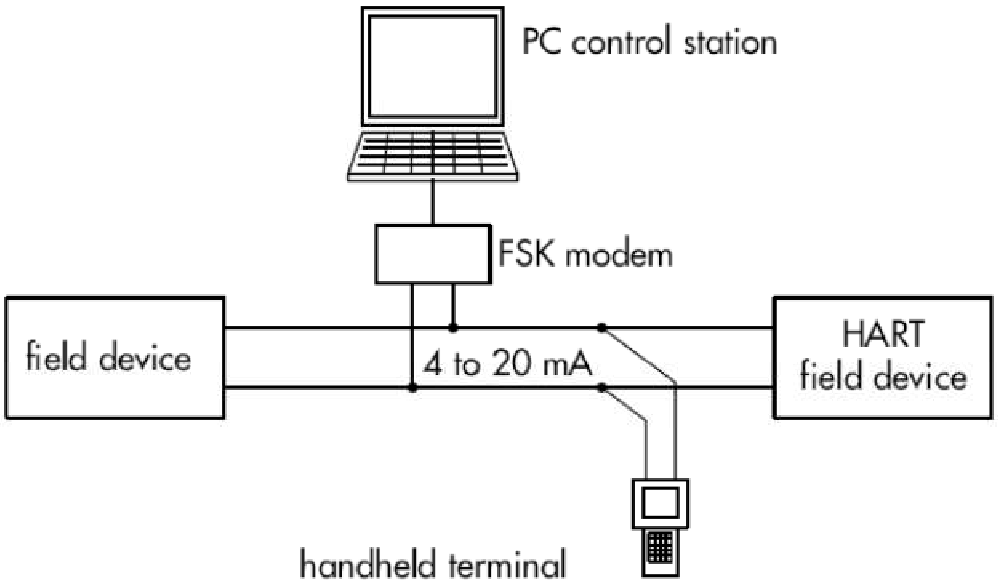
HART: MIXING OF TRADITIONAL AND SMART SENSOR



HART is an acronym for "Highway Addressable Remote Transducer".
The HART Protocol became an open communications technology in 1990.
Today the HART Communication Protocol is the global standard (IEC 61158) and the leading communication technology for smart instruments with more than 30 million HART-enabled devices installed worldwide.

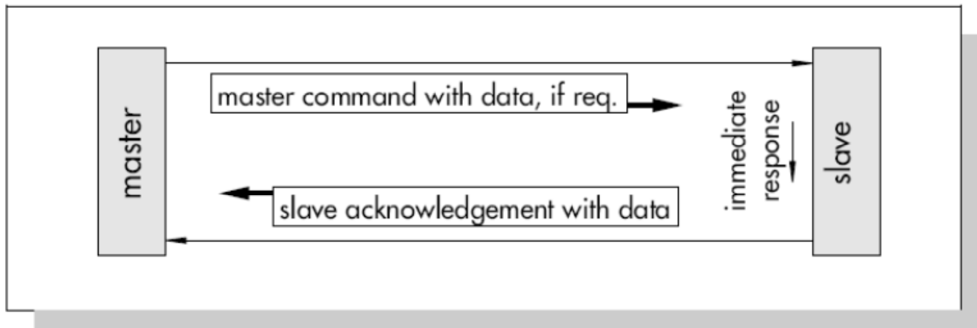
See http://www.hartcomm.org

HART: MIXING OF TRADITIONAL AND SMART SENSOR



OSI layers	HART layers
application	HART commands
presentation	
session	
transport	
network	
data link	HART protocol rules
physical layer	Bell 202

Mixed, peer-to-peer transmission



Mixed solution allows:

- device identification at warm-up
- device configuration at warm-up
- self-diagnostic at warm-up
- simplicity during normal operating conditions

Transaction time ~ 0,32s

SENSOR NETWORKS: WHERE?

AGRO-FOOD
Land monitoring, detecting of rot, bacteria, damaging, …

HEALTH
Vital parameters monitoring, disases detection,..

CIVIL AUTOMATION
Hospital, airports,…
(mains quality, air conditioning, lifting, lights,…)

MILITARY
Explosives detection, vibrations in air or water due to enemies,…

HOME AUTOMATION
(air conditioning, lighting, alarms, doors and windows control, gardens,…)

AUTOMOTIVE
Comfort in the vehicle (air quality, air conditioning, media,…)
Infrastructure
(traffic, fog, speed control)

INDUSTRIAL PLANTS
Motion control, process control, database, human machine interface, statistic analysis, …

ENVIRONMENT
climate, water level and quality, pollution, fire, earthquake, …

?

SENSOR NETWORKS: CHARACTERISTICS

What qualifies a sensor network?

- **Cost:** the cost of the network interface (transceiver, stack) should be comparable with the cost of the other electronic circuits
- **Performance:** the ability to ensure nodes synchronization, a short cycle time and a known and short latency is particularly important for real-time applications (e.g. motion control)
- **Reliability:** the communication must be guaranteed, even with noise or in hostile environments or if strict norms are required.
- **Range:** the range coverage of the sensor network is important for some applications (e.g. environment) and can be improved thanks to suitable topologies
- **Compactness:** the dimension of the sensor must be very small, especially in some **wireless** applications (e.g. health)
- **Power consumption, security, mobility, data capability, plug&play,…**

SENSOR NETWORKS: APPLICATIONS AND REQUIREMENTS

	agro-food	environment	health	military	automotive	home automation	industry
Compactness	+	+	++	++	~	-	-
Cost	+	~	~	-	++	++	+
Performance	-	-	~	+	+	~	++
Range	+	++	-	++	~	+	~
Security Robustness / EMC	~	~	++	++	++	++	++
Wireless	+	++	++	++	~	+	~

… EACH APPLICATION FIELD STARTED WITH ITS OWN SOLUTIONS

There are a lot of different sensor networks

- **Different sensor networks for different application fields**
  - The sensor networks are tailored for the need of each application field

- **Different sensor networks even in the same application field**
  - Bridges and gateway required
  - There are more than 10 different standard for industrial applications

- **This approach to design many different and "not-compatible" sensor networks will cause problems with wireless sensor networks**

SENSOR NETWORKS ARE OFTEN SIMPLE NETWORKS

ISO/OSI		Sensor network
Application		**Profiles**
Presentation		Normally unused
Session		Normally unused
Transport		Normally unused
Network		Rarely used
Data Link		**Data Link** ***Medium Access Control (MAC)***
Physical		**Physical Layer** **(connectors, electrical signals)**

PHYSICAL LAYER: BASICS

The physical level defines connectors, electrical signals,…

- **Wired connection**
  - The importance of the cables (e.g. distance among cables)
    - Category I (signals), II (power supply), III (HV, phone), IV (lighting)
    - Cables with data and power supply (e.g. USB)
    - Cables loss (repeater)
    - Insulating, grounding, shielding,…
  - Frequency, Phase, Code (NRZ, Manchester,…)

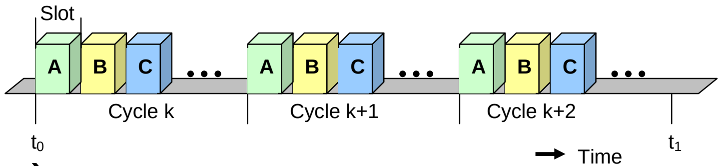
- **Wireless connection**
  - The importance of modulation schema
    - Amplitude, Phase, Frequency modulation (low noise immunity)
    - Code modulation,…
  - The antenna influence
  - The possibility to adapt the power to the need (power dissipation)
  - The spectrum usage,…

MEDIUM ACCESS CONTROL (MAC): BASICS

In a network many nodes share the same medium

➢**CSMA – Carrier Sense Multiple Access**
- A node can access the medium whenever it wants
- The node checks that the medium is free before transmitting
- If two nodes start transmitting simultaneously then a collision arises and the node could read a different state with respect to the written one
- CSMA/CD – Collision detection: all the nodes stop transmitting
- CSMA/CA – Collision avoidance: one node continue transmitting

➢**TDMA – Time Division Multiple Access**
- Communication is cyclic and the cycle is divided into several time slots
- A node can access the medium only in its own slot (no collisions)
- Importance of synchronization, Low flexibility

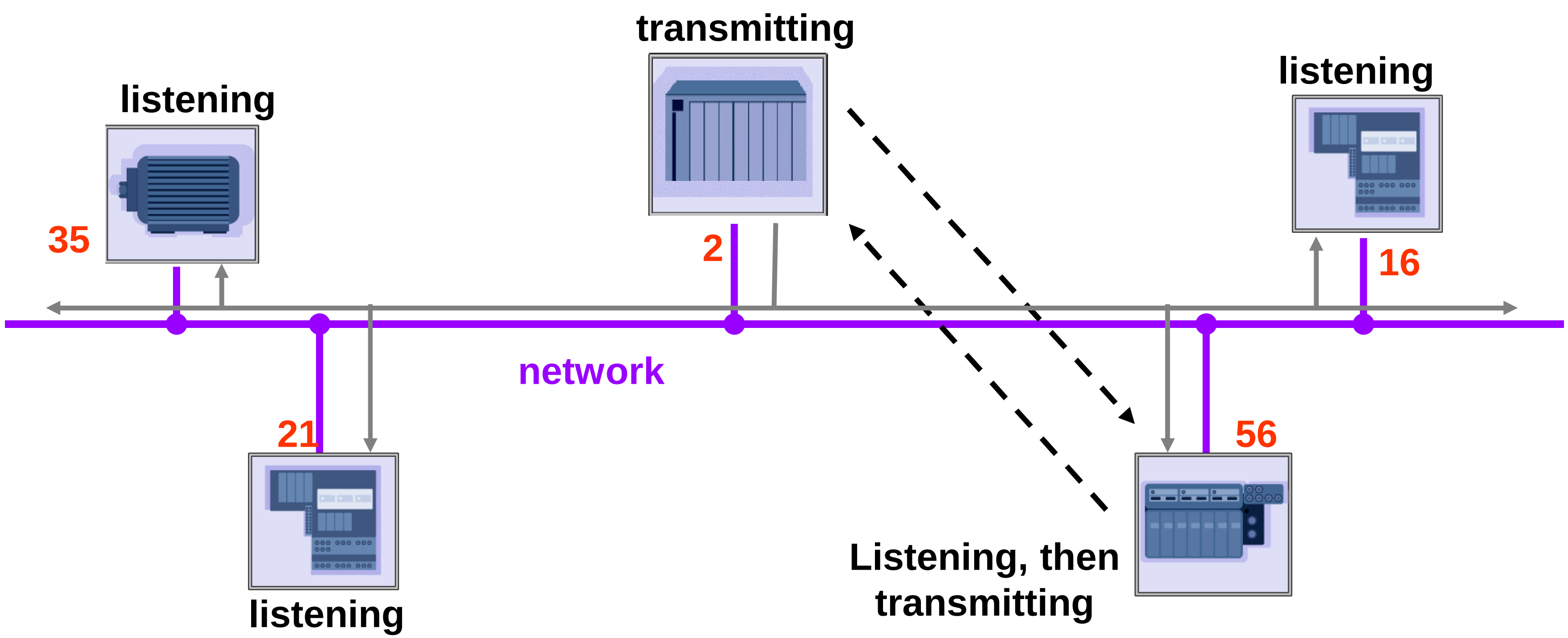


➢**Master-slave** (two types of node: master and slave)
- Slaves can communicate only if and when requested by their own master

MEDIUM ACCESS CONTROL (MAC): BASICS

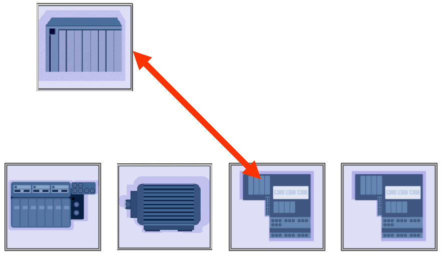
Each node must be distinguished by the others (addressing)

- Each sensor has an its own identifier (e.g. serial number)
- The MAC address can be the same of the device identifier
- The network address is useful in order to support coexistence among different networks (many sensor networks do not support a network layer)

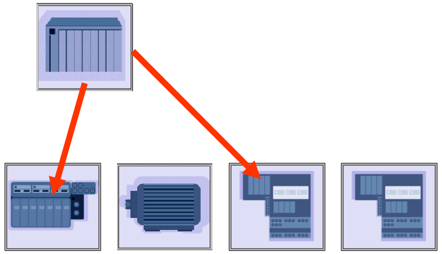


Communication relations and addressing

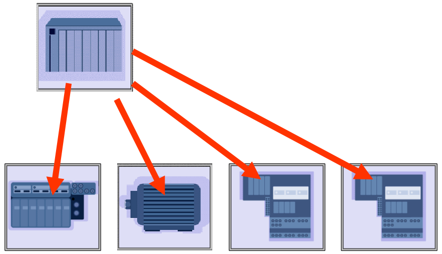
- Communication relation "peer-to-peer" (one-to-one)



- Communication relation Multicast (one-to-many)



- Communication relation Broadcast (one-to-all)

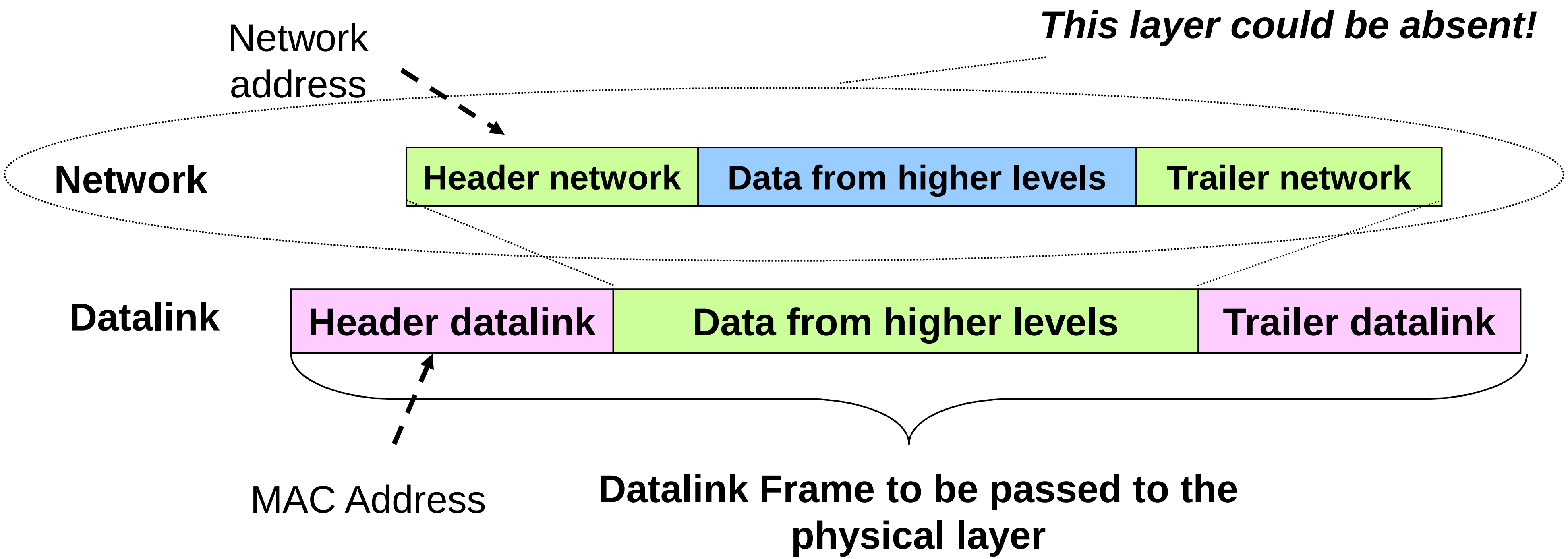


- Generally, multicast and broadcast messages have no response in order to avoid collisions

DATA LINK LAYER: BASICS

When the node accesses the medium it transmits a "frame"

- Wired sensor networks normally avoid the network layer and the Datalink is directly interfaced to the application layer
  - Separation among different networks can be made by wiring
- Wireless sensor networks normally support the network layer
  - the medium is unique



DATA LINK LAYER: BASICS

Data and information

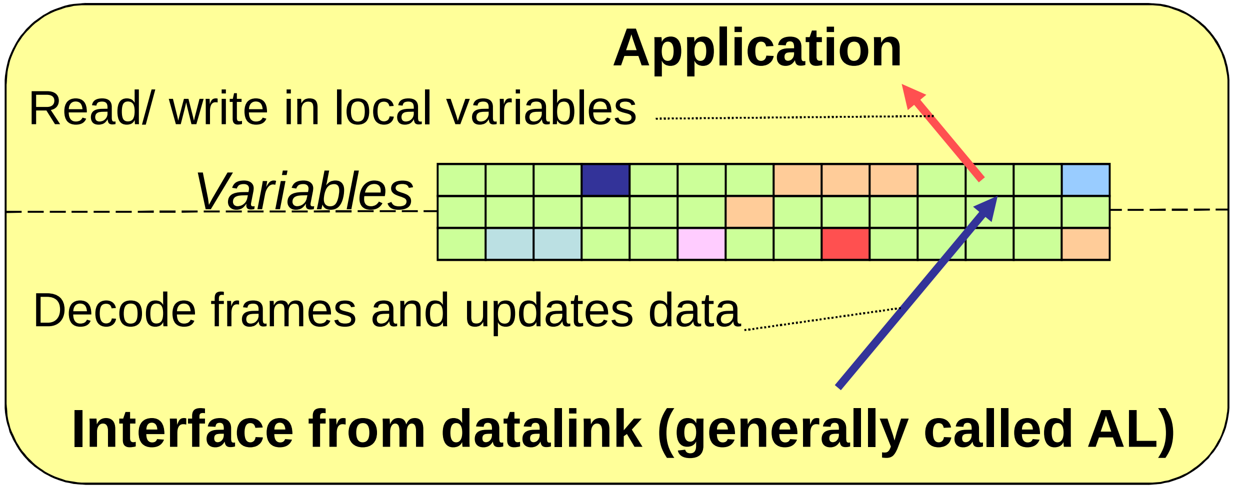
- Many types of data are transmitted over the sensor networks

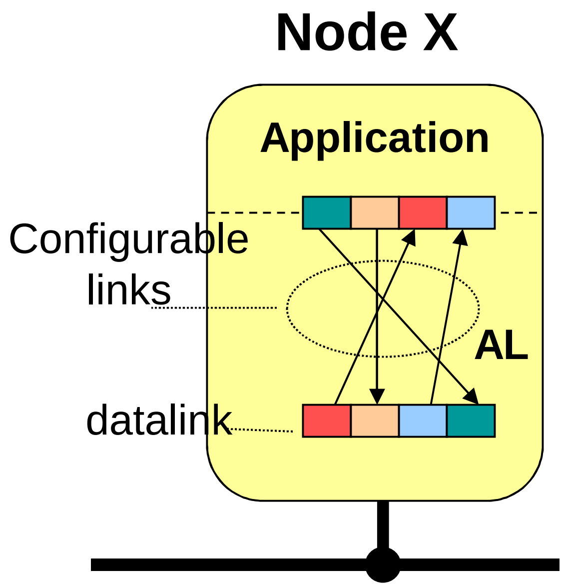
- **Measurement information:** input data from sensors and output data to be actuated
- **Events:** an acyclic condition in a sensor or in an actuator (e.g. threshold crossing of an input quantity)
- **Configuration data:** data that specify the operating mode (e.g. sampling time or a linearizing table) and/or some communication parameters for each node
- **Diagnostic data:** data that signal the status (e.g. alarms, faults) of nodes or infrastructure
- **Synchronizing information:** periodic data used by the nodes to share the same timing reference despite the drifts among the different clocks

APPLICATION LAYER: BASICS

Data are managed by the application layer as they were local

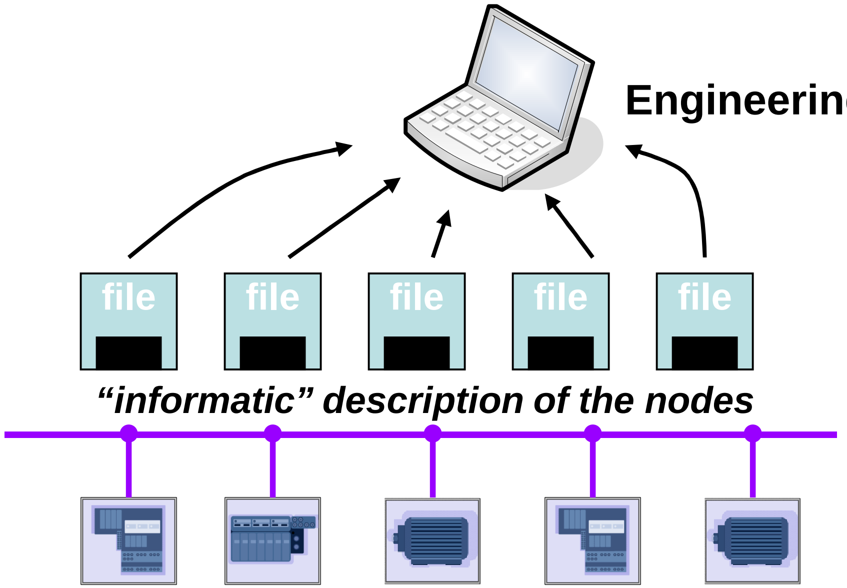
- Data can be divided between:
  - Periodically refreshed data (i.e. measurement information)
    They are managed as local data (node.object.variable)
    If a frame arrives to the datalink, it refreshes the corresponding data, while if the application write a variable, the datalink sends a frame
  - Acyclic data (diagnostics, events,…)
    Managed by Function calls





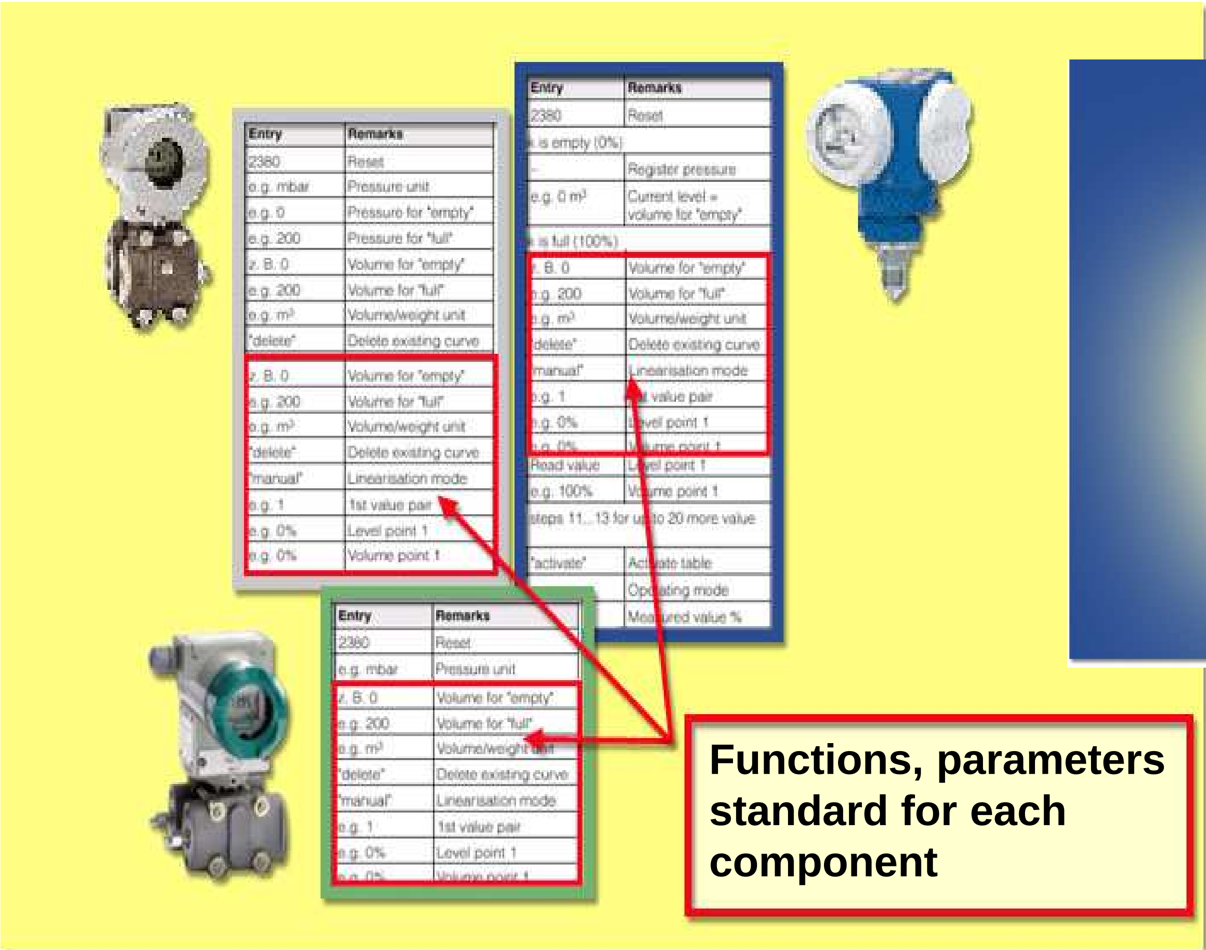
Network set-up

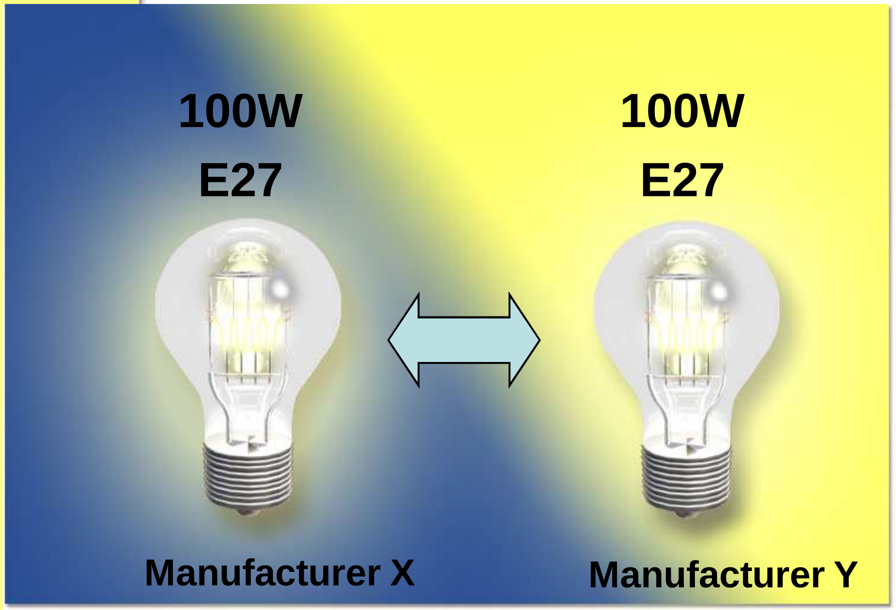
- Correspondences between datalink and application must be established
- Engineering tools to set-up the networks are needed
- Static/dynamic relations must be created starting from node description files
- At the start-up the network:
  - verifies which nodes are present (live list) and if they correspond to the ones planned by the Engineering tool (nodes list)
  - configures nodes
  - activates some services (e.g. synchronization)



APPLICATION LAYER: PROFILES

The profile for a certain sensor or actuator guarantees the correspondence among different manufacturers





SENSOR NETWORKS FOR DISTRIBUTED MEASUREMENTS

SINGLE MEASUREMENT

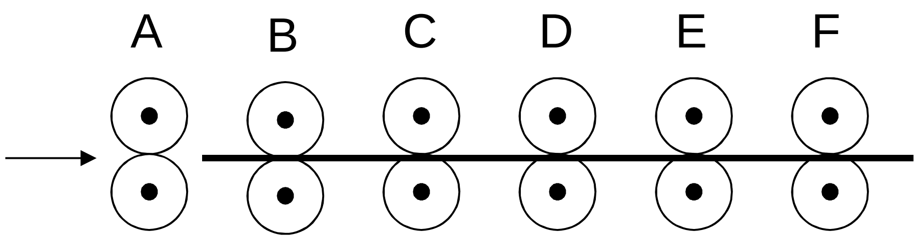
- If Temperature T is greater than a threshold L, then turn fan-coil on
  (simple to implement)

- If the motor current I is grater than a threshold L, then modify torque and set ALARM
  (less simple, fast transient could be in aliasing, especially in digital)

DISTRIBUTED MEASUREMENT

- If Temperature T near the window minus the mean temperature Tm of the room, is greater than a threshold L, then turn fan-coil F4 on
  (How Tm is computed? Which sensor is near the window?)

- If the current Ia of motor A minus the mean current I of other motors (B..F) is smaller than a threshold, then the load is releasing (Ia, Ib, Ic,… are referred to the same time?)



DATA must have space and time references

DISTRIBUTED MEASUREMENTS

TO ENSURE A GOOD MEASUREMENT, SENSOR NODES SHOULD…

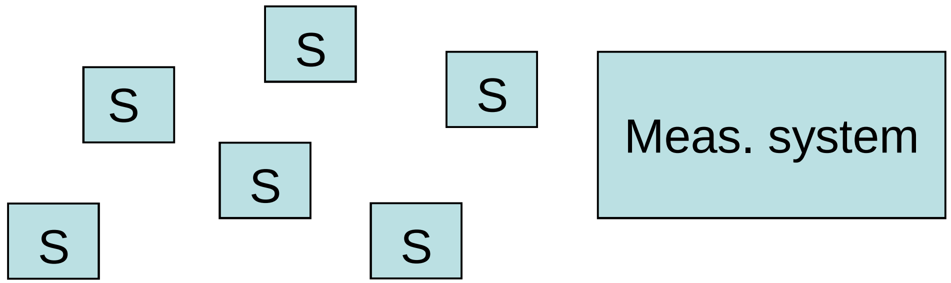
- share the same sense of time (synchronization protocols)

- be identified and localized (critical with fast-moving sensors)

- be qualified (measurement uncertainty of the single node should be known)

Sensor node information

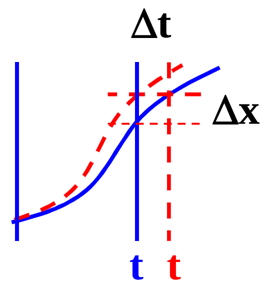
- Measurement x (value)
- Time instant t
- Localization (x, y, z)
- Uncertainty of value (confidence of the measurement)
- Uncertainty of time instant (confidence of the synchronization)
- Uncertainty of localization
- Sensor DataSheet



Timestamped data $\{x, t\}_i$

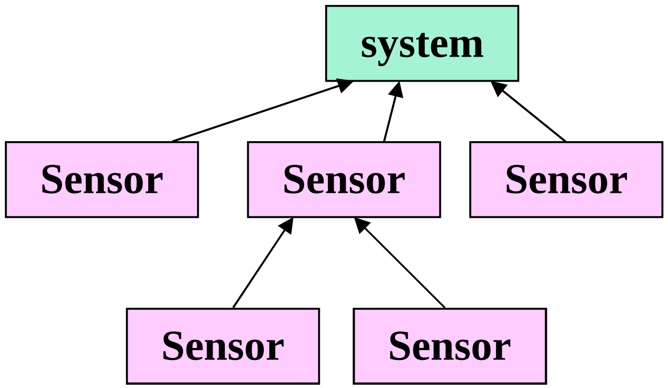
Referring to t__ a measurement related to time t_ _ is equal to have a meas. error $\Delta x \cong \Delta t$*slewrate)

Cyclic data (Δt=constant and known) normally avoid timestamp



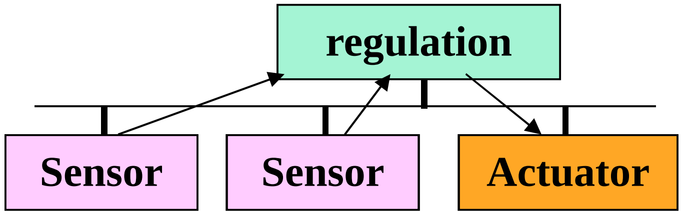
SENSOR NETWORKS FOR MEASUREMENT OR CONTROL?

Measurement



Data must be timestamped to be sorted

Loop Control



Delay from sensing to actuating must be limited (DETERMINISM) …known and fix (ULTRA-LOW JITTER) …and cyclic (ISOCHRONY)

Close loops in Process Automation:

- Process (temperature, humidity,…Tcycle > 1s)

Close loops in Factory Automation:

- Motion (positioning, speed, torque… Tcycle < 1 ms)

TERMS FOR REAL-TIME NETWORKS

DETERMINISM (HARD and SOFT REAL-TIME)

- **Capability to serve a request in a bounded and a-priori known time (maximum latency known)**

ISOCRONY

- **Capability to have a behavior strictly repetitive in time (low jitter)**

SYNCHRONIZATION SERVICES

- **Communication synchronization (TDMA)**
- **Input/output synchronization (global read, global write)**
- **Application synchronization**

SENSOR NETWORK SYNCHRONIZATION: THE PROBLEM

An example of Synchronization importance

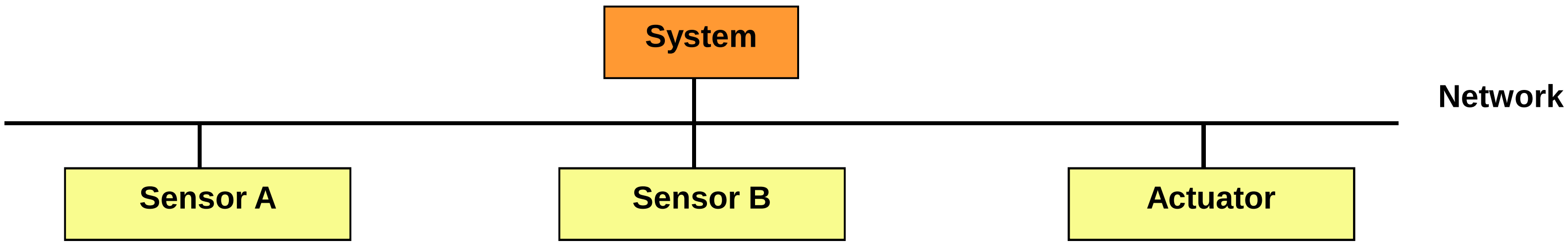
- System: if (A > B) then immediately set actuator

Problems:

- Relation between $A(t_1)$ and $B(t_2 \neq t_1)$ can generate errors
- Which are the transmission delays $t_{d,A}$ and $t_{d,B}$ from A or B to the system? ($T_{min} < t_{d,A} \neq t_{d,B} < T_{max}$)
- Which is elaboration time t_{elab}? (we suppose that elaboration starts exactly after data receiving)
- Which is the transmission time $t_{d,act}$ from the system to the actuator? ($T_{min} < t_{d,A} \neq t_{d,B} \neq t_{d,act} < T_{max}$) (we suppose that the actuator modify its output exactly after data receiving)

"immediately" = $\max(t_{d,A}, t_{d,B}) + t_{elab} + t_{d,act}$ **(Def. "event reaction time")**

($t_{d,A}$, $t_{d,A}$ and $t_{d,act}$ depend on network) ⇒ **"immediately" is variable**



THE TWO APPROACHES

- **Broadcast commands:**
  - "All read inputs now"
  - "All act outputs now"

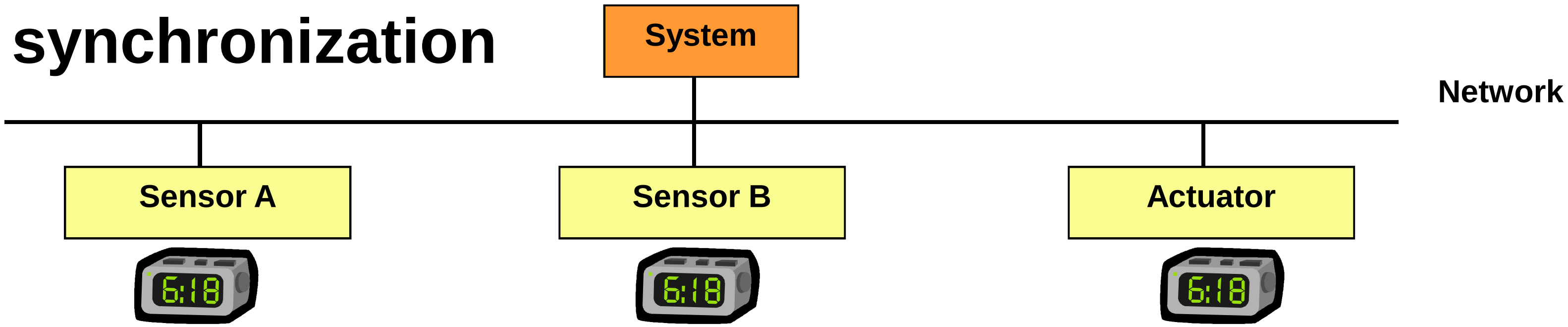
  - It works if transmission time is ~ equal for all nodes
  - It works if each node manages actions (read, act) with ~ same delay

- **Synchronization:**
  - "All read inputs at time T0"
  - "All act outputs at time T1"

  - It works if all nodes have synchronized clocks
  - It works if maximum transmission time is compatible with T0 and T1

SENSOR NETWORK SYNCHRONIZATION: A SOLUTION

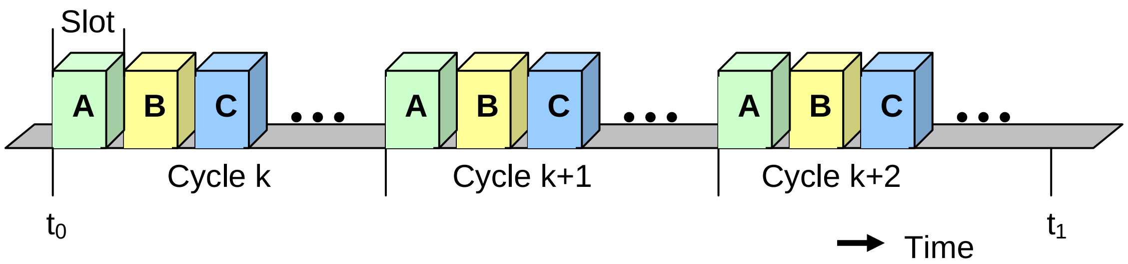
Nodes synchronization



The problem can be solved if all the nodes share the same time reference

1) Sensors are requested to measure at time t_0
2) Sensors send their data when the network is available (cycle k) taking less than time t_n (maximum value). Note that TDMA is perfect to limit t_n to the cycle time
3) The system elaborates data taking less than t_{elab} (during cycle k+1)
4) The system sends the command to the actuator taking less than time t_n (cycle k+2)
5) The actuator is requested to actuate at time t_1

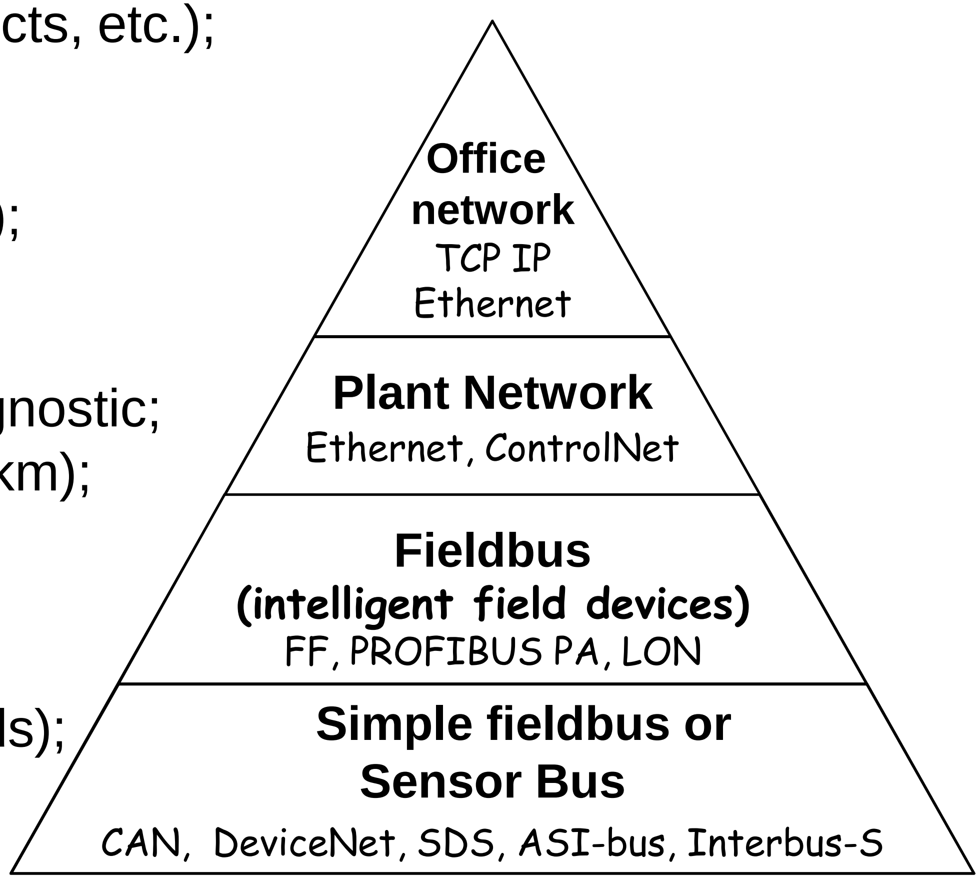
"immediately" = $t_1 - t_0 = 3t_n$



There is a fixed delay between sensing and actuating (ISOCHRONY)

INDUSTIAL FIELDBUS: A FIELDBUS IS A NETWORK THAT…

- transfers a “big number” of small length values (process variables);
- supports real-time traffic (Upper bounded response times, ex. 1ms..1s);
- operates in hazardous environments (high temperature, vibrations, em interferences, water, chemical products, etc.);
- is robust and easy to install;
- has high integrity levels (ex. absence of non-detected errors);
- has high availability (e.g. redundant architectures)
- has continuous supervision and diagnostic;
- manages long distances (100m .. 4 km);
- has good data transmission rate (e.g. 50 kbit/s … 5 Mbit/s);
- supports clock synchronization (e.g. milliseconds up to microseconds);
- Manages non real-time traffic for maintenance and diagnosis;



FIELDBUS FOR PROCESS AUTOMATION

Safety is mandatory

- Safety (particularly in chemical, oil, industries,…)
  - High availability (redundant system)
  - Reduce wiring (long distances) - the bus also powers the devices

- Speed is not important
  - Cycle time are in the order of several hundreds of ms
  - Timestamp is important in case of fault (resolution ~ 100 ms)

- There are only two big players:
  - PROFIBUS PA
  - FIELDBUS FOUNDATION (it has local loop control between devices)
- They use the same physical layer (Manchester, powered, 31.25kbaud) but they are totally different at the datalayer

- Wireless can be used for non critical processes, as it reduce wiring and allow a range extension by suitable network topologies (mesh)

FIELDBUS FOR FACTORY AUTOMATION

Performance can be a key point

- The main goals are:
  - Fast and low-cost
  - High rejection to noise
  - Safety (e.g.protection of human operator)

- Speed can be very important
  - Reduced communication times means more products, i.e. higher gain…
  - Motion control (motor drives) need isochronous communication

- More than 20 fieldbuses for Factory Automation
  - PROFIBUS DP is the most diffused but holds only the 15% of the market (RS485, max 12Mbit/s)
  - DeviceNet, CANOpen, use CANbus (max 1Mbit/s)

- Factory environment is hostile for wireless technology (metal, walls,…)

WHY FIELDBUSES INSTEAD OF ETHERNET SINCE '80?

Item	**Ethernet**	**Fieldbus**
Cost per node	High (now low)	Low
Infrastructure cost	High (Hub or switch)	No infrastructure
Determinism	No (collisions)	Yes

Ethernet was unsuitable for the sensor level also for other reasons:

- Designed for event-like long messages
- Robustness, availability, redundancy
- Requires specialized operators

… but now is different and TCP/IP is a widespread standard (fieldbus incapsulated within TCP/IP)

“Modbus” and “Modbus over TCP”

- Same application layer over different physical layers
- One of the first use of Ethernet at the field level (non time critical applications)

Modbus (Modicon –Schneider Electric– 1980)

- **Physical layer:** serial link (e.g. RS232, RS485)
- **Performance:** baud rate between 1200 and 19200
- **Configuration:** 8bit, no parity, 1 stop
- **Characteristics:** one-master, 247 slaves, minimum overhead (4 byte)

Modbus over TCP (1997)

- **Physical layer:** Ethernet
- **Performence:** 10/100 Mbit/s
- **Configuration:** TCP link over port 502 (reserved)
- **Characteristics:** one-master, 247 slaves, min. overhead (66 byte)

IEC61784: Foundation Fieldbus HSE, Ethernet/IP, PROFINET

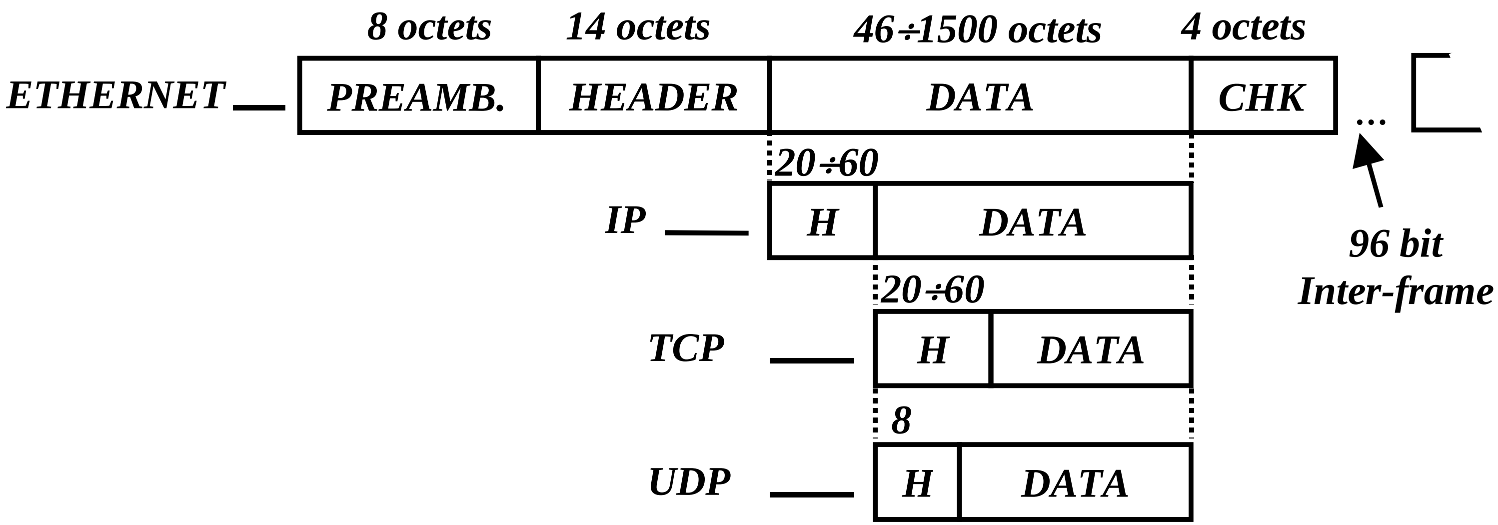
ETHERNET ADVANTAGES

- ➢ Simple interfacing with higher levels (supporting of TCP/IP traffic)
- ➢ Standard technology that is widespread, updated and supported by PC
  - 10Base5 ⟹ 10BaseT ⟹ 100BaseT ⟹ GigaEthernet
- ➢ Hardware costs are decreasing
  (some processors support Ethernet interface, as it occurs with CAN)
- ➢ Availability of ITC instruments (Information Communication Technology)
  - PC-based analyzers (Es. Wireshark -Ethereal-), simulators
  - Network analyzers with high performance
- ➢ Emerging nodes and controllers use web and java technologies
  - Soft-PLC, web-sensor,...
- ➢ Support of related technologies (optical fiber, wireless 802.11 WiFi)
  - couplers, bridges vs. subnetworks

ETHERNET MEANS INTERNET AND WEB TECHNOLOGIES

Ethernet IEEE802.3, internet (IP), web technologies

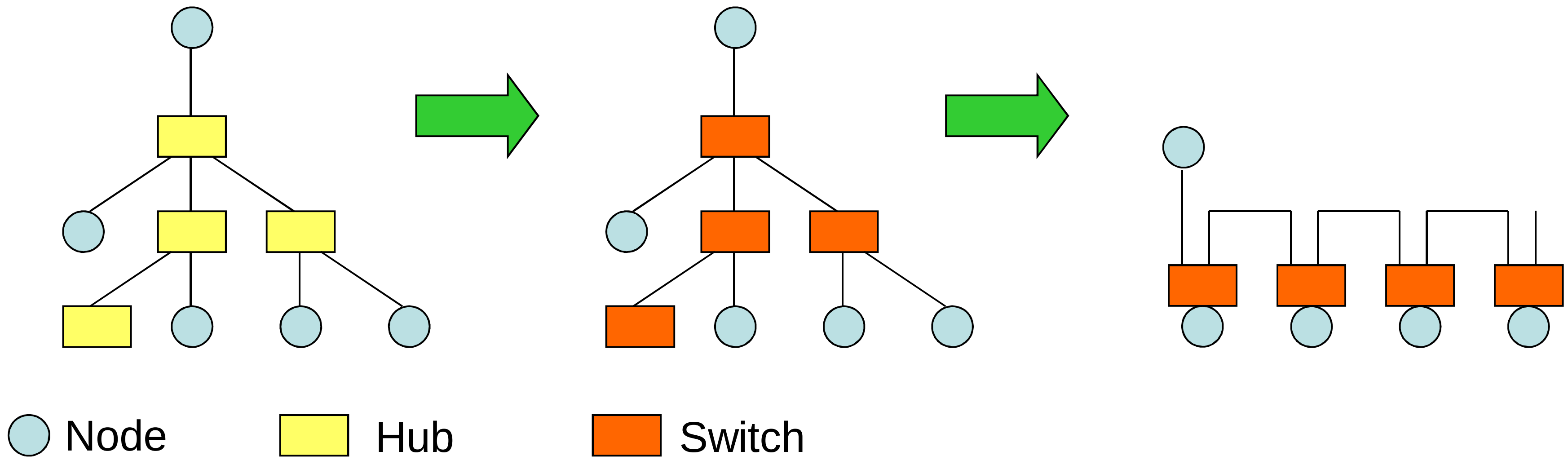
- **Network with a lot of nodes ($7 \cdot 10^{13}$ global addresses)**
- **Protocols over Ethernet**
  - **Internet Protocol (IP)**
  - **Address Resolution Protocol (ARP)**
  - **Internet Control Message Protocol (ICMP)**
  - **Transfer Control Protocol (TCP)**
  - **User Datagram Protocol (UDP)**
  - **Hyper Text Transfer Protocol (HTTP)**
  - **....**



- **100BaseT Ethernet frame: 5.76÷122µs**

WHY NOW ETHERNET? WHAT HAS BEEN CHANGED?

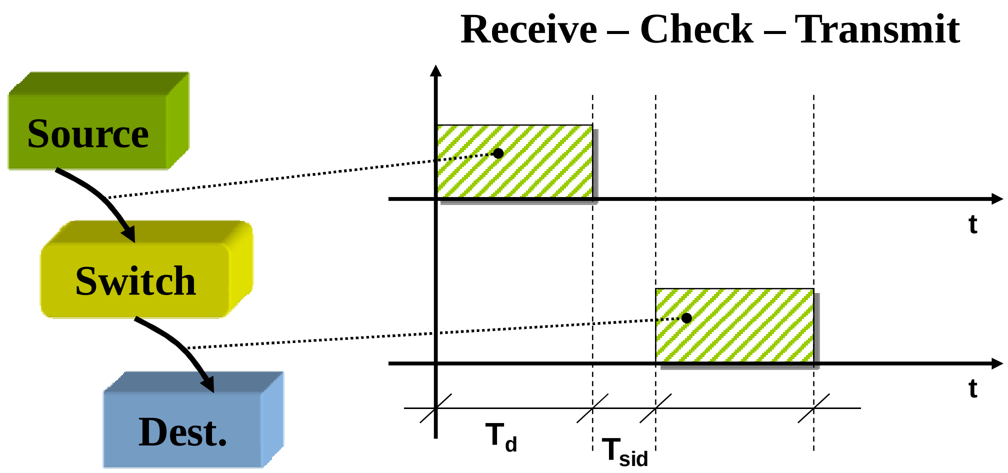
- Now Ethernet interface and infrastructure are low-cost
- No need of bridge towards high-level communications
- Availability of solutions for protocol stacks, diagnostic services, security, redundancy
- The use of switches (instead of HUB) limits collisions
- If the infrastructure is “insulated” (like a fieldbus) a good statistically real-time behaviour is ensured



SWITCH HAS A VARIABLE DELAY

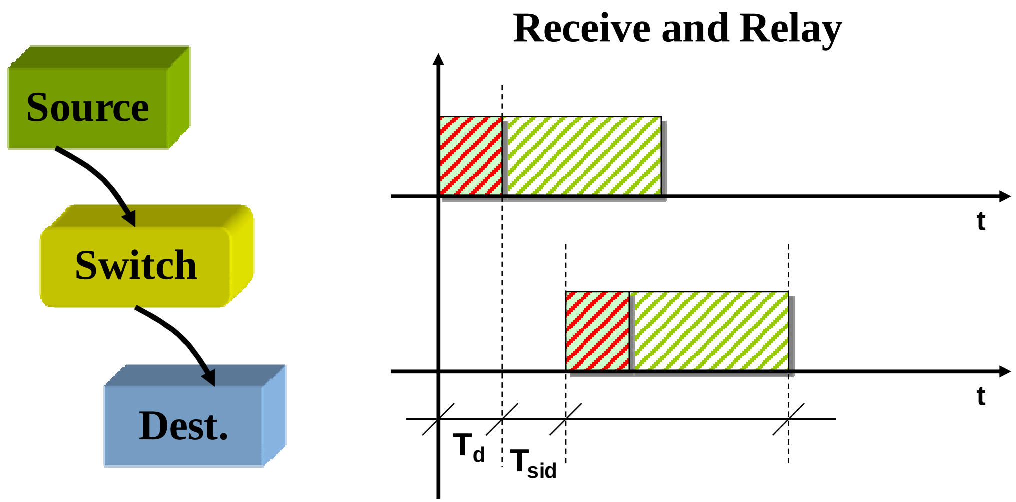
Store&Forward

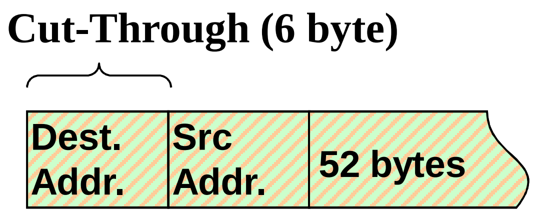
- Delay depends on frame length



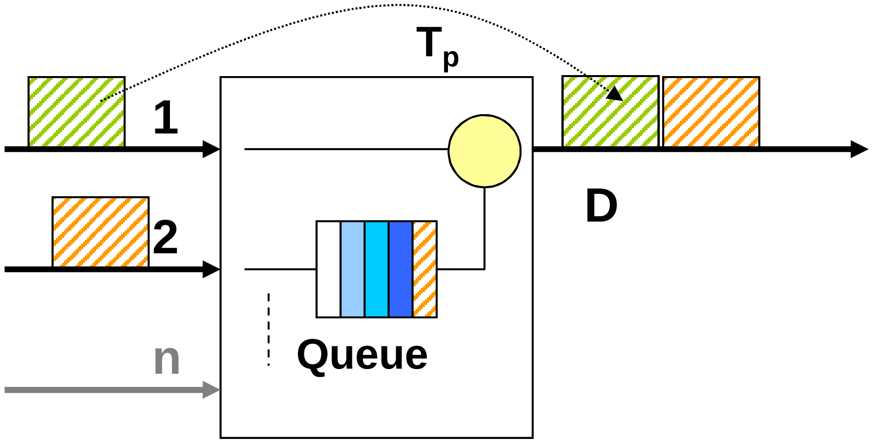
Cut Through

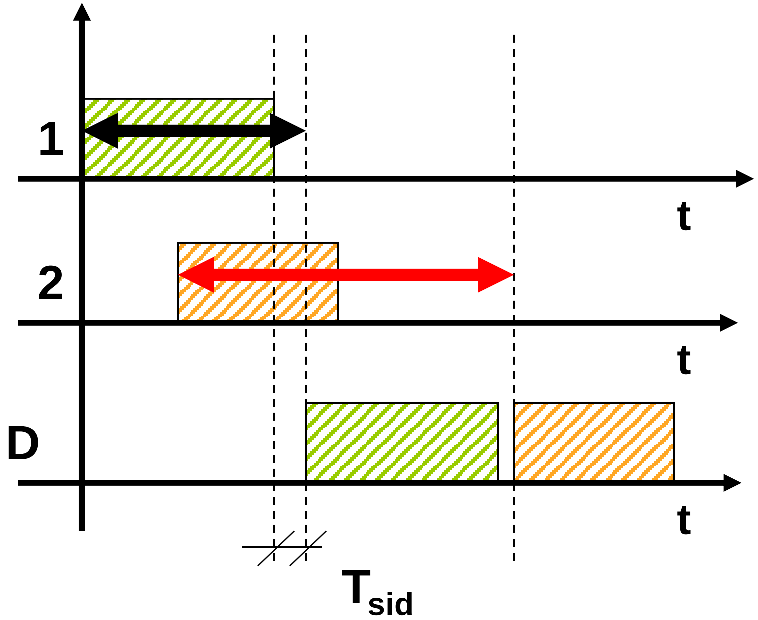
- Fast, fragments





QUEUE INTRODUCES A VARIABLE DELAY

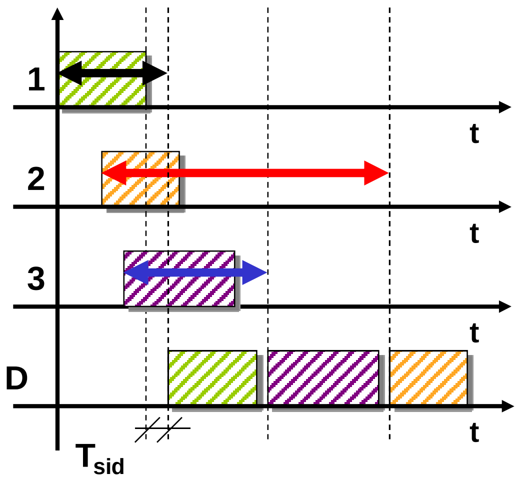


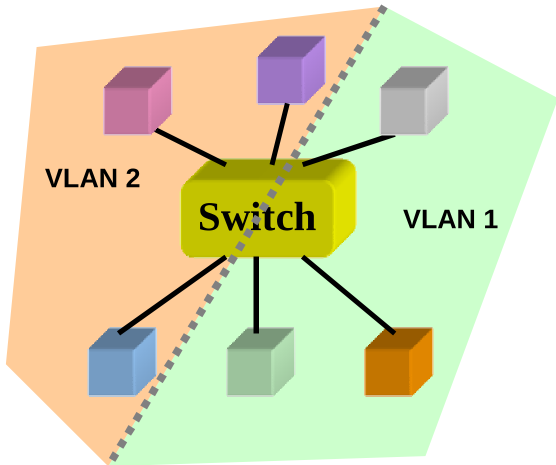


Priority (IEEE802.1p) or VLAN (IEEE802.1q) does not solve

Traffic must be a-priori known

TCP traffic is locked and trasmitted in certain time slots

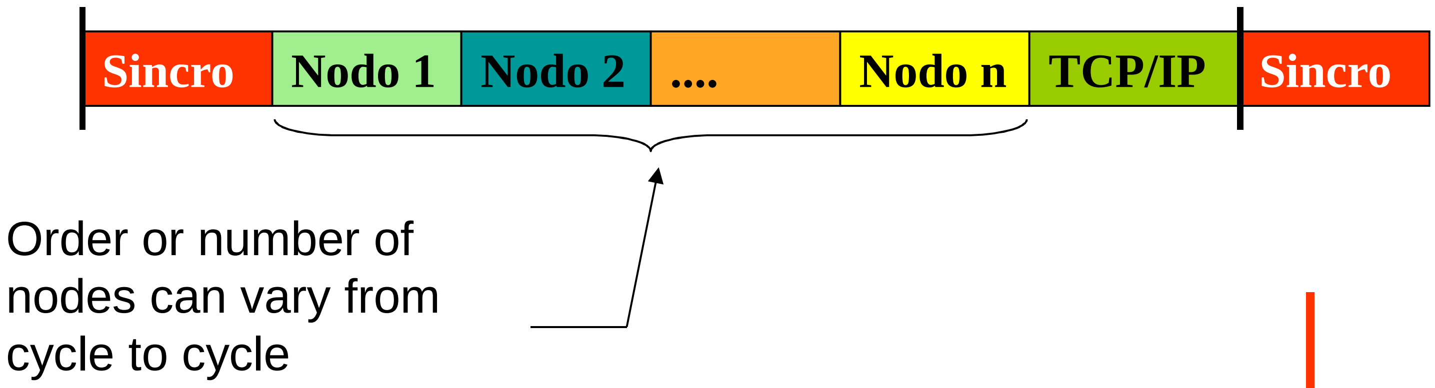




REAL TIME ETHERNET

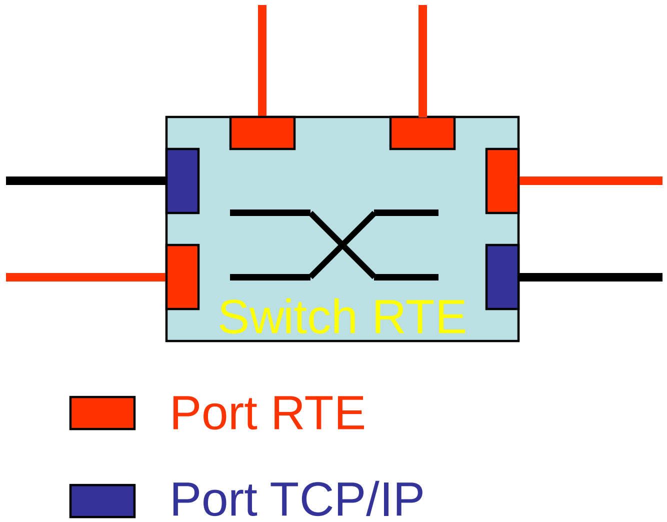
Software approach (statistical)

- TDMA, compensation of switch delay
- TCP traffic is blocked and sent at the end of the cycle (router, gateway)



Hardware approach (full determinism)

- Hardware TDMA with high synchronization
- Buffer for TCP traffic
- Modified MAC



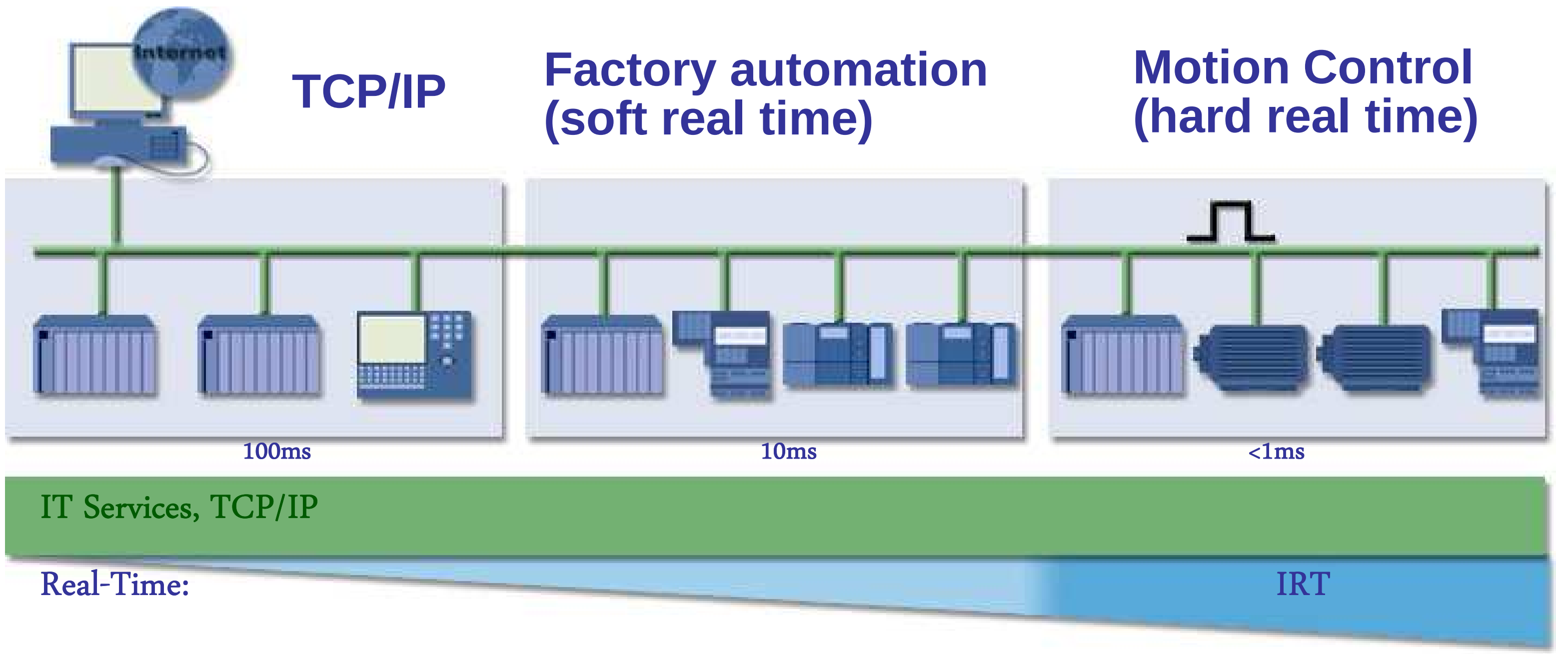
REAL TIME ETHERNET: STANDARDS

IEC 61784

- Digital data communications for measurement and control
- Some profiles:
  - CPF 2 (ControlNet) – Ethernet/IP (CP 2/3, CP 2/4, CP 2/5)
  - CPF 3 (PROFIBUS, PROFINET) - (CP 3/4, CP 3/6, CP 3/6)
  - CPF 4 (P-NET) – (CP 4/3)
  - CPF 6 (INTERBUS) – (CP 6/4)
  - CPF 10 (VNET/IP) - (CP 10/1)
  - CPF 11 (TCnet) - (CP 11/1)
  - CPF 12 (EtherCAT) – (CP 12/1)
  - CPF 13 (Ethernet Powerlink) - (CP 13/1)
  - CPF 14 (EPA) - (CP 14/1)
  - CPF 15 (MODBUS-RTPS) - (CP 15/1)
  - CPF 16 (SERCOS) - (CP 16/3)

PROFINET

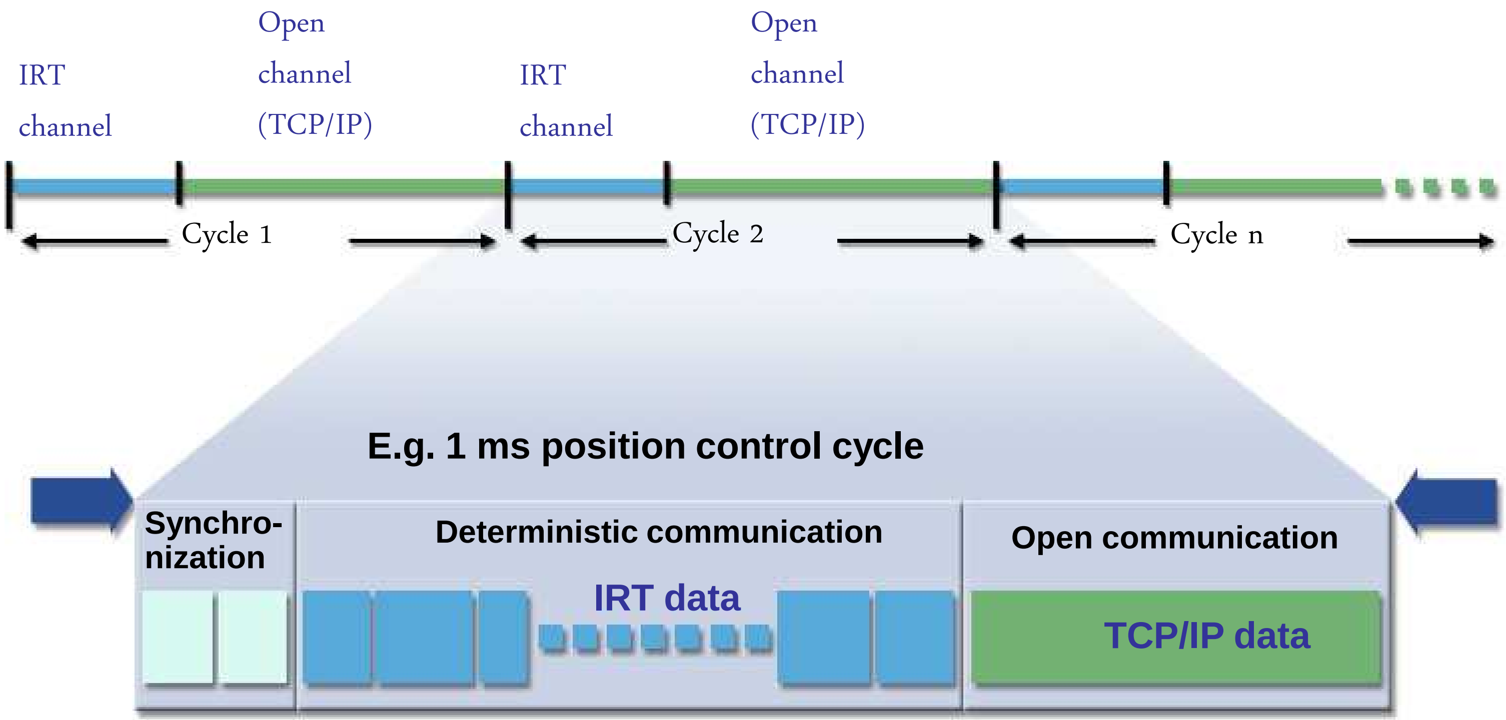
- Scalability and more than 40% of bandwidth for TCP/IP traffic
- Clock synchronization among nodes better than 1 μs
- Completely transparent to PLC programmer and sensor supplier (ASIC)

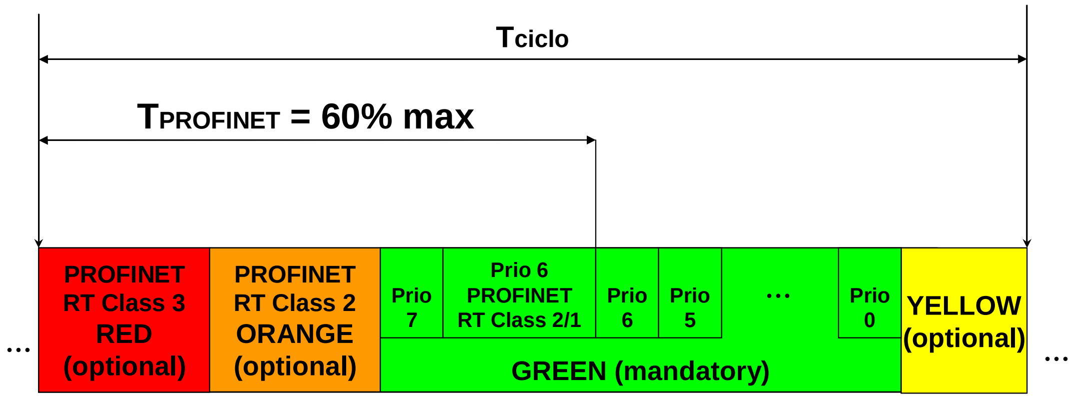


centro servizi multisettoriale e tecnologico

PI Competence Center &
PI Training Center

PROFINET: THE ORGANIZATION OF THE CYCLE



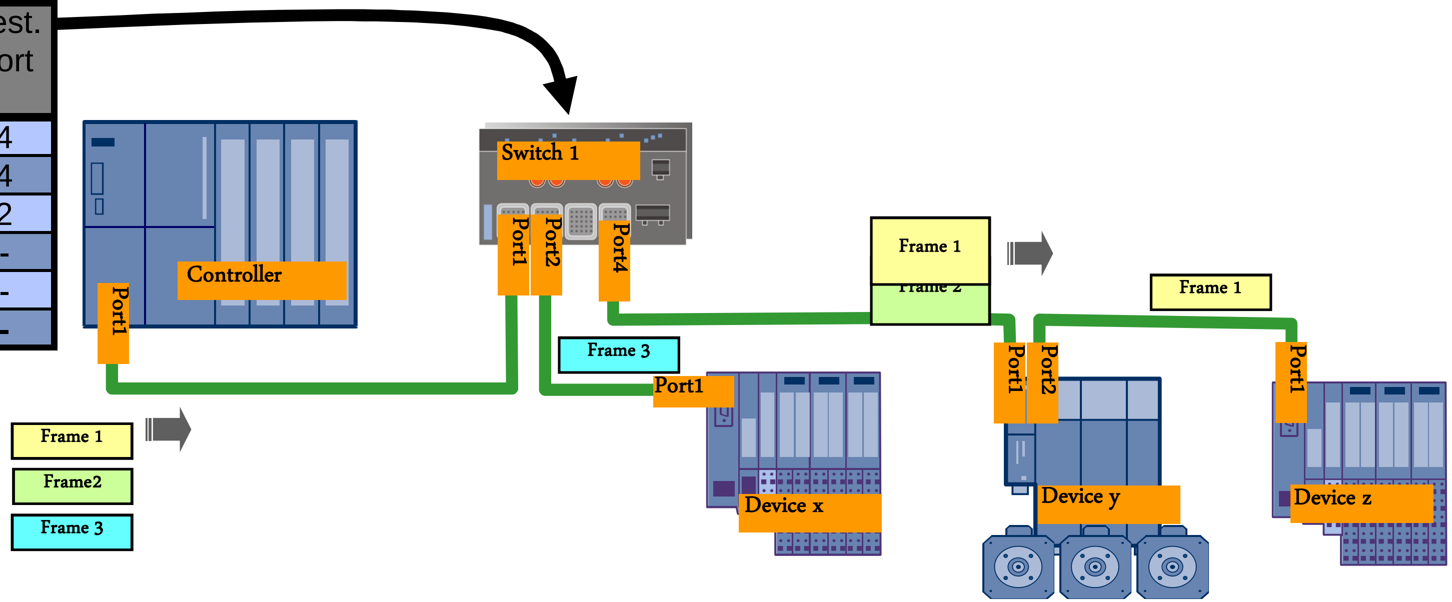


3 RT classes:
- RT_class_1, UDP/IP non synchronized
- RT_class_2 unused
- RT_class_3 isochonous

PROFINET: THE AIRPORT PARADIGM

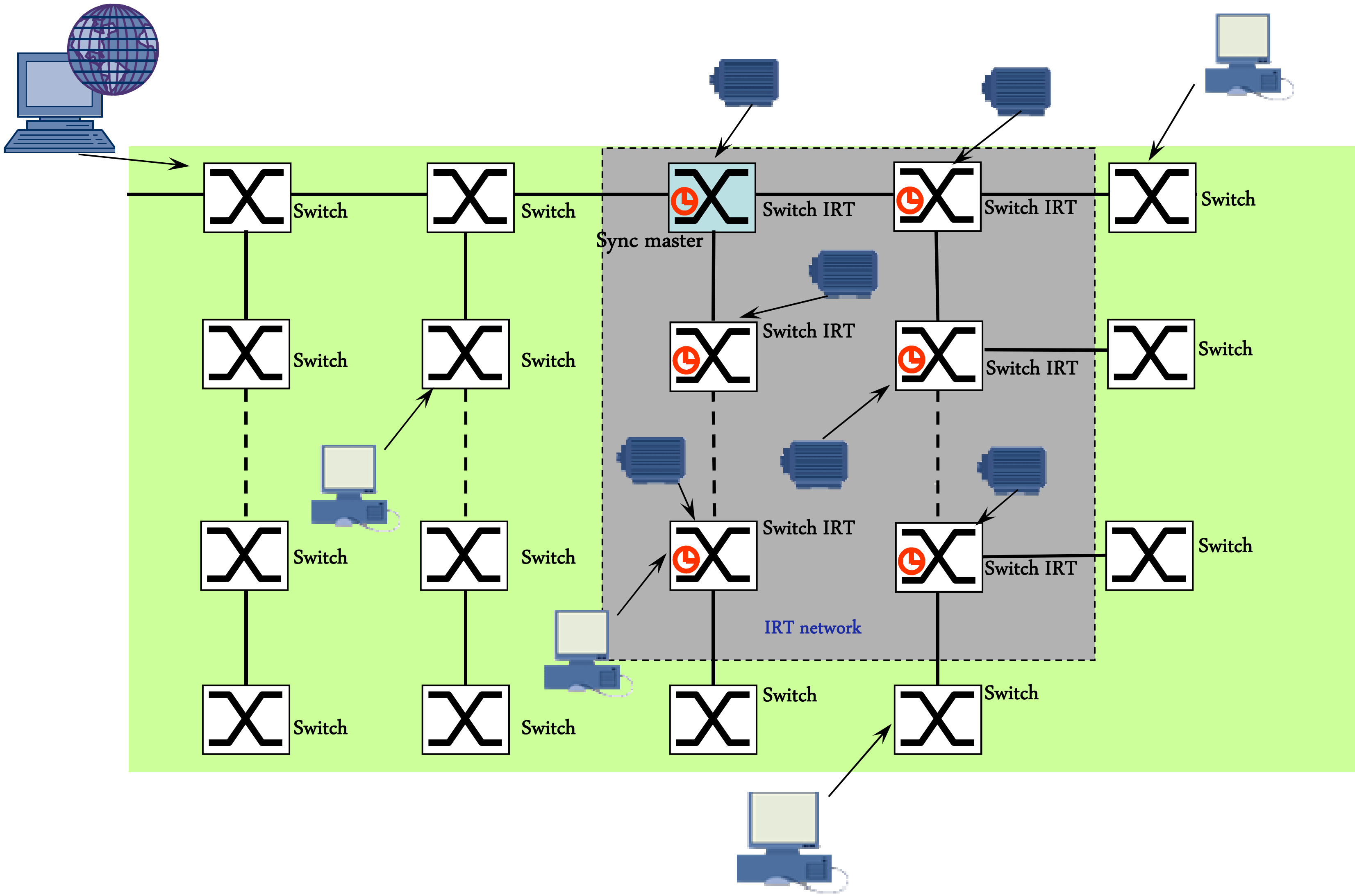
Time Table Switch 1				
Rec. Port	Arrive	Frame	Departure	Dest. Port
1	t1	1	t1+Δt	4
1	t2	2	t2+Δt	4
1	t3	3	t3+Δt	2
2	-	-	-	-
3*)	-	-	-	-
4	-	-	-	-

*) 100% available for TCP/IP



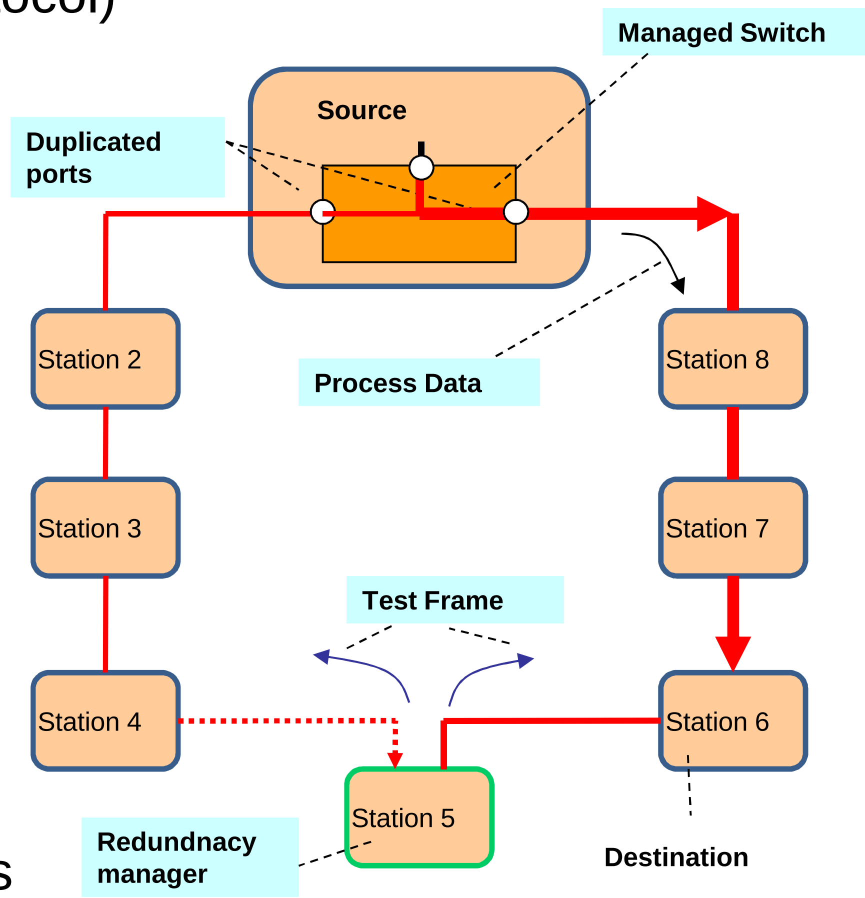
- Each switch has a time-based (not address-based) table
- Switches must be synchronized to know the exact starting time of each cycle
- Propagation time (length of cables) must be known

PROFINET: INFRASTRUCTURE



PROFINET: REDUNDANCY

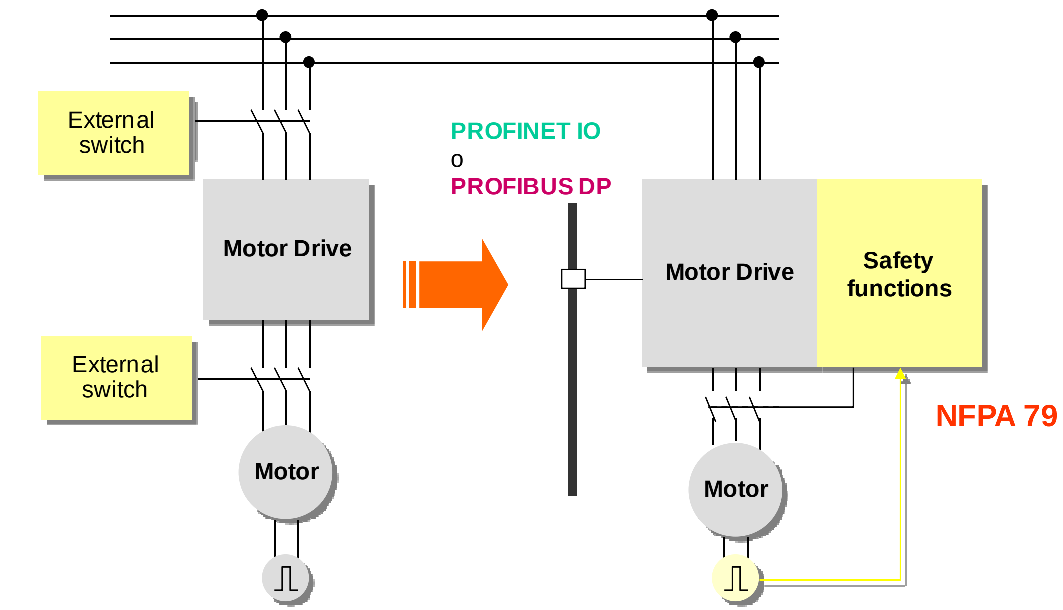
- Based on MRP (Media Redundancy Protocol)
- A Redundancy Master (RM) sends test packet to check the network
- Thanks to LLDP each node knows neighbours and activation of redundancy
- Maximum switchover time of 200 ms



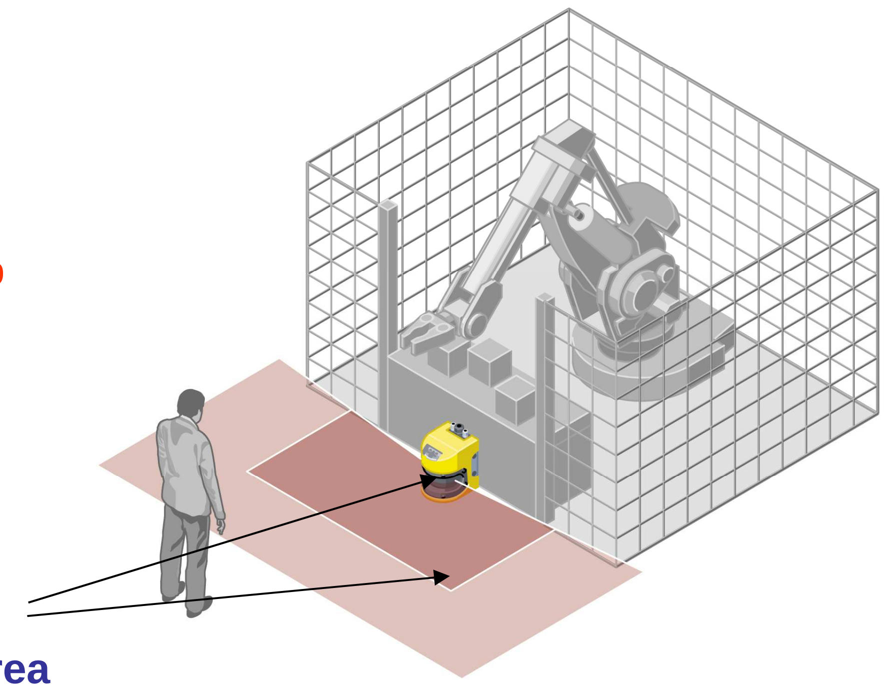
- Redundancy is mandatory in Smart Grids (e.g. IEC61850 among substations)

THE CHALLENGE OF SAFETY

- Safety for personnel, plants, environment
- Stack profiles can overcome proprietary buses for safety
- Principle of "Slow down before stopping"



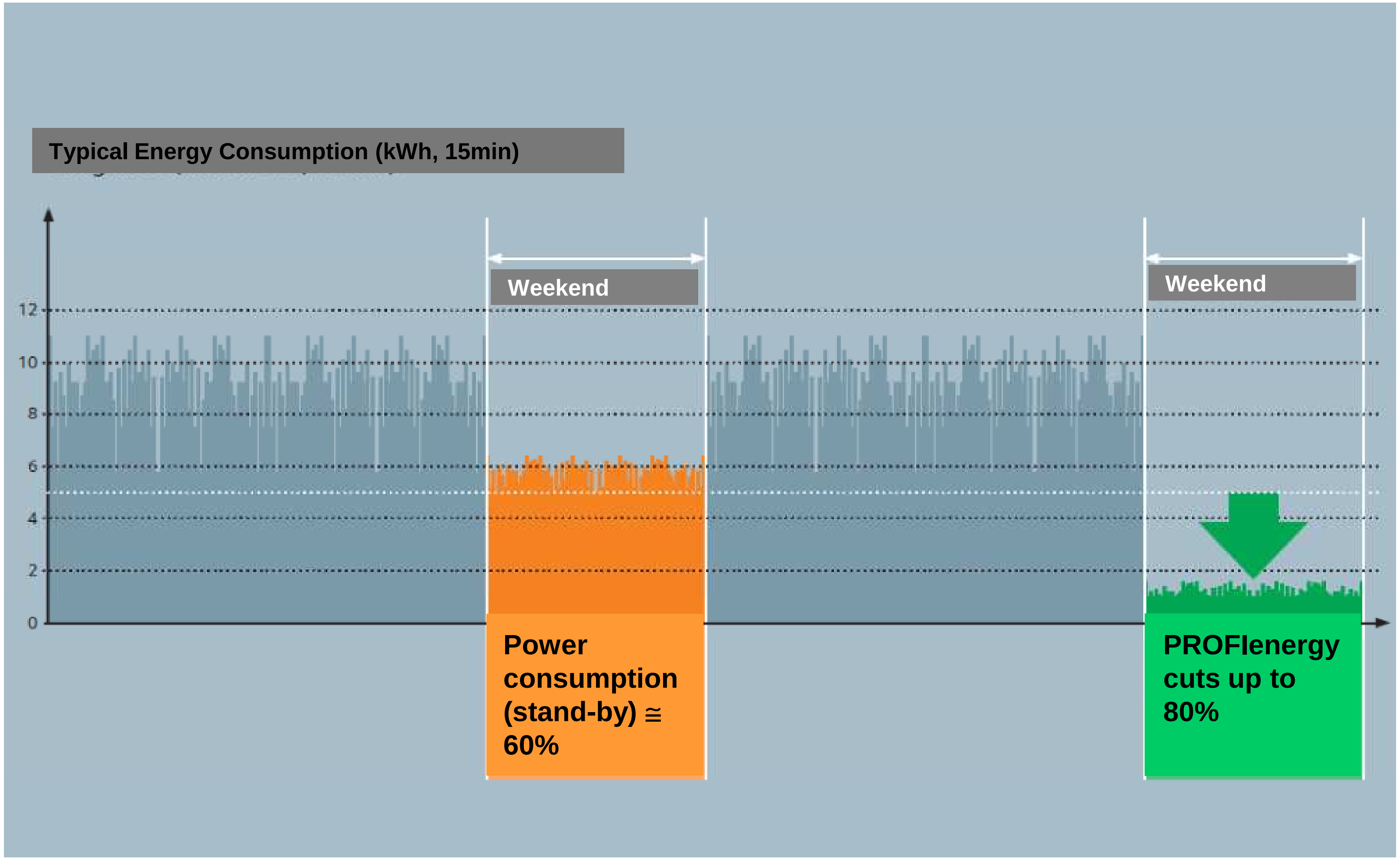
From „Emergency turn-off " to „Emergency slow-down "



Different protection area

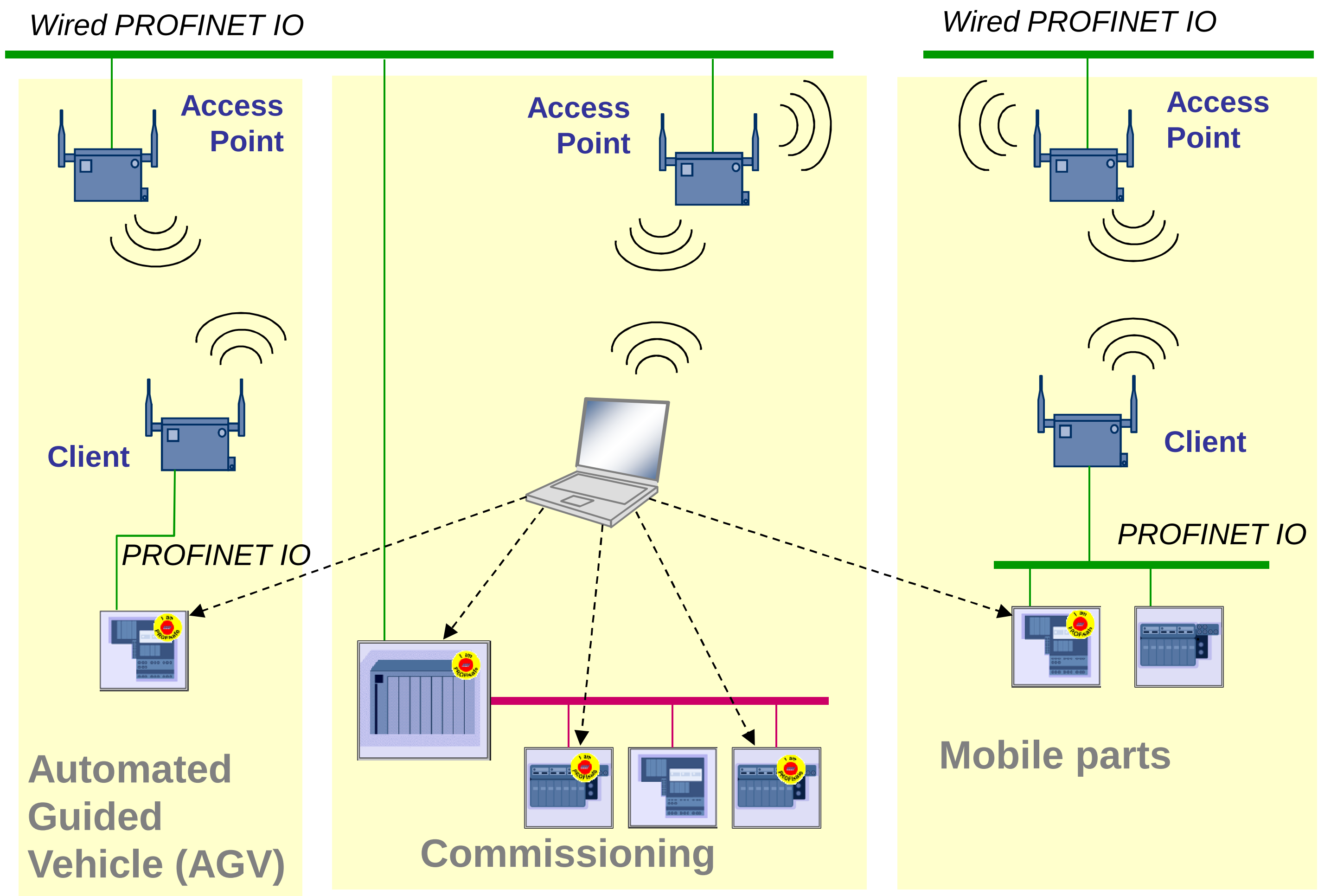
PROFINET: THE PROFILE FOR ENERGY EFFICIENCY

- A profile to improve the management of “stand-by” periods



PROFINET: THE WIRELESS CHALLENGE

- Factory automation: WiFi (modified) or (BT (modified)
- Process automation: WirelessHART (ISA100), based on 802.15.4
- Real time?
- Reliability?
- Coexistence?

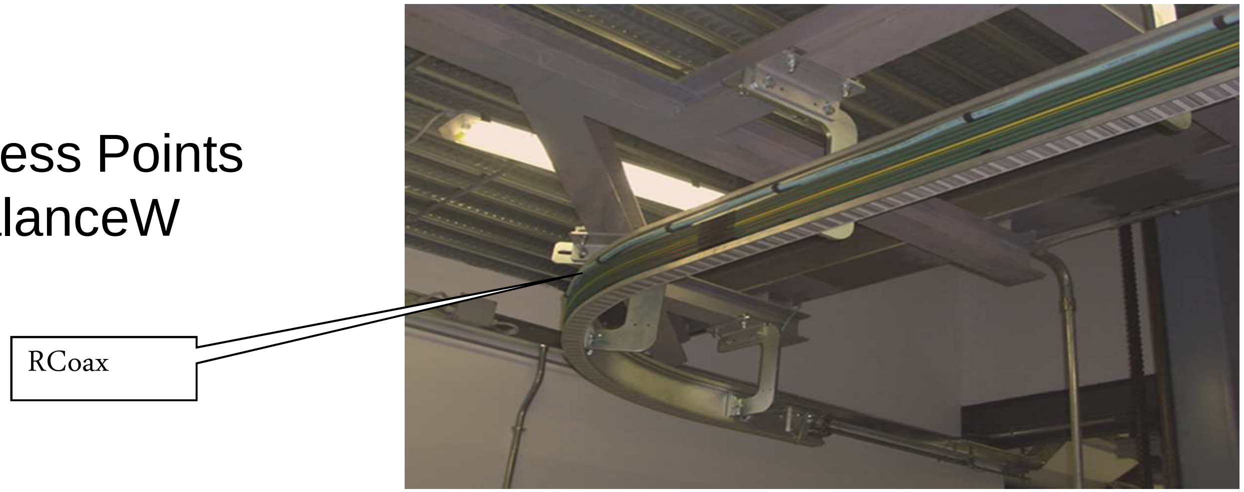


PROFINET: WIRELESS

PROFINET IO RT_Class 1: Real-time IEEE802.11 support

- Coax antenna to have a well-limited field
- Point Coordination Function (PCF) to reserve up to 8 channels after beacon (absolute priority respect to other WiFi nodes -Distribute Coordinate Function-)
- Reduced guard times (iPCF) to be always the first to reserve the channel
- Cycle time down to 20ms (PROFINET IO Class 1)
- **A wireless solution for systems, not for sensors**
- **No Coexistence**

Access Points
ScalanceW



ABB's WISA (Wireless Interface to Sensors and Actuators) … WSAN

- Wireless network of proximity switches and sensor pads powered by e.m. field
- Star topology (up to 120 nodes, 5 “virtual networks“ overlapped)
- TDMA: Superframe of 2.048 ms (latency from node to coordinator < 20 ms, 5 ms typ.)
- Communication coordinator-to-nodes is always active (1 downlink, 16 slots of 128 µs)
- Communication node-to-coordinator is event driven (4 uplinks, 32 slots of 64 µs, 1byte)
- The coordinator hardware is proprietary and it is based on 5 transceivers
- Nodes hardware is based on two standard IEEE802.15.1 transceivers

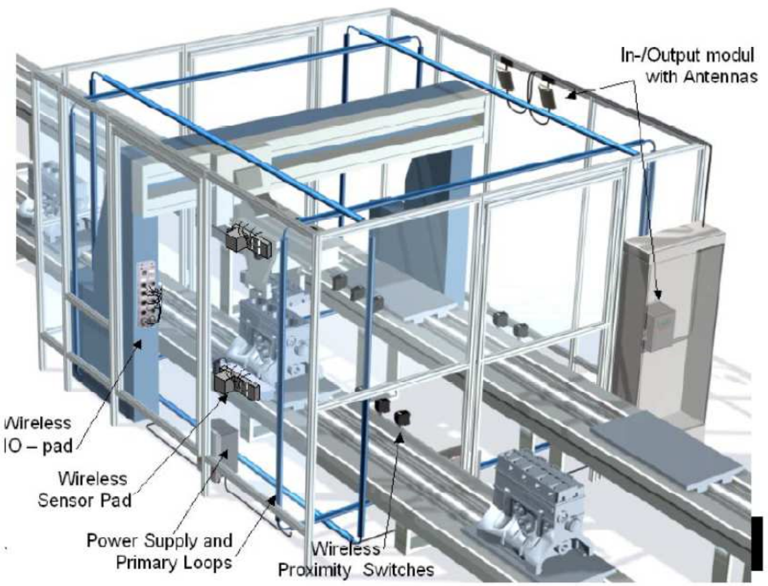
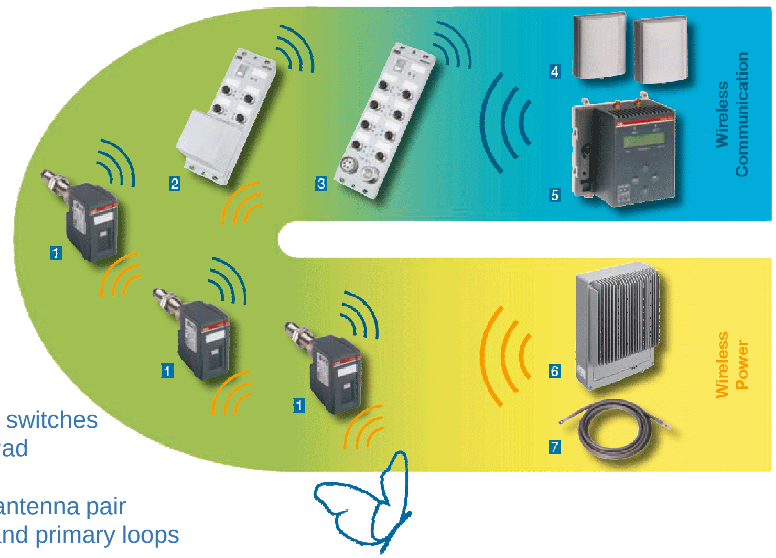


Figure 7: WISA devices installed in a typical robot type production - cell (27 m³)

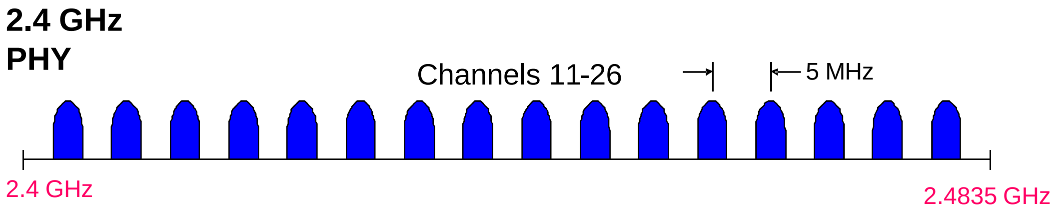


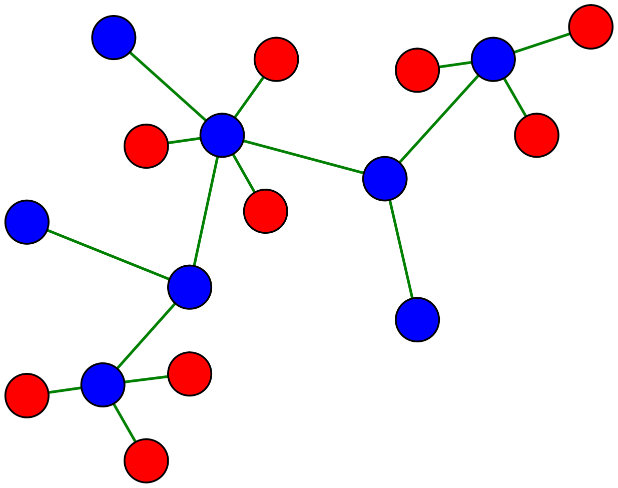
- 1 Wireless proximity switches
- 2 Wireless Sensor Pad
- 3 Wireless I/O Pad
- 5, 4 I/O-modul with antenna pair
- 6, 7, Power supply and primary loops

IEEE802.15.4 SHOULD BE THE BEST SOLUTION FOR WSN…

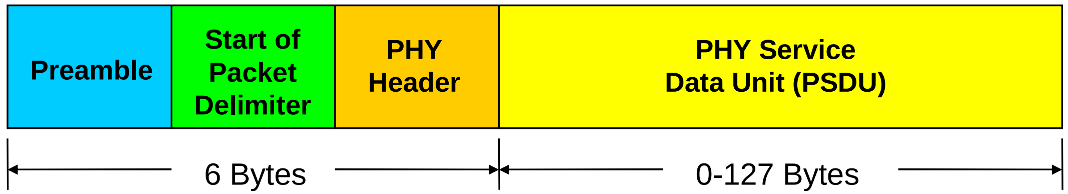
IEEE802.15.4 at 2.4GHz

- 250 kbps (1byte=32µs), 16 channels 2MHz-wide and 5MHz apart
- 8 bit at 2 $code_{32}$ = 64 chip @ 2Mchip/s = 32µs; 32kbyte/s
- unique 64 bit IEEE addresses, 1mW transmitting power
- Start and mesh networks supported
- Many PAN can coexist, each PAN has its own coordinator
- PAN coordinator:
  - manages the live list, assigns addresses, generates beacons
  - it can talk with every other node
- Two physical types of node:
  - Full Function Device (FFD)
  - Reduced Function Device (RFD): it talks only with FFDs

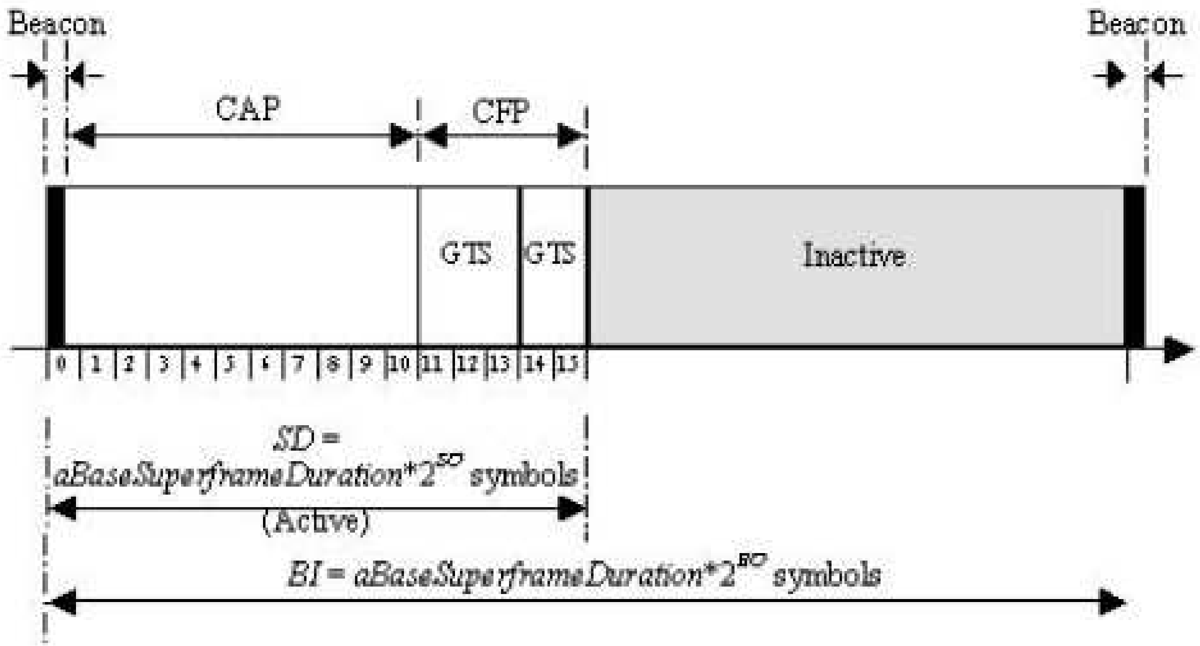




IEEE802.15.4: MAC

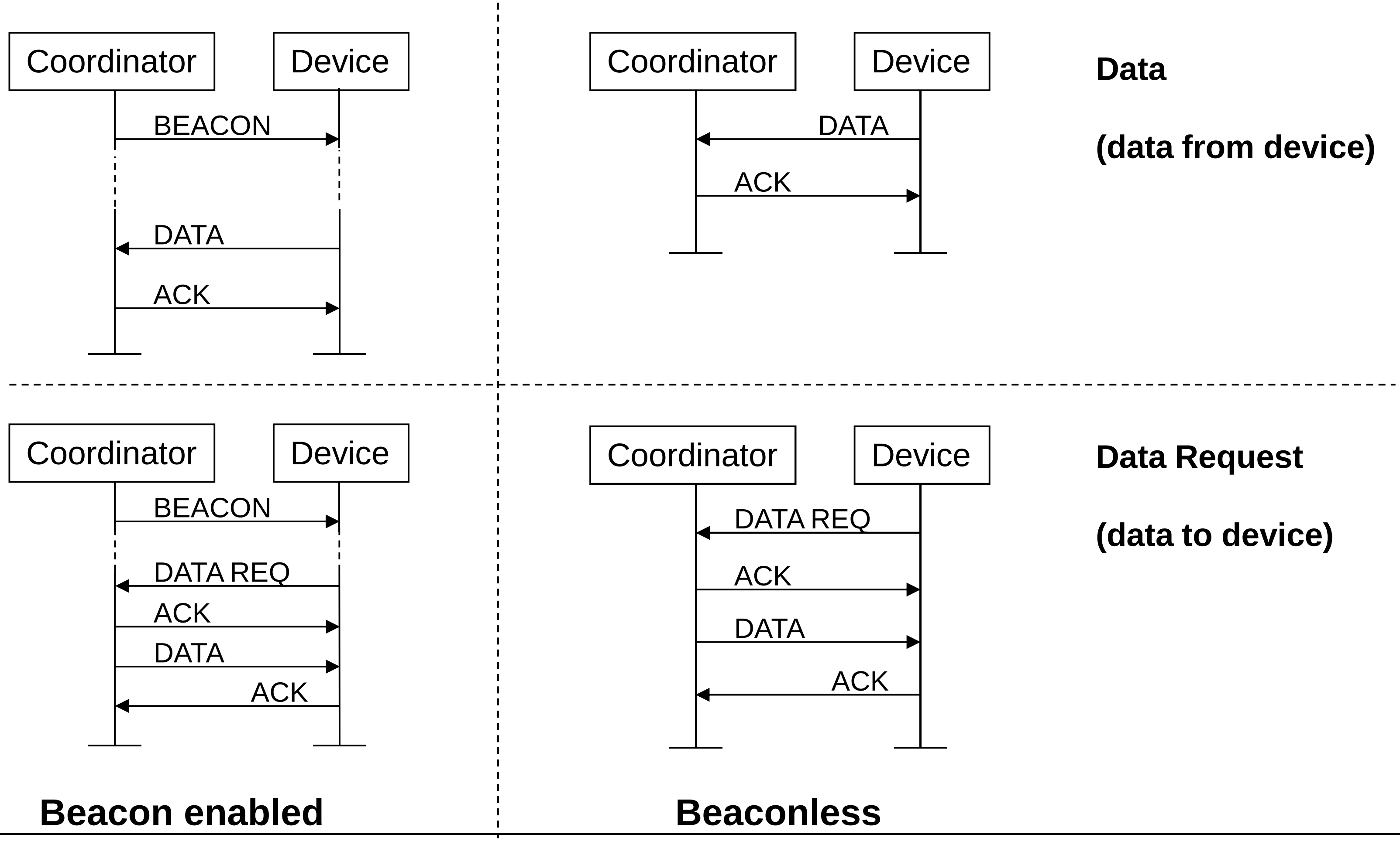


- Simple frame
- Superframe (15ms*2^{SO}, SO=0..14)
- Beacon-enabled network
  - Contention Free Period composed by Granted Time Slot (Max. 7)
- Non Beacon-enabled network
  - Contention Access Period



IEEE802.15.4 AND ZIGBEE: DATA TRANSFERS

- The use of *Beacons* implies complex, rigid, poor structures (managed by MAC)
- Most of ZB implementations and commercial stacks avoid *Beacons* (CSMA/CA, Low data-rate, no real-time ⇨ Not suitable for industrial applications)



IEEE802.15.4, 802.15.1 and 802.11 ARE A GOOD STIMULUS…

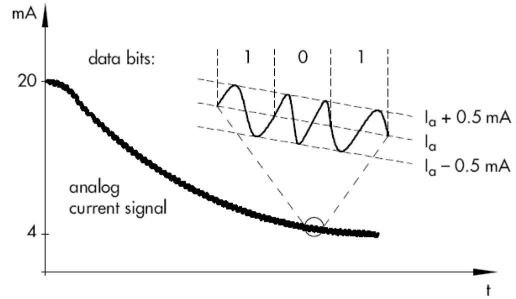
Some international consortia for Wireless in Automation:

- Wireless Industrial Networking Alliance (WINA, dal 2003, www.wina.org)
- PNO TC2 WG1 “Wireless PROFINET – IWLAN” (dal 2005, http://www.profibus.com/pi)
- ISA SP100 “Wireless Systems for Automation” (dal 2005, http://www.isa.org/)
- HCF HART Wireless WG (dal 2005, http://www.hartcomm2.org/)
- NAMUR Work Area AK 4.15 (dal 2005, http://www.namur.de/start/?L=2)

WIRELESS HART (WH)

WH Working Group organized in March 2005

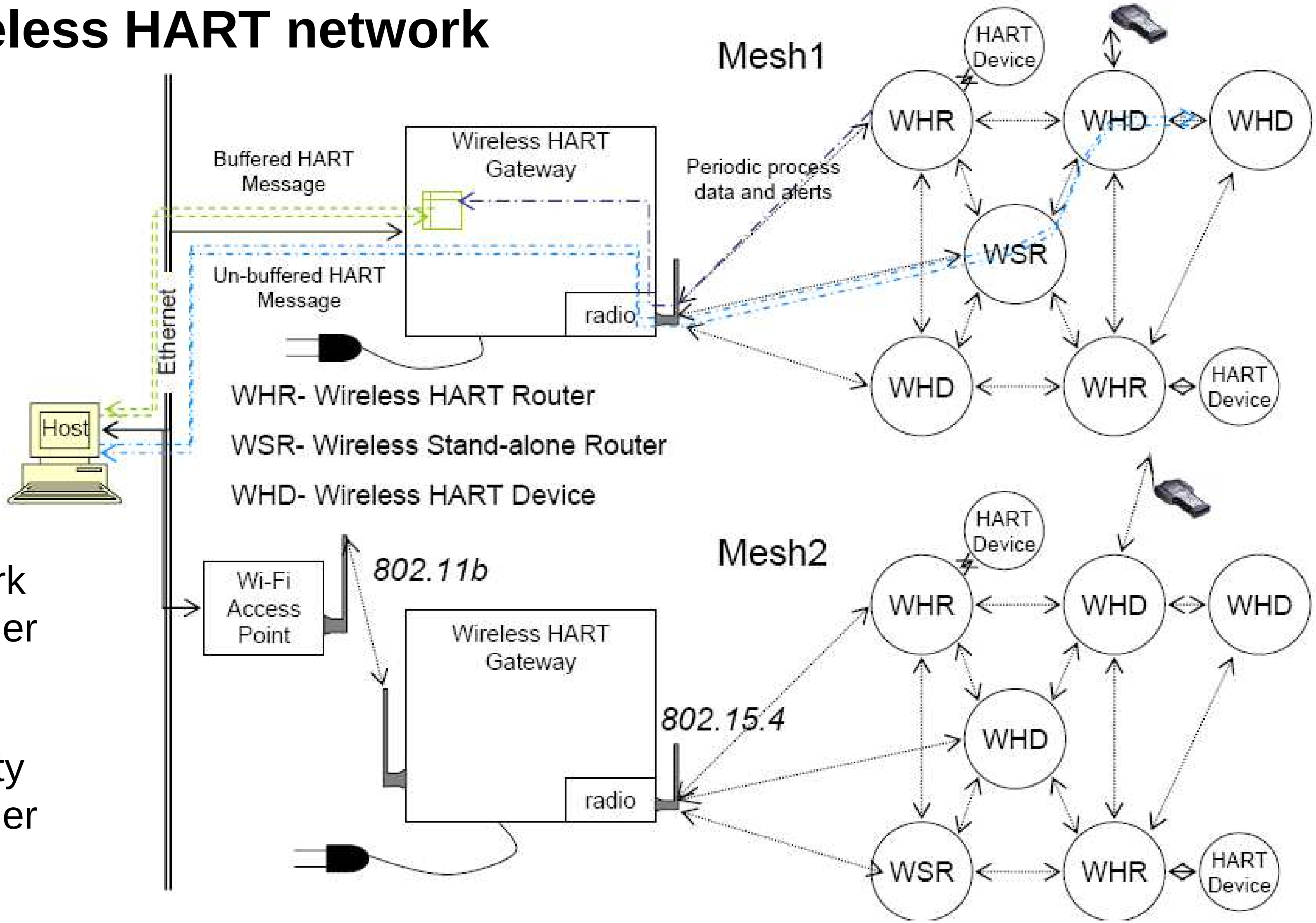
- ➢ HART 7.0 specification released 9/2007 including WH



OSI Layer	Function	HART	
		Wired FSK/PSK & RS485	Wireless 2.4GHz
Application	Provides the User with Network Capable Applications	Command Oriented. Predefined Data Types and Application Procedures	
Presentation	Converts Application Data Between Network and Local Machine Formats		
Session	Connection Management Services for Applications		
Transport	Provides Network Independent, Transparent Message Transfer	Auto-Segmented transfer of large data sets, reliable stream transport, Negotiated Segment sizes	
Network	End to End Routing of Packets. Resolving Network Addresses		Power-Optimized, Redundant Path,Self-Healing Wireless Mesh Network,
Data Link	Establishes Data Packet Structure, Framing, Error Detection, Bus Arbitration	A Binary, Byte Oriented, Token Passing, Master/ Slave Protocol.	Secure & Reliable ,Tme synched TDMA/CSMA, Frequency Agile with ARQ
Physical	Mechanical / Electrical Connection. Transmits Raw Bit Stream	Simultaneous Analog & Digital Signaling. Normal 4-20mA Copper Wiring	2.4GHz Wireless, 802.15.4 based radios, 10dBm Tx Power

WIRELESS HART FOR PROCESS CONTROL

Wireless HART network



Network Manager

Security Manager

WIRELESS HART: WELL SUPPORTED

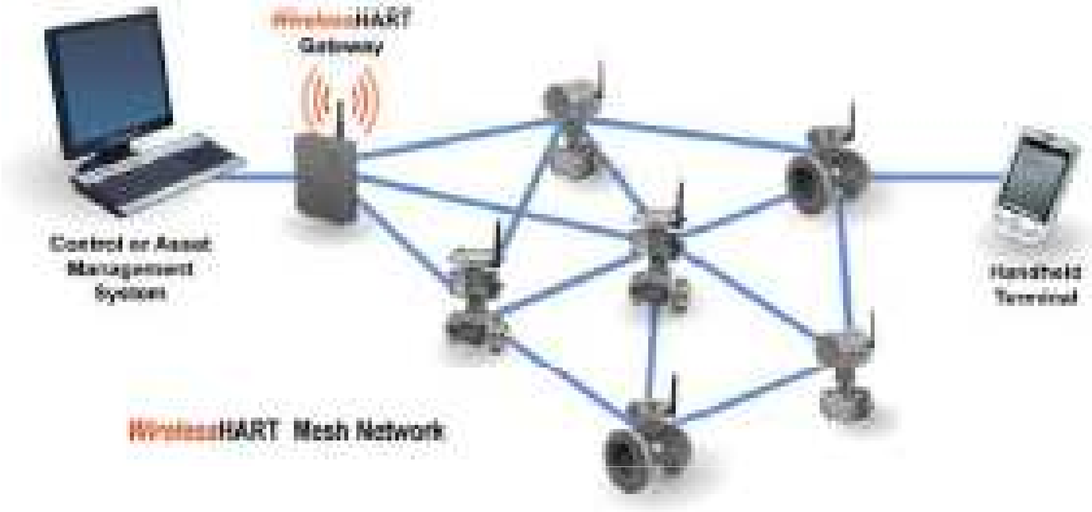
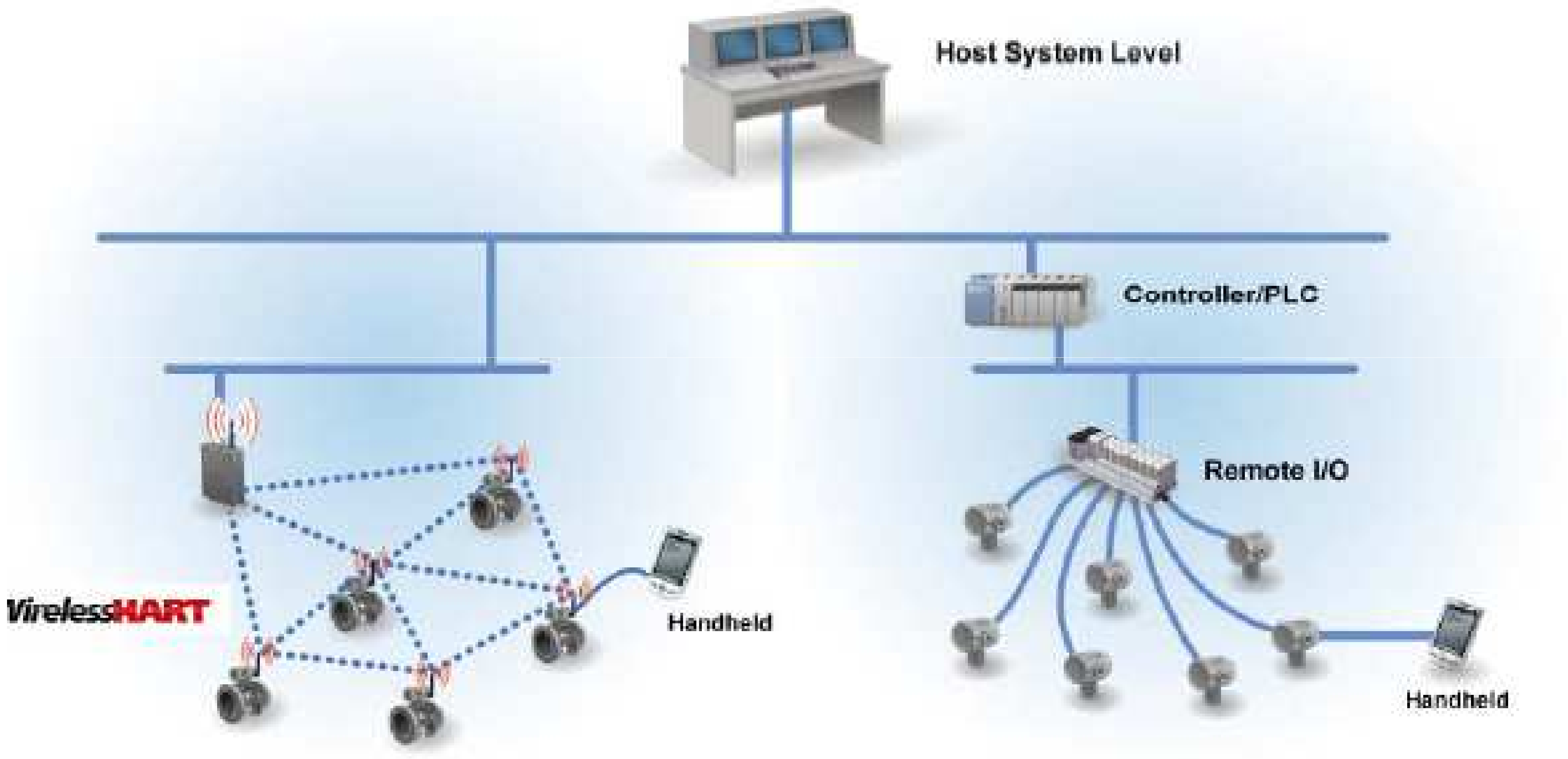


ABB
EMERSON
Endress+Hauser
SIEMENS
MACTek
PEPPERL+FUCHS
PHOENIX CONTACT
PROCOMSOL
STAHL

Courtesy of HART Consortium

WIRELESS HART: HYBRID ARCHITECTURE

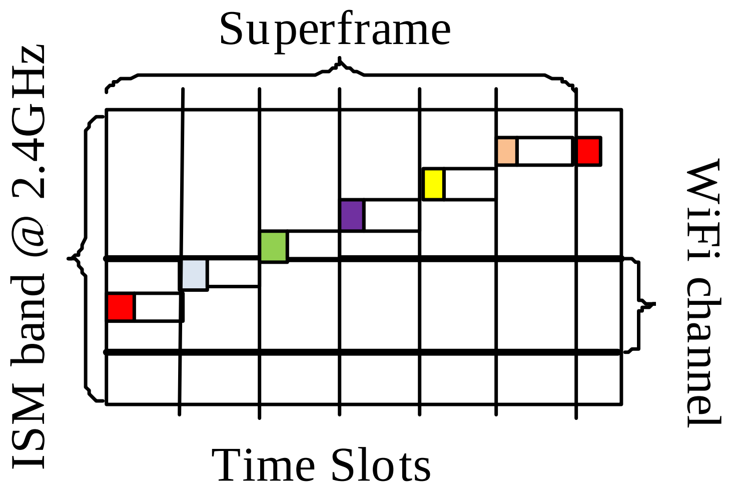


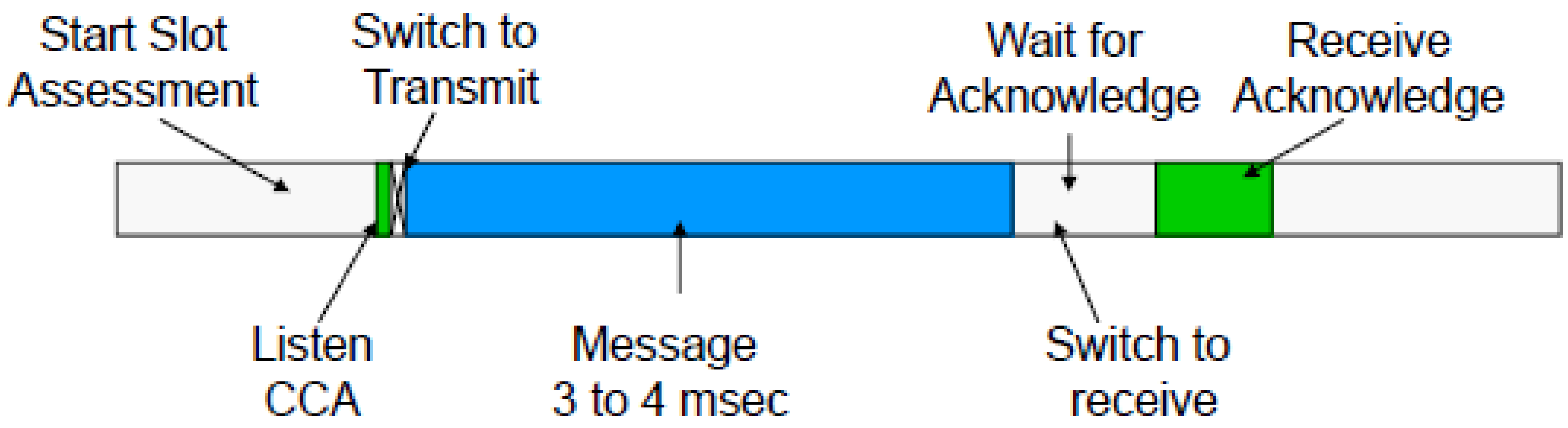
Courtesy of HART Consortium

WIRELESS HART: THE SUPERFRAME

Cycle organization

- 10ms time slots
- 1 frame (up to 8 Process Values + Status) per slot
- Assigned slots and shared slots
- Slots arranged in frequency hopping
- Blacklisting channel, Power tuning



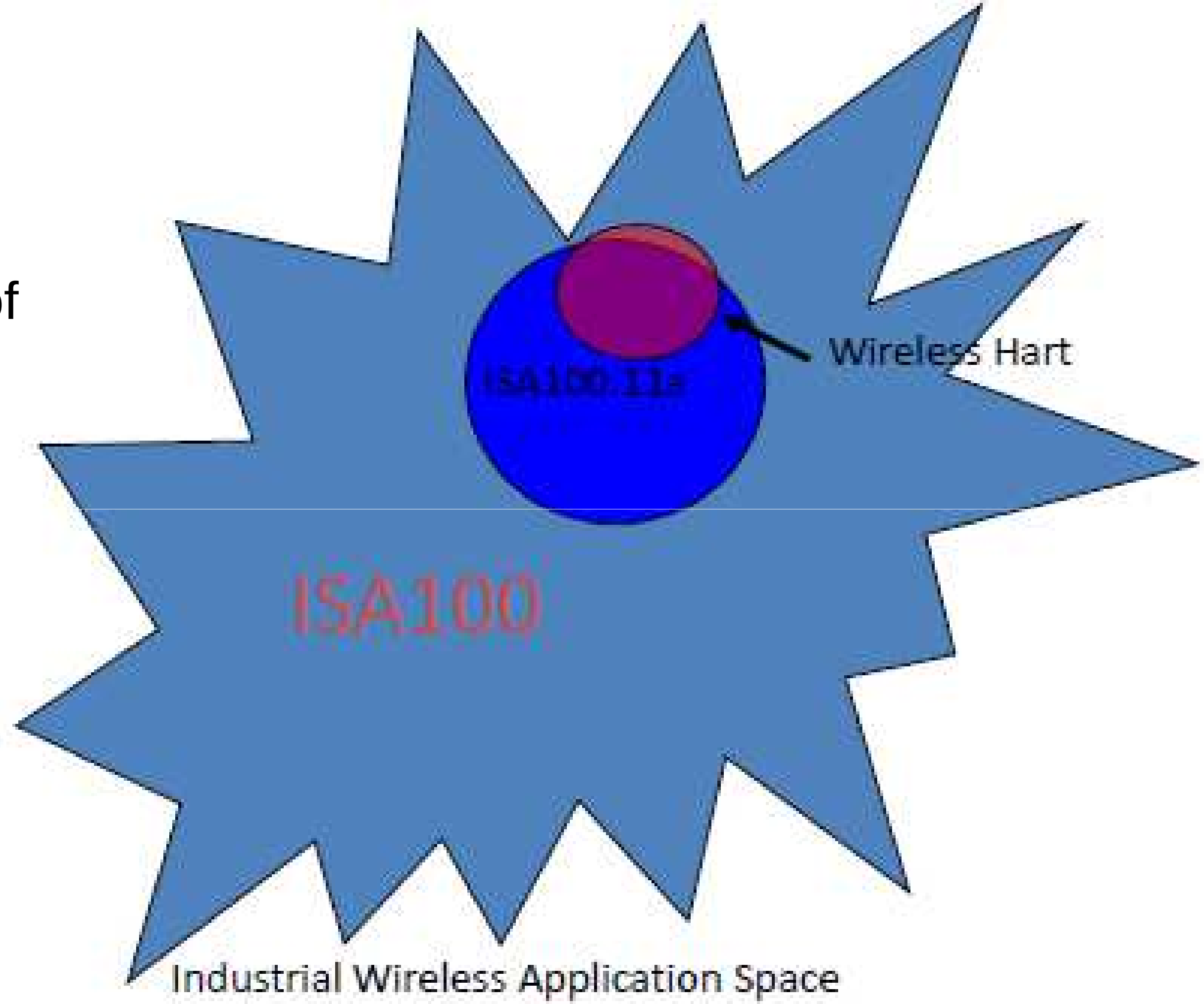


Courtesy of HART Consortium

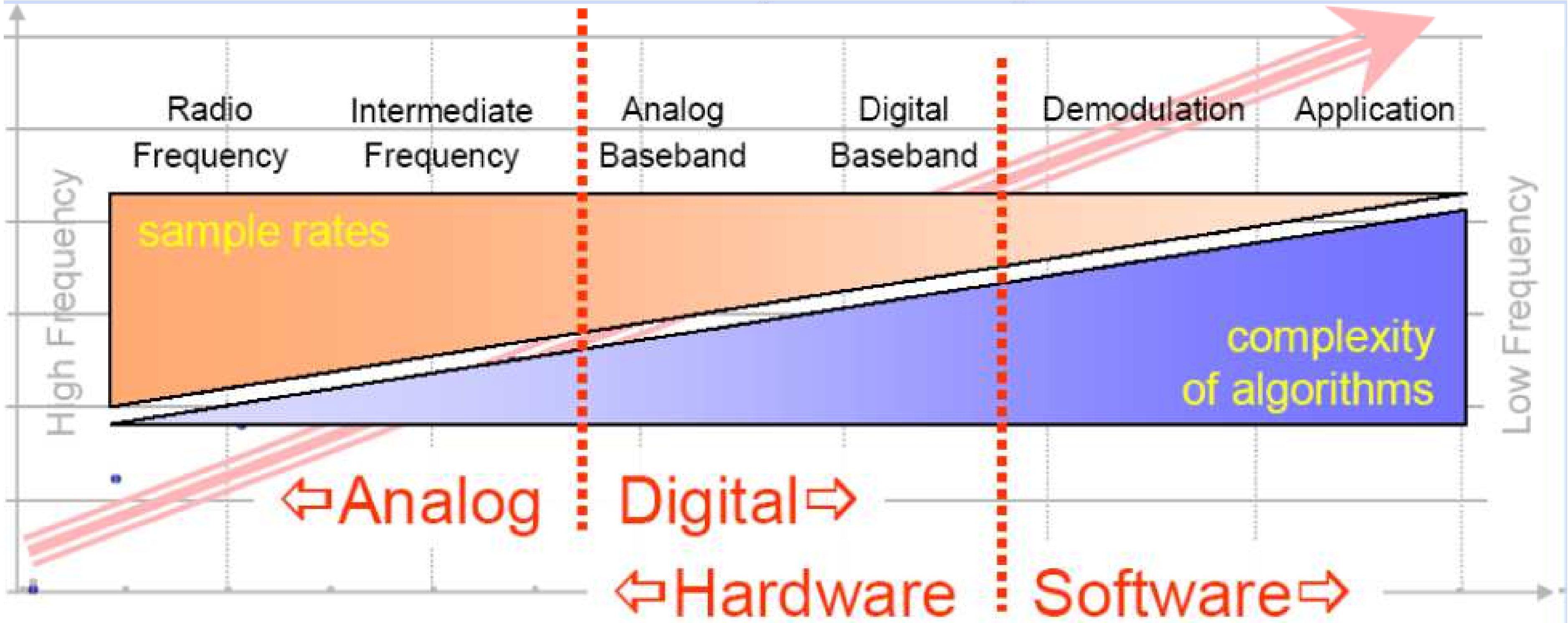
ISA 100 AND WIRELESS HART

Comparison

- Wireless Hart and ISA100.11a share many of the same reliability characteristics
- No coexistance
- ISA100.11a supports IP backbone routing



NEW TRENDS: SOFTWARE DEFINED RADIO (SDR)



Where is the border between Hardware and Software?

- ➢ Where is the border between analog and digital (where to put ADC?)
  - It is a technological matter. If we could sample and convert at 2.4GHz at low-cost and low-power dissipation it should be the best!

SMART GRID AND INTERNET OF THINGS IN INDUSTRY

- From substation down to trasformer and machines = integration between smart grid and industrial communication at field level
- Smart grid includes:
  - IEC61850 (communication among substations, TCP, less than 4 ms)
  - PLC (Power Line Communications) -> BPL (Broadband over Power Line)
  - Communications for metering (M-bus, OMS,..)
  - Wireless M2M communications
  - Vehicle2vehicle (vehicle2infrastructure) wireless communications
  - …

- TCP/IP and UDP/IP seem to be the unified network layer (e.g. 6LowPAN)
- Smartphone and tablets are mobile interface in factory and plants
- Augmented reality means information fusion among real sensors and databases (fault recovery, commissioning)

SENSOR NETWORKS FOR INDUSTRIAL APPLICATIONS

- Industrial applications require smart sensors (plug&play)
- The “real-time” constrain limits the use of consumer solutions
- Real Time Ethernet are replacing fieldbuses thanks to better performance (stack) and diagnostic (TCP/IP)
- Hibrid solutions (RTE, Wireless sensor networks, PLC) seem the opportunistic way for industrial applications at the field level
- Tools for industrial sensor networks are needed
- Smart grids and Internet of things are the next future challenges

… WE’LL TALK ABOUT IT IN THE NEXT YEARS