Initial solution for Nendica Study Item Forwarding of Fieldbus CPF 12 on 802.1 Bridges

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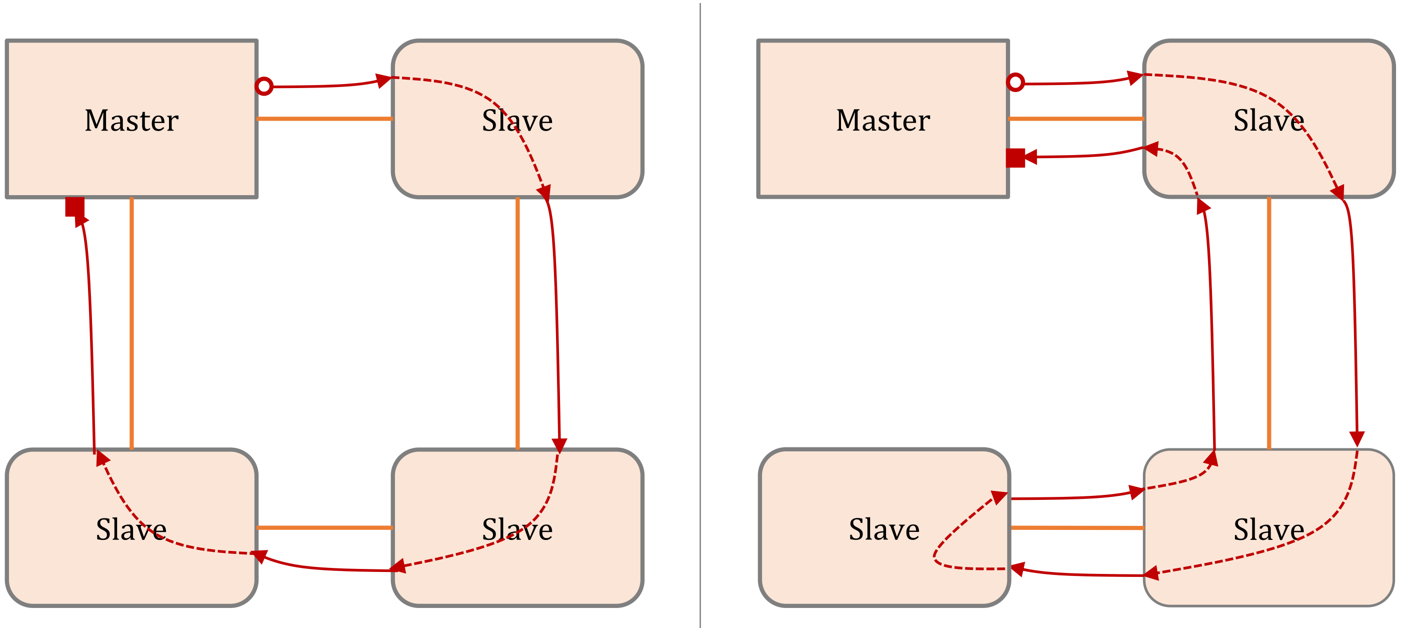
Objective

- 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 get a initial solution to assure the low latency / jitter, but the high reliability is still under study.
- Any comments are welcomed.

Contents

EtherCAT Logical-Ring Forwarding

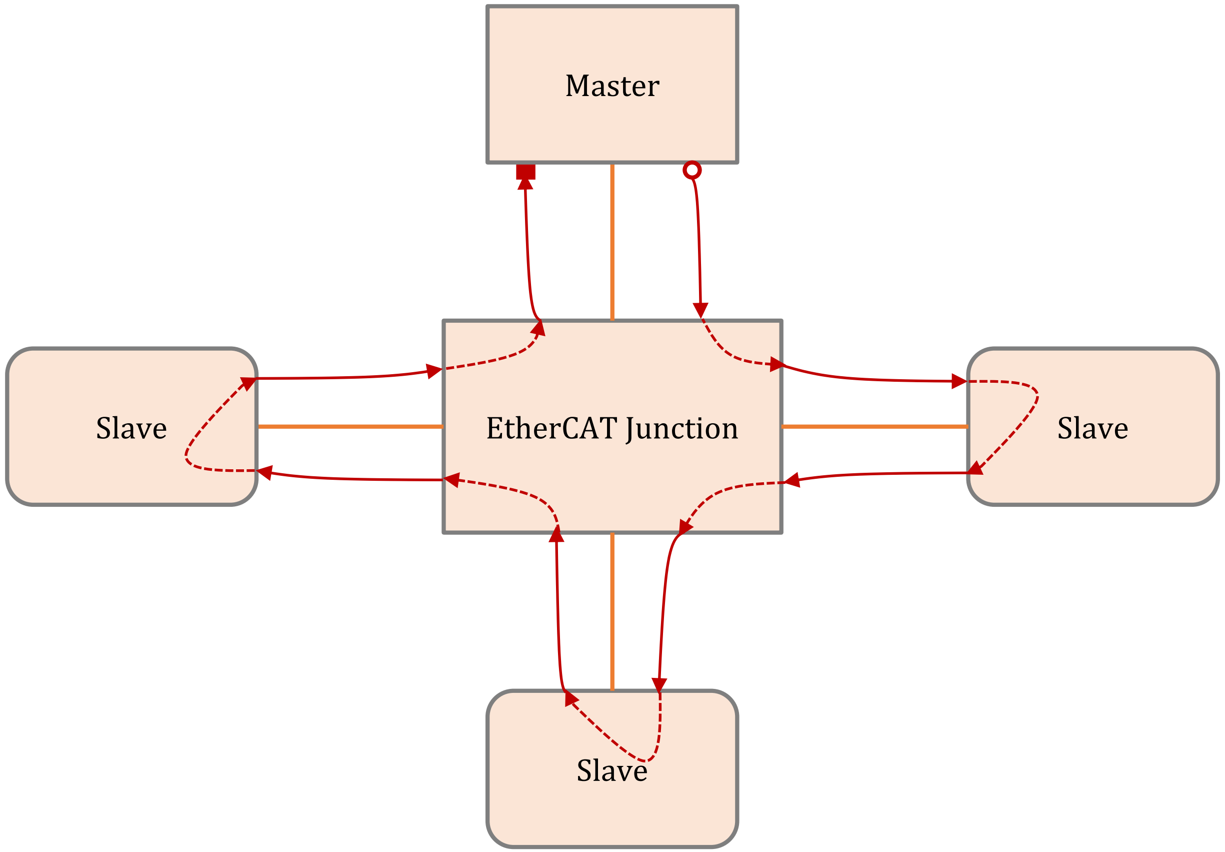
The Type 12 fieldbus in IEC 61158-3/4/5/6-12 is also known as EtherCAT. An EtherCAT network can be understood as a railway network where slave devices are treated as stations, data are treated as passengers, and EtherCAT frames are treated as trains. While the EtherCAT frames move through the slave devices,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



(a) (b)

- 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

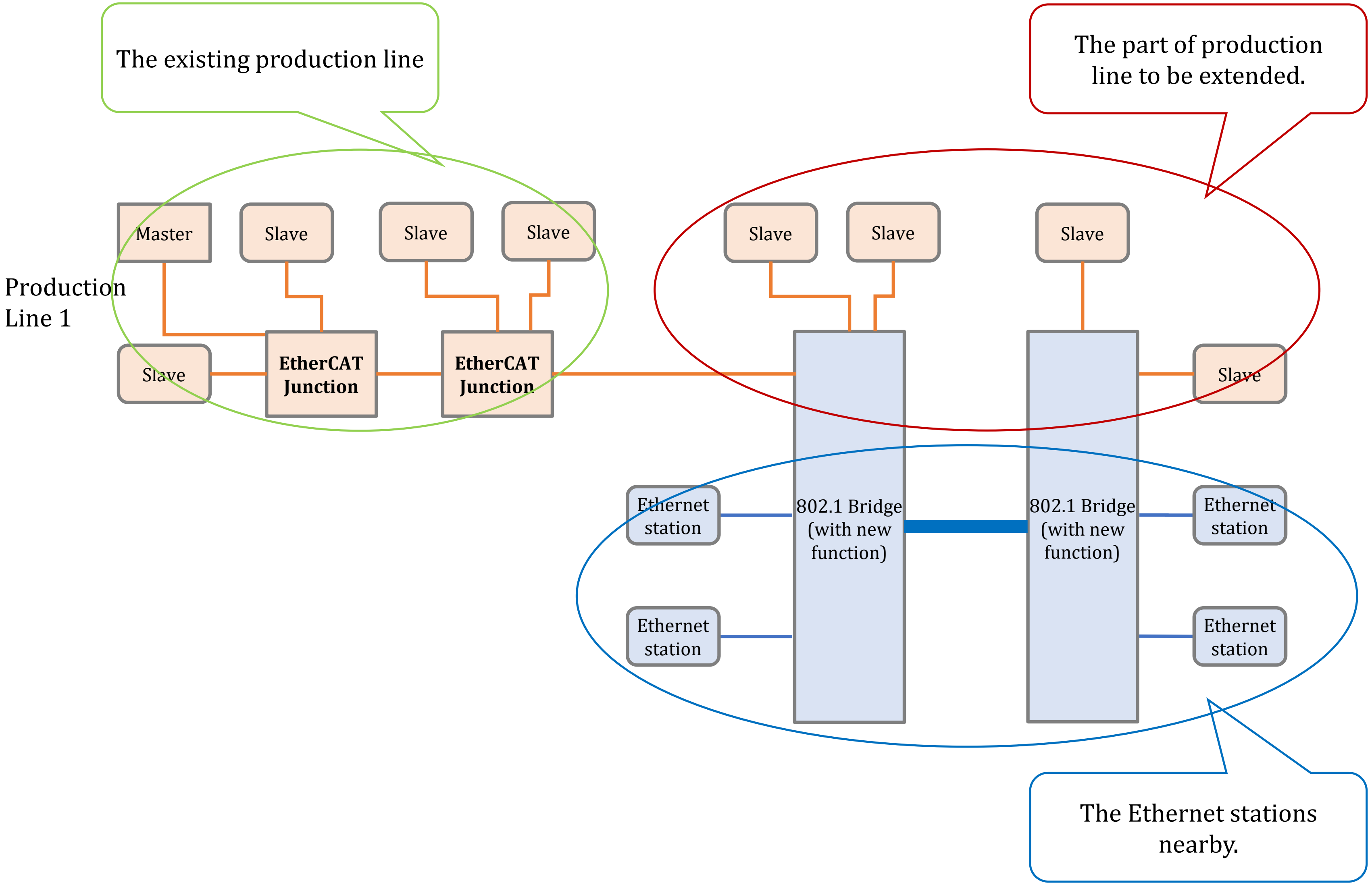
EtherCAT Junction



- 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.

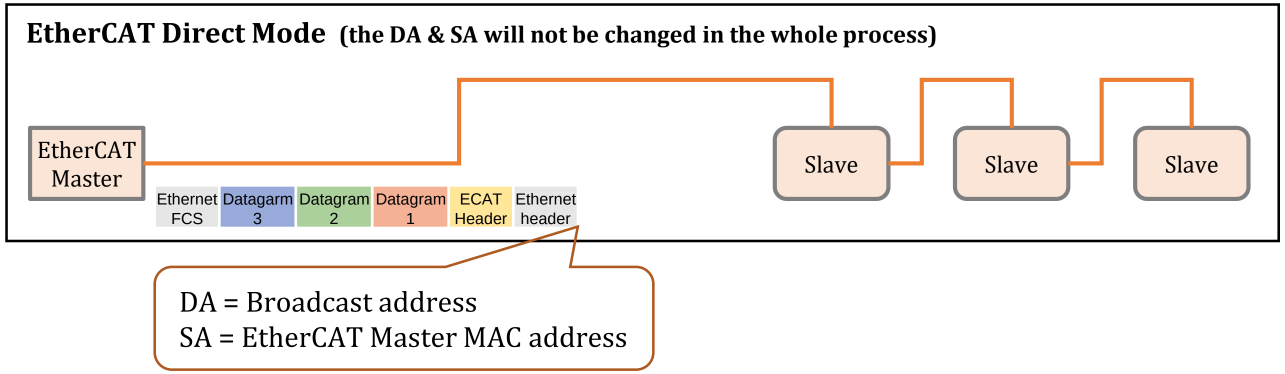
Use Case for 802.1 Bridge to Forward EtherCAT & Ethernet Frames Simultaneously



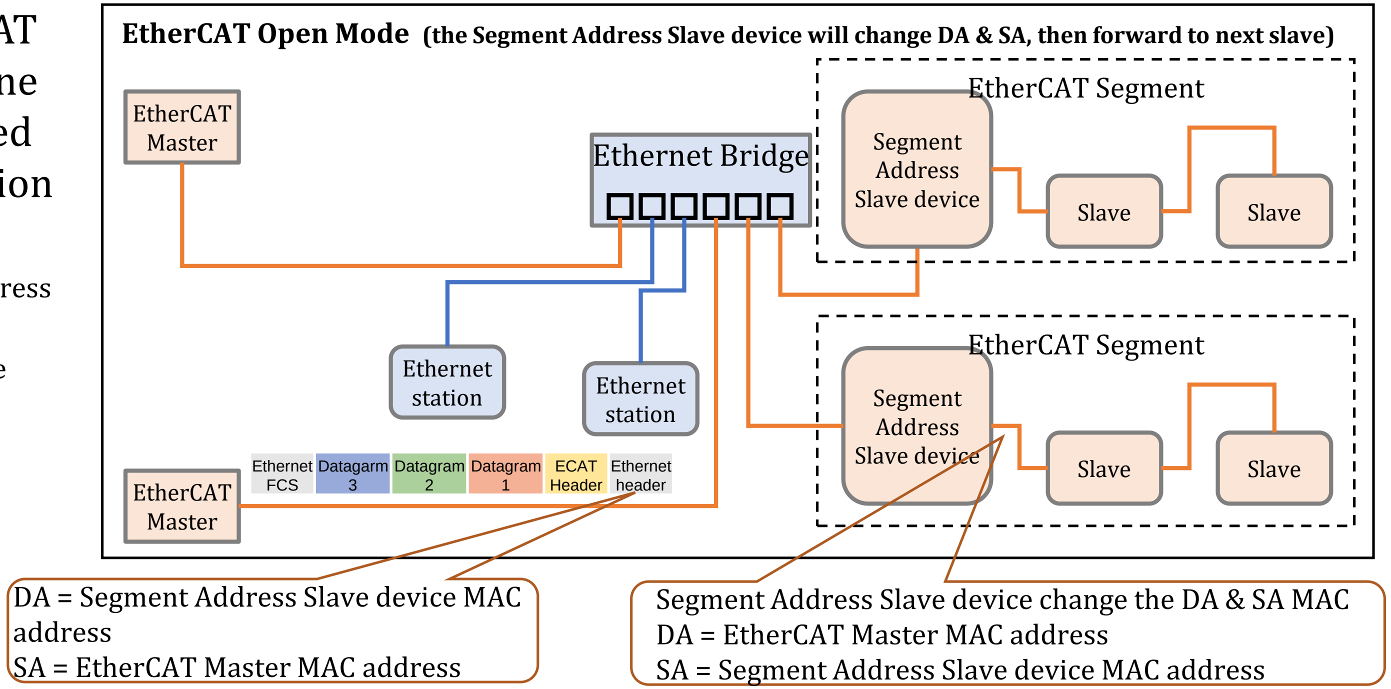
- Production line network requirement: cycle time 4ms, jitter < 10%
- Considering the space and cost, the factory seeks 802.1 Bridges to support to forward EtherCAT frames and Ethernet frames from the same link.

EtherCAT Open Mode & Direct Mode

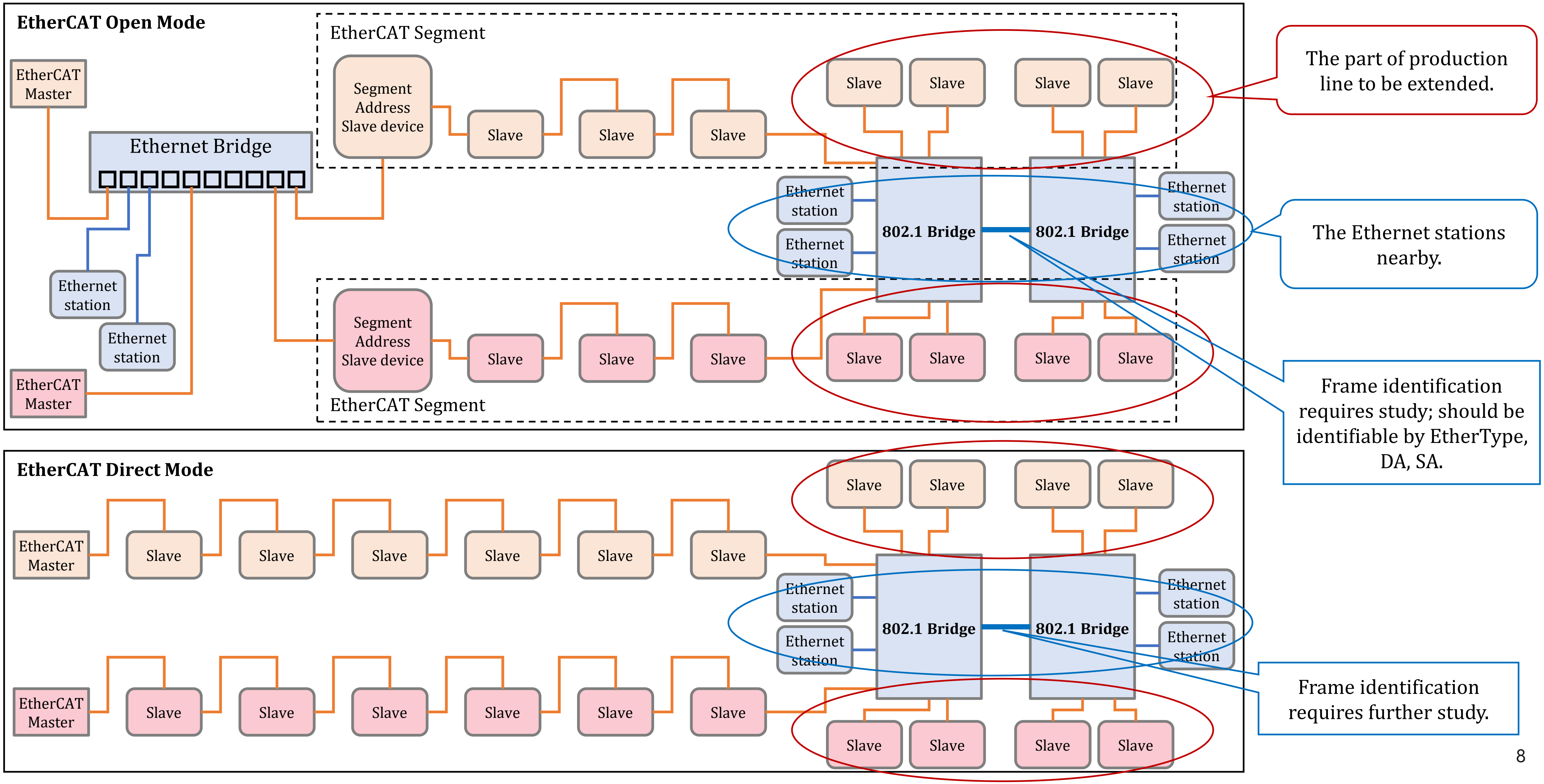
- The previous slides indicated EtherCAT direct mode. In the direct mode, the EtherCAT master and the slave devices are connected one by one, and the frames are forwarded in a logical ring, and the MAC address fields of the EtherCAT frames are not checked (the SA is the EtherCAT master address, and the DA is the broadcast address).



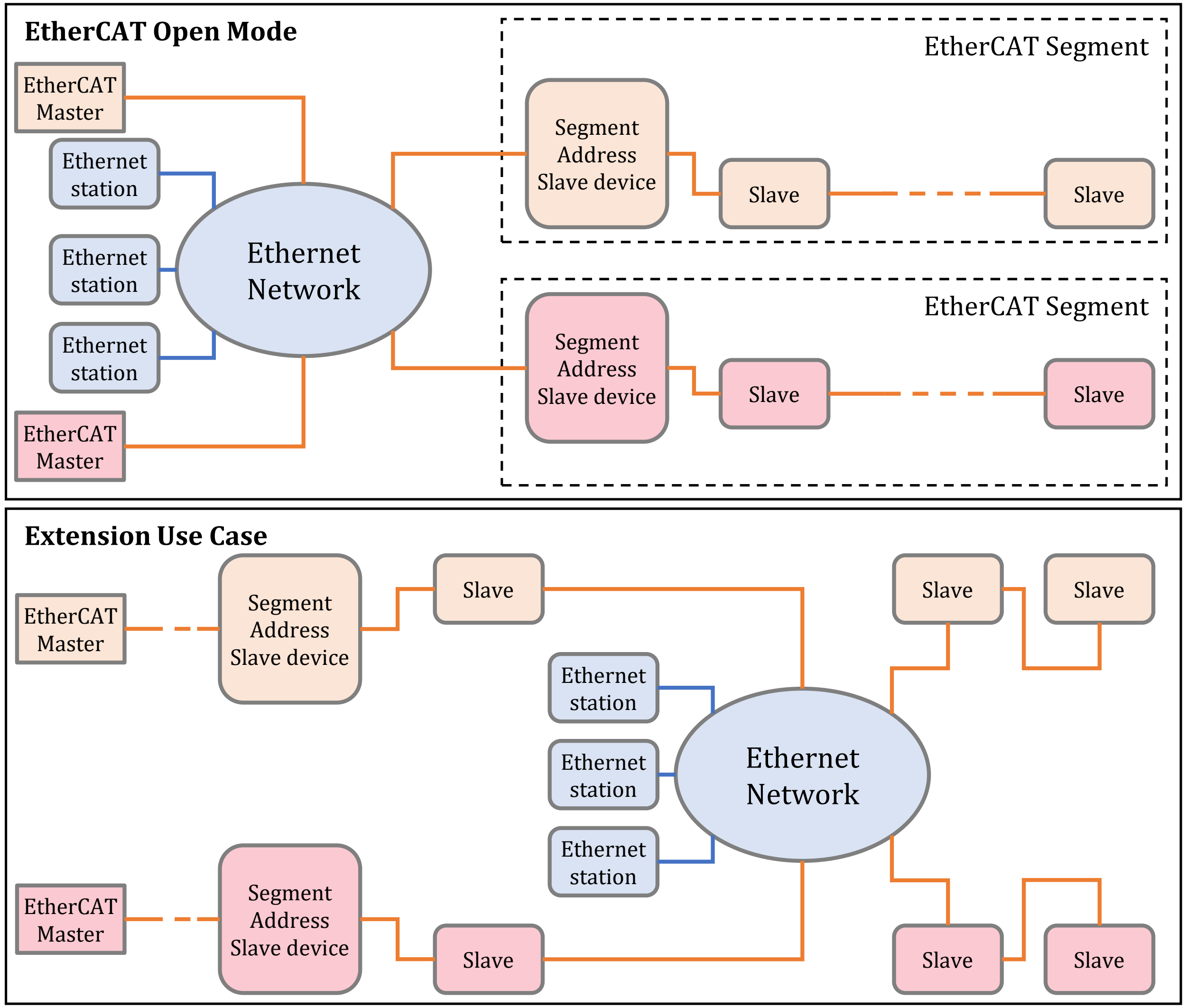
- Using the EtherCAT open mode, one or several EtherCAT segments can be connected via Ethernet bridge with one or more Master devices. Each segment can be addressed using a "Segment Address Slave" device (the head station of the segment).
  - The EtherCAT master sends the EtherCAT frame, and the DA is 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.



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



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.
  - The Ethernet Bridges not only supports to forward the EtherCAT frames according to the MAC addressing mode, but also support to forward EtherCAT frames according to EtherCAT slave inter-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

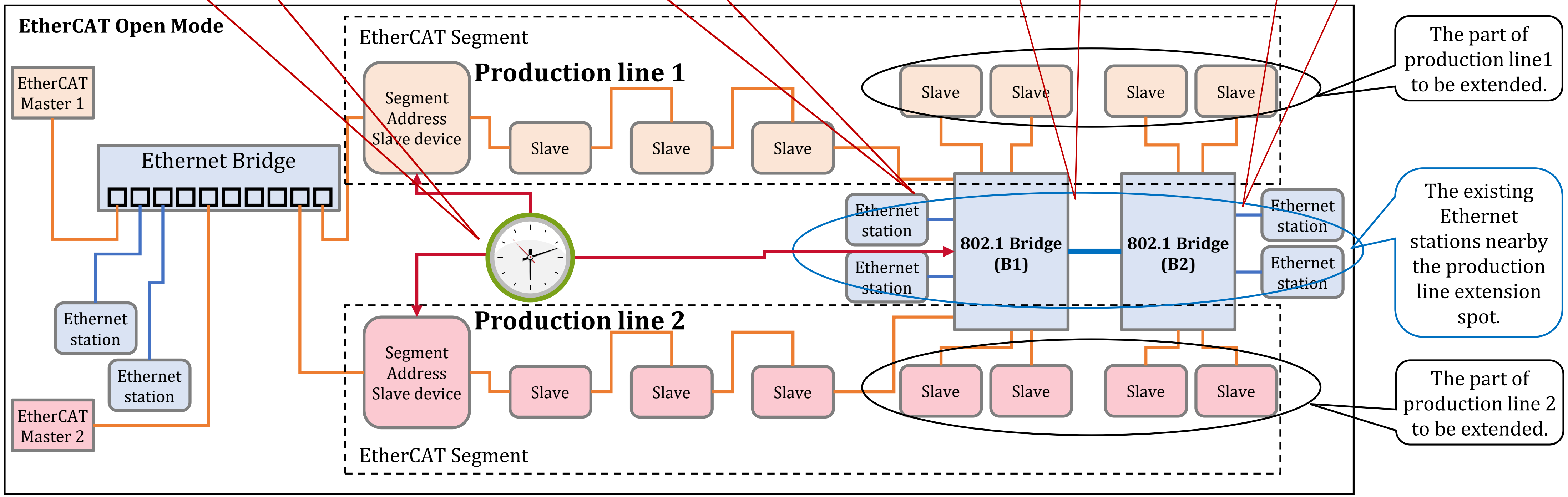
Initial Solution Points for the Use Case of EtherCAT Production Line Extension

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

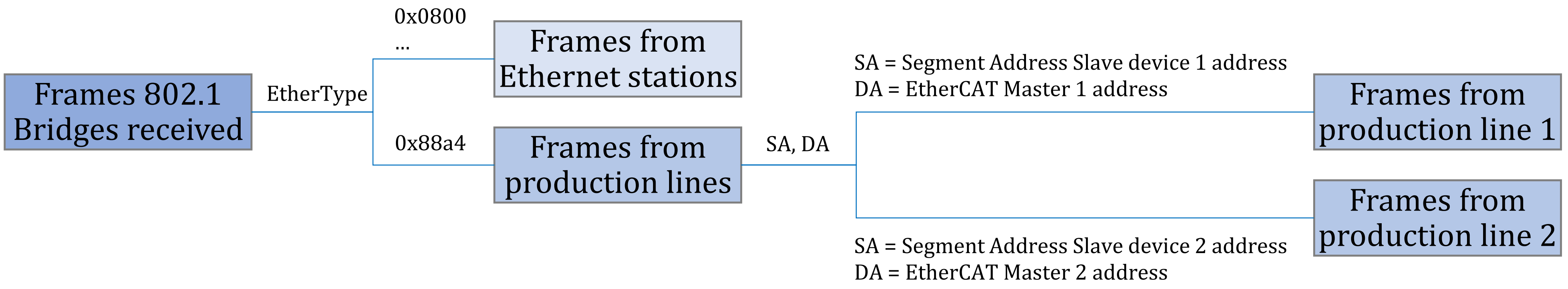
② **Identify different kinds frames, and forward to specific ports or devices according to EtherCAT**

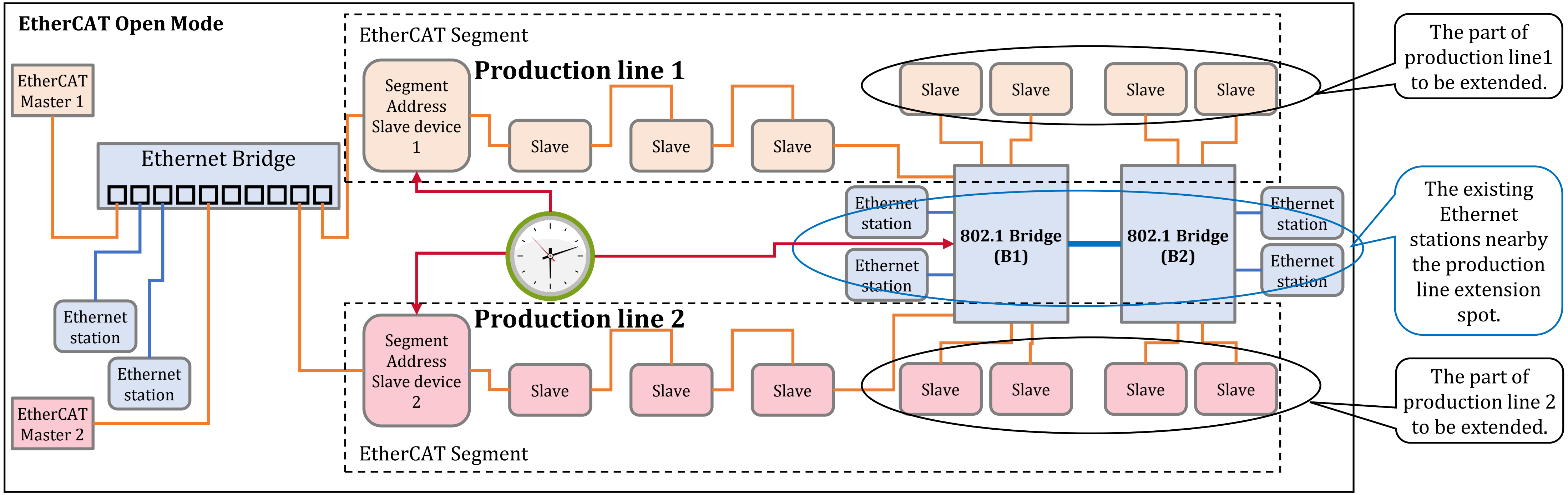
③ **Improve the latency / jitter, assure the low latency / jitter according to independent of EtherCAT network**

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

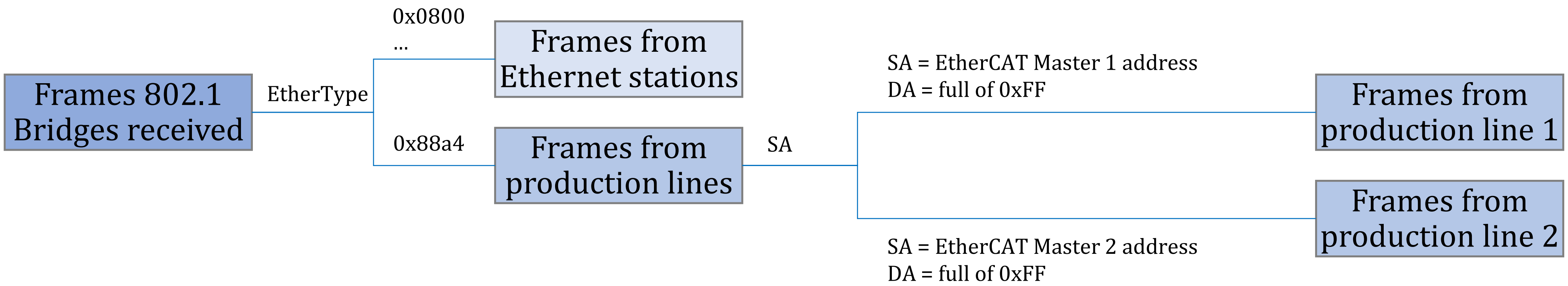


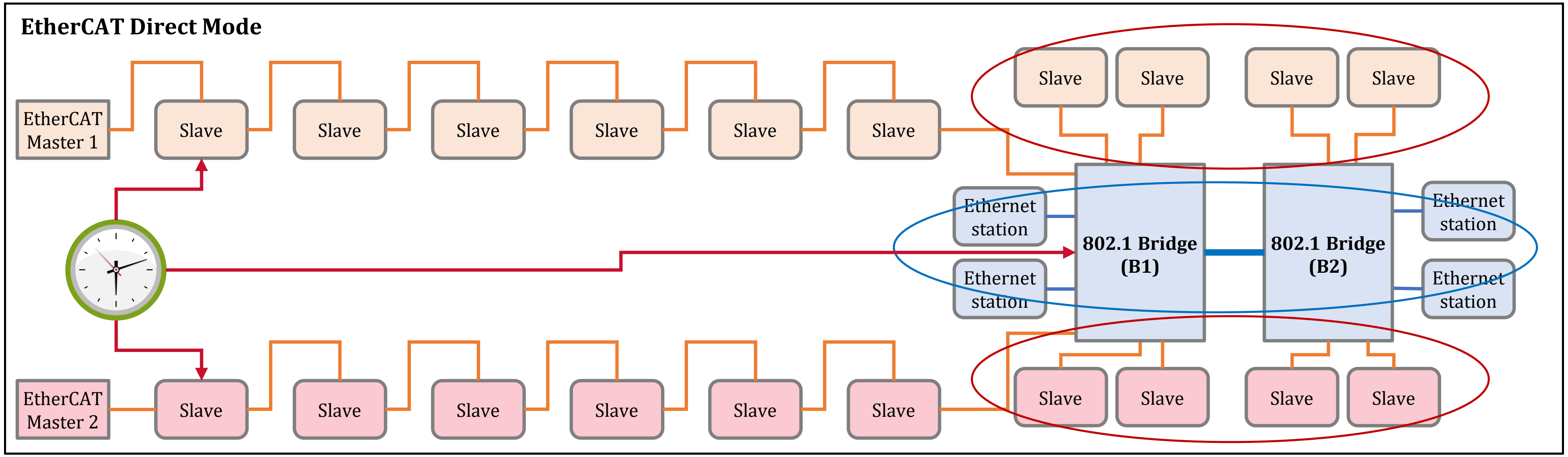
Identify Different Kinds Frames in EtherCAT Open Mode



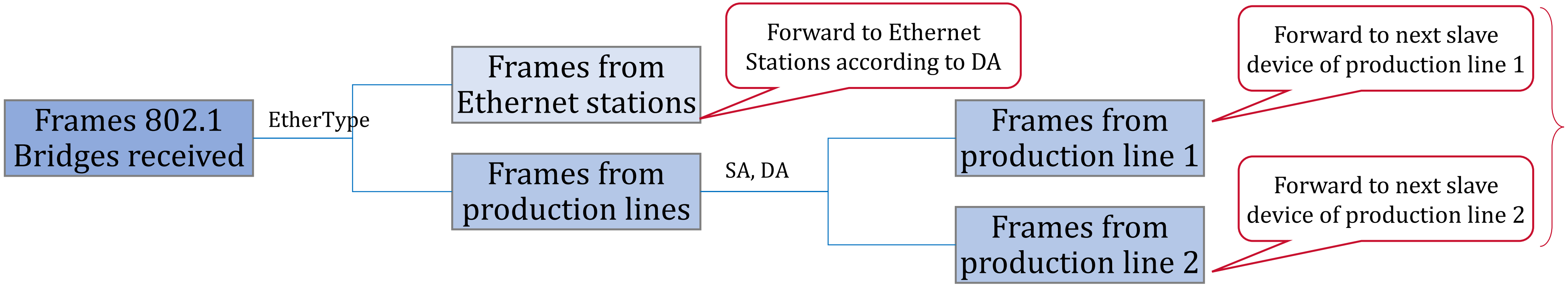


Identify Different Kinds Frames in EtherCAT Direct Mode

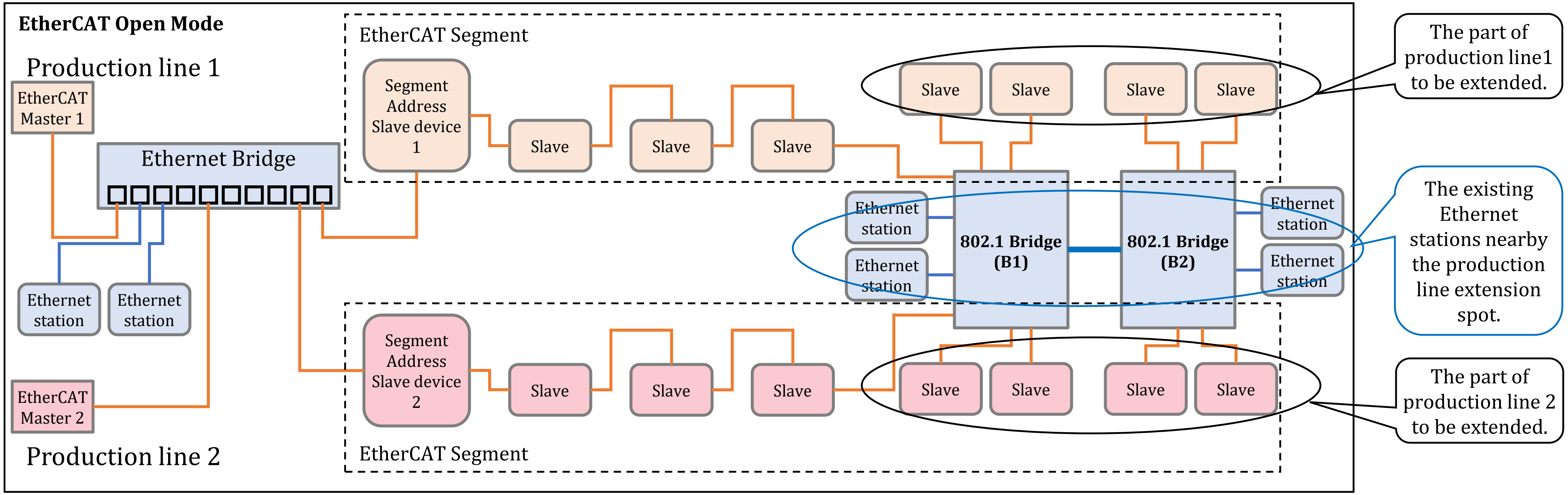




Forward the EtherCAT Frame to Specific Port

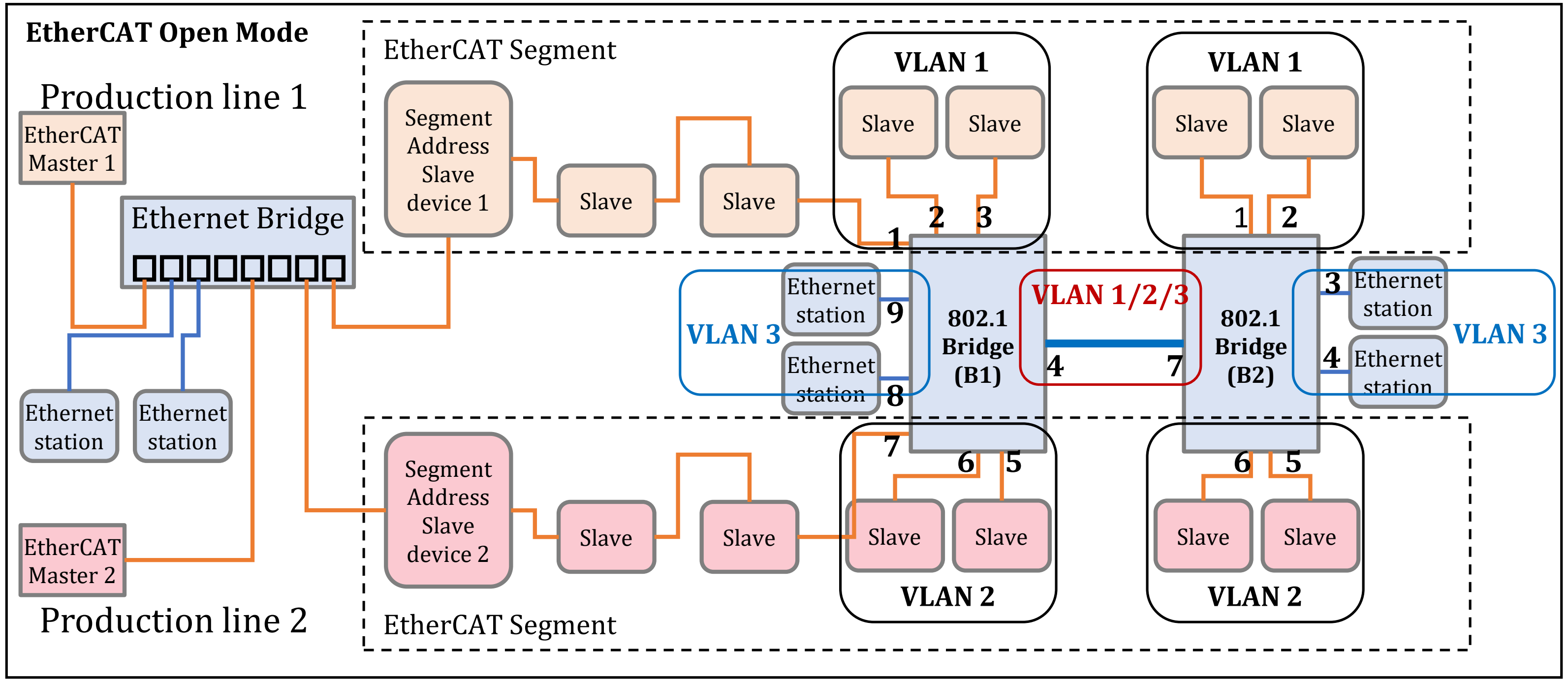


- Even it can identify the EtherCAT frames of different production line ,
- but how to forward EtherCAT frame to the correct slave device?



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.

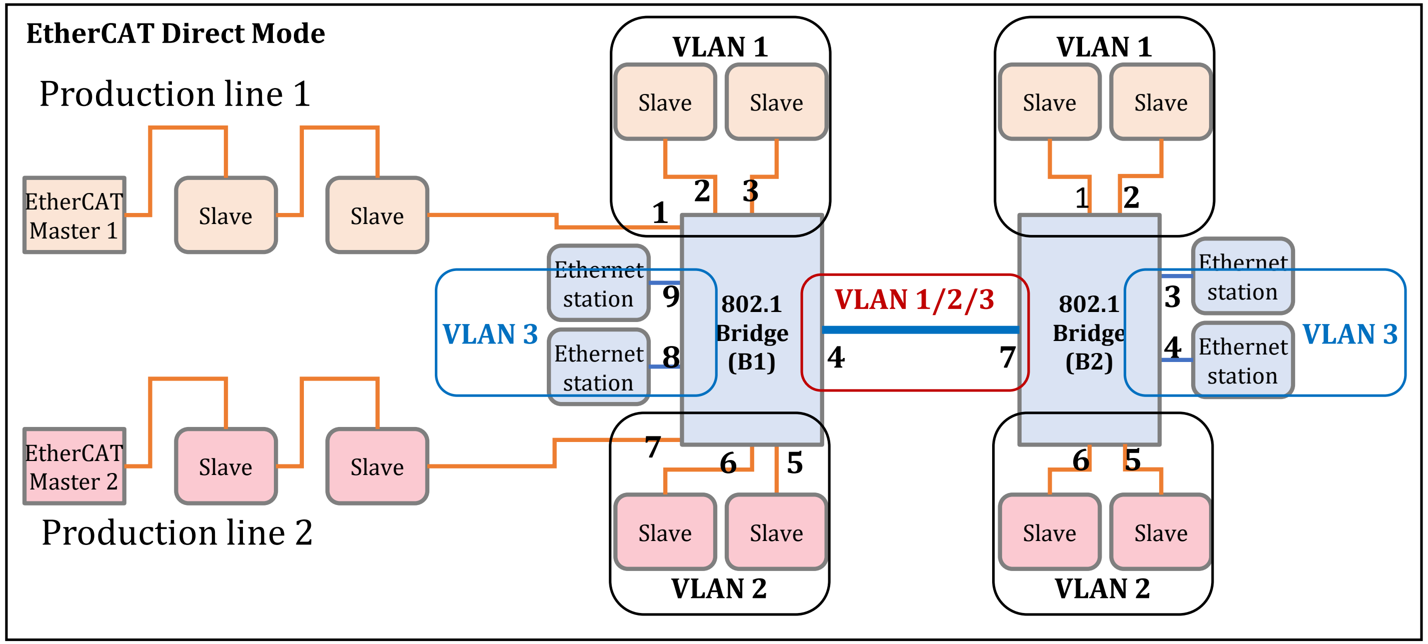


Bridge	Frames Received from	Frames Tagged VLAN	Frames Forwarded to Port
B1	Port 1	VLAN1	Port 2
	Port 2	VLAN1	Port 3
	Port 3	VLAN1	Port 4
	Port 4	VLAN1	Port 1
	Port 7	VLAN2	Port 6
	Port 6	VLAN2	Port 5
	Port 5	VLAN2	Port 4
	Port 4	VLAN2	Port 7
	Port 4	VLAN3	According to DA
	Port 8	VLAN3	
	Port 9	VLAN3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

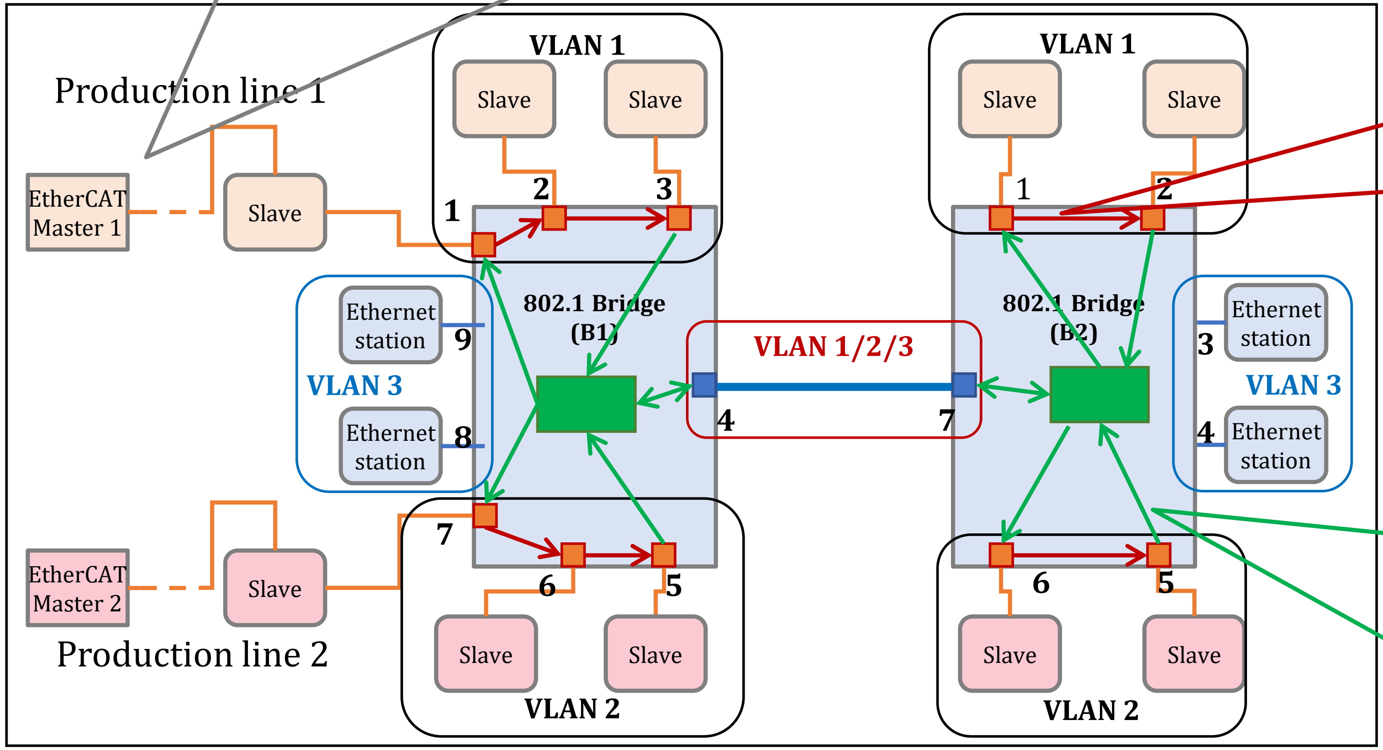
Contents

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

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.



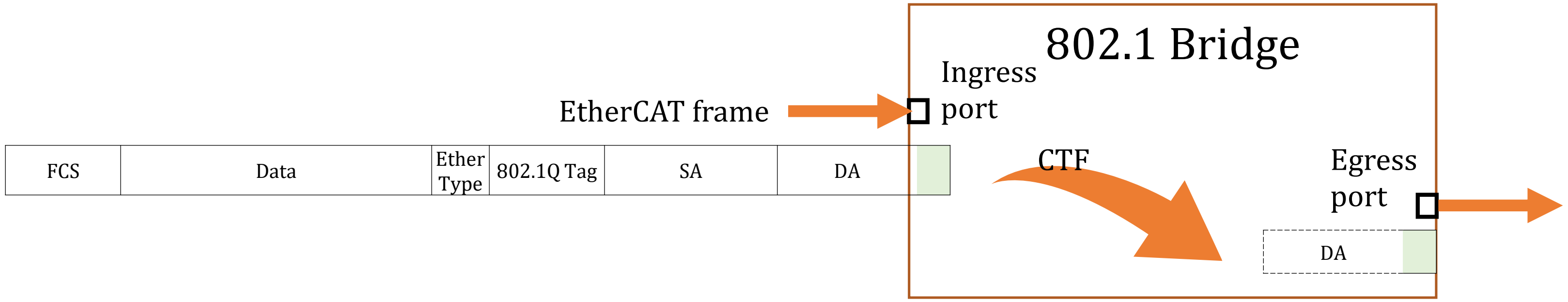
2. Forwarding latency to next EtherCAT slaves (CTF latency)
- ✓ The latency is used to forward the EtherCAT frames between the Bridge ports which are connecting to EtherCAT slaves directly.
- ✓ These ports rate are the same, also equals to rate of EtherCAT slaves.
- ✓ The **cut-through forwarding** could 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.

Cut-Through Forwarding Latency to Forward EtherCAT Frames

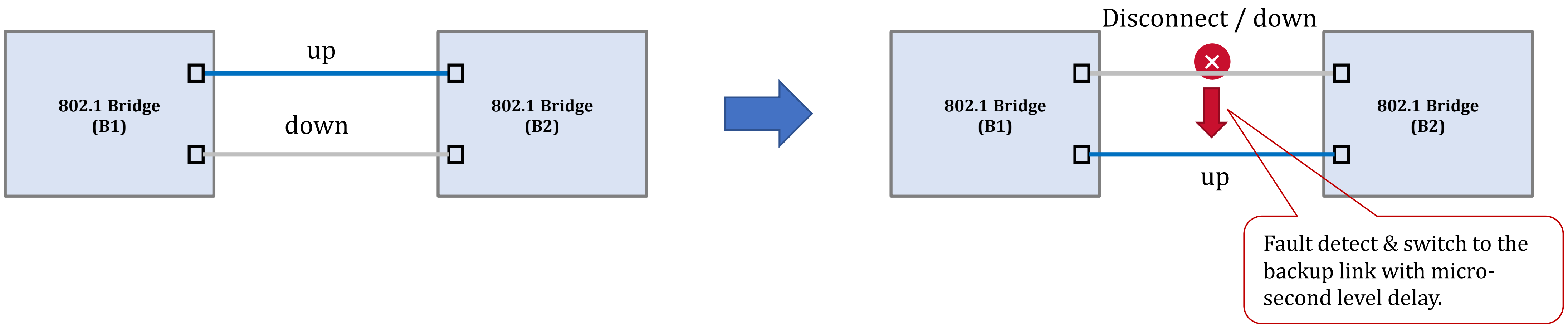
- It's necessary to implement the cut-through forwarding to minimize the forwarding latency based on the same transmission rate of the ingress port and egress port both of which are connecting to EtherCAT slave devices.



- 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 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.

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
    - ✓ To assure the low and bounded latency to mix-transfer the EtherCAT frames.
    - ✓ To mitigate the complexity of management & orchestration.
  - High reliability
    - ✓ To achieve micro-second level to detect and notify the Bridges to switch to the backup link.
    - ✓ To avoid overuse of bandwidth of the Bridges.

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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 possible solutions, to assure the QoS of EtherCAT frames, and mitigate the complexity or avoid the overuse of bandwidth.
  - Low latency & jitter
    - ✓ At first, based on 802.1Qbv, to get a solution to assure the low latency / jitter, but it might be complicated to orchestrate.
    - ✓ Second, try to outline a solution to mitigate the complication but the latency will be increased.
  - High reliability
    - ✓ According to the requirement of EtherCAT redundancy recovery time, try to outline a solution to achieve micro-second level to detect and recover to the backup link, and achieve the high reliability of 802.1 Bridges to forward the EtherCAT frames.
    - ✓ This item is still under study, it’s not present in this slides currently.

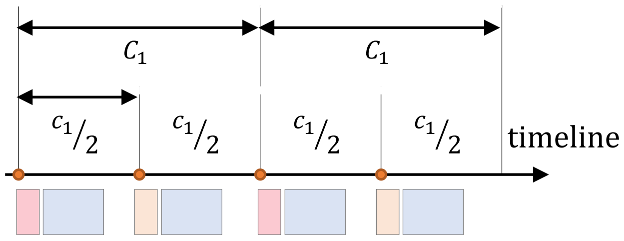
Strictly Orchestration based on 802.1Qbv to Achieve Bounded Latency

➢ Based on the clock 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-transfered in the inter-link between the 802.1 bridges.

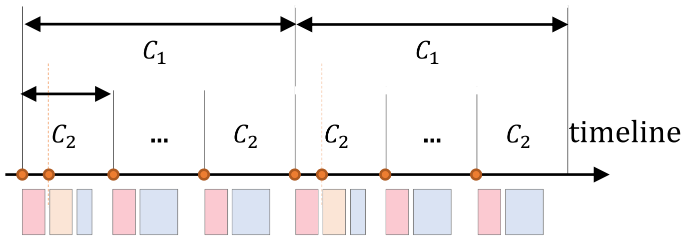
- ☐ The inter-connection bandwidth between the 802.1 bridges should be evaluated according the EtherCAT frame size and application cycle.
- ☐ The transfer delay from the EtherCAT master to 802.1 bridges should be evaluated based on the frame size and bandwidth.
- ☐ All these parameters and evaluation 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 one 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, $C_1 \geq C_2$

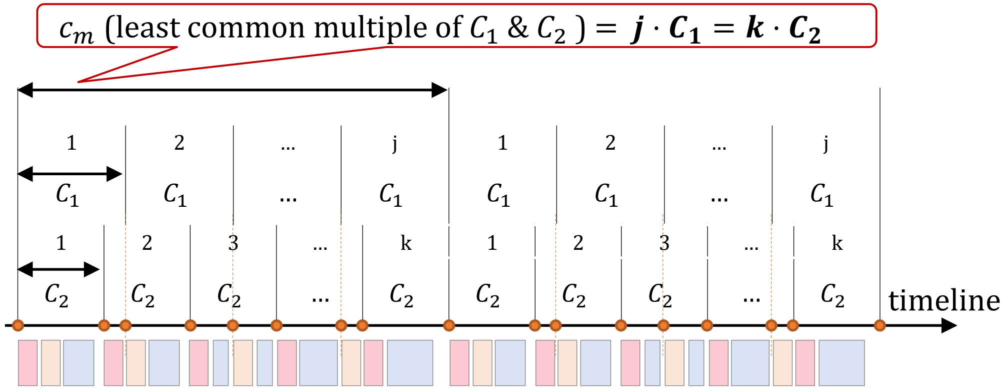
1. $\boldsymbol{C_1 = C_2}$



2. $\boldsymbol{C_1 = nC_2}$ **(n > 1 is an integer)**



3. $\boldsymbol{C_1 = mC_2}$ **(m > 1 is not an integer)**

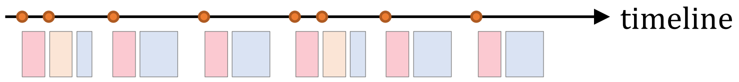


Frames from EtherCAT Master 1	Frames from EtherCAT Master 2	Frames from Ethernet Stations

Complication of Strict Orchestration and Mitigation

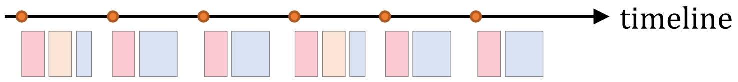
- **The complication of strict orchestration including following factors**:
  - The periods between the two adjacent time points are different.
  - The action of sending out frames has to be done as per the timeline with strict time synchronization, no earlier and no later than the time point.
  - It’s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

Specific timepoint to send specific frame.



- **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 is different, the departure time of shuttle is cyclic.
  - That is, even the shuttle arrives earlier, but the next departure time has to wait until the next cycle.
  - So, from the view of the whole network, the end to end network transmission latency is anticipated.
  - And if the network bandwidth is high enough the network transmission absolute latency value will satisfy the specific EtherCAT service requirement.

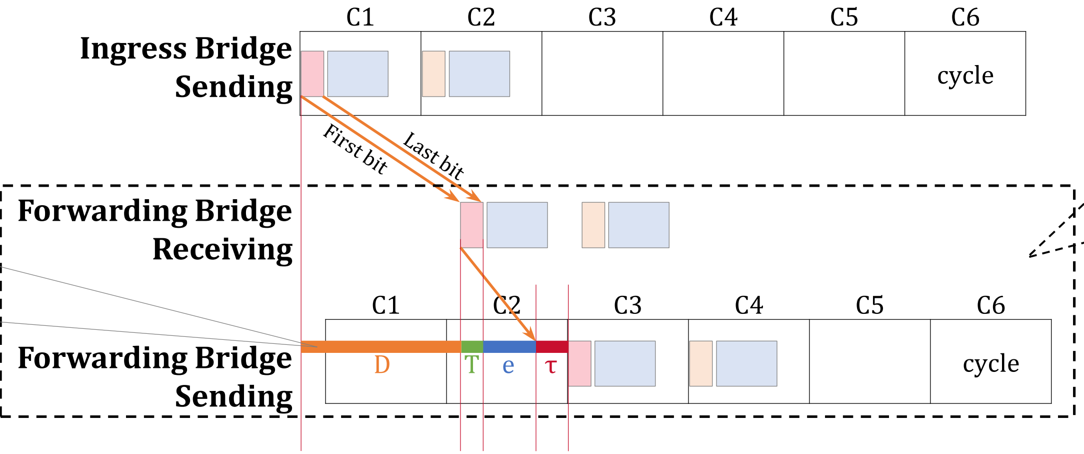
Fixed period to send frames cyclically.



Mitigate Complication to Achieve Bounded Latency

- As the figure below, the ingress Bridge and next hop forwarding Bridge divide the time slot as the same period, that is a cycle.
- Each Bridge use the cycle to send the frames to next Bridge, the latency **D** & **T** is anticipated generally according to the transmission rate, meanwhile, on the precondition of enough network resource reserved, the latency **e** is also anticipated. All these latency could be self-studied and metered.
- The latency **τ** is used to match the next complete cycle, then, the cycle mapping relationship between the adjacent Bridges could be built one by one.
- Note that, because of different transmission link, the cycle mapping relationship between the different adjacent Bridges might be different, e.g. the cycle 1 of Bridge 3 maps to cycle 3 of Bridge 4, but the cycle 3 of Bridge 4 might map to cycle 5 of Bridge 5.
- Based on the testing frames between adjacent Bridges and building the cycle mapping relationship, the end to end transmission latency of the all Bridges could be evaluated.
- Regarding the ingress Bridge, it receives each kind of stream from devices/ stations, and orchestrates each kind of stream according to the stream application cycle, priority and affordable latency (in this ingress Bridge) etc., and get the mapping table which including stream characteristics (such as DMAC, SMAC, stream direction etc.) and corresponding cycle of this igress Bridge. That is, the subsequent frames from the devices /stations will be put into specific logical queue of cycle according to mapping table.
- Finally, from end to end, the frames from devices / station are mapping into the cycle in all of the Bridges certainly, the latency & jitter could be anticipated and bounded.
- So, the complication is mitigated, but the absolute latency is increased, if the network provide enough bandwidth, e.g. 10Gb/s, the mitigation might be feasible.

- **D: transfer latency of the first bit**
- **T: transfer latency of the whole frame**
- **e: the Bridge internal processing latency**
- **τ: the additional latency to wait and match the next complete cycle**

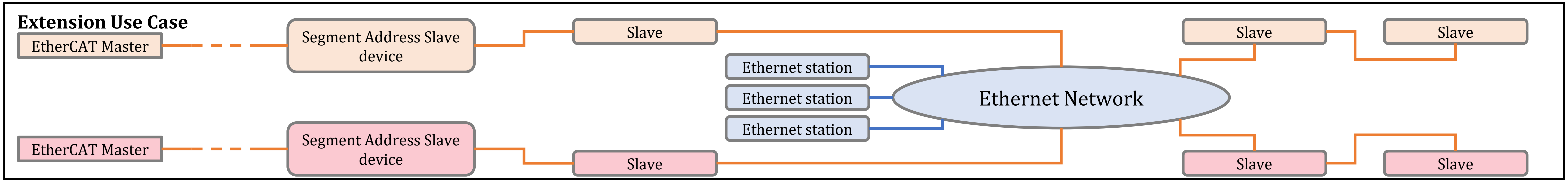


As the bridge, both of the receiving latency and sending latency are anticipated and bounded.

Frames from EtherCAT Master 1	Frames from EtherCAT Master 2	Frames from Ethernet Stations

Summary of the Mitigation

- According to the scenario below, the Ethernet network (light blue area) has to mix-transfer different kind of stream, and should assure the low latency / jitter for the EtherCAT frames and mitigate the complexity.
- The mitigation including following points:
  - In the Ethernet network, each adjacent Bridge divides the time slot as the same period, that is a cycle corresponding to a logical queue, and the cycle mapping relationship is built between each adjacent Bridge in each direction via the testing frames sent from one Bridge to another.
  - For the ingress Bridge, it receives each kind of stream from devices/ stations to study and get the stream characteristics, then report the stream characteristics to the network controller.
  - The network controller orchestrates and get the mapping table which indicates specific stream frame mapping into specific cycle in this ingress Bridge.
  - The mapping table of the ingress Bridge and the cycle mapping relationship between each adjacent Bridge will be reported to the network controller, the network controller will go through all the mapping records for each stream to check whether the network resource could afford stream requirements.
  - The network controller might orchestrate and adjust the mapping table of the ingress Bridge to assure that the subsequent Bridges of this stream's end to end routine could afford the resource requirement of this stream and other streams which are sharing network resources in the same cycle.
- All of the steps above, the testing and studying steps get the mapping records, and the orchestration scale and complexity is decreased.



High Reliability of 802.1 Bridges for EtherCAT Services

- To study the possible high reliability solution to achieve micro-second level to detect and recover to the backup link.

- Under study, hope to be discussed next Nendica meeting.

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	• 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	An informal report documenting • 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	• Huajie Bao (Huawei), or other volunteers
Timeline	• 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	• Weekly meeting or on-demand meeting • Encourage all contributions • Provide ongoing reporting to IEC/IEEE 60802