Time Sensitive Networking for Wireless Networks - A State of the Art Analysis

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***Abstract*—The trend towards using wireless networking devices for real-time applications is growing, due to the increased flexibility and better cost-efficiency in contrast to wired devices. In this paper we take a closer look at the status of recent research and developments towards enabling Time-Sensitive Networking (TSN) for wireless communication networks. First we provide a brief introduction to the already defined TSN technologies for wired networks. We then discuss some of the main challenges and gaps to overcome, in order to provide a common set of standards for reaching out towards deterministic networking on wireless media. Specifically, we will take a look at some approaches towards accurate clock synchronization via wireless links, including IEEE 802.1AS, which is a key requirement for TSN, in particular for Time Based Scheduling. We will also present some recent efforts on providing deterministic/bounded latencies for various wireless link protocols, e.g IEEE 802.11. Furthermore, we will have a look at different existing solutions, that can enhance reliability and redundancy, by e.g. using additional redundant links, and techniques for managing resource allocation on the End-to-End (E2E) network path.**

***Index Terms*—time sensitive networking, wireless networks, latency, determinism, reliability, 802.1Qbv, 802.1AS, 802.1Q**

1. Introduction

The emerging need for deterministic real-time communication in the industrial automation, automotive and audio/video sectors has pushed recent research and developments in the field of real-time communication and low latency deterministic networks. Today's industrial networks are often dominated by specialized or semi-proprietary wired media fieldbus communication, e.g. ProfiBUS, EtherCAT, CAN-BUS, Ethernet/IP and many more [1]. Although, most of these modern industrial grade Ethernet networks are fundamentally based on the Ethernet standard IEEE 802.3, they are usually closed systems, which differ from vendor to vendor and thus are in most cases not interoperable with each other or common Ethernet networks. A clear downside of these technologies is the lack of flexibility and interoperability capabilities, like the ones provided by the IEEE 802.3 Ethernet or wireless network standards. Especially wireless network infrastructure has advantages in certain deployment scenarios, where wired networks may not be suitable or more expensive to deploy. This results in the need of enabling real-time capabilities and guaranteed deterministic performance bounds, tied into already existing wireless standards, in order to meet the requirements for real-time network applications and furthermore provide an open and common network standardization.

The Institute of Electronics and Electrical Engineers (IEEE), the Internet Engineering Task Force (IETF) and the International Electrotechincal Commission (IEC) have recently proposed new standards in order to introduce deterministic networking to the Ethernet standard. The IEEE Time-Sensitive Networking (TSN) Task Group (TG), formerly named the IEEE Audio/Video Bridging (AVB) TG, has been working on proposing and defining new standardizations and also extending and enhancing already existing ones like IEEE 802.1Q [2] for Quality of Service (QoS), the IEEE 1588v2 Precision Time Protocol (PTP) [3] and IEEE 802.1AS-2011 [4] for accurate clock synchronization in a generalized and optimized manner. With these specifications for a time sensitive, real-time capable and open Ethernet standard, the IEEE TSN TG has defined a set of standards.

In contrast to wired Ethernet based communication, wireless links introduce unreliability, asymmetric channels and latencies, channel interference and signal distortion to the communication path, which makes it hard to provide guarantees for performance characteristics. Thus, wireless links are not suitable for real-time critical and ultra low latency applications by default. Some of the TSN standards already include proposed solutions to solve certain challenges for enabling TSN for wireless networks like adoptions to the IEEE 802.1AS standard, which uses IEEE 802.11 Timing Measurement (TM) [5] for accurate time synchronization over 802.11. Most of the described techniques in the IEEE TSN standards have been defined generically, without further specification on the actual layer 2 network protocol. This allows to extend and adapt the work, by specific requirements or methods to be used on common wireless network protocol standards, such as IEEE 802.11, IEEE 802.15.4 for Wireless Sensor Networks (WSN) and even the upcoming 5G standard. In this paper we take a closer look at the current research on enabling TSN for wireless networks and the main challenges, which need to be resolved.

The remainder of this paper is structured as follows: We first present and refer to some of the most interesting related works on TSN for wireless networks in Section 2. We then provide the current status of the defined TSN standards of the IEEE TSN TG and present

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a brief overview of the technologies and methodologies being used in Section 3. After that, we define the most interesting challenges for TSN over wireless networks in Section 4, and furthermore we present the current research efforts and first proposed solutions in order to overcome these problems. We will conclude and summarize the most important findings and give an outlook for future work in Section 5.

2. Related Work

In this section we introduce some recent research studies, which pave the way towards TSN for wireless networks. As this is an ongoing research area, not all remaining challenges have already been approached, thus leaving a lot of open topics for current and future works.

There have been recent efforts in order to define some of the key challenges towards TSN for wireless networks by the Avnu Alliance. The Avnu Alliance is a consortium consisting of professional, automotive, consumer electronics and industrial manufacturing companies, working on defining a common certification for iteroperable TSN standards. The white paper by Steven F. Bush et al. [6], published in January 2018, explores next steps for implementing and deploying TSN methods for industrial wireless networks as a Request for Comments (RFC). The paper covers a proposed roadmap for a seamless integration of Wireless TSN technologies into existing Industrial networks and defines a set of transition phases. It defines characteristical problems of the unreliable wireless networking technologies, which need to be considered, when defining a common Wireless TSN standard. Within each of these transition phases, the author concludes the current status with raising questions regarding open issues, which need to be addressed for the specific underlying radio technology.

The case study of A. Mahmood et al. [7] from April 2017 presented several different approaches for methodologies and protocols for accurate clock synchronization used on IEEE 802.11 wireless networks. The authors examine different existing synchronization methods, e.g. relative vs. absolute synchronization, Hard- vs. Software timestamping methods, built-in 802.11 vs. wired protocols etc., and they are compared against their use on 802.11 based networks. Depending on the use-case, and thus e.g. on the required synchronization accuracy and minimal jitter, the paper suggests to use the PTP protocol with Hardware timestamping for the most accurate method with some additional protocol overhead. Another paper, which has been published in 2011, by A.Mahmood et al. [8] also provided an approach for an implementation of an accurate clock synchronization using PTP with software timestamping for IEEE 802.11 networks. The proposed solution achieved a synchronization accuracy of a few microseconds and jitter below $1\mu s$, by also reducing the protocol overhead by using 802.11 Beacon Frames for timestamp transmission.

Another scientific work, published by A. Nasrallah et al. [9], presented a detailed study on recent developments in Ultra-Low Latency (ULL) networks. This comprehensive case study provides a sophisticated overview of the current efforts on IEEE TSN, IETF Deterministic Networks (DetNet) and 5G technologies for providing real-time and ULL capabilities for Layer 2, Layer 3 and respectively upcoming mobile wireless network standards.

TABLE 1. IEEE 802.1 TSN STANDARDS DEFINED IN [2] WITH TS = TIME SYNCHRONIZATION, BLL = BOUNDED LOW LATENCY, UR = ULTRA RELIABILITY AND RM = RESOURCE MANAGEMENT

	IEEE Std.	Features
TS	802.1AS	Time Synchronization (802.1AS-Rev in draft)
BLL	802.1Qav	Credit Based Shaper
	802.1Qbv	Time Scheduled Traffic
	802.1Qbu	Frame Preemption (also 802.3br)
	802.1Qch	Cyclic Queuing and Forwarding
	802.1Qcr	Asynchronous Traffic Shaping
UR	802.1CB	Seamless Redundancy, Stream Identification
	802.1Qci	Filtering and Policing
	802.1Qca	Path Control and Reservation
RM	802.1Qcc	Stream Reservation Protocol Enhancements
	802.1Qcp	YANG Model for Bridging
	802.1Qcw	YANG Model for Qbv, Qbu, Qci
	802.1CBcv	YANG Model for CB

3. Time Sensitive Networking

In this section we briefly introduce the Time Sensitive Networking technologies that have already been defined for IEEE 802.3 Ethernet and provide an overview of TSN in general. We will define the four key pillars of operating a Time Sensitive Network, which provide the fundamental characteristics of TSN.

One of the main goals of the development of TSN, was to provide an open and standardized technology, not affiliated to any organization or company. The demanding need for real-time capable deterministic networking, which in addition allows interoperability between devices, has pushed the development on TSN forwards. The clear benefits of using TSN over proprietary solutions, are better cost efficiency as common off the shelf (COTS) hardware can be used, establishing network convergence and the technology scales with the Ethernet standard. The TSN technology is based on four basic key concepts, accurate time synchronization, bounded guaranteed low latency, ultra reliability and resource management. For each of these key pillars, the IEEE TSN TG has defined several standards to provide the according functionality (see Table 1). In the following we will have a detailed look at each of these components and the according standards:

1) Time Synchronization (TS): In order to provide a common sense of time, shared between all participating nodes in the TSN network, IEEE 802.1AS [4] provides a generalized PTP (gPTP) profile for accurate time synchronization, using the IEEE 1588v2 PTP protocol [3]. PTP is being used to synchronize the physical hardware clocks (PHCs) of network interface cards (NICs) to a dedicated (Grand-) Master clock on Local Area Networks (LAN), with very high precision. For Ethernet, the accuracy of the offset lies in the sub microsecond range with modern hardware. In contrast to IEEE 1588v2, gPTP provides a generalized and optimized clock synchronization method and provides a set of configuration parameters referred as PTP profile. An accurate clock synchronization is a fundamental premise for most of the IEEE TSN standards, such as IEEE 802.1Qbv for Time based Scheduling. All participating nodes in the TSN-Network must be synchronized, in order to ensure real-time execution and real-time networking.

2) Bounded Low Latency (BLL): One main aspect of real-time applications is message exchange between different nodes in the network on a deterministic low latency basis. Certain traffic classes, such as Cyclic (motion-) control or isochronous (periodic) traffic as defined by A. Ademaj et al. in [12], have strict latency requirements, and thus need a guarantee by the network control for these requirements. For this purpose, the TSN standards provide several methods for ensuring bounded latencies, e.g. 802.1Qbv for Time Scheduled Traffic or 802.1av for a Credit Based Shaper. With 802.1Qbv for example, a pre-defined cyclic time schedule will be deployed throughout the network path. This cyclic time schedule defines for each time slot, which specific traffic classes will be forwarded for the specified amount of time within the cycle. The traffic classes are identified by the IEEE 802.1Q VLAN header, in particular by the priority value. In addition with using time triggered traffic sending (e.g. via SO_TXTIME socket option), time critical traffic can now be sent through the network with constant guaranteed latency, even if there is interfering traffic on the path.

3) Ultra Reliability (UR): Similar to bounded latency, real-time safety-critical applications require high reliability, to ensure their proper functionality. As most of the used traffic types in real-time applications rely on UDP and common Ethernet, there is no built-in reliability mechanism, such as retransmission of lost frames. For this purpose, the TSN standards provide e.g. 802.1CB for Seamless Redundancy and Identification for streams, which replicates frames on a per-frame basis and sends them on 2 (or more) disjoint paths to the target. The duplicate/extra frames will be eliminated on the last network node before the target. This goes hand-in-hand with 802.1Qca for Path Control and Reservation technology, for determining these paths in the network.

4) Resource Management (RM): In a TSN network, each real-time application needs certain network performance requirements, in order to function properly. Another key aspect of enabling TSN is the configuration and management of the available network resources. For this the TSN standards defined both a fully centralized and a fully distributed model for configuration of the network, namely IEEE 802.1Qcc. The trend tends towards using a centralized model, which consists of a Centralized User Configuration (CUC) and a Centralized Network Configuration (CNC) system. These systems are similar to configuration techniques from Software Defined Networking (SDN). The applications request their resource needs at the CUC, which will then trigger the appropriate actions to be taken at the CNC for resource reservation, e.g. for configuring the appropriate cycles for 802.1Qbv on the network path. For the specific data model on the endpoints and the bridges, several YANG [1] models have been designed to be used via the NETCONF or RESTCONF protocol. Figure 2 in section 4 shows a complete model of a TSN network, which uses a centralized configuration model. The Resource Management is currently still under heavy development and certification process.

[1]A data model language for network configuration - see https://tools.ietf.org/html/rfc6020

4. Towards TSN for Wireless Networks

In this section, we discuss the main challenges and gaps for Wireless TSN, which refer to the four fundamental pillars of Time Sensitive Networking, presented in section 3. First, we define the main problems and parameters of a wireless link, that directly affect the fundamental key components of TSN. After that, we will investigate current research efforts on enabling the specific key components of TSN on Wireless Networks.

Wireless Technology has brought up new possibilities and advantages for network communications, in contrast to wired networks. The newly gained flexibility of moving end stations, opened new possibilities to connect devices in a cost efficient way. But in contrast to Ethernet, wireless links introduce several characteristics like unreliability, asymmetric link delay and channels, channel interference and signal distortions from the environment. These properties make the development of suitable standards and implementations for enabling TSN for wireless networks a challenge. A noticeable research effort has already been done, in providing real-time capabilities for IEEE 802.15.4 networks [15], such as Wireless Sensor Networks. But, the overall trend leads towards enabling TSN for IEEE 802.11, due to the higher range and rate, the better interoperability and the improved security mechanisms.

1) Accurate Clock Synchronization: The most important fundamental component of a TSN network is accurate clock synchronization between endstations and also between network devices, such as bridges. For this purpose, we have already introduced the IEEE 802.1AS generalized PTP protocol in section 3. This standard also includes a proposal for clock synchronization for 802.11 in section 12 of [4] by using 802.11 Timing Measurement (TM) [10]. The synchronization procedure is shown in Figure 1.

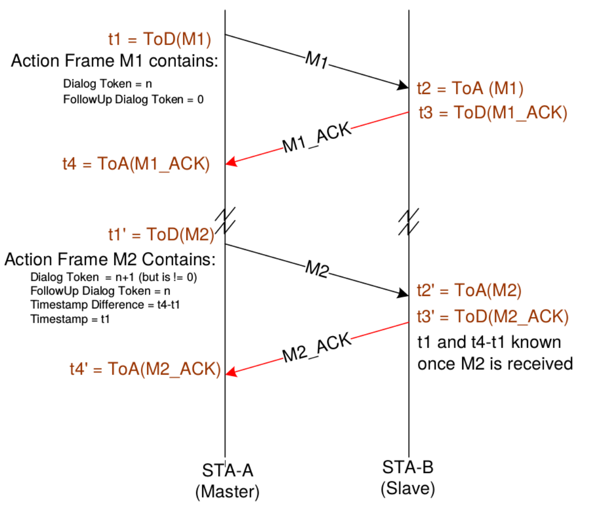

Figure 1. PTP Time Synchronization using TM, ToA = Time of Arrival, ToD = Time of Destination [11]

The biggest difference to the usual gPTP two-step protocol, is that M2 contains information about the previous two step synchronization (specifically $t1$ and $t4 - t1$). With this additional information, channel asymmetries can be detected and accounted into the offset correction calculation on the Slave. The according formulas

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for calculating the offset, link delay and the so called $neighborRateRatio$ are as following:

$$neighborRateRatio = (t1' - t1)/(t2' - t2)$$
$$linkDelay = [(t4 - t1) - (t3 - t2)]/2$$
$$timeOffset = [(t2 - t1) - (t4 - t3)]/2$$

The $neighborRateRatio$ is being used, to detect and measure current jitters occurring in unreliable wireless media. These values are then used to synchronize a system clock to the current network time, as the majority of wireless interface cards do not have a built-in PHC. The IEEE 802.1AS-Rev, which is scheduled for release end of 2018, will introduce IEEE 802.11 Fine Timing Measurement (FTM) [5] for an even more accurate clock synchronization, using PTP. Another approach, which does not rely on PTP, for accurate clock synchronization for 802.11 wireless networks, has been proposed by J.-H. Chiang et al. in [14], which uses 802.11 Beacon Frames and the internal Time Synchronization Function (TSF) for synchronizing clocks in a multi-hop wireless network in microsecond range.

2) Bounded Low Latencies: Approaching bounded low latencies is a key challenge for enabling TSN for wireless networks. The main problem is that the unreliability of the wireless media, needs to be measured and monitored, in order to detect e.g. signal quality reduction and current latencies. This is still under heavy development and research. One approach to bypass the unreliability of the wireless media, is to hide the wireless link behind a 802.1Qbv Time Based Scheduler as proposed in [6]. The network nodes need to be synchronized in time to ensure accurate clock synchronization for implementing the time-based cycle. As there do not exist any current implementations of the in Section 4.1 defined clock synchronization methods for wireless networks, one would need to rely on clock synchronization mechanisms for wired ethernet. The cycle needs to take possible retransmissions and maximum latencies of the wireless media into account. Furthermore, the Wireless NIC needs to be capable of controlling the message transmission time and implement the 802.1Qbv scheduler, which is still an open research topic. Although, there have also been approaches to implement a Time-Division Multiple Access (TDMA)-MAC for access control as e.g. by G.-H. Liaw in [13], these techniques cannot meet the requirements of certain use-cases with latencies in the millisecond range e.g. for an industrial real-time application.

3) Providing Reliability: As the IEEE 802.11 standard includes an Automatic Repeat Request (ARQ) mechanism for retransmitting packets that have been lost on transmission, these introduce uncertainties in regards to bounded latency. In Reference [6] the introduction of a redundant system using a wireless network is being proposed, in order to support the redundancy of wired TSN networks, and furthermore gradually introduce wireless networks to industrial IoT use-cases. The Author also states, that 802.11 supports IEEE 802.1CB for Seamless Redundancy and Stream Identification, but that when moving towards enabling TSN for wireless given wireless retransmissions schemes, needs careful design and analysis.

4) Resource Management: In regards of Resource Management, the wireless networks could be used, as a first step, to manage the configuration links between CUC and endpoints and CNC and network devices. In Figure 2 the complete structure of a decentralized configuration based TSN network can be seen. As suggested in [6], the dotted lines could be deployed as wireless links, as this is only for control not for operation. One advantage would be that there could be mobile Access terminals, which would allow to control the applications via wireless networks. Furthermore, replacements of equipment could be simplified, as no physical wiring needs to be changed. Of course, once there are suitable TSN standards to operate a TSN network over wireless media, there will be the need of certain standards for a configuration model specification for wireless bridges and endpoints. These would have different configuration parameters as wired stations. Furthermore there would be the need of an analyzing or monitoring instance, which would collect and analyze data about the current status of the wireless channels, in order to ensure resource availability.

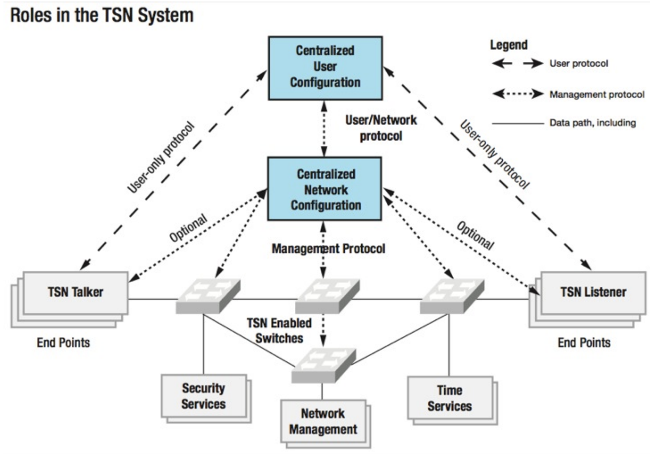

Figure 2. TSN Resource management [5]

5. Conclusion and Future Work

In this paper we showed only an excerpt of the current efforts to enable TSN on wireless networks. We discussed the main challenges for providing accurate clock synchronization, reliability, deterministic or bounded latencies and resource management and provided an insight to current developments, in order to approach some of them. The current status of TSN for wireless is in an early development stage and there are still many open topics to address for an open standardization. Accurate clock synchronization for wireless networks still needs further investigations and improvements, especially improved hardware support for 802.1AS for wireless NICs. Another future work would be to investigate the performance improvements of clock synchronization using the upcoming 802.1AS-Rev standard, in comparison with 802.1AS and 802.11 Beacon Frame methods. In terms of bounded latencies, further developments of time based packet transmission, as done for Ethernet, need to be considered for future work. Furthermore, there is the need for a sophisticated solution for measuring and monitoring quality parameters of the wireless links, in order to make guarantees for resource management.

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