A Survey on Time-Sensitive Networking and its applications in Industrial IoT

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***Abstract*—Modern industrial automation is changing rapidly due to the increasing spread of the Internet-of-things in this area. But despite this, further development of the industrial IoT is hampered by the lack of a common approach for real-time networks. Such networks require determinism, reliability, and frame synchronization, which are challenges for classic Ethernet. This paper provides an overview of TSN standards and the potential benefits they promise for industrial IoT in various use cases.**

***Index Terms*—synchronization, Industrial IoT(IIoT), time-sensitive networking (TSN), generic precision time protocol (gPTP).**

I. Introduction

Network data can be categorized as time-sensitive or non-time-critical; more often than not, both share network resources to reduce costs and better utilize resources [1]. In time-sensitive applications, task completion is dependent not only on the logical correctness of the result but also on its successful delivery within some deadline [2]. So, it is essential to guarantee low latency for time-sensitive traffic while also providing prioritization and separation from non-time-critical communication. Moreover, timing is not the sole important factor to consider; reliability, security, and fault tolerance are also crucial requirements for these applications [1]. Physical separation of time-sensitive or non-time-critical networks is feasible (using fieldbus), but it causes interoperability issues, is expensive, requires constant upkeep, and adds complexity [1], [2].

The forwarding mode of most Ethernet is "best-effort", where when a frame arrives at the sending port and is ready to be sent, the sender forwards it on a first-in, first-out basis. Usually, with enough bandwidth, this best-effort Ethernet network can accommodate most situations today. However, when there are multiple frames to be sent at the same time, the data is queued and the waiting time is determined by a number of factors such as queue length and data transmission speed. If there is too much traffic in the network, congestion or frame loss can occur, and queuing times become unpredictable and uncertain, leading to problems with traffic scheduling, time synchronization, traffic monitoring, and standardization of fault tolerance mechanisms. In some applications, this uncertainty is intolerable, such as telemedicine or network-assisted autonomous driving [3]. In these security or life-critical network applications, a single transmission uncertainty can have irreversible consequences. In order to guarantee the deterministic behavior of some of the more important controlled physical systems, a real-time network with deterministic, low network latency, and delay variation (jitter) is required. As a result, TSN standards have been proposed [3].

In time-sensitive networks high-priority deterministic information flows (e.g. motion control) can share the physical medium with other communication traffic (e.g. audio and video streams). Different services have different requirements for latency, especially in those areas of services where deterministic transmission is required and where the requirements for latency and jitter are particularly sensitive.

TSN standards defined in IEEE Std. 802.1 help achieve deterministic behavior in the network for time-critical applications. IEEE Std 802.1AS-2020 [4], which deals with timing and synchronization for TSN applications, IEEE 802.1Qb [5] and IEEE Std 802.1CB-2017 [6] are discussed in Section II of this paper, with a detailed discussion on applications of TSN in *Industrial IoT* in Section III, and current trends and challenges are discussed in Section IV.

II. TSN standards

A concise overview of the current state of TSN standards, with a focus on *time synchronization*, *frame preemption*, and *streaming reliability* is discussed. While there are many other important aspects of TSN, we have chosen to focus on these specific features to provide a concise and in-depth examination of the current state of the field. The choice of the specific features to be discussed is based on the authors' research interests and space constraints, which limited the scope of the survey.

A. Timing and Synchronization

Time synchronization in communication refers to the process of aligning the time of clocks among different devices in a network so that they are all in agreement about the current time. This is important because many applications and protocols rely on accurate time stamps to function correctly. Time synchronization is critical in many systems and protocols, as it enables devices to accurately exchange information and coordinate their actions in real-time [2].

The high-precision *time synchronization* characteristic of TSN achieved generic precision time protocol (gPTP) [7].

Std. IEEE 802.1AS [4] deals with timing and synchronization in TSN. This standard defines and establishes the time synchronization requirements for TSN applications [4]. IEEE 802.1AS uses the foundation of PTP (Precision Time Protocol) [4] from the IEEE 1588 working group. A generic precision time protocol (gPTP) has been introduced in IEEE 802.1AS-2020. *gPTP* employs a *Grand-master* Clock [4] which sends a continuous multi-cast message often through intermediate bridges to slaves in a hierarchical manner as represented in the Fig. 1, slaves calculate *link delay* and offset to precisely synchronize with an accuracy of few hundreds of nanoseconds (ns) [4], [7]. IEEE 802.1AS-Rev includes the inclusion of a redundant grand master to support multiple domains(backup GM, as in Fig. 1), which acts as Grand-Master(GM) if the other fails to provide time correctly. Time synchronization is

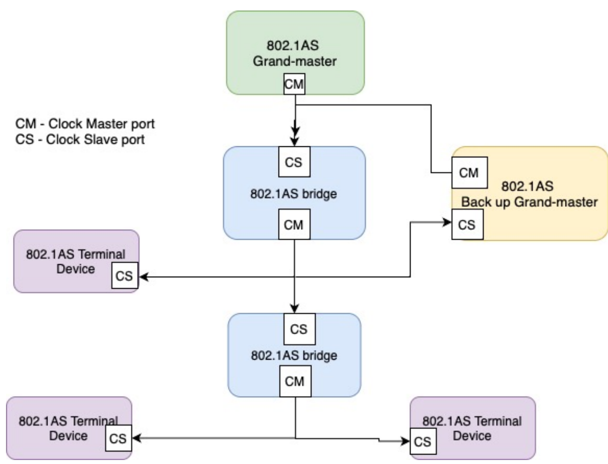

Fig. 1. The architecture of gPTP with redundant Grand-master.(deduced from [8])

fundamental in TSN, as it enables the achievement of low latency for time-sensitive applications by using gPTP time synchronization.

B. Frame Preemption

The IEEE 802.1Qbu standard [5] offer solutions to overcome the prioritization problem described above for Ethernet frames. They suggest defining special classes of service for time-critical frames that will force the transmitter to stop transmitting non-critical frames while the critical ones are being transmitted. The standart describes an interface to configure, detection and management of the preemptive service. It is mandatory for connected ports to mutually agree to enable frame preemption in order to activate it. [9]

This standard is one of the key standards in future industrial Ethernet-based networks because it ensures that critical data is exchanged with minimal delay. Otherwise, the data link will not provide the required level of traffic prioritisation. Preemption is necessary to let ahead a frame with a critical latency. Without it, such a frame will wait for other less urgent frames to complete sending, increasing latency.

The Fig. 2 shows how a large, none time-critical red (LP) frame may start before a time-critical green (HP) frame. As a result, information that requires a high class of service gets the highest priority, while lower priority information gets extra delay.

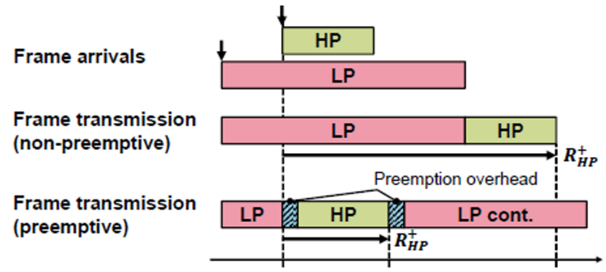

Fig. 2. Example of non-preemptive and preemptive frame transmission. [9]

C. Streaming Reliability

Given the large number of unpredictable anomalies and unexpected failures in network communications, this can lead to significant delays in data transmission and even data loss. To mitigate such contingencies, TSN introduces a redundant path mechanism. To this end, TSN has published the independent standard IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) standard [6].

The IEEE 802.1CB standard [10] achieves spatial redundancy by backing up data and sending it to a different link. The 802.1CB protocol is mainly responsible for the redundant backup transmission of data, and uses the redundancy mechanism to solve the problem of information transmission error or loss. [6] In implementing redundant transmission paths, data frames need to be replicated before transmission and then transmitted over two separate paths. When the first data frame reliably arrives at the target node, it is forwarded to the application layer, and then the second redundant data frame is identified and discarded. When the redundant path mechanism is implemented, the data sent will be specially labelled and sequentially numbered and will be copied and transmitted through different nodes. When data frames are aggregated, the data that arrives first will be selected and other duplicate data frames will be discarded. Both faults and frame loss are steady, and even if there are faults at certain locations, other paths will still work, thus increasing the reliability of data transmission.

The IEEE 802.1CB standard defines a FRER mechanism for spatially redundant transmission through frame duplication and cancellation, but this undifferentiated frame duplication has a large overhead. Therefore, the literature [11] investigates active redundancy and hybrid temporal redundancy to cope with temporary failures while reducing unnecessary overheads. As critical service flows are the main target of reliability protection, to further reduce redundancy resource consumption, literature [12] considers fault tolerance of ST flows in the calculation of GCL phases. The literature [13] proposes a joint routing and scheduling computation method based on a conflict degree aware greedy heuristic algorithm to minimise the conflict degree between generating graphs. The method provides different redundancy guarantees by grouping highly interdependent flows and creating non-intersecting transport paths for identical source and destination flows.

D. Summary of standards

In this paper we have mentioned some of the TSN IEEE standards which are listed in the Table I.

TABLE I
TSN IEEE STANDARDS COVERED IN THE PAPER

Standart	Description
802.1AS	Timing and Synchronization for Time-Sensitive Applications
802.1Qbu	Frame Preemption
802.1Qbv	Enhancements for Scheduled Traffic
802.1CB	Frame Replication and Elimination for Reliability

In addition, the TSN family of standards includes more members. Some of them are listed in the Table II.

TABLE II
TSN IEEE STANDARDS NOT COVERED IN THE PAPER

Standart	Description
802.1Qcr	Asynchronous Traffic Shaping
802.1Qch	Cyclic Queuing and Forwarding
802.1Qci	Per stream filtering and policing
802.1Qcc	Stream reservation enhancements
802.1Qav	Forwarding and Queuing Enhancements for Time-Sensitive Streams
802.1Qat	Stream Reservation Protocol
802.1Qca	Path Control and Reservation

III. INDUSTRIAL IOT APPLICATIONS

A. Real-Time Monitoring Systems

One of the requirements for the factory of the future (Industry 4.0) is considered to be the ability to operate in real time. This demands the system's ability to adapt quickly to new requirements, such as changes in the market or in the production chain. The speed at which possible problems can be detected and resolved is a priority in the factory of the future [14]. For this, the system must be able to report on its status in real time. Then its various components can make timely decisions and provide monitoring to the management. The real-time response of the system provided by TSN will enable the system to reorganise and recover quickly. The 802.1Qbv standard [15] helps in queuing process to schedule bridges and end stations for frame transmission. TAS uses periodic static scheduling for gate control in combination with 802.1Qbu [5] for greater effect. In this way, determinism and minimal jitter are possible with proper timing [16]. TSN could be a future-proof solution that can help standardise monitoring systems. Ethernet as the underlying transmission technology avoids many different interfaces and uses a single standard that allows devices and sensors to be connected directly or via a hub to the real-time network. This results in a unified solution for production plants with configurability and almost unlimited scalability which can match and even outperform traditional field buses like CAN or Modbus.

B. Industrial Robotics

Typical industrial IoT application scenarios include sensor readings such as pressure, temperature, humidity, acceleration, position in space and sending them to the controller for further actions. In industrial robotics the many processes are very dynamic, so applying TSN can play a role. Additionally, the choice of Ethernet as a communication interface promotes unification, which potentially helps to handle complexity and can be beneficial in industrial robots design [17]. Industrial robots need to operate in real time, so traditionally such systems have been designed as a single unit to optimise processes and minimise delays. With the introduction of TSN, it is possible to introduce modularity into industrial robots as well, assembling them from a variety of generic Industrial Internet devices and connecting them to each other via an Ethernet network. One of ABB's industrial robots in the Fig. 3, supports communication via Ethernet, and given the company's interest in TSN, we can expect the development of industrial robotics in this direction for the foreseeable future.

Fig. 3. ABB Yumi industrial robot. [17]

C. Safety and Emergency Systems in Industrial Plants

TSN can be used to enable real-time communication among safety devices in industrial plants, such as emergency shutdown systems. TSN can provide the low latency and high reliability required for these critical safety systems [18]. In an emergency shutdown system, TSN can be used to enable real-time communication between sensors, actuators, and other devices. For example, if a sensor detects a hazardous condition, it can send a message to an actuator to shut down a process or piece of equipment. TSN can also be used to enable real-time communication between control systems and operators, allowing them to monitor and respond to emergency situations in real-time. In addition to emergency shutdown systems, TSN can also be used in other safety-critical systems in industrial plants, such as fire and gas detection systems and access control systems.

One of the key issues in TSN is integrating existing safety systems into TSN network. The study [18] found that integrating critical safety (non-TSN) devices to industrial TSN network system is feasible with deterministic properties. The results demonstrate that this system operates reliably even under the most challenging circumstances, such as when external broadcast traffic completely fills the available bandwidth. The benefits of TSN's time synchronization features, which enable common time among safety systems, are also detailed [18].

D. Visual Quality Control System

Visual monitoring of manufactured products to spot possible issues or defects using image processing techniques is a widely employed quality control method. The video feed generated in this process can easily overload the network. TSN's ability to isolate network data based on time-sensitive requirements to ensure that the real-time data is transmitted with the required accuracy will be beneficial in this case. This is achieved through a combination of techniques such as precise time synchronization, bandwidth reservation, and quality of service (QoS) mechanisms [19].

The paper [19] discusses the difficulties associated with using large amounts of data in a production setting. Using high-quality video feeds can generate a large amount of data, which can cause network congestion in the plant. It is not always possible to isolate and create a separate network for each video feed. Because this would necessitate upgrading each time a new service is introduced. The most practical option is to use a time-sensitive network based on TSN standards, which can be retrofitted into existing plants once and eliminates the need for continuous upgrades. TSN is a more efficient and cost-effective solution for dealing with large data streams in a production environment.

E. Industrial Device Linking with TSN

With the application and development of the Industrial Internet, communication networks and physical systems will be closely linked, i.e. factory networks connect processors and sensors at the production site, allowing industrial production equipment to communicate with each other, thus enabling intercommunication and forming a smart factory.

In November 2019, Bosch and Qualcomm demonstrated two industrial devices working together via real-time 5G networks using TSN at the Smart Production Solutions trade fair in Nuremberg, Germany [20]. The two parties jointly demonstrated two industrial terminals connected wirelessly and operating in a time-synchronised manner, showing that the combination of TSN and 5G enables precise synchronisation without the need for a wired connection .

The demonstration uses a 5G industrial test terminal to enable real-time communication between two Bosch core controllers under a 5G test network. Users can view two industrial devices (Bosch motors and industrial flashers) running in time synchronization via a wireless connection. One of the TSN core controls can also be assigned the 3.7 to 3.8 GHz band for real-time interaction via 5G. This band is currently designated by Germany for use by industrial companies as a dedicated 5G network. This lays the foundation for TSN to enable private network interconnection.

F. TSN and 5G-Based Production Management

Intel and Bosch have established an early proof-of-concept project for TSN and 5G convergence technology [21]. The project is based on Intel's 5G prototype solution for remote control, production, and real-time monitoring needs of smart factories.

In this project, supported by the plant's wired infrastructure, two sets of TSN programmable logic controllers use a unified architecture protocol standard for open platform communication for 5G communication, enabling control of industrial equipment movement angles and high-speed rotor speed synchronisation. In terms of specific performance, the project demonstrated 5G system-based TSN synchronisation with timing errors well below 1 microsecond and unidirectional delays of up to 4ms for time-critical motion control commands, as well as live 4K UHD video streaming in a dedicated 5G industrial band. This project was one of the first to demonstrate the capabilities of TSN and 5G convergence technologies, enabling 802.1as-based synchronisation and 802.1qbv-based time-aware keyframe delivery under 5G systems. Industrial time synchronization of the entire plant system over a 5G + TSN network allows network devices to operate in perfect unison across multiple plant sites, a key requirement for flexible automated production.

IV. Current Trends and Challenges

A. TSN integration in 5G and Wireless networks

TSN evolved from traditional Ethernet for time-critical applications, but in recent times, it has been observed that there is an increase in research papers published on TSN with the keywords ”wireless communication” and ”5G”. In light of the increased complexity of more connected devices, most industries require wireless communication networks. Wireless communication provides greater flexibility than wired ethernet communication, such as TSN [7]. The integration of TSN technology with 5G networks to enable real-time communication between wireless devices is one trend in TSN. This can be especially helpful for low-latency, complex wireless applications with a large volume of connected devices, like industrial *IoT* and automation, robotics, and aviation. The authors in [7] proposed and investigated the effectiveness of the ”over-the-air time synchronization” technique in their paper, which is time synchronization among wireless devices, this is important progress in 5G/TSN integration.

B. Hybrid TSN

The aforementioned use of TSN in wireless networks generates both wired and wireless TSN; however, integrating both to form a hybrid TSN is difficult because all devices in the hybrid network must be time synchronized [22]. The authors in [22], conducted a detailed study on the Wired and Wireless TSN, for the integration of wireless and wired TSN communication, the authors proposed a thorough design of a hybrid TSN architecture. Technology-independent and adaptable, the hybrid TSN architecture supports a variety of *WLAN* protocols. A network proof-of-concept and successful deployment of a hybrid TSN network were based on this design. According to the authors' results, the hybrid TSN network offers guaranteed acceptable low latency for TSN applications.

C. Integration Challenges

TSN is also currently facing challenges and these must be addressed in order to make it more mature. Integration with existing legacy protocols or technologies is one of them. There have been studies evaluating the integration of TSNs with a powerful communications middleware called OPC-UA [23] to provide interoperability between systems, but this is only the basics. Such integration must be specifically targeted to more complex communication systems. The smart factory of the future will be connected between devices via 5G, Wi-Fi, ZigBee, Bluetooth, etc., thus allowing mobility and scalability. So for industrial purposes, TSNs need to be able to be integrated and still allow for fast and precise control [21].

V. Conclusion

In this paper, various advantages of TSN standards in industrial IoT, the adoption of TSN in wireless domains, and the challenges of hybrid TSN were discussed. In addition to low delay, low jitter, and high reliability, TSN allows low deployment costs by sharing resources and strong compatibility with standard Ethernet technology. With these advantages, TSN is expected to become the backbone network technology carrying industrial IoT in the future. The industry now has an incentive to develop an open standard for exchanging data between IoT devices and will be able to adapt it to their needs in a unified way. The potential of the TSN set of standards now enables enterprises to adapt to their growing needs without losing compatibility with existing networks.

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