The bridge to possible

Industrial Utilities Resiliency

PRP and HSR Best Practices

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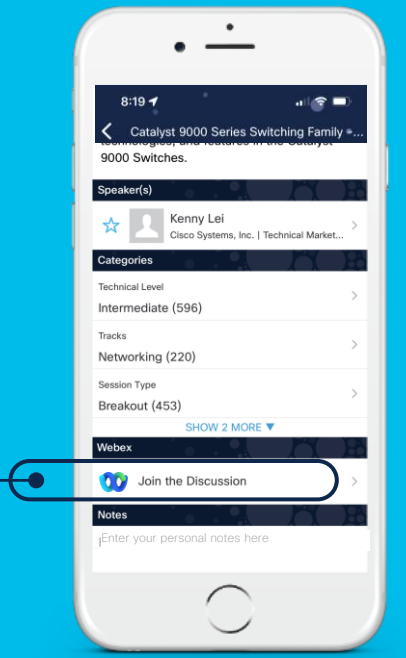

"The electric grid's resilience is a foundational building block for our decarbonized clean energy future, which requires renewable resources, energy storage, and electrification—the optimal deployment of which depends on investments in a resilient, modern grid. "

IEEE PES-TR83

Agenda

- Talking about Resiliency and Redundancy
- Parallel Redundancy Protocol (PRP)
  - Intro, Cisco Support, Guidelines
- High-Availability Seamless Redundancy (HSR)
  - Intro, Cisco Support, Guidelines
- What about timing (PTP) over PRP or HSR?

Industrial Redundancy and Resiliency

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Redundancy

Credit: Airbus

Redundancy contributing to Resiliency

Substation Automation – Critical Infrastructure

1 Substation landscape keeps evolving

Substation Automation has opened doors to new technologies in support of SCADA.

Simple requirements have evolved into the most stringent critical needs in the utilities industry.

2 IEC 61850 frames this evolution

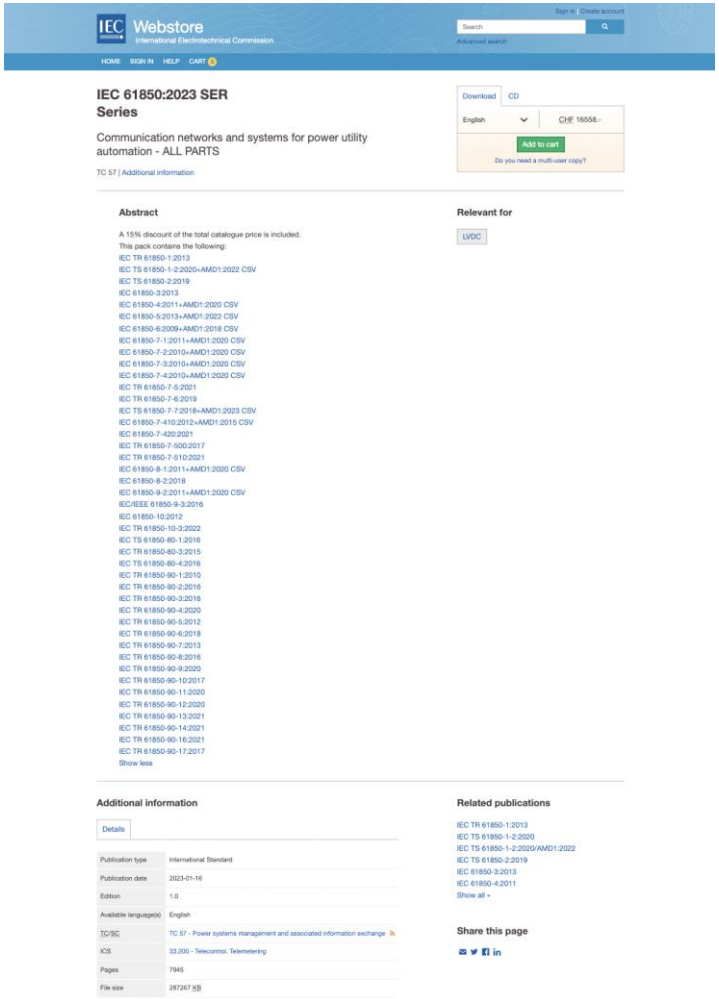
Framework and applications target handling this growth – intelligent devices with larger data quantities and faster communication needs.

3 Critical Infrastructures and services

Systems monitoring and management demand higher levels of reliability, solid protection, and performance.

IEC 61850

- International Electrotechnical Commission
- Communication networks and systems for power utility automation
- Only €16.5K ☺ (inc. 15% discount!)



The Challenge with Evolving Redundancy

- Protection and Control systems in modern substations are being digitized – requiring higher levels of reliability
- IEC 61850-90-4 defines the need for Local Area Networks (LAN) in the Transmission Substation to take advantage of established, fast and proven communication standards.

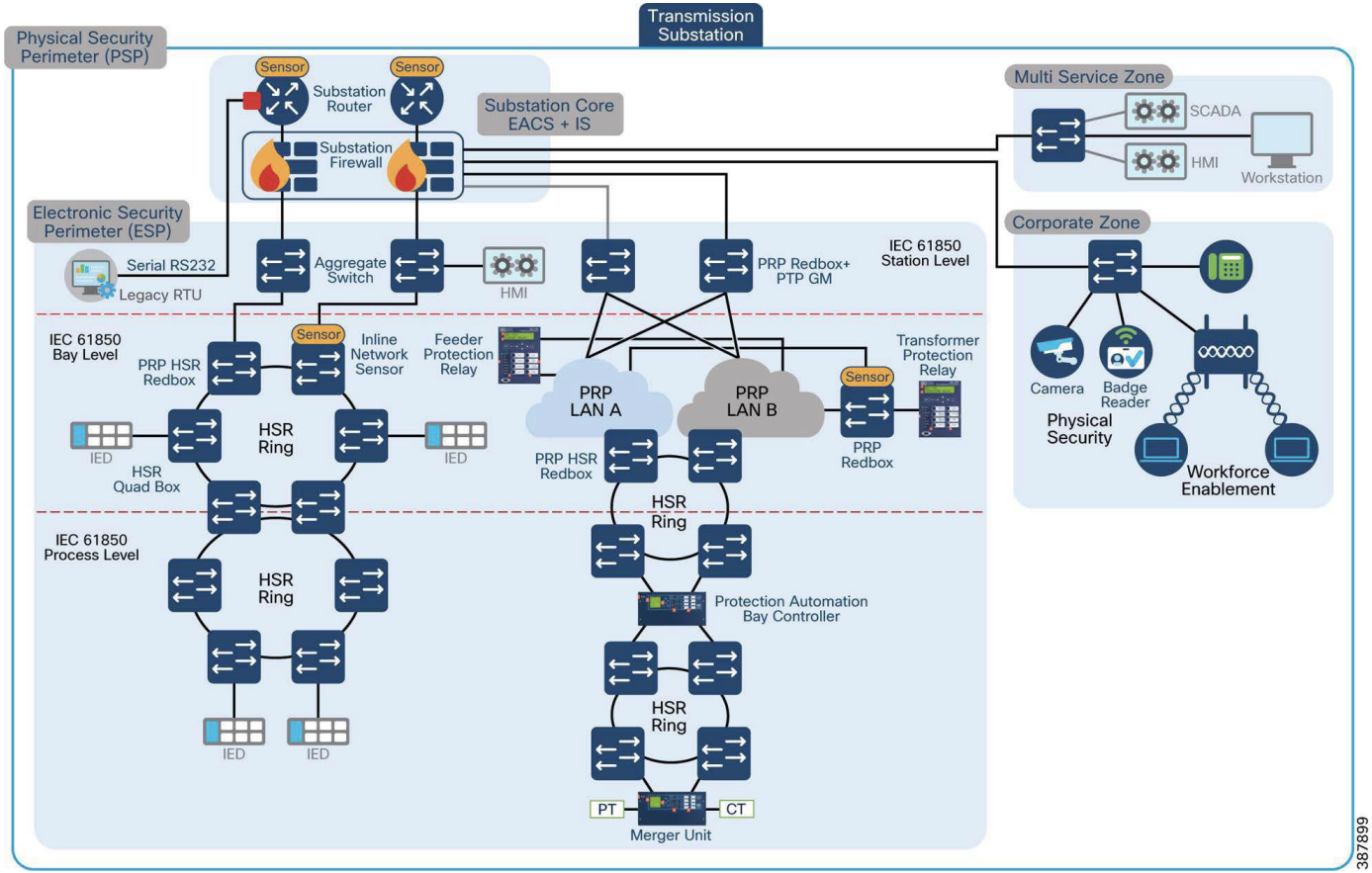
Challenge:

- Traditional network redundancy protocols offer substandard protection for mission-critical protocols in the substation.

Solution:

- IEC 62439-3 defines protocols (PRP/HSR) that offer seamless redundancy and align with substation needs for highly reliable and available networks.

Substation Automation – Critical Infrastructure



Cisco Substation Automation Reference Architecture

Transmission Substation Zones

Electronic Security Perimeter (ESP)

Contains all grid operations infrastructure

- Most critical security zone (utility monitoring and control)
- Requires highest level of security and availability
- Variety of network topologies
- High-availability mechanisms required
- Choice of topology and redundancy protocols on substation size, application requirements, etc.

- Some ESP devices
  - Remote Terminal Units (RTU)
  - Intelligent Electronic Devices (IED)
  - Programmable Logic Controllers (PLCs)
  - Relays
- Devices grouped based on needs in either
  - Station Level / Bus
  - Process Level / Bus

Multiservice Zone

Physical security component

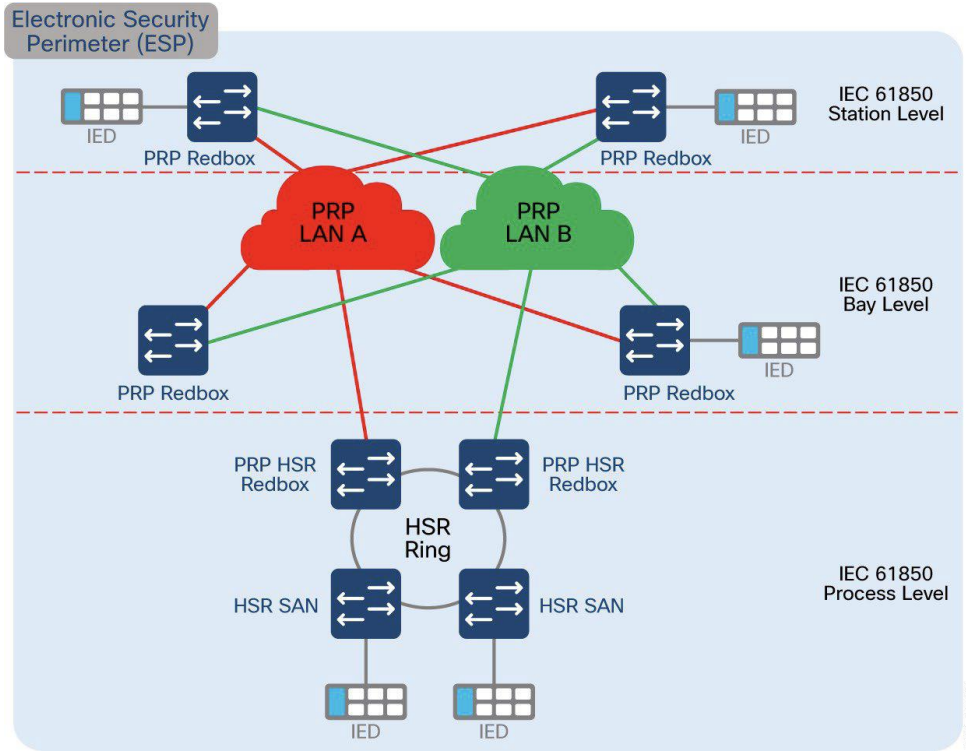
- Badge readers
- Video surveillance cameras
- Local access management
- Security applications

Corporate Zone

Extension of corporate network in the substation

- Wi-Fi connectivity
- Voices services (e.g. VoIP)
- General employees' network connectivity to services

ESP Station and Process Level



Cisco ESP Zone Reference Architecture

Station Level

- SCADA servers, HMIs, and other substation monitoring services (including the operators).

Station Bus

Bay Level

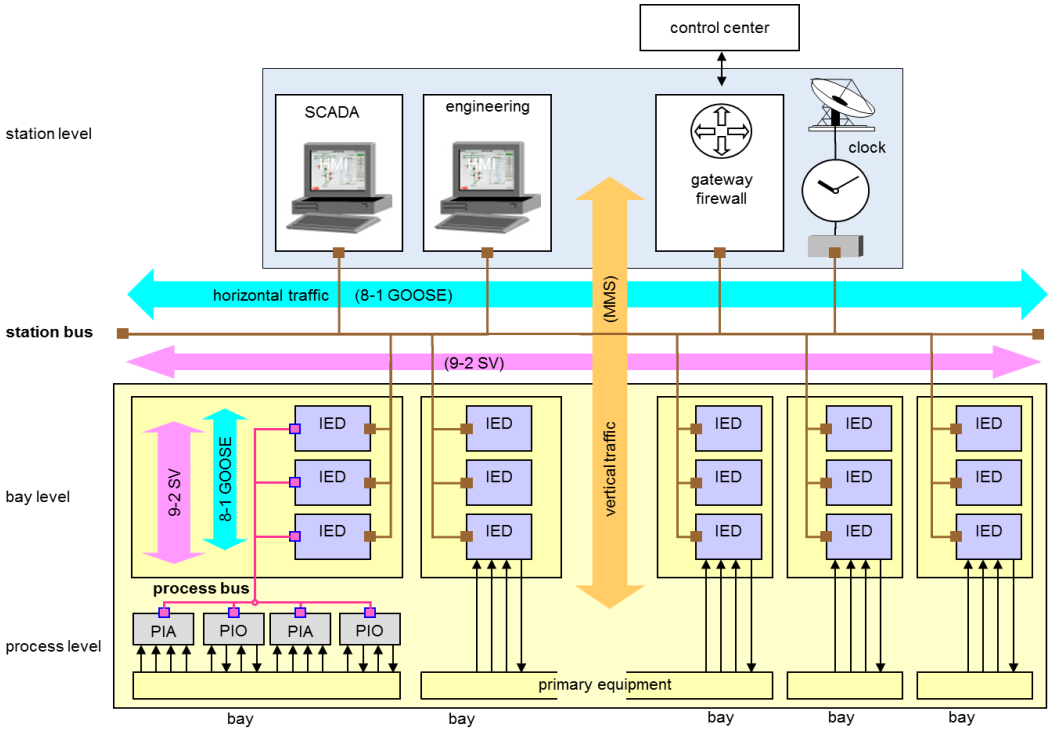
- Consists of Intelligent Electronic Devices (IEDs) that collect measurements provided by the Process Level.
- IEDs communicate with other IEDs, SCADA systems, or execute local control actions.

Process Bus

Process Level

- Made up of devices like circuit breakers and data collecting devices used to measure current, voltage, and other parameters in different areas of the substation

IEC 61850 Traffic Classes and Flows



Source: IEC TC57, IEC 61850-90-4

Manufacturing Message Specification (MMS)

- Client-Server (unicast) protocol (Layer 3 based)
- MMS client (e.g. SCADA) accesses all IEDs
- Traffic flows on the Station and Process bus

Generic Object-Oriented Substation Events (GOOSE)

- IEDs data exchange (Layer 2 multicast based)
- Tasks: interlocking, tripping circuit breakers, etc.
- Traffic flows on the Station and Process bus

Sampled Values protocol (SV)

- Transmission of analogue values (current & voltage) from sensors to IEDs (Layer 2 based)
- Traffic flows normally on the Process bus but may flow over the station bus.

What are we protecting?

- IEC 61850 standards define a model for critical traffic flows.
- GOOSE and SV traffic flows require the highest priority with the lowest latency, among others.
  - GOOSE latency ranges → 3 to 100 msec
  - Sample Values (SV) ranges → 3 to 10 msec
- Adding to the mix… timing and synchronization (PTP) traffic is critical as it relies on low latency.

Protocol selection should always be based on the application with the most stringent requirements in the substation ESP zone.

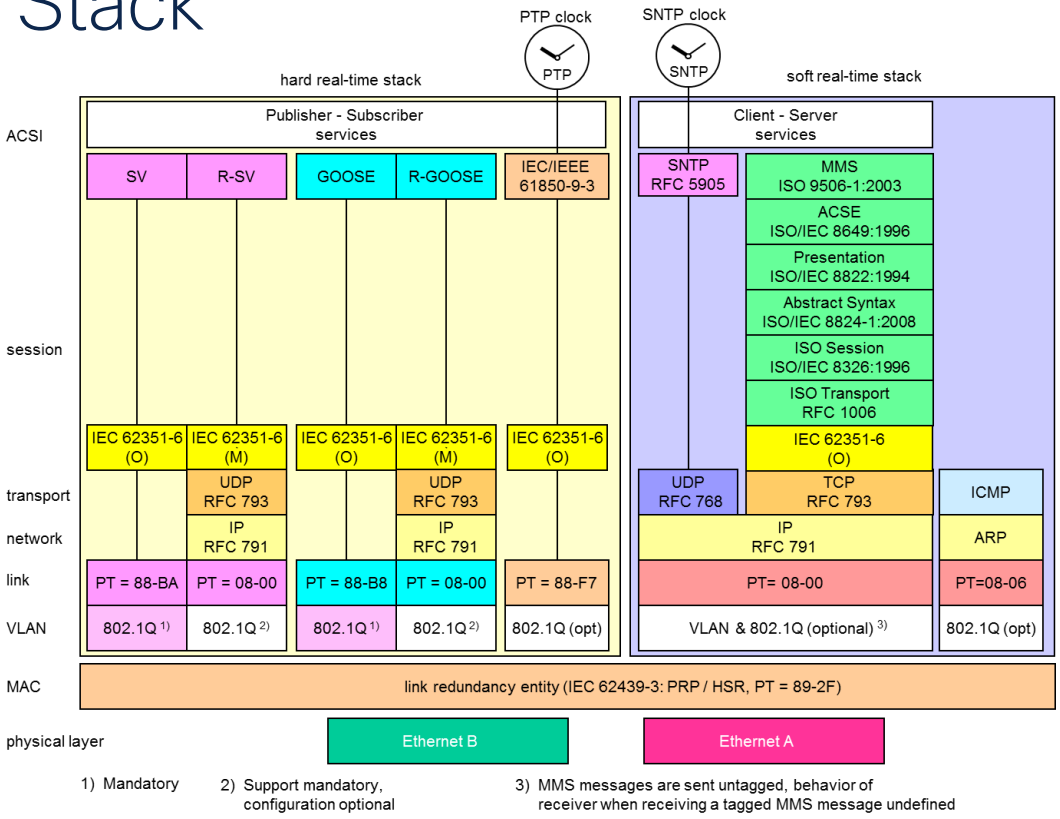
IEC 61850 Tolerated Communications Delays

Substation Automation LAN Traffic and Resiliency Requirements

Communication Partners	Service	Application Recovery Tolerated Delay	Recovery delay of communication	Redundancy protocol mapping
SCADA to IED, Client-Server	IEC 61850-1	800ms	400ms	REP
IED to IED interlocking	IEC 61850-1	12ms	4ms	PRP and/or HSR
IED to IED, reverse blocking	IEC 61850-1	12ms	4ms	PRP and/or HSR
Protection trip excluding Bus Bar protection	IEC 61850-1	8ms	4ms	PRP and/or HSR
Bus Bar protection	IEC 61850-2 on station bus	< 1ms	Bumpless – 0ms	PRP and/or HSR
Sampled Values (SV)	IEC 61850-2 on process bus	< 4ms	Bumpless – 0ms	PRP and/or HSR

IEC 61850 Protocol Stack

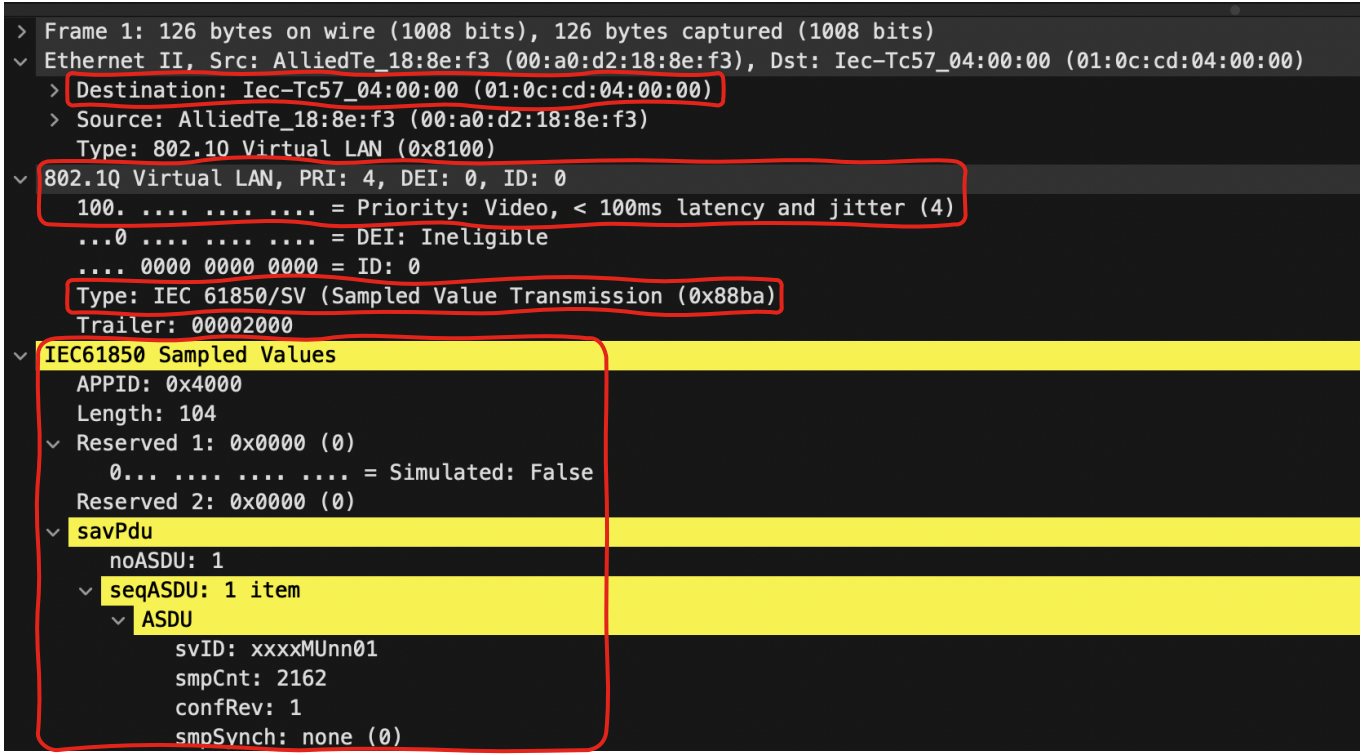
- “hard real-time stack”, based on layer 2 multicast, supporting the services of SV, GOOSE and PTP; Publisher-Subscriber services on layer 3 multicast supporting Routed GOOSE and SV services
- “soft real-time stack”, based on layer 3 unicast supporting the MMS communication, the network time synchronisation SNTP, and ancillary protocols mentioned in IEC 61850-8-1



Source: IEC TC57, IEC 61850-90-4 Ed.2

IEC 61850 SV: Example

- Destination multicast MAC
- .1Q header with 802.1p-based priority value
- Custom EtherType for SV
- SV itself



Layer 2 Redundancy Protocols

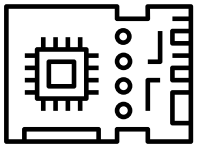
Most prevalent redundancy protocols in the industry

IEC 62439-3

Protocol	Topo	Claim to Fame	Typical Convergence
PRP Parallel Redundancy Protocol	Any	Lossless – Network and Node, multi-vendor support	0ms
HSR High-Availability Seamless Redundancy	Ring	Lossless – Network and Node, multi-vendor support	0ms
DLR Device Level Ring	Ring	Fastest convergence, standards based, beacon based	3ms
MRP Media Redundancy Protocol	Ring	Multi-vendor support, standards based, beacon based	30ms
REP / REP Fast Resilient Ethernet Protocol	Ring	Easiest to deploy, work across stack, supported by Cisco portfolio, not just industrial	50 / 25ms
R(PV)STP / MSTP Rapid / Multiple Spanning Tree Protocol	Any	Last resort, standards based	1s or more

Layer 2 Redundancy Protocols

You need the right Hardware!



PRP or HSR … or Both?

The increased need for higher resiliency in modern large substations calls for a hybrid system that combines both, PRP and HSR.

PRP is best choice for large or complex applications.	HSR is best choice for small and simple applications.

HSR rings for small sections of the substation, Process Bus I/O (line bay). These HSR rings attached to a station-wide PRP network.

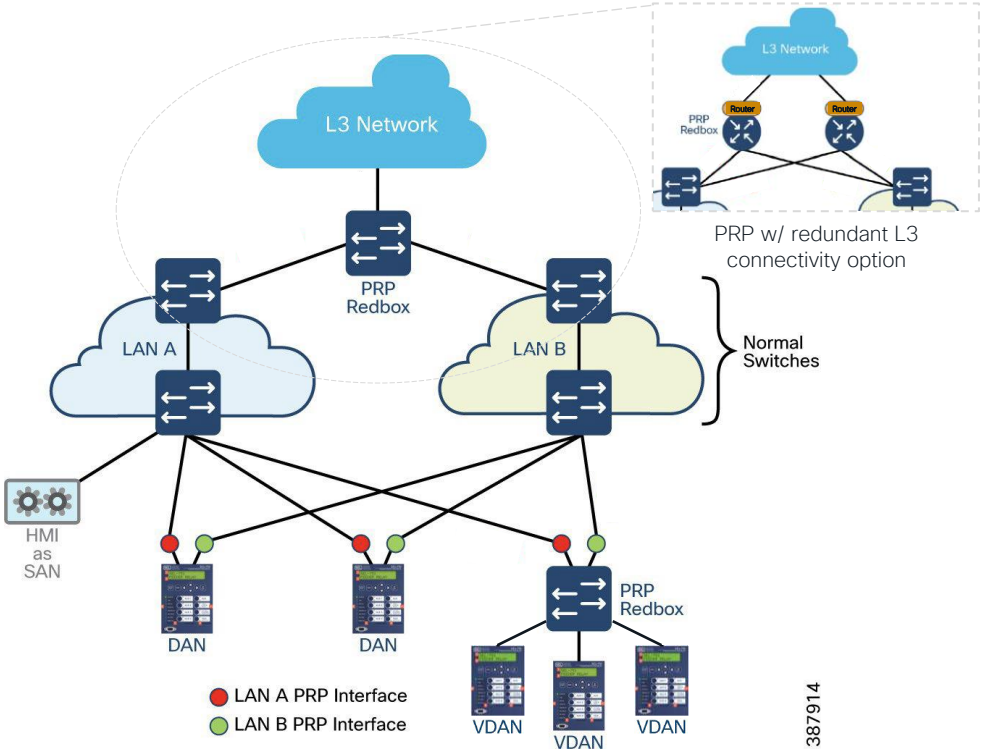
PRP

Parallel Redundancy Protocol (PRP)

- Defined in the International Standard IEC 62439-3
- Designed to provide seamless or bumpless redundancy (zero recovery time) in Ethernet Networks
- Uses two parallel independent Local Area Networks (LAN A, LAN B)
- Frames duplication and deduplication mechanism* sent over the parallel LANs

* Same mechanism used by PRP and HSR. Seamless redundancy continuity when used together.

Parallel Redundancy Protocol – Basic Topology



LAN A and LAN B

- Can differ in performance and topology
- No need for PRP-aware switches
- No links or shared switches in-between
- Fail independent redundancy schemes

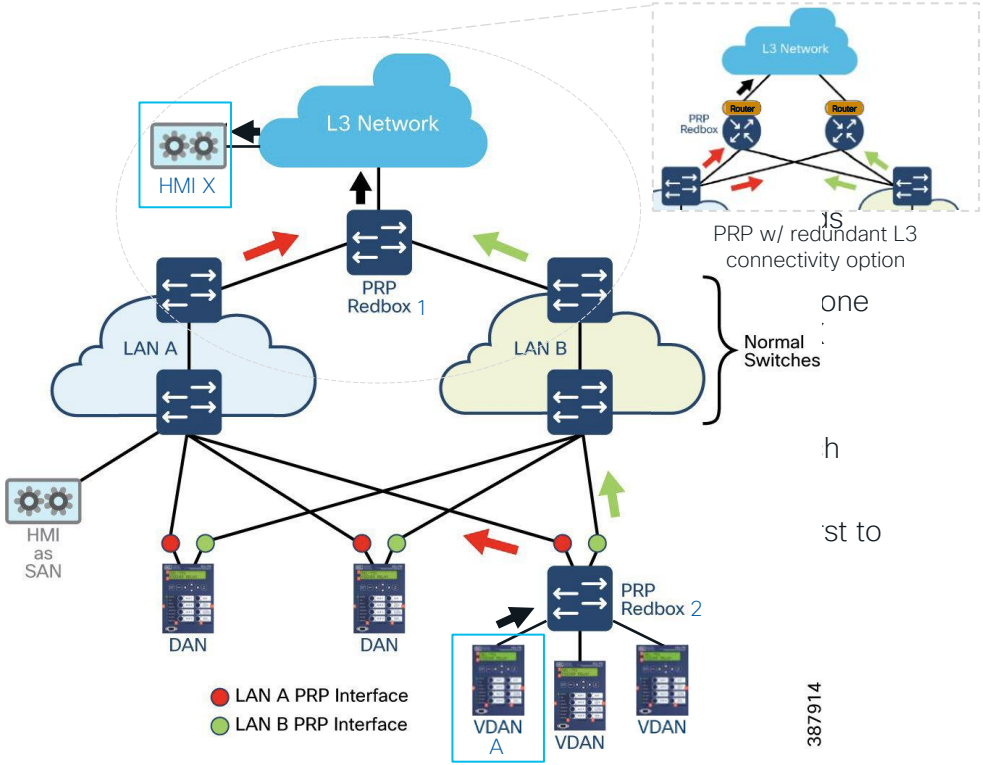
PRP Nodes

- DAN : Dual / Double Attached Node
- SAN : Single Attached Node
- RedBox : Redundancy Box
- VDAN : Virtual Dual Attached Node

Parallel Redundancy Protocol – Nodes & Roles

Node	Name	Description
 SAN	Single Attached Node (No PRP functionality)	• Device that does not support PRP, connected to LAN A –OR- LAN B • Communicates with nodes attached to same LAN • Network redundancy provided by LAN internal redundancy scheme • e.g., HMIs, Printers, etc.
 DAN / DANP	Dual / Double Attached Node (PRP functionality)	• Two ports (Port A → LAN A, Port B → LAN B) • Sends duplicate frames out of each port (over each LAN) • Receives and consumes the first frame and discards the duplicate • e.g., Dual-homed IEDs or Layer2 switches that support PRP protocol.
 PRP RedBox	Redundancy Box (PRP functionality)	• Behaves like a DAN (frame duplication towards both LANs) • Provides PRP functionality / redundancy (LAN A, LAN B access) to multiple non-PRP devices • e.g., L2 Switches w/ PRP support
 VDAN	Virtual Dual Attached Node (No PRP functionality)	• VDAN is a SAN emulated as a DANP by the PRP Redbox • Non-PRP device single attached to a PRP RedBox, needing PRP redundancy (PRP Redbox takes care of the duplication/de-dup) • VDAN(s) communicate with devices in both LAN A and LAN B • Redbox generates the PRP Supervision frames on behalf of the SAN hence the SAN is seen as a DANP to other DANPs in both LANs.

Parallel Redundancy Protocol – Basic Functionality



PRP w/ redundant L3 connectivity option

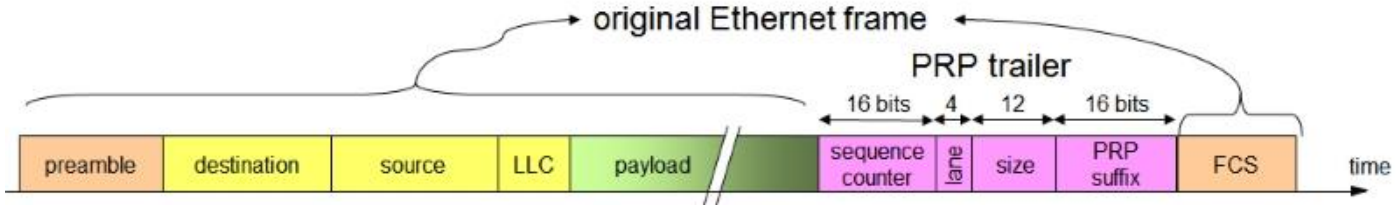
Scenario: VDAN A → HMI X

- RedBox 2 (duplication)
  - Receives VDAN A frame, duplicates it and appends PRP RCT trailer to each copy
  - Transmits duplicated VDAN A frames (2 frames), one out each LAN port (LAN A, LAN B) towards HMI X
- RedBox 1 (deduplication)
  - Receives VDAN A duplicated frames, 1x from each LAN at different intervals
  - Removes the PRP RCT trailer and transmits the first to arrive out to HMI X
  - Discards the 2nd frame as the duplicate

No Impact to HMI X applications even if:

- Only one frame from VDAN A arrived
- Network failure in either LANs triggered traffic reconvergence of slower redundancy protocols

PRP Frame – Redundancy Control Trailer (RCT)

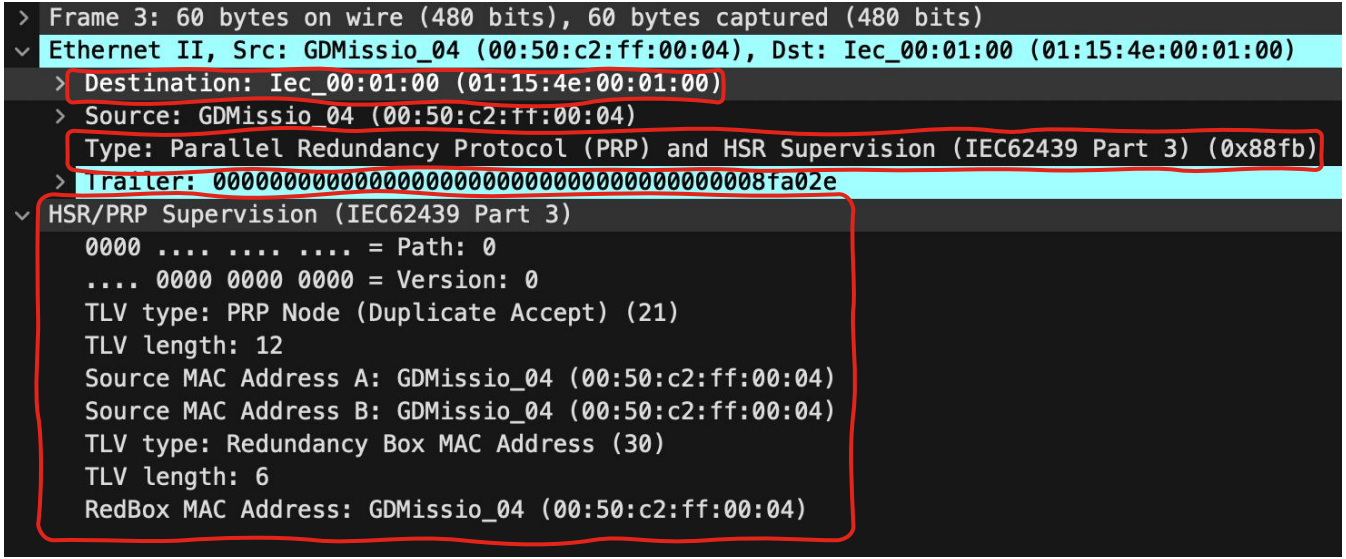


PRP capable entities modify the transmitted frames by placing a PRP trailer in the frame's payload. Non-PRP devices will ignore this PRP trailer as part of the data.

RCT Field	Description
Sequence Number (SeqNr)	16-bit sequence number, incremented by one for each frame the DANP sends. Combination of SRC MAC + SeqNr uniquely identify copies of the same frame.
LAN Identifier (LanId)	4-bit, carries distinct identifier to LAN A (1010) or LAN B (1011)
Link Service Data Unit Size (LSDUsize)	12-bit field, allows the receiver to distinguish PRP frames from non-redundant
PRP Suffix (PRPsuffix)	16-bit field, identified PRP frames and distinguish those from other protocols that also append a trailer to their useful data

PRP Frame – Supervision Frame

- Destination multicast MAC
- Custom EtherType for PRP/HSR Supervision
- Supervision message itself



Parallel Redundancy Protocol

In favor of PRP

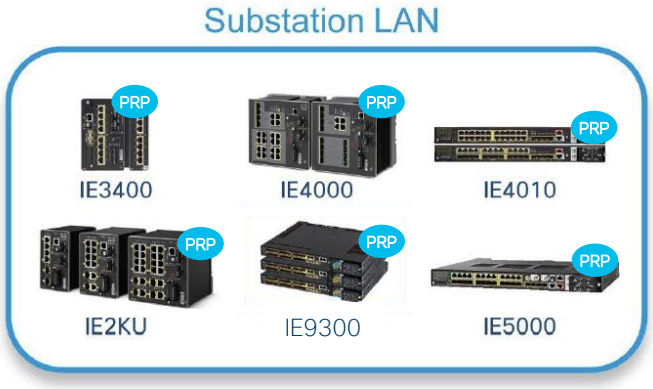
- IEC standard – PRP interoperability in multi-vendor environment
- Provides seamless or “bumpless” redundancy
- Parallel LANs can be implemented with legacy switches (non-PRP switches)
- Parallel LANs can support any topology, any redundancy protocol schemes
- Use of fiber Ethernet avoids potential EMC issues that impact copper Ethernet
- Shortens maintenance intervals – planned outage invisible to applications

Possible cons…

- Higher cost due to the need to implement independent network infrastructures for LAN A and LAN B.
- Doesn’t protect from end-node failures

Cisco PRP Support and Recommendations

Cisco Substation LAN Portfolio – PRP Support



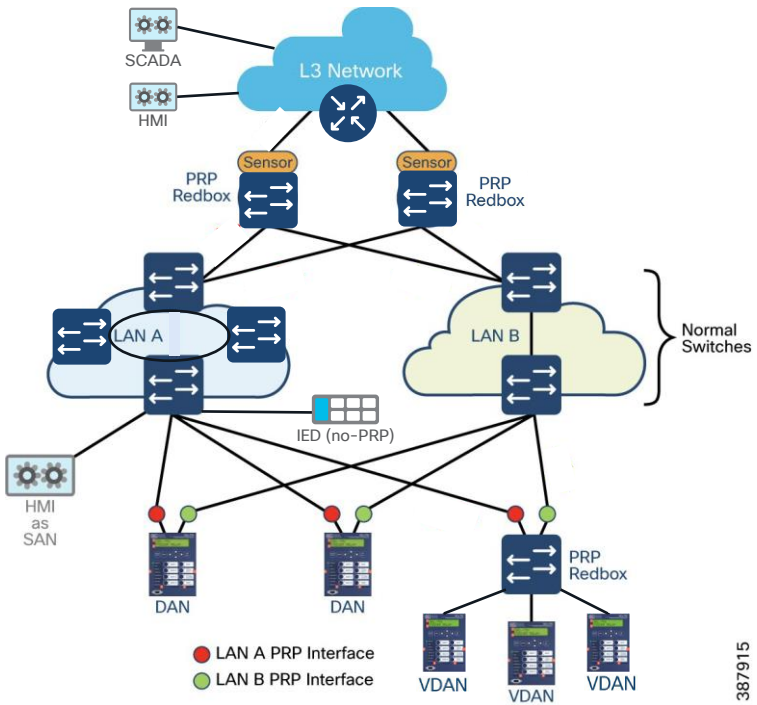
Substation LAN Positioning

PRP RedBox	IE3400, IE4000, IE4010, IE5000, IE9300
PRP Infrastructure (LAN A, LAN B)	IE2KU, IE3400, IE4000, IE4010, IE9300

PRP	IE2000U	IE 3400	IE 4000	IE 4010	IE 5000	IE 9300
#PRP channel groups*	1 or 2	2	2	2	2	2
Dynamic Node/VDANs**	512	512	512	512	512	512
Static Node/VDANs	16	16	16	16	16	16

(*) 1x PRP Group = 1x LAN A, 1x LAN B ports
(**) Max number of VDAN nodes table entries

PRP Network Level Recommendations (1/2)



PRP Do's

Design to avoid single points of failures
- Use redundant PSU, power sources, different fiber paths etc.
- Keep each LAN A and LAN B resilient
  - REP if all-Cisco, RSTP if multi-vendor

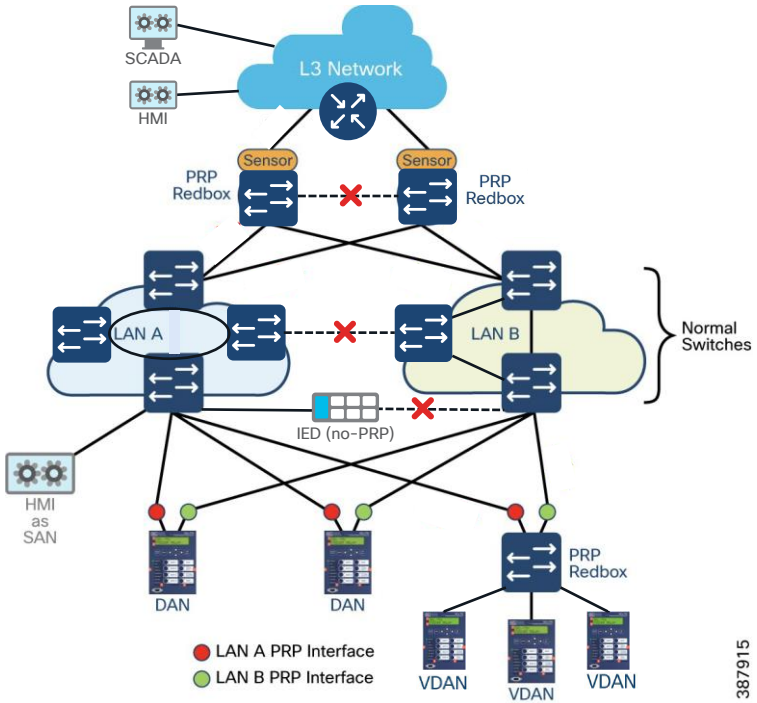
If possible, implement similar topologies for both LANs
- Not mandatory but helps with traffic latencies

DANs must be attached to both LAN A and LAN B
- Same unique MAC and IP address on both ports

SANs must be attached only to one LAN
- Unique MAC and IP address in the network

System MTU in LAN A and LAN B devices must be increased to 1506b to compensate for PRP RCT trailer

PRP Network Level Recommendations (2/2)



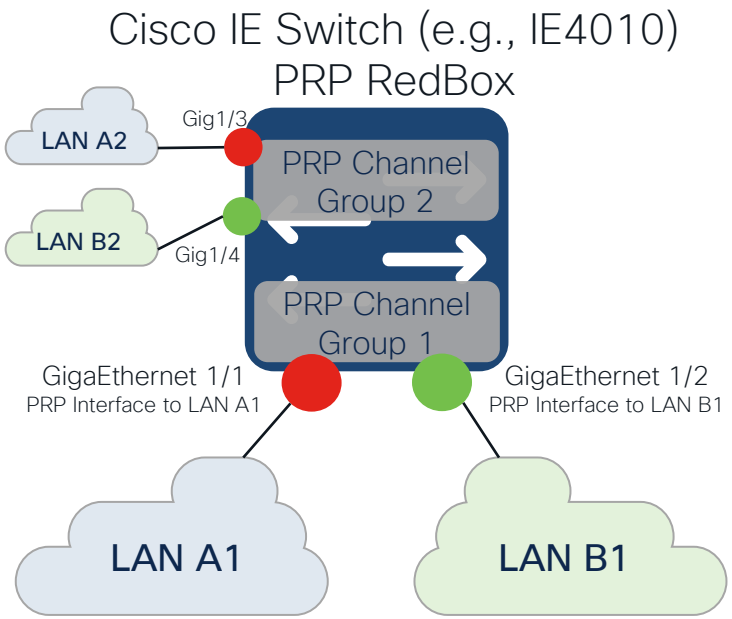
PRP Don'ts

DO NOT connect non-PRP devices to both LAN A and B
- ONLY PRP-capable (DANs) or RedBoxes should
- Possible exception may include compute nodes with ACTIVE / STANDBY links.

DO NOT interconnect RedBoxes via any Layer2 paths that bridges any of the Layer2 domains (VLANs) that exist in the PRP network
- This will create network loops that could bring both LANs down – officially disrupting all communications.

DO NOT interconnect LAN A and LAN B in any way
- LAN A and LAN B must be kept separate in order to ensure full PRP functionality and redundancy

Cisco Industrial Ethernet (IE) – PRP Channel



Cisco IE PRP implementation uses PRP Channel to connect to LAN A and LAN B

PRP Channel (2x GigE Interfaces to LAN A and LAN B)

- A PRP Channel Group is a logical interface that aggregates two identically configured GigE interfaces into a single link.
  - Can be Access, VLAN Trunk, or Layer3 interface
  - Load balancing between members is NOT supported
  - Only the PRP Channel can be shutdown (not members)
- Cisco Industrial Ethernet switches can have 2x PRP Channels for 2 separate PRP domain implementations
- L3 address, if needed, must be configured in the PRP Channel Group interface

PRP – Cisco Design Considerations

More on PRP Channel group interface

L2 control protocols (e.g., LLDP, CDP) must be disabled on the PRP interfaces.

PRP Channel must not participate in any other redundancy protocols

If using RSTP as the redundancy protocols with LAN A and LAN B

- Filter STP BPDUs at the PRP channel, create independent STP domains in the LANs
- STP boundary – it is recommended to enable PortFast edge feature (if a VLAN trunk) to improves STP convergence within the LANs

Traffic load on the PRP interfaces (GigE) can't exceed 90% bandwidth utilization.

LAN A and LAN B

Recommended to use fiber ethernet links – provide faster convergence than copper links

Remember that bandwidth impact the latency and number of nodes in the PRP networks

Critical traffic (e.g., GOOSE, SV) should be classified into HIGH priority egress queues on the interfaces

Configure unique VLANs for each IED to avoid multicast flooding

Enable storm control on the access interfaces facing IEDs

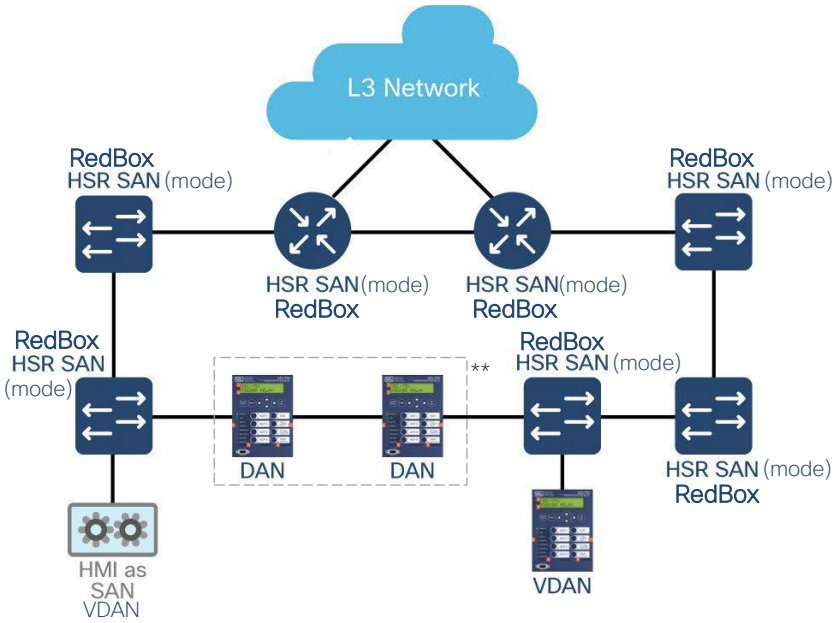
HSR

High-Availability Seamless Redundancy (HSR)

- Defined in the International Standard IEC 62439-3
- Designed to provide seamless or bumpless redundancy (zero recovery time) in a ring topology
- Rings and ring-of-rings configurations
- Redundancy provided by transmitting duplicate* frames in both ring directions

* Duplication mechanism used by PRP and HSR. Seamless redundancy continuity when used together.

HSR – Basic Topology (single ring)



(*) HSR Redbox can operate in different modes that dictate packet handling
(**) DANHs (HSR end-nodes) can be ring nodes but may become performance bottle necks. Aggregate behind high-performing L2-switches (RedBox)

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Ring Topology - only

- Devices in the ring are HSR aware
- Each node implements bridging with cut-through (forward port to port in µsec)

HSR Nodes

- DANH : Dual / Double Attached Node
- SAN : non-HSR Single Attached Node
- HSR RedBox : Redundancy Box
- VDAN : Virtual Dual Attached Node

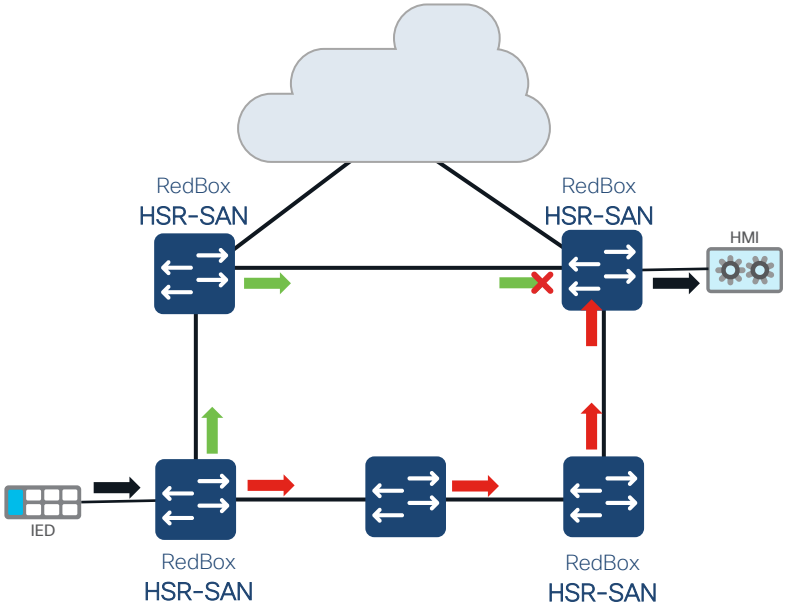
HSR Modes of operation*

- HSR-SAN : HSR to SAN connectivity
- HSR-HSR : HSR ring to HSR ring
- HSR-PRP : HSR to PRP connectivity

HSR – Nodes & Roles

Node	Name	Description
 SAN	Single Attached Node (No HSR functionality)	• Devices that do not support HSR, cannot be part of the HSR ring • Must attach to the HSR ring through a RedBox (becomes a VDAN) • e.g. HMIs, printers, laptops, etc.
 DAN / DANH	Dual / Double Attached Node (HSR functionality)	• Two ports (in ring topology) • Sends duplicate frames out each ring direction • Processes frame destined to it (accepts one copy, discards duplicate), bridges ring transient traffic (i.e., not destined to it) • e.g. IEDs or Layer2 switches that support HSR protocol.
 HSR RedBox	Redundancy Box (HSR functionality)	• Acts as a DANH for all traffic for which it is the source or destination • Multiple operating modes (HSR-SAN, HSR-HSR, HSR-PRP) • Provides HSR functionality to SANs, couple HSR rings, or couples HSR with PRP • e.g. L2 Switches w/ HSR support to aggregate SAN(IEDs)
 VDAN	Virtual Dual Attached Node (No HSR functionality)	• Non-HSR device singly attached to a HSR RedBox (HSR-SAN mode) • VDAN is a SAN emulated as a DANH by the HSR Redbox (HSR-SAN) • Redbox generates the HSR Supervision frames on behalf of the SAN hence the SAN is seen as a DANH on the ring. • No frame duplication by VDAN (HSR RedBox takes care of that)

HSR – Basic Operation (HSR-SAN)

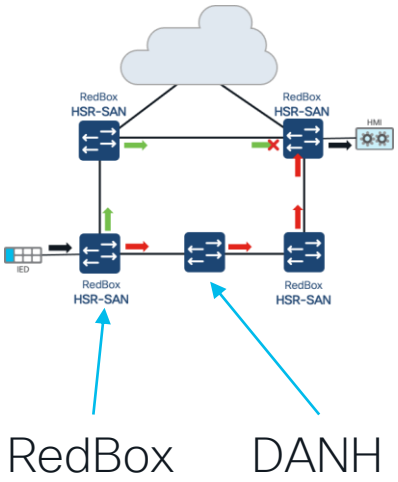


(*) HSR info in tag in the frame header, PRP info in the RCT (frame trailer)
(**) DANHs (HSR end-nodes) can be ring nodes but may become performance bottle necks. Aggregate behind high-performing L2-switches (RedBox)

Operational Basics

- HSR information – HSR tag in frame header*
- Source DANH prefixes frame with HSR tag and sends frame in both directions
  - If DANHs – insert HSR tag to its traffic.
  - If Redbox (HSR-SAN) – then inserts the HSR tag on behalf of the SAN and forwards in both directions.
- Destination DANH receives two identical frames from each port (if no failure), removes HSR tag keeps first frame and discards any duplicate.
  - If RedBox (HSR-SAN) – then process the received frames as a DANH before forwarding to the SAN
- Transient traffic – HSR nodes support IEEE802.1D bridge functionality to forward frames through.

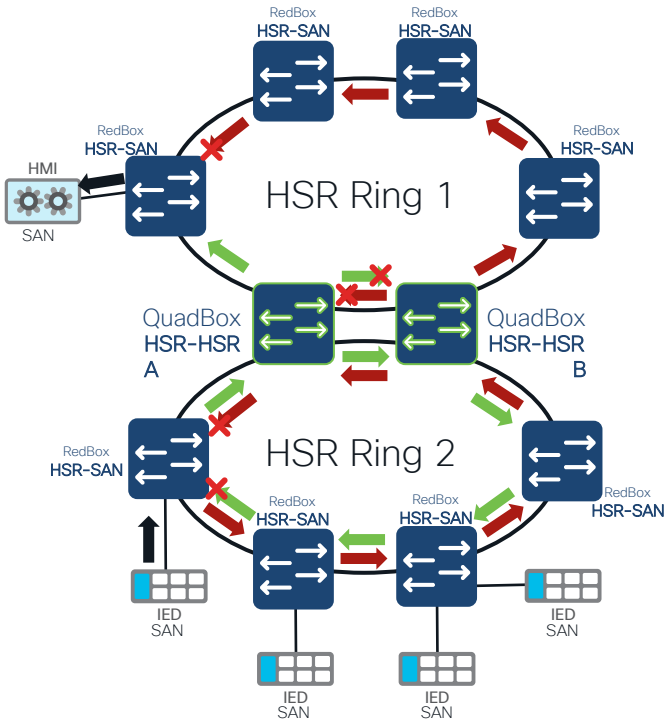
HSR – DANH Node Traffic Forwarding Rules



- A node will NOT forward a frame that it injected into the ring
- A node will NOT forward a frame for which it is the unique destination (except for applications like redundancy supervision)
- A port will NOT send a frame that is a duplicate of a frame that it already sent into that same direction
- A port will (optionally) refrain from sending a frame that is a duplicate of a frame that it already received from the opposite direction (except for supervision and timing frames)

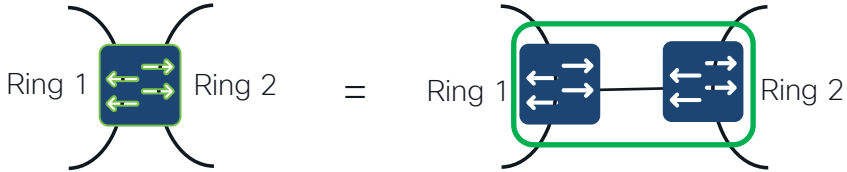
This is how loops are avoided in the HSR ring!

HSR – Basic Operation (HSR-HSR QuadBox)

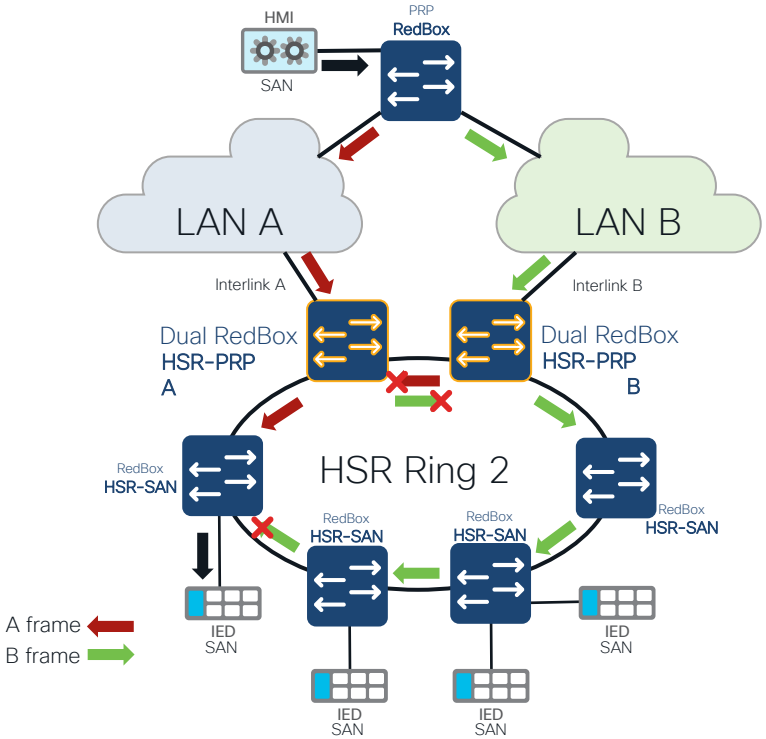


Operational Basics

- QuadBox (quadruple ports) link two HSR rings
- QuadBoxes filter traffic between rings
  - Discards frames it injected in the ring or frames injected by the other QuadBox when deployed in a pair (see image).
- QuadBoxes don't learn MAC addresses
- A QuadBox has similar implementation as a 2x RedBoxes back-to-back connected via an internal link. This helps keep each ring redundancy independent.



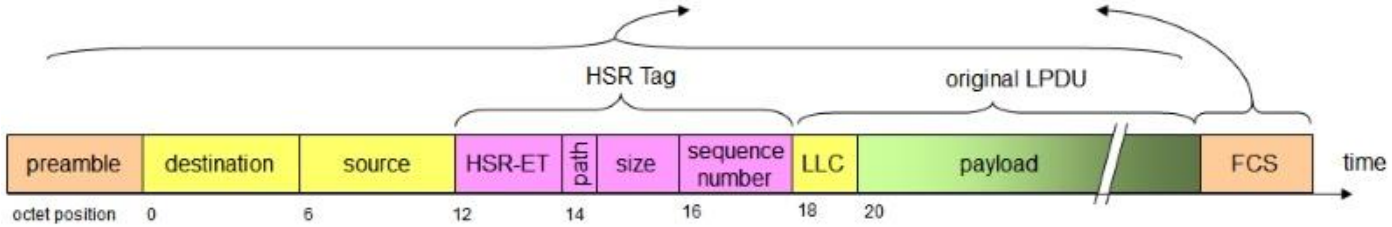
HSR – Basic Operation (HSR-PRP Dual RedBox)



Operational Basics

- Dual RedBox provides PRP redundancy on the Interlink port and HSR redundancy towards the ring ports.
- Sequence Number from PRP's RCT* is reused for the HSR tag and vice versa – Integration!
  - Allows for frame identification from one network to another
- Multicast or Unicast w/o a receiver in the ring are removed by the Dual Redbox that inserted them in the ring.
- To avoid reinjection into the PRP network by the 2nd Dual Redbox each HSR frame carries PRP PathID that ID the PRP LAN it came from.

HSR Frame – Header Tag



If the frame has a VLAN tag, the HSR tag is inserted after the VLAN tag

RCT Field	Description
HSR EtherType	16-bit EtherType = 0x892F
Path Identifier (PathId)	4-bit, identifies frame direction in the ring and prevents reinjection of frames coming from one PRP network to another.
Link Service Data Unit Size (LSDUsize)	12-bit field, allows the receiver to distinguish HSR frames from non-redundant
Sequence Number (SeqNr)	16-bit sequence number, incremented by one for each frame the DANH or RedBox sends. Combination of SRC MAC + SeqNr uniquely identify copies of the same frame.

HSR Frame

- Destination broadcast MAC
- Custom EtherType for HSR
- Path / Lane
- Sequence #

```
> Frame 15: 66 bytes on wire (528 bits), 66 bytes captured (528 bits)
v Ethernet II, Src: 3Com_4d:0c:db (00:0a:5e:4d:0c:db), Dst: Broadcast (ff:ff:ff:ff:ff:ff)
  > Destination: Broadcast (ff:ff:ff:ff:ff:ff)
  > Source: 3Com_4d:0c:db (00:0a:5e:4d:0c:db)
    Type: High-availability Seamless Redundancy (IEC62439 Part 3) (0x892f)
v High-availability Seamless Redundancy (IEC62439 Part 3 Chapter 5)
    0000 .... .... .... = Path: 0
    000. .... .... .... = Network id: 0
    ...0 .... .... .... = Lane id: Lane A (0)
    .... 0000 0011 0100 = LSDU size: 52 [correct]
    Sequence number: 5
    Type: ARP (0x0806)
v Address Resolution Protocol (request)
    Hardware type: Ethernet (1)
    Protocol type: IPv4 (0x0800)
    Hardware size: 6
    Protocol size: 4
    Opcode: request (1)
    Sender MAC address: 3Com_4d:0c:db (00:0a:5e:4d:0c:db)
    Sender IP address: 192.168.1.101 (192.168.1.101)
    Target MAC address: 00:00:00_00:00:00 (00:00:00:00:00:00)
    Target IP address: 192.168.1.10 (192.168.1.10)
```

High-Availability Seamless Redundant Consider this!

In favor of HSR

- IEC standard – HSR interoperability in multi-vendor environment
- Provides seamless or bumpless redundancy
- Ring topology eliminates the need for duplicate networks / connections as with PRP and still provide n-1 redundancy.
- Ring topology easy and cheaper build up.
- Use of fiber Ethernet avoids potential EMC issues that impact copper Ethernet
- Shortens maintenance intervals – planned outage invisible to applications

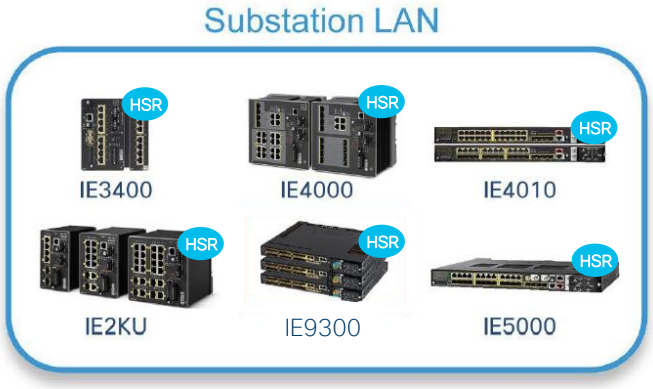
Possible cons …

- All nodes in the ring MUST support HSR-special hardware (FPGA or ASIC) to forward / discard frames within microseconds.
- Ring topology inherently reduces available bandwidth.
- Bandwidth available in ring is further reduced by up to half due to packet duplication.
- Latency increase (messages must traverse the ring over multiple hops)

Cisco HSR Support and Recommendations

cisco Live!

Cisco Substation LAN Portfolio – HSR Support



Substation LAN Positioning

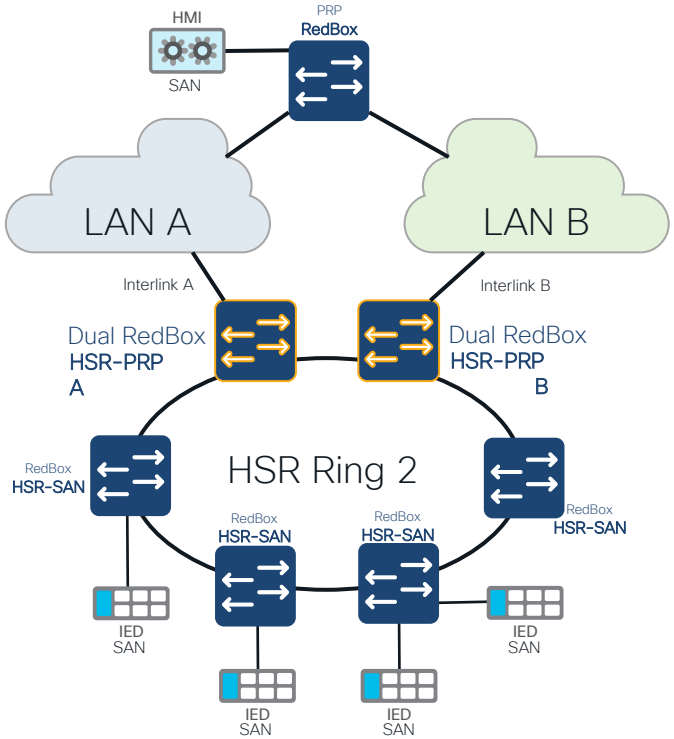
HSR RedBox	IE3400, IE4000, IE4010, IE5000, IE9300
HSR QuadBox HSR Dual RedBox	IE4000

Protocol	IE 3400	IE 4000	IE 4010	IE 5000	IE 9300
HSR	Yes	Yes	Yes	Yes	Yes
• HRS-SAN (RedBox)	Yes	Yes	Yes	Yes	Yes
• HSR-PRP (Dual RedBox)	---	Yes**	---	---	---
• HSR-HSR (QuadBox)	---	Yes***	---	---	---

**IE-4000 in HSR-PRP (Dual RedBox) – 3 active uplinks, all other ports disabled.

***IE-4000 in HSR-HSR (QuadBox) – 4 active uplinks, all other ports disabled.

HSR Network Level Recommendations (1/2)

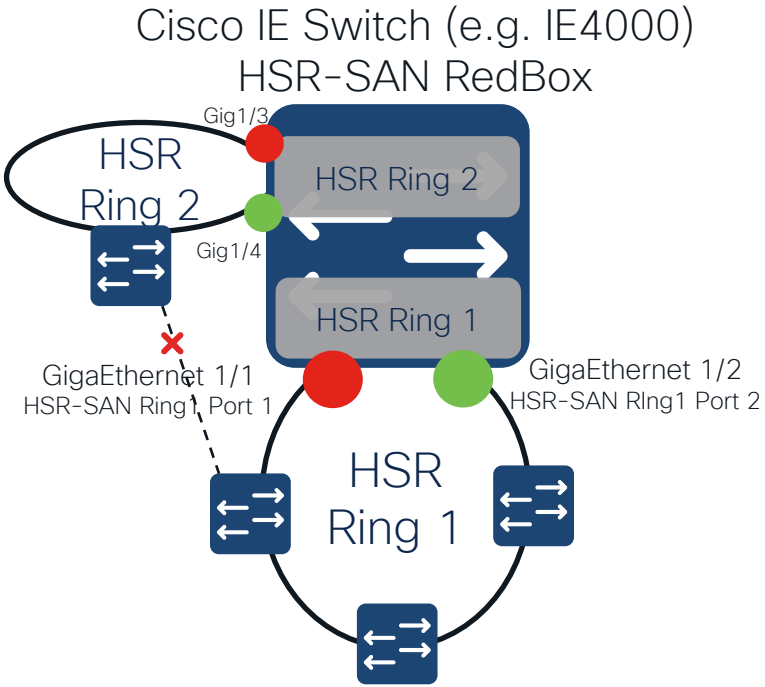


HSR Do's

- Design to avoid single point of failures
  - Use redundant PSU, power sources, diff fiber paths

  HSR-PRP Scenario – follow PRP network guidelines
- All nodes in the ring must be DANH nodes
- Non-HSR devices can only be connected to an HSR ring using HSR-SAN RedBox.
- SANs must be attached only to one HSR-SAN RedBox unless has Active / Standby links
- HSR-PRP supports higher MTUs (up to 1998 Bytes)

HSR Network Level Recommendations (2/2)



HSR Don’ts

DO NOT connect non-HSR devices in the HSR ring
- ONLY HSR-aware (DANH) or RedBoxes should

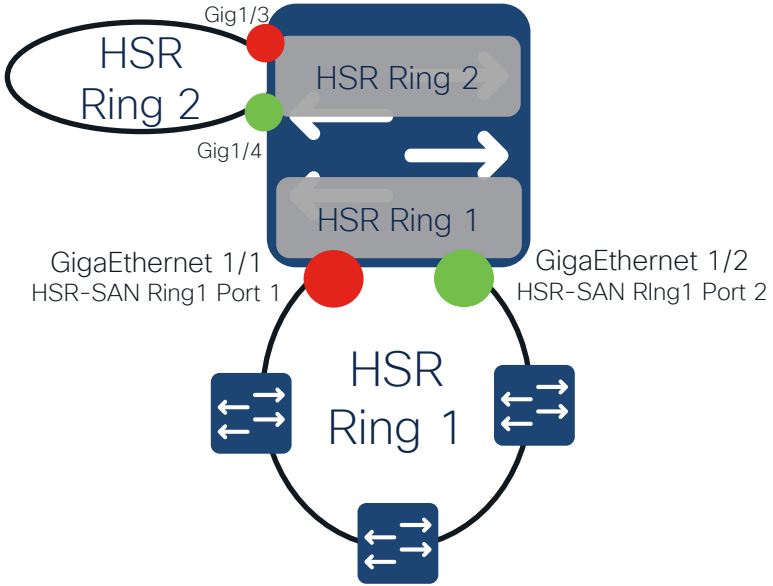
DO NOT interconnect RedBoxes via any Layer2 paths that bridges any of the Layer2 domains (VLANs) that exist in the HSR ring
- This will create loops that could bring rings down – officially disrupting all communications.

DO NOT install links of different speeds and media between HSR ring nodes.
- Performance will be impacted – remember that duplication reduces ring bandwidth

DO NOT exceed number of nodes per ring.
- IEC 62439-3 Annex C suggests 16 nodes to account for time inaccuracy needs

Cisco Industrial Ethernet (IE) – HSR-SAN Redbox

Cisco IE Switch (e.g. IE4000)
HSR-SAN RedBox



Cisco IE HSR uses HSR-Ring interface to connect to the ring (up to 2 HSR rings)

HSR-Ring Interface (2x GigE Interfaces per ring)

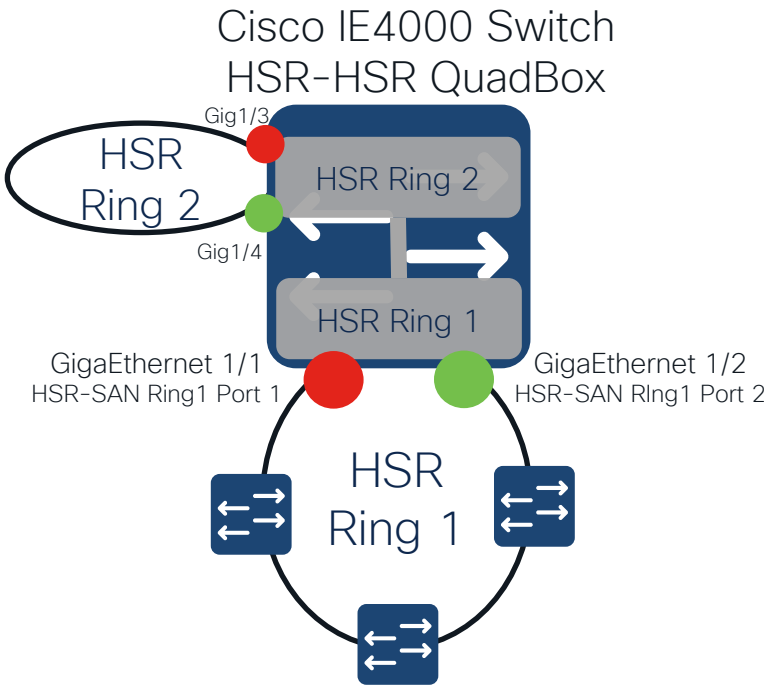
HSR-Ring interface is a logical interface that aggregates two identically configured GigE interfaces into HSR

- Can be Access or VLAN Trunk
- Load balancing between members is NOT supported
- Only the HSR-Ring interface can be shutdown (not members)

Cisco Industrial Ethernet switches can have 2x HSR-Ring interfaces (HSR-SAN) for 2 separate HSR domains

TIP During configuration it is recommended to shutdown the physical ports in all switches to prevent MAC flaps.

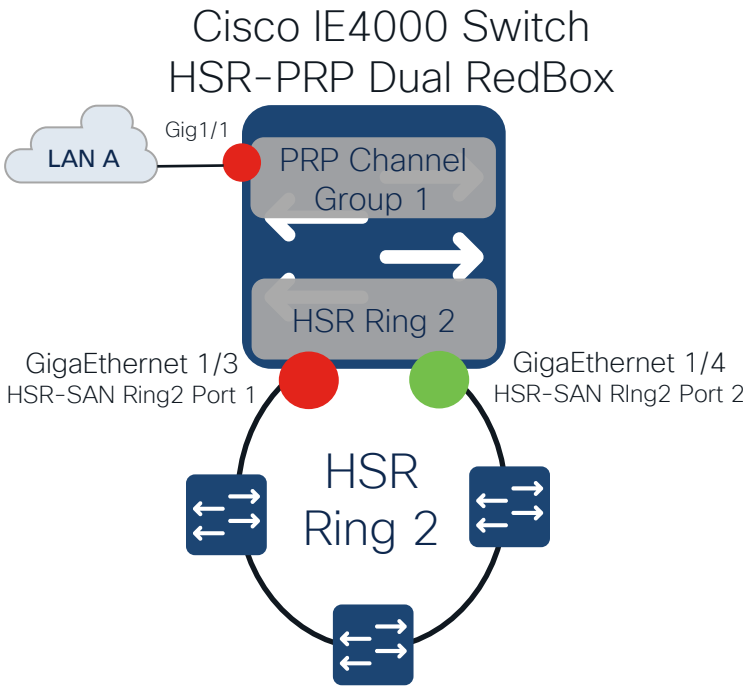
Cisco Industrial Ethernet (IE) – HSR-HSR *(Quadbox)*



HSR-PRP mode is only supported in the IE4000

HSR-HSR Interface (4x GigE Interfaces)
HSR-Ring interfaces' configuration guidance applies
MAC address learning is disabled in HSR-HSR mode
HSR-HSR QuadBox enabled only the 4 ports will remain active - ALL other ports shutdown / disabled
When HSR-HSR is disabled, ALL ports become operational and return to their default (original configuration is lost)
Switchport mode access is restricted in HSR-HSR mode
MTU size is fixed to 2020 in HSR-HSR (can't be changed)
PTP is by default disabled

Cisco Industrial Ethernet (IE) – HSR-PRP *(Dual RedBox)*



HSR-PRP mode is only supported in the IE4000

HSR-PRP Interface (3x GigE Interfaces)

- HSR-Ring interface and PRP Channel configuration guidance applies in this HSR-PRP mode.
- 3ports participate in the HSR-PRP network, only HSR Ring 2 can be configured in HSR-PRP mode
- HSR-PRP Dual RedBox enabled only the 3 ports will remain active - ALL other ports shutdown / disabled
- When HSR-PRP is disabled, ALL ports become operational and return to their default configuration (original configuration is lost.)

HSR – Cisco Design Considerations

More on HSR Ring interface group

- Mutually exclusive protocols (PRP, EtherChannels, LACP, PAgP, REP) on HSR ports.
- HSR rings: Maximum of two per Cisco IE switch
- Maximum number of nodes in node table is 512
  - Nodes = DANH, VDAN devices in the ring
  - Not a hard limit but exceeding may increase packet duplication in some cases.
- STP is NOT supported on the HSR rings. Disabled by default.
- MACsec, HSR, and PRP not allowed together

- 50 nodes per HSR ring – impacts timing and delay
- TIP Deploying 2x QuadBoxes – config must be same
- TIP Recommended to use fiber ethernet links – provide faster convergence than copper links
- TIP Remember that bandwidth impact the latency and number of nodes in the HSR ring
- TIP Critical traffic (e.g. GOOSE, SV) should be classified into HIGH priority egress queues on the interfaces
- TIP Enable storm control on the access interfaces facing IEDs

What about timing over PRP / HSR?

PTP is a critical foundational requirement for the modern Substation. Safeguarding PTP with PRP/HSR protects business continuity.

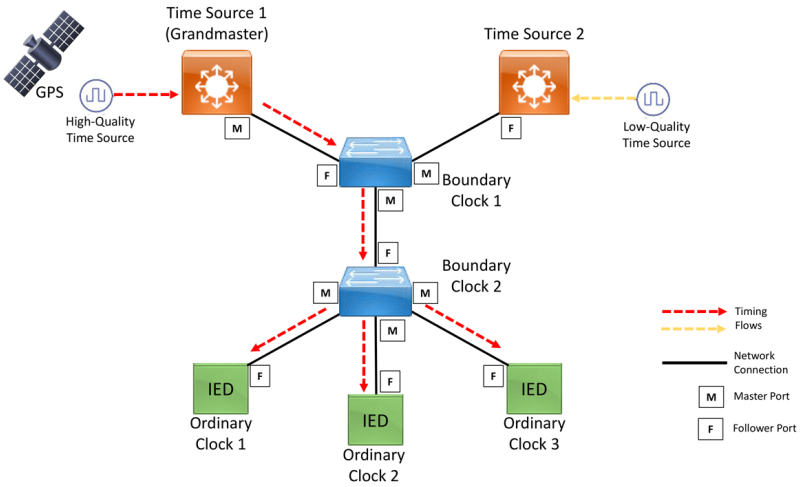
Precision Time Protocol (PTP)

- Time precision and synchronization protocol – IEEE Std. 1588
- Message-based (packet networks like Ethernet)
- Integrates time synchronization in the industrial ethernet network
- Sub-microsecond accuracy
- Multiple profiles with variety of requirements*

*PTP Power Profile focuses on Substation timing requirements

PTP Network – Clock Types

Quick value points



- Grandmaster Clock (GMC)
  - Primary time source in PTP hierarchy
- Boundary Clock (BC)
  - Normally a LAN switch.
  - One port Follower (Slave) towards GMC others are Master ports towards Follower (Slaves)
  - Introduces 200ns or less of time inaccuracy.
- Transparent Clock (TC)
  - Normally a LAN switch.
  - Corrects time interval and forwards PTP messages.
  - Introduces less than 50ns of time inaccuracy.
- Ordinary Clock (OC)
  - End-client device. Industrial devices, sensors, relays, monitoring and metering systems (e.g., IEDs)

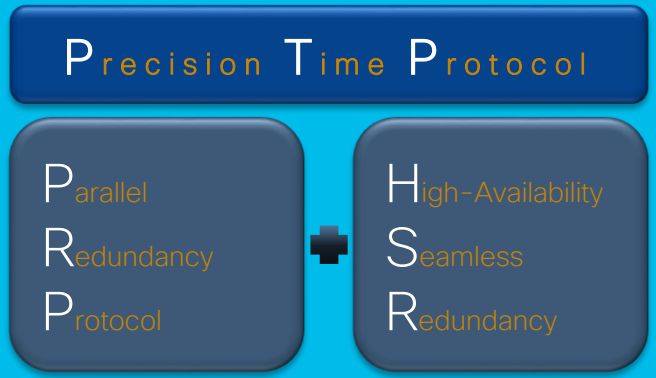
PTP – Profiles & Timing Requirements

Power Profile	
	• Specified for Power Utility Automation (IEC/IEEE 61850-9-3) • Transported over Layer 2 (ethernet - multicast) • Using peer-to-peer delay measurement (P2P) • Based on IEC 61588:2009, Clause J.4

High-level Time Requirements* (relevant to the PTP / PRP or HSR topic)		
Network time inaccuracy	Better than +/- 1 µs through ~15 TCs or 3 BCs	0.000001s
TC Requirements	Shall introduce less than 50ns of time inaccuracy, measured between ingress port and egress port	0.00000005s
BC Requirements	Shall introduce less than 200ns of time inaccuracy between port in Follower / Slave state and any port is Master state.	0.0000002s
Links Requirements	Shall present a propagation asymmetry of less than 25ns. Calculated by peer-to-peer delay measurement (FYI: ~ 5 µs/Km for fibre or copper)	0.000000025s

*some of IEC 62439-3:2016, Annex C timing requirements – not all

PTP Protection



- Defined in IEC-62439-3
- PTP over PRP/HSR can coexist in network devices and end-nodes.
- Redundant connections of PRP/HSR-nodes increase PTP resiliency & reliability
- PRP/HSR packet duplication would complicate timing information – special processing required

PTP over PRP / HSR

PRP and HSR redundancy work on packet duplication on different network paths to a destination.

vs.

PTP time synchronization accuracy relies on a clear understanding of paths and transit delays.

Challenges

- Different delays in PRP (LAN A vs. LAN B) and opposite sides of the ring (HSR)
- PRP: TC* modifies frames through the LAN
- PRP: TC* in LANs not PRP-aware – not required to forward RCT w/ PTP messages
- PRP: BC** in LANs not PRP-aware – no RCT in PTP messages)
- DANP or DANH don't receive the same PTP message on both ports even if sent from same source

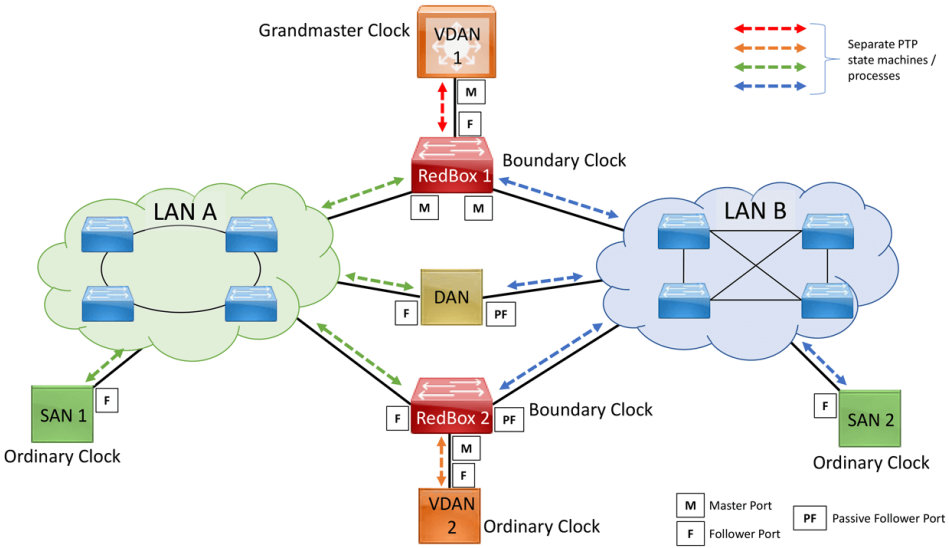
Solution

- IEC 62439-3 Annex C – specifies different handling of PTP – for PRP and HSR – It is a standard!
- PRP: PTP packets are not to be appended with a PRP RCT (Redundancy Control Trailer)
- PTP packets are not duplicated by PRP or HSR (Peer-Delay messages are link local – no duplication)
- Applies to Default and Power Profile

*PTP Transparent Clock
**PTP Boundary Clock

PTP over PRP or HSR

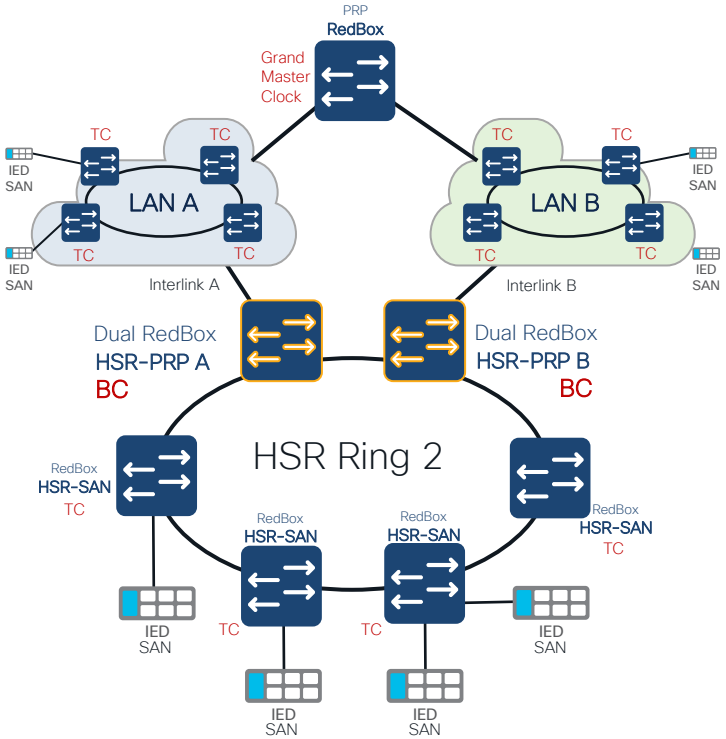
Quick view – How it works



PTP over PRP example

- Master Clock (or Boundary towards other clocks) - Sync messages out of each port (2 ports) every sec
- Ordinary Clock (e.g., DAN)– receives the two Sync messages at different times and applies BMCA (Best Master Clock Algorithm).
- When the two Sync messages come from the GMC then clock quality is used to decide.
  - Keep in mind that the Follower (aka Slave or Ordinary Clock) will normally listen on one port and supervise the other (no bouncing between ports).

PTP Network Level Recommendations



PTP on PRP/HSR Do's and Don'ts

Design LAN A and B with Transparent Clocks (TC)

- It is critical to use PTP aware devices that will keep time inaccuracy to the lowest predictable number.

Use Boundary Clocks (BC) HSR-PRP RedBoxes

- Two BCs are treated as redundant clocks on HSR w/ one being the primary other backup
- Adds layer of time synchronization protection
- Provides end-point scalability, reduces load on GMC

DO NOT use Transparent Clocks (TC) HSR-PRP RedBoxes – not recommended by IEC

- May cause the injection of 4 PTP messages as none serves as primary source - not redundant clocks

Keep in mind the HSR node ring limits vs. time inaccuracy recommendations.

Key Take Aways

Key Take Aways

1	HSR or PRP? Probably both!
2	If done right, you get true A+B networking and 0ms recovery, if done wrong, you don't!
3	Support for HSR and PRP in Cisco IE switches and IR8340 router, features in IOS & IOS-XE
4	Cisco Substation Automation CVD: https://www.cisco.com/c/en/us/solutions/design-zone/industries/power-utilities.html

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