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1 INTRODUCTION

1.1 SWGI4.0 / TEG Background

The Sino-German standardization cooperation on Industrie 4.0 (I4.0) / Intelligent Manufacturing (IM) initiated the study on communication technologies of interest to this Sino-German collaboration. Potential topics were identified, such as wireless communication, co-existence management, Wireless Industrial Application (WIA), and Time-sensitive Networking (TSN) profiling for industrial automation.

The Technical Expert Group (TEG) Network Communication (NetCom) was created to drive I4.0 / IM industrial communication-related subjects as mentioned above. It also reviewed the IEC NP for TSN profiling for industrial automation. In addition, it raised for discussion in international standardization the aspects of spectrum and co-existence management. Although TEG NetCom started out with a focus on WIA and TSN areas, it was agreed to extend its scope to include wire-line communications. Hence, the specifications, guidelines, and testing activities in addition to general IEEE 802 standards and projects are at the core of the Sino-German TSN activities. The IEC/IEEE 60802 TSN profile for industrial automation also extends our joint activities.

1.2 Objectives

Through the formulation of a strategic roadmap in 2023, the objective is to delineate forthcoming research endeavors, testing, and collaborative initiatives between the German Labs Network Industrie 4.0 (LNI 4.0) and the Chinese Alliance of Industrial Internet (AII).

2 COOPERATION

Proposal for Cooperation Between LNI 4.0 and AII

LNI 4.0 and AII have a long history of collaborative engagement within international committees. Both entities test and validate draft standards from international working groups, with a particular emphasis on IEEE 802.1 TSN TG (Task Group) and IEC SC 65C WG 18 among others like IEC/IEEE 60802.

In the light of this well-established foundation, it is proposed to initiate a direct exchange of research and test findings, and to formalize and strengthen this collaborative endeavor in the future.

This collaborative effort yields this comprehensive Sino-German study report, with a primary emphasis on the exchange of test results related to draft standards emanating from the IEEE 802.1 Working Group and IEC SC 65C Working Group 18. Additionally, the report will endeavor to explore insights derived from relevant study items, namely, "large-scale TSN networking" and "LRP RAP" (the standardization reference is IEEE Draft Standard P802.1Qdd), as expounded upon in the forthcoming chapters.

During the development of IEEE P802.1Qdd, it was decided by the IEEE 802.1 experts in 2024 to withdraw the Project Authorization Request (PAR) intended as an amendment of IEEE 802.1Q (see **http://bit.ly/4ol7KeM**, the reference is slide 75). The future activities are driven as standalone project IEEE P802.1DD (see **http://bit.ly/3Jhm3SC**).

3 STUDY ITEM LARGE-SCALE TSN NETWORKS

3.1 Current Status in China

TSN technology has gradually started to be promoted and applied in China, with many industrial enterprises attempting to deploy TSN networks within their factories. Using a TSN network as the foundational network for carrying all business operations within a factory has become a trend. Therefore, it is necessary to study the problems in the process of TSN networking.

Although the IEEE 802.1 TSN task group has defined a relatively comprehensive set of TSN protocols, many issues have been identified in practical applications. These issues include the gradual increase in clock synchronization cumulative errors as the network scale grows, varying precision levels among switches from different manufacturers, and the overall lack of unified management tools leading to cumbersome manual configurations. However, there are many reasons for these problems, such as inconsistent clock accuracy of TSN chips, differences in manufacturers' understanding of TSN protocols, and so on. These engineering implementation problems significantly hinder the large-scale deployment and application of TSNs.

China has deployed a corresponding large-scale TSN network test bed, which is continually expanding. It is expected that the number of TSN network nodes in this test bed will exceed 30. The test bed includes commercial TSN switches from several manufacturers, NXP TSN evaluation boards, TSN controllers, and more. Conducting research on large-scale TSN network deployment through this test bed serves two purposes: addressing practical application issues and contributing to further improvements of existing TSN standards. In the future, in view of the above engineering problems, we will design the test environment, test indicators, and test schemes based on the test bed to solve the problems in the actual deployment of TSN.

A preliminary test bed has been set up for initial testing, which included six Moxa switches, two Dongtu switches, and two Sanwang switches, as well as four Feiling TSN evaluation boards. To carry out large-scale TSN network testing, we have sorted out the TSN network test indicators and made a general classification. Three types of test indicators are listed below:

- **Clock synchronization test indicator:**
  Multi-hop clock manual source selection
  Multi-hop clock automatic source selection
  Multi-hop clock synchronization accuracy

- **Traffic shaping test indicator:**
  Multi-hop gate control shaping
  Multi-hop gate control accuracy
  Multi-hop gate control minimal delay
  Frame preemption and recovery
  Flow filtering based on speed limit
  Flow filtering based on gate control

- **Reliability test indicator:**
  Redundant clock source backup
  Link failure recovery
  Multiplex transmission

With the expansion of the scale of the TSN network, the complexity of the network has also increased greatly, and we have encountered many problems in the test process; the most important problems include the complexity of network configuration and management, the inconsistency of the implementation of various product protocols, and the difference of clock accuracy. The results of these tests are conducive to further updates to the 802.1 TSN family of standards.

3.2 Current Status in Germany

The international TSN test bed of LNI 4.0 was established in 2017 by industrial automation companies with the ambition to bring industrial communication stakeholders and market participants together to foster the next level of Ethernet technologies in industrial applications. Here, the use cases of small and medium-sized enterprises are at the centre of the LNI 4.0 TSN test bed. Organizing plugfests allow the international experts to test their components with other development products based on the basic underlying standards and review as well as feed back pre-competitively the draft standards of the standardization organizations mentioned above. The LNI 4.0 TSN test bed does this jointly with all international partners.

The study item large-scale TSN network is yet not in the focus of LNI 4.0 due to its SMEs focus, which usually do not have the need to operate large networks in their factories but rather act as system providers or system integrations for exemplarily large-scale networks. The collaboration supports the alignment on the topic for future applications.

3.3 Prospects in China and Germany

Both countries understand that use cases are the driver for the market adaption of TSN technologies. The economical as well as technological use cases need to be articulated on a global scale to ensure that the TSN technologies leverage at low cost based on joint global standards. The study item large-scale networks based on TSN standards enables a vast amount of possible use cases where lot of them require a different selection of features.

China and Germany choose to focus on production line use cases (see Figure 1). The main criteria of these use cases are a TSN network connecting different machines from various vendors. In the Industrie 4.0 context, this means that both centrally as well as ad-hoc flexible configurations of machines in TSN networks are necessary.

These use cases typically come with the following requirements:

- OT personal is in charge of production: Avoiding extra costs for specialists, e.g., network operator
- The production rate must be met: Begin the design with sequence of actions with time constraints
- Stepwise commissioning of machines to be supported: Start with partial network in operation

Downtime must be minimized to increase overall equipment effectiveness: Limit the effects of failures, avoid side effects caused by components not needed in production, and minimize dependencies between connected machines

Upcoming requirements, which are addressed by large-scale TSN networks:

- Multiple applications must be supported on a single network: Integrate formerly dedicated connections: Eliminate discrete cabling, additional interfaces, installation, and associated error sources. Here, the link to the next study item LRP RAP is closely given
- Make machine data accessible for smart manufacturing: Avoid the reprogramming of machines to get access to useful data

In order to achieve these requirements, we provide guidance and testing abilities for these time-sensitive applications. The following characteristics to be considered by applications are emphasized:

- Dynamic E2E stream allocation for "plug & produce." Here, the link to the next study item LRP RAP is closely given
- Exposure of stream diagnostics
- Leverage existing production line networking technology for real time. Here, the link to the next study item LRP RAP is closely given
- Support for Minimum Viable Solutions

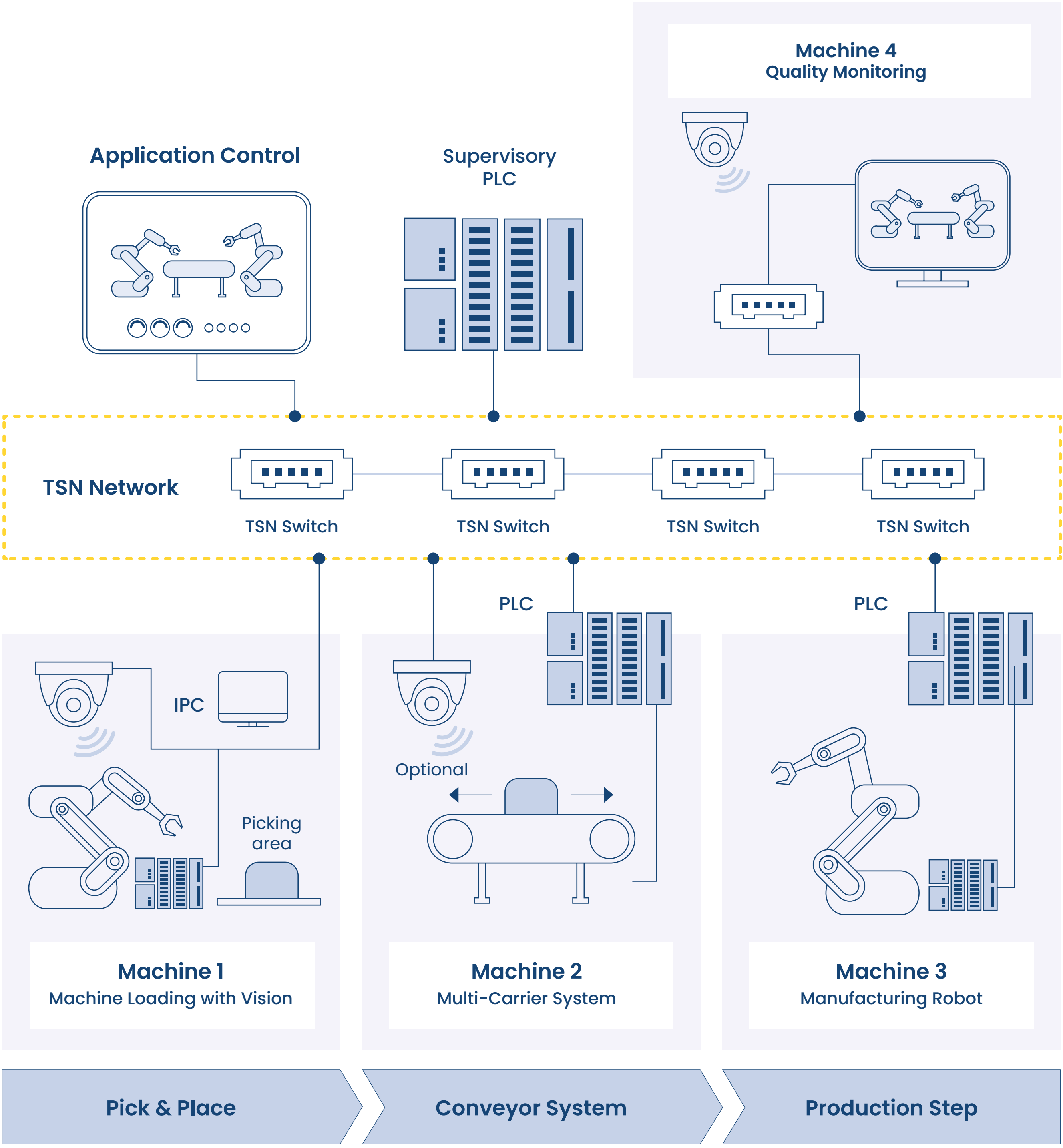


Figure 1: Production lines use case with TSN

4 STUDY ITEM LRP RAP

Each network uses standards for the stream reservation protocol. In the context of TSN, there are additional options to be selected, such as the Link-local Registration Protocol / Resource Allocation Protocol (LRP RAP).

4.1 Current Status in China

Currently, there are no specialized institutions in China dedicated to researching LRP RAP at the protocol level. Instead, most research efforts are focused on link discovery and resource reservation from the perspective of devices or networks. If there is an interest in collaborating on this topic in the future, it may be considered to combine it with research conducted on the large-scale TSN network test bed. China can provide the relevant test environment and test instruments, and can also cooperate with Germany to jointly develop the LRP RAP protocol validation prototype

4.2 Current Status in Germany

In Germany, the LNI 4.0 TSN test bed chose the drafted stream reservation protocol IEEE 802.1Qdd, which is based on MSRP, a distributed stream reservation protocol defined in the Q standard of IEEE for quite some time. In the current IEEE 802.1Qdd draft D0.9 standard, there are so-called Resources Allocation Classes (RA-Class) for streams. Each RA-Class includes a mathematical model for the dimensioning of the required bandwidth, per-hop max latency, and network resources. Based on the use case and the IEEE 802.1Qdd draft D0.9, an RA-Class has been designed from the LNI 4.0 TSN test bed members.

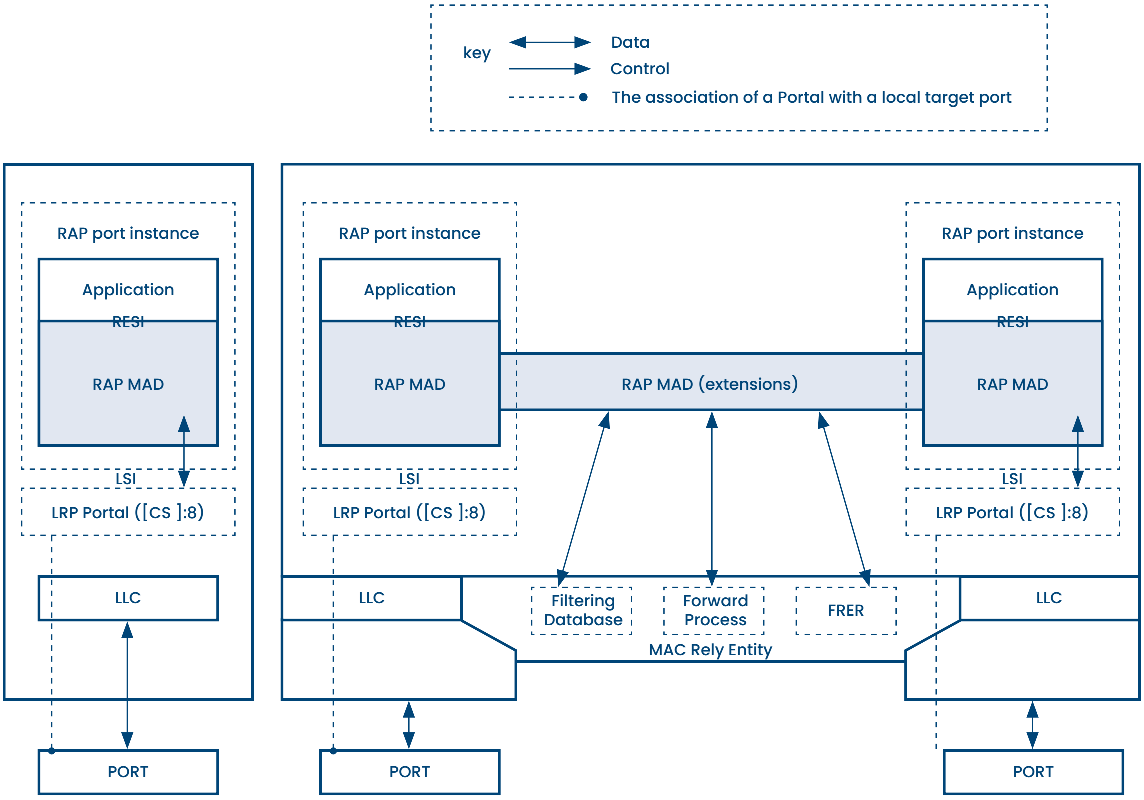
Various different draft versions of RAPs have been implemented and plugged. While doing so in the LNI 4.0 plugfest meetings, the feedback has been formally given to IEEE. Both technical as well as formal issues in those drafts have been commented upon. In addition, information exchanges between individual IEEE members of the LNI 4.0 TSN test bed took place.

In the IEEE plenary meeting in July 2024, the Project Authorization Request (PAR) IEEE 802.1Qdd Resource Allocation Protocol (RAP) was withdrawn. The reason for this is that integration to the 802.1Q standard is deemed to be difficult and further development as a standalone project will gain easier recognition for a broader market. Therefore, RAP is considered to be a standalone IEEE 802.1 standard. So, the replacement of the amendment Draft P802.1Qdd is further driven as the new standalone project P802.1DD. The new PAR was approved in September 2024.

As a consequence, various parties joined the development of the 802.1DD project resulting in a major rework of the internal architecture within the May Interim in 2025, in Rennes.

The adoption of the new architecture resulted in the release of the draft 1.2 along with the July Plenary in 2025. In this Plenary further contributions and coordination leading to a full reworking of the draft towards the new architecture and style have been made. The future IEEE 802.1DD standard will be able to more efficiently describe the design of RA classes and will be referenced more easily by other standards-developing organizations (SDOs). In this context, LNI 4.0 will contribute towards IEEE 802.1DD to make the RA class template mechanisms more flexible for I4.0/IM applications.

There have been contributions from the LNI 4.0 plugfests to improve RAP towards a resource reservation framework that is capable of supporting future TSN standards and different data-plane concepts. This can be done by defining new resource-allocation templates. LNI 4.0 uses its own time-aware scheduling (TAS)-based template, which uses resource allocation inside exclusive time-based windows for frame transmission without interference from unallocated traffic. To be able to do so, LNI 4.0 suggested adding the required type-length-value (TLV) directly to the standard. LNI 4.0 did also show that those



extensions are required for any time-based data-plane concept. Yet, due to time limitations and the lack of other finished RA class templates, the decision made was to not integrate them but retain those changes for future work.

The LNI 4.0 TSN test bed also serves as an information distribution hub for small and medium-sized enterprises that are not part of the IEEE 802.1 standardization work, but can provide valuable input for the discussed use cases and requirements. The input is summarized inside the test bed and provided by individual participants, as well as a formal liaison between IEEE and LNI 4.0. A regular information exchange is also an important part of the regularly organized LNI 4.0 TSN test bed virtual meetings. There are more than 50 participants interested in the topic. The plugfests also include a general information session for remote participants.

In the LNI 4.0 TSN plugfests it has been shown that the participation of switch, end device, and test device vendors is crucial in order to progress the TSN developments. Another key finding is that resource allocation within the switches represents another piece in the TSN puzzle. Major gaps remain, especially in terms of the configuration of aspects of a global network. Examples are the path management, the time-synchronization configuration, RA class management, and the device security concept.

In the last LNI 4.0 TSN plugfest meetings, the focus was on the validation of the current IEEE 802.1Qdd redundancy functionality, which is based on Frame Replication and Elimination (FRER), another IEEE standard. In this context, two main usage modes as well as the required mandatory subset of FRER features have been selected. Redundancy is based on virtual LANs (VLAN) thus in order to provide independent paths, a Multiple Spanning Tree Protocol (MSTP) is required also. RAP does not limit the number of paths thus, more than two can be used. It is up to the network management to configure the network in such a way that

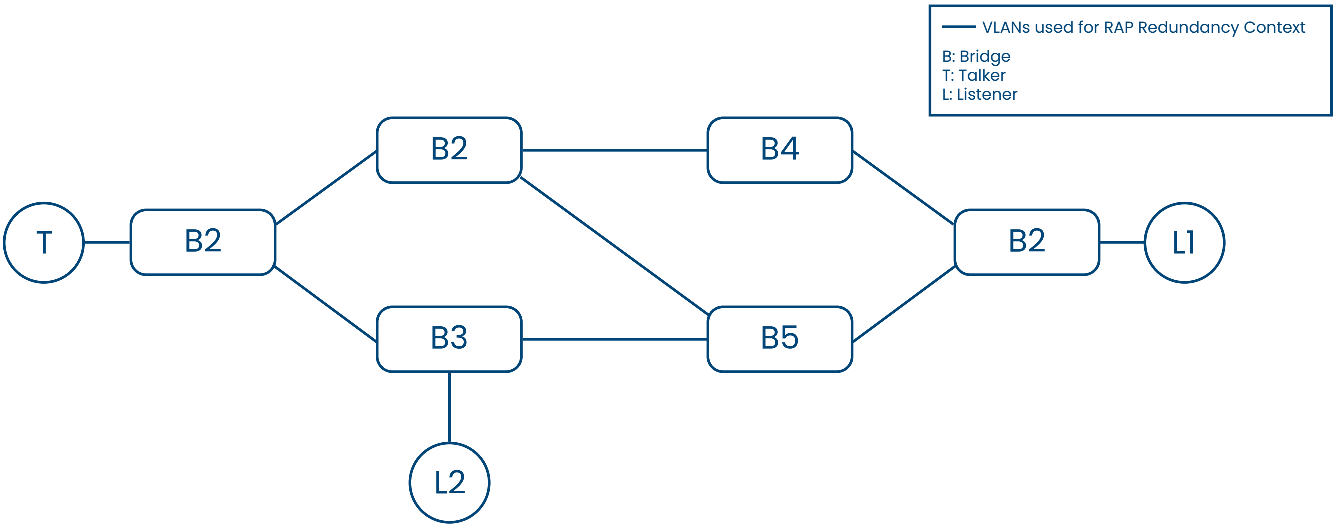


Figure 3: LNI 4.0 Topology for the TSN redundancy (VLANs: Virtual LANs, T: Talker, L: Listener, B: Bridge)

the VLANs used for redundancy are able to provide the best-possible independent paths. The first redundancy model, end device FRER relies on doing most of the redundancy functionality inside the end devices. In this case, the network only makes sure that the individual streams are reserved along their paths. In a network FRER case, the end devices do not necessarily have to possess any data-plane redundancy feature (or their capabilities are already exceeded). In this case, the last link between network and end device obviously is not redundant. The network itself makes sure that individual paths are taken starting from the first switch. Along with the features, a couple of requirements in terms of the network environments have been identified and validated, thus the current IEEE 802.1Qdd draft includes a working approach to perform a resource allocation for redundant streams within a suitable IEEE-based network.

In addition to RAP, the LNI 4.0 plugfest meetings tested the IEEE 802.1AS2020 time-synchronization standard. It was plugged and the interoperability of various implementations and versions were evaluated. The results have been shared among the plugfest participants to improve the products and fed back to IEEE.

Overall, LNI 4.0 contributed to multiple standards. Some of the specific results are:

- Optimized unclear or imprecise formulations in standard drafts (e.g., IEEE 802.1Qdd, IEC/IEEE 60802)
- IEEE 802.1AS
- No live (re)configuration possible
- Latency, timeout value problems possible at 100 MBit
- Time jump of grand master can happen. Negative delay problems
- IEEE 802.1Qbu
- Frame Preemption: new learnings on not connected pre-emption
- IEEE 802.1CB
- Unintended configuration limitations were discovered and will be fixed by a corrigendum

4.3 Prospects in China and Germany

Both countries understand that a successful realization of the mentioned use cases requires standardized stream reservations. China as well as Germany will therefore foster the standardization activities in this field with IEEE as well as IEC and support the adaption by the markets.

5 SUMMARY AND OUTLOOK

China and Germany agree that the results of these collaborations can be considered in international standardization organizations like IEEE and IEC, such as methods for testing TSN networks and feedback on draft standards. Examples for affected standards are the IEEE 802.1DD and IEEE 802.1AS standards families. Both organizations commit to the verification work for IEEE 802.1DD standards. Additional meetings on this topic will be conducted on a regular basis.

For this purpose, LNI 4.0 and AII intend to process further specific study items and use cases that both organizations focus on.