Nendica Study Item Report (Forwarding of Fieldbus CPF 12 on 802.1 Bridges)

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Introduction

➢ This document is the result of the Study Item "Forwarding of Fieldbus CPF 12 on 802.1 Bridges" within the IEEE 802 "Network Enhancements for the Next Decade" Industry Connections Activity known as Nendica.

➢ This document introduces the use case in which tries to use the 802.1 Bridges to connect the EtherCAT SubDevices and Ethernet stations and forward the EtherCAT frames and Ethernet frames simultaneously.

➢ This document studies this use case and analyzes the feasibility to forward the EtherCAT frames via the 802.1 Bridges, and initially analyzes the related evolving technology to assure the QoS for EtherCAT frames.

➢ Finally, this document provides possible recommendation to initiate a work item for further analysis.

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 MDevice**: means the EtherCAT Main Device, it's a EtherCAT PLC or controller and includes only one MDevice instance in this document generally unless explicit notes.

◻ **EtherCAT SubDevice**: means the EtherCAT Subordinate Device, it's controlled by the EtherCAT MDevice.

◻ **EtherCAT frame**: the frame sent by EtherCAT MDevice and forwarded by EtherCAT SubDevice or 802.1 Bridges, and the EtherType of the frame equals 0x88a4.

◻ **Ethernet frame**: the frame sent by general Ethernet Stations in this document, and the EtherType of the frame doesn't equal 0x88a4.

◻ **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 which is mapping the MAC address to the port.

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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 EtherCAT SubDevices are treated as stations, data are treated as passengers, and EtherCAT frames are treated as trains. While the EtherCAT frames move through the SubDevices, the SubDevices can off-load and re-load data into EtherCAT frames.

(a)

(b)
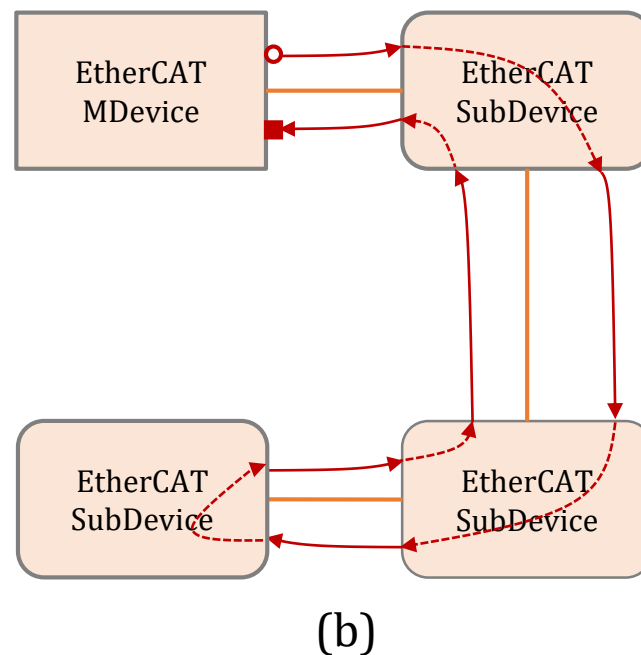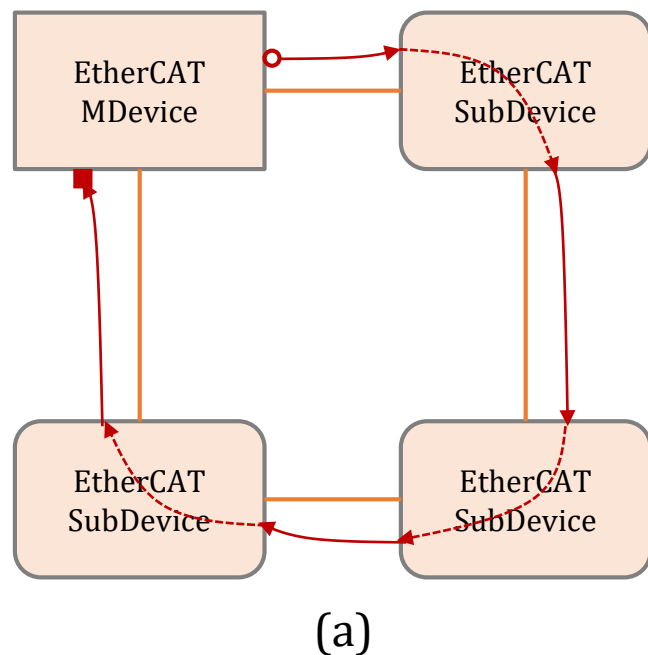
➢ EtherCAT frame MAC & PHY follow Ethernet specs
  ▫ with distinct EtherType

➢ Frame originates at EtherCAT MDevice, passes each SubDevice (which may modify it) and is returned to MDevice

➢ Logical topology is a ring
  a) physical ring topology
  b) physical line topology
    ✓ Single-port SubDevice forwards frame back to sender

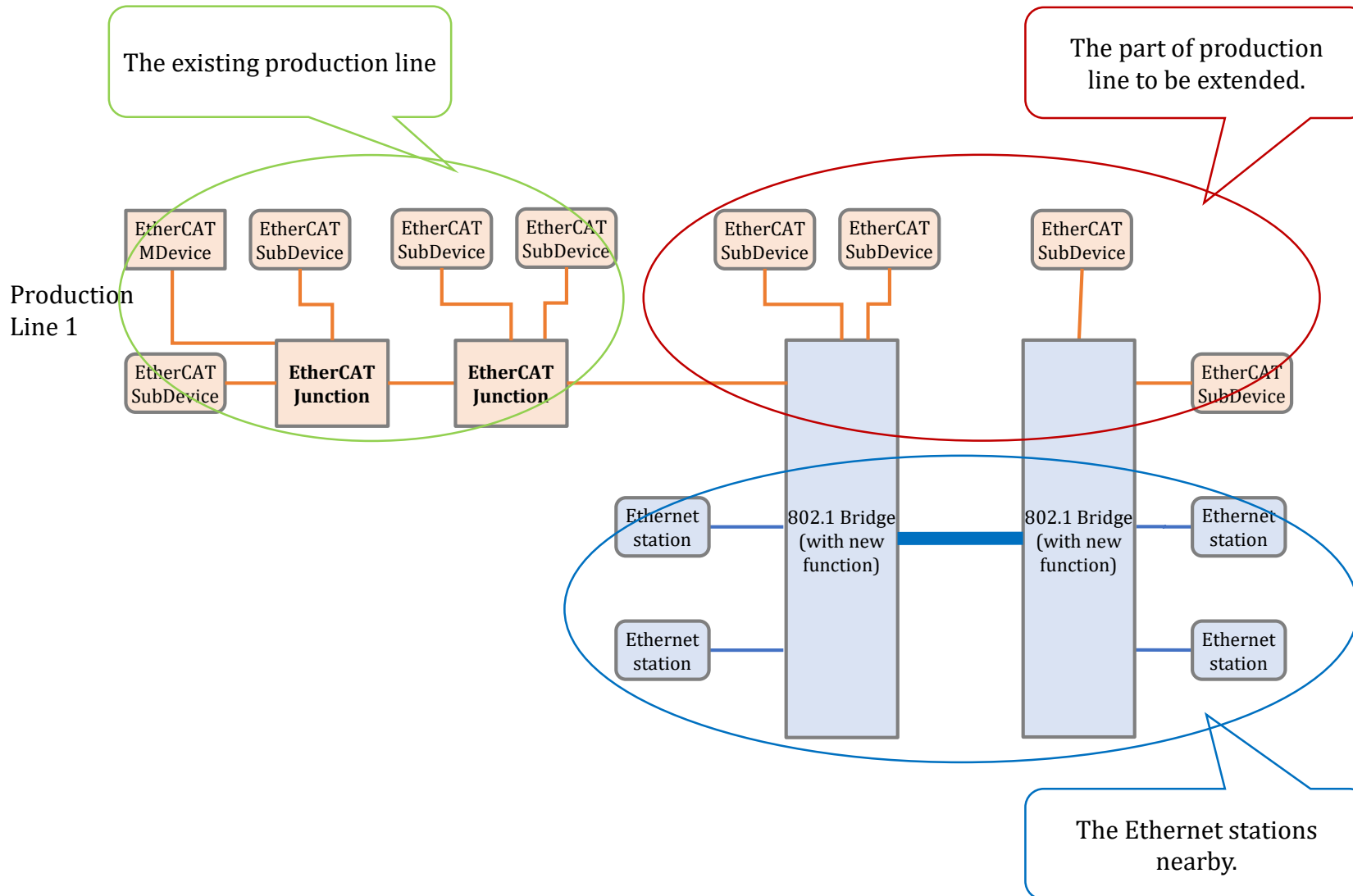# EtherCAT Junction
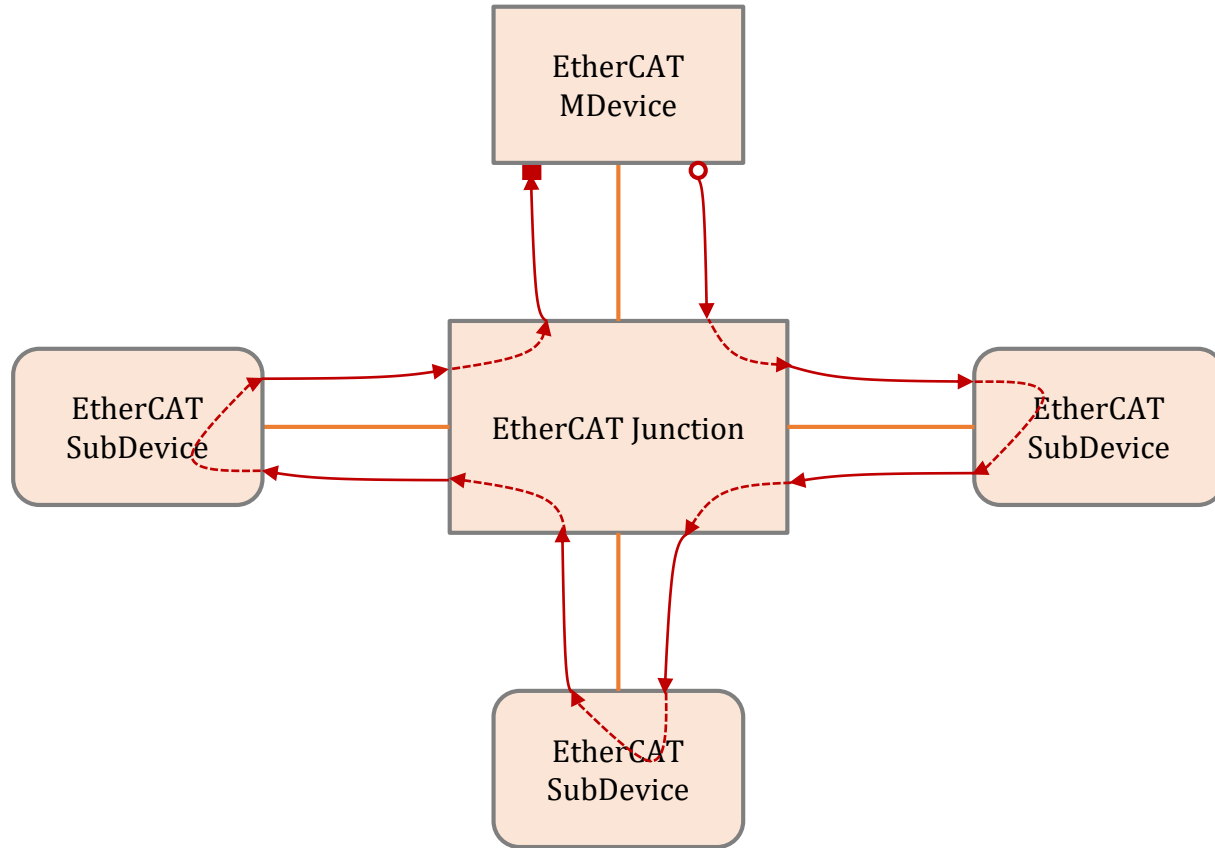
- ➢ EtherCAT Junction operates something like a switch
- ➢ Forwarding port is statically determined based on ingress port alone
  - ☐ Frames are cut-through forwarded to next port
- ➢ EtherCAT Junction is not a bridge

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

The existing production line

The part of production line to be extended.

Production Line 1

EtherCAT MDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT SubDevice

EtherCAT Junction

EtherCAT Junction

EtherCAT SubDevice

802.1 Bridge (with new function)

802.1 Bridge (with new function)

Ethernet station

Ethernet station

Ethernet station
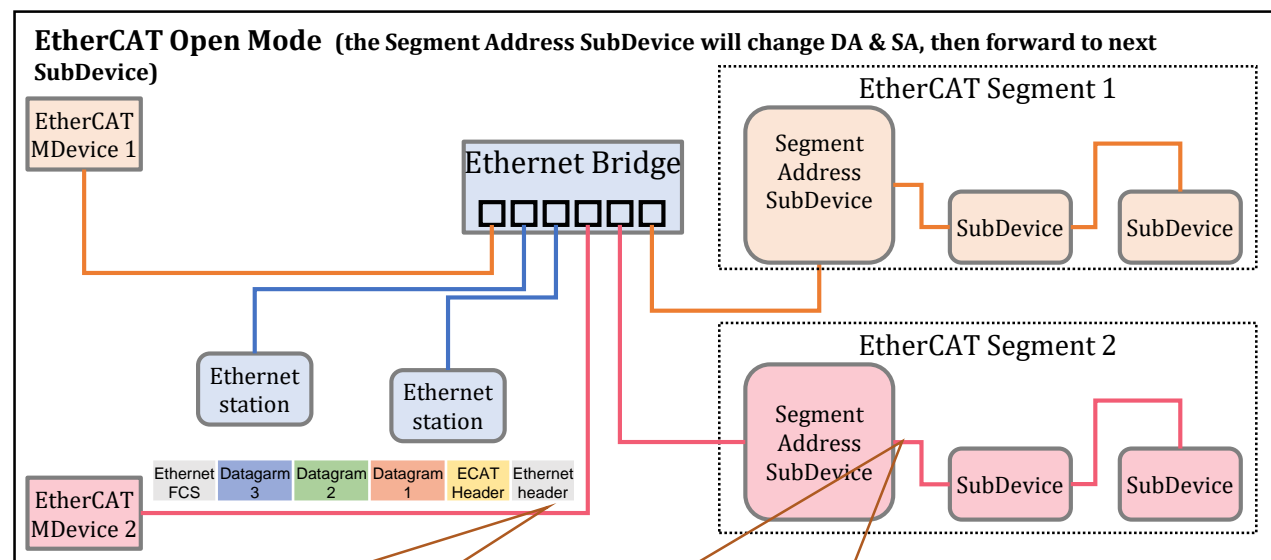
Ethernet station

The Ethernet stations nearby.

➢ 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.

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EtherCAT Open Mode & Direct Mode

➢ The previous slides indicated EtherCAT direct mode. In the direct mode, the EtherCAT MDevice and the SubDevices 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 MDevice address, and the DA is the broadcast address).

➢ Using the EtherCAT open mode, one or several EtherCAT segments and respective EtherCAT MDevices can be connected via Ethernet Bridge. Each segment can be addressed using a "Segment Address SubDevice" (the head station of the segment).

□ The EtherCAT MDevice sends the EtherCAT frame, and the DA is the MAC address of the Segment Address SubDevice.

□ The Ethernet Bridge forwards the EtherCAT frame to Segment Address SubDevice.

□ This Segment Address SubDevice replaces the DA with the SA (address of MDevice) 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 MDevice by the Ethernet Bridge.

□ Note that, in the figure right side, the EtherCAT MDevice just communicates with one segment only, that is, as the figure right, the EtherCAT MDevice 1 communicates with EtherCAT segment 1 only via orange link, and the EtherCAT MDevice 2 communicates with EtherCAT segment 2 only via light red link.

EtherCAT Direct Mode (the DA & SA will not be changed in the whole process)

DA = Broadcast address
SA = EtherCAT MDevice MAC address

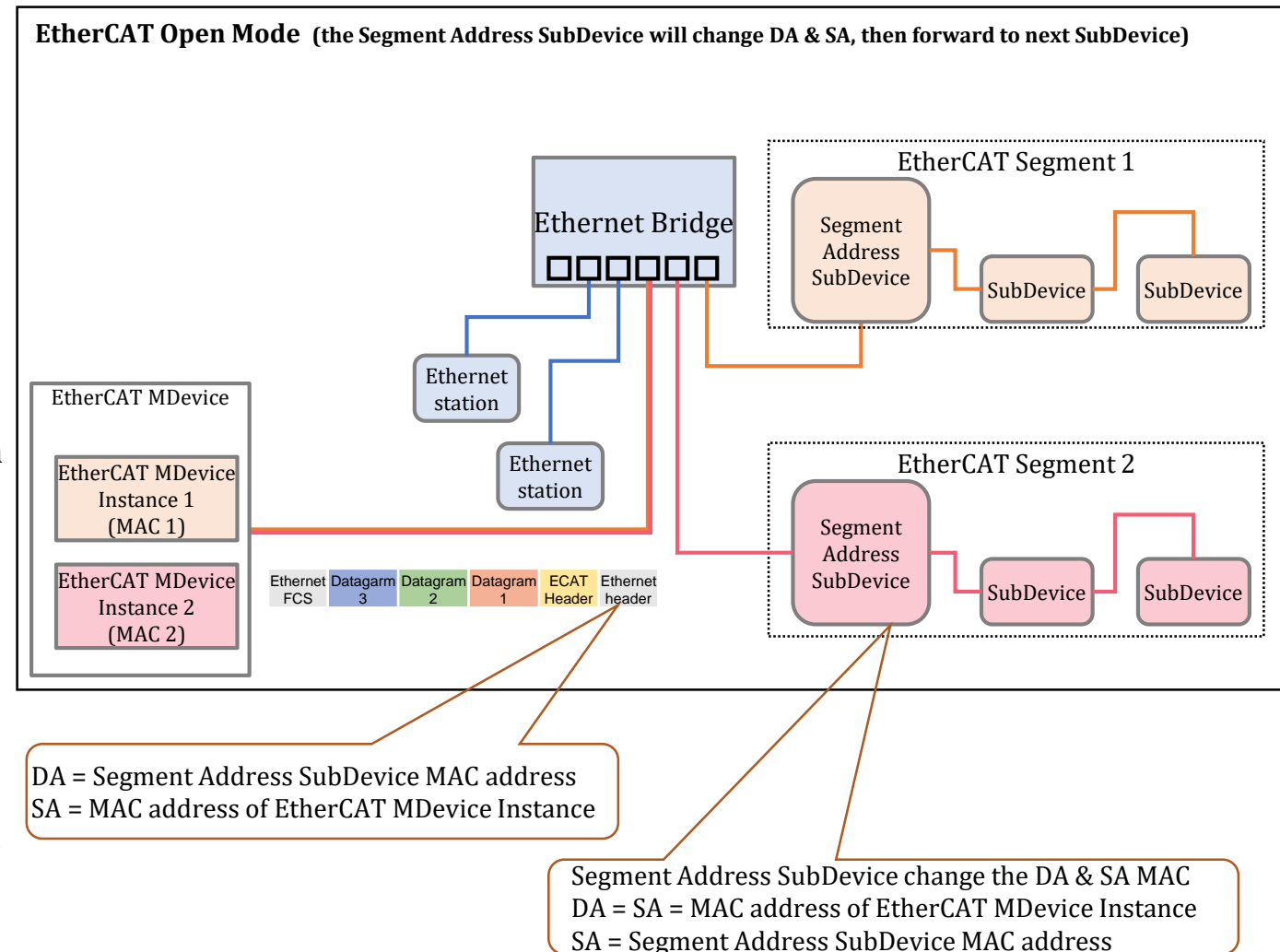**EtherCAT Open Mode** (the Segment Address SubDevice will change DA & SA, then forward to next SubDevice)

DA = Segment Address SubDevice MAC address
SA = EtherCAT MDevice MAC address

Segment Address SubDevice change the DA & SA MAC
DA = EtherCAT MDevice MAC address
SA = Segment Address SubDevice MAC address

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EtherCAT MDevice with Multiple MDevice Instances in Open Mode

➤ In actual EtherCAT network environment, the EtherCAT MDevice might contain several MDevice instances as the figure right side, and each EtherCAT MDevice instance communicates with the segment controlled by itself.

- ☐ The MDevice instance 1 communicates with segment 1 via orange link with MAC address 1.

- ☐ The MDevice instance 2 communicates with segment 2 via light red link with MAC address 2.

- ☐ The EtherCAT MDevice connects the Ethernet Bridge with one link with two colors (orange and light red), it means both of the MDevice instance 1 and MDevice instance 2 send and receive the EtherCAT frames via this link with MAC of its own.

- ☐ And the MAC addresses of EtherCAT MDevice instances are administered locally with mechanism to avoid MAC address duplication.

➤ From the network view, this scenarios as figure right side, it's equivalent as the previous slide, and this document just analyze the EtherCAT MDevice with only one MDevice instance.

EtherCAT Open Mode (the Segment Address SubDevice will change DA & SA, then forward to next SubDevice)

EtherCAT Segment 1

Ethernet Bridge

Segment Address SubDevice — SubDevice — SubDevice

Ethernet station

Ethernet station

EtherCAT MDevice

EtherCAT MDevice Instance 1 (MAC 1)

EtherCAT MDevice Instance 2 (MAC 2)

EtherCAT Segment 2

Segment Address SubDevice — SubDevice — SubDevice

Ethernet FCS | Datagarm 3 | Datagram 2 | Datagram 1 | ECAT Header | Ethernet header

DA = Segment Address SubDevice MAC address
SA = MAC address of EtherCAT MDevice Instance

Segment Address SubDevice change the DA & SA MAC
DA = SA = MAC address of EtherCAT MDevice Instance
SA = Segment Address SubDevice 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 MDevices.

➤ The new extended EtherCAT MDevices requested by production line, the existing EtherCAT devices and some other Ethernet stations are connected by Ethernet network of 802.1 Bridges as the figures below, and the frame identification requires further study.
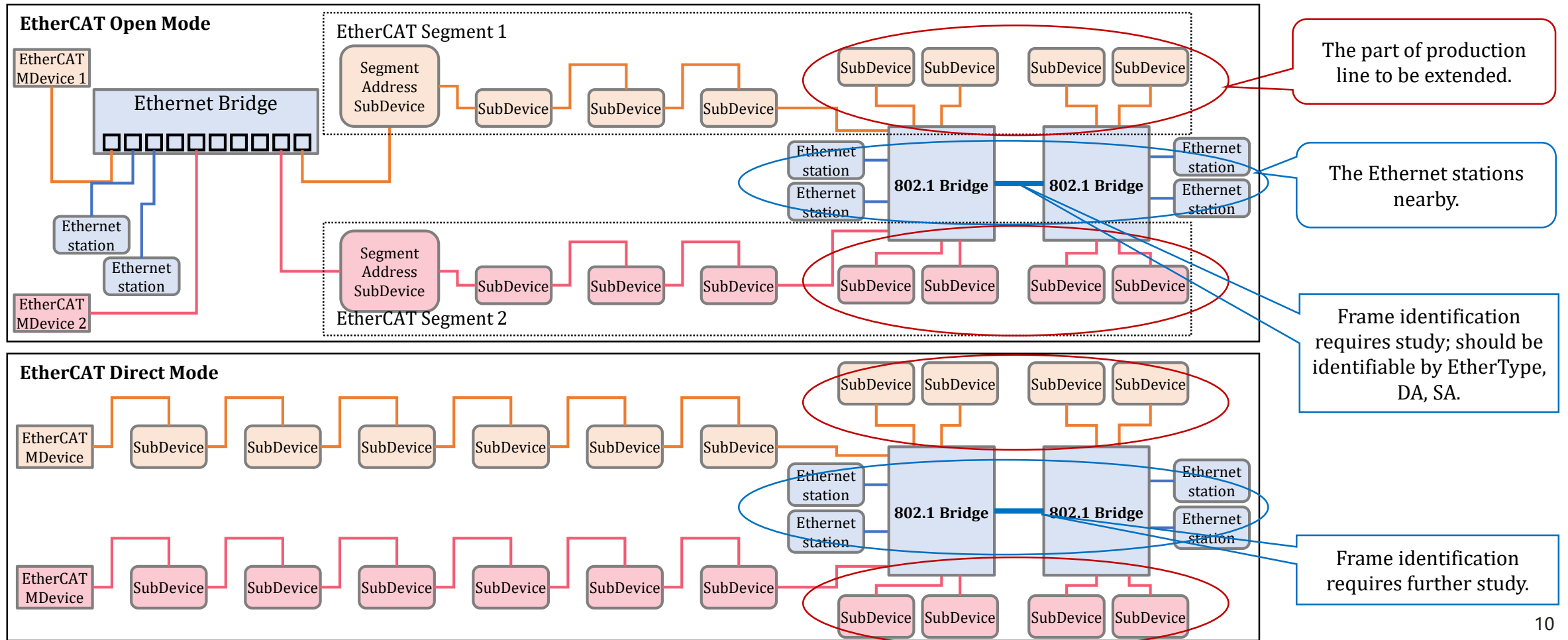
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Compare of the Extension Use Case and the EtherCAT Open Mode

The dash line means there might be other devices between the MDevice and this SubDevice.
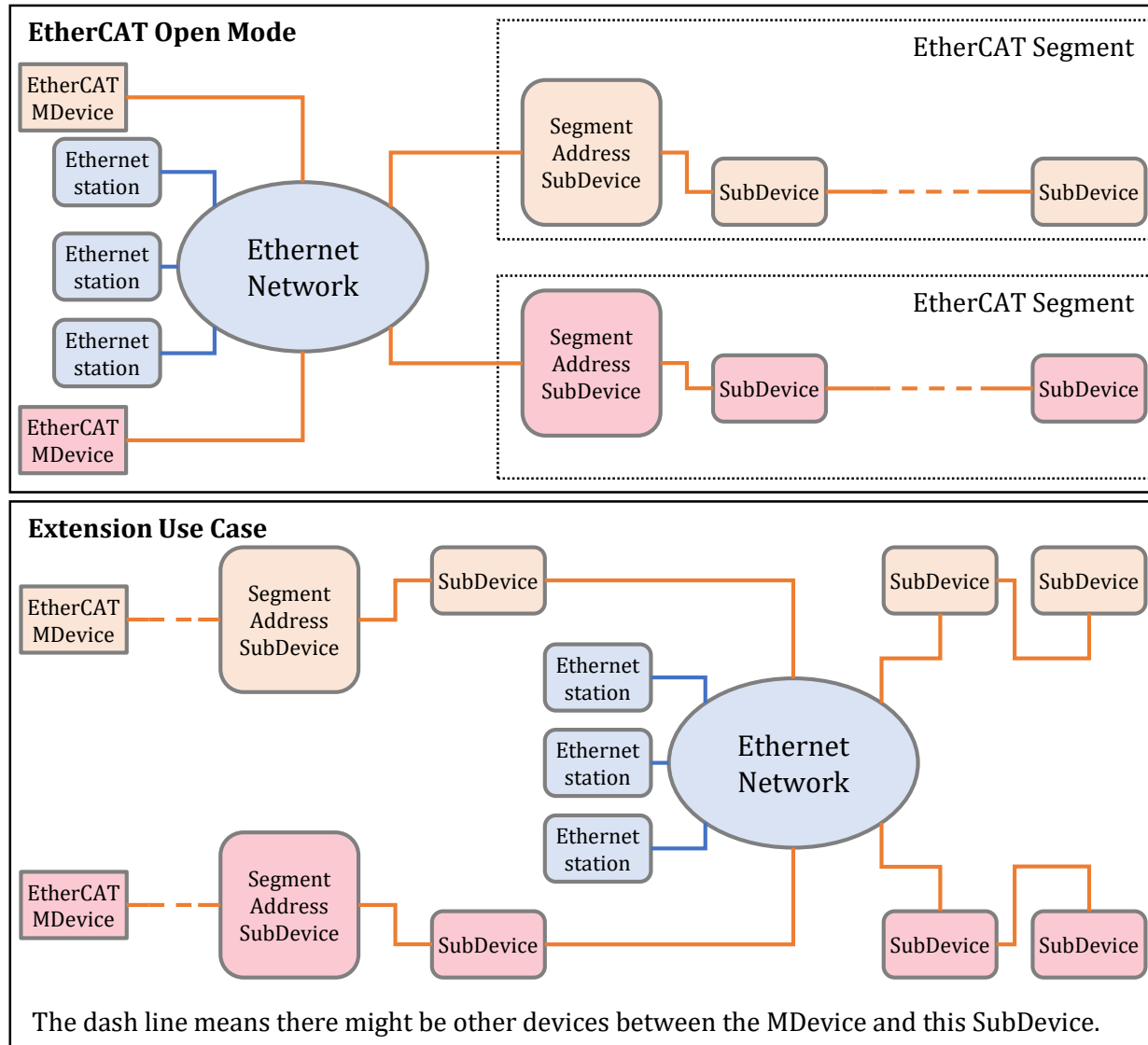
- ➤ The EtherCAT Open Mode:
  - ☐ The Ethernet network (including TSN capability) connects the EtherCAT MDevices and EtherCAT segments.
  - ☐ The Ethernet Bridges just forward the EtherCAT frames according to the MAC address forwarding mode.
- ➤ The Extension Use Case:
  - ☐ The Ethernet network (including TSN capability) is deployed into EtherCAT segments, and connects the EtherCAT MDevices.
  - ☐ 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, and mitigate the complexity of orchestration and implementation.
- ➤ It's valuable to study these aspects of the use case, and might be referential value for EtherCAT open mode.

Potential Benefits

➢ From the technology view:

☐ As the compare of the previous slide, the Ethernet network connected EtherCAT SubDevices has to assure the QoS of EtherCAT frames and the corresponding related technology evolution or optimization might be valuable to EtherCAT Open Mode.

☐ And it's beneficial for 802.1 Bridges to evolution or optimization to be more agile and versatile and to support the industrial field scenarios better.
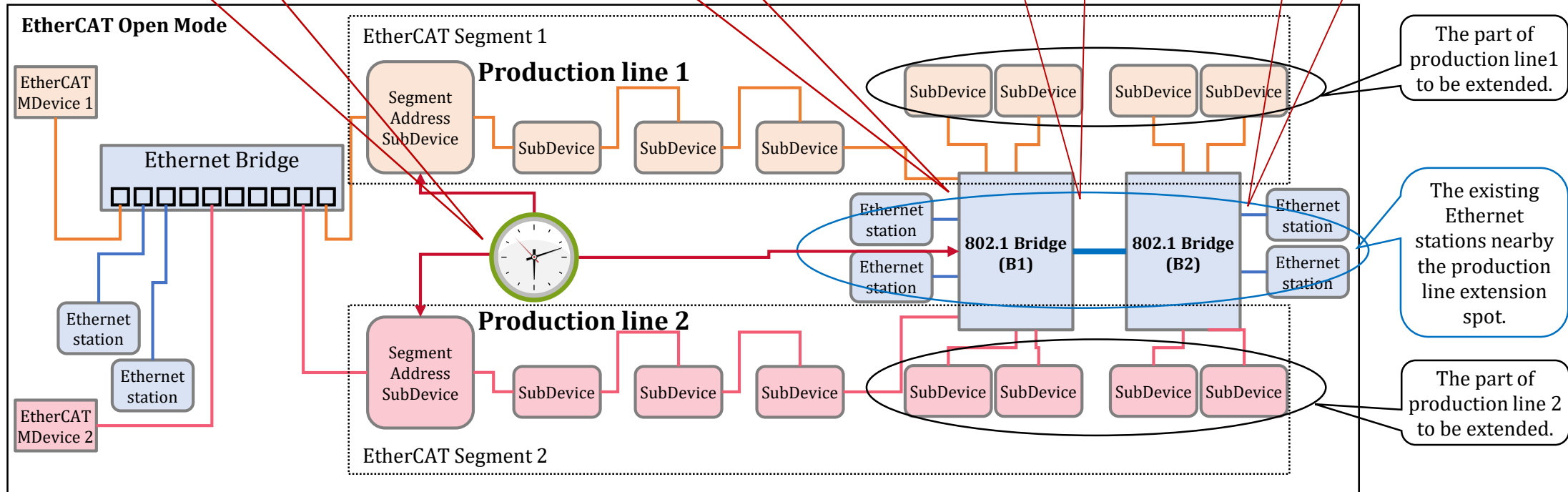
➢ From the factory view:

☐ The Bridges of Ethernet network connect the existing EtherCAT devices, new extended EtherCAT SubDevices and some other existing Ethernet stations, if the whole solution is feasible, it could save cost for the production line.

☐ Also, it could take full advantage of the existing space of the current workshop to layout the devices reasonably with a higher integrated level.
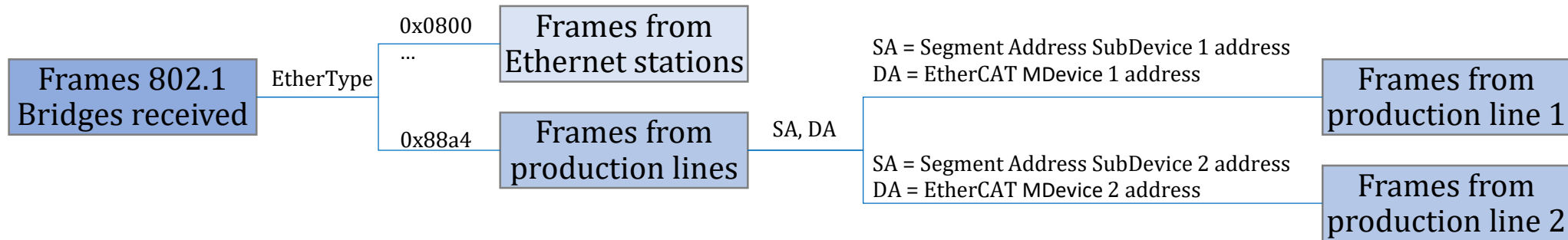
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# Initial Solution Points for the Use Case of EtherCAT Production Line Extension

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 this document)

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

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**

EtherCAT Open Mode

EtherCAT Segment 1

Production line 1

EtherCAT MDevice 1

Ethernet Bridge

Segment Address SubDevice

SubDevice   SubDevice   SubDevice

SubDevice   SubDevice   SubDevice   SubDevice

Ethernet station

Ethernet station

802.1 Bridge (B1)   **802.1 Bridge (B2)**

Ethernet station

Ethernet station

EtherCAT MDevice 2

Production line 2

Segment Address SubDevice

SubDevice   SubDevice   SubDevice

SubDevice   SubDevice   SubDevice   SubDevice

EtherCAT Segment 2

The part of production line1 to be extended.

The existing Ethernet stations nearby the production line extension spot.

The part of production line 2 to be extended.

# Identify Different Kinds Frames in EtherCAT Open Mode

- ➤ All the SubDevices of the segment will not change the destination MAC address of the EtherCAT frame, and the EtherCAT frames will be forwarded to next specific SubDevice other than according the destination MAC address.
- ➤ That is a new request for the 802.1 Bridges to forward the EtherCAT frames to specific port.


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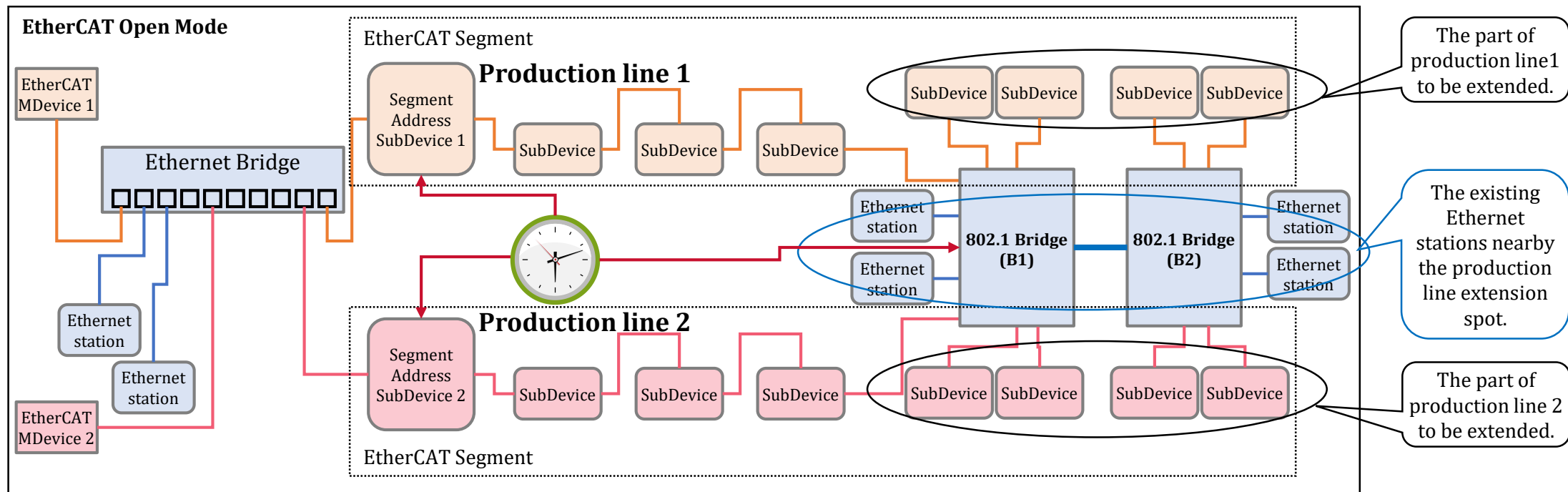
Identify Different Kinds Frames in EtherCAT Direct Mode
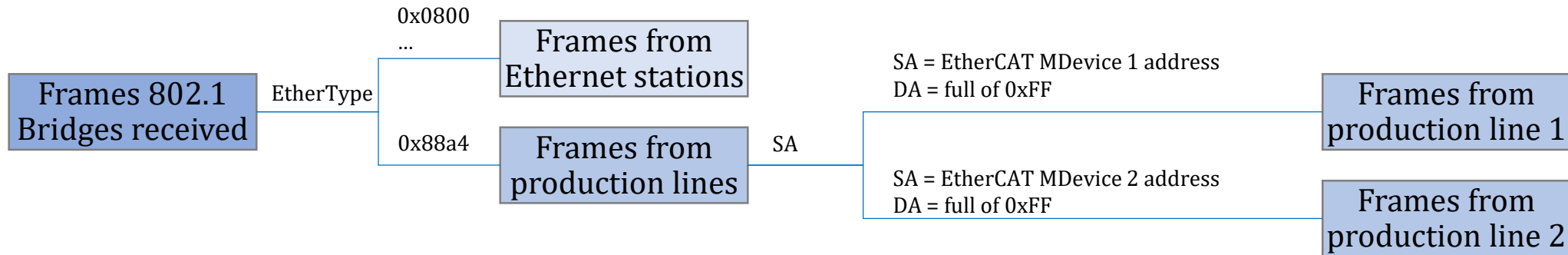
- ➢ Even the destination address is the broadcast address, the 802.1 Bridges have to forward the EtherCAT frames according to EtherCAT topological forwarding mode other than the Ethernet address forwarding mode.
- ➢ That is a new request for the 802.1 Bridges to forward the EtherCAT frames to specific egress port other than broadcasting to all ports.
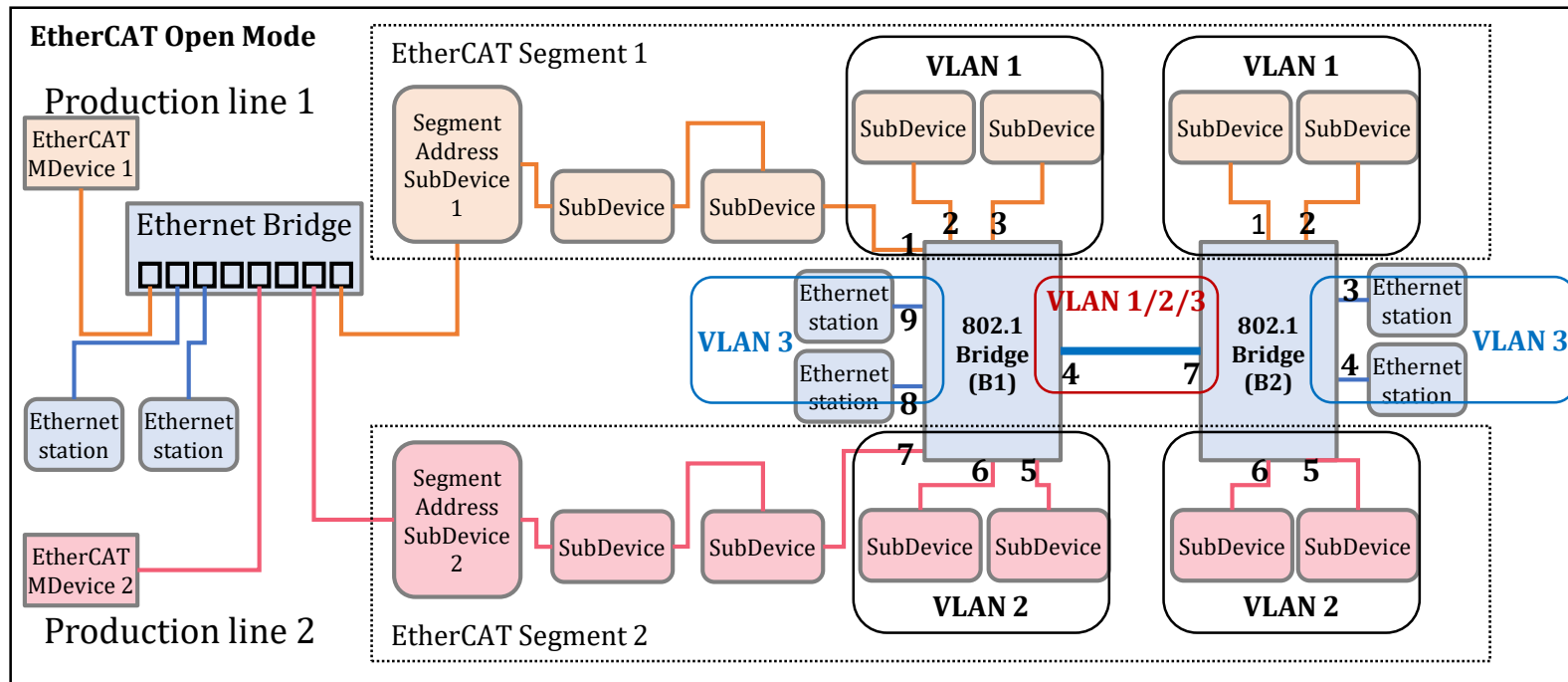

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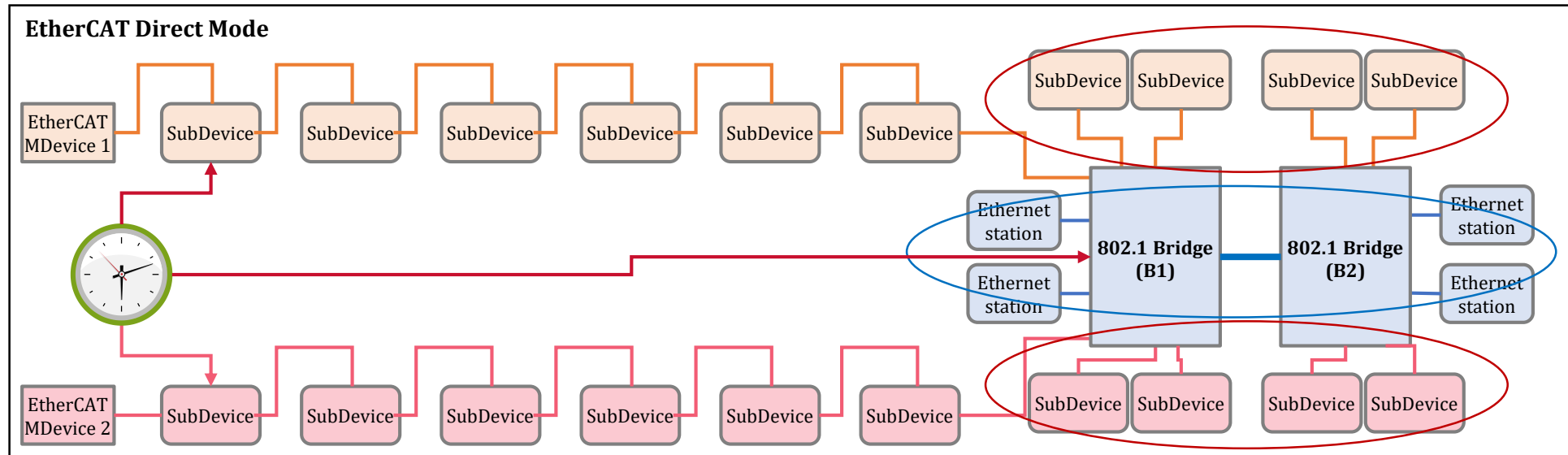
Forward the EtherCAT Frame to Specific Port
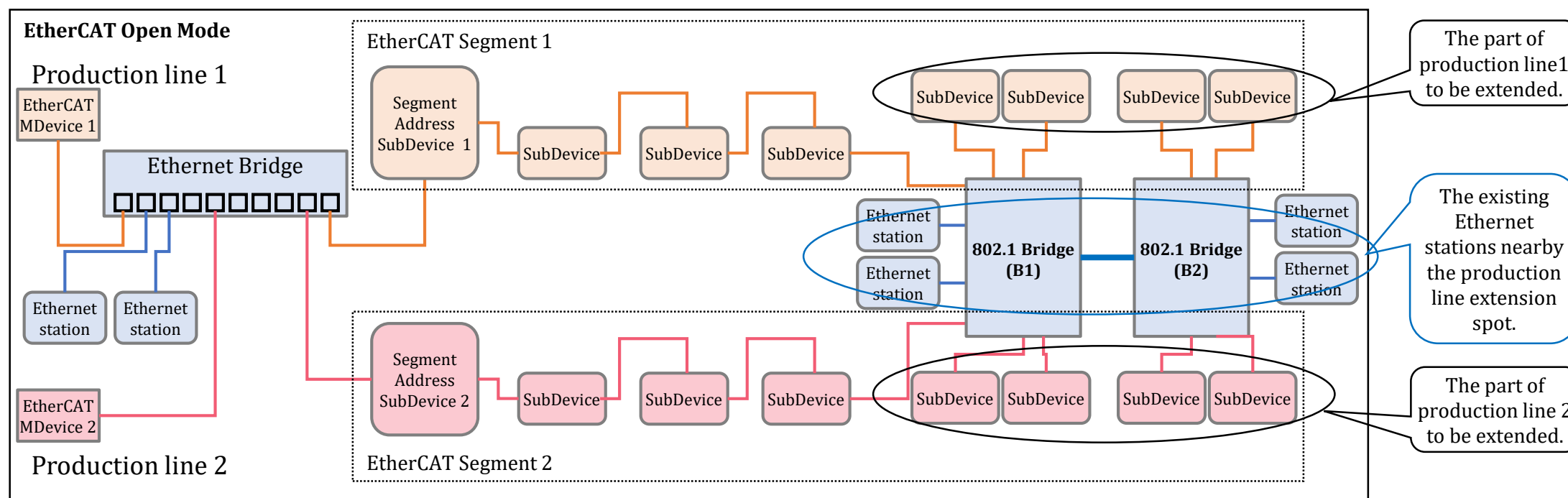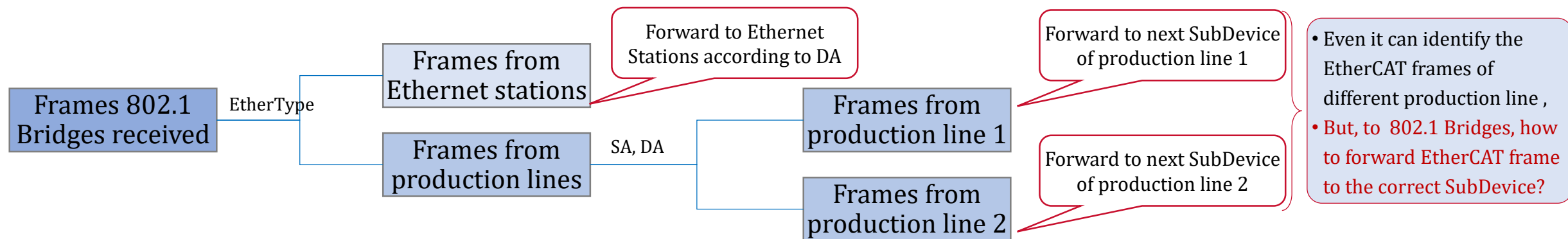
Identify the Next SubDevice of the Current Production Line in EtherCAT Open Mode

- 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 according to the table right side.
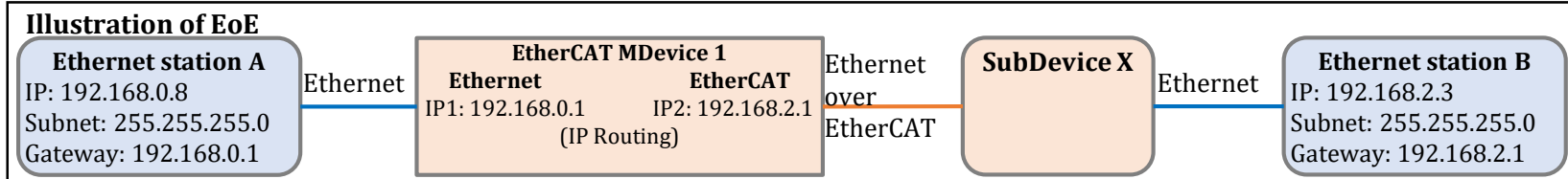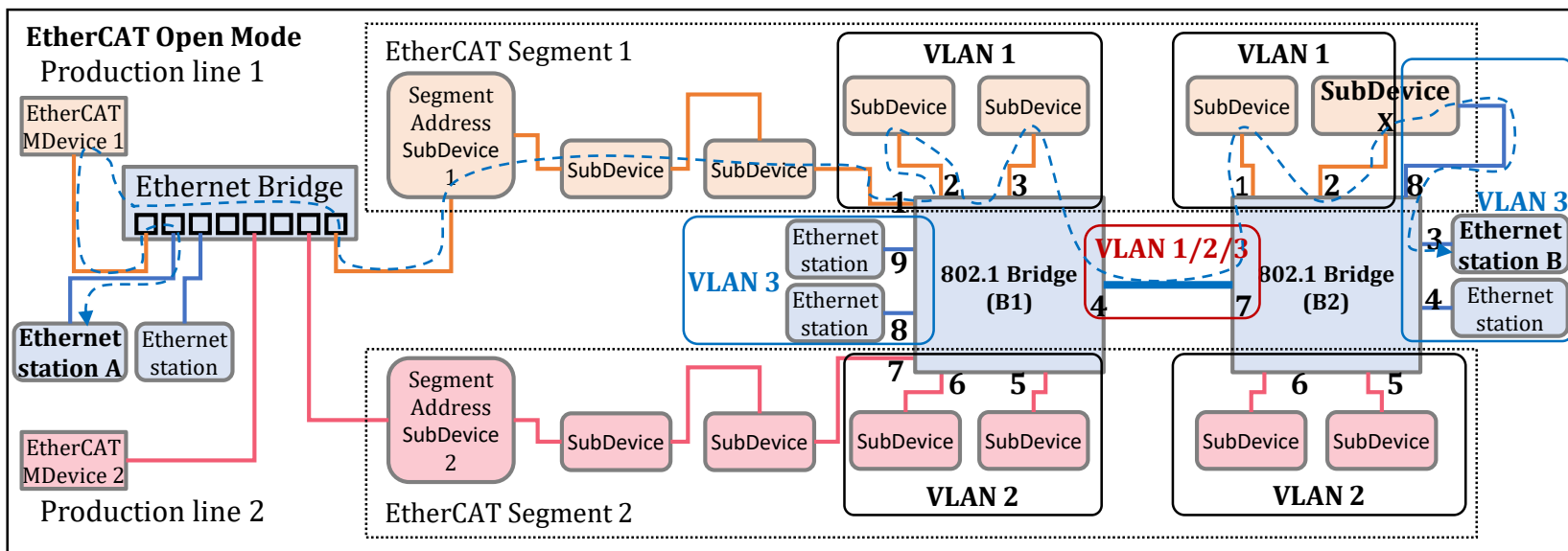
Bridge	Frames Received from	Frames Tagged VLAN	Frames Forwarded to Port
B1	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 3
	Port 3	VLAN1	Port 4
	Port 4	VLAN1	Port 1
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 4
	Port 4	VLAN2	Port 7
	Port 4	VLAN3	According to DA
	Port 8	VLAN3	
	Port 9	VLAN3	
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.
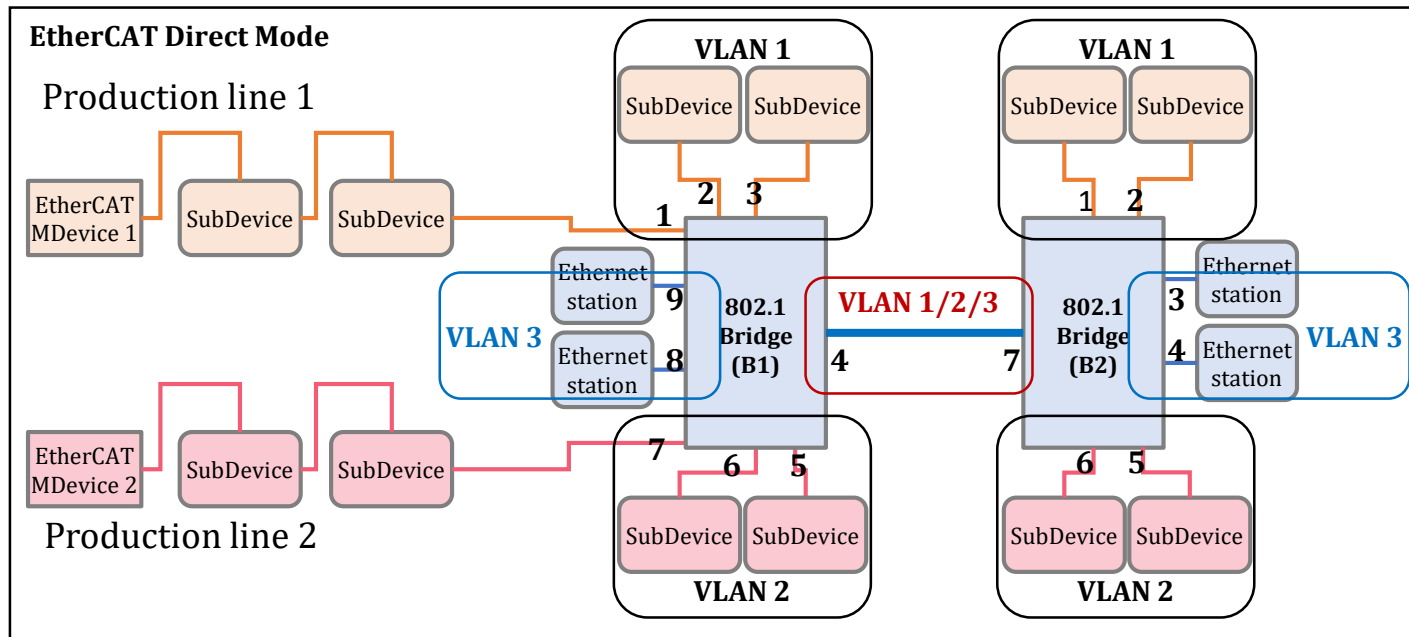

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The Affecting of Ethernet over EtherCAT

- **Ethernet over EtherCAT** (EoE) transparently tunnels standard Ethernet communication via EtherCAT. Tunneling allows the EtherCAT devices to support Ethernet communication without affecting the real-time communication between the EtherCAT MDevice and EtherCAT SubDevices.

- EoE is typically used for devices with TCP/IP stack, such as a web server, or for infrastructure devices such as switch ports, to which peripheral devices can be connected.

- The EtherCAT MDevice and specific EtherCAT SubDevices operate like a "virtual" layer 2 Ethernet switch whose ports are distributed in the field. The EtherCAT based field network is the backbone of this switch.

- As the figure below, the Ethernet station A communicates with Ethernet station B via EoE, the dash blue line illustrates the communication link routine. The EtherCAT SubDevice X in segment 1 should has the functionality to connect to the port 8 of Bridge 2 via its Ethernet port, and the port 8 will be set into VLAN 3 as access type.

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 8	**VLAN3**	**According to DA**
	Port 3	VLAN3	
	Port 4	VLAN3	

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Identify the next SubDevice 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 according to the table right side.

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.

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Summary of Feasibility Issues of Basic Forwarding Functionality

➤ As the forwarding rule analyzed in the previous slides, the basic functionality of Forwarding the EtherCAT frames by 802.1 Bridges is feasible.

➤ Also, no matter the Direct Mode or Open Mode, the EtherCAT frames could be forwarded to the correct port and correct SubDevices according a same forwarding rule.

➤ Besides the basic forwarding functionality, it's necessary to study the impact of QoS, such as low latency, low jitter, high reliability which are as important as the basic forwarding functionality.

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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 MDevice latency and corresponding SubDevices / cable latency.
   - ✓ This part latency & jitter is the same as the EtherCAT independent network.
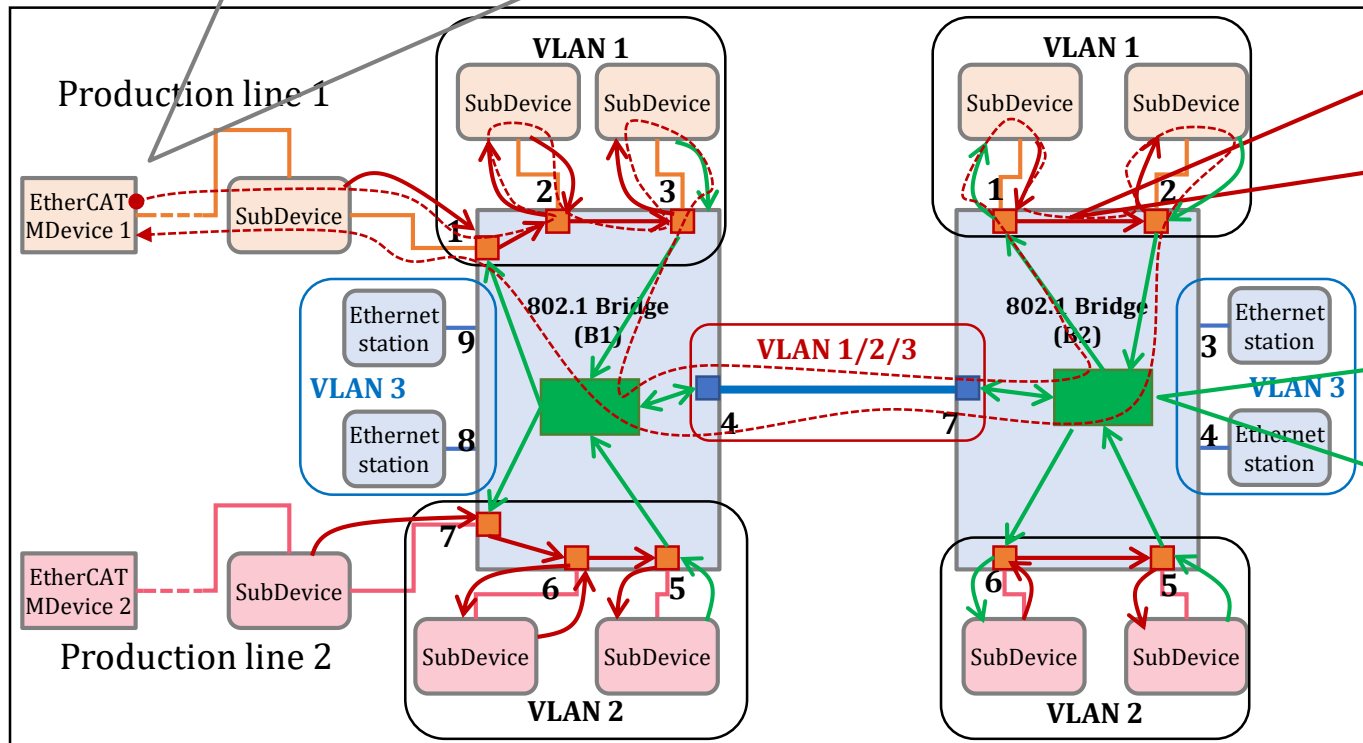
2. Forwarding latency to next EtherCAT SubDevices (**CTF latency**)
   - ✓ The latency is used to forward the EtherCAT frames between the Bridge ports which are connecting to EtherCAT SubDevices directly.
   - ✓ These ports rate are the same, also equals to rate of EtherCAT SubDevices.
   - ✓ So, the **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 SubDevice) 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 MDevice 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 SubDevices 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.

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To Identify the EtherCAT Streams

➢ According to Talker & Listener concept of 802.1Q, Talker is the source or producer of a stream, and Listener is the destination, receiver, or consumer of a stream. Stream is a unidirectional flow of data (e.g., audio and/or video) from a Talker to one or more Listeners.

❑ In this scenario, the EtherCAT MDevice should be the Talker originating the EtherCAT frames through Bridges to the last SubDevice as the listener, then the last SubDevice loops back the EtherCAT frames to the EtherCAT MDevice through the Bridges.

❑ Because of the EtherCAT topological forwarding mode, the MAC addresses of EtherCAT frames are the same while transferring from Talker to Listener or Listener to Talker.

❑ It has to include the stream direction to identify the streams, even the source MAC address and destination MAC address are the same, but the direction is different, they should be different stream.

➢ And frames of different stream might be processed according to different rules to assure QoS.

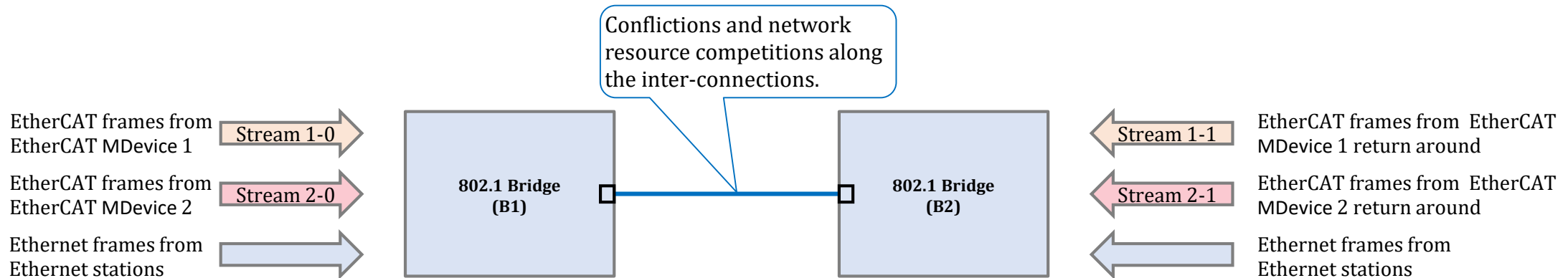# Cut-Through Forwarding Latency to Forward EtherCAT Frames

➢ 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 MDevices.
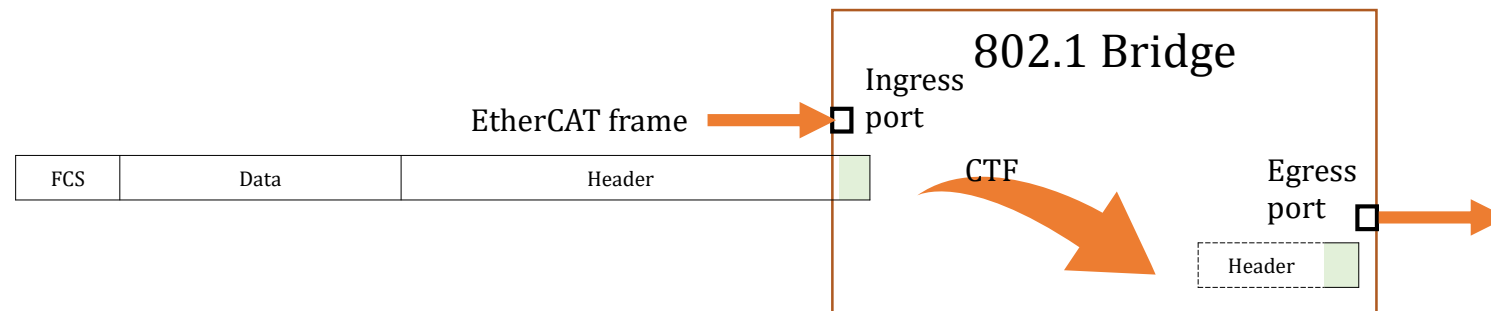
➢ According to the forwarding rule, the egress port could be identified by the ingress port and VLAN ID and there is no confliction, then just cut-through forward the EtherCAT frame to the egress port.

➢ So, the latency and jitter is anticipated and bounded, and the CTF latency is not the key point of this document, this document will analyze the mix-transfer latency and jitter issues.

# Feasibility Issue 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 confliction and network resource competition along the inter-connection between 802.1 Bridges.

➢ The EtherCAT frames from EtherCAT MDevice 1 and MDevice 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.

Conflictions and network resource competitions along the inter-connections.

EtherCAT frames from EtherCAT MDevice 1 — **Stream 1-0**

EtherCAT frames from EtherCAT MDevice 2 — **Stream 2-0**

Ethernet frames from Ethernet stations

802.1 Bridge (B1)

802.1 Bridge (B2)

Stream 1-1 — EtherCAT frames from EtherCAT MDevice 1 return around

Stream 2-1 — EtherCAT frames from EtherCAT MDevice 2 return around

Ethernet frames from Ethernet stations

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

Feasibility Issue of High Reliability of the Inter-Connection between the 802.1 Bridges to EtherCAT Frames

➢ According to EtherCAT application cycle requirements, the redundancy recovery time is micro-second level as specified in IEC 61784-2, which is implemented with co-operation of EtherCAT devices via ring topology generally.

➢ Even 802.1CB could implement the high reliability for the frames, but the frame is replicated, transmitted via two different routine, and double bandwidth is used out.

➢ In order to make full use of network bandwidth, it might be the obvious gap for Ethernet network of 802.1 Bridges to support the high reliability of micro-second level recovery time based on the physical ring topology as figure below.
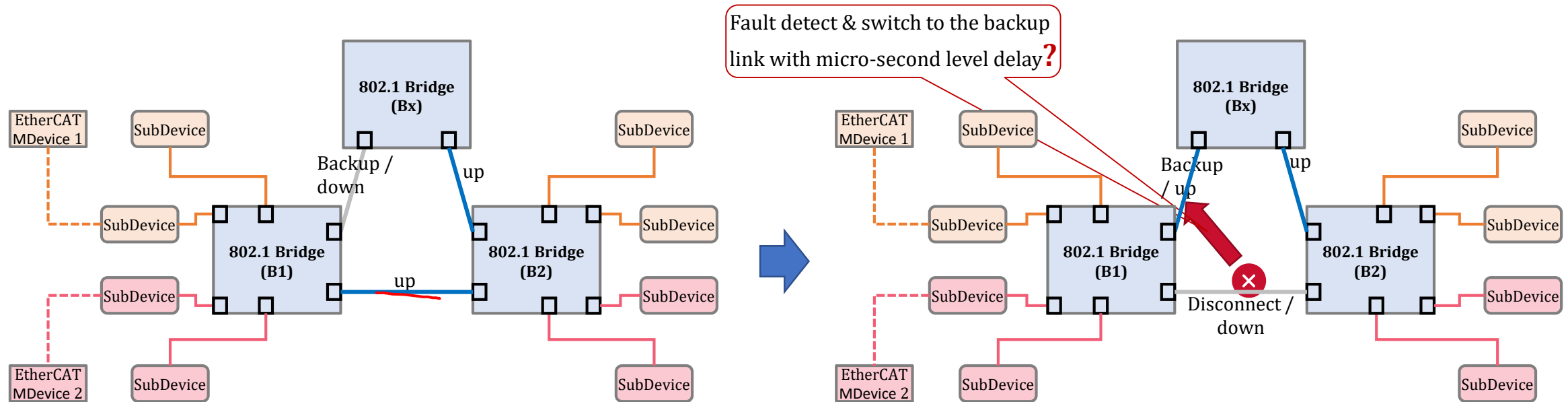
- In actual network environment, the Ethernet network might be deploy as ring network for high reliability.
- This is the simple example of Ethernet network to illustrate the high reliability of network topology.
- The dash line means there might be many SubDevices or other devices between the MDevice and this SubDevice.

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Summary of Feasibility Issues of QoS Assurance for EtherCAT Frames

➢ As analysis and compared with independent EtherCAT network and corresponding specification, this document focuses on the following feasibility issues of QoS assurance.

1. Mix-transfer latency / jitter
   - ✓ The EtherCAT frames from different EtherCAT MDevice 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.

2. High reliability
   - ✓ The EtherCAT frames request high reliability of redundancy recovery time as micro-second level as specified in IEC 61784-2.
   - ✓ The Ethernet network of 802.1 Bridges connecting the EtherCAT devices should be the ring topology physically, and provide the backup link to be up to forward the EtherCAT frames while one link is disconnected.
   - ✓ Compared to independent EtherCAT network, the high reliability recovery time of the Ethernet network of 802.1 Bridges might be micro-second level, and avoid to overuse the network bandwidth.
   - ✓ It's necessary to study and analyze the feasibility to assure the recovery time of the Ethernet network of 802.1 Bridges to micro-second level.

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Introduction of Impact and Optimization of Evolving technologies to Assure QoS of EtherCAT Frames

➢ As the previous sections analyzed, this document focuses the feasibility issues to assure the QoS of EtherCAT frames, including issues of low latency / jitter and high reliability to mix-transfer EtherCAT frames via Ethernet network of 802.1 Bridges.

➢ In this section, based on the mix-transfer scenario, this section analyzes the impact of technologies to assure the QoS of EtherCAT frames, and possible optimization directions to mitigate the complexity and avoid the overuse of bandwidth.

❑Low latency & jitter

✓ At first, analyze solution of 802.1Qbv to assure the low latency / jitter.

✓ Second, try to outline the feasibility to mitigate the complication.

❑High reliability

✓ According to the requirement of EtherCAT redundancy recovery time, analyze the existing high reliable capability and the gap.

✓ Initially analyze the possible optimization directions to achieve micro-second level to detect and recover to the backup link, and avoid to overuse network bandwidth.

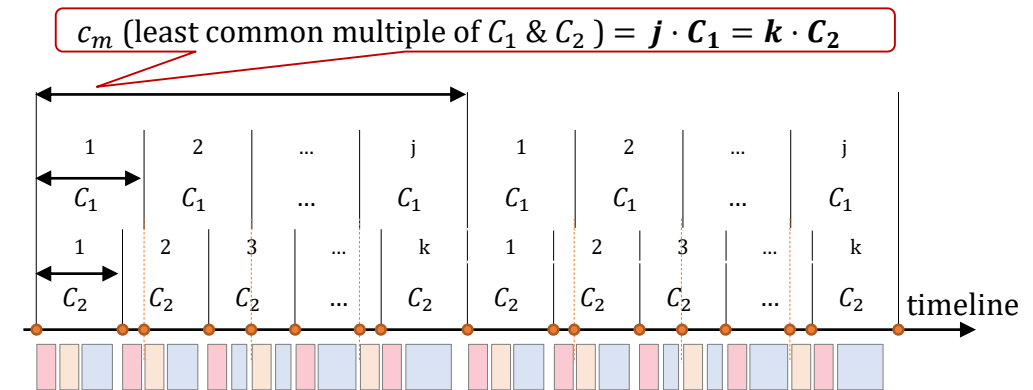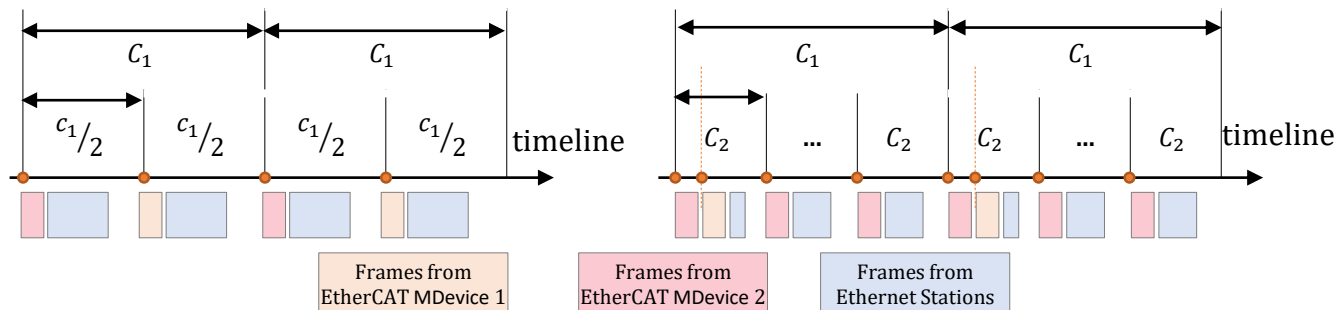# Impact of Strictly Orchestration based on 802.1Qbv to Achieve Bounded Latency

- ➢ Based on the time synchronization to two production lines and the 802.1 bridges, the frames from EtherCAT MDevice 1 / EtherCAT MDevice 2 and the Ethernet stations will be mix-transfered 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 MDevice 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 indicates the Bridge have to receive the frame and send to next Bridge.
  - ☐ Along the end to end routine, each Bridge should receive the EtherCAT frames and send to next Bridge as per the timeline strictly.
  - ☐ According to the figures below, generally, the periods between each adjacent time points are different, it could achieve low latency as low as possible, each EtherCAT frame are received on time and sent out on time.
  - ☐ Based on 802.1Qbv, it's complicated to implement such orchestration.

- • C_1 = Cycle of EtherCAT MDevice 1, C_2 = Cycle of EtherCAT MDevice 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)

c_m (least common multiple of C_1 & C_2) = $j \cdot C_1 = k \cdot C_2$

Frames from EtherCAT MDevice 1

Frames from EtherCAT MDevice 2

Frames from Ethernet Stations

Analysis of Complication of Strict Orchestration and Possible Optimization to Mitigate the Complexity

➤ **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.

Specific timepoint to send specific frame.

timeline with unfixed period
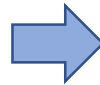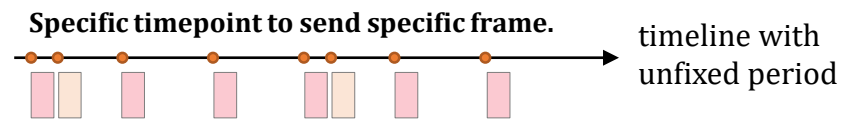
➤ **The mitigation is making the Bridges to send the frames according to a same rhythm cyclically other than a strict timeline.**

- ☐ 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 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, even the frame has to wait until the complete cycle in each Bridge, the end to end transmission latency of frame might afford the specific EtherCAT service requirement, and the complexity of orchestration could be mitigated.

Fixed period to send frames cyclically.

timeline with fixed period
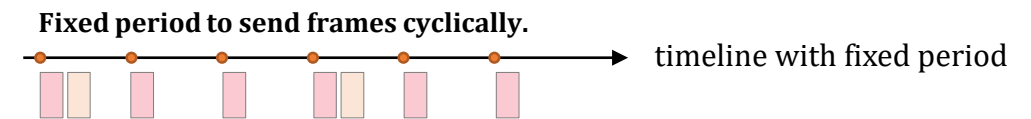
Analysis of the Existing High Reliable Capabilities

➢ 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.

Possible Optimization Directions to Achieve the Micro-second Level Recovery Time to Forward EtherCAT Frames via 802.1 Bridges

➢ As specified in IEC 61784-2, the redundancy recovery time of EtherCAT is micro-second level.

➢ 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.

➢ Currently, based on Ethernet network of 802.1 Bridges, with the aim to achieve micro-second level recovery time and avoid double network bandwidth usage, via initial analysis, the possible optimization directions are provided as following:

☐ 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 additional 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.

➢ For further analysis, it's still need depth studies of EtherCAT requirements, technologies, and respective evolutions.

Summary of Impact and Optimization of Evolving technologies to Assure QoS of EtherCAT Frames

➢ This document focuses the key points 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 outline a feasibility of possible optimization to mitigate the complexity 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 transmission rate is high enough, the end to end latency could satisfy the EtherCAT requirements, then the mitigation might be feasible technically.

❑ High reliability

✓ Analyzed the possible optimization directions to achieve the high reliability of Ethernet network for EtherCAT requirements.

- To make use of ring topology and suggest to enhance network low layer capabilities to detect link down and activate the backup link.
- To avoid influence to end devices not only compatibility but also bandwidth usage by detection & notification frames.

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Possible Recommendation to Initiate a Work Item

➢ This document analyzes the use case of 802.1 Bridges to forward EtherCAT frames and Ethernet frames simultaneously, summarizes the feasibility issues, and provides corresponding initial optimization directions of technologies.

➢ In order to further analyze the requirements, technologies, and respective evolutions, and future directions, this document recommends Nendica consider to initiate a Work Item to document the followings in full details:

☐ The use case of forwarding EtherCAT frames and Ethernet frame simultaneously via 802.1 Bridges, and corresponding environment factors to be considered of EtherCAT communication.

☐ To analyze the requirement evolution from EtherCAT application and production line level.

☐ The topology of Ethernet network of 802.1 Bridges connecting EtherCAT devices and Ethernet stations, and typical topology of EtherCAT used in factory level might be considered.

☐ The multi-forwarding modes of 802.1 Bridges to forward EtherCAT frames and Ethernet frames.

☐ The related technology evolution and gap analysis, and the feasibility issues to assure the QoS for EtherCAT frames .

☐ Other aspects to be considered to assure the compatibility and completeness for EtherCAT application and Ethernet network.

☐ Future directions towards enhancements of 802.1 Bridges to co-operate with EtherCAT to assure QoS of EtherCAT frames.

☐ Based on detail aspects of requirements, challenges and evolutions, to consider the possible standardization recommendations.

Thank you.