Demonstration of Industrial-grade Passive Optical Network

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Abstract: We demonstrate a TDM-PON operating according to industrial-grade standards. Using a suitably configured PON-MAC and jitter compensation we achieved constant low latency upstream transmission and successful interworking with a TSN network and time-critical flows.

1. Introduction

Passive optical networks (PON) are a mature, standardized and low-cost technology to provide broadband fiber access for residential applications in point-to-multi-point (P2MP) topologies. In recent years, new use cases for PON have been demonstrated, including the transport of 5G data in functional-split configuration targeting small-cell environments [1], passive optical LAN, and conceptually also industrial applications [2]. Today's factory solutions are demanding such a P2MP system to allow for the convergence of information technology (IT) and operation technology (OT) into a single infrastructure for enabling augmented reality and digital twin applications, centralization of controllers and virtualization in enterprise data centers [3].

For industrial applications time sensitive networking (TSN) [4] plays an important role. TSN extends the Ethernet IEEE 802.1 standard by providing several means for temporal control of flows in Ethernet switches. For the convergence of OT/IT the most relevant flavor is IEEE 802.1qbv, which implements gates at the switches' outgoing ports that are scheduled to control the transmission of time-critical packets. In this paper we will use the term TSN to refer to IEEE 802.1qbv. Converged industrial networks are currently built with TSN switches that typically have few ports, demand for a large number of switches and require complicated scheduling at each hop.

However, PON inherently supports P2MP communication and employs scheduled upstream transmission that can serve factory applications. So PON could integrate TSN switching functionality, interface with TSN switches and even replace parts of the TSN network to further reduce cost and complexity. One challenge for the PON is to satisfy the strict timing of time-critical applications and/or of TSN. In the industrial environment, time-critical flows are typically cyclic with fixed size packets repeated every period. Mismatches between the flows and the PON reservation cycles, as well as uncontrolled offsets would create latency variations (jitter) which could disrupt the time-critical applications. Thus, the traditional PON must be augmented to achieve industrial-grade performance by adding a jitter compensation (JC) functionality and modifying the conventional Dynamic Bandwidth Assignment (DBA) process for upstream transmission.

We demonstrate in this paper, for the first time, an industrial-grade PON operation. We enhanced a commercial TDM PON system by using a low-latency medium access control (MAC) [1] and JC modules that are connected as gateways to the optical network unit (ONU) and to the optical line terminal (OLT) (see logical functions depicted in Fig. 1). Our industrial-grade PON successfully interworked with a TSN network and time-critical flows. We observed the proper operation of the TSN schedule and measured equal levels of jitter (less than 1 μs) of the time-critical flows for various scenarios of mismatching cycle times between the PON and the time-critical application.

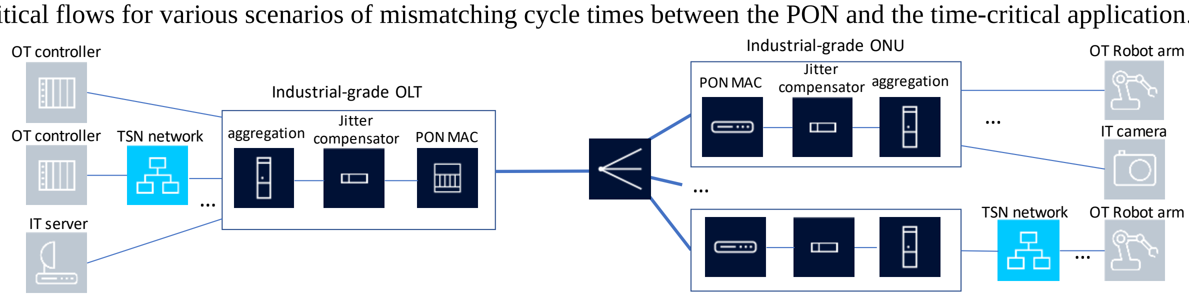

Fig. 1: Logical reference of industrial-grade PON architecture: OT (controllers and machines) and IT (e.g.video) applications served over a traditional TDM PON augmented with jitter compensation (JC) and TSN-grade aggregation switching.

2. Proof of Concept (PoC) setup, TSN switching, low latency MAC and jitter compensated PON

We developed a PoC setup for industrial-grade PON based on an XGS-PON that implements a low latency MAC [1]. We implemented JC gateways in FPGAs and used 2 TSN switches (Hirschmann RSPE35) as shown in Fig. 2.

To set the scene, we briefly review how TSN (here IEEE 802.1qbv) works. TSN requires a common network timebase to operate the gates of each switch according to a global schedule [5]. Synchronization is achieved through the IEEE 802.1AS precision time protocol (PTP) profile, which requires any two time-aware devices separated by 7 or fewer hops to be synchronized within 1µs peak-to-peak accuracy [6]. Synchronization and propagation errors are accounted for by adding margins in the scheduling. Time-critical flows are cyclic with fixed size packets. We particularly focus on isochronous flows with cycles lower than 1 ms and acceptable jitter lower than 1 µs [7]. TSN switches employ queues in their outgoing ports followed by gates and repeat a gate opening schedule every TSN switch cycle, set as the least common multiplier of the flows' cycles. Typically, one of the queues is allocated to best effort (BE)/IT traffic and served during inactive periods of critical traffic. The gate opening offset (w.r.t. the TSN switch cycle) is calculated by the transmission time at the previous switch, as well as the propagation time and the switching time of the current switch. Isolation from other flows is achieved in time (delaying at a previous hop) and/or space (using different queues). The gate opening duration is calculated based on packet size and margins. The interdependence of flow timings, the diversity in paths, packet sizes and cycles makes scheduling difficult (NP-hard [5]). The TSN network isolates time-critical flows, and maintains their cycles, with constant latency and low jitter.

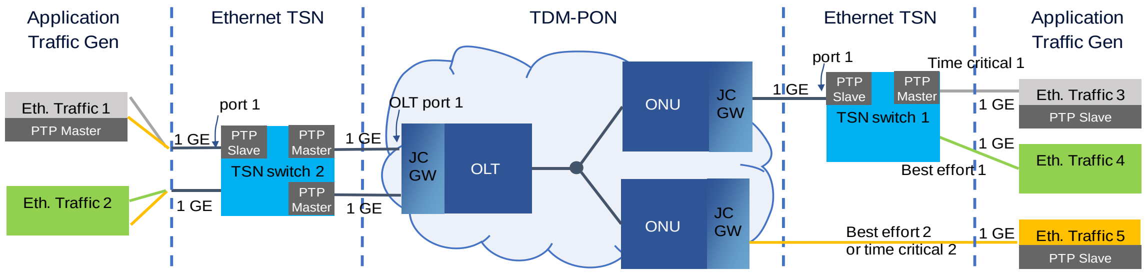

Fig 2. PoC setup, with 2 TSN switches, XGS-PON and jitter compensation gateways (JC-GWs).

We propose to integrate or even replace parts of a TSN network with an enhanced TDM PON system. Interworking of the PON with time-critical applications and TSN switches requires support of the PTP protocol within the needed accuracy (1 µs [6]), and a constant and known latency to be able to calculate and maintain the timing of the applications and TSN schedule. In the following we outline the solution developed for upstream transmission in PON. In [1] a low latency MAC was demonstrated which served an upstream flow with multiple periodic bursts per PON frame. However, the granularity of the burst cycles must be a multiple of or a divisor of the PON frame, while there is also limited control of the phase of those periodic bursts with respect to the PON frame. Serving time-critical flows with various cycles and specific offsets could result in mismatches, which cause jitter that disrupts the time-critical applications. Also, in our set-up, the PON has a higher rate (10Gb/s) compared to TSN ports (1 Gb/s), and such a rate conversion alters the timing of packets, thus creating jitter [8].

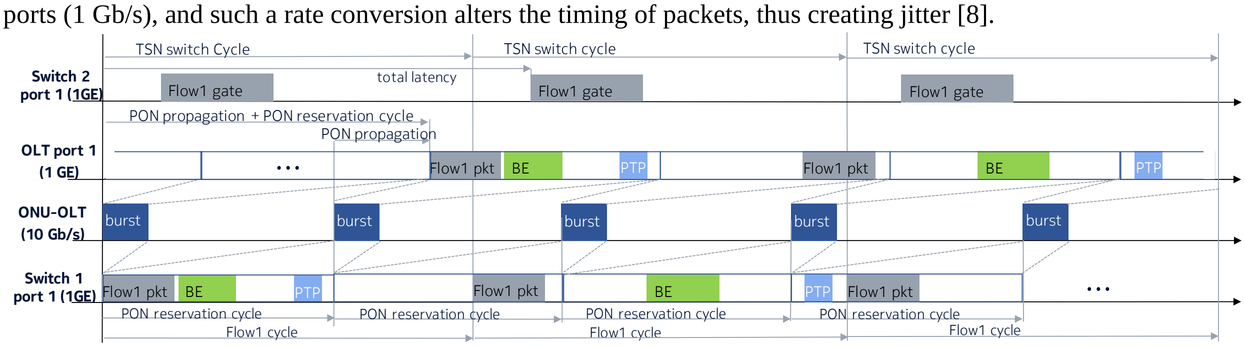

Fig. 3: Proposed solution for non-matching reservation cycles and uncontrolled offset in a TSN-PON network with the introduction of a jitter compensator (JC) that creates a tunnel from an ONU port to an OLT port, see text for details.

To solve these issues, we enhanced the PON with a jitter compensator (JC). For our PoC we developed a JC extending the approach described in [8]. The developed JC includes a gateway (GW) at the ONU side that periodically (every PON reservation cycle, i.e. 31.25 µs in the PoC) encapsulates the 1GE bitstream (including idles) arrived during that period in an Ethernet frame. This frame is then transmitted in a PON burst (reserved as fixed bandwidth of 1.1 Gb/s) of the XGS-PON. The frame reaches the OLT and is forwarded to the egress JC-GW which decapsulates and forwards the data to the dedicated 1GE output port of the OLT. This creates a tunnel from an ONU port to an OLT port and yields known latency (= PON reservation cycle + PON propagation) which is constant (measured jitter below 200 ns peak-to-peak). A similar but simplified solution is applied in downstream as there is no need to match the time-critical flow and bursts cycles. The upstream-downstream latency asymmetry is known and constant. Therefore, the PON+JC system acts as an asymmetric cable connection. The known latency and asymmetry can be accounted for in PTP, the TSN scheduling (shown in Fig. 3) and/or the applications.

3. Proof of Concept Demonstration

We performed experiments using the PoC of Fig. 2 and a configurable Ethernet traffic generator and analyzer (IXIA Novus). We report results for 4 traffic scenarios. Traffic scenario T1 has the following flows, *time-critical 1*: Eth3-Eth1, 1250 Byte payload every 200 µs, *best effort 1*: Eth4-Eth2 200 Mb/s random size packets (64-1518 Byte), *best effort 2*: Eth5-Eth2 400 Mb/s random size packets. In scenario T2, *best effort 2* flow was replaced with *time-critical 2* with the same size and cycle as *time-critical 1* but different source (Eth5 instead of Eth2). Scenarios T3 and T4 are as T1 and T2, but with time-critical flows of 3000 Bytes (implemented as 2x1500 Byte packets) every 500 µs. Note that the 200 µs cycle in T1 and T2 would cause jitter, since it is not a multiple or divisor of the PON frame.

Fig. 4a shows the measured latencies for a reference TSN network (cf. Fig. 2, but without the PON). The calculations for TSN scheduling followed [5]. Assuming traffic generation at 0 µs, the offset for the TSN switch 1 was set to 12 µs for the 1250 Byte flows, and to 16 µs for the 3000 Byte flows (calculated for the first 1500 Byte packet). The gate opening duration were set to 12 µs and 32 µs, respectively. Calculations included 1 µs PTP margin, 200 ns gating overhead, and 1 µs margin for prototyping. For switch 2, the offsets were set to 26 µs and 32 µs for 1250 Bytes and 3000 Bytes flows, respectively, and same gate duration as switch 1. The measured average latencies of the time-critical flows were very close to the offset set in switch 2. We observed a latency variation of 800 ns, which was within the 1 µs accuracy of PTP [6]. Looking at Fig. 3, we can visualize that the gate of switch 2 moves by 1 µs due to PTP inaccuracy. Then for a time-critical packet that has arrived before the gate opens, we measure the gate opening time (offset) and its variation. Arriving of the packet at the correct time relies on the proper timing of the previous gate, and so on, and thus we verify the proper operation of the whole schedule. We also verified that the addition of best effort traffic did not affect the latency and jitter of the time-critical flows.

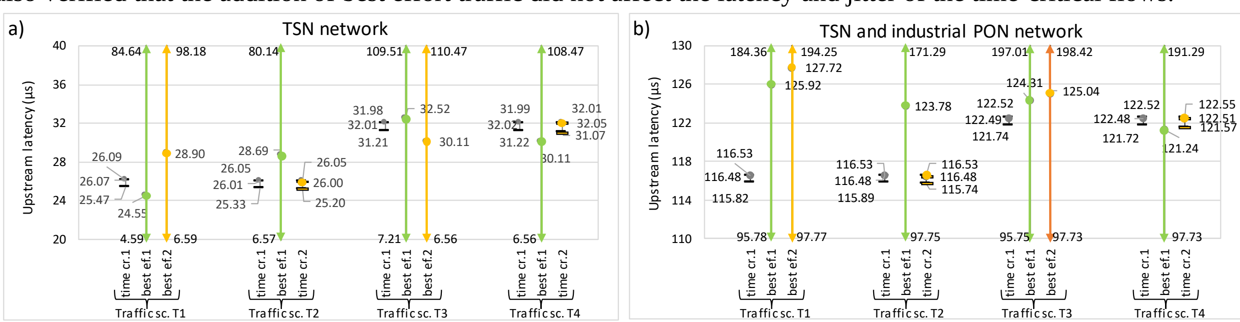

Fig. 4: Measured minimum and maximum upstream latency for the 4 traffic scenarios over a) the TSN network, and b) the TSN and industrial-grade PON network (note the difference in scale of the y-axis).

Fig. 4b shows the measurements for the TSN and industrial-grade PON network. The mismatch of the time-critical flows and PON cycles and the lack of control of the offset in PON were corrected through the JC, and the industrial-grade PON yielded upstream latency of 90.5 µs between any 1GE ports on ONU and OLT and peak-to-peak jitter of 200 ns. This latency includes the JC functionality (31.25 µs to compensate for the random offset plus FPGA processing), and ONU and OLT processing. It can be reduced with shorter burst cycles and improvement of JC operation. Thus, as shown in Fig. 4b, we measured an increase in latency of 90.5 µs with respect to the TSN network (Fig. 4a) and jitter again lower than 1 µs, within the acceptable range of isochronous flows [7] and of IEEE 802.1AS [6]. These results demonstrate the successful interworking of industrial-grade PON with TSN and time-critical flows.

4. Conclusions

We demonstrated a TDM-PON operating according to industrial-grade standards. We enhanced a commercial PON with a low-latency MAC and added jitter compensation (JC) modules, so that it successfully interworks with a TSN network and time-critical flows. We observed the proper operation of the TSN network and measured equal levels of jitter, less than 1 µs end-to-end, of the time-critical flows for various traffic scenarios.

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5. References

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