

Initial solution for Nendica Study Item

Forwarding of Fieldbus CPF 12 on 802.1 Bridges

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Objective

- According to the proposal for Nendica Study Item (Forwarding of Fieldbus CPF 12 on 802.1 Bridges) and comments of previous discussion, this presentation includes use case and basic feasibility analysis, and analyze the feasibility to assure the low latency / jitter and the high reliability.
- Any comments are welcomed.

Definition

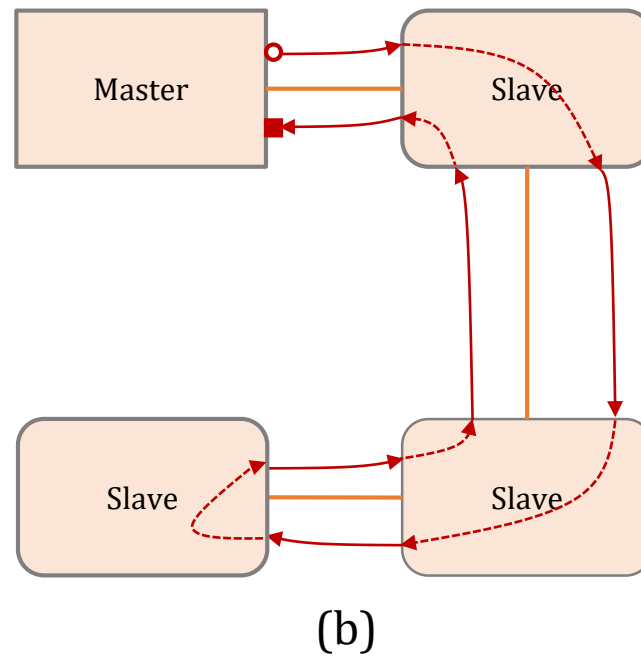
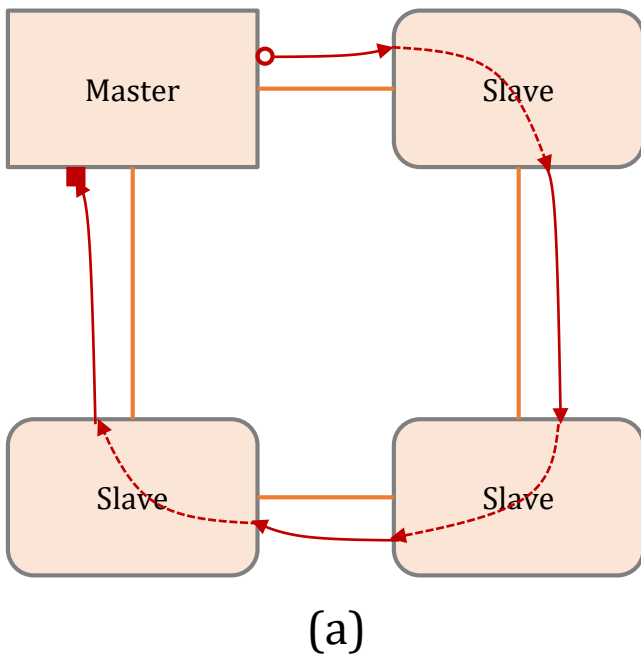
- Generally, the terms mentioned in this document comply with the definition of 802.1Q, EtherCAT specifications or other standard specifications. In order to void confusion or misunderstanding, the following definitions are explained.
 - ❑ **EtherCAT frame:** the frame sent by EtherCAT master and forwarded by EtherCAT slave or 802.1 Bridges, and the EtherType of the frame equals 0x88a4.
 - ❑ **Ethernet frame:** the frame sent by general Ethernet Stations in this Study Item, and the EtherType of the frame doesn't equal 0x88a4.
 - ❑ **EtherCAT master:** means the EtherCAT master device, it's a EtherCAT PLC or controller.
 - ❑ **EtherCAT slave:** means the EtherCAT slave device, it's controlled by the EtherCAT master.
 - ❑ **EtherCAT topological forwarding mode:** the EtherCAT frames received from specific ingress port are being forwarded to specific egress port according to specific configuration regardless of MAC address of the EtherCAT frames.
 - ❑ **MAC address forwarding mode:** the 802.1 Bridge forwards the frames to the specific port according the destination MAC address of the frame and the MAC address table of the Bridge which is mapping the MAC address to port.

Contents

1. Detail use case and practical requirements for intermixed EtherCAT and Ethernet forwarding
2. Feasibility of operation
3. Impact on functionality, including latency, compared to independent networks
4. Feasibility of assuring QoS for EtherCAT and Ethernet

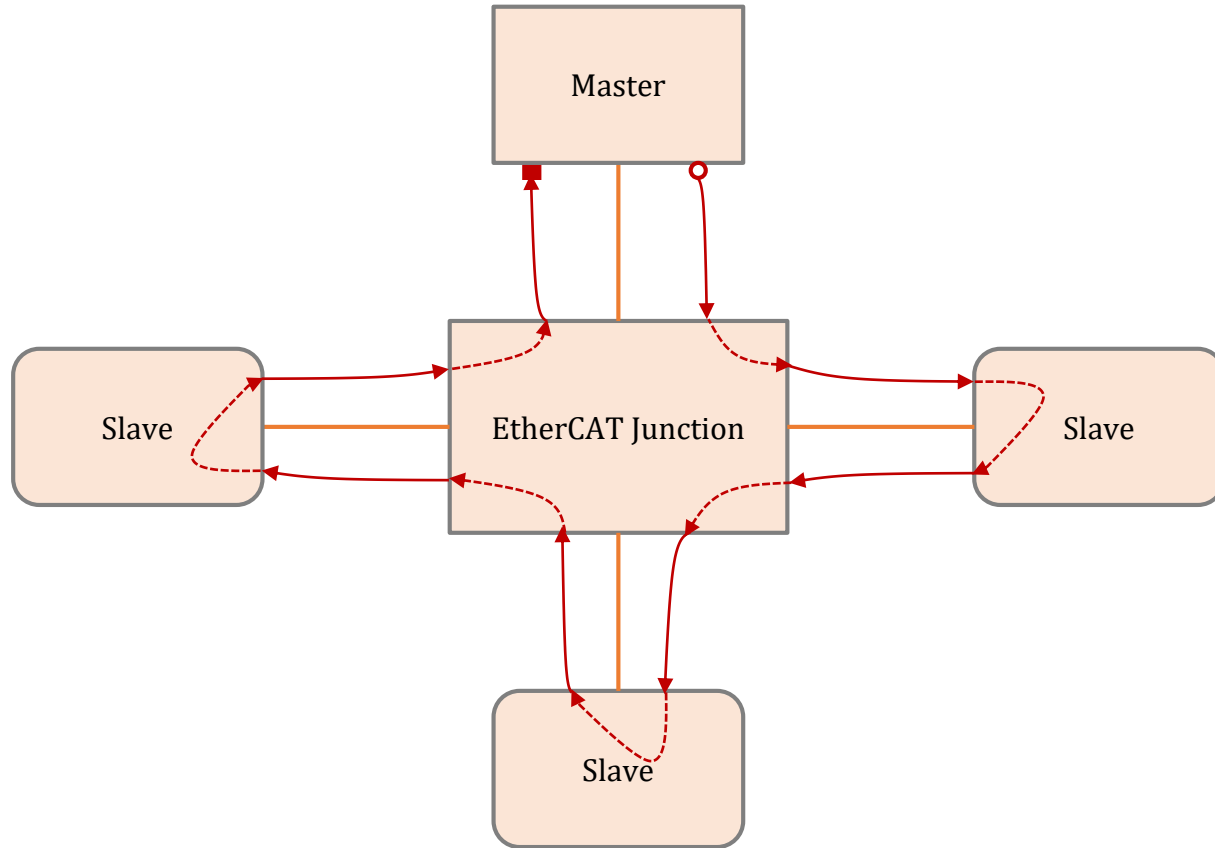
EtherCAT Logical-Ring Forwarding

The Type 12 fieldbus in IEC 61158-3/4/5/6-12 is also known as EtherCAT. An EtherCAT network can be understood as a railway network where slave devices are treated as stations, data are treated as passengers, and EtherCAT frames are treated as trains. While the EtherCAT frames move through the slave devices, the slave devices can off-load and re-load data into EtherCAT frames.



- EtherCAT frame MAC & PHY follow Ethernet specs
 - ▣ with distinct EtherType
- Frame originates at master, passes each slave (which may modify it) and is returned to master
- Logical topology is a ring
 - a) physical ring topology
 - b) physical line topology
 - ✓ Single-port slave forwards frame back to sender

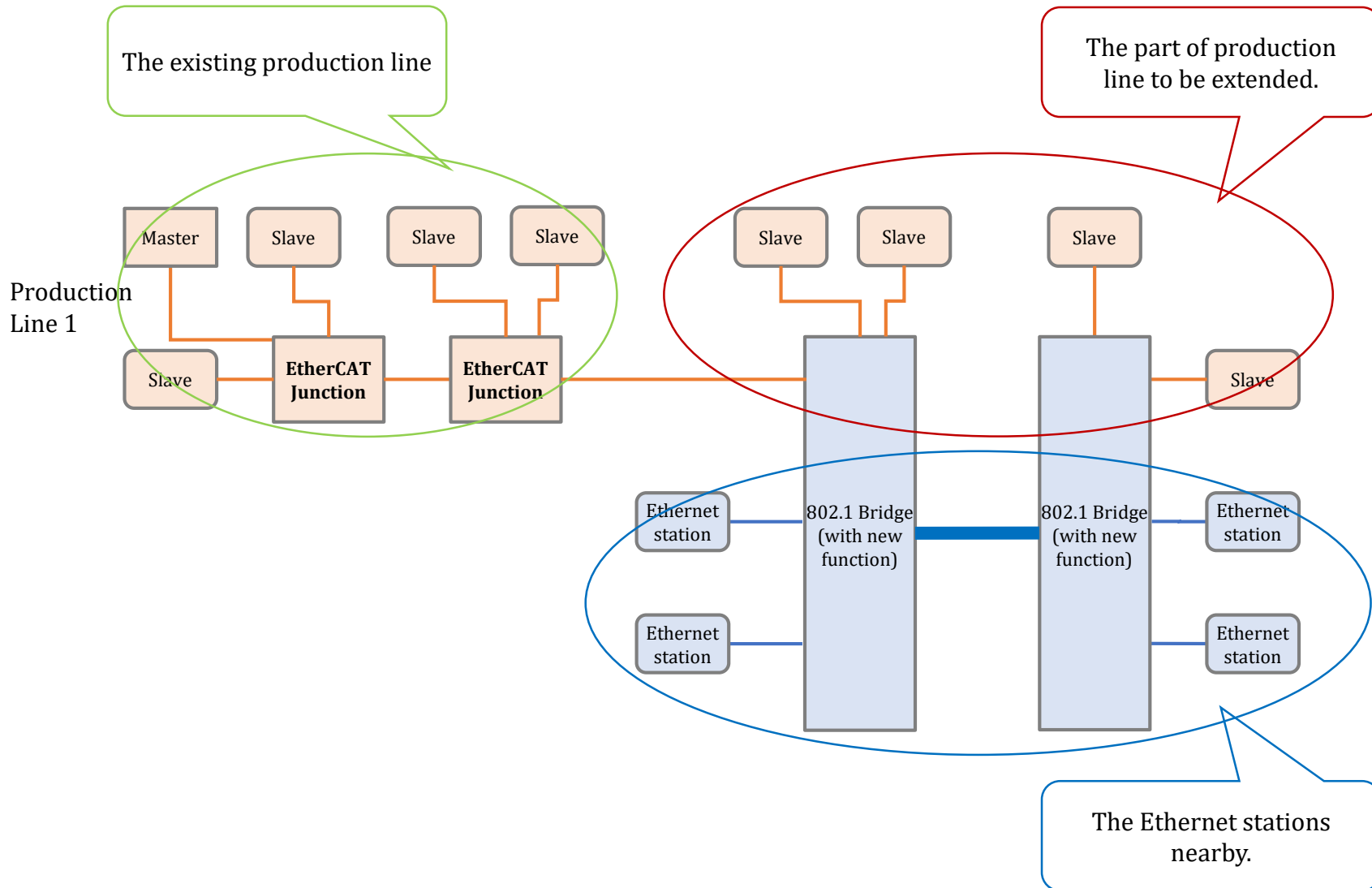
EtherCAT Junction



- EtherCAT Junction operates something like a switch
- Forwarding port is statically determined based on ingress port alone
 - ❑ Frames are cut-through forwarded to next port
- EtherCAT Junction is not a bridge

The EtherCAT Junction, as a reference, there are requirements that would request 802.1 bridges to serve as both an EtherCAT Junction and an Ethernet bridge.

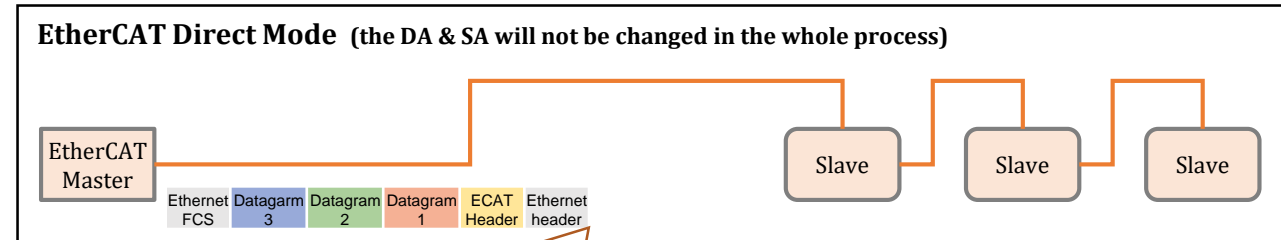
Use Case for 802.1 Bridge to Forward EtherCAT & Ethernet Frames Simultaneously



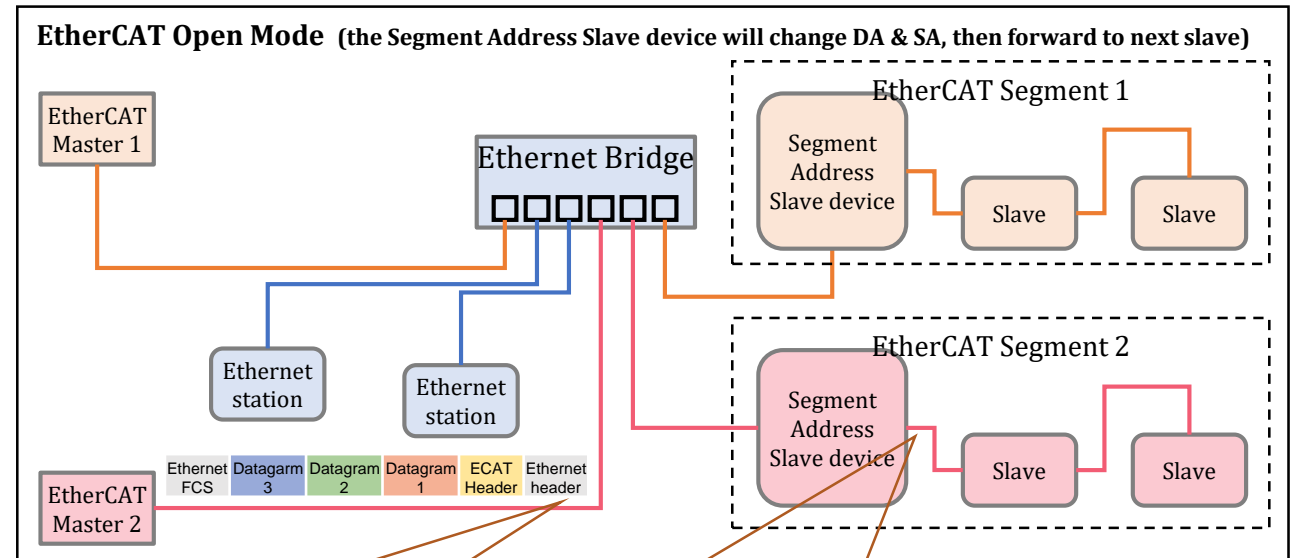
- Production line network requirement: cycle time 4ms, jitter < 10%
- Considering the space and cost, the factory seeks 802.1 Bridges to support to forward EtherCAT frames and Ethernet frames from the same link.

EtherCAT Open Mode & Direct Mode

- The previous slides indicated EtherCAT direct mode. In the direct mode, the EtherCAT master and the slave devices are connected one by one, and the frames are forwarded in a logical ring, and the MAC address fields of the EtherCAT frames are not checked (the SA is the EtherCAT master address, and the DA is the broadcast address).
- Using the EtherCAT open mode, one or several EtherCAT segments can be connected via Ethernet bridge with one or more Master devices. Each segment can be addressed using a “Segment Address Slave” device (the head station of the segment).
 - ❑ The EtherCAT master sends the EtherCAT frame, and the DA is the MAC address of the Segment Address Slave device.
 - ❑ The Ethernet bridge forwards the EtherCAT frame to Segment Address slave device.
 - ❑ This Segment Address Slave device replaces the DA with the SA (address of master) and replaces the SA with its own MAC address.
 - ❑ The EtherCAT frame loops as the rule of EtherCAT in the segment network.
 - ❑ Finally, the EtherCAT frame is forwarded to master by the Ethernet bridge.
 - ❑ Note that, the EtherCAT master as figure right below is a EtherCAT master device, in the scenarios mentioned in this document, it just communicates with one segment only, that is, the EtherCAT Master 1 communicates with EtherCAT segment 1 only via orange link, and the EtherCAT Master 2 communicates with EtherCAT segments 2 only via light red link.



DA = Broadcast address
SA = EtherCAT Master MAC address

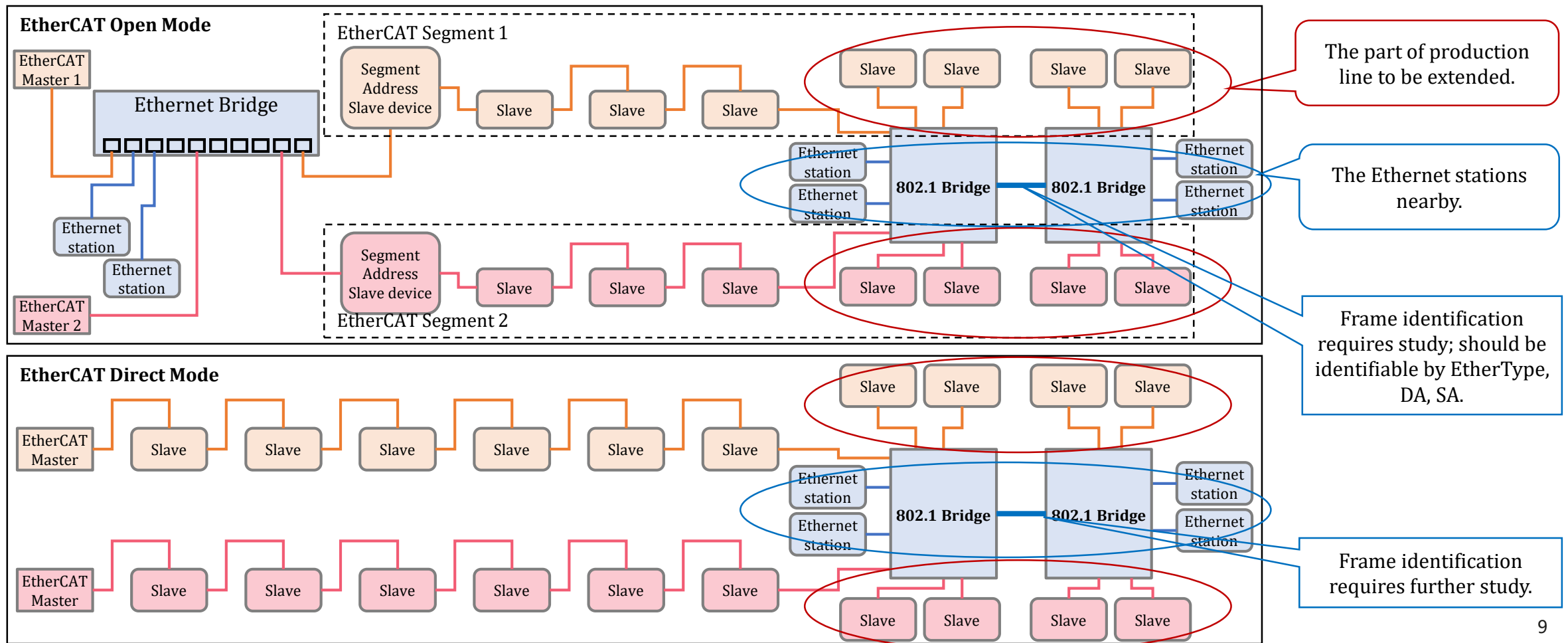


DA = Segment Address Slave device MAC address
SA = EtherCAT Master MAC address

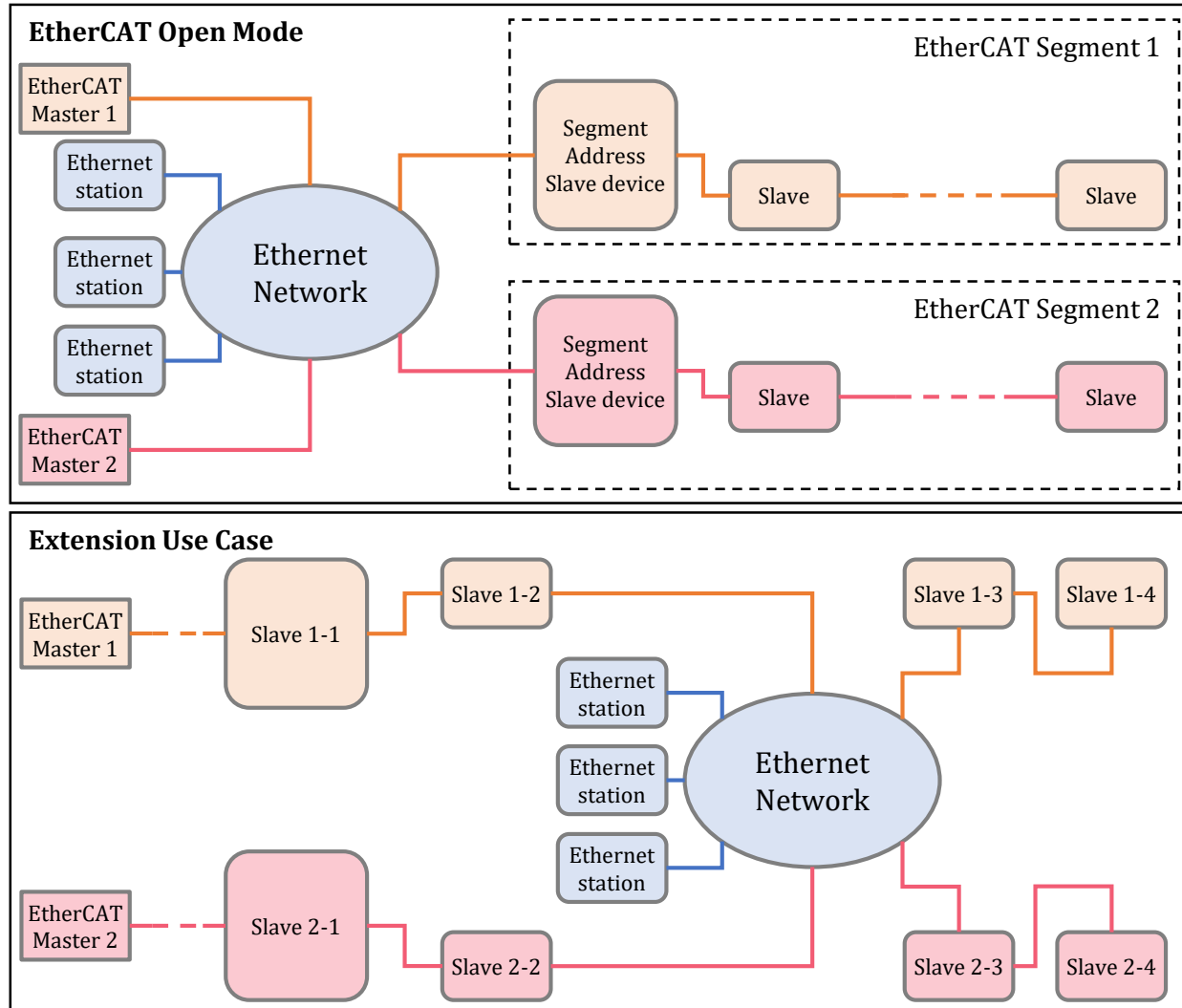
Segment Address Slave device change the DA & SA MAC
DA = EtherCAT Master MAC address
SA = Segment Address Slave device MAC address

Extension Use Case based on 802.1 Bridges According to EtherCAT Open Mode & Direct Mode

- The existing production line built based on EtherCAT which might be Open Mode or Direct Mode, the production line request to extend some EtherCAT slave devices.
- The new extended EtherCAT slave devices requested by production line, the existing EtherCAT devices and some other Ethernet stations are connected by 802.1 Bridged network as the figures below.



Compare of the Extension Use Case and the EtherCAT Open Mode



- **The EtherCAT Open Mode:**
 - ❑ The Ethernet network (including TSN capability) connects the EtherCAT masters and EtherCAT segments.
 - ❑ The Ethernet Bridges just forward the EtherCAT frames according to the MAC addressing mode.
- **The Extension Use Case:**
 - ❑ The Ethernet network (including TSN capability) is deployed into EtherCAT segments, and connects the EtherCAT slaves no matter it's EtherCAT open mode or direct mode.
 - ❑ The Ethernet Bridges not only supports to forward the Ethernet frames according to the MAC address forwarding mode, but also support to forward EtherCAT frames according to EtherCAT topological forwarding mode.
- **Common points:**
 - ❑ Both of them should assure the QoS for EtherCAT frames via some deterministic and high reliable capabilities, or mitigation of management / orchestration complexity.
- It's valuable to study some points in these aspects, and might be referential value for EtherCAT open mode.

Contents

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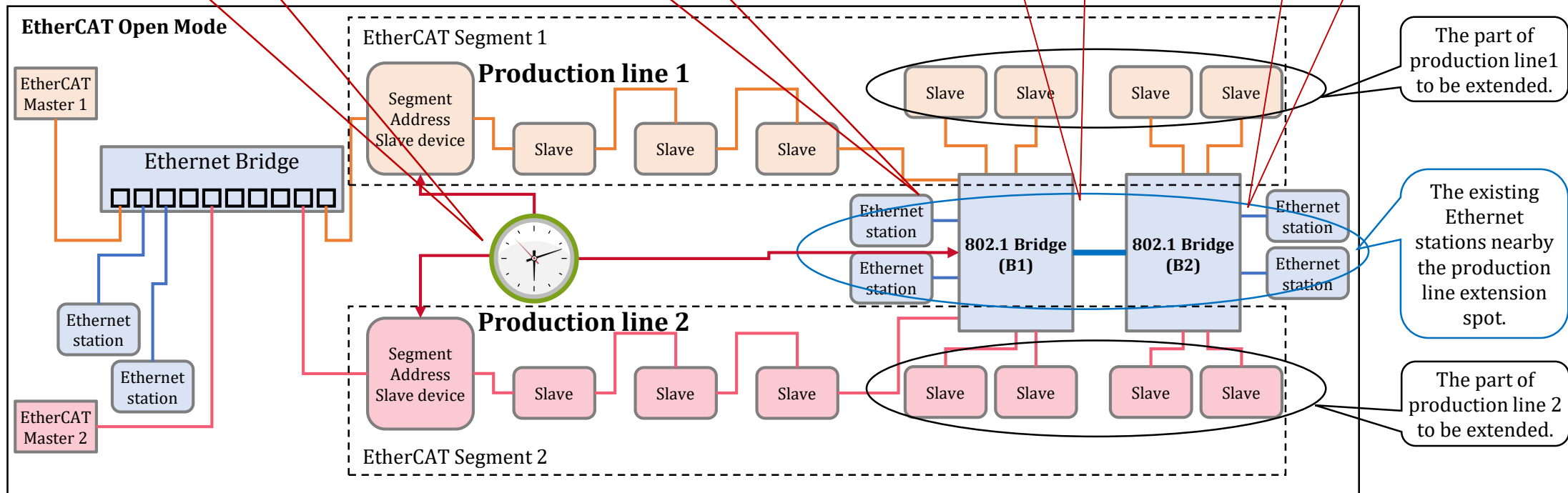
Initial Solution Points for the Use Case of EtherCAT Production Line Extension

① **Time Synchronization:** time synchronized to all of the two production lines and the 802.1 Bridges based on the current time synchronization solution. (outside of current Study Item)

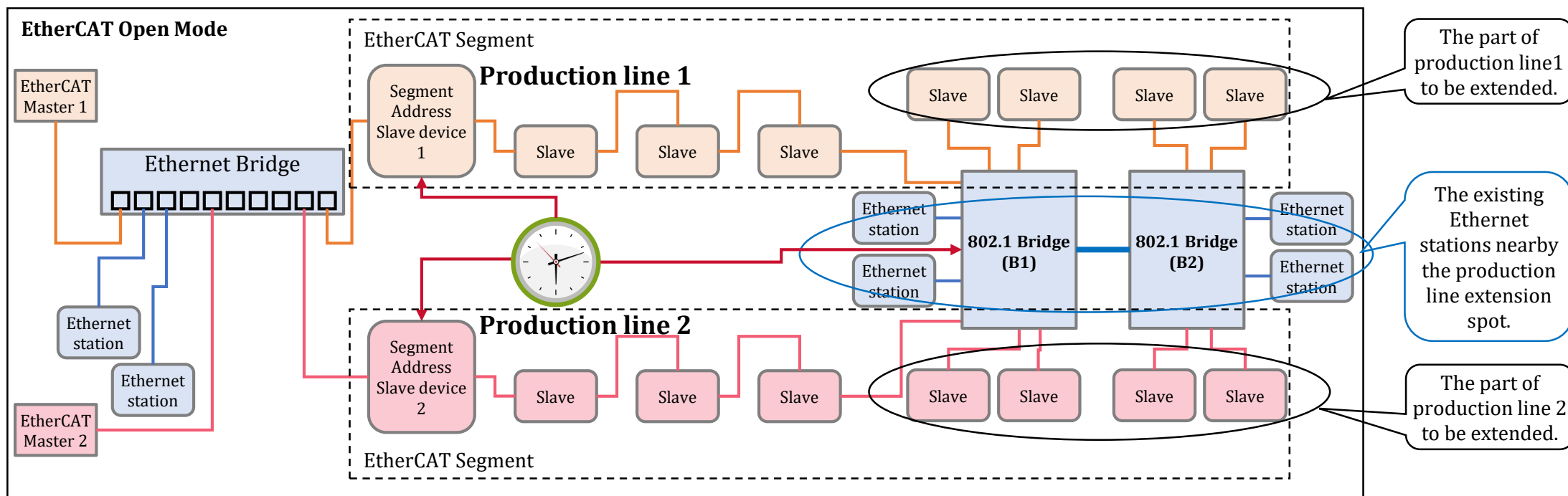
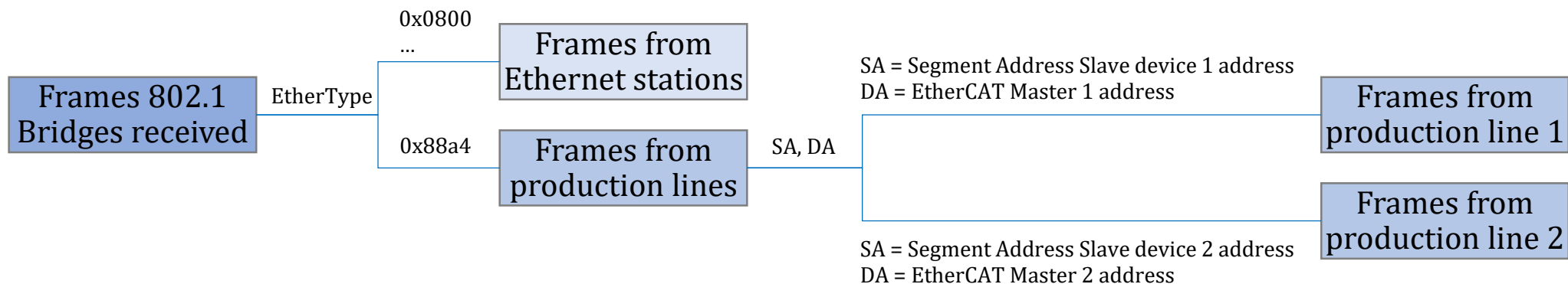
② **Identify different kinds frames, and forward to specific ports or devices according to EtherCAT**

③ **Improve the latency / jitter, assure the low latency / jitter according to independent of EtherCAT network**

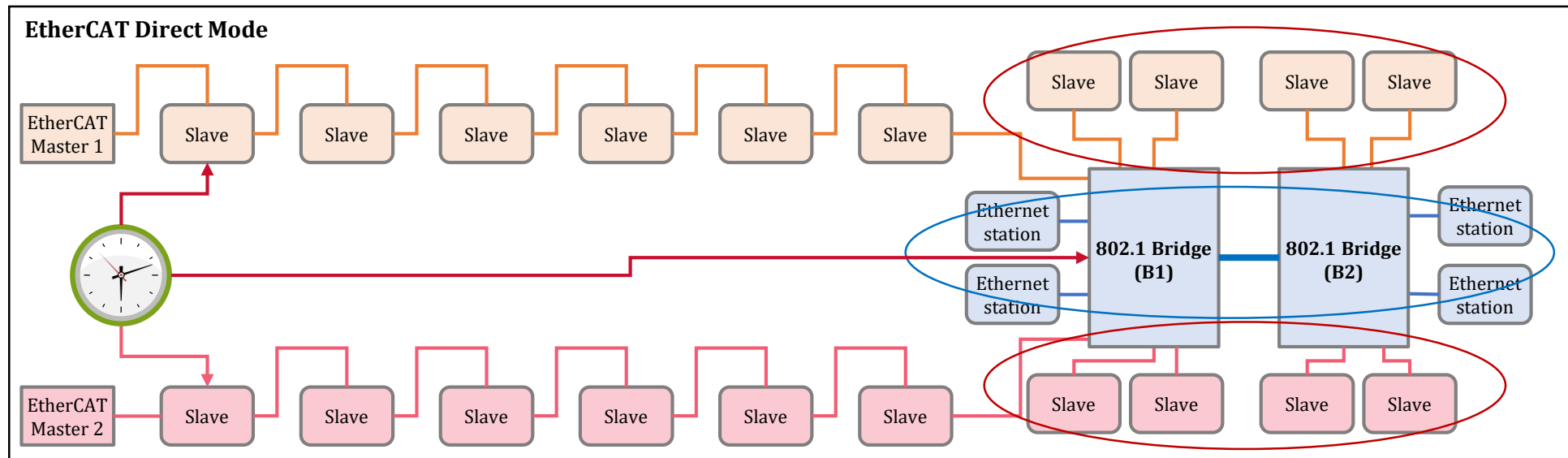
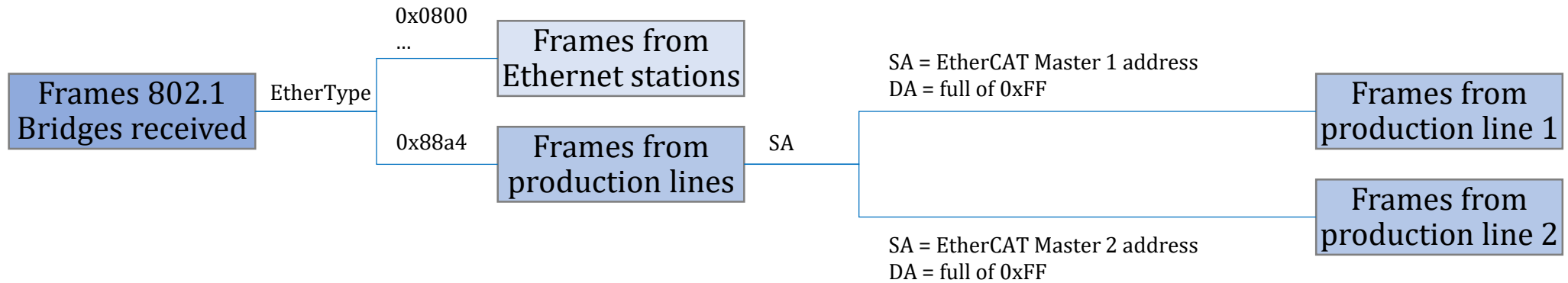
④ **Build reliable capability, assure the high reliability according to independent of EtherCAT network**



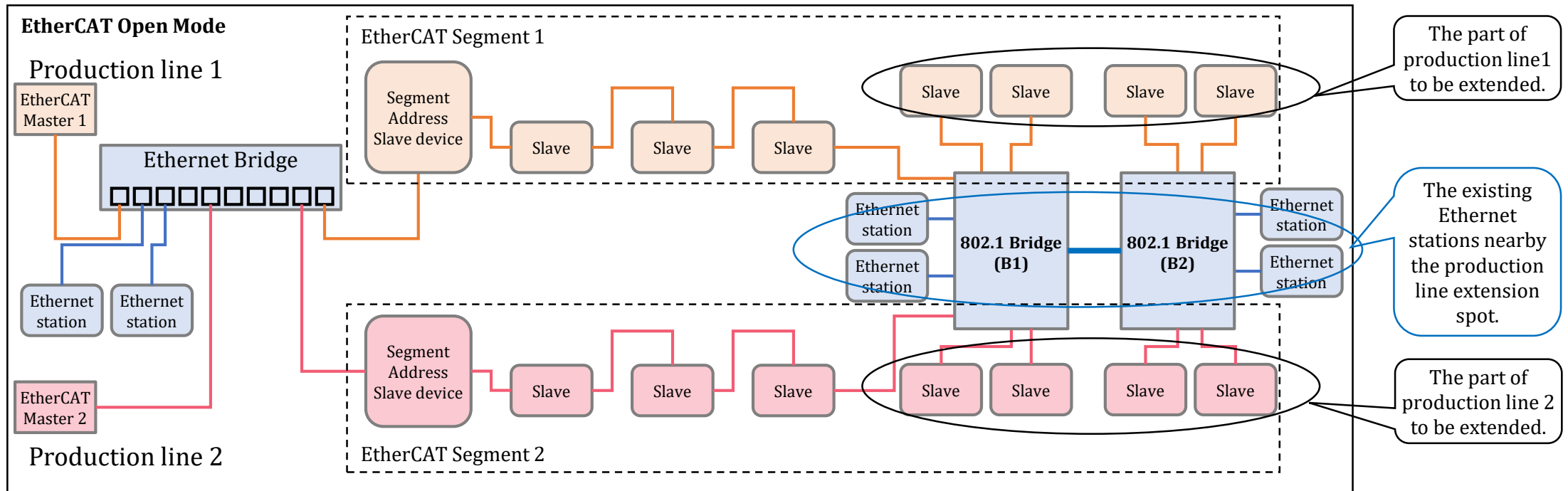
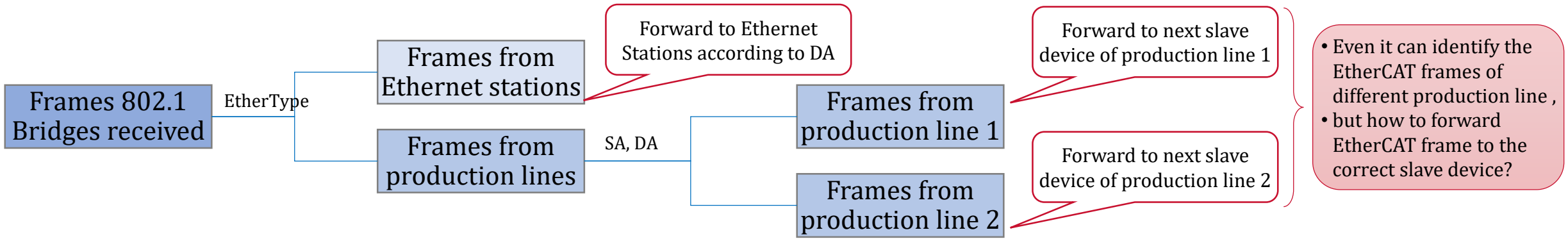
Identify Different Kinds Frames in EtherCAT Open Mode



Identify Different Kinds Frames in EtherCAT Direct Mode

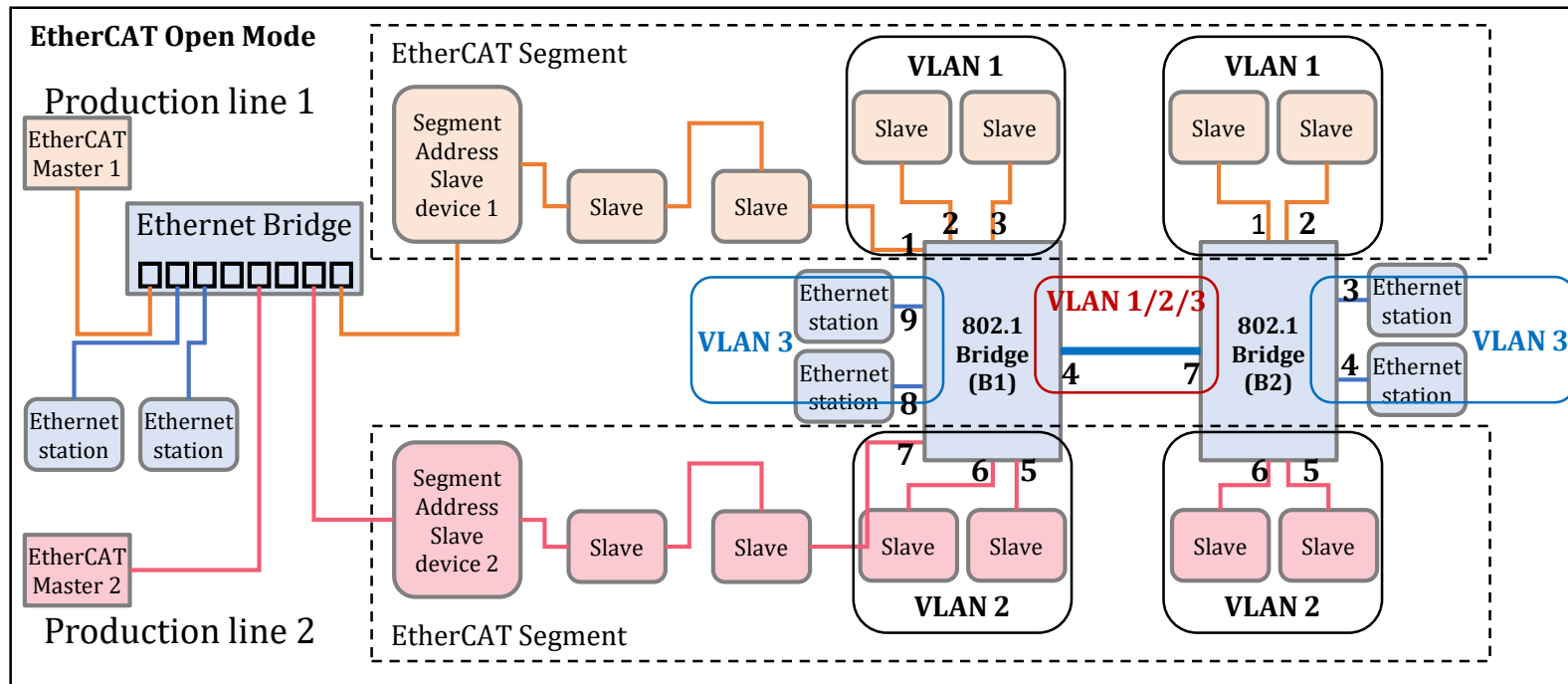


Forward the EtherCAT Frame to Specific Port



Identify the Next Slave Device of the Current Production Line in EtherCAT Open Mode

- Set 3 VLANs for 802.1 bridges B1 & B2
 - ❑ Set the ports connecting production line 1 devices into VLAN 1 as access type
 - ❑ Set the ports connecting production line 2 devices into VLAN 2 as access type
 - ❑ Set the ports connecting Ethernet stations into VLAN 3 as access type
 - ❑ Set the ports inter-connecting the 802.1 Bridges into VLAN 1 / 2 / 3 as trunk type
- The frames received from the port connecting to production line devices will be forwarded to next port as the right table.

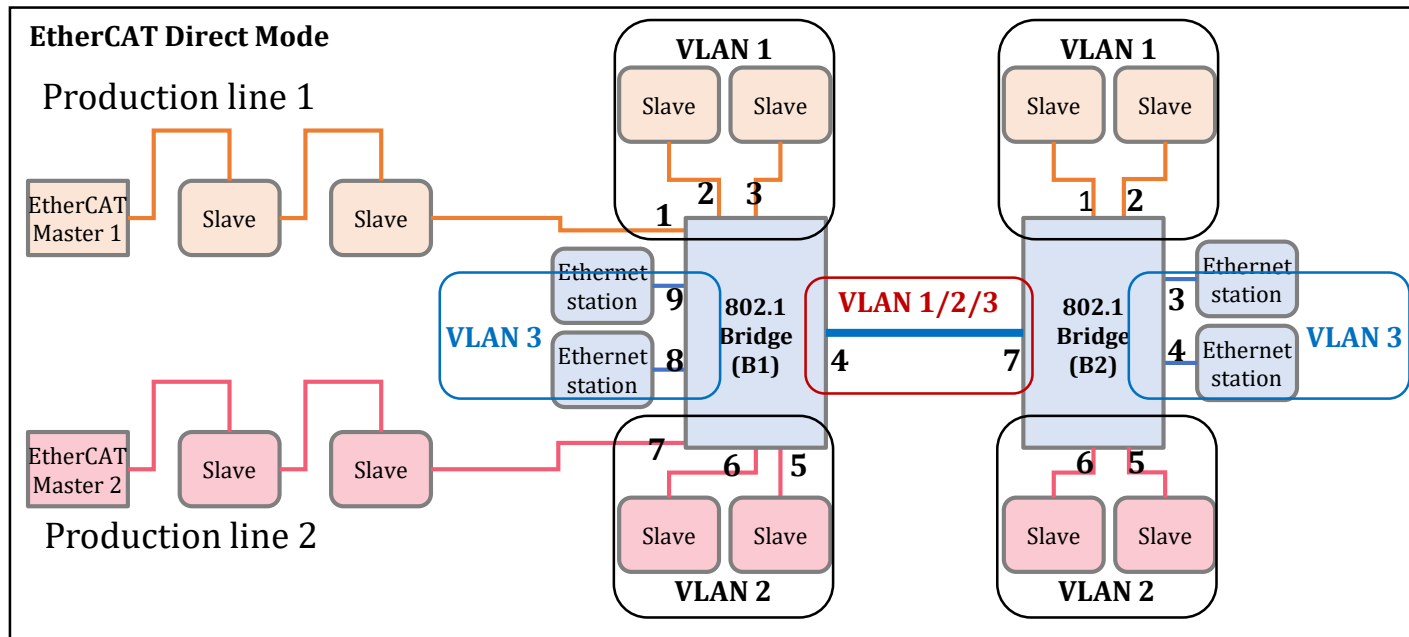


Bridge	Frames Received from	Frames Tagged VLAN	Frames Forwarded to Port
B1	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 3
	Port 3	VLAN1	Port 4
	Port 4	VLAN1	Port 1
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 4
	Port 4	VLAN2	Port 7
	Port 4	VLAN3	According to DA
Port 8	VLAN3		
Port 9	VLAN3		
B2	Port 7	VLAN1	Port 1
	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 7
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 7
	Port 7	VLAN3	According to DA
	Port 3	VLAN3	
	Port 4	VLAN3	

The table background color represents the frame type corresponding to the figure left.

Identify the next slave device of the current production line in EtherCAT Direct Mode

- Set 3 VLANs for 802.1 bridges B1 & B2
 - ❑ Set the ports connecting production line 1 devices into VLAN 1 as access type
 - ❑ Set the ports connecting production line 2 devices into VLAN 2 as access type
 - ❑ Set the ports connecting Ethernet stations into VLAN 3 as access type
 - ❑ Set the ports inter-connecting the 802.1 Bridges into VLAN 1 / 2 / 3 as trunk type
- The frames received from the port connecting to production line devices will be forwarded to next port as the right table.



Bridge	Frames Received from	Frames Tagged VLAN	Frames Forwarded to Port
B1	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 3
	Port 3	VLAN1	Port 4
	Port 4	VLAN1	Port 1
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 4
	Port 4	VLAN2	Port 7
	Port 4	VLAN3	According to DA
Port 8	VLAN3		
Port 9	VLAN3		
B2	Port 7	VLAN1	Port 1
	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 7
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 7
	Port 7	VLAN3	According to DA
	Port 3	VLAN3	
	Port 4	VLAN3	

The table background color represents the frame type corresponding to the figure left.

Summary of Feasibility

- As the forwarding rule discussed in the previous slides, it's feasible to support the EtherCAT forwarding rules via the 802.1 Bridges technically.
- Also, no matter the Direct Mode or Open Mode, the EtherCAT frames could be forwarded to the correct port and slave device according a same forwarding rule.
- So, it's necessary to discuss about the impact, such as low latency, low jitter, high reliability.

Contents

1. Detail use case and practical requirements for intermixed EtherCAT and Ethernet forwarding
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3. Impact on functionality, including latency, compared to independent networks
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Impact of Latency and Jitter to Forward EtherCAT frames by 802.1 Bridges

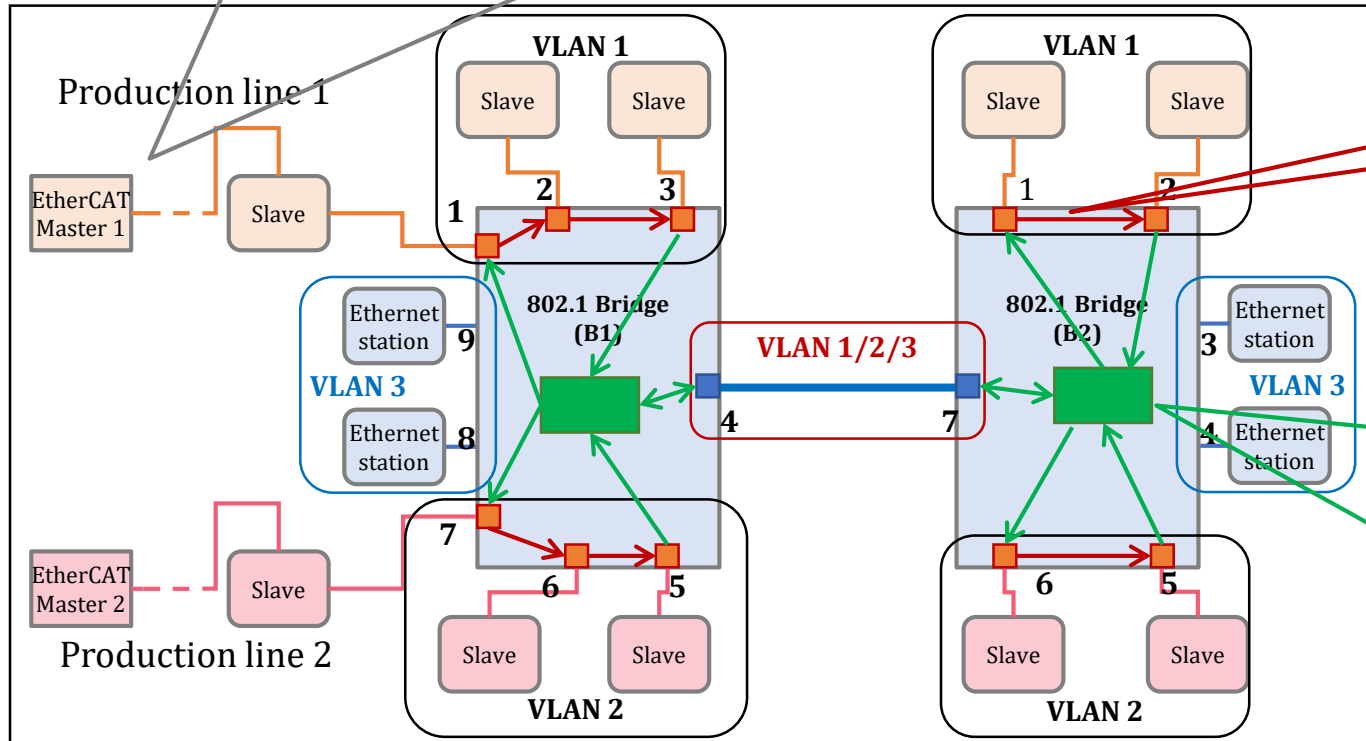
➤ Compared with the independent EtherCAT network, the main latency & jitter of the network as below includes following categories.

1. EtherCAT devices related latency

- ✓ The EtherCAT master latency and corresponding slave / cable latency.
- ✓ This part latency & jitter is the same as the EtherCAT independent network.

2. Forwarding latency to next EtherCAT slaves (CTF latency)

- ✓ The latency is used to forward the EtherCAT frames between the Bridge ports which are connecting to EtherCAT slaves directly.
- ✓ These ports rate are the same, also equals to rate of EtherCAT slaves.
- ✓ The **cut-through forwarding** could be used to minimize the latency and jitter.



3. Forwarding latency to next bridge (mix-transfer latency)

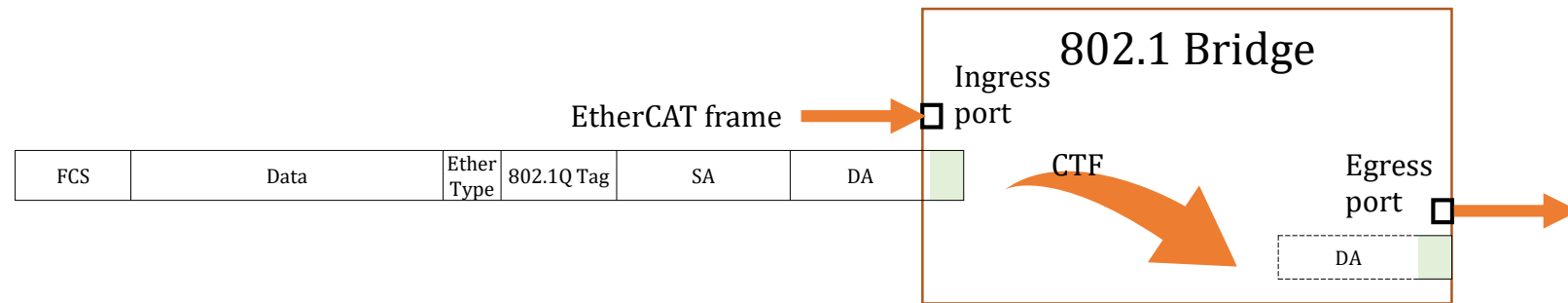
- ✓ The latency is used to forward the EtherCAT frame between the port (connecting to EtherCAT slave) to another port (connecting to next bridge).
- ✓ The transmission rate of the two ports are different, store and forward mode has to be mandatory.
- ✓ And, the streams from different EtherCAT master will be mix-transferred in the inter-link, so it's necessary to orchestrate to achieve low latency & low jitter.
- ✓ Besides, **mitigate the complexity** should be considered.

- ❑ **CTF (cut through forwarding) Latency:** The red lines indicate that the EtherCAT frames are cut-through forwarded between the ports connecting to slaves directly.
- ❑ **MT (mix-transfer) Latency:** The green lines / blocks indicate that the EtherCAT frame are stored and forwarded between the ports belonging to different VLAN.
- ✓ The different kinds of frames have to be orchestrated to achieve low latency and low jitter.

- According to Talker & listener of TSN conception, the talker sends frames to the listener, and listener responds with a frame.
 - ❑ In this scenario, generally, the slave sending the EtherCAT frame to Bridge is the talker, and the slave receiving the EtherCAT frame from Bridge is the listener.
 - ❑ Because of the EtherCAT topological forwarding mode, the streams between the talker and listener should identified by stream direction. But it will not affect the forwarding QoS of the 802.1 Bridges.

Cut-Through Forwarding Latency to Forward EtherCAT Frames

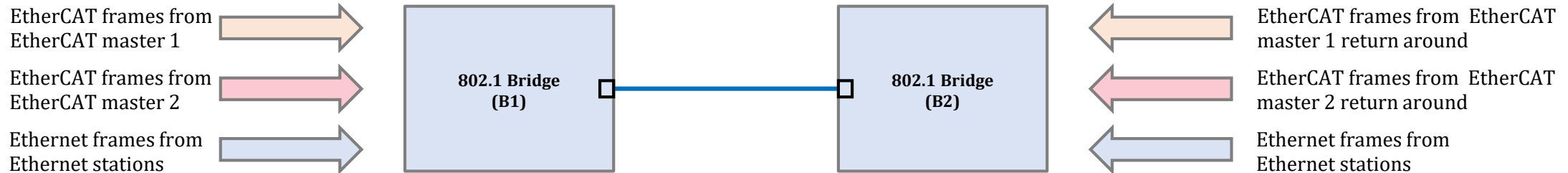
- It's necessary to implement the cut-through forwarding to minimize the forwarding latency based on the same transmission rate of the ingress port and egress port both of which are connecting to EtherCAT slave devices.



- According to the forwarding rule, the egress port could be identified by the ingress port and VLAN ID, then just cut-through forward the EtherCAT frame to the egress port, and there is no confliction.
- So, the latency and jitter is anticipated and bounded, and the CTF latency is not the key point of this Study Item, this Study Item will study the mix-transfer latency and jitter issues.

Impact of Mix-transfer Latency to Forward EtherCAT Frames

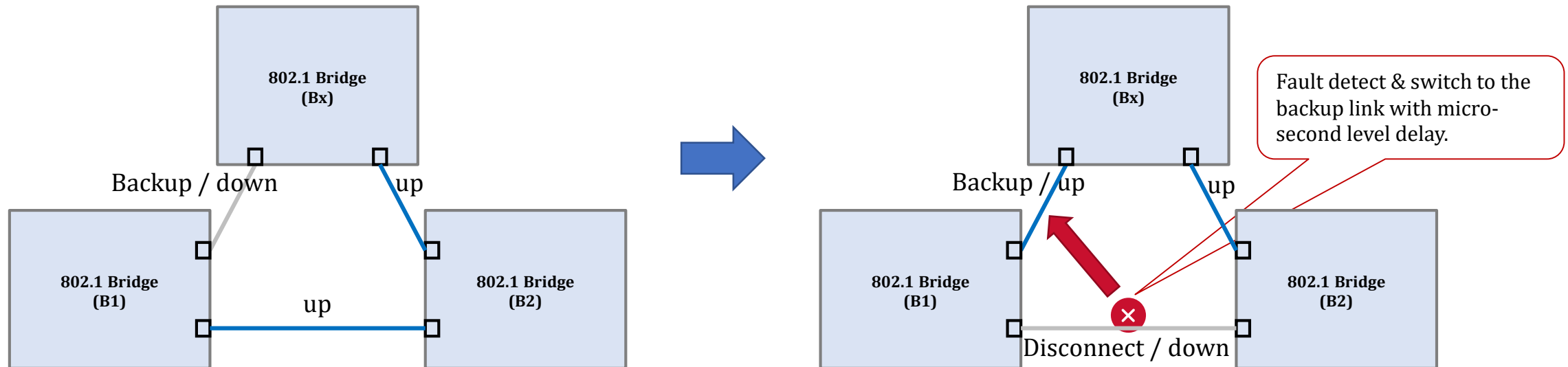
- In this scenarios, there is several kinds of frames to be mix-transferred along the inter-connection between 802.1 Bridges.
- Each kind of frame has its own requirement of low latency / jitter with different value.
- So, there will be different confliction and network resource competition along the inter-connection between 802.1 Bridges.
- The EtherCAT frames from EtherCAT master 1 and master 2 have to be orchestrated and scheduled to assure the low latency / jitter for all of them, meanwhile, it's better to mitigate the orchestration complexity as low as possible.
- The rest of Ethernet frames from Ethernet stations will be forwarded with best efforts.



This is the simple example of Ethernet network to mix-transfer different kind of frame.
There will be more 802.1 Bridges in actual network environment.

Impact of High Reliability of the Inter-Connection between the 802.1 Bridges

- According to EtherCAT application cycle requirements, the redundancy recovery time is micro-second level as specified in IEC 61784-2.
- The inter-link between the 802.1 bridges should support micro-second level to detect and notify the Bridges to switch to the backup link, meanwhile, the high reliability should avoid waste of bandwidth.
- So, it's necessary to study the high reliability issue in this Study Item.



In actual network environment, the Ethernet network might be deploy as ring network for high reliability. This is the simple example of Ethernet network to illustrate the high reliability requirement.

Summary of Impact

➤ As analysis and compared with independent EtherCAT network and corresponding specification, this Study Item focus on the mix-transfer latency / jitter and high reliability issues.

❑ Mix-transfer latency / jitter

- ✓ The EtherCAT frames from different EtherCAT masters request different low latency / jitter.
- ✓ Compared to independent EtherCAT network, it causes the confliction and network resources competition along the inter-connection between Bridges.
- ✓ The confliction and network resources competition along the inter-connection between Bridges affect the latency / jitter of each EtherCAT frame.
- ✓ It's valuable to study and analyze the feasibility to achieve low and bounded latency and to mitigate corresponding complexity of implementation.

❑ High reliability

- ✓ The Ethernet network connecting the EtherCAT slaves should be the ring topology physically, and provide the backup link to be up to forward the frames while one link is disconnected.
- ✓ In order to avoid the overuse of network bandwidth, the recovery time of the backup link in the Ethernet network of ring topology might be milli-second level.
- ✓ It's the obvious gap to micro-second level of recovery time as requested by EtherCAT specification.
- ✓ It's necessary to study and analyze the feasibility to assure the recovery time of the Ethernet network to micro-second level.

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Introduction to Feasibility of Assuring QoS

- As the previous sections analyzed, this Study Item contributes to assure the QoS of EtherCAT frames, including low latency / jitter and high reliability. And the Ethernet frame from the Ethernet stations will be forward as best effort.
- In this section, based on the mix-transfer scenario, this Study Item analyzes the feasibility to assure the QoS of EtherCAT frames, and mitigate the complexity or avoid the overuse of bandwidth.
 - ❑ Low latency & jitter
 - ✓ At first, analyze solution of 802.1Qbv to assure the low latency / jitter, but it might be complicated to orchestrate.
 - ✓ Second, try to outline the feasibility to mitigate the complication but the latency will be increased.
 - ❑ High reliability
 - ✓ According to the requirement of EtherCAT redundancy recovery time, analyze the existing high reliable capability and the gap.
 - ✓ Try to analyze the feasibility of technical direction / points to achieve micro-second level to detect and recover to the backup link, and avoid to overuse network bandwidth.

Strictly Orchestration based on 802.1Qbv to Achieve Bounded Latency

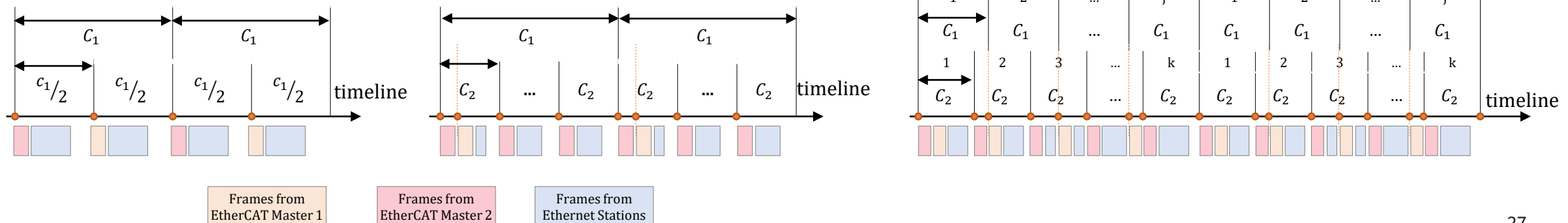
- Based on the time synchronization to two production lines and the 802.1 bridges, the frames from EtherCAT master 1 / EtherCAT master 2 and the Ethernet stations will be mix-transferred in the inter-link between the 802.1 bridges.
 - ❑ The inter-connection bandwidth between the 802.1 bridges should be evaluated according the EtherCAT frame size and application cycle.
 - ❑ The transfer delay from the EtherCAT master to 802.1 bridges should be evaluated based on the frame size and bandwidth.
 - ❑ All these parameters and evaluation results will be input as per 802.1Qbv, and orchestrate the streams to get the specific timeline, and distribute the timeline to each bridge.
 - ❑ The timeline contains a list of time point, each time point indicate the bridge should have received the frame and send to next node.
 - ❑ Along the whole routine, the bridge should receive the EtherCAT frames and send to next bridge as per the timeline strictly.
 - ❑ According to the figures below ($C_1 \neq C_2$), the periods between the two adjacent time points are different, it could achieve low latency as low as possible (received on time and sent out on time), but it's complicated to implement such orchestration.

• $C_1 =$ Cycle of EtherCAT master 1, $C_2 =$ Cycle of EtherCAT master 2, $C_1 \geq C_2$

1. $C_1 = C_2$

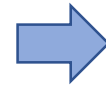
2. $C_1 = nC_2$ ($n > 1$ is an integer)

3. $C_1 = mC_2$ ($m > 1$ is not an integer)

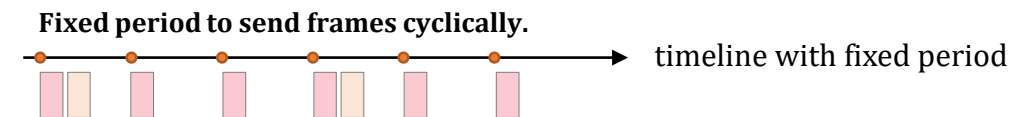


Complication of Strict Orchestration and Mitigation

- **The complication of strict orchestration including following factors:**
 - ❑ The periods between the two adjacent time points are **different**.
 - ❑ The action of sending out frames has to be done **as per the timeline** with strict time synchronization, no earlier and no later than the time point.
- It's being more complicated while increasing the network scale and stream quantity.



- **The mitigation is making the Bridges to send the frames according to a same rhythm cyclically than a strict timeline.**
 - ❑ Each bridge use the **same period** to send the frames cyclically, and the EtherCAT frame is sent out as the cyclic shuttle.
 - ❑ No matter the routine is long or short, and corresponding transmission time of the shuttle along the link is different, but in a Bridge, the departure time of shuttle is **cyclically fixed**.
 - ✓ That is, even the shuttle arrives at a Bridge earlier, but the next departure time has to wait until the timepoint of next cycle, and absolute latency value of frame is increased.
 - ✓ The stream meter & self-studying capabilities could be built to get the features of streams, and make the adjacent Bridges to get to work in a same rhythm.
 - ✓ So, from the view of the whole network, the end to end network transmission latency is anticipated and bounded.
- If the network bandwidth is enough the network transmission absolute latency value could satisfy the specific EtherCAT service requirement, and mitigate the complexity of implementation.



Analysis of the Existing High Reliable Capabilities

- The table below list the main reliable capabilities, most of which the recovery time is milli-second level except 802.1CB and IEC 62439-3.
- Both of them replicate the frame and transmit along two different routine path to achieve high reliability of zero recovery time, that is twice of network bandwidth needed.

NO.	Redundancy / Reliable Capability	Topology Supported	Recovery Time Level
1	Rapid Spanning Tree Algorithm and Protocol (802.1w)	Ring, Mesh	Hundreds of milliseconds
2	Medium Redundancy Protocol (IEC 62439-2)	Ring	Dozens - hundreds of milliseconds
3	Distributed Redundancy Protocol (IEC 62439-6)	Ring	Hundreds of milliseconds
4	Spatial Reuse Protocol (RFC 2892)	Ring	Hundreds of milliseconds
5	Cross-network Redundancy Protocol (IEC 62439-4)	Mesh	Hundreds of milliseconds
6	Ethernet Ring Protection Switching (ITU-T G.8032)	Ring	Dozens milliseconds
7	Ethernet Linear Protection Switching (ITU-T G.8031)	Linear	Dozens milliseconds
8	Frame Replication and Elimination for Reliability (802.1CB)	Ring, Mesh	Zero
9	Parallel Redundancy Protocol (IEC 62439-3)	Mesh	Zero

Milli-second level recovery time.

Zero recovery time, but network bandwidth doubled.

The Feasibility to Achieve the Micro-second Level Recovery Time

- As specified in IEC 61784-2, the redundancy recovery time of EtherCAT is micro-second level.
- The Ethernet network connects EtherCAT slaves, the recovery time of micro-second level should be achieved.
- As we recap the existing high reliable capabilities except FRER, all of them are build upon the level 2 or high layer, that might be the reason, the recovery time is milli-second level.
- In order to achieve micro-second level recovery time and avoid network bandwidth overuse, the feasibility of technical direction includes:
 - ❑ To make use of Ethernet network ring topology, detect the link fault and activate the backup link.
 - ❑ To build the network fault detection capability in low layer other than layer 2 or high layer.
 - ❑ To build the network recovery capability in low layer to achieve quick deliver the fault point information and trigger to activate the backup link.
 - ❑ To build the high reliable capability in network level completely to avoid any co-operation of end device.
 - ❑ To avoid the influence to data frames, it's better for the fault detection and notification frame to use no more than 1% of the network bandwidth.

Summary of Feasibility Analysis

➤ This Study Item focus the key point of mix-transfer latency / jitter and high reliability.

▣ Mix-transfer latency / jitter

- ✓ As analyzed, the 802.1Qbv could afford the low latency / jitter, but it's complicated to implemented.
- ✓ And raised a feasibility of mitigation via fixed period of each Bridge to send frames cyclically.
 - Even the frame arrives at the Bridges earlier, it has to wait until the next fixed period.
 - So, the absolute latency is increased, but the end to end latency is anticipated and bounded.
 - If the network bandwidth is enough, the end to end latency could satisfy the EtherCAT requirements, and the mitigation is feasible technically.

▣ High reliability

- ✓ Analyzed the technical direction to achieve the high reliability of Ethetnet network for EtherCAT requirements.
 - To make use of ring topology and to enhance low layer capabilities.
 - To avoid influence to end devices not only abut compatibility but also about bandwidth usage by detection & notification frames.

Thank you.

Proposal for Nendica Study Item

- For Nendica to initiate a study item on **Forwarding of Fieldbus CPF 12 on 802.1 Bridges**

To be studied	<ul style="list-style-type: none">• Detail use case and practical requirements for intermixed EtherCAT and Ethernet forwarding• Feasibility of operation• Impact on functionality, including latency, compared to independent networks• Feasibility of assuring QoS for EtherCAT and Ethernet• This study item excludes aspects that are covered by project IEC/IEEE 60802
Deliverable	<p>An informal report documenting</p> <ul style="list-style-type: none">• Summary requirements according to industrial scenarios• Potential benefits• Summary of feasibility issues• Impact & optimization of evolving technologies• Possible standardization needs• Possible recommendation to initiate a work item
Leader	<ul style="list-style-type: none">• Huajie Bao (Huawei), or other volunteers
Timeline	<ul style="list-style-type: none">• Start in June 2022, finish in Nov 2022• Draft version Aug 2022• Call for comments Sept 2022• Complete Study Item Report Nov 2022
Work schema	<ul style="list-style-type: none">• Weekly meeting or on-demand meeting• Encourage all contributions• Provide ongoing reporting to IEC/IEEE 60802