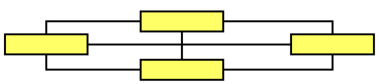
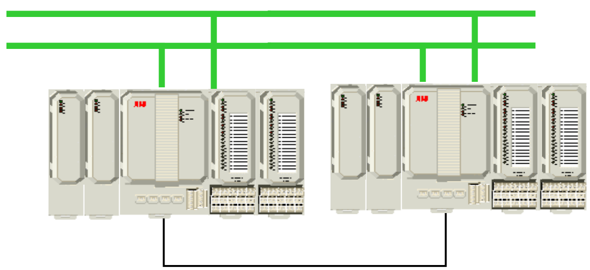
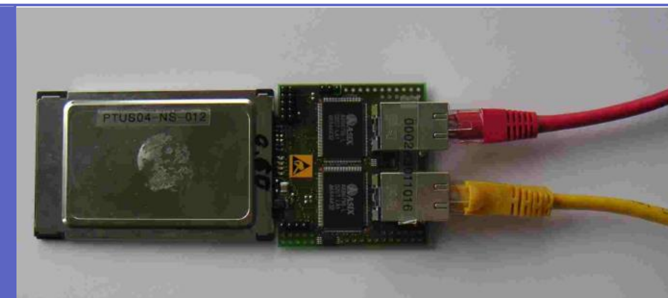
Highly Available Automation Networks Standard Redundancy Methods

Rationales behind the IEC 62439 standard suite

Hubert Kirrmann
ABB Switzerland Ltd,
Corporate Research







© 2012 ABB

Scope

"The good thing about "Industrial Ethernet" standards is that there are so many to choose from (IEC 61784) - you can even make your own"

It remains to be proved that the new networks are more reliable than the field busses that they are supposed to replace.

However, customers require the new technology to be "at least as dependable as the one it replaces"

But few "Industrial Ethernets" care about redundancy.

This talk shows what must be looked at when considering automation network redundancy and which solutions IEC 62439 proposes

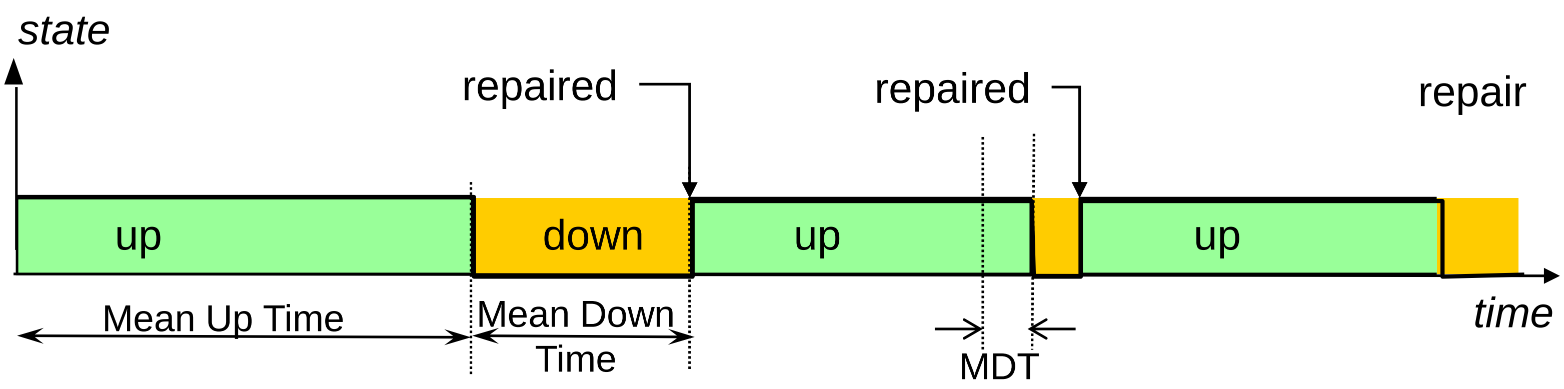
IEC 62439 includes seven specifications

IEC 62439-1	defines the terms specifies how to calculate the reliability and availability specifies how to calculate the recovery time of **RSTP** (IEEE 802.2d)
IEC 62439-2	**MRP** (Media Redundancy Protocol), the Profinet ring protocol supported by PNO, Siemens, Hirschmann, Phoenix-Contact
IEC 62439-3	Two seamless protocols (**no recovery time**) **PRP** (Parallel Redundancy Protocol) **HSR** (High-availability, Seamless Redundancy) supported by ABB, Siemens, Hirschmann, ZHAW, Flexibilis
IEC 62439-4	**CRP** (coupled redundancy protocol) used by supported by Fieldbus Foundation, Honeywell
IEC 62439-5	**BRP**, similar to CRP supported by Rockwell & ODVA.
IEC 62439-6	**DRP** (Distributed Redundancy Protocol), similar to MRP and including a clock synchronization, supported by SupCon (China)
IEC 62439-7	**RRP** (in preparation) another ring redundancy protocol supported by RAPIEnet, LS Industrial Systems Co (Korea).

Some terms

Availability applies to *repairable* systems

Availability is the fraction of time a system is in the “up” state (capable of operation)
It is expressed in % (“duty cycle”), e.g. 99.99%.

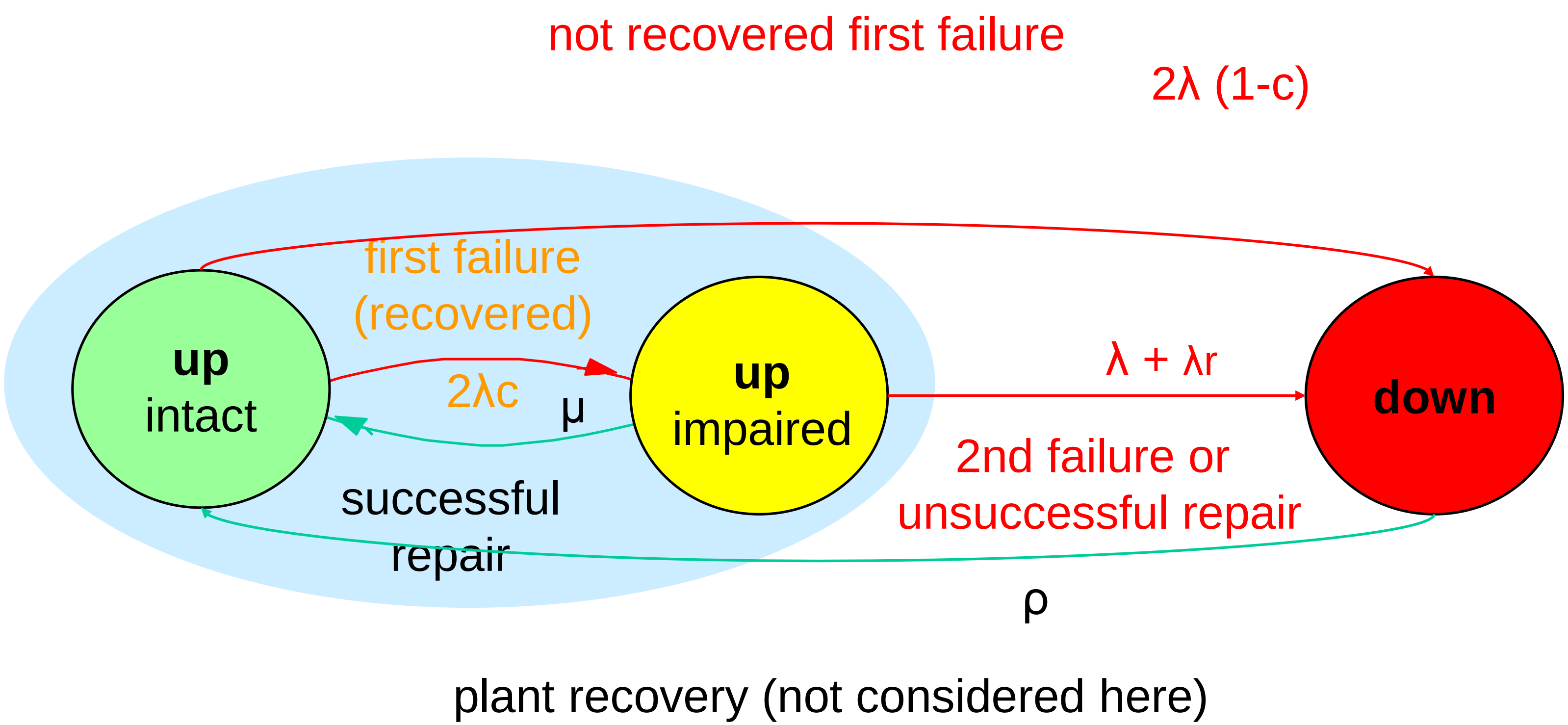


We consider systems in which availability is increased by introducing redundancy
(availability could also be increased by better parts, maintenance)

Redundancy is any resource that would not be needed if there were no failures.

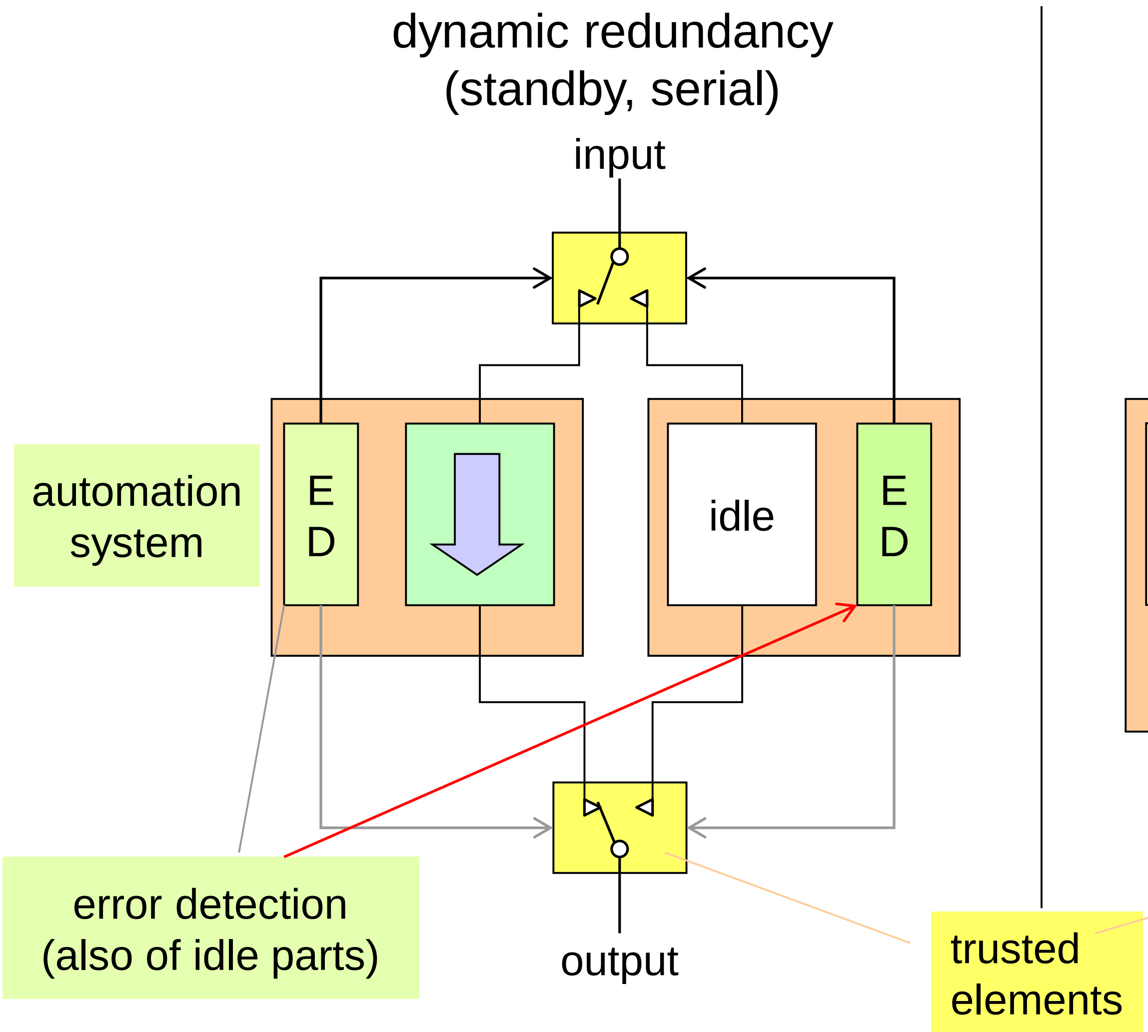
We consider automatic insertion of redundancy in case of failure (fault-tolerant systems)
and automatic reinsertion after repair.

Availability states

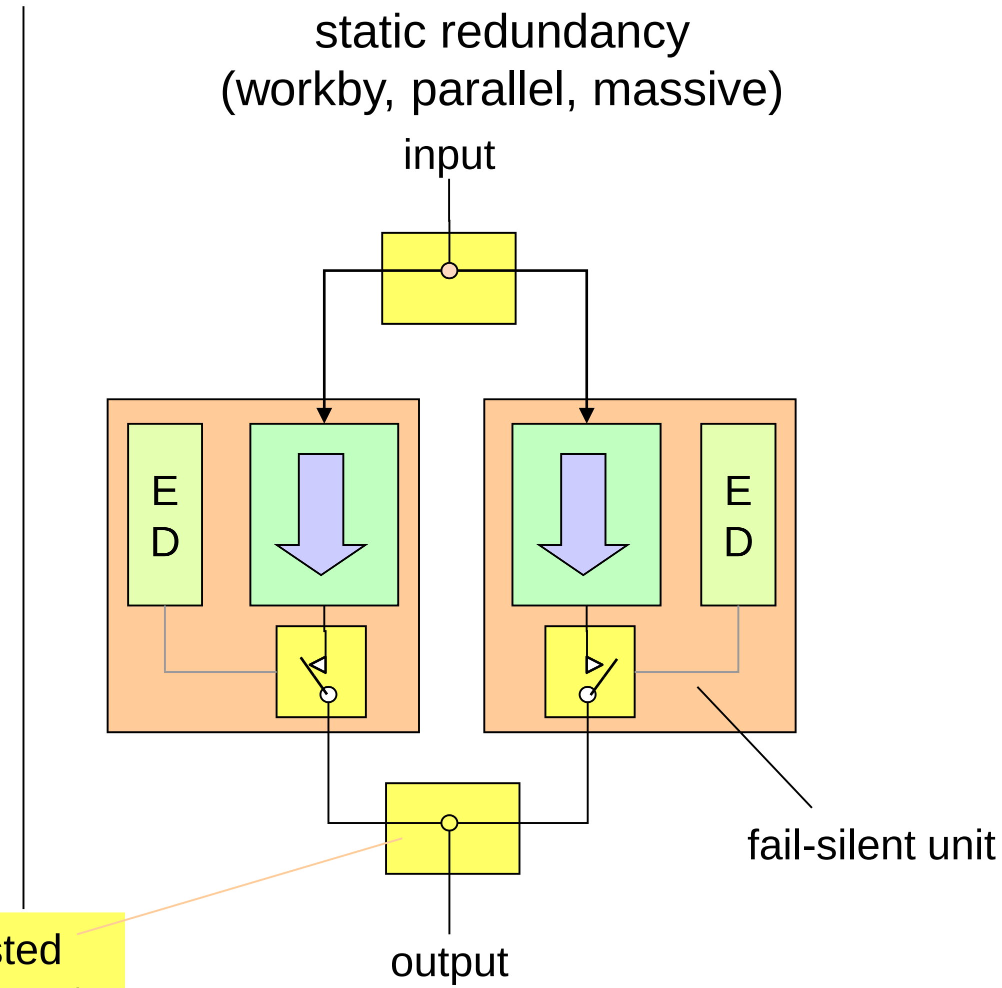


we must consider all transitions, not just what happens after a failure

Classification of redundancy methods (1)



paradigm: spare tire



paradigm: double tires in trucks

Classification of redundancy methods (2)

Dynamic (standby, serial) redundancy	Static (parallel, workby) redundancy
Redundancy is not actively participating in the control. A switchover logic decides to insert redundancy and put it to work	Redundancy is participating in the control, the plant chooses the working unit it trusts.
This allows to:	This allows to:
+ share redundancy and load	+ provide seamless switchover
+ implement partial redundancy	+ continuously exercise redundancy and increase fault detection coverage
+ reduce the failure rate of redundancy	+ provide fail-safe behavior
+ reduce common mode of errors	
- but switchover takes time	- but total duplication is costly

Requirements of fault-tolerant systems

degree of redundancy (full, partial duplication)
- “Hamming Distance”: minimum number of components that must fail to stop service

guaranteed behavior when failing
- fail-silent or not

switchover delay
- duration of loss of service in case of failure

reintegration delay
- duration of disruption to restore redundancy after repair (live insertion)

repair strategy
- 365/24 operation, scheduled maintenance, daily stops,…

supervision
- detection and report of intermittent failures (e.g. health counters).
- supervision of the redundancy (against lurking errors)

consequences of failure
- partial / total system loss, graceful degradation, fault isolation

economic costs of redundancy
- additional resources, mean time between repairs, mean time between system failure

factors depending on environment
- (failure rate, repair rate) are not considered here.

switchover time and grace time

The switchover delay is the most constraining factor in fault-tolerant systems.

The switchover delay is dictated by the **grace time**, i.e. the time that the plant allows for recovery before taking emergency actions (e.g. emergency shut-down, fall-back mode).

E.g. recovery time after a communication failure must be shorter than the grace time to pass unnoticed by the application.

The grace time classifies applications:

Uncritical	< 10 s	(not real time) Enterprise Resource Planning, Manufacturing Execution
Automation general:	< 1 s	(soft real-time) human interface, SCADA, building automation, thermal
Benign	< 100 ms	(real-time) process & manufacturing industry, power plants,
Critical:	< 10 ms	(hard real time) synchronized drives, robot control, substations, X-by-wire

Recovery delay demands as shown in IEC 61850-5 Ed. 2

Communicating partners	Service	Application recovery tolerated delay	Required Communication Recovery Time
SCADA to DAN, client-server	IEC 61850-8-1	800 ms	400 ms
DAN to DAN interlocking	IEC 61850-8-1	12 ms (with Tmin set to 4 ms)	4 ms
DAN to DAN, reverse blocking	IEC 61850-8-1	12 ms (with Tmin set to 4 ms)	4 ms
Protection trip excluding Bus Bar protection	IEC 61850-8-1	8 ms	4 ms
Bus Bar protection	IEC 61850-9-2 on station bus	< 1 ms	Bumpless
Sampled Values	IEC 61850-9-2 on process bus	Less then two consecutive samples	Bumpless

To fulfill these requirements, IEC 61850-8-1 and -9-2 uses redundancy solutions standardized for Industrial Ethernet by IEC 62439-3.

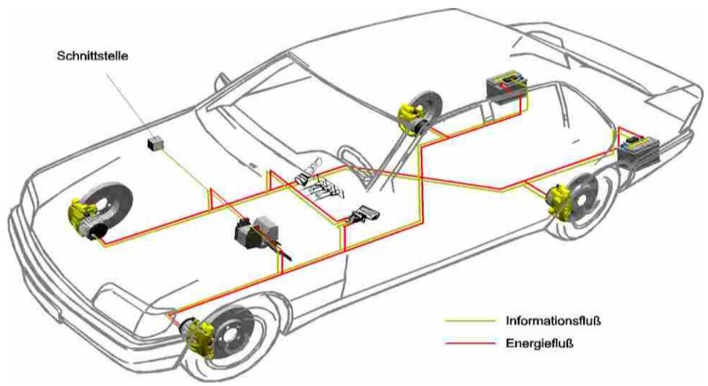
Grace time depends on the plant (typical figures)

cement: 10s

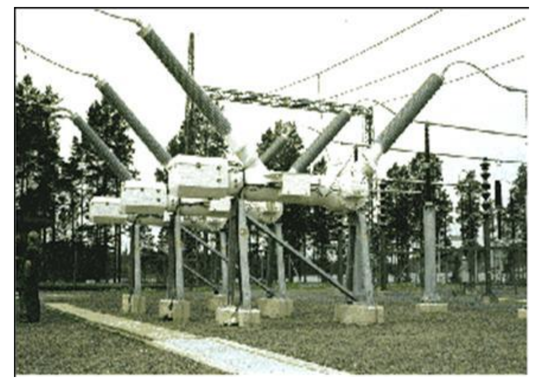
chemical: 1s

printing: 20 ms

tilting train: 100ms

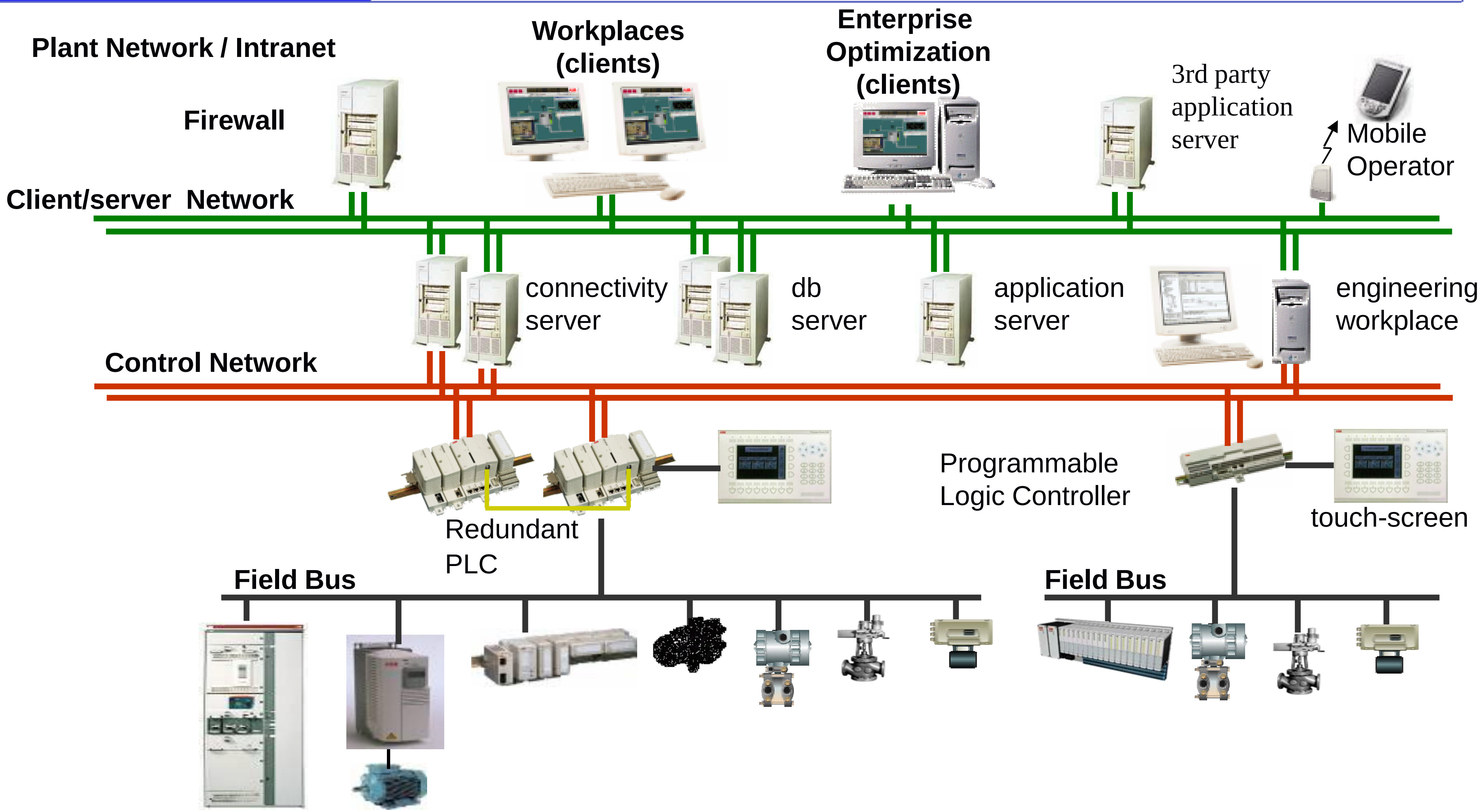


X-by wire: 10ms



substations: 5 ms

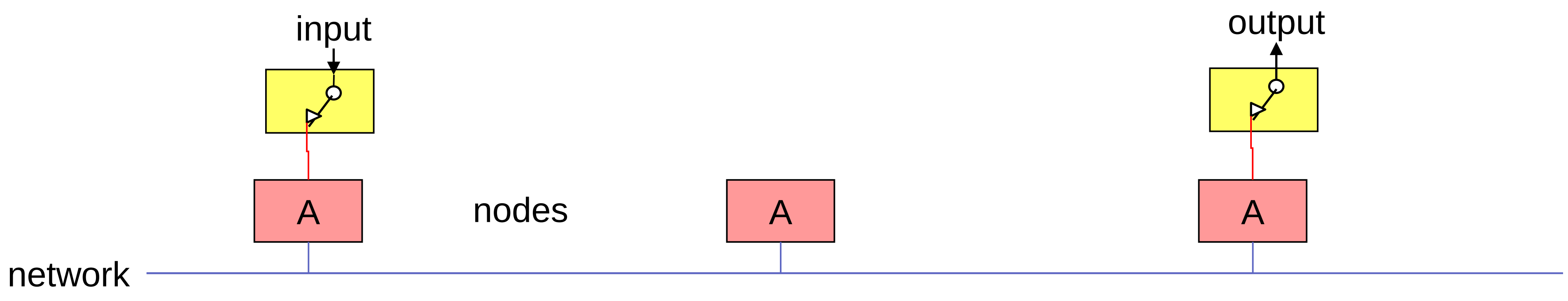
Automation Networks: fully duplicated architecture



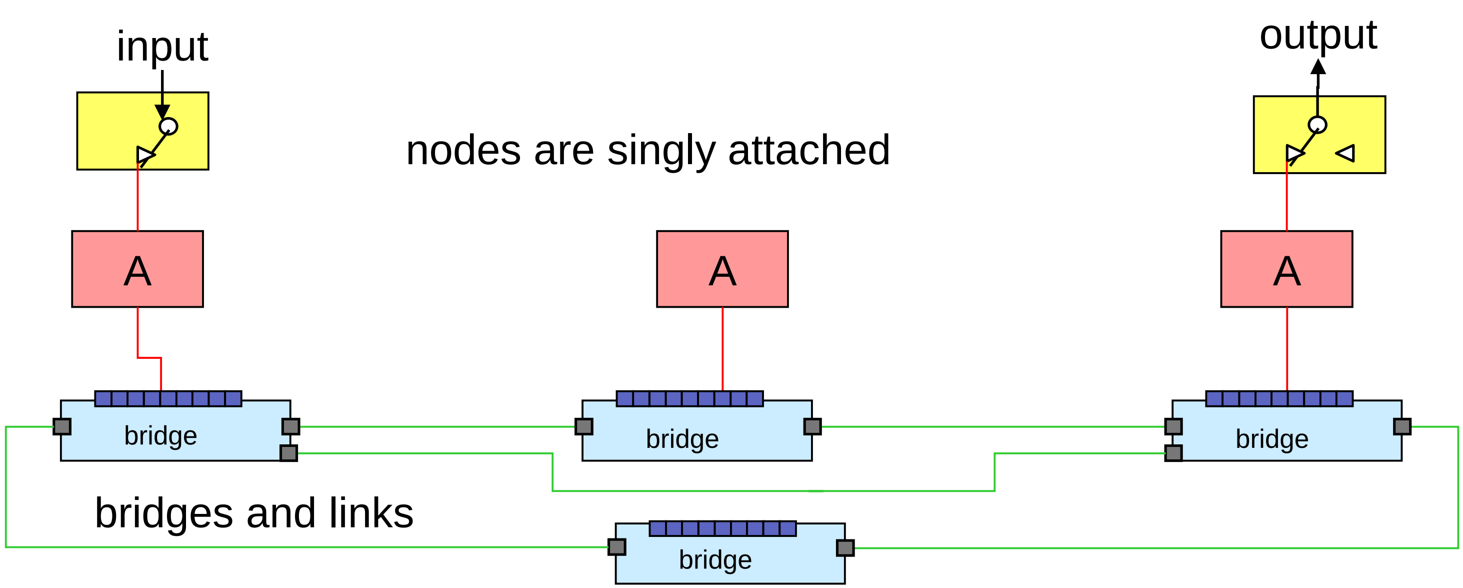
We consider networks for automation systems, consisting of nodes, bridges and links.

Device and network redundancy (1)

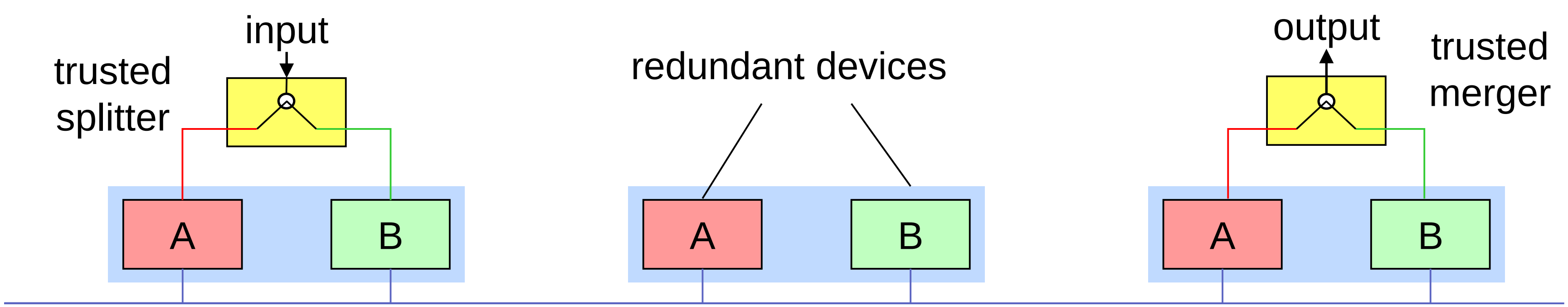
1) No redundancy (except fail-silent logic)

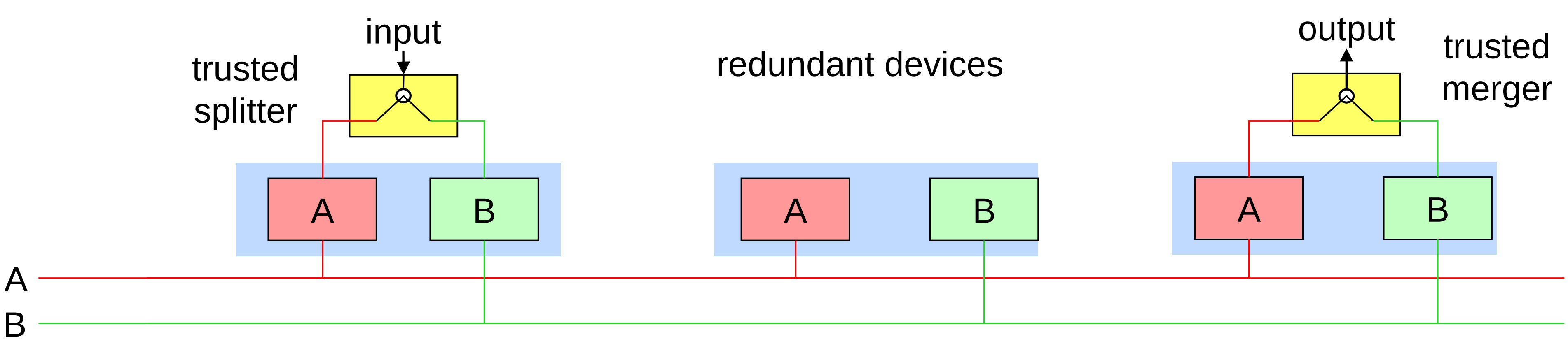


2) Redundancy in the network: protects against network component failures



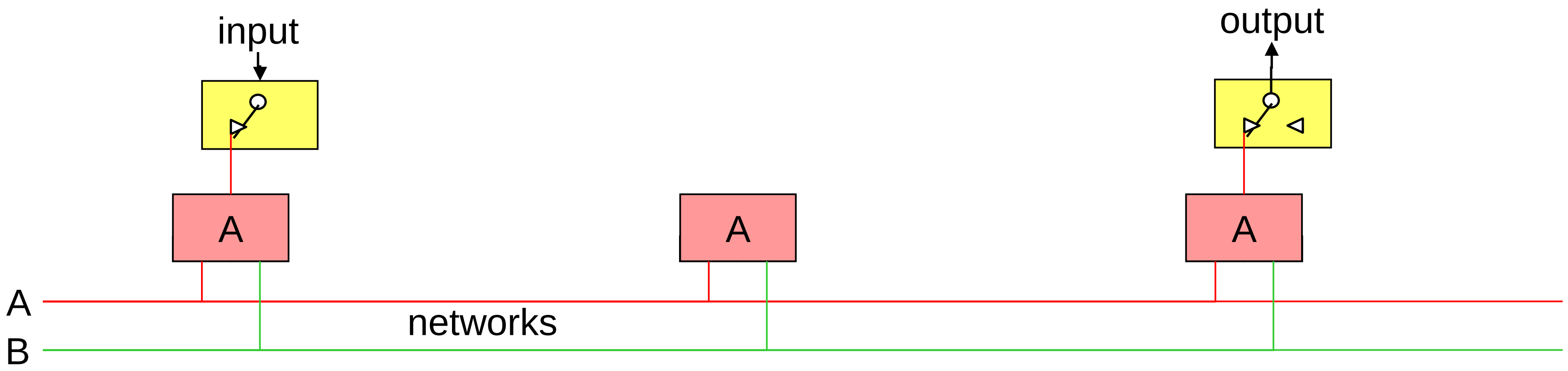
Device redundancy and network redundancy (1)



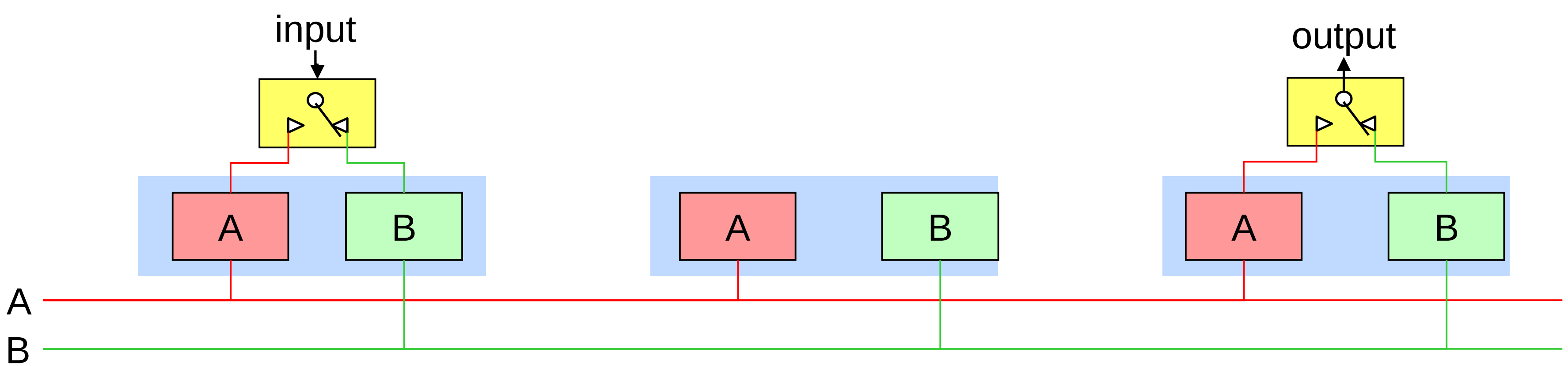


Device and network redundancy (2)

3) Doubly attached nodes protects in addition against network adapter failures

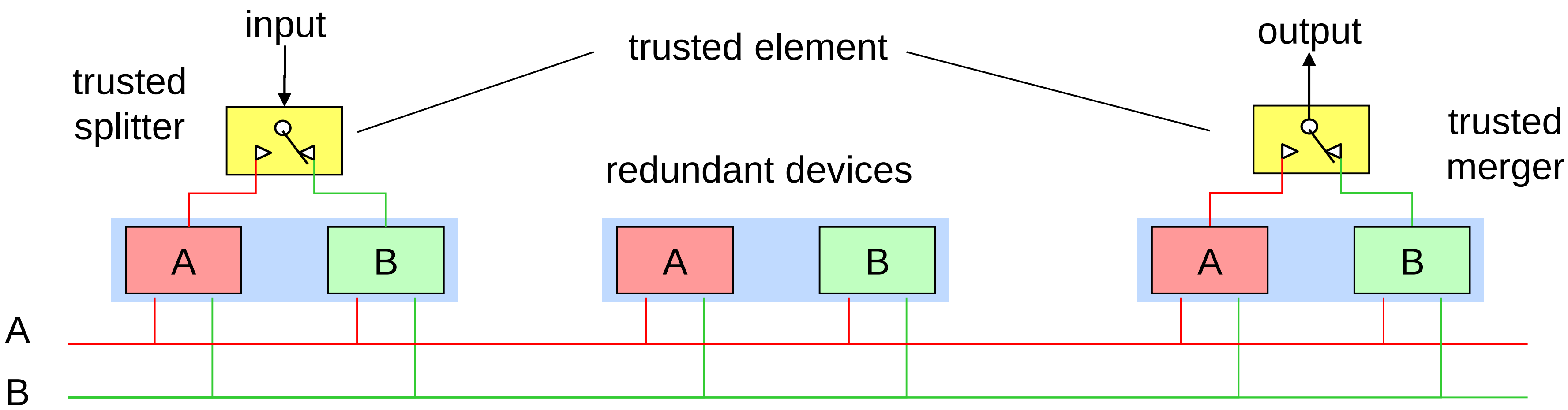


4) Redundant, singly attached nodes protect against node <u>or</u> network failures



Device and network redundancy (3)

5) Doubly attached nodes and network crossover protect against node and network failure

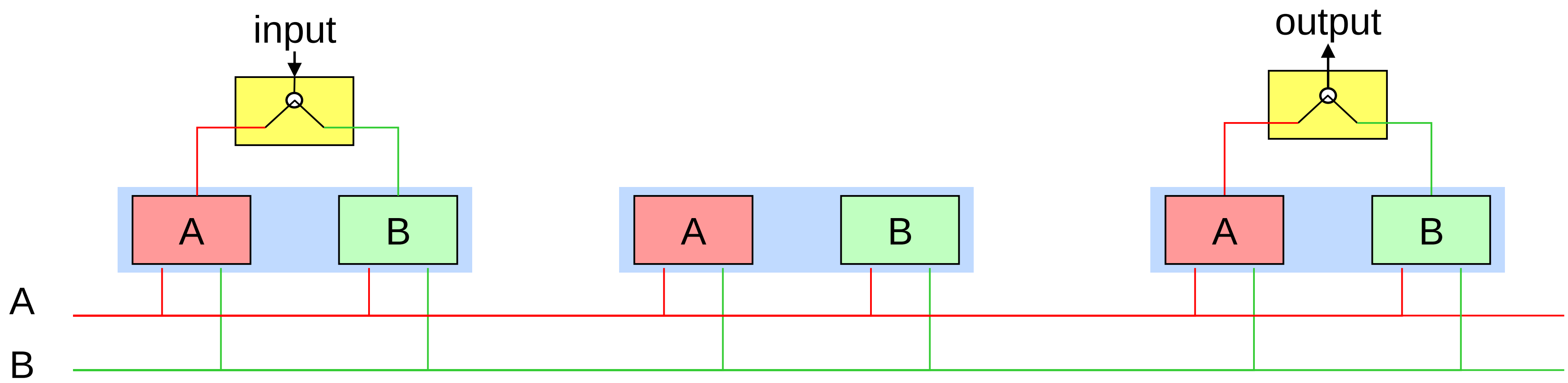


Crossover redundancy allows to overcome double failures (device and network).

However, use of crossover must be cautious, since crossover relies on elements that can represent single points of failure and should be very reliable to bring a benefit.

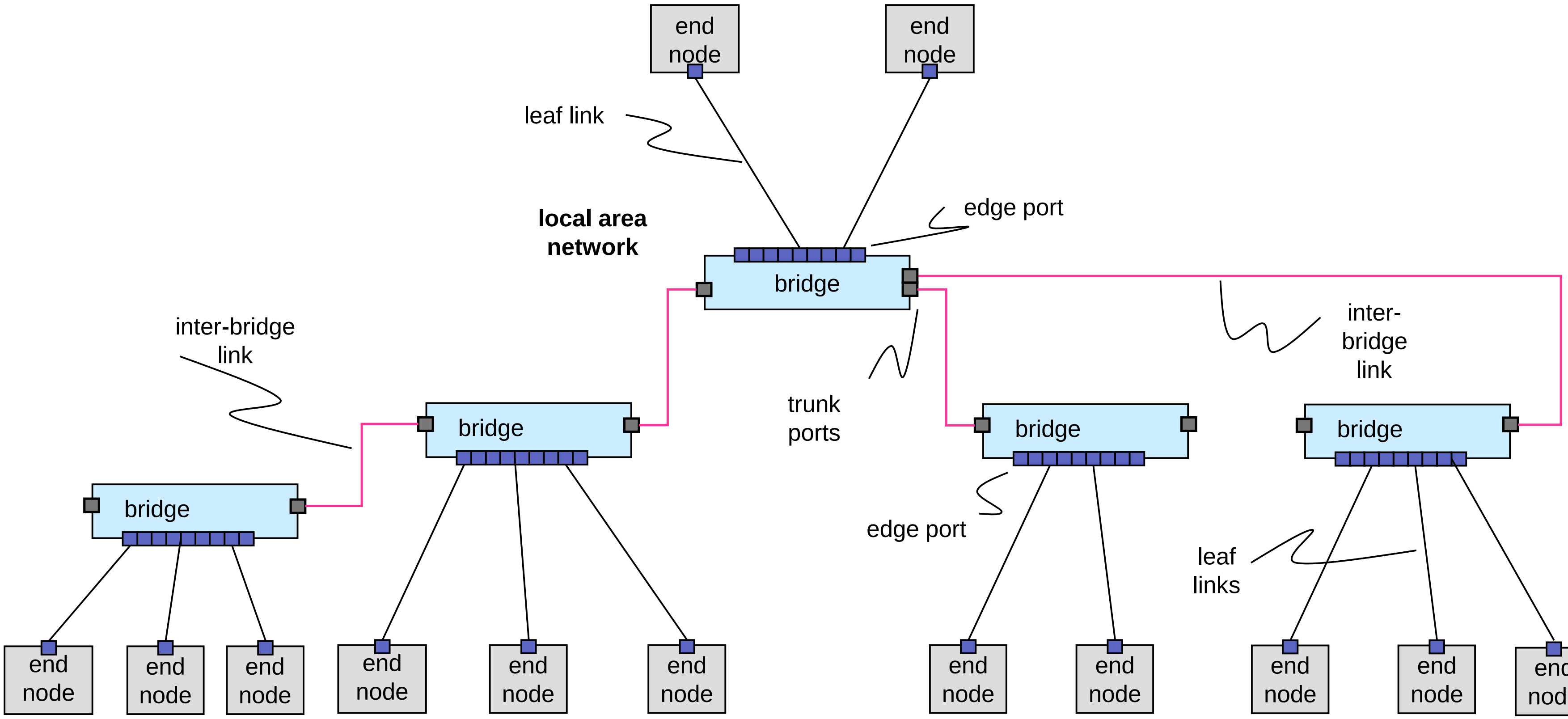
IEC SC65C addresses redundancy types 2 and 3 –
redundancy types 4 and 5 can be built out of the 2 and 3 solutions

Workby operation



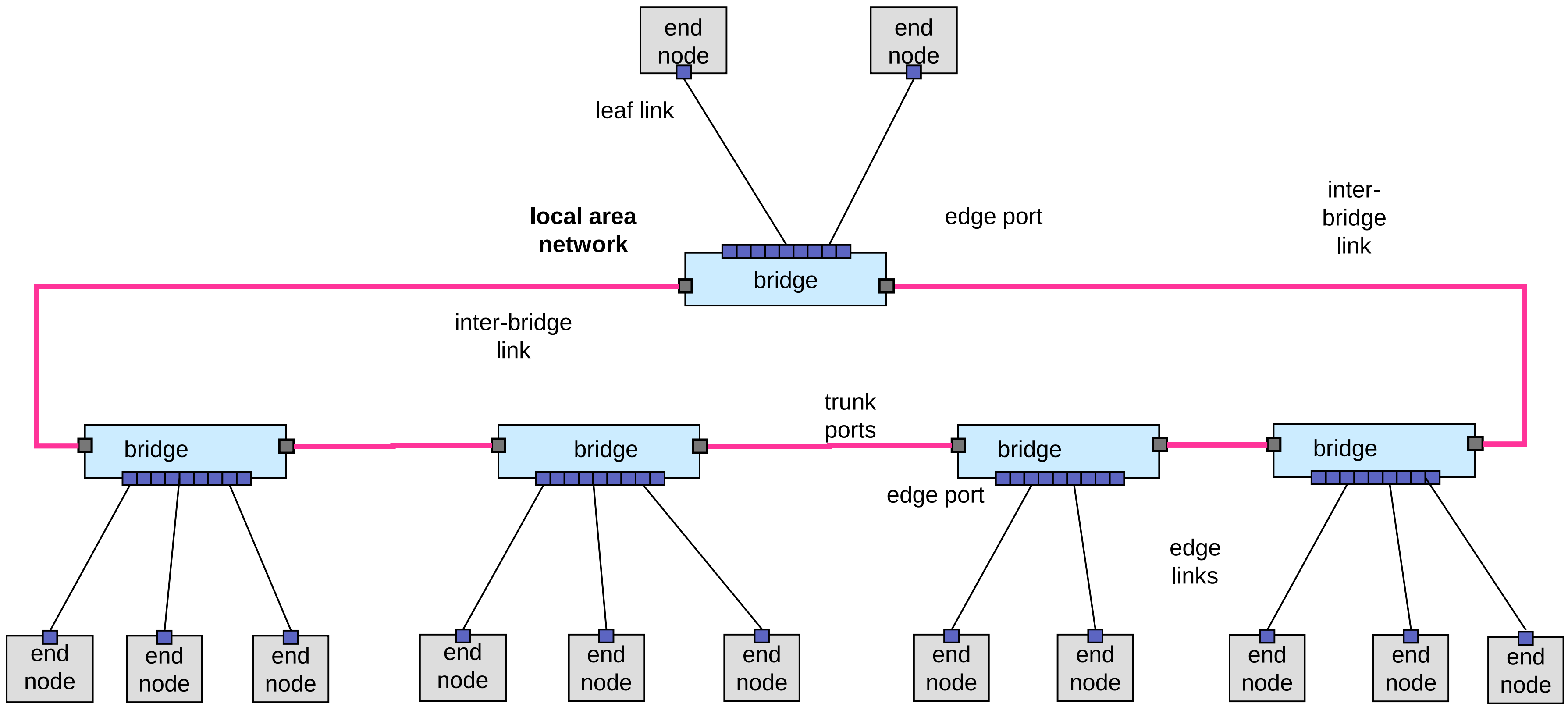
© 2012, ABB,

Ethernet-based automation networks (tree topology)



in principle no redundancy

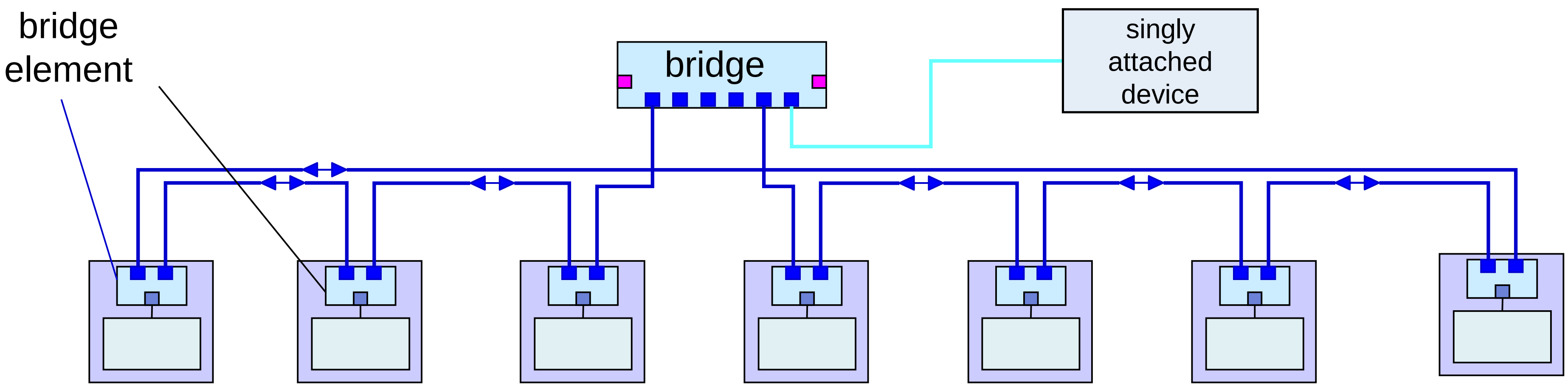
Ethernet-based automation networks (ring topology)



longer delays, but already has some redundancy

© 2012, ABB, 23

Ethernet-based automation networks (ring of nodes)



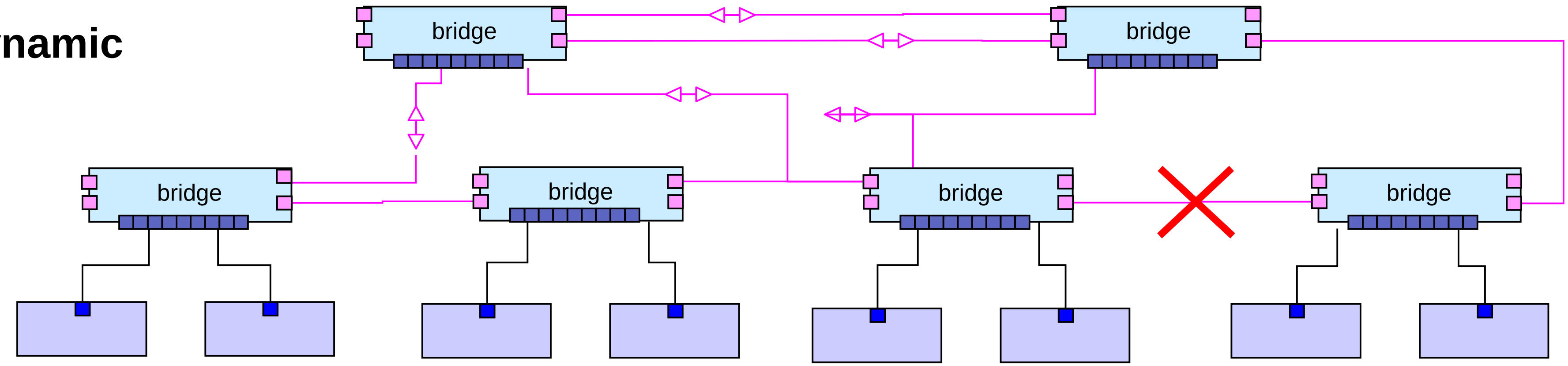
This topology is becoming popular since it suppresses the (costly) bridges and allows a simple linear cabling scheme, while giving devices a redundant connection.

Operation is nevertheless serial redundancy, i.e. requires a certain time to change the routing.

Devices are doubly-attached, but do not operated in parallel.

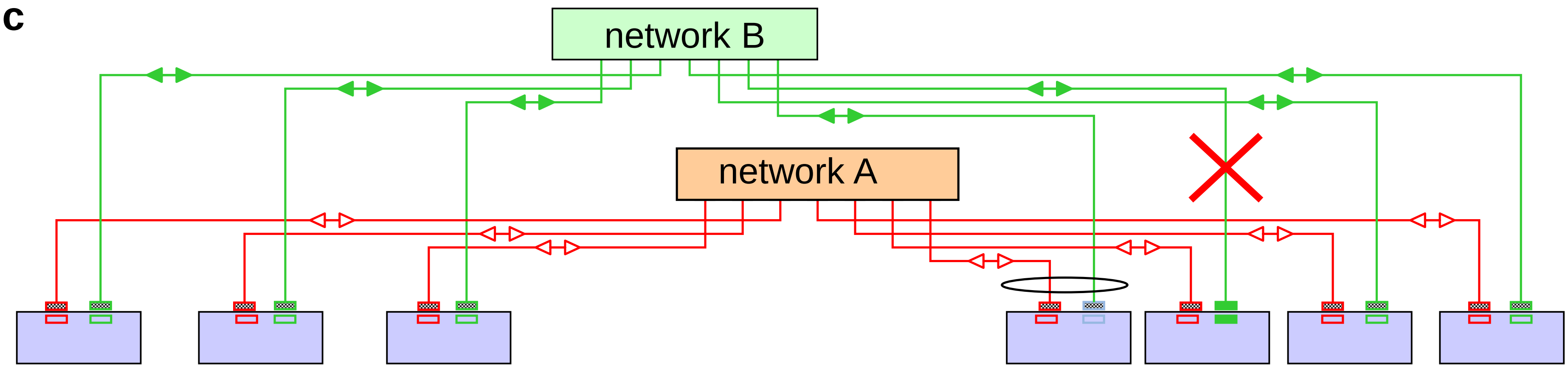
Dynamic and static redundancy in networks

Dynamic



in case of failure, bridges route the traffic over an other port – devices are singly attached

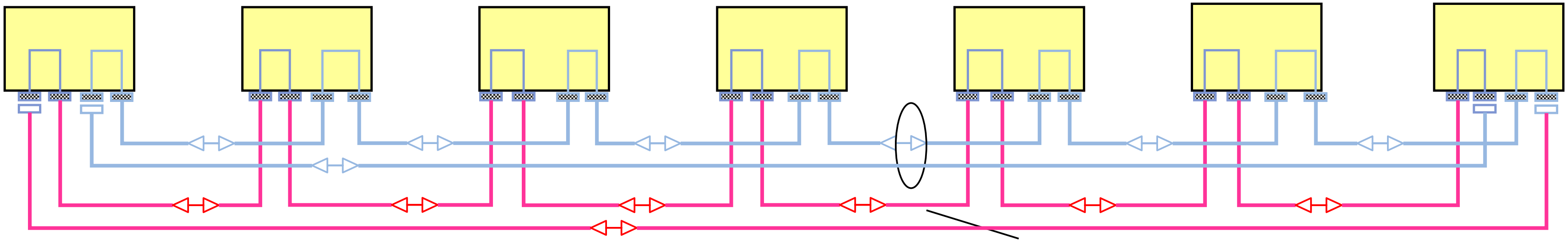
Static



in case of failure the doubled attached nodes work with the remaining channel.
Well-known in the fieldbus workd

Redundant Layout

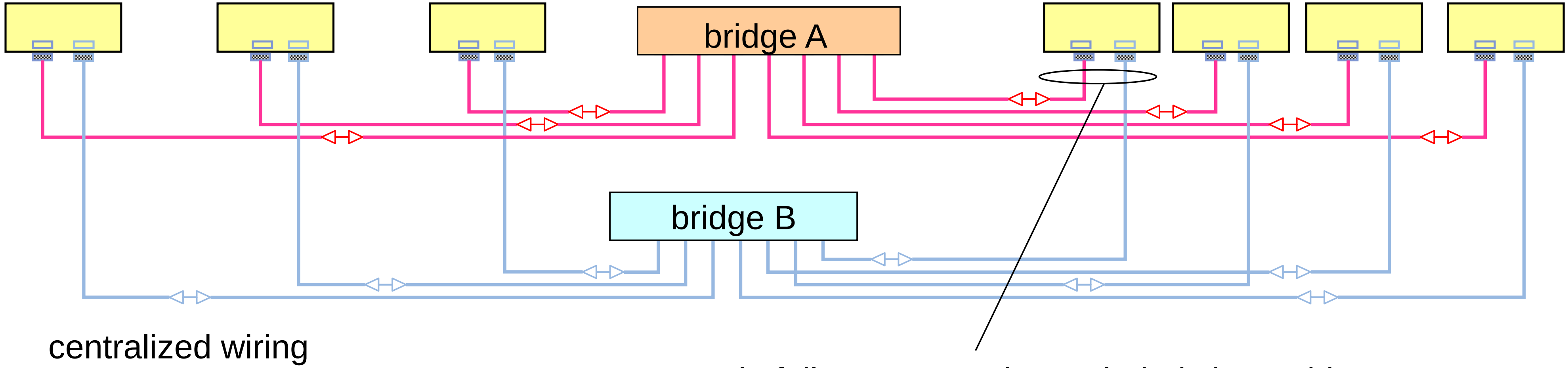
Party-Line topology (mixed B and C)



both cables can run in the same conduct
if common mode failure acceptable

Star topology (C)

bridges shall be separately powered

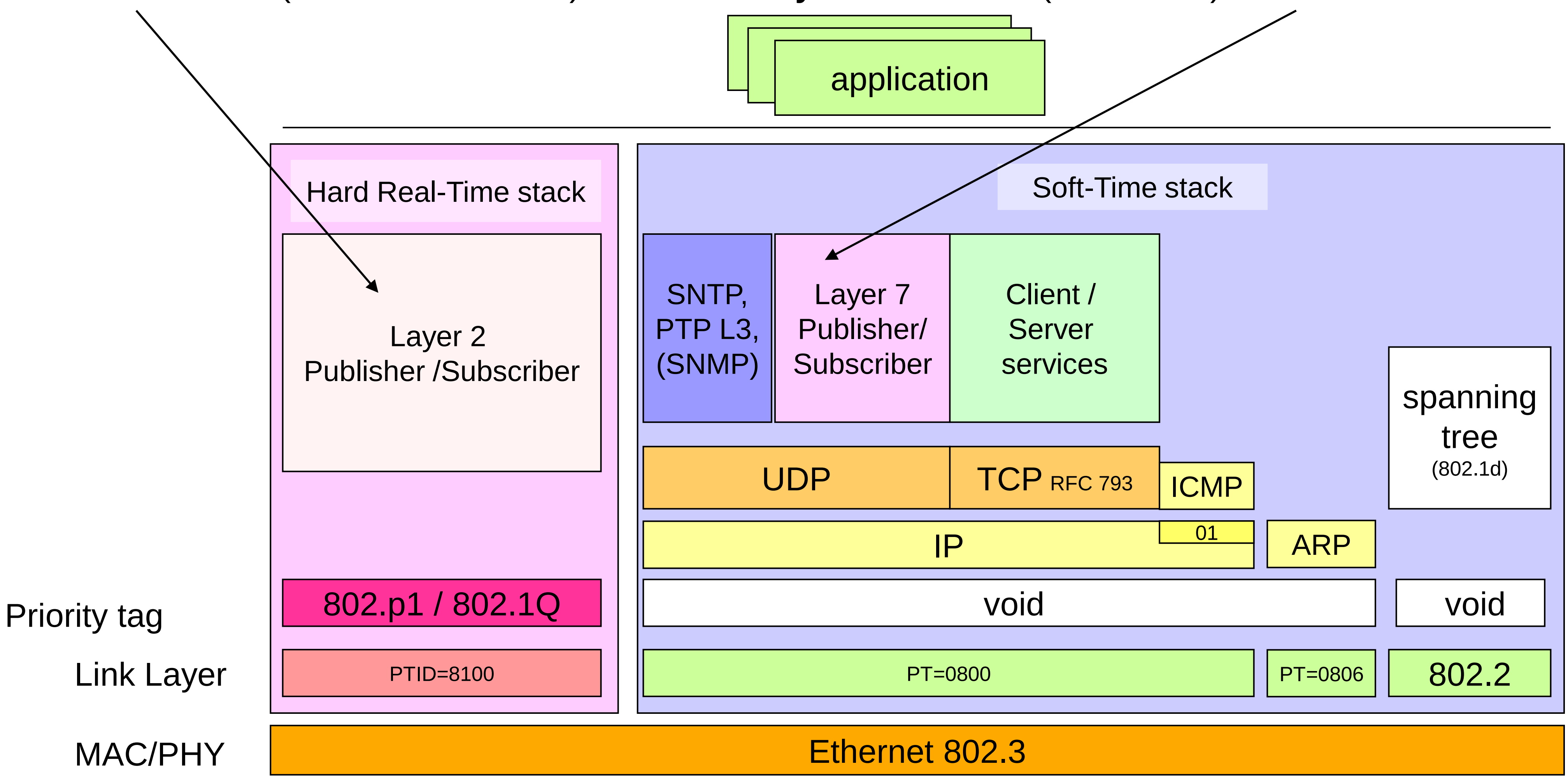


centralized wiring

common mode failures cannot be excluded since wiring
comes close together at each device

What makes Industrial Ethernet special

Most “Industrial Ethernet” uses the classical TCP-UDP-IP stack and in addition **a layer 2 traffic** for real-time data (but some use UDP) and a **clock synchronization** (IEEE 1588)



Therefore, Industrial Ethernet redundancy must operate at level 2

Communication stack and redundancy

The redundant Ethernet solutions distinguish themselves by:

- the OSI level at which switchover or selection is performed.

- whether they operate with dynamic or static redundancy

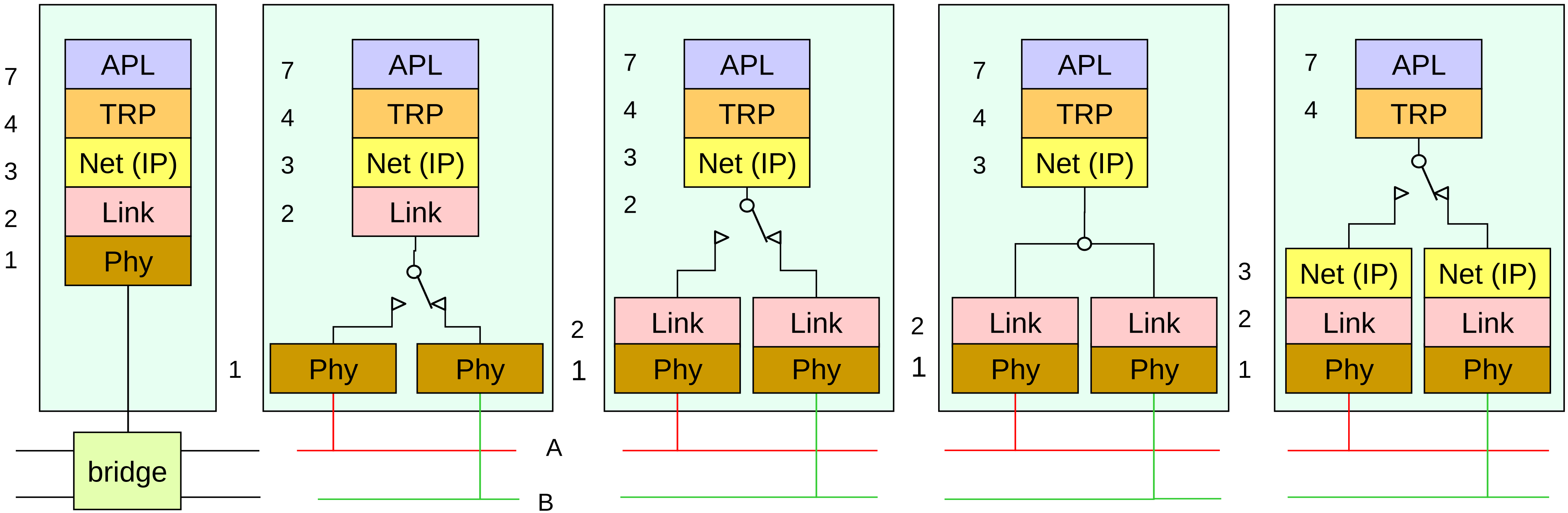
Industrial protocols operate both at network layer (IP) and at link layer (e.g. Real Time traffic, clock synchronization traffic),

Redundancy only at network level is not sufficient, it must be implemented at layer two to account for industrial Ethernets that use these layers.

Since standard methods handle effectively redundancy at the network layer (TCP / IP), network level redundancy is separated from the device-level redundancy.

Commercial solutions to redundancy in the nodes

(no duplication of nodes)



only redundancy within the network	physical layer (drivers)	link layer (drivers and controller)	link layer (drivers and controller)	network layer (drivers, controller and network routing)
1N	1 Ethernet controller	2 MAC Addresses	1 MAC Addresses	2 IP Addresses

the level of redundancy can be identified by the addresses used

Methods for dynamic redundancy in networks

-IP protocol	Layer 3 (network)	10s or more – unsuited for Industrial Ethernet
-RSTP (IEEE 802.1D)	Layer 2 (bridges):	1 s typical, less in fixed topography
-HyperRing	Layer 2 (ring)	50 ms (typical, depends on ring size)
-CRP	Layer 2	400 ms (typical, depends on LAN size)
-BRP	Layer 2	10 ms (typical, depends on beacon frequency)
-DRP	Layer 2	?
-RRP	Layer 2	?

-The switchover time of dynamic redundancy is limited by the detection time of the failure.

(or rather, by the interval at which the non-failure is checked, since failures can't be relied upon to announce themselves).

1. Terms: availability and redundancy
2. Classification of requirements
3. Levels of device and network redundancy
4. Industrial Ethernet topologies
5. Industrial Ethernet stack and redundancy
6. IEC 62439 solutions
7. Conclusion

Rules of order of WG15

1) the standard redundancy solution is independent of the higher protocols used

2) the standard shall be compatible with existing equipment, especially commercial PCs and bridges, where no redundancy is used

3) the standard shall define the layout rules and especially the integration of different levels of redundancy

4) the standard shall define means to supervise the redundancy, e.g. using SNMP

5) the standard shall define scenarios for life insertion and reintegration of repaired components

6) the standard shall define measurable performance goals, such as switchover times and reintegration time

7) if several solutions emerge, the standard shall specify their (distinct) application domains and recommendation for their use

WG15 shall not consider safety or security issues – for this there are other standards.

IEC 62439 solutions

WG15 decided to address requirements separately

A) general automation systems
the standard recommends to use **RSTP**
(base: IEEE standards, RSTP) – no need for a new standard < 500 ms

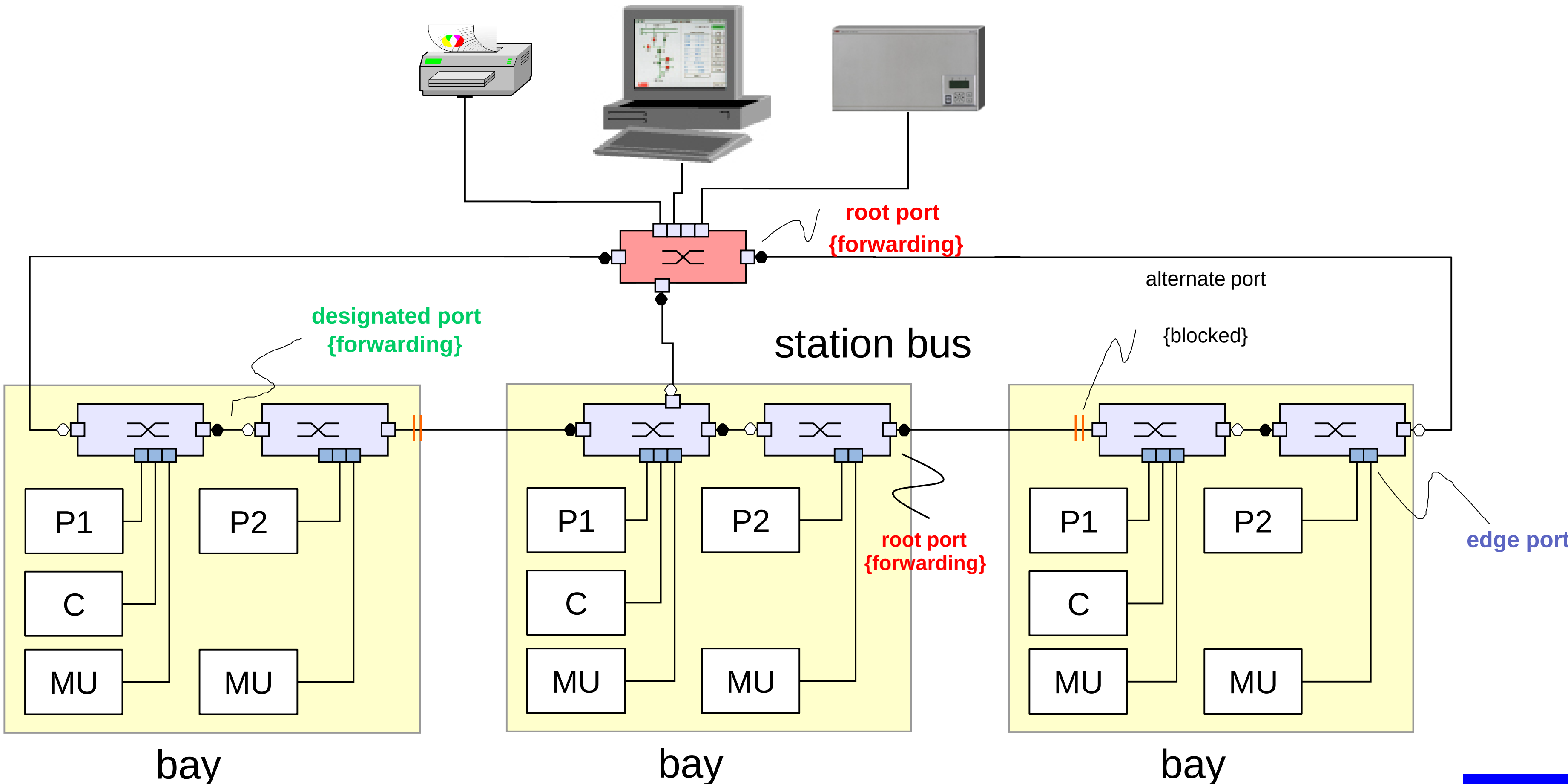
B) benign real-time systems that are cost-sensitive, grace time < 200 ms
the standard shall define an adequate bridge redundancy scheme and redundant devices attachment.
(base: RSTP and further developments – solution: **MRP, DRP, RRP**

C) critical real-time systems that require higher coverage, grace time 0 ms
the standard shall define a parallel network solutions and redundant device attachment.
(base: ARINC AFDX and similar – solution **PRP, HSR**

D) legacy solutions based on Fieldbus Foundation
CRP **<**

62439-1 RSTP (Rapid Spanning Tree Protocol, IEEE 801.2D)

62439-1 does not specify RSTP, but just how to calculate its recovery time.



RSTP performance

+: IEEE standard, field proven, large market, cheap

+: no impact on the end nodes (all end nodes are singly attached)

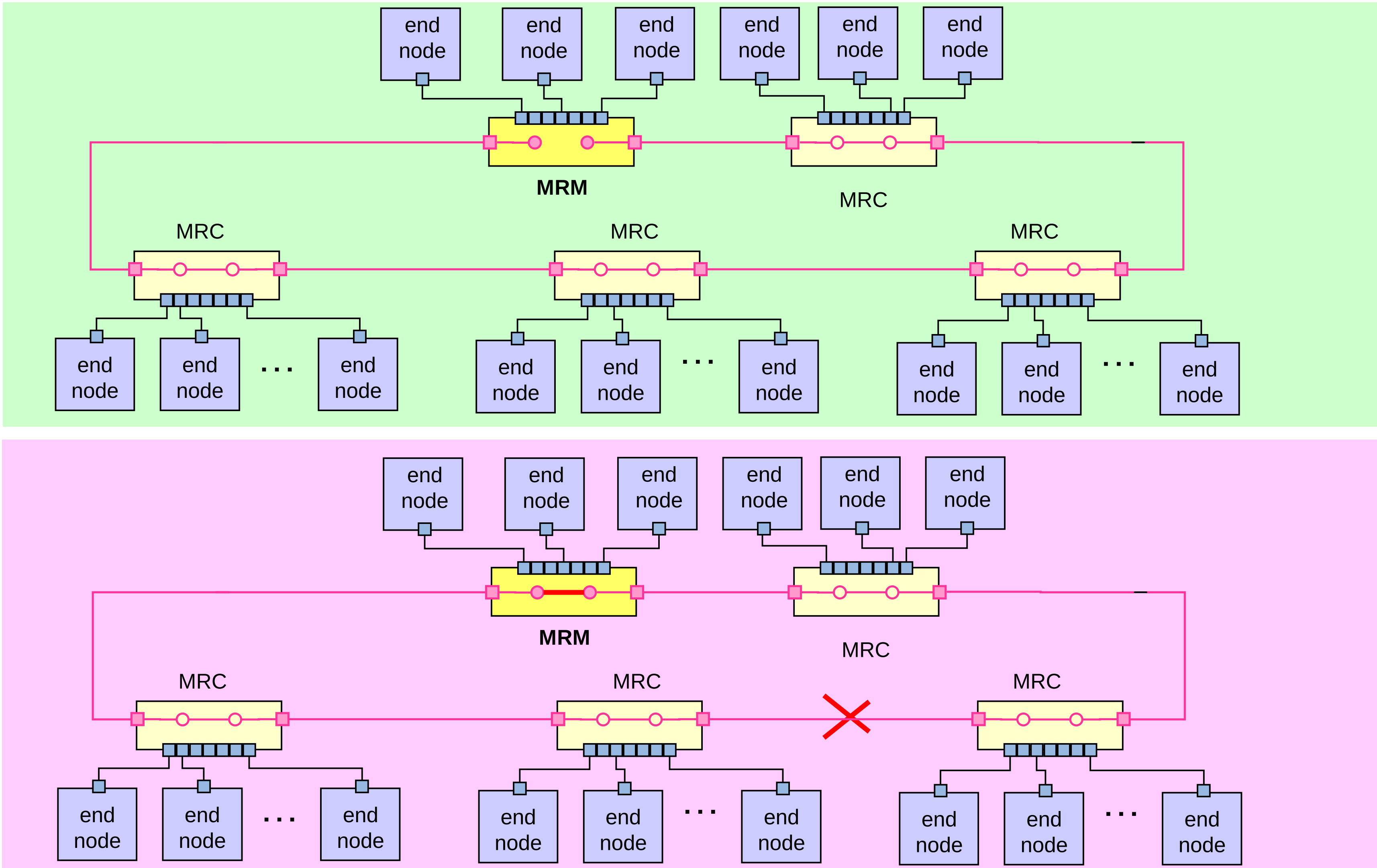
+: can be implemented in the nodes if the nodes contain a bridge element

-: RSTP is in fame of being rather slow (some seconds switchover time).
However, if its topology is fixed, RSTP bridges can learn the topography
and calculate alternate paths in case one should fail. Some manufacturers claim recovery delays <100 ms for selected configurations

62439-2 MRP (Siemens-Hirschmann hyperring)

intact ring

broken ring



the Medium Redundancy Master (MRM) controls the ring
the Medium Redundancy Clients (MRC) close the ring

MRP performance

The MRM checks the integrity of the ring by sending in both direction test frames.

These test frames are forwarded by all intact bridges and inter-bridge links.

If the MRM does not receive its own frames over its other interface, it closes the ring at its location, reestablishing traffic.

Supervision frames allows to locate the source of the trouble.

+: fast switchover (< 200ms worst case)

+: no impact on the nodes

+: no increase in network infrastructure.

-: MRP bridges are not compatible with RSTP bridges, limited market

-: limited to one ring topology

CRP performance

The Coupled Redundancy Protocol is derived from the Fieldbus Foundation H3 network.

It uses two separate networks, to which devices are attached through two network adapters.

The networks are used alternatively rather than in parallel.

+: provides cross-redundancy (double fault network and node)

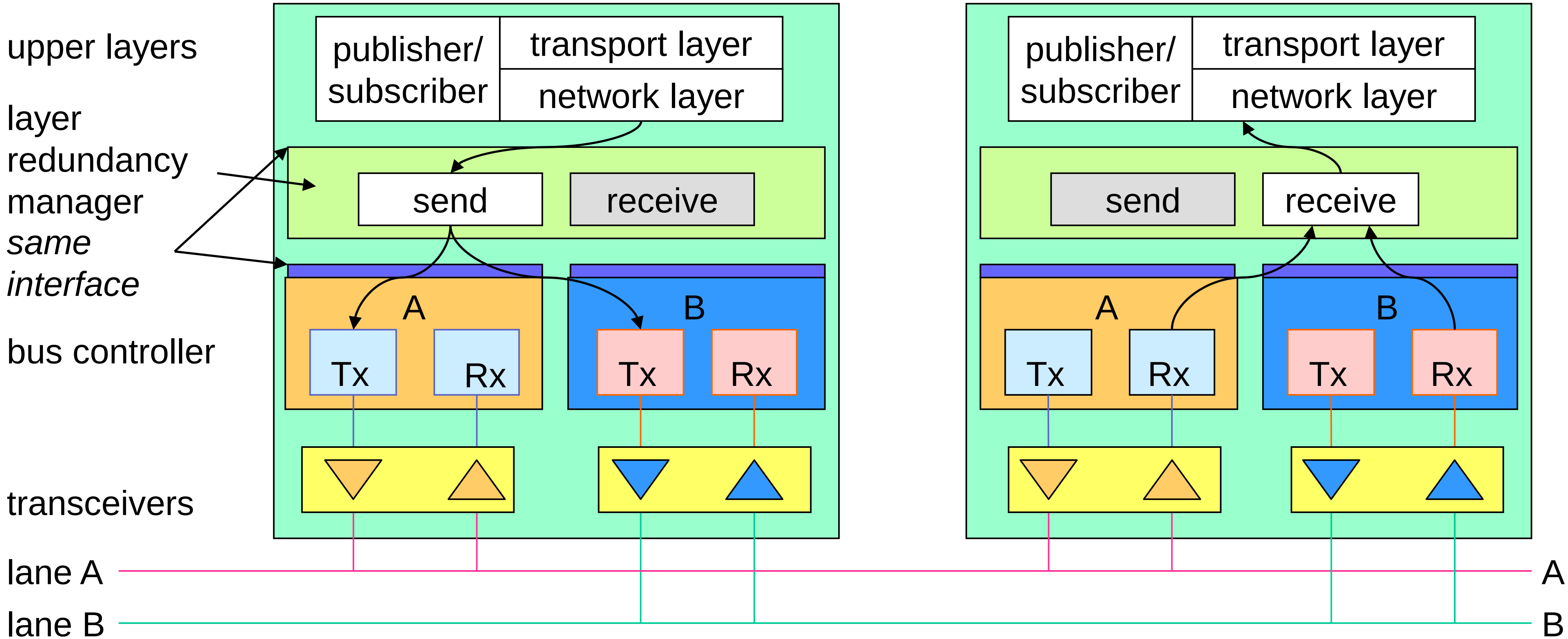
+: provides protection against adapter failures

-more than double network costs with respect to non-redundant networks

-large effort for building doubly-attached nodes.

-switchover time not specified

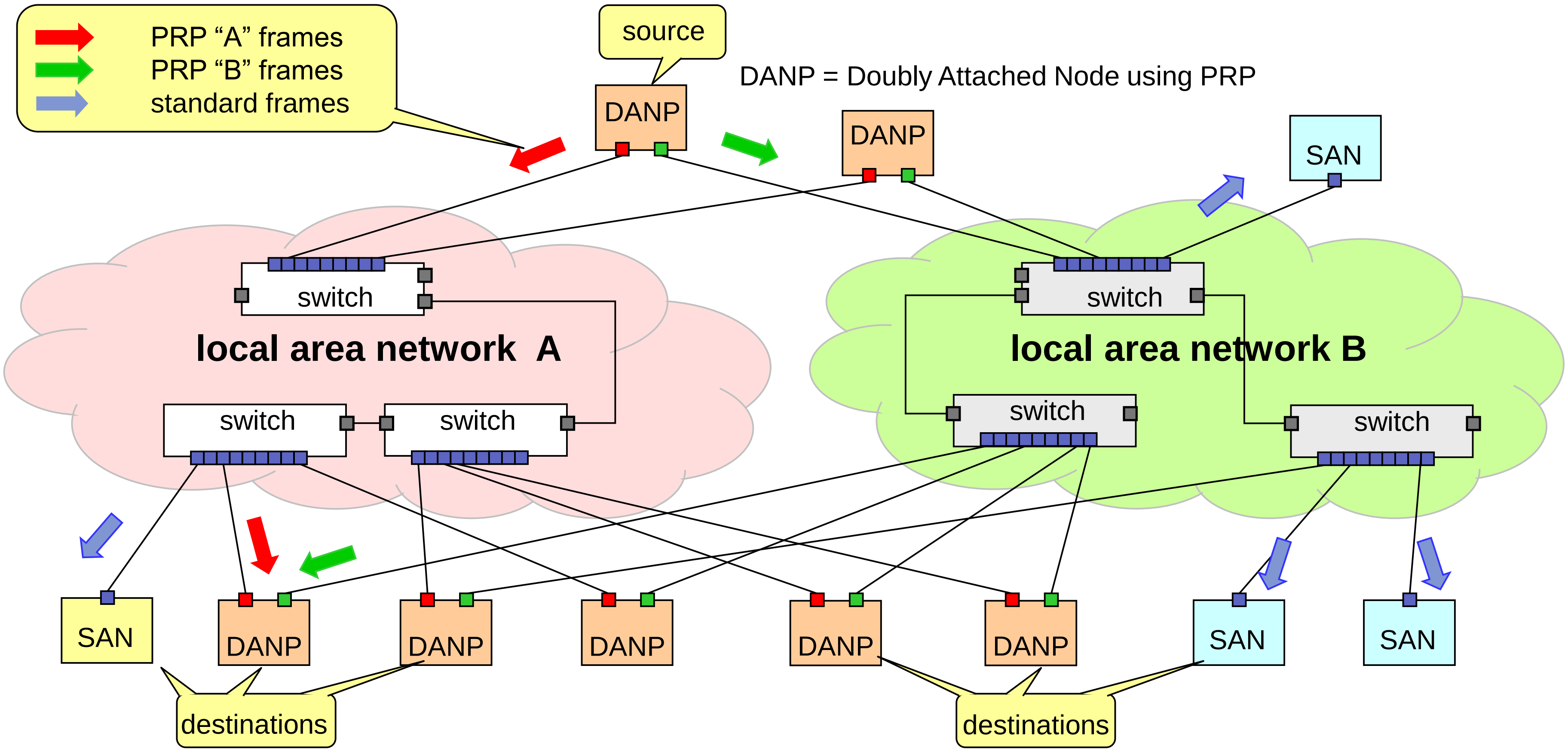
62439-3.4 Parallel Redundancy Protocol



send on both lines: each frame is send on both A and B lines, frames over A and B have different transmission delays (or may not arrive at all)

receive on both lines: the stack receives both frames from both lines treated as equal, a "merge layer" between the link and the network layer suppresses duplicates.

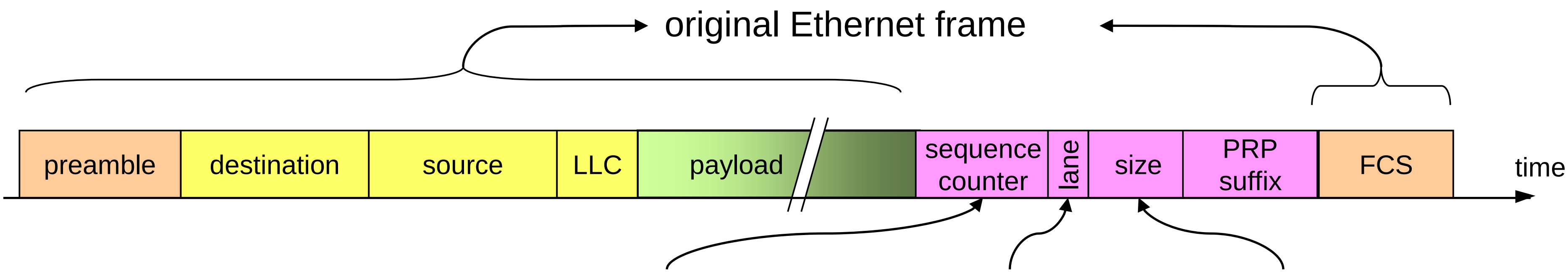
PRP layout examples



PRP suppressing duplicates

To ease duplicate rejection, PRP nodes append a sequence number to the frames along with a size field that allows to determine that the frame belongs to the PRP protocol. This trailer is invisible to the higher layers (considered as padding)

Receivers discard duplicates using a variety of methods



- each frame is extended by a sequence counter, a lane indicator, a size field and a suffix * inserted <u>after</u> the payload to remain invisible to normal traffic.

- the sender inserts the same sequence counter into both frames of a pair, and increments it by one for each frame sent.

- the receiver keeps track of the sequence counter for each for each source MAC address it receives frames from. Frames with the same source and counter value coming from different lanes are ignored.

PRP performance

+ PRP allows seamless switchover, no frames are lost

+ During normal operation, PRP reduces the loss rate

+ doubly attached nodes (DANP) are simple to build

+ SANs can readily communicate with DANPs

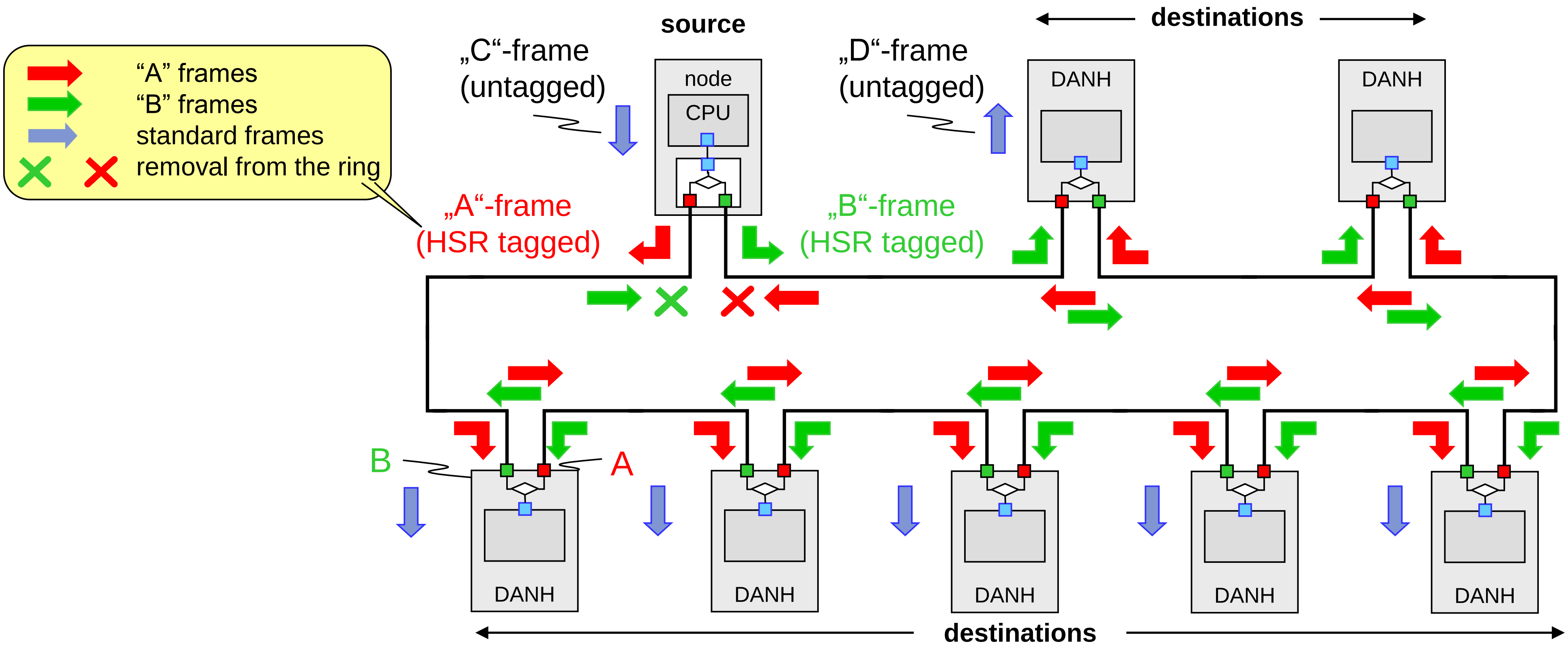
+ PRP checks the presence of nodes by periodical supervision frames that also indicate which nodes participate in the protocol and which not

- double network costs

- SAN of one LAN cannot communicate directly with SANs of the other LAN

- frame size must be limited to prevent frames from becoming longer than the IEEE 802.3 maximum size (but most bridges and Ethernet controllers accept frames up to 1536 octets)

62439-3.5 HSR (High availability seamless redundancy)



Nodes are arranged as a ring, each node has two identical interfaces, port A and port B.

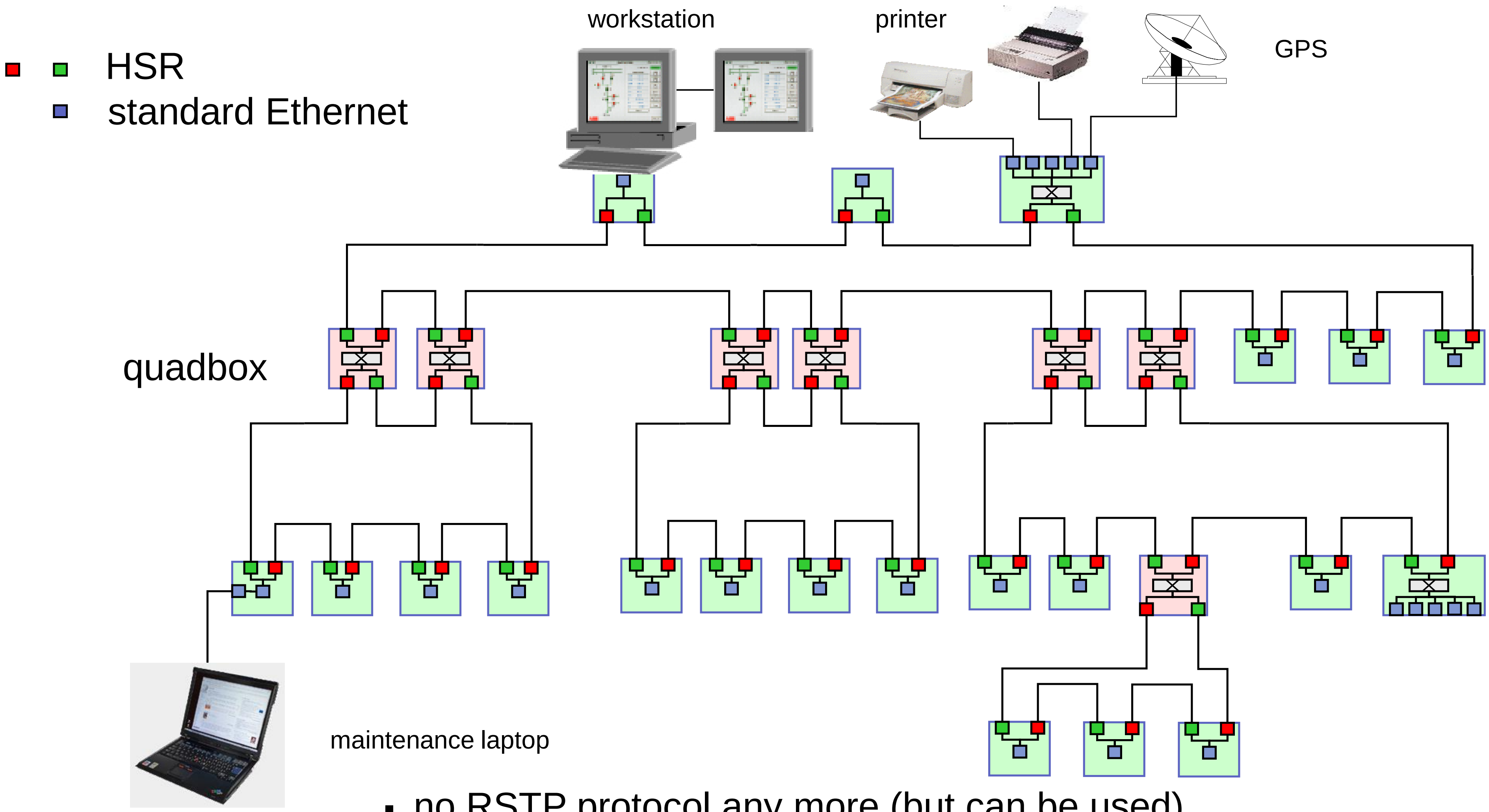
For each frame to send ("C"-frame), the source node sends two copies over port A and B.

Each node relays a frame it receives from port A to port B and vice-versa, except if it already forwarded it.

The destination nodes consumes the first frame of a pair and discards the duplicate.

In case of interruption of the ring, frames still continue to be received over the intact path.

HSR topology: rings of rings



- no RSTP protocol any more (but can be used)
- note that level 3 is singly attached (only one quadbox)

HSR performance

+ HSR allows bumpless switchover, no frames are lost

+ During normal operation, HSR reduces the loss rate

+ HSR checks the presence of nodes by periodical supervision frames that also indicate which nodes participate in the protocol and which not

+ cost-effective solution once devices include HSR bridgeing hardware

+ flexible topology: rings and rings of rings

+ can be connected with PRP

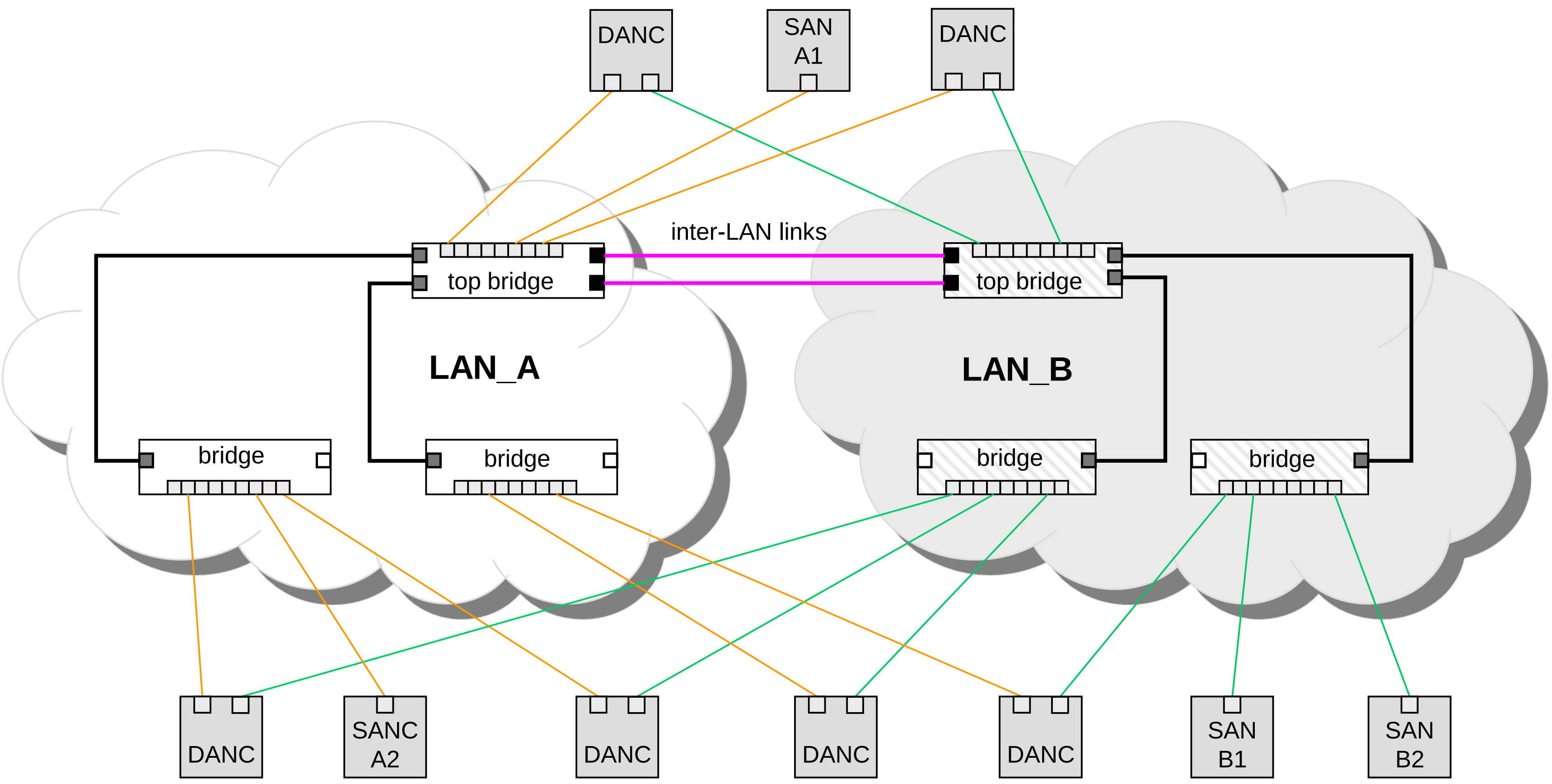
+ full concept for IEEE 1588 clock synchronization

-: doubly attached devices require an initial development cost (hardware)

-: SANs must be attached through RedBoxes

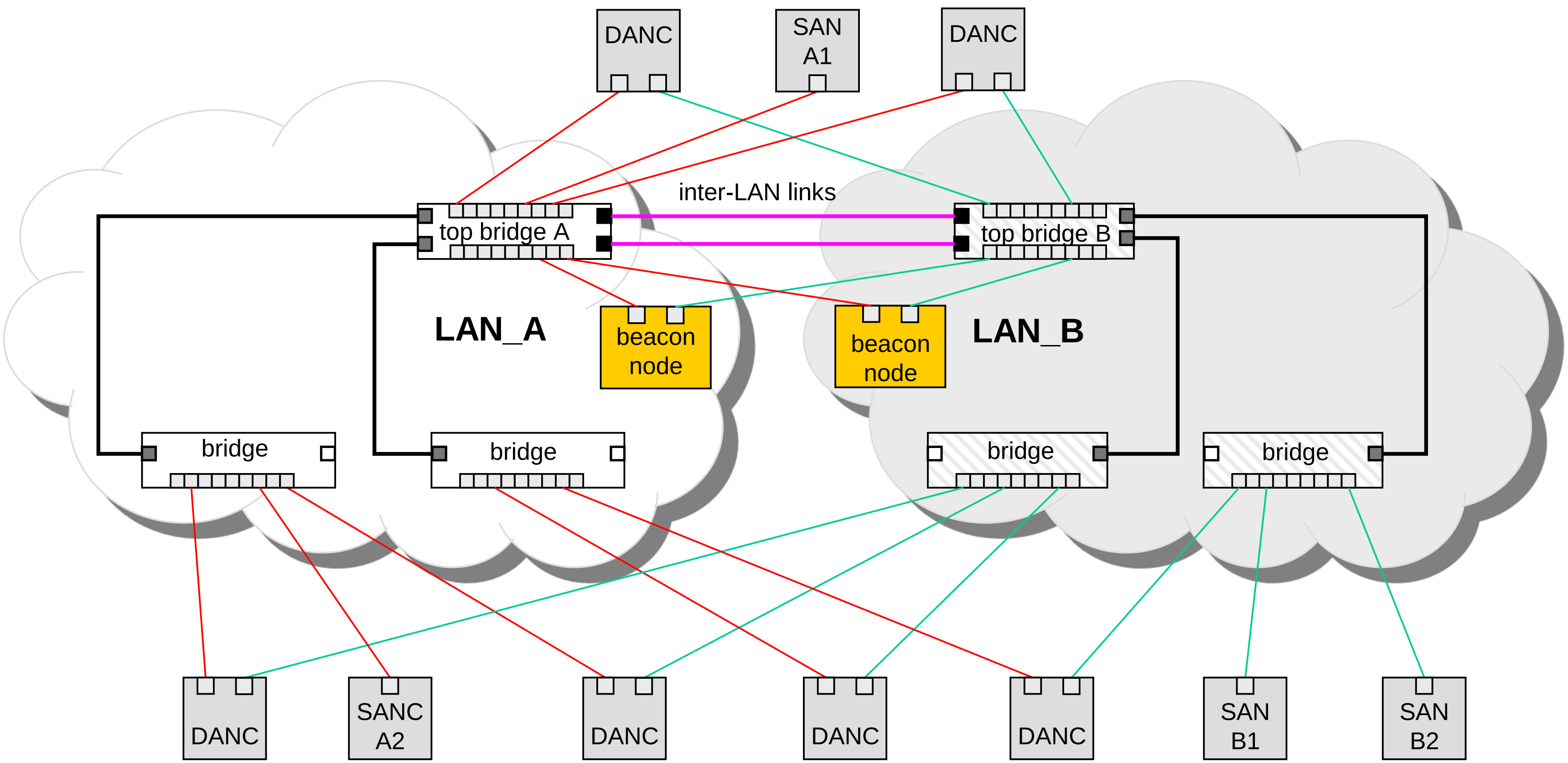
IEC 62439-4 Coupled Redundancy Protocol

Honeywell contribution
Redundancy- in-the-nodes, legacy from the Fieldbus Foundation protocol
All traffic must be routed through the inter-LAN links.
Allows SAN from both LANs to communicate (unlike PRP)



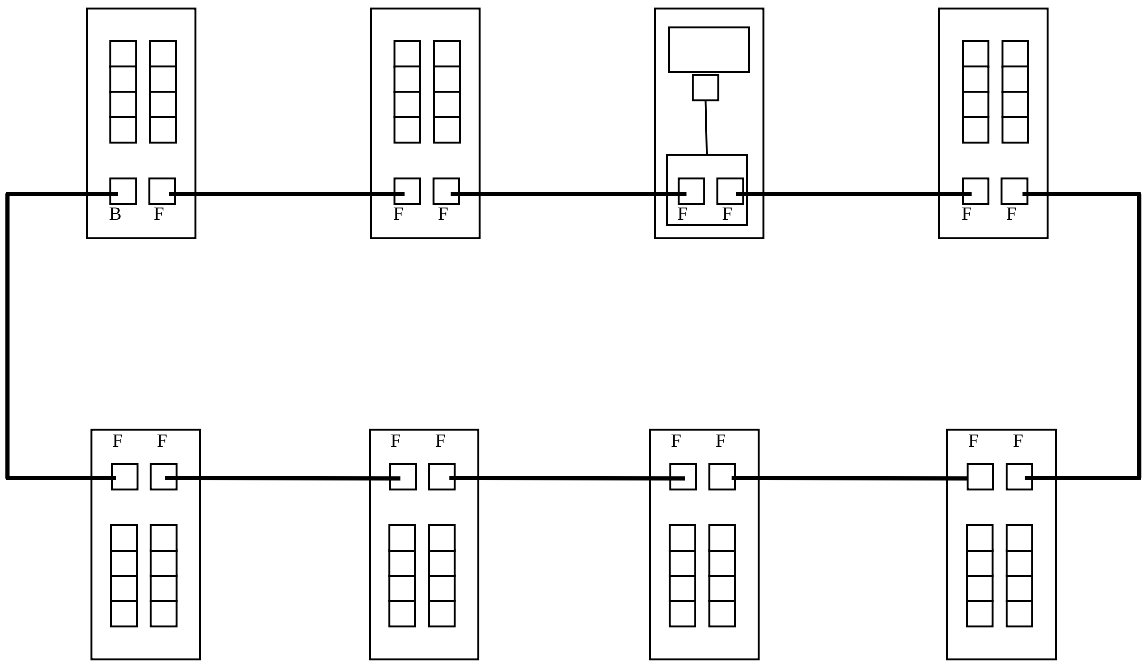
IEC 62439-5 Beacon Redundancy Protocol

Rockwell contribution
Adds to the CRP principle two beacon nodes for faster recovery, at a high communication cost.
Endorsed by ODVA, advertised for CIP, but no products known.
Some unsolved technical issues.



IEC 62439-6 Distributed Redundancy Protocol

Chinese contribution.
Adds to the MRP ring principle a clock synchronization protocol to achieve TDMA behaviour.
Double ring possible.
Benefits unclear



1. Terms: availability and redundancy
2. Classification of requirements
3. Levels of device and network redundancy
4. Industrial Ethernet topologies
5. Industrial Ethernet stack and redundancy
6. IEC 62439 solutions
7. Conclusion

Conclusion

IEC 62439 satisfies the needs of the Industrial Ethernets belonging to the IEC 61784 suite with eight solutions:

-RSTP: mainstream, sufficient for most applications–with improvements for fixed configuration

-MRP: ring-based protocol for demanding automation networks and singly attached nodes, especially useful with bridgeing nodes.

-PRP: seamless protocol suited for critical applications requiring doubly attached nodes.

-HSR: seamless protocol suited for critical applications, cost efficient ring structure

-CRP: Honeywell's legacy protocol for Fieldbus Foundation, using doubly attached nodes.

-BRP: Rockwell's extension of CRP for ODVA/CIP

-DRP: SupCon's extension of MRP with a clock

-RRP: (in preparation) LSIS's extension of DRP.

IEC 61850 decided in favor of RSTP, PRP and HSR, while PNO selected MRP.
the future of the other solutions is clouded.