TIME-SENSITIVE NETWORKING: AN INTRODUCTION

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ABSTRACT

Ethernet is cheap and ubiquitous. As such, people want to use it to carry all sorts of traffic for which it was not originally intended. A popular current application area is the transport of multiple flows of data, each having different timing requirements. Such applications exist in professional audio, industrial and automotive networks, among others. This article briefly traces the history of the features of IEEE 802 Bridging intended to address those needs, and then describes recent advances in time-sensitive networking in more detail. As well as completed standards, some current projects are described. Areas for future standardization are identified. Encoding the priority of packets in the header allows high-priority packets to be scheduled for transmission ahead of lower-priority packets, providing a better quality of service for urgent traffic. Time-sensitive flows have varying requirements for maximum latency and latency variation. Audio-video bridging provides guaranteed quality of service in terms of those parameters, for booked traffic in a bridged network comprising only compliant bridges. Some types of flow (particularly in industrial networks) are very sensitive to packet loss. Time-sensitive networking can provide bounded latency and zero packet loss due to congestion. The most stringent guarantees and most efficient use of network resources is provided by cyclic queuing and forwarding, which combines time synchronization, transmission scheduling and per-stream filtering and policing to provide just-in-time delivery of time-sensitive streams. This requires careful planning and centralized control. Less stringent use cases allow use of distributed control techniques.

INTRODUCTION

Ethernet, as originally designed, did not distinguish between different flows of traffic. Each frame was treated identically, regardless of whether it was urgent, private or not. Traffic classes using eight priorities were introduced in 802.1D-1998 [1], allowing transmission of urgent traffic before less urgent traffic. Virtual LANs (VLANs) came in 802.1Q-1998 [2], enabling separation of different streams of traffic on the same LAN. These mechanisms considerably enhanced Ethernet's usefulness for the transport of traffic flows with different requirements on the same physical medium. For example, multimedia streams such as video and voice could be transmitted, using different priorities to distinguish their requirements. However, mixing multiple flows results in additional latency (the time taken for a frame to get from its source to its destination) and packet delay variation (PDV, sometimes referred to as packet jitter). These service degradations limit Ethernet's deployment for the transport of particularly time-sensitive traffic.

In order to address these more time-sensitive traffic flows, the Ethernet industry has considered four main approaches:

- Emulation of time-division multiplexing.
- Time synchronization and approaches based on it.
- Gap preservation.
- Urgency-based scheduling and asynchronous traffic shaping.

EMULATION OF TDM

Time-division multiplexing (TDM) is the traditional approach to the transport of multiple, continuously varying signals such as digitized telephone calls and video, side by side on the same wire. It has the ability to transport these signals without significant interference, through time slicing. The dedicated nature of these time slices is also a limitation, in that unused slices cannot be used to carry other traffic.

TDM emulation has a long history in layer-2 networking, including Isochronous Ethernet (IEEE 802.9a [3], now withdrawn), TDM Circuits over MPLS Using Raw Encapsulation (IP/MPLS Forum MFA 8.0.0), and the Emulation of PDH Circuits over Metro Ethernet Networks (MEF 8 [4]).

Synchronous Ethernet [5, 6] is related to these methods, and provides a way to extend the synchronization domain of PDH and SDH across an Ethernet network, enabling the transport of TDM signals over Ethernet. However, it does not prevent interference between different traffic streams or traffic types when multiplexing traffic. It relies on a playout buffer on the receive side for smoothing out PDV caused by interference.

TIME-SENSITIVE NETWORKING

TSN evolved as a development of audio-video bridging (AVB), growing to encompass several additional market segments. Its main goals are to provide zero loss from congestion and bounded latency for a variety of time-sensitive data streams coexisting on a network that also supports best effort traffic. The tools in the TSN toolset are described below, with indications on how they can be combined to meet the needs of common classes of time-sensitive traffic.

AUDIO-VIDEO BRIDGING

Precision clock synchronization was defined by IEEE 1588 [7] in 2002, to allow sub-microsecond synchronization of clocks in measurement

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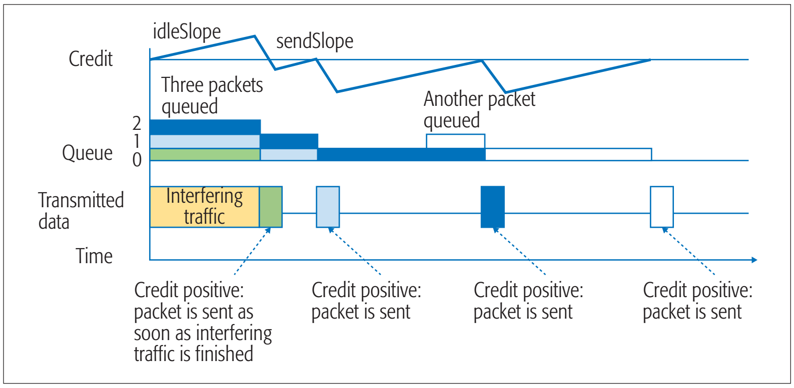

Figure 1. 802.1Qav credit-based shaper. Packets are spread out in time, reducing bursts.

and control systems. Michael Johas Teener, an Apple architect who had worked on FireWire, was looking for new technologies to bring high-quality audio and video to a larger market. He developed modifications to IEEE 1588 to make it suitable for AV-quality synchronization on Ethernet and brought this into IEEE 802.1 as 802.1AS [8] in order to have synchronization at the heart of layer-2 switches. This work generated a lot of excitement, and a new task group was formed to standardize it, initially called Audio-Video Bridging. Combining accurate synchronization with a simple stream reservation protocol (802.1Qat[1]) and a credit-based shaper (802.1Qav) produced a solution capable of supporting lossless guaranteed bandwidth over Ethernet for pro-audio studio applications. This market has grown to a substantial size led by companies such as Harmon.

The 802.1Qav credit-based shaper does not deal with individual streams of traffic. Instead, a stream admitted through the reservation protocol is allocated a particular priority value that the sender must then use in that stream's VLAN tags. The shaper operates on classes of frames determined by priority alone, which simplifies implementation by removing the need for special frame tagging and complicated classifiers. The shaper uses a "token bucket" algorithm to determine whether a queued frame can be transmitted. This is a simple algorithm in which tokens are added to a "bucket" at a constant rate (idleSlope in Fig. 1) and if there is positive credit in the bucket, a frame can be transmitted. During transmission, tokens are removed from the bucket (sendSlope in Fig. 1). If there aren't enough tokens, then the frame is queued until there are. The effect is to spread the packets out in time so that bursts are reduced or eliminated. This reduces pressure on the queues in downstream bridges and means that only short queues are required, in turn limiting the overall latency of AVB streams, and providing protection of the network from traffic sources that send more than they are supposed to. Congestion is avoided because the reservation architecture requires that bridges allocate full bandwidth to each admitted stream.

Audio-video bridging is used in large deployments to deliver hundreds of streams on thousands of screens to large crowds in environments such as Universal Studios' theme parks.

From AVB to TSN

Following on from the success of AVB, various vendors proposed enhancements to 802.1AS to provide greater clock accuracy and to incorporate innovations developed in the forthcoming v3 of IEEE 1588. Applications such as industrial control, autonomous vehicle operation and high-quality audio/video need enhanced performance in terms of decreases in PDV, wander, and deviation in time. People also realized that there was more to determinism than getting packets to their destinations as soon as possible: the important thing is to get them there at the right time. Overall network efficiency might be better served by delivering packets just-in-time, rather than ASAP.

Preemption (or Interspersing Express Traffic): 802.1Qbu and 802.3br

Traditional Ethernet transmits one packet at a time and pays no attention to urgency or priority. At relatively low network speeds such as 100 Mbit/s, a large packet can take considerable time to transmit (160 μs for a 2000-byte packet).

Large packets are common because they use the medium more efficiently than small packets, by avoiding the overhead of additional packet headers. The extended transmission times of large packets are inconsistent with time-sensitive traffic's need for low latency and PDV. One solution to this problem is to interrupt the transmission of a packet in order to transmit a more urgent packet, and this is what is done in 802.3br and 802.1Qbu. Instead of just abandoning the interrupted packet and retransmitting it later, as some proprietary implementations have done, these standards suspend transmission of a preemptable packet while an express packet is transmitted, and then resume transmission of the preemptable packet from where it left off. Further, the Ethernet MAC can be instructed to hold back preemptable traffic. In this way, an "express lane" can be made available for high-priority traffic, and this is used by more advanced TSN mechanisms described later (e.g., 802.1Qbv). The MAC-layer aspects of interspersing express traffic are specified in 802.3br, whereas the queuing aspects are in 802.1Qbu.

Before preemption can be used on a link, support for it must first be negotiated between the two ends of the link using LLDP (802.1AB [9]) and its Additional Ethernet Capabilities TLV. This is important to prevent the new low-level signaling methods used for invoking preemption from confusing traditional Ethernet MACs or PHYs. Following this negotiation, there is a verification phase that tests the capability of the link and link partner to support the underlying signaling mechanism.

Besides supporting the 802.1 protocols described below, the capabilities of 802.3br could be used in other interesting ways, while still conforming to the standards. For example, an Ethernet implementation capable of supporting 802.3br can be used with preemption disabled, but it still supports two transmit queues at the wire interface. These capabilities can support the fronthaul and backhaul of radio traffic over Ethernet, as is being documented in 802.1CM.

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[1] See Table 1 for details of TSN standards and projects.

ENGINEERED TSN NETWORKS FOR AUTOMOTIVE AND INDUSTRIAL CONTROL

Networks for industrial and automotive applications need to transport time-sensitive traffic through multiple hops from controllers to actuators and from sensors to controllers. Typically, the traffic supports control loops that rely on regular delivery of updates within a time window; if the information is delayed or lost, then the feedback loop may misbehave or fail. Typical industrial applications can support single packet loss. The traffic is characterized by its cyclical nature: its regular transmission cycles and constant bandwidth.

An industrial or automotive network may have multiple of these traffic streams in parallel, with varying requirements for latency, PDV and bandwidth. While these traffic streams have stringent requirements, they are often quite low in bandwidth (perhaps excepting sensor data in automobiles, which could be quite large). It is useful to be able to support other types of traffic (e.g., best effort traffic, or less time-sensitive traffic) on the same network.

802.1 TSN supports such applications with a combination of recent amendments to 802.1Q:

- 802.1Qbv-2015: Enhancements for Scheduled Traffic, which defines transmission gates per port and local time schedules to control them.
- 802.1Qci-2017: Per-Stream Filtering and Policing.
- 802.1Qch-2017: Cyclic Queuing and Forwarding.

TIMED TRANSMISSION GATES

To support the regular transmission of "control" traffic, 802.1Qbv provides scheduled transmission of traffic controlled by transmission gates. Referring to Fig. 2, a regular cycle ("periodic window") is established for each port, and at any particular time in that window, only certain gates are open and thus only certain traffic classes can be transmitted. This can create a protected "channel" that is reserved for a particular traffic class. A complication in such a scheme is that once a packet has begun transmission, it cannot be immediately cut off when the gate closes, but must continue until it has finished transmission (or at least until it can be preempted). Therefore, it is necessary to establish a guard band (shown in orange in Fig. 2) before the scheduled time of opening of a gate for a time-sensitive stream. During the guard-band period, no packets are selected for transmission. In the simplest implementation, the guard band has to be as long as the longest possible packet, unless preemption is used, in which case it need be only as long as the shortest fragment time. The reduced guard band resulting in the use of preemption (shown in Fig. 2) results in less idle time and thus more efficient link utilization. More advanced implementations just need to ensure that whatever frames are selected for transmission are guaranteed to have finished before the protected stream's gate opens.

The standard defines the low-level mechanisms of the gates (in terms of state machines) and how to control them with managed objects, but doesn't define how they should be used to achieve network-wide reservation guarantees. At the start of each cycle, the port follows a set of programmed instructions comprising a set of gate states and a time period in nanoseconds. When the cycle time expires, it starts again. There is a mechanism that can be used to coordinate the operation of multiple ports.

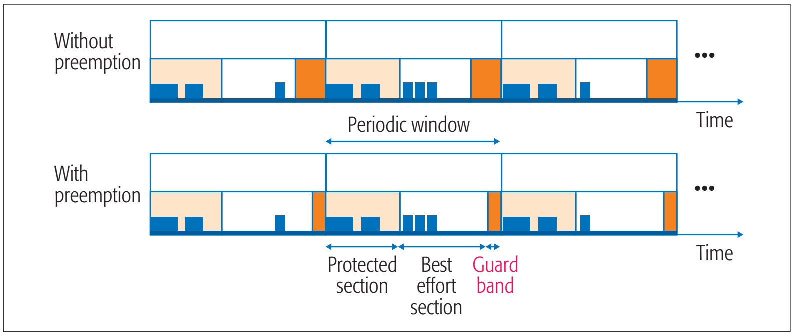

FIGURE 2. Timed transmission gates and preemption: 802.1Qbv. Using preemption reduces the size of the required guard band to the minimum fragment size.

PER-STREAM FILTERING AND POLICING

802.1Qci uses the stream-identification capabilities of 802.1CB to provide filtering and policing functions on a per-stream basis, identifying streams by mapping combinations of header fields to an internal priority value (IPV), which determines a traffic class. The stream identification can use various combinations of MAC source address, destination address, VLAN and IP header fields, and is extensible to allow proprietary classification schemes. 802.1Qci augments those stream-identification methods to define stream filters, which allow further classification into different streams based on when the packet was received in a time cycle, and a frame's priority value. Stream filters direct traffic streams through a stream gate to a particular flow meter and hence to an output queue, and can detect and block certain error conditions.

Stream gates, based on the cyclic capabilities of 802.1Qbv, pass frames if they are open and block frames if they are closed. They can detect certain error conditions (such as receiving a frame when the gate is closed, or exceeding bandwidth) and optionally remain closed until management intervention. Frames that are passed are assigned an IPV. A stream gate can also have a list of timed gate control operations that are executed in order, allowing the cycle time to be subdivided into periods of time in which the gate is open or closed, and changing the IPV. This feature forms the basis of the operation of cyclic queuing and forwarding, below.

Flow meters allow 3-colour policing of frames, based on the parameters defined in MEF 10.3 [10], such as committed and excess information rate and burst size.

CYCLIC QUEUING AND FORWARDING

802.1Qch explains how to use the capabilities in the previous standards to build a network that provides bounded latency and guaranteed bandwidth for time-sensitive streams, at the same time as best-effort traffic. The latency has both low and high bounds by virtue of the forwarding algo-

Designation	Title	Incorporation	Further information
802.1Qat	Stream reservation protocol	802.1Q-2011	http://standards.ieee.org/findstds/standard/802.1Qat-2010.html
802.1Qav	Forwarding and queuing enhancements for time-sensitive streams	802.1Q-2011	http://standards.ieee.org/findstds/standard/802.1Qav-2009.html
802.3br	Interspersing express traffic	Standalone standard	http://standards.ieee.org/findstds/standard/802.3br-2016.html
802.1Qbu	Frame preemption	802.1Q-2018	http://standards.ieee.org/findstds/standard/802.1Qbu-2016.html
802.1Qbv	Enhancements for scheduled traffic	802.1Q-2018	http://standards.ieee.org/findstds/standard/802.1Qbv-2015.html
802.1Qci	Per-stream filtering and policing	802.1Q-2018	http://standards.ieee.org/findstds/standard/802.1Qci-2017.html
802.1Qch	Cyclic queuing and forwarding	802.1Q-2018	http://standards.ieee.org/findstds/standard/802.1Qch-2017.html
802.1CB	Frame replication and elimination for reliability	Standalone standard	http://standards.ieee.org/findstds/standard/802.1CB-2017.html
802.1CM	Time-sensitive networking for fronthaul	Standalone standard	https://standards.ieee.org/findstds/standard/802.1CM-2018.html
P802.1Qcr	Asynchronous traffic shaping	802.1Q amendment project	http://www.ieee802.org/1/pages/802.1cr.html
P802.1Qcc	SRP enhancements and performance improvements	802.1Q amendment project	http://www.ieee802.org/1/pages/802.1cc.html
P802.1AS-Rev	Timing and synchronization for time-sensitive applications – revision	Standalone project	http://www.ieee802.org/1/pages/802.1AS-rev.html

Table 1. Time-sensitive networking standards and projects.

rithm, which alternately receives and transmits frames for a fixed interval of time in a repeating cycle. Thus, the time taken for a packet to get through the network is dominated by the cycle time of the forwarding mechanism rather than queue delays or transmission times. The upper bound of latency is the sum of the per-hop delays:

$$(n + 1) \times T_w \tag{1}$$

The scenarios that can be constructed by using these capabilities are many and varied. Worked examples of how to configure cyclic queuing and forwarding are provided in Annex T of the standard.

Timed transmission gates and the per-stream filtering and policing capabilities of these standards enables a variety of options. The next generation of TSN could define a multitude of capabilities based on these mechanisms. An interesting question is how implementations of those standards will enable or limit such designs; the flexibility or otherwise of the implementations (such as the number of stream filter instances supported, etc.) will affect their suitability for more innovative uses.

PUTTING THE PIECES TOGETHER

Taken together, the capabilities described in 802.1Qch, building on those of 802.1Qci and 802.1Qbv, allow various types of real-time traffic to share 802 networks such as Ethernet with traditional best-effort traffic, while providing zero loss from congestion and bounded deterministic latency. However, these benefits do come at a price:

- Time synchronization must be achieved throughout the TSN network, typically requiring the implementation of 802.1AS and/or IEEE 1588 in each node.
- Considerable planning and coordination is required across the TSN network. Priority labels need to be assigned to specific time-sensitive traffic classes, and cyclic time schedules and stream gate control list subdivisions for each port on the path need to be designed.

PROTECTION

Some time-sensitive applications require extremely high reliability. 802.1 bridged networks already offer several different approaches to restoration, but for higher levels of reliability, 802.1CB offers frame replication and elimination. This is a hot-standby approach, where traffic can be sent over more than one link at a time. The separate paths through the network can join and re-separate. At points where they join (at the final destination, for example), redundant copies of frames already received are recognized through sequence numbering and eliminated. 802.1CB also defines an extensible mechanism for stream identification based on frame headers.

GAP PRESERVATION

One of the challenges in transporting constant bitrate traffic is burstiness. Forwarding delays in bridges can result in packets that were evenly spread in time becoming bunched together. Burstiness causes buffers in downstream bridges to fill more than they would have otherwise, which in turn increases latency. One approach to trying to avoid burstiness is to examine the spacing of incoming packets and preserve the spacing in time between the packets on the outgoing port. This can be done even when the outgoing port is an aggregation port operating at a higher media speed. This can eliminate PDV caused by aggregation. There have been presentations [11] suggesting such an approach in 802.1, but they have not as yet progressed as far as a project proposal.

ASYNCHRONOUS TRAFFIC SHAPING AND URGENCY-BASED SCHEDULING

It has been argued that zero congestion loss and bounded latency can, in certain controlled environments, be achieved without the need for ubiquitous synchronization. To achieve this, an additional layer of shaping is introduced in the egress processing of a bridge, and additional queues are provided. These techniques are being explored in the P802.1Qcr project.

STANDARDS GAPS AND NEXT STEPS

There is no standard that explains how to control the constituent parts of TSN to achieve the desired overall operation for different use cases, in the way that 802.1BA [13] did for AVB. It would be beneficial to profile the combined capabilities provided by 802.1Q for particular market segments.

The mechanisms described above require significant management to configure paths through the network to carry traffic streams. Work is underway on a project (P802.1Qcc) to define an Enhanced Stream Reservation Protocol. Currently envisaged approaches rely on a central network controller to coordinate reservations and program network elements through management protocols. To make these mechanisms useful in dynamic, multi-vendor networks, control-layer standardization is also required. What is the role of the path computation entity or similar control layers, and should these be standardized?

Not all applications require the performance levels that central planning and network engineering can achieve. Some industrial applications would benefit from a distributed control approach where new machines could be brought on-line without re-planning the network. New proposals are being developed [14] in 802.1 to address such use cases.

CONCLUSION

Advances in bridging have transformed the Ethernet market, taking it from enterprise networks to carrier networks to Pro-AV applications and, with the help of TSN, into mobile backhaul, industrial and automotive sectors. The development of these powerful tools in the network toolbox demonstrates that TSN is the leading innovation technology in layer-2 networking, ideally placed to expand Ethernet into further new markets. Where will the next generation of TSN take us?

APPENDIX

Table 1 shows the TSN standards and projects referred to in this article. In the case of amendments to IEEE Std. 802.1Q, the version of the standard that includes, or will include, the amendment is given.

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BIOGRAPHIES

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