IEEE TSN (Time-Sensitive Networking): A Deterministic Ethernet Standard

More than ten years ago, TTTech started a research program to answer the question as to whether it would be possible to provide real-time and safety capabilities over Ethernet, in a way that is fully compatible with IEEE 802 Ethernet standards. Based on the company's expertise in time-triggered and scheduled networks, a solution was developed and evolved over time. The solution first appeared as Time-Triggered Ethernet, and was designed in to NASA's Orion project in the mid 2000's. The Orion spacecraft, with TTTech technology on board was successfully launched into space in 2014. In the decade since it was first developed, Time-Triggered Ethernet has been standardized as SAE AS6802 and used as a deterministic communication protocol in a range of aerospace, automotive, and industrial controls applications. Today, TTTech offers a Deterministic Ethernet solution which integrates SAE AS6802 along with IEEE 802.1 AVB (Audio-Video Bridging) and the emerging IEEE 802.1 TSN (Time-Sensitive Networking) standards. This paper will focus on TSN, and its constituent sub-standards, giving an overview of TSN technology, its applications and the advantages of using it.

Real-Time Ethernet

Ethernet technology has proven incredibly successful and is a near ubiquitous method of communication in the IT world. It is a very well standardized and open technology that is easily accessible to everyone, provides a wide range of bandwidth and physical layer options, and has significant support in a diverse range of application areas. Up until now there has been no real-time support in IEEE standardized Ethernet, leading to a number of proprietary modifications of Ethernet being used in industrial and transportation systems where real-time communication is a critical requirement. These solutions have typically been developed for specific tasks or domains, e.g. Profinet, EtherCAT and Ethernet/IP which compete for recognition in industrial automation. While these protocols perform their specialized tasks capably, they have limits when it comes to combining with standard (classical) Ethernet networks and devices. The scalability of adapted Ethernet solutions for different industries is also limited as each is tailored for a specific application area.

For this reason the IEEE Time-Sensitive Networking task group has been working since 2012 on standardizing real-time functionality in Ethernet. TSN (Time-Sensitive Networking) is the set of IEEE 802 Ethernet sub-standards that are defined by the IEEE TSN task group. The new standards describe several mechanisms for improved or even guaranteed real-time delivery of

Ethernet traffic. Most prominently, TSN defines the first IEEE standard for time-triggered message forwarding in a switched Ethernet network, and therefore fully deterministic real-time communication within the 802 suite of standards.

TSN achieves deterministic real-time communication over Ethernet by using global time and a schedule which is created for message paths across multiple network components. By defining queues which transmit their messages based on a time schedule, TSN ensures a bounded maximum latency for scheduled traffic through switched networks. In control applications with strict deterministic requirements, such as those found in automotive and industrial domains, TSN offers a way to send time-critical traffic over a standard Ethernet infrastructure. This enables the convergence of all traffic classes and multiple applications in one network.

Standard	Description
802.1Qbv	Time-aware shaping (per-queue based)
802.1ASrev	Timing and synchronization (mechanisms for faster fail-over of clock grandmasters)
802.1CB	Redundancy (frame replication and elimination)
802.1Qca	Path control and reservation (based on IEEE802.1aq; IS-IS)
802.1Qbu	Frame pre-emption
802.1Qcc	Enhancements and improvements for stream reservation
802.1Qch	Cyclic queuing and forwarding
802.1Qci	Per-stream filtering and policing

Figure 1: Selection of TSN sub-standards

Advantages of TSN

Industrial applications such as machine control, robotics, power generation, process control and transportation all require real-time communication to perform safely and securely. To ensure that this critical requirement is met, industrial systems have typically either implemented modified Ethernet variants or dedicated standard Ethernet networks running in parallel. Now, industrial systems are expanding out from small closed networks to an Industrial Internet of Things, where reliable, converged, remote, secure access to all network components is needed. Limited Ethernet access will no longer suffice for customers wishing to incorporate IoT concepts into their industrial systems to increase productivity, increase up-time or reduce maintenance. TSN supports both industrial control and IoT connectivity needs, enabling industrial real-time systems to benefit from techniques such as remote system management and maintenance, centralized data analytics and machine to machine coordination.

TSN (Time-Sensitive Networking)

In general, IEEE TSN standardization extends the functionality of standard Ethernet to now ensure that:

- Message latency is guaranteed through switched networks
- Critical and non-critical traffic can be converged in one network without risk of impact on the delivery of the critical traffic by collisions with the non-critical traffic
- Higher layer protocols can share the network infrastructure with real-time control traffic
- Components can be added to real-time control systems without network or equipment alterations
- Network faults can be diagnosed and repaired faster because of more precise information on their source

Description of Key TSN Standards

802.1Qbv

At the core of Time-Sensitive Networking is a time-triggered communication principle. In TSN this concept is known as the "time-aware shaper" (TAS), which deterministically schedules traffic in queues through switched networks. It is being standardized as IEEE 802.1Qbv. The principle operation is depicted below.

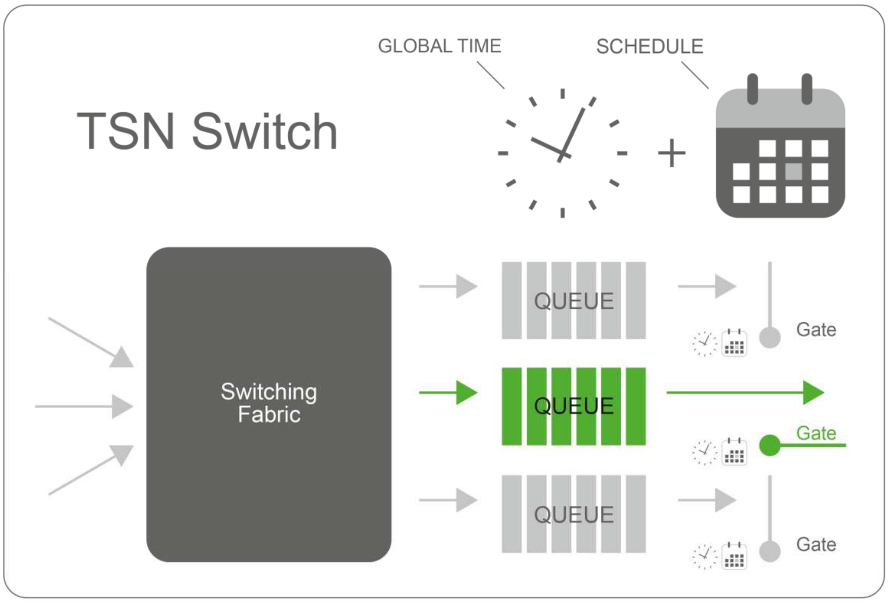

Figure 2: Representation of TSN queues and transmission gates

With the time-aware shaper concept it is possible to control the flow of queued traffic from a TSN-enabled switch. Ethernet frames are identified and assigned to queues based on the priority field of the VLAN tag. Each queue is defined within a schedule, and the transmission of messages in these queues is then executed at the egress ports during the scheduled time windows. Other queues will typically be blocked from transmission during these time windows, therefore removing the chance of scheduled traffic being impeded by non-scheduled traffic. This means that the delay through each switch is deterministic and that message latency through a network of TSN-enabled components can be guaranteed.

The TAS introduces the concept of transmission gates. A gate has two states, ‘open’ and ‘closed’. The transmission selection process, which selects the next message for transmission at the egress, will only select messages from those queues whose gates are in the ‘open’ state. The state of the gates is also defined by the network schedule. Closing gates to non-scheduled traffic queues is another method of providing immunity to time-critical messages in order to guarantee bounded maximum latency through the network.

While the TAS guarantees that critical messages are protected against interference from other network traffic, it does not necessarily result in optimal bandwidth usage or minimal communication latency. Where these factors are important, a pre-emption mechanism can be used.

802.1Qbu

IEEE 802.1Qbu works together with IEEE 802.3br (Interspersing Express Traffic Task Force) on a standardized pre-emption mechanism. This standard addresses the fact that the TAS described in IEEE 802.1Qbv avoids transmission jitter by blocking lower priority queues (for the duration of one maximum interfering frame) in advance of the transmission point of the critical frame. In cases where minimal latency for scheduled messages is desired, the TAS mechanism may not be the optimal solution. Therefore on links where pre-emption as defined by IEEE 802.1Qbu is supported, the transmission of standard Ethernet or jumbo frames can be interrupted in order to allow the transmission of high-priority frames, and then resumed afterwards without discarding the previously transmitted piece of the interrupted message. There are a few use cases in which a communication option to preempt an ongoing transmission is beneficial, e.g. to allow immediate transmission of a scheduled message and ensure minimum communication latency, or to facilitate maximum bandwidth usage on network links with a large amount of scheduled traffic.

802.1ASrev

Clock synchronization is a vital mechanism for achieving deterministic communication with bounded message latency in TSN. A robust mechanism for providing global time lays the foundation for the scheduling of traffic queues through each participating network component. The IEEE 802.1ASrev project is working to create a profile of the IEEE 1588 PTP synchronization protocol for TSN. This profile will enable clock synchronization compatibility between different TSN devices. The work is happening in parallel with a project in the IEEE 1588 working group in order to harmonize the two standards, such that IEEE 802.1AS eventually becomes a profile of IEEE 1588.

802.1ASrev also addresses support for fault tolerance and multiple active synchronization masters.

FaultTolerance:

IEEE 802.1ASrev standardizes the use of multiple grandmaster clocks as well as the possibility to make multiple connections to these grandmaster clocks. Replication of grandmaster clocks results in shorter fail-over times in cases when a grandmaster becomes faulty. In these cases, system elements such as end nodes and bridges are still able to remain synchronized by taking the time from the redundant grandmasters. Having redundant connectivity from the end nodes and bridges to the redundant grandmaster clocks also allows the network to tolerate the loss of network links or even bridges while still maintaining a synchronized timebase.

Multiple Synchronized Times:

There are many use cases that show the benefit of having the network concurrently support a “working clock”, used to trigger time-critical events, and a “universal clock” or “wall clock”, typically used to timestamp events. For these cases, IEEE 802.1ASrev will support multiple synchronized clocks. This enables the timestamping of events such as production data or measurements, and the synchronization of applications such as sensors, actuators and control units.

802.1CB

The IEEE 802.1CB standard implements a redundancy management mechanism similar to the approaches known from HSR (High-availability Seamless Redundancy – IEC 62439-3 Clause 5) and PRP (Parallel Redundancy Protocol – IEC 62439-3 Clause 4). In order to increase availability, redundant copies of the same messages are communicated in parallel over disjoint paths through the network. An existing standard, Path Control and Reservation – IEEE 802.1Qca, defines how such paths can be set up. The redundancy management mechanism then combines these redundant messages to generate a single stream of information to the receiver(s). While the TSN working group has not yet finalized the standardization of a particular redundancy management mechanism, it is likely that it will be based on sequence numbers. Sequence numbers (and potential additional meta information) will be transported in a dedicated redundancy tag within the Ethernet frame similar to the VLAN tag. This redundancy mechanism will eliminate duplicates (i.e. redundant copies of the same message), but will likely not guarantee in-order delivery of the messages.

802.1Qcc

TSN also provides mechanisms to improve existing reservation protocols such as SRP (Stream Reservation Protocol – IEEE 802.1Qat) in order to meet the requirements of industrial and automotive systems. These include support for more streams, configurable SR (Stream Reservation) classes and streams, better description of stream characteristics, support for Layer 3 streaming, deterministic stream reservation convergence, and UNI (User Network Interface) for routing and reservations. TSN configuration can be achieved statically by a network designer, or dynamically by a network service. For example, the Path Computation Element (PCE) as developed by the IETF (RFC 4655) and the corresponding Path Computation Communication Protocol (RFC 5440) could be extended not only to find routes through a network, but also to configure the communication schedules for time-aware shaping.

Scheduling

The configuration of large and complex networks is no simple task, but it is easily achieved using the right tools. For unsynchronized communication networks, configuration tools need to perform complex calculations in order to provide the worst-case latencies, communication jitter, and buffer requirements in the switches. Synchronized communication as defined in TSN requires scheduling, but does not suffer the same burden of network calculus. Scheduling takes into account the necessary latencies, jitter and buffer requirements and delivers provable determinism. For example, in IEEE 802.1Qbv the times of message transmissions in the end nodes and the forwarding times in the switches can be aligned to each other with respect to a network-wide synchronized time (as for example established by IEEE 802.1AS).

The transmission and forwarding times of different messages need to be sufficiently offset from each other, such that queueing delays can be minimized. The definition of these various points in time for all synchronized traffic is called the communication schedule. Tools that produce such a schedule have to solve a complex search problem but remove the burden of network calculus and testing from network engineers. Those companies with experience developing such scheduling tools typically embed them in customer tool chains or offer them as specialized products.

Use Cases

As noted earlier, there are a wide range of application areas requiring real-time communication where TSN can enable greater flexibility and ease of use without sacrificing deterministic performance. For example in wind turbines, deploying critical control over Ethernet helps to cut downtime and increase production efficiency. In railway applications, convergence of critical train control networks over Ethernet saves space, weight and power, in addition to improving system reliability. Similarly, in-car controls communication can be converged over a TSN backbone network to offer a safe, yet low-cost solution for applications like autonomous driving. Let's take a look at two use cases in a little more detail:

Factory Automation

In a discrete automation plant with multiple robots working on production lines, TSN will enable far greater operational flexibility. Today these robots are controlled locally, with limited synchronization between them, and bottlenecks for data access from beyond the factory floor. Where there is connectivity, it is either done over proprietary networks or via gateways. By removing local control functions or converging non-critical traffic in the same network, one could jeopardize the guarantees for communication of critical messages. By utilizing a TSN connection between these robots, the controls communication is guaranteed across the network even when converged with non-critical traffic, and all robots are synchronized to the same global time. This means that controls networks can be integrated with data networks, and many control functions can be centralized away from the robot cell, into a controls cloud where greater computing power can be utilized. Importantly, huge amounts of data from the robots are now also visible to higher layer networks without the need for gateways, enabling Machine as a Service (MaaS) type business models – simultaneously improving service and maintenance from machine builders and lowering capital expenditure for end users.

Power Generation

TSN will enable more precise optimization of plants, cheaper energy production and reduced maintenance costs. Power plants are large and complex, with new applications being added to the plant infrastructure over time. These multiple different systems must operate together to produce energy efficiently. However, there is often a wide variety of communications platforms, which only serves to further increase the system complexity. Where there are real-time communications requirements, these systems can be especially isolated from higher level networks. By using TSN Ethernet as a standard communications platform for all of the various systems, plant infrastructure can be greatly simplified. With TSN, systems requiring deterministic and reliable communication are integrated by scheduling time-critical traffic, while the higher layer protocols needed for SCADA management and security are able to run on the same network. The ease of maintaining only one network is clear, but TSN also has the advantage that network faults can be more quickly identified and fixed at the component level. Closer integration of power plant systems allows for further efficiency improvements. TSN opens up the possibility of giving cloud-based services access to real-time plant and turbine data to optimize performance and reduce the cost of production.

Industry Support for TSN

TSN has garnered the attention of major players from all sides of the industry. Companies such Cisco, GE, National Instruments and TTTech are supporting TSN as a networking platform for the Industrial Internet of Things. They are all members of the Industrial Internet Consortium (www.industrialinternetconsortium.org), which aims to implement technologies in real-world applications, and is setting up a test bed for TSN in order to further define and develop the reference architecture and frameworks necessary for interoperability. The AVnu Alliance (www.avnu.org) is a key body working to create an interoperable ecosystem for TSN. AVnu members including Bosch, Intel, NXP and TTTech have a mandate to define certification which ensures that TSN is easy to implement and has broad global market appeal. Because of its non-proprietary nature, TSN is being championed by robot-maker KUKA as the real-time communication standard for Industry 4.0. To this end, the OPC UA working group within the OPC Foundation (www.opcfoundation.org) is aiming for a real-time expansion of OPC UA to include TSN.

These groups are primarily focusing on using TSN as a method of machine2machine communication and as a platform for systems of systems convergence. It is therefore not being developed as a replacement for specialized solutions in the low data, low latency areas of I/O or drive control. TSN is intended to be as interoperable with existing Ethernet-based protocols as possible.

TTTech and TSN

TTTech is a member of AVnu, the Industrial Internet Consortium and the OPC Foundation. It is actively supporting the standardization process in the IEEE TSN task group, and is also offering a pre-standard implementation of TSN in its Deterministic Ethernet products. TTTech's products implement 802.1Qbv with the time-aware shaper for scheduling critical traffic. They also support the mechanisms for implementing 802.1QASrev for grandmaster clock fault tolerance. In addition, TTTech provides a full range of tools for creating network communication schedules.

TTTech has also partnered with NXP to develop an ASSP for the automotive market. The Deterministic Ethernet chip IP used in this NXP ASSP supports Time-Triggered Ethernet (SAE AS6802) as well as the IEEE AVB and IEEE TSN sub-standards. The chip will be available in series production early in 2016. TTTech is also releasing a Deterministic Ethernet Starter Kit, with the TSN 802.1Qbv sub-standard as its main focus. This kit enables customers to learn more about TSN and evaluate their own applications over a Deterministic Ethernet network.

Conclusion

TSN enables real-time communication over IEEE standard Ethernet. For this reason it is being strongly supported by a broad alliance of major industrial companies. These companies see TSN as a standard and securable network that provides a platform for connecting critical system infrastructure with IT features. This network platform, combined with high-quality scheduling tools, will help companies in the fields of industrial automation, transportation and energy production to realize the commercial value of integrating real-time systems into the Internet of Things.

Contact

TTTech Computertechnik AG
Schoenbrunner Strasse 7
A-1040 Vienna, Austria
Tel.: +43 1 585 34 34-0
Fax: +43 1 585 34 34-90
E-mail: office@tttech.com
Web: www.tttech.com