

Asynchronous Traffic Shaping in Practice

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Abstract—Modern industrial applications impose strict requirements on bandwidth, latency, and jitter that standard Ethernet cannot meet. This is particularly critical for safety-critical systems, which rely on real-time data transmission to function properly. The Time Sensitive Networking (TSN) was introduced to address this problem by enabling real-time data transmission and no loss due to buffer congestion by precisely timing packets using synchronized clocks between all switches. However, not all devices are capable of this precision. Consequently, TSN was expanded by Asynchronous Traffic Shaping (ATS). ATS enables precise packet timing without relying on a globally synchronized clock. While TSN is well-established and utilized in existing commercial network solutions, a research gap exists regarding the practical application of ATS, as the literature is limited in highlighting specific use cases of ATS. This paper examines the capabilities of ATS in various practical use cases and analyzes its viability, concluding that in some cases, ATS is a superior solution to synchronized TSN.

Index Terms—asynchronous traffic shaping, time sensitive networking, latency, jitter, determinism

1. Introduction

Nowadays, industrial control systems require strict guarantees regarding latency, jitter, and bandwidth. However, networks are usually based on best-effort, which attempts to deliver packets as quickly as possible without any guarantees of reliability and robustness [1], [2]. This is an issue when safety-critical applications, like a LIDAR for autonomous driving, are operating in the network that requires packets to be delivered with low latency and no loss [1], [3], [4]. The Time Sensitive Networking (TSN) standard was introduced to address this problem by guaranteeing a limited worst-case latency and zero-congestion loss, ensuring deterministic data transmission. This is achieved by synchronizing the clocks of all bridges and switches within the network with sub-microsecond level precision [1], [5], [6]. However, there are scenarios where synchronizing clocks with this precision might not be feasible, e.g., when geographical distances between nodes are too large [7]. For these scenarios, TSN was expanded with Asynchronous Traffic Shaping (ATS). ATS enables similar features as synchronized TSN, while omitting the dependency on a synchronized clock [2], [8].

TSN is already well-known in the industry and has been implemented in several solutions and devices. However, ATS is not as widespread and has limited literature

regarding its use cases and applicability in practice [9], [10]. As most use cases are only for synchronous TSN, this paper analyzes existing literature on how synchronous TSN is used and argues whether ATS is also a valid solution for these, thereby addressing the viability of ATS. We further determine whether ATS offers advantages in certain use cases compared to synchronous TSN.

The paper is organized as follows: Section 2 provides relevant background information. Section 3 presents a literature analysis on the use of TSN in practice, examining academic papers and industrial white papers. For every use case, we determine the requirements and explain why ATS is as well a suitable fit, and analyze the advantages and disadvantages. In Section 4, we discuss the practical relevance of ATS based on the identified use cases. We finally conclude our paper in Section 5.

2. Background

This section introduces background information about TSN and ATS. Additionally describes the advantages and disadvantages of each approach.

2.1. Time Sensitive Networking

TSN extends standard Ethernet to support both best-effort and real-time traffic on the same link. While best-effort networks do not provide any time or bandwidth guarantees, TSN reserves the required bandwidth in each bridge that participates in transmitting traffic. Each bridge then uses scheduling and shaping to precisely time packets, enabling traffic prioritization. This allows zero packet loss due to buffer congestion and an extremely low packet loss caused by equipment failure. Additionally, the reserved bandwidth guarantees an upper bound on latency, as packet transmission becomes deterministic. To enable this precise timing, all bridges are synchronized with high precision. This results in a global schedule that dictates exactly when which data can be transmitted [1], [11]–[15].

2.2. Asynchronous Traffic Shaping

ATS is a shaping and scheduling mechanism within the TSN toolset that does not rely on synchronized clocks but achieves similar features. Instead, ATS uses the local clock on every device for timing, resulting in per-hop shaping that calculates the eligibility time of every packet at each switch. ATS algorithms have higher complexity and computational effort than synchronized TSN algorithms,

but do not require hardware support for high-precision synchronization. The ATS algorithms are specified in the IEEE 802.1Qcr standard and based on algorithms such as Paternoster and Length-Rate Quotient [2], [8], [13], [16], [17].

3. Analysis of Practical Use Cases

This section examines the various practical applications of ATS and assesses the benefits and drawbacks of utilizing ATS for these use cases. As there is limited availability of literature about applied ATS, we analyze the use cases of TSN in practice and assess the suitability of ATS for these use cases.

IEEE defines six profiles of use cases: Aerospace, Industrial Automation, Automotive, Fronthaul, Service Provider Networks, and Audio-Video-Bridging [18]–[23].

3.1. Aerospace onboard Ethernet Communication

The IEEE P802.1DP is a profile intended for use in aerospace applications ranging from commercial and military aircraft to the space domain. It describes certain functions that are needed to meet the constraints of aerospace networks [18], [24], [25]. These constraints range from the capability of handling very low data flows of 10 Mbit/s, up to very high bandwidths of >10 Gbit/s [24], [25].

The main challenge for aerospace networks is the demand for varying determinism, real-time transmission, and reliability, depending on the type of communication, while meeting specific safety requirements, such as fault tolerance. Traditionally, aerospace networks rely on legacy protocols like SpaceWire, MIL-STD-1553, or ARINC-664, which often fail to meet the increasing demand for bandwidth, as modern architectures require higher data throughput due to the installation of more sensors and devices [3], [24], [25].

3.1.1. Commercial Aircraft. One use case of TSN lies in commercial aircraft. Commercial aircraft typically consist of three distinct types of networks: the Aircraft Control Domain (ACD), the Airline Information Service Domain (AISD), and the Passenger Entertainment and Network Service Domain (PIESD). ACD consists of systems and networks to ensure the safety of the flight. This includes, for example, flight control systems like engine control, autopilot. This network requires a low bandwidth, while determinism, bounded-latency, and real-time transmission are crucial. The AISD covers data that is not directly necessary for safety but is still important, such as safety information provided to passengers. This has medium requirements on determinism. The PIESD handles network and entertainment services for passengers. It requires low determinism but a high bandwidth [3], [18].

TSN is able to converge these three networks into a single network while still being able to meet the requirements of the respective bandwidth, determinism, synchronization, and real-time transmission, due to its capability of flow prioritization and policing [3], [14], [18].

As ATS offers similar features to TSN, it can be applied as well. Additionally, ATS offers the advantage

of reduced configuration complexity and increased robustness due to its lack of global clock dependency. However, ATS has a higher computational overhead than TSN for high data rates, e.g., when large amounts of passengers stream videos [3], [26], [27].

3.1.2. Military Aircraft. Another use case for TSN is military aircraft. They typically deploy two different types of networks. The first domain is the Air Vehicle System, which is responsible for the safe control and monitoring of the aircraft. The second domain is the Mission System, which can be used for various applications, including weapon systems, radar, and other sensors. Both domains require real-time data transmission, high bandwidth, and high determinism, which again can be achieved by TSN [3], [18], [28].

In contrast to synchronized TSN, ATS has reduced configuration complexity, as it does not rely on synchronized clocks. Hence, the used network devices do not need hardware support for high-precision synchronization. However, mission-critical systems require high reliability, which might not be given by ATS, as it doesn't guarantee ultra-low jitter like TSN [2], [3], [28].

3.1.3. Satellites and Space Travel. The last major use case for TSN in the aerospace industry is satellites and space travel. Satellites usually consist of two domains: the flight control system, which requires high determinism, and the payload network that is responsible for communications, transponders, cameras, and scientific research instruments, which need a high bandwidth [3].

Sanchez et al. [29] have successfully integrated and validated TSN for the avionics of the Miura 1 sounding rocket, a suborbital research rocket, and verified its applicability to similar scenarios. This means that the feasibility of using TSN for building avionics networks has been illustrative shown. Compared to other space bus and interface standards, such as SpaceWire, TSN offers more promising results in terms of flexibility, determinism, reliability, and bandwidth capability. Additionally, convergence of networks allows for cable reduction, leading to a lower weight [3], [14], [18], [29], [30].

While ATS inherits most features of TSN, it offers the additional advantage of being less prone to faults caused by radiation than TSN. The reason behind this is that for synchronized TSN, the timing of packets relies on a global schedule and synchronized clock. If radiation causes a fault in the schedule, by flipping bits, the properties of TSN cannot be guaranteed. However, ATS uses a local clock on every device, hence it is less prone to this kind of failure as only a single device would suffer a fault when bits are flipped by radiation, not the entire transmission [1]–[3], [24], [27].

3.2. Industrial Automation

Networks in industrial automation usually consist of two parts: the Industrial Ethernet (IE) and a network for non-critical traffic. IE is used to transport critical traffic between devices, such as the interaction between programmable logic controllers and robots. It usually requires special-purpose standards and solutions, such as EtherCat [31]–[33]. Additional non-critical networks are

required, e.g., to facilitate data exchange between the enterprise and operations to optimize production processes and increase efficiency. IEs are expensive and hinder interoperation between these networks [31], [34].

These constraints result in another use case of TSN as described in the IEEE/IEC 60802: TSN Profile for Industrial Automation. Industrial control applications require consistent and deterministic delivery of data from sensors to controllers and actuators. Additionally, data is needed for information and analytical systems, which require a high bandwidth [4], [19], [32], [35], [36]. TSN enables both critical and non-critical traffic to share the same physical network, ensuring that time-critical data is delivered on time by securing bandwidth [4], [32], [34], [37]. It also has the potential to connect the industrial world in real-time to other systems, enabling the retrieval of massive amounts of information from factories and migrating production control capabilities from local controllers to more central enterprise servers [4], [32], [34].

Multiple automation manufacturers have already integrated TSN into their standards and automation devices, and it is expected to replace IE in the future. Additionally, some industrial protocols, such as CC-Link IE TSN or PROFINET, have adopted communication using the TSN mechanism [32].

The challenge with synchronized TSN, however, is that it requires a centralized, global schedule for the whole factory. When adding new devices, the schedule has to be recalculated by a Centralized Network Controller. Adding a new device results in recalculating the network's whole schedule. ATS enables that new devices can be used immediately without a setup change, which is desirable for the flexible Industry 4.0. This is enabled by class-based shaping, where only the configuration for the specific class need to be updated [2], [4], [32]. Additionally it might be desired to connect devices using Fifth Generation (5G) to maintain high flexibility in the setup. For this technology, high-precision clock synchronization is not feasible, resulting in ATS being a superior solution [31], [33], [38].

3.3. Automotive In-Vehicle Communications

In-vehicle networks support various types of traffic that require different levels of determinism and bandwidth. Some systems require hard real-time performance for functional safety, such as power trains and vehicle body control systems. Additional bandwidth with high determinism is required for automatic driving features to transfer data from sensors, while simultaneously delivering audio and video streams to individual devices, to provide glitch-free infotainment [5], [6], [37].

As most of the traffic in the in-vehicle network is predictable, TSN is a suitable candidate for the network, as the predictability of traffic enables it to provide low latency and zero loss of critical data while transmitting it in real-time. Additionally, it enables the implementation of different bandwidth and determinism requirements for in-vehicle networks within a single physical network. TSN enables high-speed Ethernet and communication to enter multiple segments of modern vehicles, supporting future autonomous driving technology up to the highest level of driving automation [6], [14], [35], [36], [39].

As ATS provides similar functionality to synchronized TSN, it initially appears to be a good candidate, offering real-time support while not relying on clock synchronization. ATS is capable of achieving lower end-to-end latencies than TSN for some scenarios, as TSN allows traffic bursts to accumulate, whereas ATS smooths out traffic bursts due to its per-hop shaping property. Hence, ATS is a suitable choice for shaping bursty traffic generated by radar and LIDAR sensors [6], [39], [40].

However, ATS can cause unbounded latencies in networks providing redundancy as well as in non-FIFO networks, which are often used for in-vehicle networks. ATS is challenging for these kinds of networks as ATS guarantees real-time delivery of critical data and requires careful design. Failure to do so could result in non-conformity to automotive functional safety as outlined in ISO 26262 [6], [39], [40].

3.4. Fronthaul

The IEEE P802.1CM is a TSN Profile for Fronthaul. It describes the network segment that connects cellular radios to their base-band controllers using deterministic Ethernet. Traditionally, this connection requires dedicated, expensive point-to-point fiber cables [21], [37].

As 5G networks demand ultra-reliable, low-latency, and high-bandwidth, TSN is an appealing technology to meet these constraints. 5G requires real-time transmission for interconnecting 5G network functions and services [31], [37], [38].

Additionally, it facilitates data transfer between the cellular radio and the base-band controllers, allowing mobile traffic to coexist with critical services without relying on dedicated hardware [31], [37].

Due to its lower complexity and higher scalability, Prados et al. [31] suggest using ATS over TSN for this type of application, as fronthaul networks often cover large geographical distances, making precise clock synchronization challenging. However, using ATS might result in higher jitter compared to TSN, which is additionally amplified by wireless transmissions [31], [41].

3.5. Service Provider Networks

Service Provider Networks are large-scale telecommunication infrastructures. Their profile is defined in IEEE P802.1DF. These networks include 5G access, backhaul, and multi-access edge computing systems. They provide connectivity services to vertical industries such as industrial automation. They facilitate complex scenarios, such as the remote control of cranes [5], [22], [41].

Service Provider Networks have special requirements regarding bandwidth and reliability. Currently, service provider networks often operate on a best-effort basis, which does not meet current industry demands. The industry requires determinism and real-time data transmission while ensuring low packet loss [5], [41].

TSN is able to provide the required bandwidth while guaranteeing reliability and determinism. However, due to hardware compatibility, it can be beneficial to use ATS, as it does not rely on clock synchronization and can therefore be implemented on existing quality of service devices,

which often do not provide hardware support for high-precision synchronization. However, ATS might not offer the same precision as TSN regarding jitter [15], [41].

3.6. Utility Operational Network

Another use case is utility operational networks, which are used to manage the distribution of electricity on the transmission and distribution grid. This involves substations and various protective and control devices that communicate over an additional network. Special-purpose digital connections are used to separate these networks [7].

These networks require low latency and real-time performance on the network to support critical applications, such as teleprotection, substation automation, and Distributed Energy Resource management. E.g., teleprotection requires a very low latency of <10 ms and highly consistent end-to-end latency. Additionally, these networks need the possibility to integrate new devices [7].

TSN fits this use case, as it provides bounded latency and zero congestion loss. It offers a converged architecture to support both real-time applications and regular communication, providing the required reliability [7].

However, TSN has the disadvantage that the integration of new devices requires recalculating the global schedule, and clock synchronization over long distances is difficult. Therefore, ATS would offer some benefit over TSN, as it does not have these disadvantages [7], [31].

4. Discussion

The analysis of use cases in Section 3 shows that ATS is not just a fallback for TSN, but a practical solution with distinct advantages in specific domains. While the industry currently favors TSN, our analysis highlights scenarios where ATS offers superior viability.

4.1. Scalability and Robustness

The most significant advantage of ATS compared to synchronized TSN is that it eliminates the dependency on a synchronized clock. As seen in the *Fronthaul* and *Utility operational network* use cases, achieving a sub-microsecond precision clock synchronization over large geographical distances or in large networks is technically challenging due to propagation delay and jitter [7], [31].

Omitting global clock synchronization also increases the robustness for certain scenarios. As seen in the *Satellites and Space Travel*, a radiation-induced fault in the grandmaster clock can desynchronize the entire network. As ATS uses per-hop shaping and relies on the local clock of every device, this is not an issue. ATS even smooths out bursts, further increasing the robustness [3].

4.2. Flexibility

Another key advantage of ATS over synchronized TSN is that ATS provides greater flexibility when the network is reconfigured. Adding a new device to a network with synchronized TSN requires recalculating the global schedule. This plays a major role in the *Industrial Automation*, *Utility Operational Network*, and *Service Provider Networks*

use cases. ATS enables a "plug-and-play" approach, due to per-class shaping, which allows adding new devices without reconfiguring the entire network, as long as bandwidth is available within the specific class [2], [41].

4.3. Further Advantages

While synchronized TSN often requires new specialized hardware for clock synchronization, ATS is capable of running on hardware that doesn't support high-precision synchronization but is often already used in industry. This can be advantageous in the *Fronthaul*, *Industrial Automation*, *Service Provider Networks*, *Automotive In-Vehicle Communications*, and *Aerospace Onboard Ethernet Communication*. Finally, synchronous TSN consumes link capacity more than asynchronous approaches due to the need for synchronization communication [31].

4.4. Limitations

However, ATS is not a universal replacement for synchronized TSN. While ATS guarantees bounded latency and zero congestion loss, it is not capable of achieving the ultra-low jitter that synchronized TSN can. Because of this, for applications requiring precise periodic data arrival, synchronized TSN remains superior. Finally, as discussed for the *Automotive In-Vehicle Communications* use case, ATS results in high latencies in non-FIFO networks and TSN should be preferred [40].

4.5. Practical Comparison of Synchronized TSN and ATS

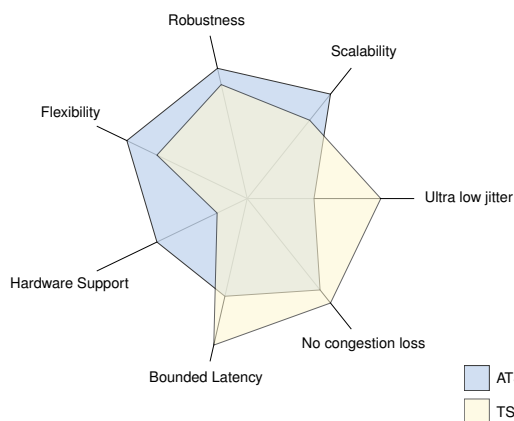


Figure 1: Practical Comparison of TSN and ATS

Overall, we can summarize our findings that ATS and synchronized TSN both have superior properties depending on the use case. Figure 1 summarizes our findings and shows for which properties how suitable TSN and ATS are. For use cases that require scalability and flexibility, ATS is a more suitable candidate as it does not rely on a global schedule. If robustness is required, ATS and TSN can be chosen equally, while for space applications ATS is superior as it is less prone to failures induced by radiation. ATS should also be used for use cases, where hardware does not support high precision clocks and synchronization. However for use cases that require ultra low jitter,

no congestion loss and bounded latency, TSN should be preferred to ATS, as TSN guarantees these features more reliable due to its determinism in transmitting packets, while ATS can lead to unbounded latency and hence to congestion loss and higher jitter for certain scenarios.

5. Conclusion

To conclude, we can state that ATS has some advantages over TSN, which is already widely used and implemented in several devices. These use cases span over aircraft networks, industrial automation, automotive in-vehicle communications, fronthaul, audio and video streaming, service provider networks, and many more. We pointed out that ATS can be applied to most of the presented use cases, because ATS offers advantages for some of these use cases compared to TSN.

While TSN currently dominates the industry, we have shown that ATS addresses several limitations regarding scalability, robustness, and flexibility, underlining its practical viability. As ATS does not require global clock synchronization with sub-microsecond precision, it is a more suitable solution when there are large geographical distances between two devices, providing greater robustness. Additionally, it requires orchestration overhead to synchronize the clocks in large networks, which is not necessary for ATS, thereby providing better scalability. Another benefit of not relying on the global clock is increased flexibility, as devices can be added or removed more easily using ATS. However, even though ATS offers advantages for these scenarios, it is still not used in practice. One reason might be that ATS is still experimental and lacks widespread implementations. Future work should focus on the experimental validation of ATS's performance in real-world scenarios.

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