1. **Network Topology**

1.1 What is Substation Network Topology?

Modern power systems have grown both in size and complexity. The layout pattern consists of interconnections between various devices and nodes built within the substation network topology. It mirrors the electrical topology based on two separate networks in a substation: a station bus and a process bus. An Ethernet communication switch is a key component in the structure of the topology.

In reality, topology is mainly implemented according to different applications. Every big substation end user prefers their own topology. For instance, separate ring topology for station and process buses, star topology in a station bus or HSR ring in a process bus, etc.

1.2 Which Topologies can be Applied?

Generally, network topology comprises the following fundamental topologies: bus, tree, star, ring, or mesh (star-ring). According to the different size, complexity and design criteria of the network, topologies like ring, star, or a combination of ring and star can be applied.

**Single Star Topology**

In star topology each station (peer) is connected directly to a common central node or switch. Transmission occurs through switches between components. It is the only topology that can operate with an unmanaged switch.

Nowadays many substation vendors apply star topology in a station bus because of the following advantages:

- Easy to pinpoint the location of a problem and isolate and solve it
- Low electromagnetic interference
- Easy steps for troubleshooting
- Modification flexibility, easier to maintain
- Failure of one node does not affect the network
- Very high speeds of data transfer
- High maintainability
- Multicast island can be built, traffic is reduced, high latency tolerance
- Easy plug-and-play of power equipment
At the same time, star topology is less reliable because all IEDs are connected to a single central Ethernet switch which is highly susceptible to environmental and EMI conditions of the power substation. A failure in one switch can disrupt the network. Because a large number of bridges in a big substation network need a large number of wires to connect the network, the cost of building such a network with star topology is relatively high.

**Double Star Topology**

In order to enhance substation network reliability and availability, double star or redundant star topology is often implemented. Some utility vendors just apply physical double star topology with double IEDs. Others apply logical double star topology by using double Ethernet switches. For logical double star topology, each critical device should have a double access interface (DAN, Double Access Node) and be connected to two independent LANs. PRP (Parallel Redundant Protocol) or RSTP (Rapid Spanning Tree Protocol) can be applied with a double network infrastructure for full redundancy. Figure 2 shows a double star topology with two RSTPs in a station bus.

**Single Ring Topology**

Ring topology uses point-to-point communication links. All Ethernet switches are connected in a loop and other devices are connected with a switch. The data is transmitted between source and destination through nodes in one or two directions in the ring. Every node can simultaneously send a message to its neighbor. Figure 3 shows single ring topology with MRP and HSR for the station bus.

Ring topology is normally required for a larger network. Latency increases with the increased number of bridges and aggregate bandwidth, but it can be improved with HSR (High Speed Seamless Ring) technology.
Failure of one switch component can affect the entire ring network, redundancy like RSTP or MRP (Media Redundancy Protocol) against link failures can be applied but not against edge port or bridge failure, unless each device is a bridge. Reliability of ring topology can be improved by using a wiring concentrator, which helps to bypass a faulty node. With the development of the embedded Ethernet switch, some IEDs themselves will have switching capability with an integrated switch board. This helps to simplify redundant network architecture and makes it easy to implement advanced redundant protocols like HSR and PRP in a ring topology.

**Multiple Ring Topology**

In order to ensure high availability of the substation system, multiple ring topologies are applied with high-capacity Ethernet switches. The flow diagrams on this page show some examples of multiple ring topology including parallel ring, ring with subrings and ring-ring topology.

Communication between devices might be disrupted or destroyed by various environmental influences.
Star Topology Compared to Ring Topology

In order to choose the right topology many factors like redundancy, efficiency, diagnostics, expandability, cable connectivity, latency and reliability, etc. must be considered. The performance of a communication network especially for a process bus is mainly determined by the end-to-end delay for time-critical message transmission. The following table shows a comparison of different topologies in terms of important design factors.

<table>
<thead>
<tr>
<th>Feature Factor</th>
<th>Star</th>
<th>Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redundancy</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Eff. Data Throughput</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Expandability</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Cable Connectivity</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Latency</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>In Large Network</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>In Small Network</td>
<td>++</td>
<td>+++</td>
</tr>
</tbody>
</table>

- Redundancy enhances the reliability of a network by providing more data transmission routes. With ring topology it is much easier to build in redundancy mechanisms.
- Data throughput includes features like transmission speed, aggregate bandwidth (how many hosts can simultaneously send messages) and bisection bandwidth (how many links have to break before the network is cut in two halves).
- Diagnostics include detection of device failure, troubleshooting, problem resolution and maintenance.
- Expandability includes modification flexibility and expansion of the existing network.
- Cable connectivity means complexity of layout, reliability of signal transfer by implementation and easy access to all nodes.
- Latency determines the performance of a communication network by the end-to-end delay for time-critical message transmission. The timing requirements for the station and for the process bus are distinct; they dictate the redundancy method to be used.

- In large substations, the rings of the different voltage levels can be connected in a tree form at the station level. The station bus therefore requires a mixed ring or tree topology.
- In small substations like high voltage substations, there are typically very few transmission lines with few protection nodes. In medium voltage substations, there is typically only one IED per bay and each IED incorporates a switch element, so the IEDs can be chained into a ring.

The general purpose of media redundancy is to prevent single points of failure. If a failure does occur, the network must recover within a given short time. Redundancies create more than one path between the source and destination to reroute traffic at the time of failure.

In practice, the networks for a station bus and a process bus are sometimes separate. Each network itself needs to be designed with redundancy. Network interconnections between station bus and process bus networks must always be redundant, so that if one connection element fails, communication is still possible through a secondary connection. This can be achieved through redundant network coupling or by using multiple media redundant interfaces in one connecting Ethernet switch.

With media redundancy, maximum latency in communication between source and sink is reduced and the frame loss is tolerated. Meanwhile, the MTTF of the whole substation network is greatly increased.

2. Media Redundancy Technologies

2.1 Why Media Redundancy is Required?

A substation communication network is a mission-critical network and the total system must tolerate a single point of failure.

2.2 How does Media Redundancy Work?

Ring topology uses different network redundancy compared to star topology. The fault in a ring can then be repaired while the network is still running. This is sometimes referred to as a “self-healing ring.”
When one link in a ring fails, the ring automatically changes into a line and all devices are still interconnected. Since Ethernet is a broadcast protocol and would start to loop indefinitely on a ring network, a redundancy (control) protocol is needed to administer the redundant links. Due to the different requirements of station and process bus networks, different protocols need to be implemented according to their specific performance characteristics.

2.3 Station Bus and Process Bus Requirements

Some media redundancy protocols require a certain time to recover from a media failure. This is called the (network) recovery time. Since the recovery time directly impairs the transmission of information from source to sink, the recovery time of a redundancy protocol must always be smaller than the maximum latency requirement of the substation network, also taking into account the transmission time on the network media as well.

Station Bus

The station bus network is mainly used to carry event-driven Ethernet messages for supervising the system. It interconnects the whole substation and provides connectivity between central management and the individual bays. The station bus typically carries GOOSE (Generic Object Oriented Substation Event) traffics and TCP/UDP traffics. GOOSE is a layer 2 multicast message and TCP/UDP traffics are unicast messages including MMS (Manufacturing Messaging Specification), SNTP (Small Network Time Protocol), SNMP (Small Network Management Protocol), etc. Traffics in station bus can tolerate frame losses. Lost TCP/IP packets are resent due to sequence numbering and checking in the higher protocol layers.

Process Bus

The process bus is mainly used to carry measurement traffic, in the form of sampled values (SV) traffic. These are small Ethernet frames carrying measurement values, sent by merging units for example. Since only complete sample sets can be evaluated, SV traffic does not tolerate frame loss. Sometimes referred to as “9-2LE”, which sets requirements for SV traffic and is widely accepted as a valid and practical interpretation of the IEC standard. With a 50 Hz alternating current being sampled at a rate of 80 per period, the resulting transmission frequency will be 80 x 50 Hz = 4000 Hz. This means that about every 250 ms, a sampled value frame needs to be transmitted, just for one measurement of a single phase current only for example. Therefore, media redundancy must work virtually without interruption, as SV frames would immediately be lost at this transmission rate.

2.4 Which Protocols can be Used for Network Redundancy?

RSTP is a very flexible protocol that can provide media redundancy for arbitrarily meshed networks. However, with topologies other than single rings, pre-calculating deterministic network recovery times is a challenge. In a single ring network, RSTP network reconfiguration can be deterministic. RSTP is only viable for use in station bus networks because during network reconfiguration, frames may be lost. This violates a basic requirement for process bus applications.

When planning a substation automation network, it should be observed that the maximum network recovery time that can be experienced is lower than the requirement for GOOSE communication for example.

Media Redundancy Protocol (MRP)

MRP, in contrast to RSTP, only applies to single ring topologies and is not capable of supporting multiple rings or meshes without additional supporting protocols (e.g. subring manager or ring coupling). Since it is specially developed to handle ring topologies, its performance is superior to RSTP under comparable circumstances.

MRP defines fixed consistent sets of parameters for the participating switches. A consistent set of parameters directly translates into an upper-bound maximum worst-case network recovery time. MRP is recommended for worst-case recovery times of 500, 200, 30 and 10 ms. When all devices in a ring support a consistent set, this recovery time can be guaranteed in worst-case situations, typical recovery times are much faster.
• **MRP with Subring Manager**

To realize complex topologies, MRP rings can be attached to Hirschmann™ Switches that are configured as subring managers (see Figure 9). Ring recovery in the subring is handled independently from recovery in the main ring. This means that recovery times may be chosen independently between subring and base ring and, unless a subring manager switch experiences a fault, that both base ring and each subring can experience a fault without suffering communication outage. Multiple subrings can be connected to one base ring for further flexibility.

• **MRP Redundant Ring coupling**

To realize more complex topologies with MRP, multiple MRP rings can be coupled together with redundant ring coupling, a feature available in many Hirschmann™ Switches. Two switches are selected to provide the coupling (see Figure 10). The ring coupling master keeps its connection to the second ring on standby to prevent loops and activates the link when a fault renders the second link from ring 1 to ring 2 inoperable.

In this way, MRP rings can be coupled to flexibly accommodate more complex topology requirements.

The following protocols can be used with the process bus:

• **Parallel Redundancy Protocol (PRP)**

PRP, unlike the previously mentioned RSTP and MRP, does not rely on providing redundancy through additional media connections. PRP simply doubles the necessary network infrastructure. All devices that need to take advantage of this redundant network infrastructure must be connected with a dual attachment network interface that connects both interfaces, each to one of the two redundant LANs A and B. Both networks are used simultaneously and both networks carry the same data that is sent redundantly by the Dual Attached Nodes; the DANs. Each DAN duplicates its entire network traffic that travels over both LAN A and LAN B.

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![Figure 9: Ring with subring](image)

![Figure 10: Redundant ring coupling](image)

![Figure 11: Example PRP network](image)
When one of the two LANs experiences a fault, e.g. a failing network connection or switch, the network traffic still runs over the other LAN without interruption. When the whole network is in good health, a duplicate detection mechanism filters out doubly received traffic through LAN A and LAN B in the DANs. The PRP can therefore be used with the process bus, because in case of a failure in one network, the SV traffic can still safely travel through the other network to its destination.

- **High Availability Seamless Redundancy (HSR)**
  HSR builds directly on the PRP concept. While PRP uses doubled network topologies, HSR relies on the proven ring topology. As Figure 12 shows, the PRP principle of doubled transmission of data is applied by sending two frames not over two networks, but in both directions of the ring. If there is a single fault on the ring, communication from sender to receiver still takes place over the second network path. To prevent a doubled frame reception if the network is undamaged and to prevent the frames from looping, each HSR device implements a duplicate detection mechanism that filters out duplicate or looping frames when the network is in good health.

  Since communication over an HSR network still continues without interruption when there is a network failure, HSR can be used in process bus applications.

**Comparison of the Different Protocols**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Determinism/Reconfiguration Time</th>
<th>Flexibility (Topology)</th>
<th>Costs</th>
</tr>
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<tbody>
<tr>
<td>RSTP</td>
<td>++</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>MRP</td>
<td>++</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>PRP</td>
<td>+++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>HSR</td>
<td>+</td>
<td>+</td>
<td>++</td>
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</tbody>
</table>

- **RSTP**: In terms of determinism and reconfiguration time, RSTP fulfills the requirements set by the station bus, provided usage and installation guidelines are observed and the implementation is optimized, like the RSTP provided in Hirschmann™ switches. RSTP is completely flexible in supported topologies, but only behaves deterministically in simple topologies.

- **MRP**: In terms of determinism and reconfiguration time, MRP is superior to RSTP and clearly fulfills the requirements of the station bus, but is restricted to a physical single ring topology. It therefore relies on network coupling protocols to provide additional flexibility.

- **PRP**: In terms of determinism and reconfiguration time, due to the seamless switchover concept, PRP is superior to both RSTP and MRP. It is very flexible in terms of physical topologies (the two LANs can be in any shape and form), but always needs specialized attachments or RedBoxes to connect devices redundantly. In terms of costs, PRP is comparatively expensive because it needs a completely doubled network infrastructure.

- **HSR**: In terms of determinism and reconfiguration time, HSR is identical to PRP. In contrast to PRP, HSR is limited to ring topologies only and it shares PRP’s limitation in that it needs RedBoxes to connect standard Ethernet equipment without dedicated protocol interfaces. The advantage of HSR over PRP is that no doubled network infrastructure is required and installations are more cost-effective.

2.5 **Summary and Outlook**

Choosing the right network topology and redundancy protocol for the right use can be a challenge, especially with more complex physical topologies. With the right technology however, requirements for substation automation can be fulfilled.

This white paper provides a brief description of the technologies relevant in the field of substation automation. Further information about the technologies described can be obtained from other white papers available at www.hirschmann.com. For the design of substation automation, additional support and consulting can be obtained from the Hirschmann™ Competence Center.

**References:**

1. IEC61850 Communication Networks and Systems in Substations, IEC standard in ten main parts, 2002
3. Hirschmann White Paper, WP 1003HE, Media Redundancy Concepts, 06/201
Appendix: Further Support

Technical Questions and Training Courses

In the event of technical queries, please contact your local Hirschmann™ distributor or Hirschmann™ office. You can find the addresses of our distributors on the Internet: www.hirschmann.com

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