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TSN in the Railway Sector: Why, What and How?

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ABSTRACT
Railway sector has evolved serial Train Communication Networks to Ethernet based solutions. The lack of real-time traffic communication and functions isolation capabilities of traditional Ethernet has limited the adoption of standardized Ethernet based solutions.
TSN overcomes the identified limitations, and it has been identified as the next generation Data Link layer for railway communications by the railway manufactures and operators.
This paper summarizes Why TSN has become the preferred next-generation network protocol for the sector, what is TSN and How is introduced within the train networks.
Additionally, a proposal for a TSN-capable Edge-computing device and an advanced TSN set-up are presented in the paper.

KEYWORDS
TSN
Railway
TCN
ETC
ECN
PTP
Ethernet

WHY TIME-SENSITIVE NETWORKING (TSN) IN THE RAILWAY SECTOR?

In 1999 a train on-board communication standard was published by the IEC (1; 2). This standard, the IEC 61375 or TCN (Train Communication Network), allows interchanging data among the different electronic subsystems, supplied by several manufacturers. Also, the standard allows to joint different trains or vehicles. For interoperability among trains of different manufacturers and countries, the Union Internationale des Chemins de Fer (UIC) defines the semantics of the exchanged variables and messages in the UIC-556 leaflet (3).

Nowadays, the TCN standard allows a safe, reliable, and robust communication, as it is required for a passenger transport system. The information exchanged inside transportation systems has grown so much, that TCN has become obsolete and expensive. As an example of these limitations, Wire Train Bus (WTB) defined in TCN supports a maximum data rate of 1 Mbit/s that limits the usage of the backbone to control and status commands, only. Video surveillance, for example, needs a much higher bandwidth – passenger comfort functions may demand even more. As a result of these limitations, the evolution of TCN has derived in many cases in solutions based on existing Industrial-Ethernet solutions mixed with original TCN standard.

To move forward on an interoperable Ethernet based solution for the Sector, in 2005, IEC commissioned a new working group to publish a new standard based on Ethernet devices. As a result, Ethernet Train Backbone (ETB) was proposed as the train wide communication backbone. It replaced WTB in Train Communication Network in the IEC-61375-2-5 standard. IEC-61375-3-4 defined the Ethernet Consist Network (ECN) for the communications inside the car, replacing the Multifunction Vehicle Bus (MVB) specified in the original TCN standard.

Thus, these IEC 61375-family standards define a faster TCN based on standard 100Mbit/s Ethernet in combination with proprietary higher layer protocols like TRDP, IPTCom or CIP. Indeed, current trains use these proprietary protocols, creating a complex ecosystem.

The adoption of Ethernet within this context has revealed some limitations. The standard Ethernet lacks for mechanisms to isolate traffic for different functions and for real time traffic communication. Therefore, it has been used typically for non-critical applications in parallel with specialized networks for the critical ones. Due to this fact, usually multiple buses coexist in the same consist, turning into an increase of Life Cycle Cost (LCC).

Time-Sensitive Networking (TSN), the next generation standard Ethernet, provides strict determinism, redundancy, high-bandwidth, and interoperability. TSN overcomes the limitations identified in the sector. Thus, it can offer simpler network infrastructure and simplifies the whole sub-systems integration. As it will be presented in the next section, the new generation train communications networks proposed by the Train manufactures are based on TSN.

The relevance of TSN in the sector is not only driven by the train manufacturers. Railway operators, like Deutsche Bahn AG or SNCF have push Open CCS On-board Reference Architecture (OCORA). platform for cooperation to the benefit of the European Railway sector to develop an open reference architecture for on-board command-control and signaling systems. TSN is the proposed Data Link layer for real time traffic in this architecture (4).

WHAT IS TSN?

A significant success in merging critical and best effort traffic in a single media was achieved by Audio Video Bridging (AVB) initiative. Indeed, some of their technical solutions were valuable alternatives to other sectors.

As a result, the original AVB working group evolved to IEEE Time-Sensitive Networking (TSN) Task Group (5), which oversees developing the standards related to TSN. These standards propose enhancements for IEEE 802.3 networks to define a unique Ethernet based solution for OT and IT.

The fundamental base in TSN is the Time-Aware Shaper. It is designed to separate the communication on the Ethernet network into fixed length, repeating time cycles. These cycles are divided into timeslots according to the TSN configuration agreed between peers. The different time slots can be configured and can be assigned to one or several of the eight Ethernet priorities. The operation of the Time-Aware Shaper is defined in IEEE 802.1Qbv.

Considering this functionality, three basic traffic types are defined: *Scheduled traffic*, *Best-effort Traffic* and *Reserved Traffic*. *Scheduled Traffic* type is appropriated for the hard real-time messages, and the *Best-effort Traffic* is the general Ethernet traffic that is not sensitive to any other Quality of Service metrics. The *Reserved Traffic* type is for frames allocated in different timeslots but with a specified bandwidth reservation for each priority type.

The *Time Aware Shaper* allows defining the number of time slots available in each cycle, their duration and which priorities can be transmitted. Thanks to this mode of operation, the *Scheduled Traffic* has dedicated time slots to ensure the expected deterministic behavior. The *best-effort* traffic is accommodated in the remaining timeslots of each cycle of operation. An important improvement for the prioritization and bandwidth usage optimization in TSN is the support of *Credit Based Shaper*, as defined in IEEE 802.1Qav. This functionality allows using *Reserved Traffic* type, upgrading the priority of designed traffic in a state between the *Scheduled Traffic* and the *Best-effort* one. The technical challenge of providing nanosecond range synchronization accuracy among the TSN devices that compose the network is faced using IEEE 1588 timing synchronization protocol. Thanks to the accuracy provided by this technology, it is feasible ensuring controlled network delay and jitter implanting effective time-triggered Ethernet based solution. The specific IEEE 1588 profile for TSN is named IEEE 1588ASrev.

The configuration plane of a TSN Network is one of the most active topics in the standardization groups, industry, and academia. TSN communications are based on a data streams set between a Talker and a Receiver. Based on the agreed parameters for each Stream, it is necessary to configure all the elements of the TSN network to switch the frames based on the selected parameters. As it is shown in Figure 1, this operation is performed by a Centralized Network

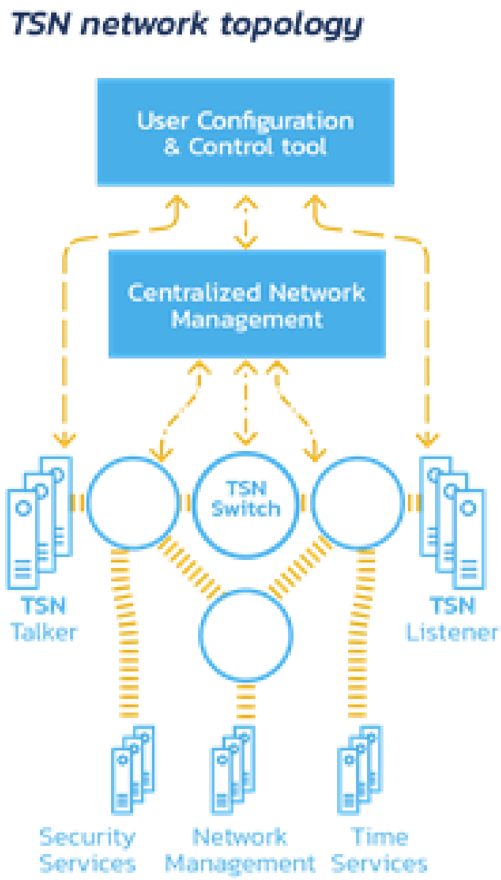

Figure 1 TSN network architecture.

Configuration (CNC) node. This CNC shall be able to talk to the equipment of different vendors in a standardized way. The early advances in this field are based on IEEE 802.1Qcc standard.

As it can be depicted from this introduction, TSN is not a single standard. Instead, it is a group of standards that are evolving at a different pace. Furthermore, many of them are still draft versions and probably, its evolution will depend on the real demand of these specific features from the market. The following list summarizes the most relevant standards involved in TSN: 802.1ASrev Timing and synchronization (currently, 802.1AS is used in most TSN implementations); 802.1Qbv Time-aware shaping; 802.1Qcc Stream Reservation Protocol Enhancements and Performance Improvements; 802.1Qci Per-stream filtering and policing; 802.1CB Redundancy; 802.1Qbu Frame pre-emption and 802.1Qch Cyclic queuing and forwarding.

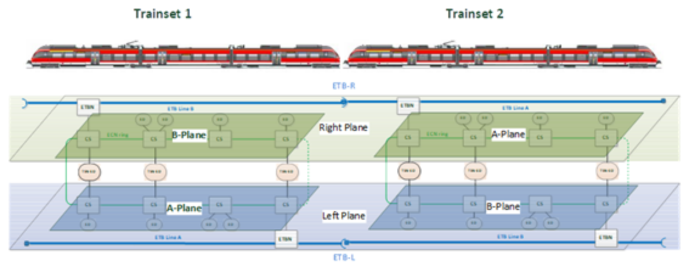

Figure 2 TSN based ETB and ECN networks in NG-TCN (6)

HOW TSN IS INTRODUCED IN THE RAILWAY SECTOR?

Train manufacturers and Railway operators are pushing TSN to overcome the technical limitations of standard Ethernet and to ensure interoperability at different levels (on-board equipment, trains, tracking infrastructure, signaling, etc.).

A comprehensive overview of this trend can be seen in the integration of Universal Vital Control and Command Bus (UVCCB) defined in OCORA initiative (pushed by the railway operators) (4).and in the Next-Generation Train Communication Network (NG-TCN) elaborated by the train manufacturers in Shift2Rail projects (6).

Figure 2 shows a redundant network structure combining ´ladder´ (Right Plane B and Left Plane A) for the Ethernet Backbone (ETB) and ring configuration in the Consist Networks (ECN). Non-critical devices are attached to the ECN via a single link while the critical ones connect to Plane B and Plane A.

The Consist Switches (CS) will oversee the networking in the ring and separating the ETB traffic for ETB Line A and ETB Line B to ensure the redundant operation.

One of the key TSN features in this approach is IEEE802.1CB. This substandard defines a procedure of frame replication and elimination at stream level. IEEE802.1CB offers zero-delay recovery time in case of network failure, as PRP or HSR, under any network topology.

As it is depicted in Figure 3, OCORA UVCCB can be integrated in NG-TCN network because both are based on TSN technology. The logical separation

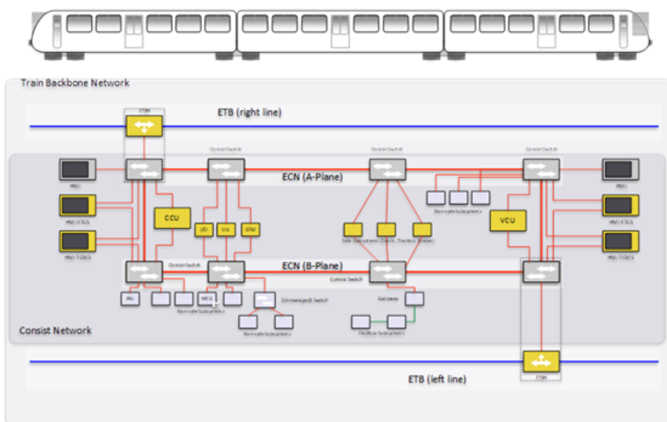

Figure 3 OCORAUVCCB integrated in ECN (ng-TCN) (4)

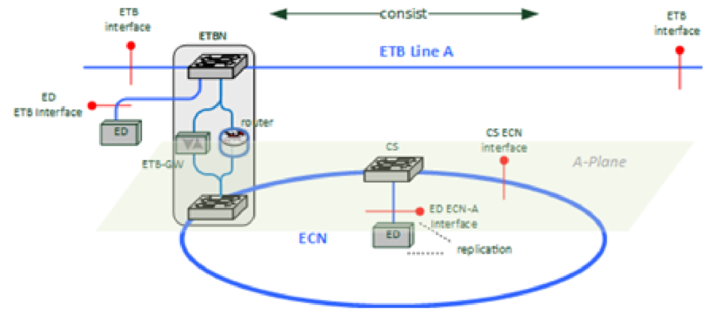

Figure 4 5x ports ETBN (6)

between different operator services can be done using different virtual local area networks (VLAN) enriched with the traffic shaping capabilities of TSN.

Attending NG-TCN ETB and ECN network topologies, the two type of switch devices are Ethernet Train Backbone Node (ETBN) and Consist Switch (CS).

CS are TSN bridges capable of supporting high-speed TSN networking in the ring. Currently, 1 GbE is the target speed, but 10 GbE is being considered as well. CS shall support Qbv and Qci among other TSN standards for a reliable mix of traffics with different criticality in the ring, and there is a demand for variants with a different number of ports. IEEE802.1CB in combination with MSTP will offer seamless redundancy for designated traffic, even in the ECN rings.

ETBN devices provide the physical connection between ECN and ETB as shown in Figure 2. The minimum configuration for an ETBN is three ports, two for ETB and one for ECN. However, there are many variants that need to be addressed. As an example, a five ports ETBN is suggested in the specification as shown in Figure 4. Two ports connect ETB line, two additional ports allow direct connection to ECN ring and an additional port offers direct connectivity to non-critical Electronic Devices (ED).

The functionalities defined for ETBNs are wider than TSN bridging operation. As an example, they will oversee the ETB inauguration and control, TND info services management and support IP routing for the best-effort traffic. Therefore, ETBN nodes shall be seen more as a complete Edge computing equipment with TSN networking capabilities than simple networking devices.

From the hardware and software technology point of view, it is a challenge defining and developing a flexible, robust and long-term embedded platform able to fulfill all these requirements. Solutions based on powerful reconfigurable platforms that combine multiple CPUs and FPGA in the same semiconductor, like Zynq Ultrascale+ MPSoC from Xilinx, are gaining popularity within this high-end equipment for the Industry in general, and for the Railway sector, in particular (7). The FPGA vendors ensure long-term supply of their integrated circuits. In addition, the reconfigurability nature of these devices enables hardware upgrades attending the evolution of the standards or potential fixes to cybersecurity vulnerabilities.

This new generation of Railway equipment combines several new and complex technologies. As an example, there are technology companies specialized on TSN that can provide field proven TSN technology or cybersecurity stacks. These third-party hardware or software IPs can be integrated in reconfigurable platforms in combination with vendor specific services. As a result, the time-to-market and the design risk of these projects might be significantly reduced.

Figure 5 shows a block diagram, which illustrates how a five port ETBN can be implemented on a Xilinx Zynq Ultrascale+ MPSoC device. The MTSN switch IP (8) implemented on the FPGA bridges TSN traffic. This IP switches and shapes TSN supporting redundancy according IEEE802.1CB, key TSN feature for NG-TCN.

The four ARM-A53 CPUs run a networking-oriented Operating System. Among other services, it

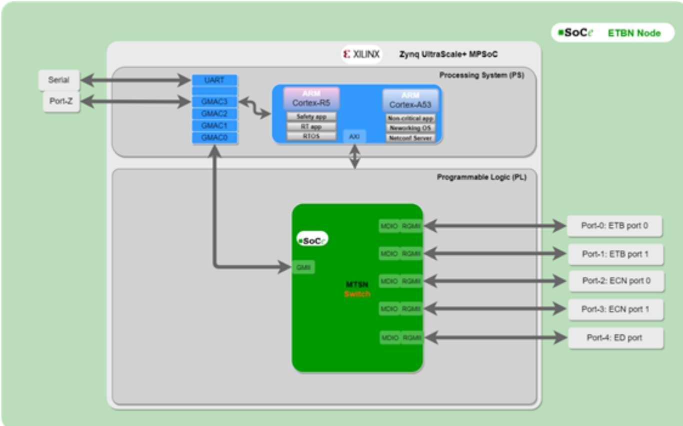

Figure 5 SoC design for a five port ETBN

provides TSN configuration management, IP routing and cybersecurity. The two ARM-R5 CPU hosts safety-critical and real time services, operation isolated from the networking services.

This TSN IP can be configured at synthesis time to support up to thirty-two ports. The number of ports and the TSN features included in the IP implementation can be selected at HDL code synthesis time by the designer. This flexibility ensures that the generated design is optimum in terms of FPGA resources utilization. For the design presented in Figure 5, the IP has been configured to support six TSN ports. Five externals, providing connectivity to ETB, ECN (ring) and to external ED, and one internal connecting the Processing System section to the switch.

The equipment manufactures that are introducing TSN within their products demand solutions to test and verify this new technology. There are several ongoing pilot TSN activities in Aerospace, Industry and Railway sector. Some of these initiatives are carried out by a group of manufacturers focusing on interoperability test (9; 10; 11). However, manufactures and research centers are developing their own TSN pilot according to the specific goals of each sector.

In general, the first hands-on with TSN is done running a comprehensive TSN kit (12). A complete video demonstration is embedded in the set-up to facilitate the exploration of the effects of the synchronization, traffic scheduling and traffic shaping under network saturation. A one snapshoot of the demonstration application is represented in Figure 8. In addition to the functional operation analysis provided by the

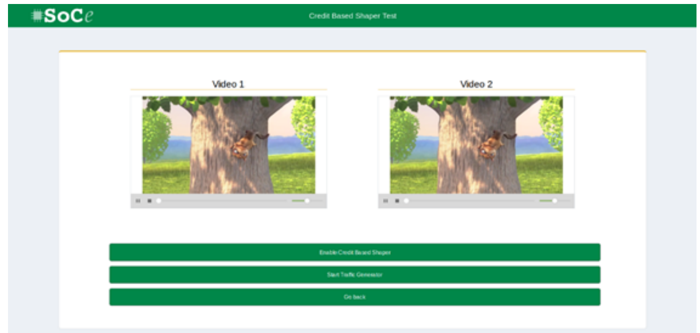

Figure 6 Credit Based Shaper test using an evaluation kit

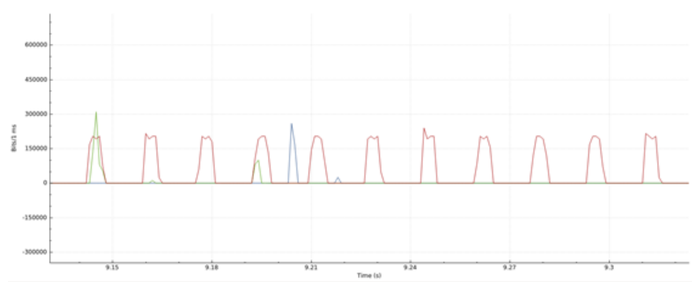

Figure 7 TSN traffic shaping monitoring

Videos, the traffic shape can be visualized using the popular Wireshark application on the PC as shown in Figure 7.

The next step is defining a more complete pilot that allows TSN evaluation, testing and verification. Figure 8 summarizes an example of TSN pilot (13). The TSN end-node operation is evaluated in host computers using the RELY-PCIe TSN cards and in third-party end-point shields. The bridging operation is carried out by the four and twenty-four port TSN bridges (14).

In these setups, the customer can analyze how run its own applications, and the whole network configuration and behavior. To perform a deeper analysis, the TSN traffic can be timestamped and recorded using specific equipment like the two RELY-TSN-REC devices shown in Figure 8.

CONCLUSION

Railway sector has evolved serial Train Communication Networks to Ethernet based solutions. The lack of real-time traffic communication and functions isolation capabilities of stand Ethernet has limited the adoption of standardized Ethernet based solutions.

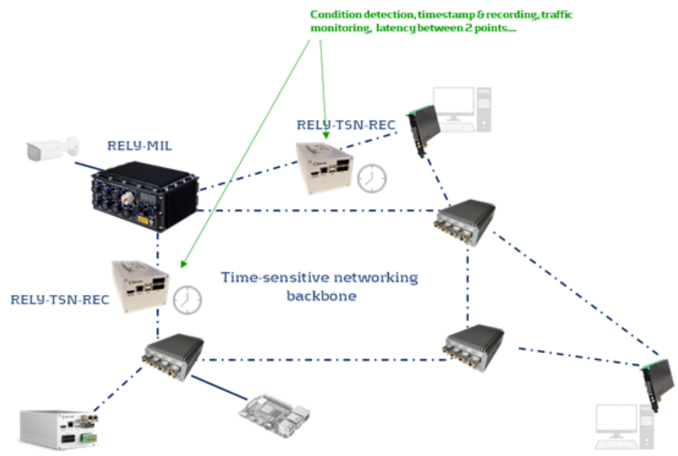

Figure 8 Example of TSN Pilot network configuration

TSN overcomes the identified limitations, and it has been identified as a strong candidate for the next generation Data Link layer for railway communications by the railway manufactures and operators.

The new generation of TSN capable Edge-computing equipment for the Railway requires the integration and development of a variety of technologies and capabilities. Reconfigurable platforms (SoCs) with powerful hardware and software capabilities combined with specialized third-party IPs cores, like MTSN IP from SoC-e, are the preferred alternative to reduce design risks and time to market of these emerging products.

The process of evolving to new technology like TSN is not straight forward. It requires hands-on, testing, validation and jointly work among the different players. In this sense, Railway sector has put TSN working in real train (15) and the wide ongoing research and development activity in this field show that the future is here.

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