Overview of Communications In Power Systems Protection and Control (PAC) Applications

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Outline

- Protection and Control Applications
  - Protective Relaying
  - Wide Area P&C
- Substation P&C Communications
- Time Distribution in P&C Applications

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Overview – P&C Communications

- Existing Schemes
- Fiber in Power Systems
- Multiplexers – TDM
- Packet Networks

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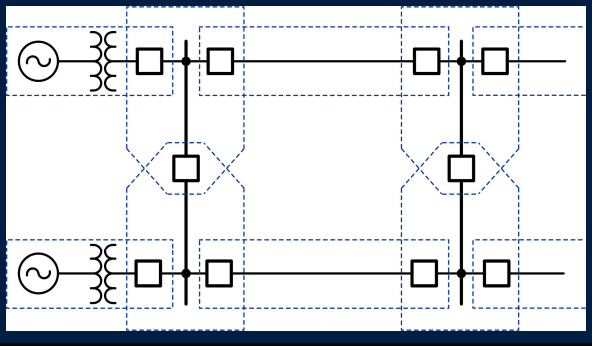
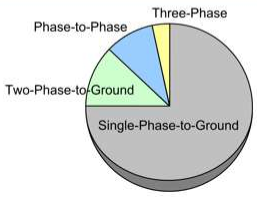
Power System Protective Relaying

- Fault Detection
- Faulted Element Disconnection
- Fault Indication



Typical Short-Circuit Statistics

Single-phase-to-ground:	70–80%
Phase-to-phase-to-ground:	17–10%
Phase-to-phase:	10–8%
Three-phase:	3–2%



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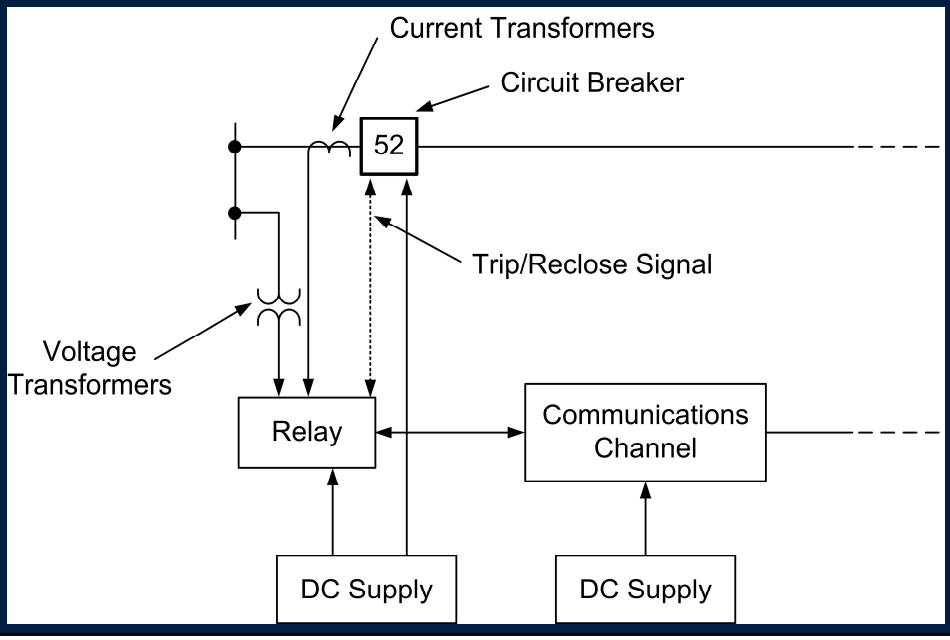
Protective Relaying System



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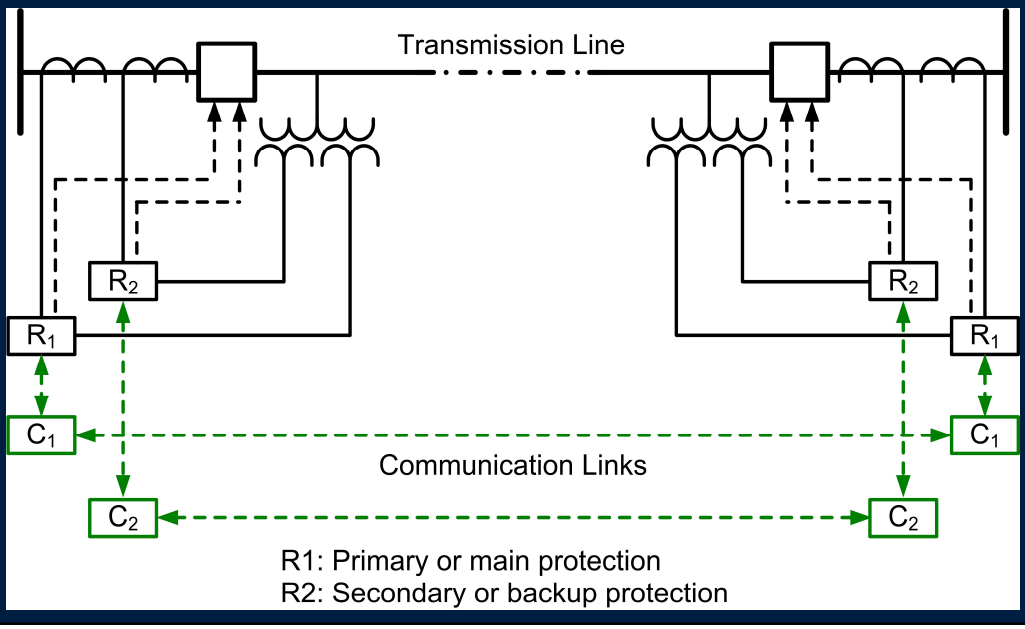
Common Transmission Line Protection Scheme



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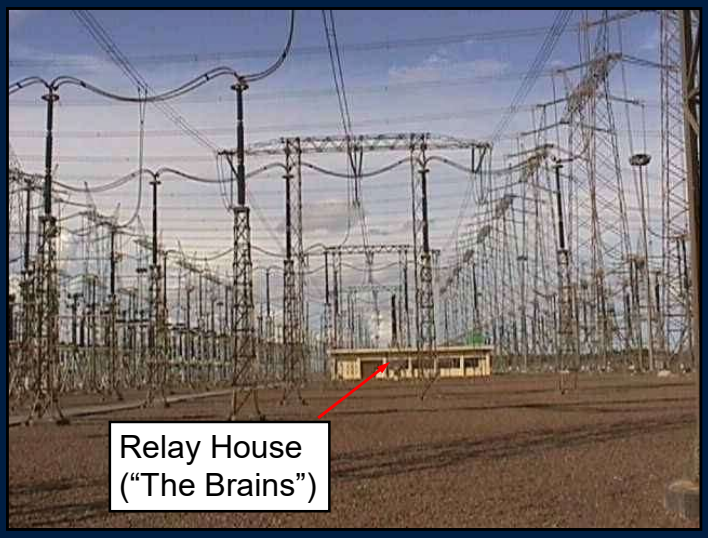
Where Are the Protective Relays?



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Protective Relays

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Power system stability

…is the ability of a Power System, for a given initial operating condition, to regain a state of operating equilibrium after being subject to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.”

– IEEE / CIGRE Task Force

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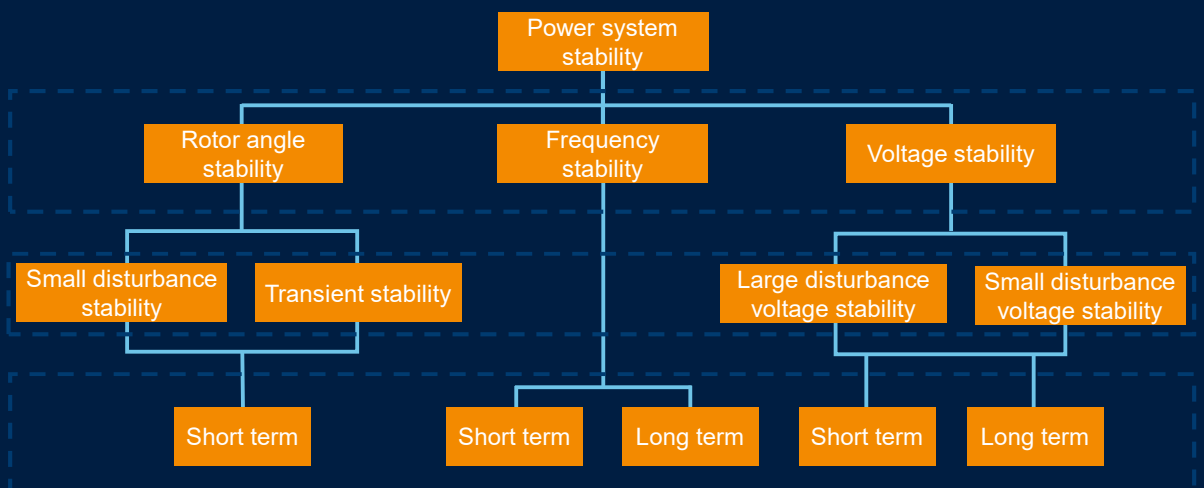
Power system stability classification



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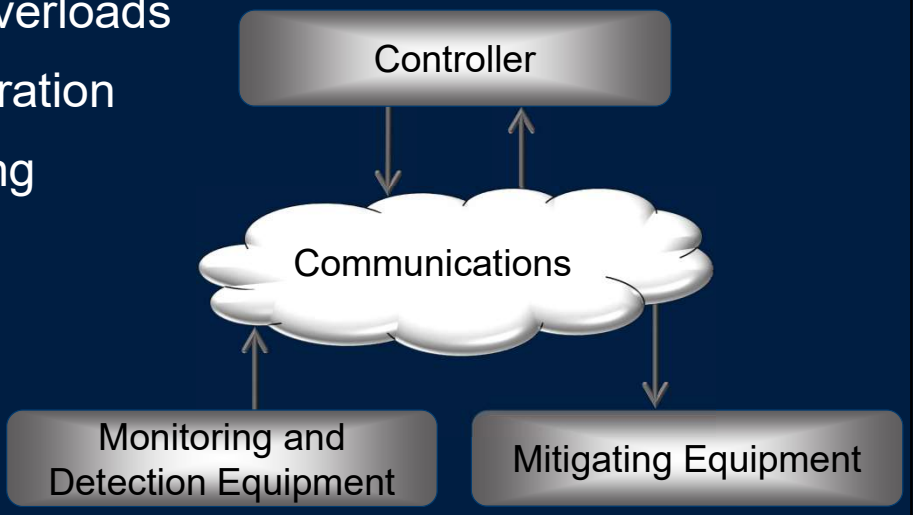
Power System Control

- Equipment overloads
- Excess generation
- Load shedding
- Islands
- Oscillations



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Protection and Control Communications

- Reliable
- Fast
- Secure
- **Fundamental**

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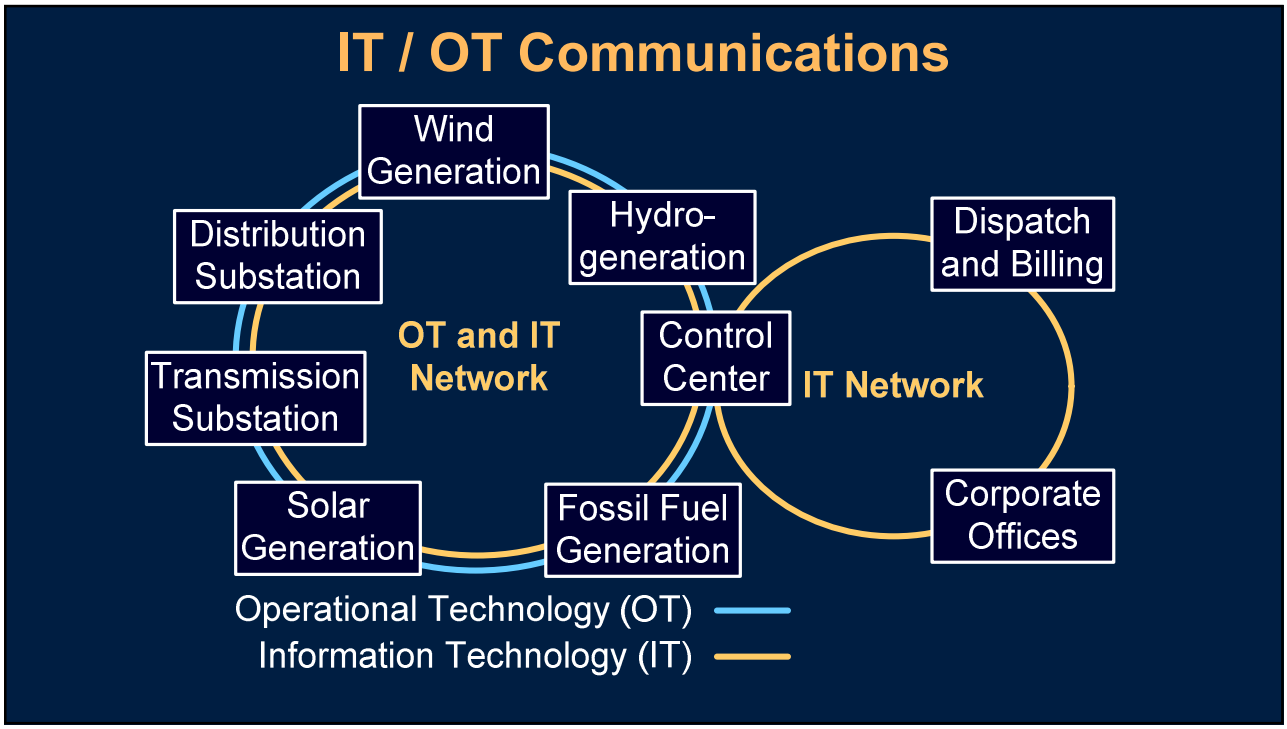

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Evolution of Communications in Power Systems for PAC

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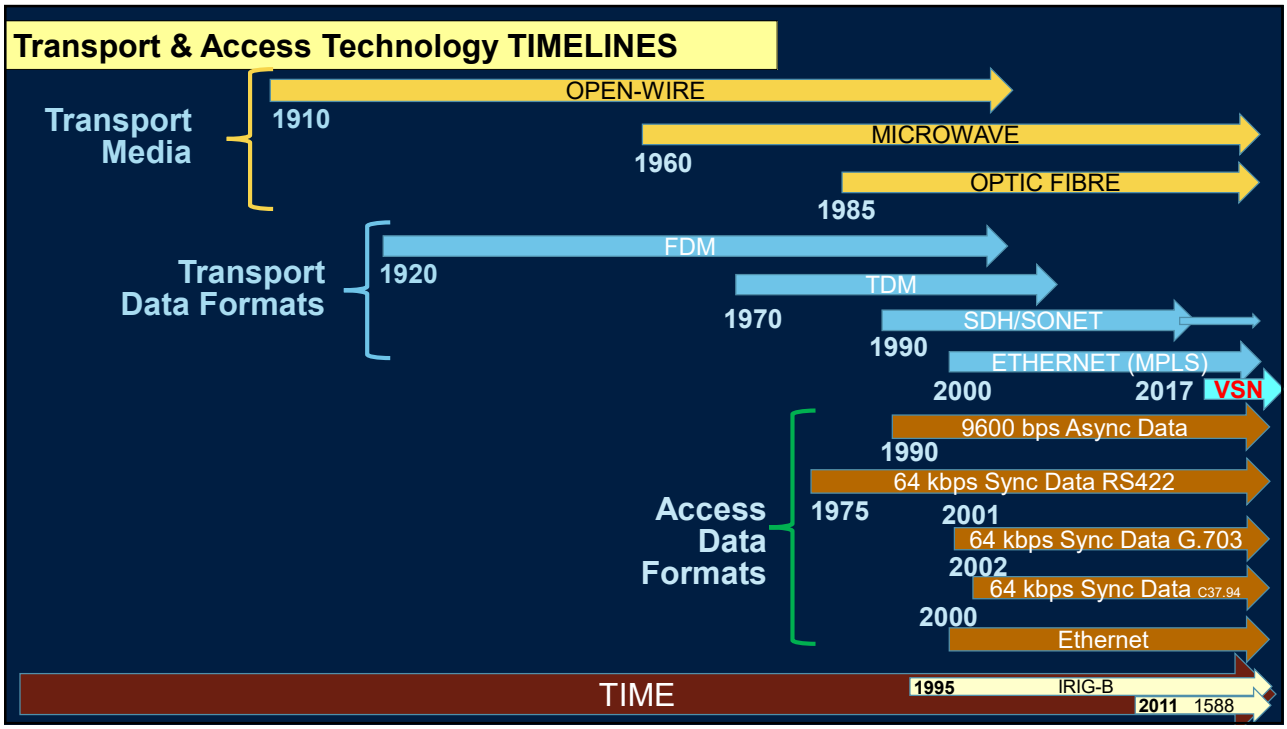

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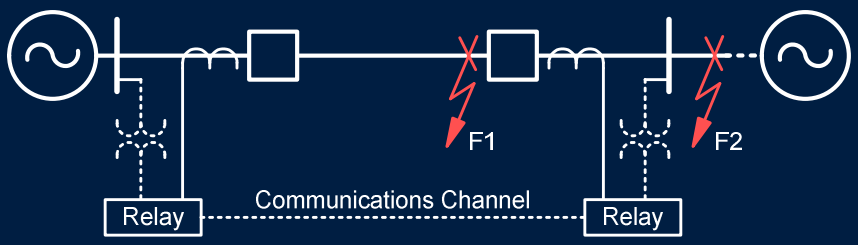
Pilot Protection



- Directional comparison (V, I)
- Current only (I)
  - Phase comparison
  - Differential

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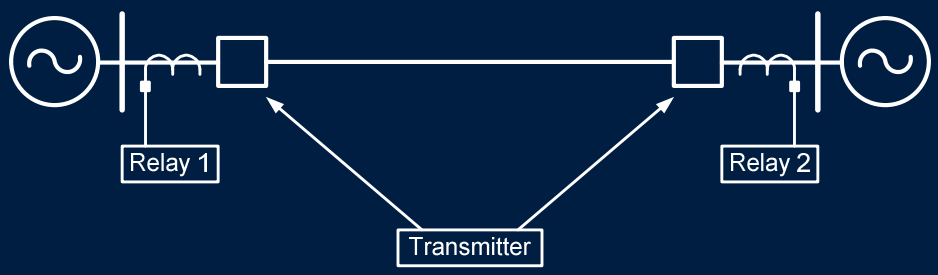
DTT Scheme



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Analog Communications

- Audio tone
- Power line carrier (PLC)
  - Line tuner
  - Wave trap

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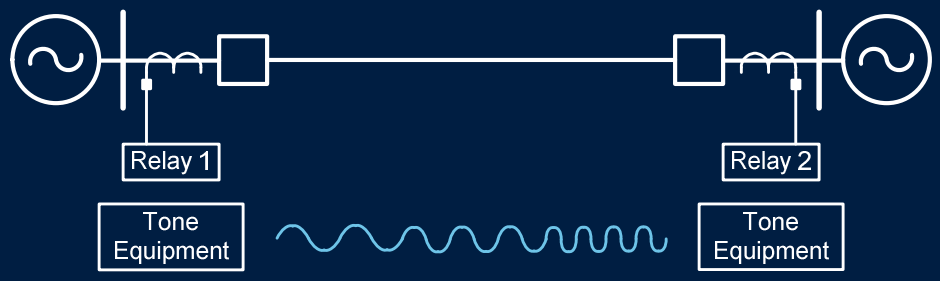
Audio Tone Scheme



- Communication is via audible tone over telephone lines
- Simple frequency shift differentiates guard and trip signals

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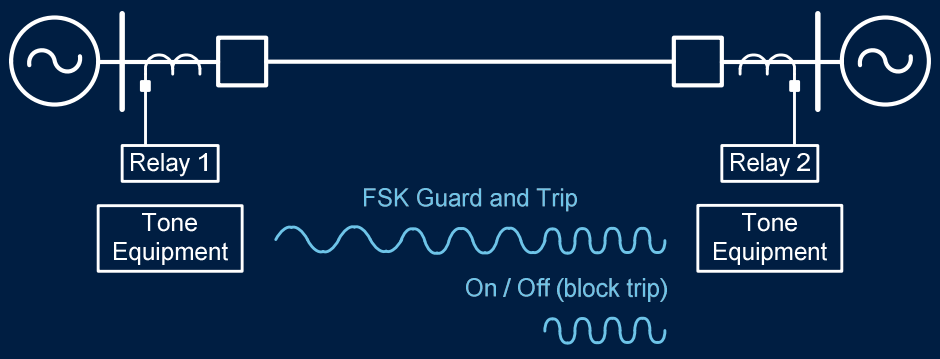
PLC Scheme



- Communication via high-frequency signals
- Signals sent directly over power lines

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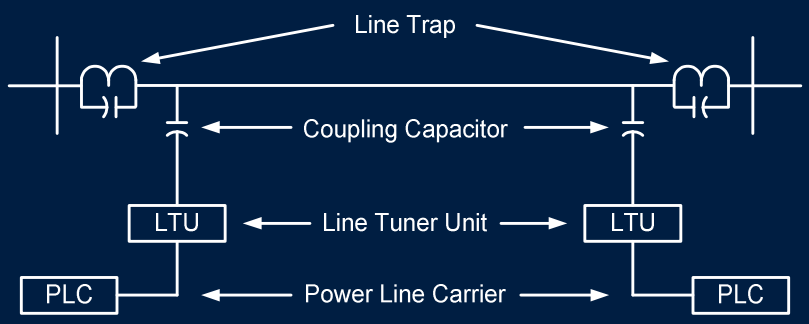
Power Line Carrier System Components



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Line Tuner

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Line Trap



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Power Line Carrier

- Utility owned
- Fast (< 1 cycle)
- Relatively low bandwidth
- High initial terminal equipment cost
- Susceptible to fault-generated noise

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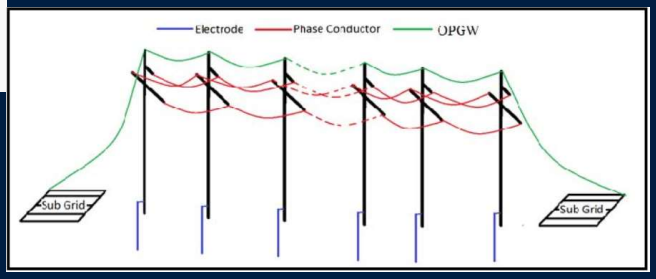
Fiber Optics – OPGW



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Types of Digital Communications

- Direct fiber
- Multiplexed fiber optics
  - Synchronous optical network (SONET)
  - Packet Networks (Ethernet / MPLS)
- Digital radio

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Direct Fiber Optic

- Immune to electrical interference
- Fast (latency < 5 μs / km)
- Initial costs proportional to distance
- Low maintenance
- Long distances (> about 80 miles) need repeaters

Works well for all protection and control schemes

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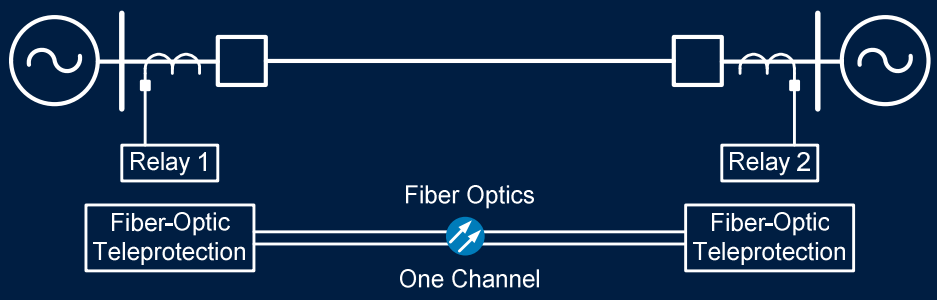
Dedicated Fiber Optics



Converts relay contact information into modulated light over fiber-optic cables

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Multiplexed Fiber Optics

- TDM - SONET / SDH
- Packet Comm - Ethernet / MPLS

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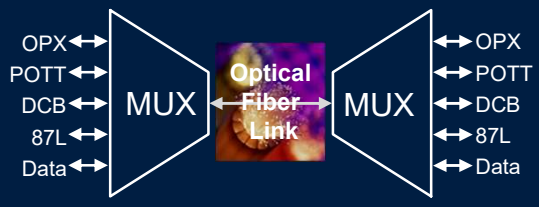
Multiplexed Fiber Optic

- Similar to direct fiber optic
- Slight additional delay introduced
- Spreads costs over more users
- Self-healing ring improves reliability – **TDM is most deterministic**
- Increases complexity, cost
- Long distances (> about 80 miles) need repeaters



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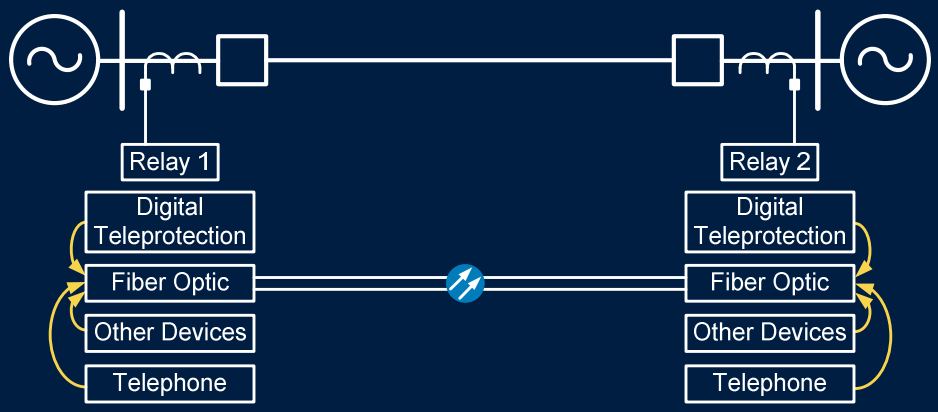
Multiplexed Fiber Optics



- Large channel capacity
- Many different channels can fit onto fiber pair

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Radio

Digital radio systems convert digital teleprotection signals to radio waves and transmit them via air

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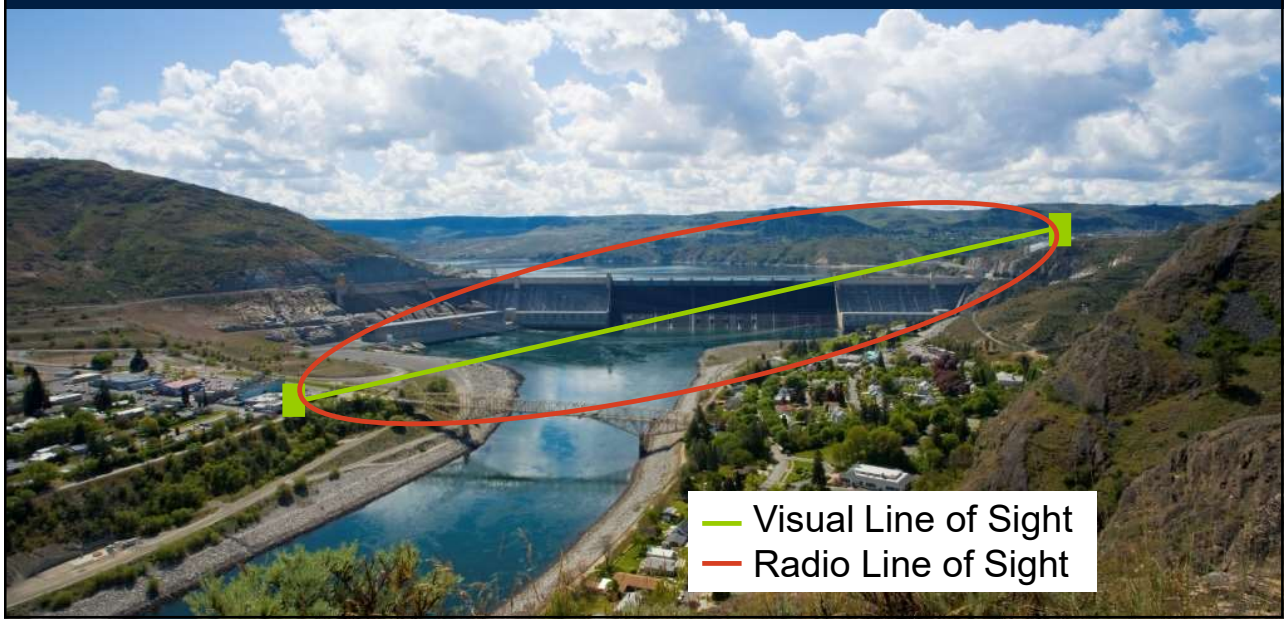
Digital Radio Line of Sight



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Utility Communications
Wide-Area Networking

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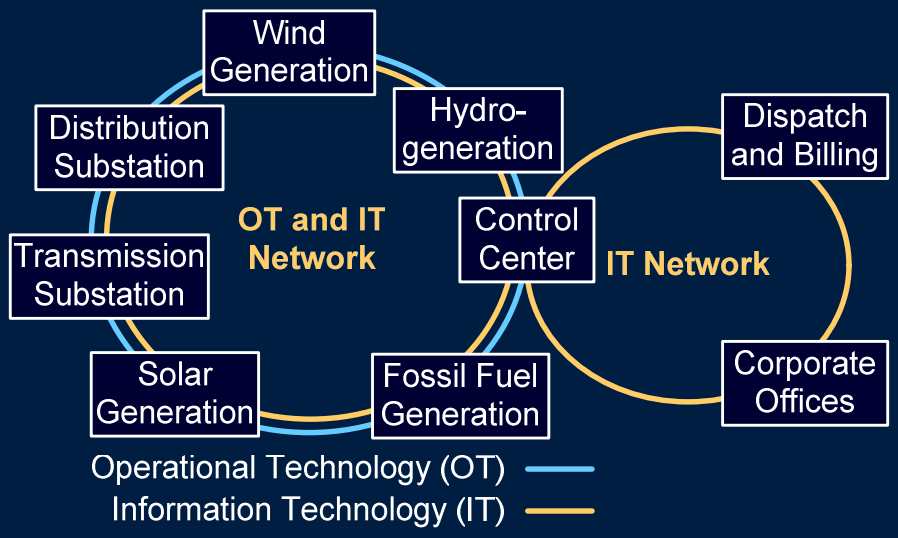
Power Utility WAN Combines OT and IT Services



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WAN Transport Technologies

- Time-division multiplexing (TDM)
  - Dedicated bandwidth
  - SONET, and SDH
- Packet-based communication
  - Shared bandwidth
  - Ethernet, Carrier Ethernet, MPLS, and SDN

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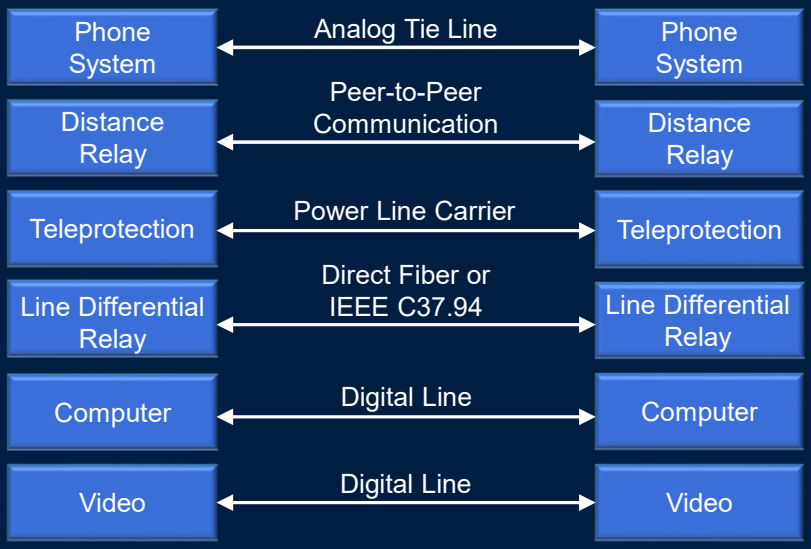
Communication Without Multiplexing



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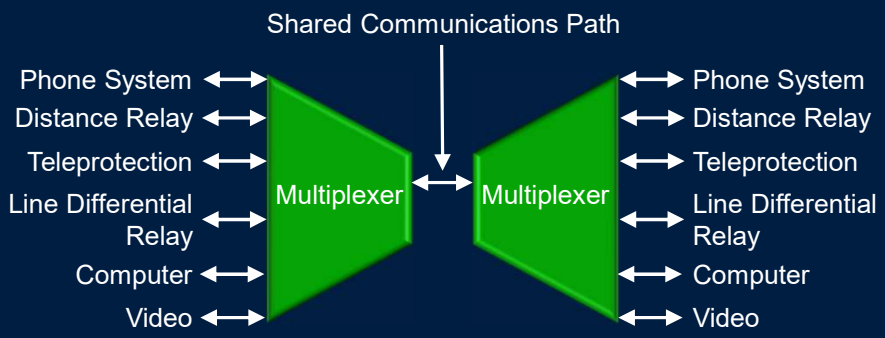
Communication With a Multiplexer



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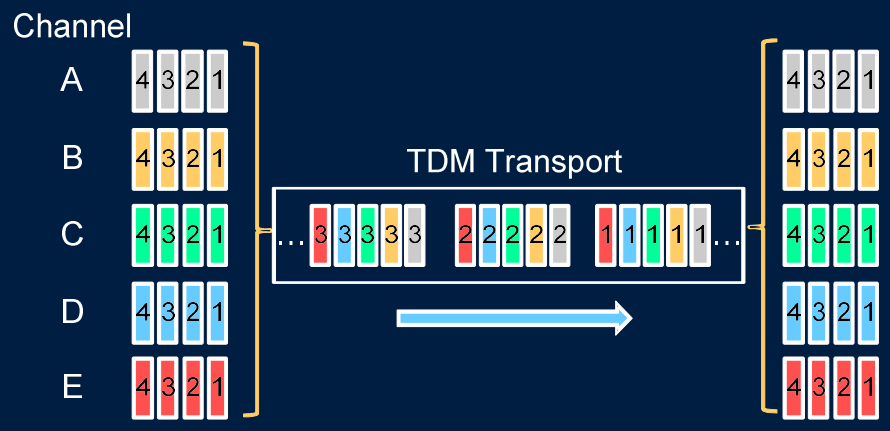
TDM Communication
Fixed Latency and Bandwidth



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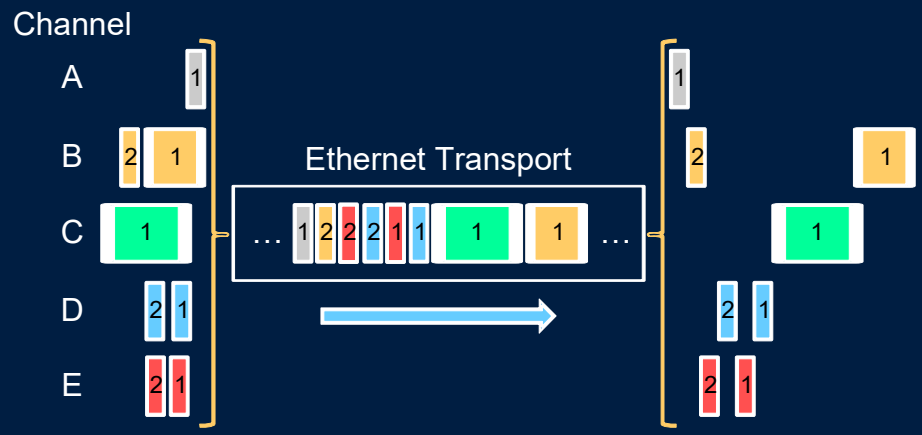
Ethernet Packet-Based Communication
Larger Bandwidths, Faster Transport



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Comparison of TDM and Packet-Based Systems

Attribute	TDM (SONET, SDH)	Packet-Based (Ethernet)
Latency	Fixed	Variable
Determinism	Yes	No
Bandwidth	Dedicated	Shared
Multicast and broadcast	No	Yes
In-band OAM	Yes	No

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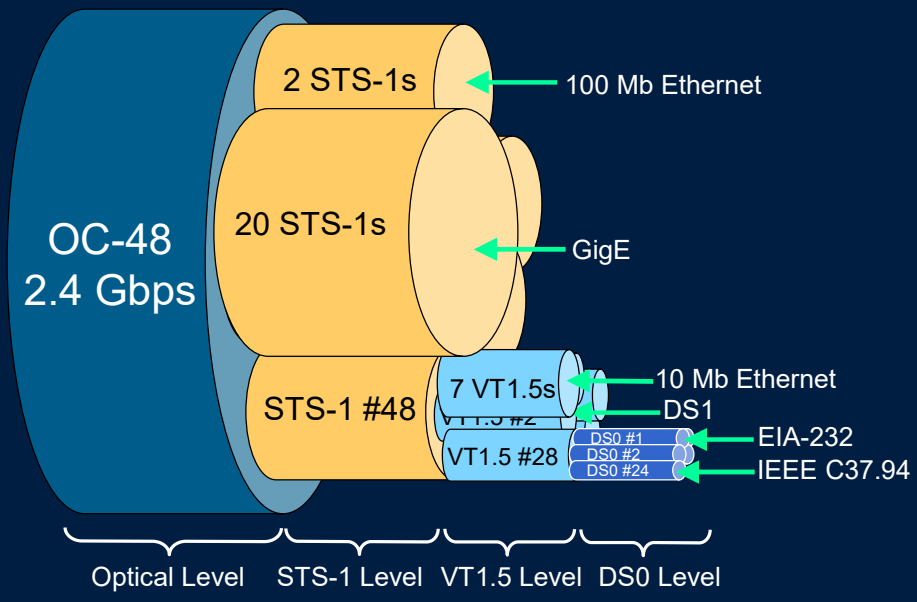
TDM Traffic Segmentation



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SONET Synchronous Rates and Formats

Level / Interface	Bit Rate (Mbps)	DS0 Channels	Number of DS1s
VT1.5*	1.728	24	1
STS-1**	51.84	672	28
EC-1	51.84	672	28
OC-1	51.84	672	28
OC-3	155.52	2,016	84
OC-12	622.08	8,064	336
OC-48	2,488.32	32,256	1,344
OC-192	9,953.28	129,024	5,376

* Internal level – encapsulates DS1
** Internal level – native or encapsulates DS3

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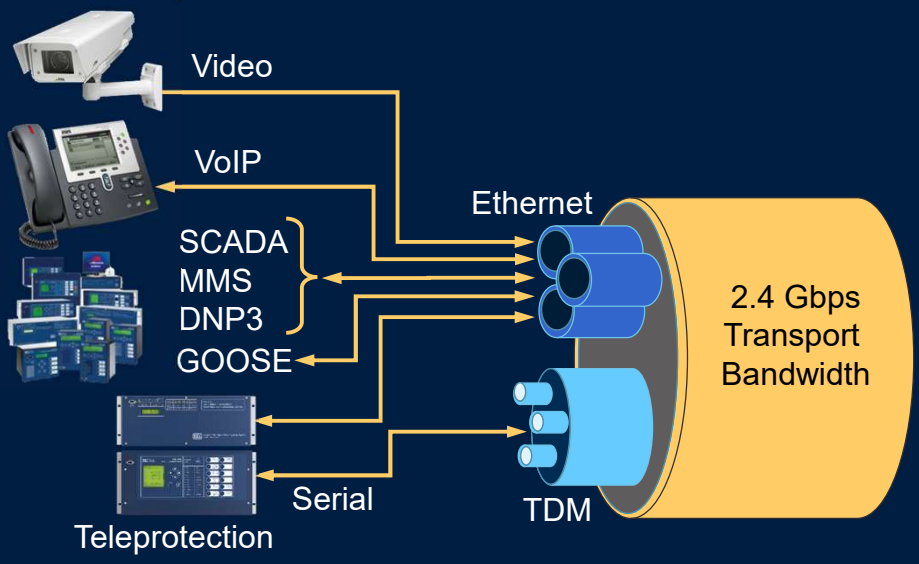
Dedicated Data Pipes for TDM and Ethernet Services



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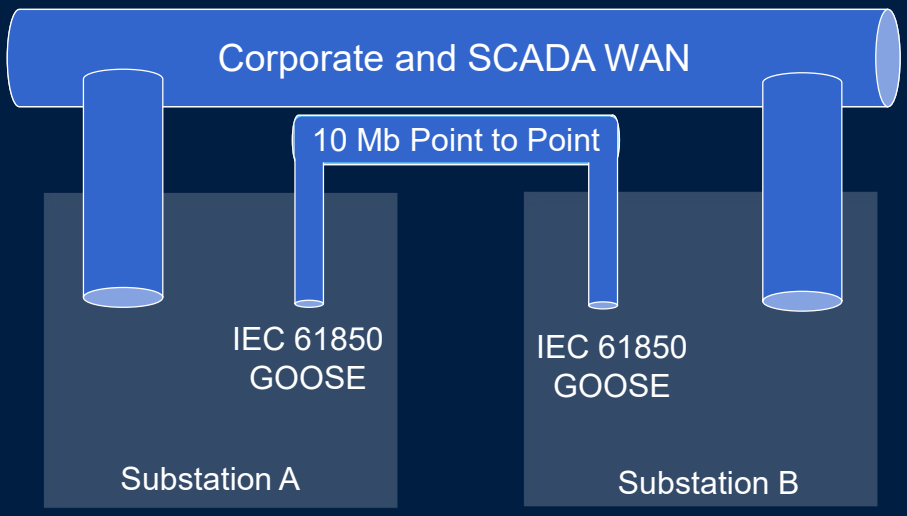
Ethernet Pipes Isolate IEC 61850 Intersubstation GOOSE Messages



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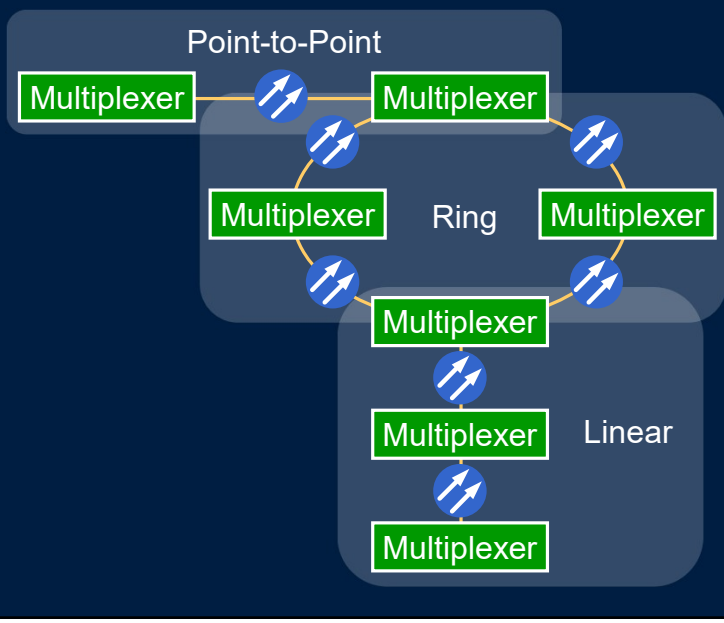
Network Topologies



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Ring Topology Is Preferred

- Restores service
  - 60 ms for original SONET specification
  - 5 ms for modern substation multiplexers
- Protects against single points of failure
  - Cut fiber
  - Node failure
  - Equipment failure

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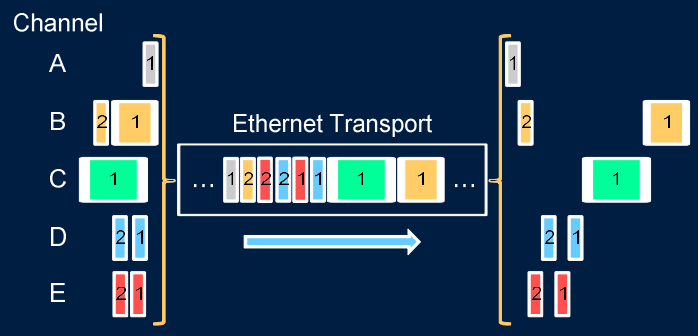
Packet Networks



- Data Packet Transport
- WAN – Wide Area
- LAN - Substation

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Multiprotocol Label Switching (MPLS)

- Was developed for high-bandwidth telecommunications core networks
- Provides 1- to 40-GigE backbones
- Uses labels direct data through network
- Uses labels to identify virtual links (paths) between nodes
- Is used to transport TDM, Ethernet, ATM, frame relay, and DSL

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Ethernet

- Popular Technology – IT
- OT
- Deficiencies
  - Determinism / Traffic / Reconfiguration
- Variations / OT
  - PRP
  - SDN

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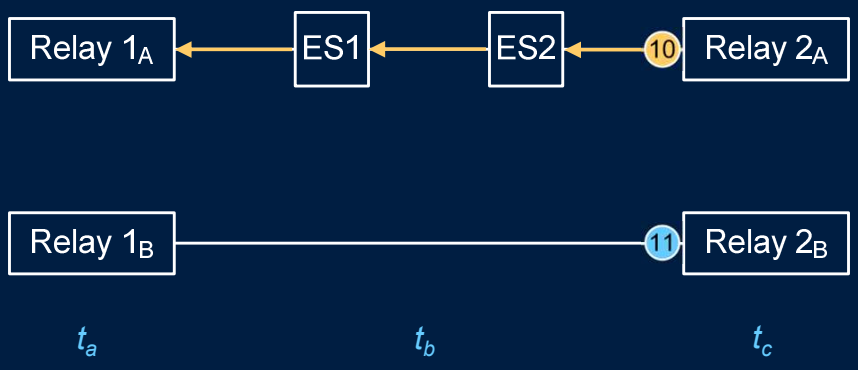
Message Latency and Variation Affected by IEDs and Network



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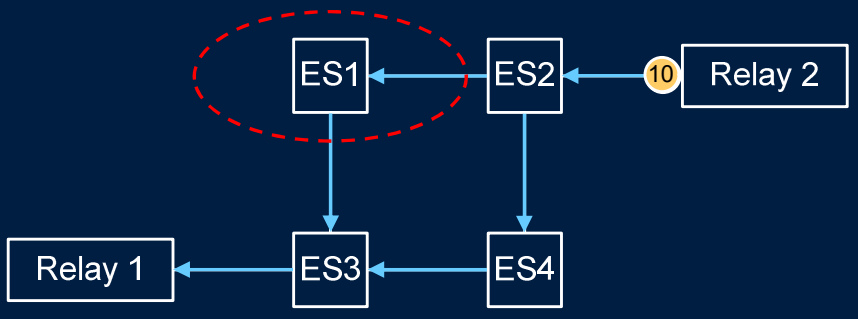
RSTP (Rapid Spanning Tree Protocol)



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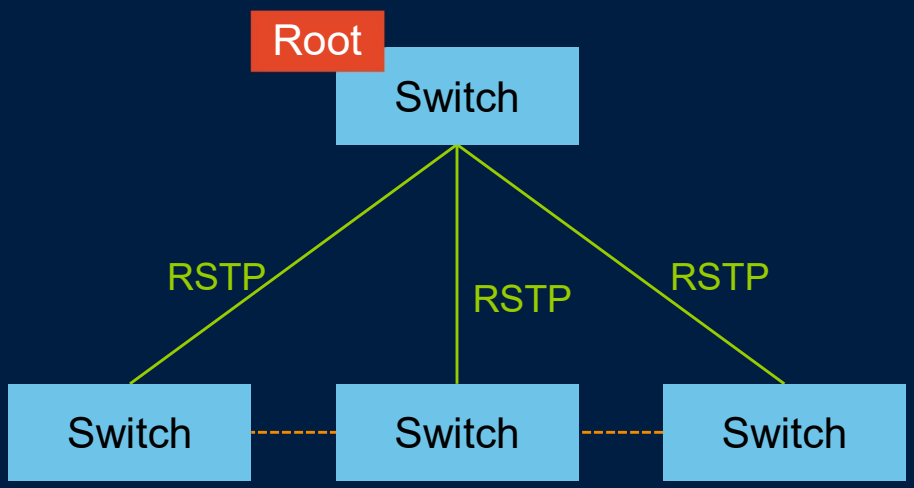
Ethernet Networks Require Constant Communication to Manage



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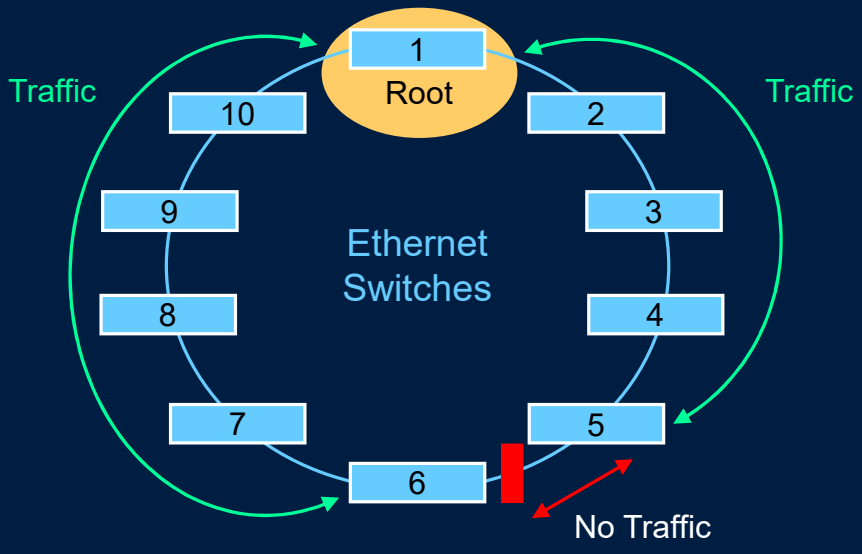
RSTP Tree Balancing Example



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You Must Engineer Your Network

- RSTP makes it very easy to plug-n-play
- Default settings just make it *(appear to)* work *(most of the time)*
- PROBLEM: No guarantee of performance or behavior in failure conditions without good engineering practices

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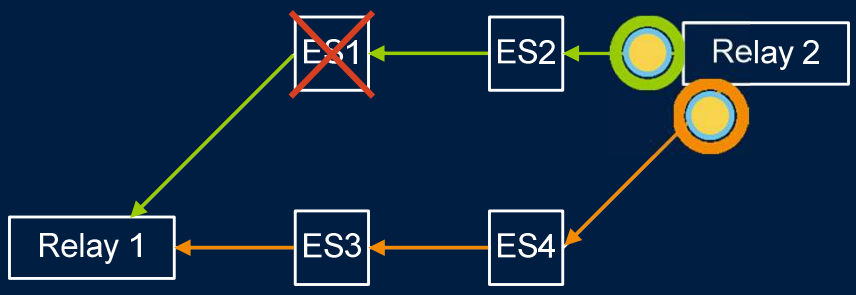
PRP Duplicates Packets on Two Separate Networks



PRP adds additional tag to packet

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What Is Traffic Engineering?

The proactive designing and planning of how each data frame will be transported from source to destination and how the communications infrastructure will react to failure states

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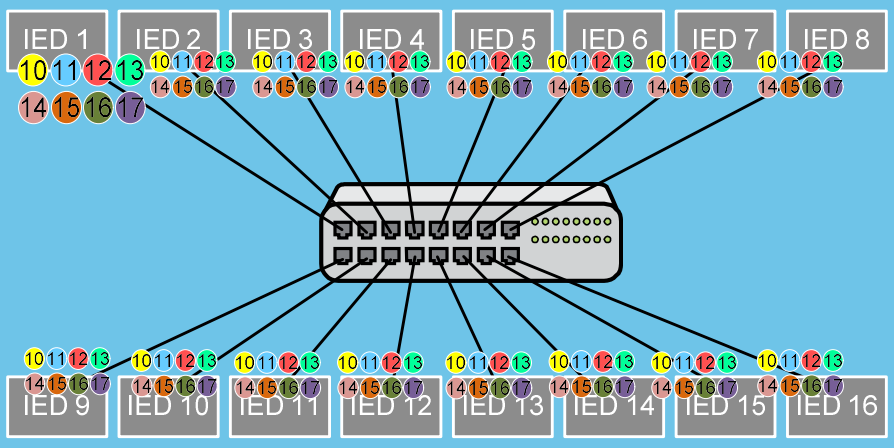
Like GOOSE, the Trouble With Tribbles Is That "They Are Born Pregnant" – Dr. McCoy, Star Trek



Left unmanaged, GOOSE replication will devour necessary resources in network and PCM IEDs

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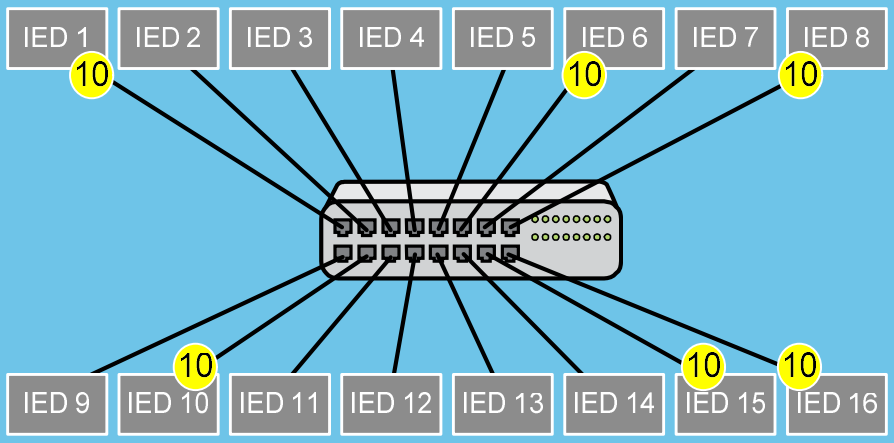
Switch Design Required to Prevent Unwanted Messages



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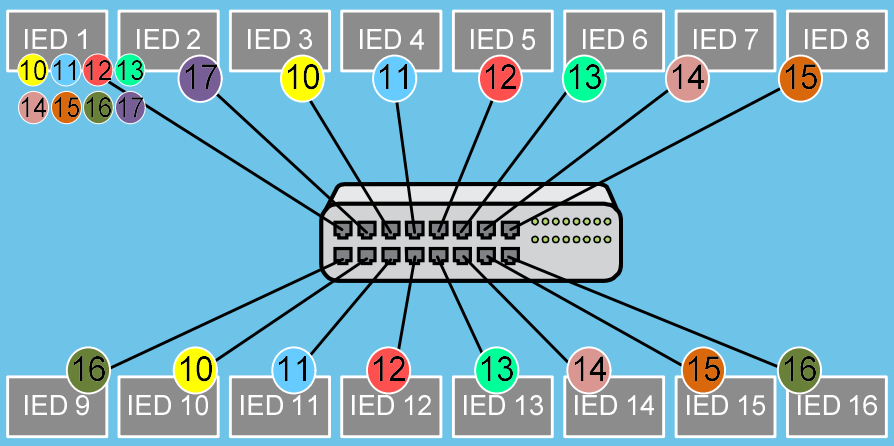
Switch Design Required to Segregate Via QVLAN Tag Settings



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Traffic Engineering Improves Network Performance

- Topology-independent performance
- Network simplicity
- Faster failover
- Application-focused configuration
- Greater security
- Maximized efficiency and throughput
- Centralized management and monitoring

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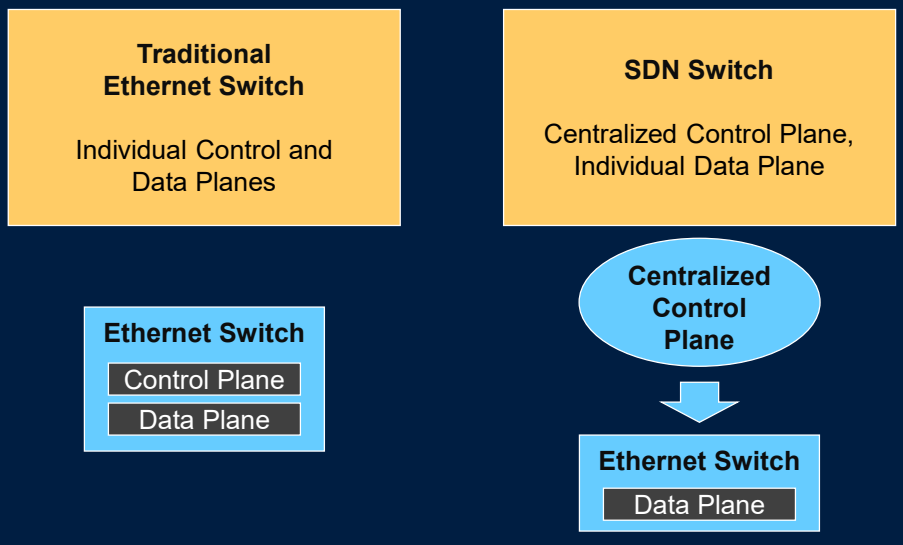
Software-Defined Networking Brings Traffic Engineering to Ethernet



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SDN Ethernet for OT Applications

- Broad topology support
- No RSTP
- Fast failover
- Application-focused circuits
- Greater cybersecurity
- Greater network efficiency
- Centralized management

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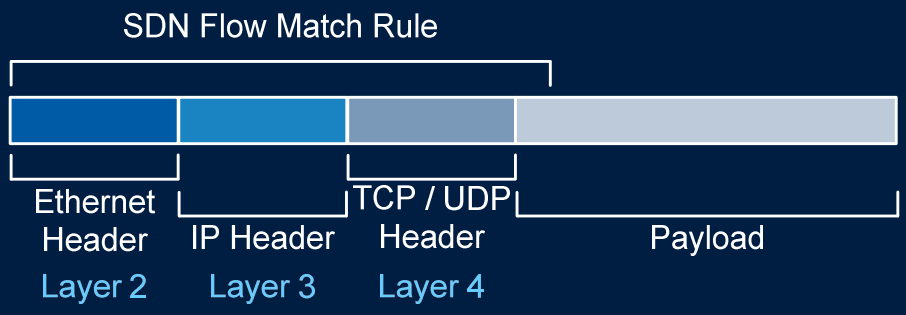
Multilayer Matching Rules Forward Approved Packets



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OpenFlow Match / Action Example
Ethernet Hub

Physical Port ID	Src MAC	Dst MAC	Ether Type	VLAN ID	IPv4 Src	IPv4 Dst	TCP/UDP Src	TCP/UDP Dst
*	*	*	*	*	*	*	*	*

Action
Output Forward All (Flood)

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OpenFlow Match / Action Example
L2 Unmanaged Switch

Physical Port ID	Src MAC	Dst MAC	Ether Type	VLAN ID	IPv4 Src	IPv4 Dst	TCP/UDP Src	TCP/UDP Dst
1	*		*	*	*	*	*	*

00:30:A7:06:11:97

Action
Output Forward Port 4

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OpenFlow Match / Action Example
L3 Router

Physical Port ID	Src MAC	Dst MAC	Ether Type	VLAN ID	IPv4 Src	IPv4 Dst	TCP/UDP Src	TCP/UDP Dst
1	*		*	*	1.1.1.2	2.2.2.2	*	*

00:30:A7:06:13:29

Action	Action
Set Source MAC 00:30:A7:06:29:01	Output Forward Port 3

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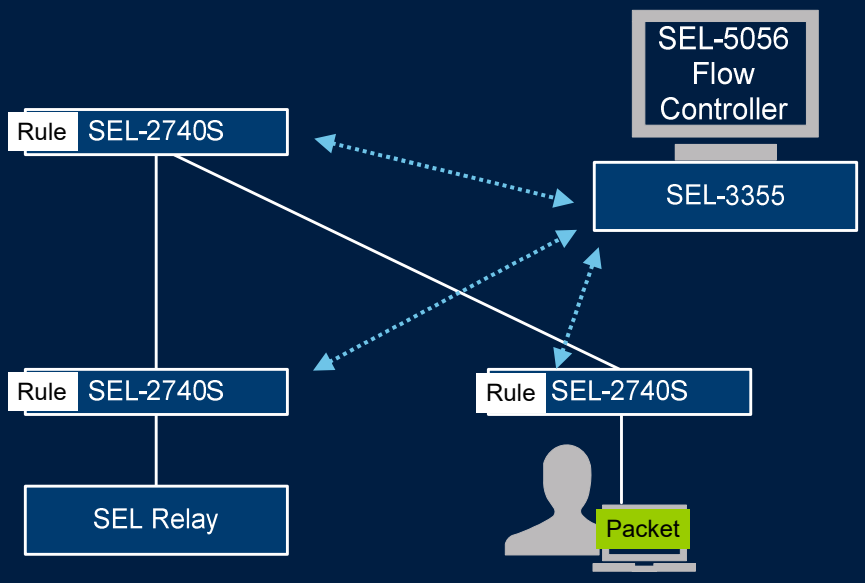
Reactive SDN in Operation



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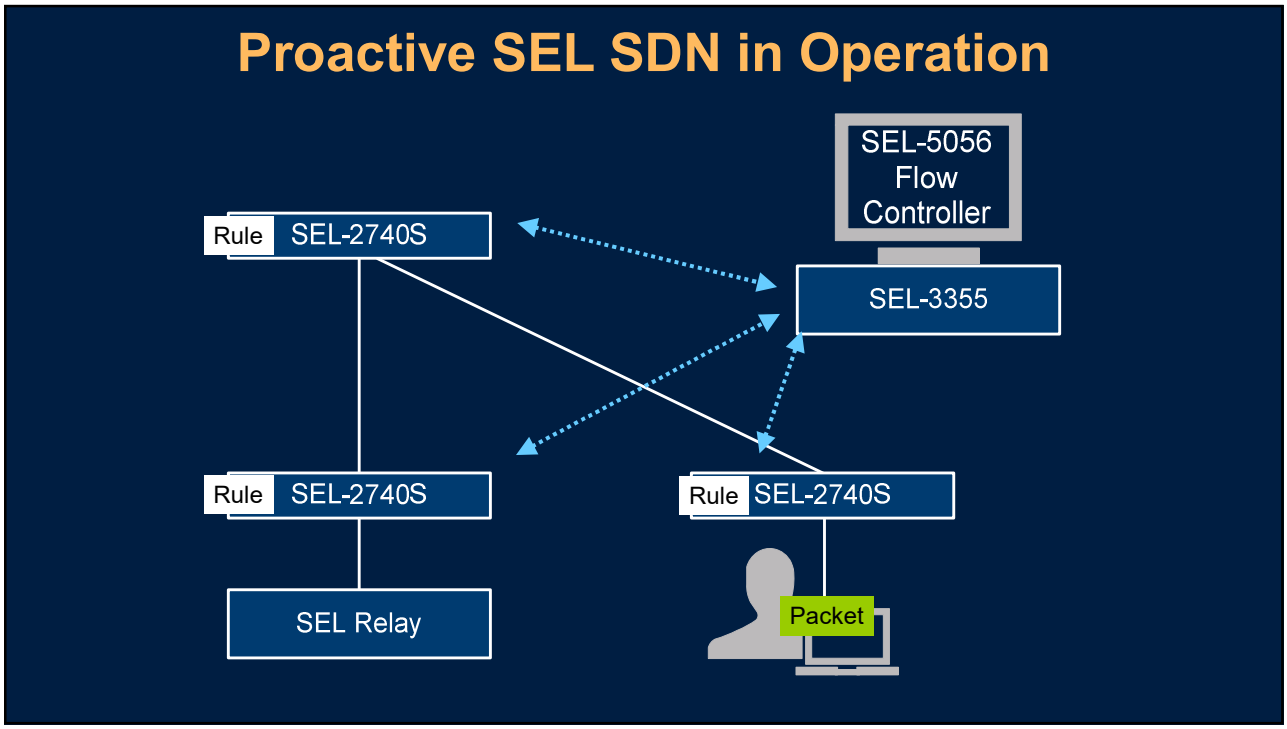
Proactive SEL SDN in Operation
SEL-5056
Flow
Controller
SEL-3355
Rule
SEL-2740S
Rule
SEL-2740S
Rule
SEL-2740S
SEL Relay
Packet

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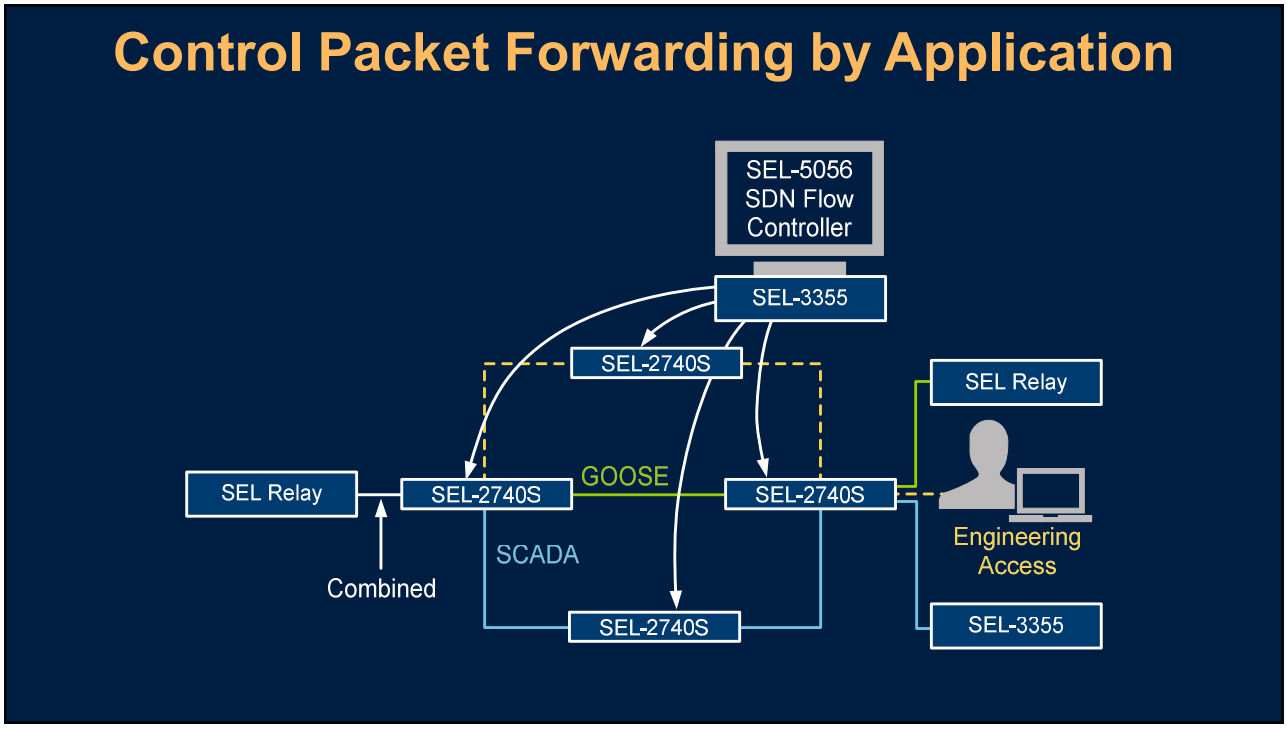
Control Packet Forwarding by Application
SEL-5056
SDN Flow
Controller
SEL-3355
SEL-2740S
SEL Relay
SEL Relay
SEL-2740S
GOOSE
SEL-2740S
SCADA
Combined
SEL-2740S
Engineering
Access
SEL-3355

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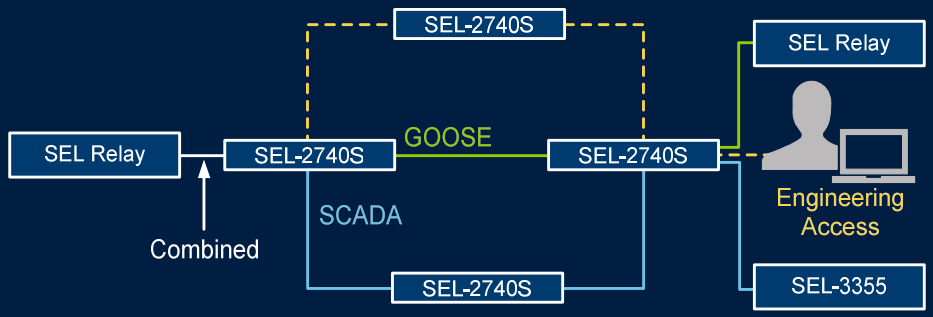
Flow Controller Is Not Required for Network Operation

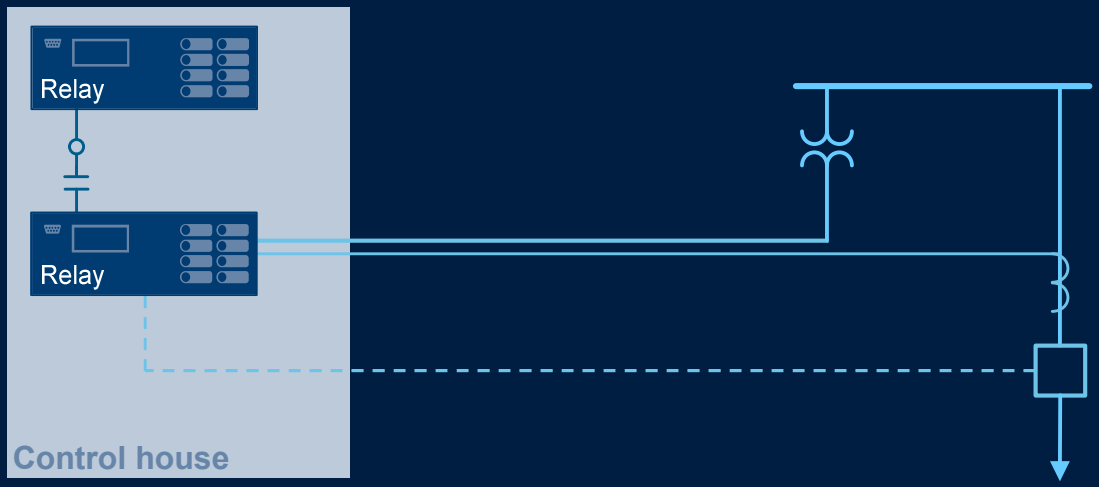


77

Communications in the Substation

78

Using hardwired connections has been standard



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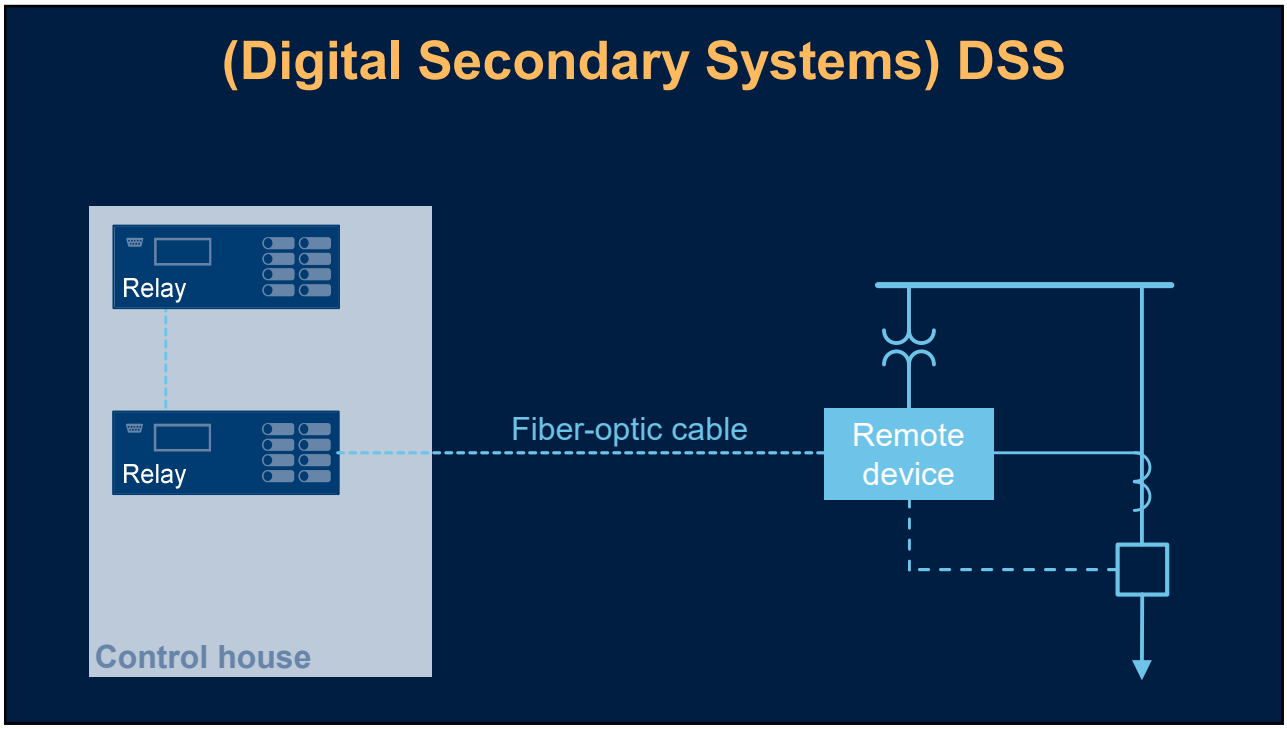
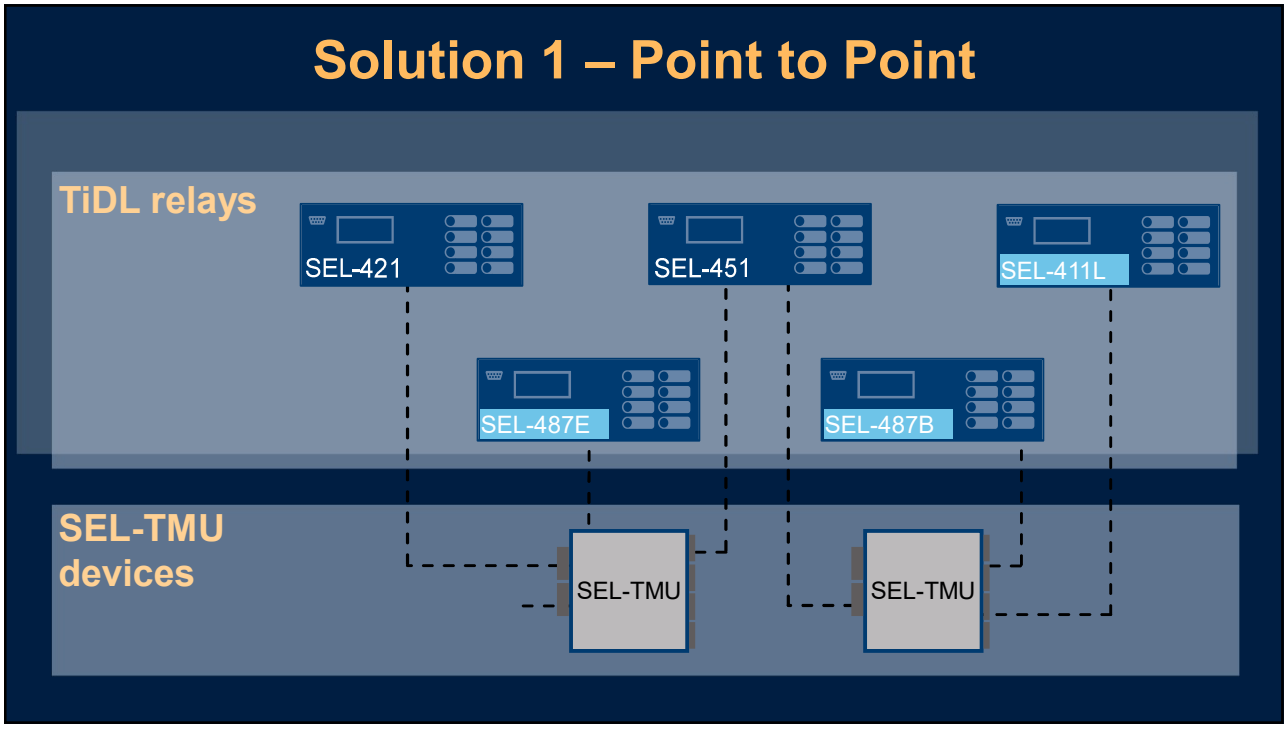
Reduce Costs

- Use 4 fibers instead of 64 wires to transfer 32 digital I/O points
- Reduce material cost by over 50%
- Reduce labor
  - Design
  - Documentation
  - Installation
  - Testing
  - Maintenance

80

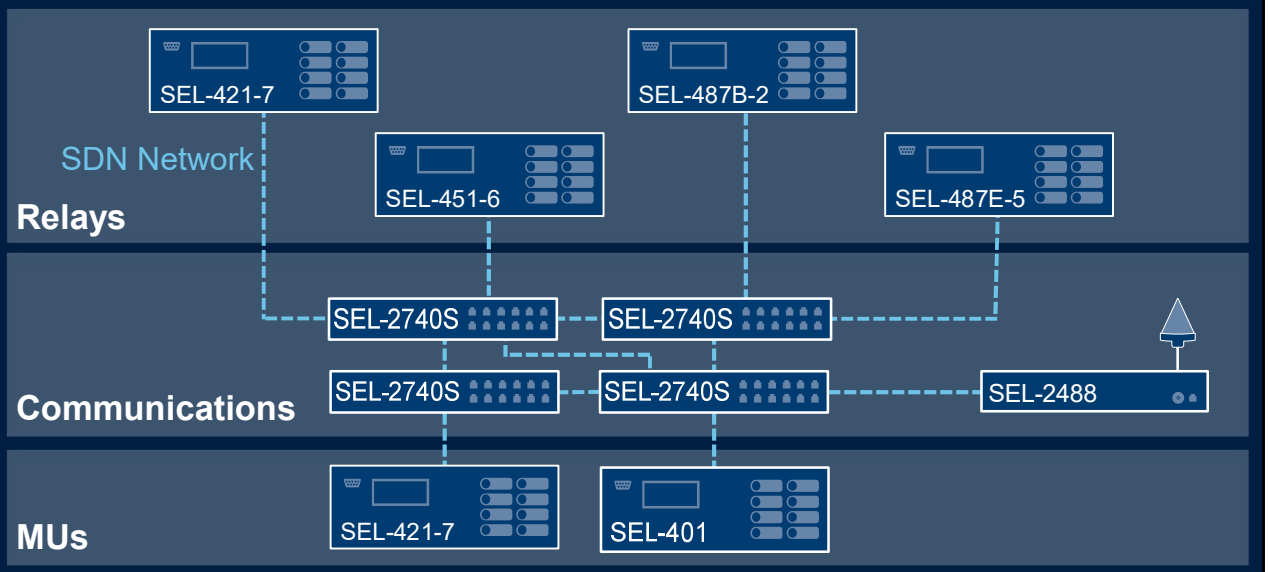

(Digital Secondary Systems) DSS
Relay
Relay
Control house
Fiber-optic cable
Remote device

81


Solution 1 – Point to Point
TiDL relays
SEL-421
SEL-451
SEL-411L
SEL-487E
SEL-487B
SEL-TMU devices
SEL-TMU
SEL-TMU

82

Solution 2 – SV/GOOSE (IEC 61850)



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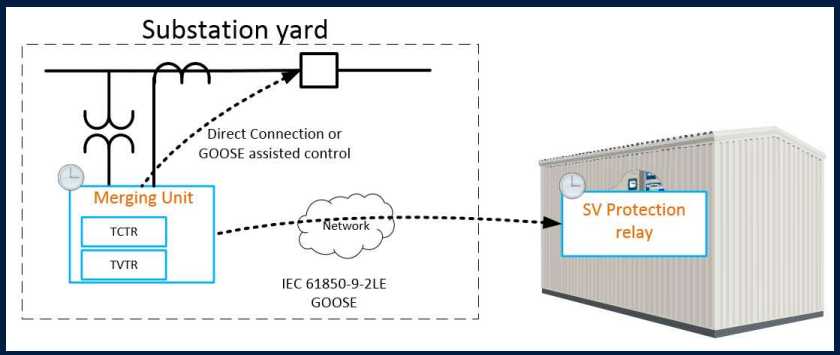
What Is SV?



To promote interoperability and adoption of the SV technology, the UCA foundation has developed a vendor-agreed IEC 61850-9-2 Light Edition

9-2LE: Implementation Guideline for Digital interface to Instrument Transformer using IEC 61850-9-2

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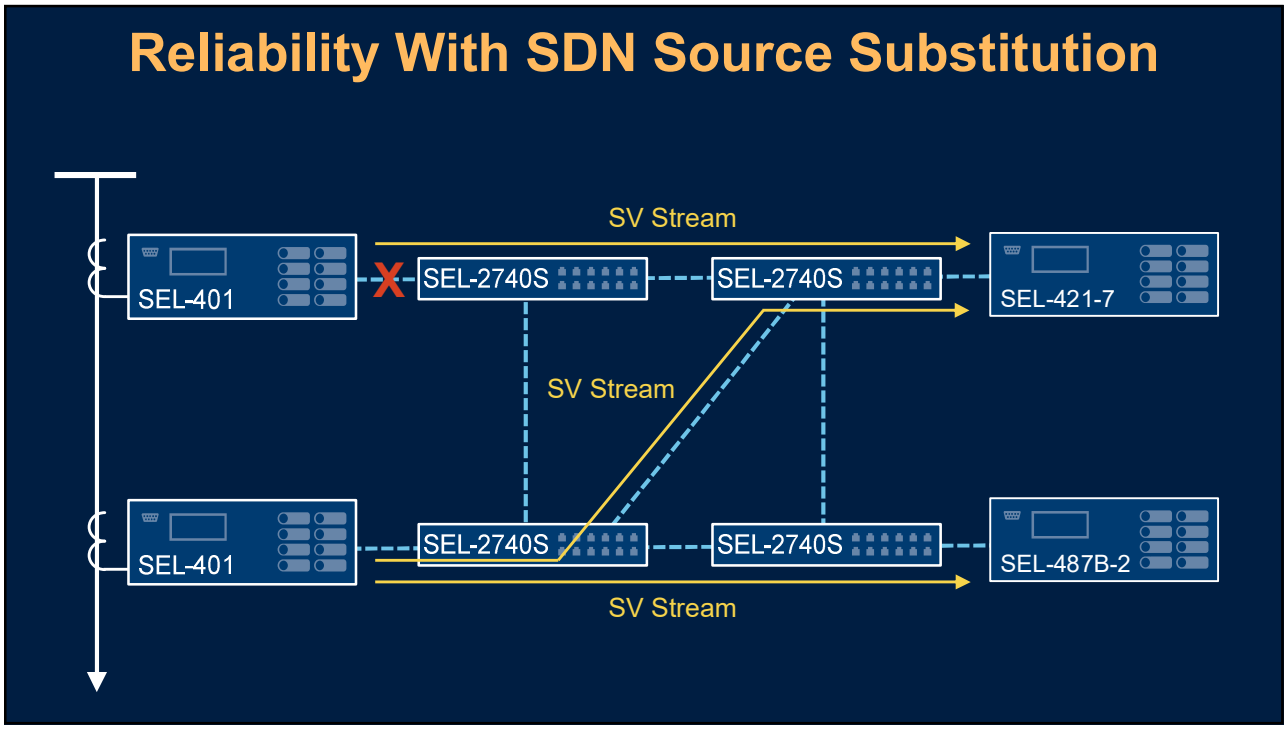
Reliability With SDN Source Substitution
SV Stream
SEL-401
SEL-2740S
SEL-2740S
SEL-421-7
SV Stream
SEL-401
SEL-2740S
SEL-2740S
SEL-487B-2
SV Stream

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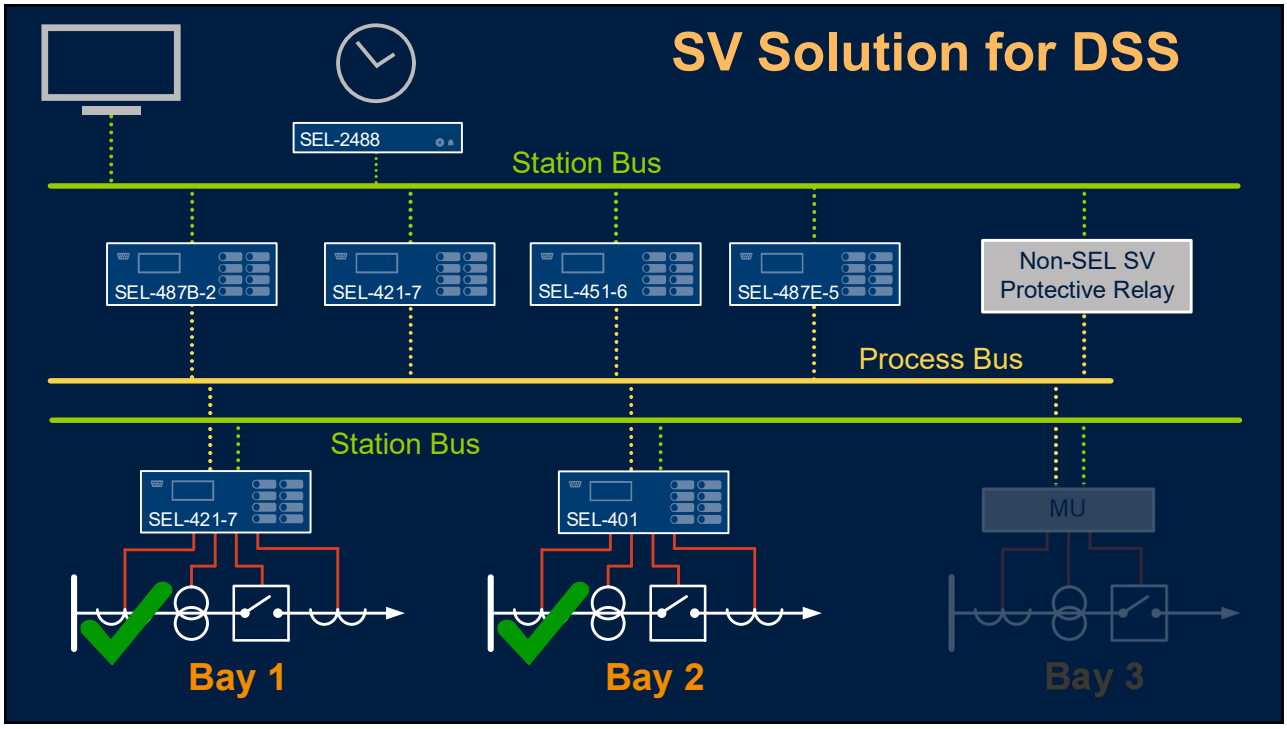
SV Solution for DSS
SEL-2488
Station Bus
SEL-487B-2
SEL-421-7
SEL-451-6
SEL-487E-5
Non-SEL SV Protective Relay
Process Bus
Station Bus
SEL-421-7
SEL-401
MU
Bay 1
Bay 2
Bay 3

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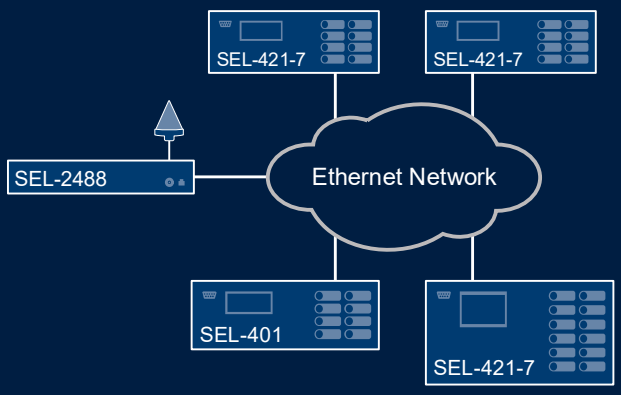
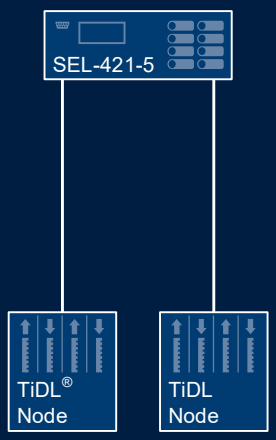
DSS Architectures

Network-Based Solution



Point-to-Point Solution



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TIME DISTRIBUTION

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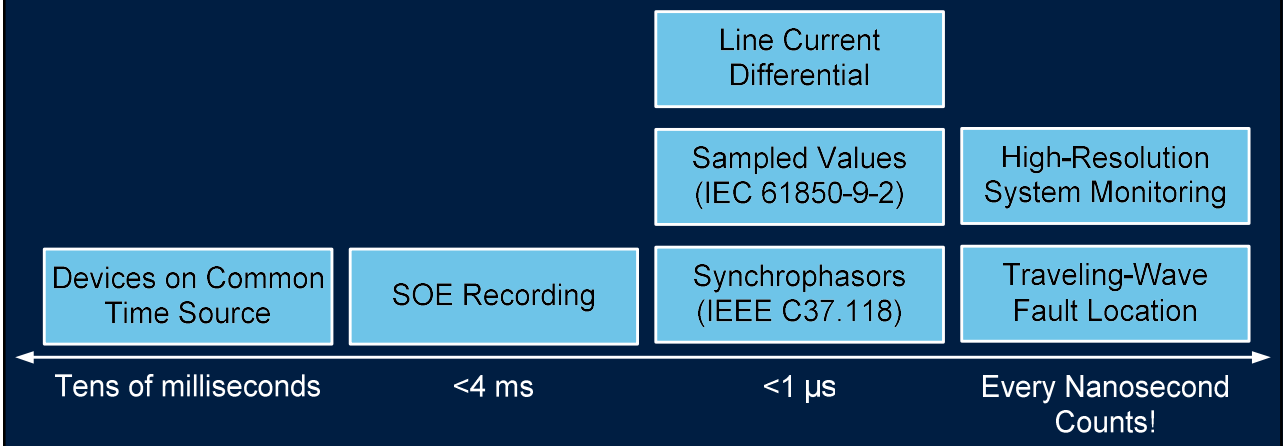
Precise Time Adds Value to Power System



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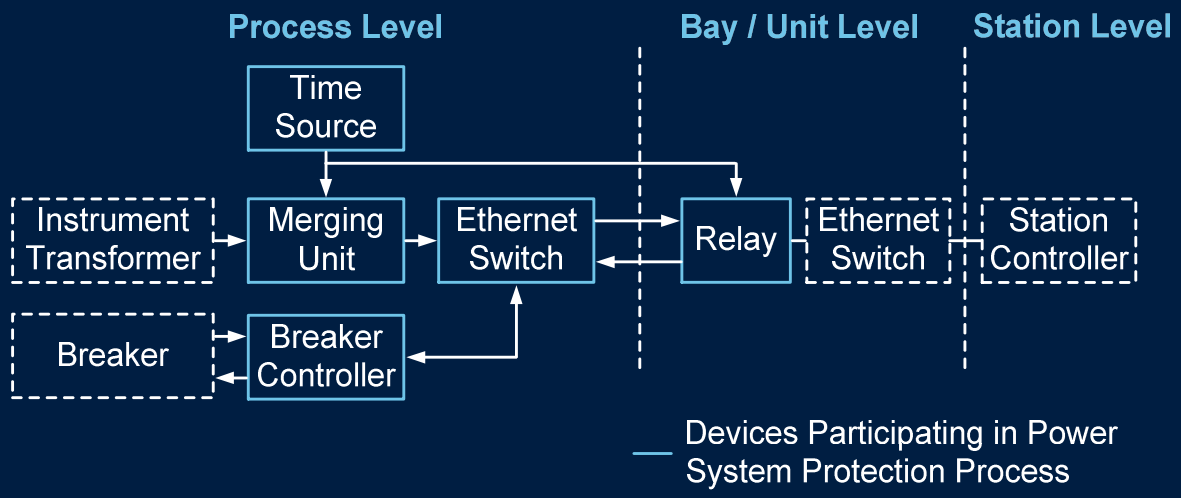
Timing Requirements for Synchrophasors
IEEE C37.118.2-2011

- Standard requires ≤1% total vector error for entire system
  - 0.01 radians (0.57 degrees)
  - ±26 µs in 60 Hz system
- Time source must be highly reliable
  - Standard assumes accurate time
  - PMUs require 1 µs accuracy

90

Sampled Measured Values (IEC 61850-9-2)



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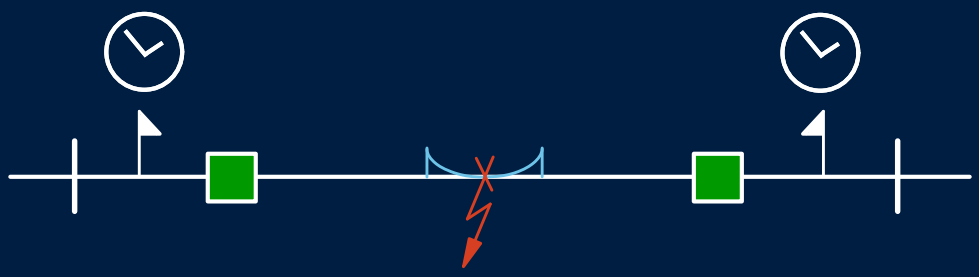
Traveling-Wave Fault Location



Every nanosecond of inaccuracy can result in 1 foot of fault location uncertainty

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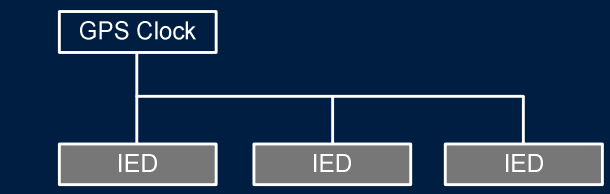
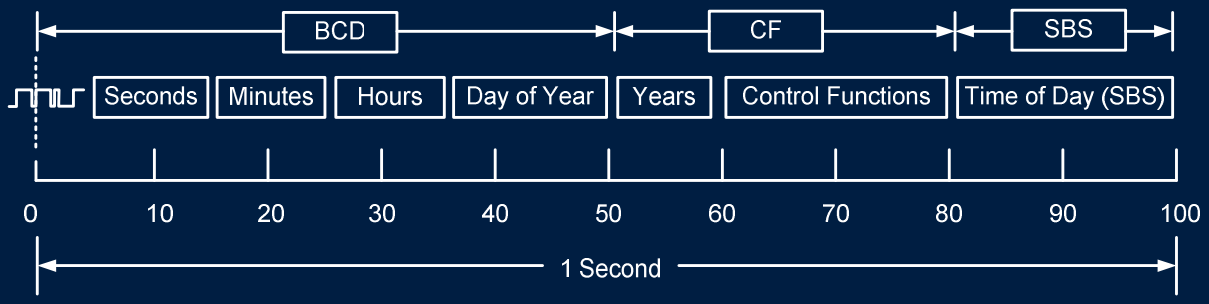
IRIG-B



- Dedicated cabling
- Simplicity and accuracy (100 ns to 1 µs)



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Precision Time Protocol

- Works over packet-based networks
- Can achieve submicrosecond accuracy
- Provides International Atomic Time (TAI)
- Profiles define accuracy and precision requirements – not main standard
- End devices do not have PTP accuracy or precision requirements

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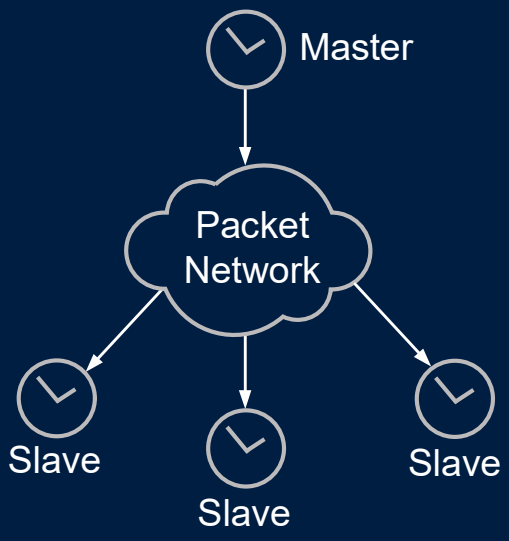
What Is Precision Time Protocol (IEEE 1588)?

- Message-based time transfer protocol
- Submicrosecond accuracy
- Hardware and software implementations



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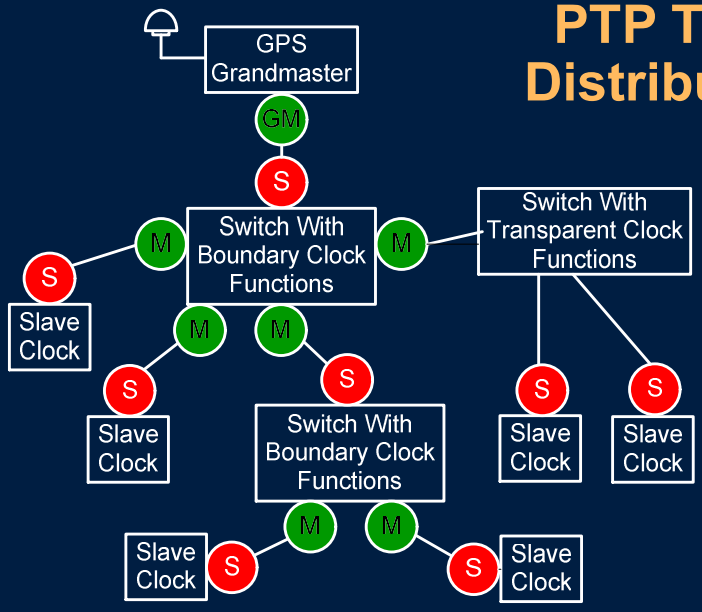
PTP Time Distribution



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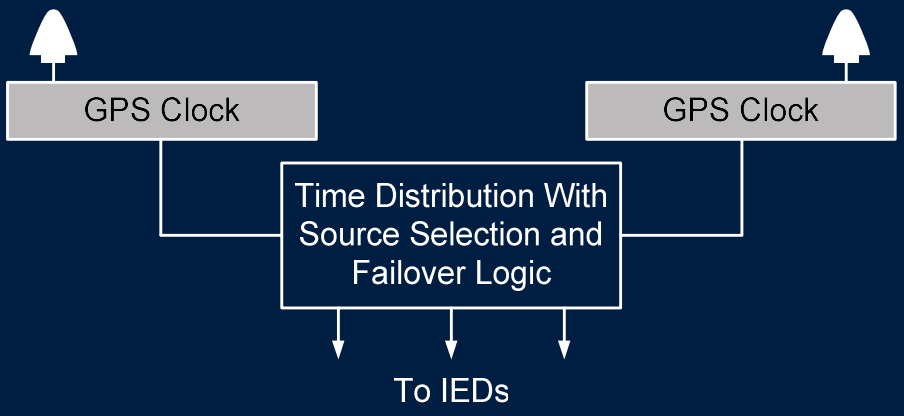
Redundant Clocks



Signals are received by GPS clocks that are installed in different locations

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Time Distribution Considerations

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Consider Potential Vulnerabilities

- Antenna failures
- Device failures
- Multipath errors
- Solar flares
- Jamming
- Spoofing

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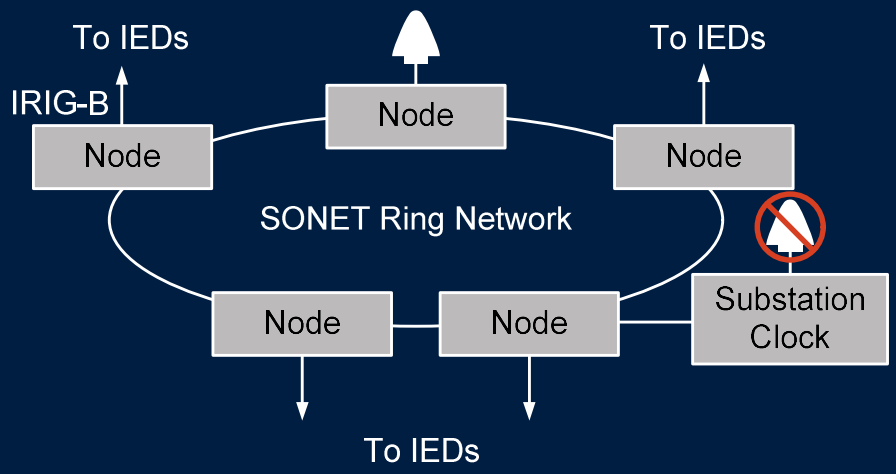
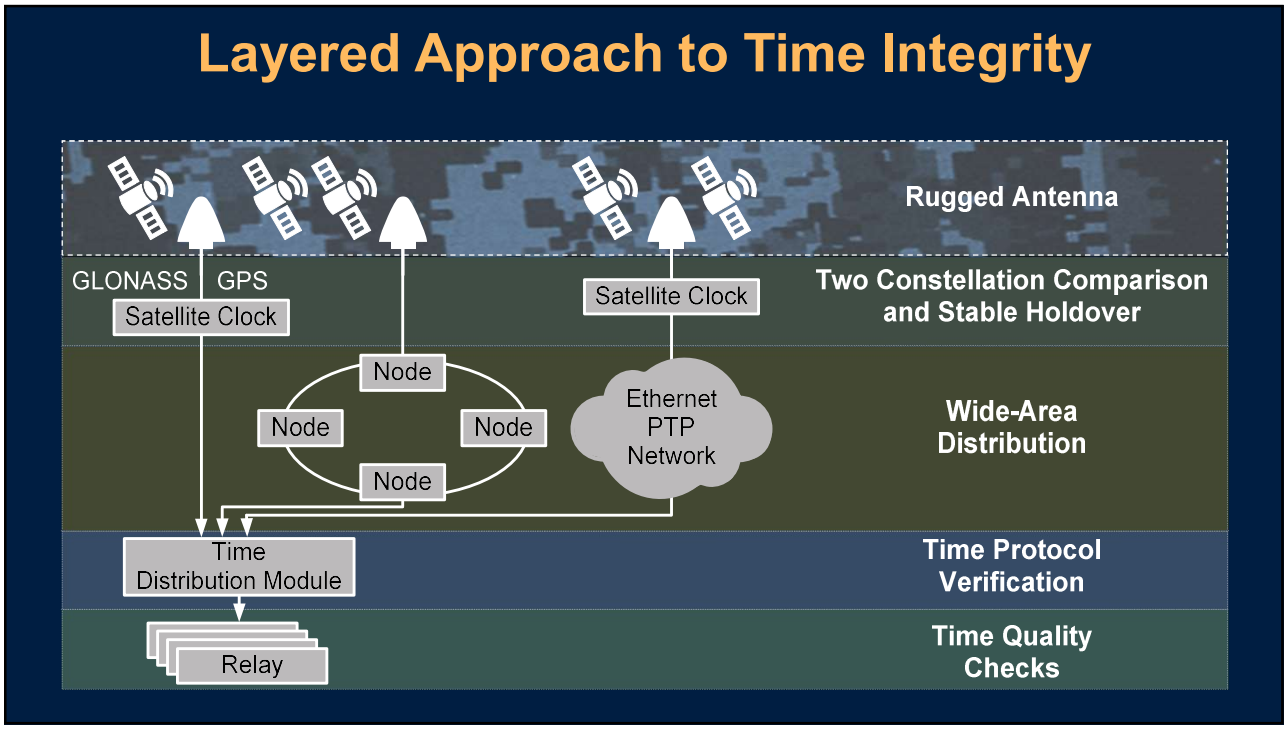
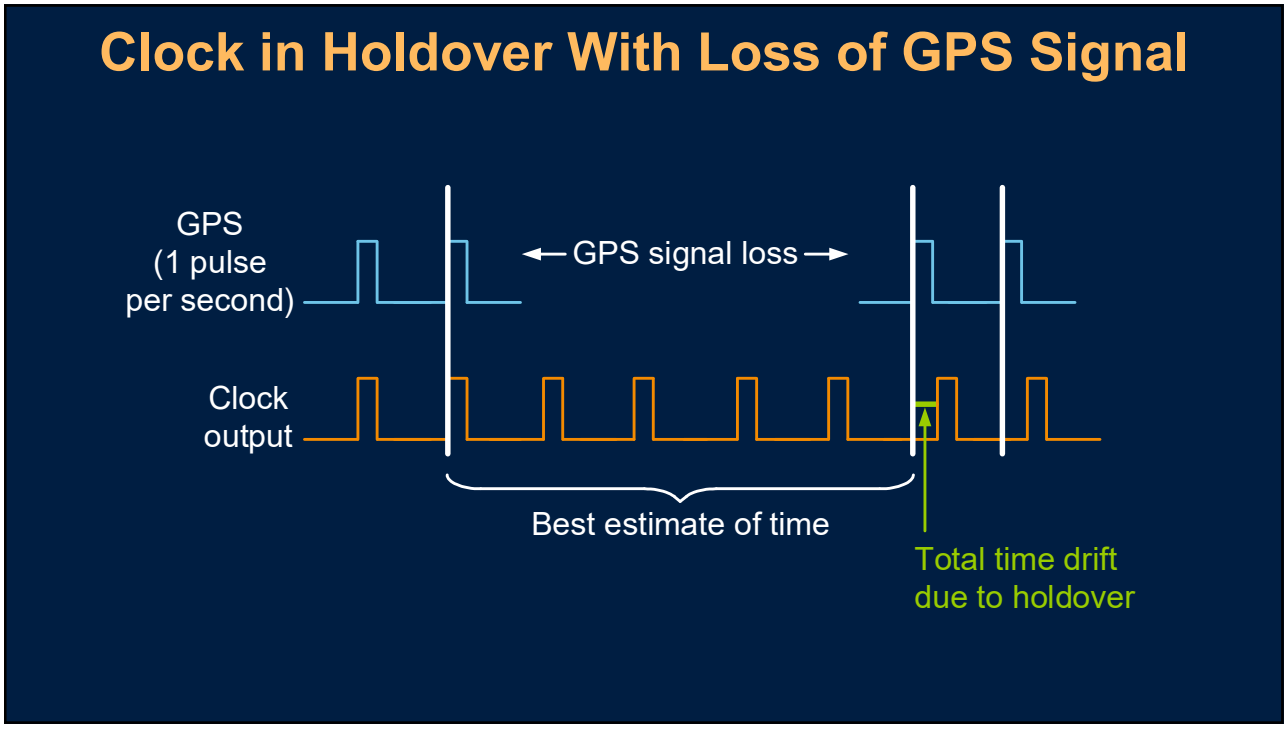
Wide-Area Time Distribution
Mitigates Local Vulnerabilities



100


Layered Approach to Time Integrity
Rugged Antenna
GLONASS
GPS
Satellite Clock
Satellite Clock
Two Constellation Comparison and Stable Holdover
Node
Node
Node
Node
Ethernet PTP Network
Wide-Area Distribution
Time Distribution Module
Time Protocol Verification
Relay
Time Quality Checks

101


Clock in Holdover With Loss of GPS Signal
GPS (1 pulse per second)
GPS signal loss
Clock output
Best estimate of time
Total time drift due to holdover

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