TDM-PON supporting IEEE-802.11CB based deterministic networking for reliability in industrial TSN networks

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Abstract: We demonstrate a novel scheme and configuration that allows commercial TDM-PON systems to support 802.1CCB-FRER for enhanced reliability in TSN. We experimentally evaluate and compare the performance of 802.1CB-FRER traffic flow and normal (non-FRER) traffic flow co-existing in the same TDM-PON infrastructure in case of link-fault.

1. Introduction

Reliability and determinism are two essential requirements for next-generation industrial Time-Sensitive Networks (TSN) (Industry 4.0+). To address these needs, the IEEE-802.1 (TSN) Task Group (TG) has developed standards, including IEEE Std 802.1CB, that enhance reliability via Frame Replication and Elimination for Reliability (FRER). Specifically, resilience against link and node failures is achieved by transmitting duplicate packets over redundant paths, and by eliminating the duplications at the receiver [3]. While current point-to-point Ethernet TSN switches support this, they are costly, power-intensive, and complex to scale. Time-division multiplexed passive optical networks (TDM-PON), originally designed for residential access, are now being explored for industrial applications for their cost and power efficiency and their scalability [1]. Recent works have demonstrated that TDM-PON can meet the latency and jitter requirements of TSN IEEE802.1Q through deterministic scheduling [2]. However, commercial PON systems do not inherently support the reliability enhancement offered by 802.1CB-FRER.
This work presents the first feasibility demonstration of 802.1CB transport over a commercial TDM-PON system, experimentally evaluating the reliability of FRER and non-FRER traffic coexisting within the same infrastructure.

2. TDM-PON architecture for IEEE802.11CB-FRER based TSN for reliability

FRER is the only TSN standard ensuring seamless protection against packet loss due to link or node failures. As shown in Fig.1-(a), IEEE 802.1CB-FRER achieves reliability in TSN networks through three key elements: (i) packet replication at the TSN talker, (ii) transmission via multiple paths, and (iii) duplicate removal at the TSN listener. The talker assigns a unique sequence number to each packet, replicates it, and embeds the same sequence number in all copies within the Redundancy Tag (R-TAG). The listener identifies streams via MAC addresses or VLAN IDs, verifies sequence numbers, and reconstructs the stream by accepting valid packets while discarding duplicates. Latent error detection ensures all expected packets are received using predefined redundancy information.

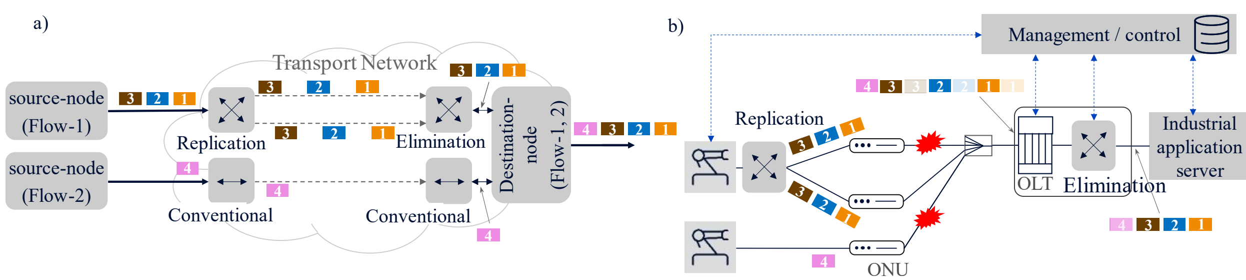

Fig. 1 (a) basic representation of IEEE802.1CB-FRER. (b) Architecture of TDM-PON supporting IEEE802.1CB-FRER based determinism

Fig. 1-(b) illustrates how TDM-PON can support IEEE 802.1CB-FRER for TSN. Its point-to-multipoint architecture enables multiple disjoint paths via different ONUs within a single PON tree, allowing replicated traffic transmission. By duplicating traffic at the TSN talker and sending streams through different ONUs, the system ensures link-fault tolerance-outages in an ODN branch or ONU do not disrupt transport since duplicated packets still reach the receiver. However, while this method protects against access-side faults (from ONUs to splitter), it does not cover failures in the feeder section (from splitter to OLT). This can be mitigated by using ONUs across separate PON trees to ensure disjoint feeder paths. The management and control module oversees remote configuration and monitoring of PON parameters and TSN network interfacing.

3. Experimental Setup for TDM-PON supporting IEEE802.1CB-FRER based reliability in TSN

Fig. 2 illustrates the experimental setup used to validate the proposed FRER scheme used to validate the proposed PON architecture supporting FRER (Fig. 1-(b)). The “Replication” module and a traffic generator act as the TSN talker, while the "Elimination" module and a subsequent traffic analyzer serve as the TSN listener. Both modules were implemented using a TSN Ethernet switch. Commercial Nokia TDM-PON hardware was used together with a novel and unique configuration tailored by Bell Labs to enable transport of FRER duplicated traffic through PON. Three traffic types were tested: FRER traffic (duplicated via ONU-1 and ONU-2), non-FRER traffic (single path via ONU-1), and background traffic (via ONU-3 and ONU-4) to demonstrate TSN-FRER coexistence with broadband services. A Variable Optical Attenuator (VOA) in the ODN was used to emulate a fiber cut by disrupting the signal from ONU-1, allowing performance comparison under link-fault conditions.

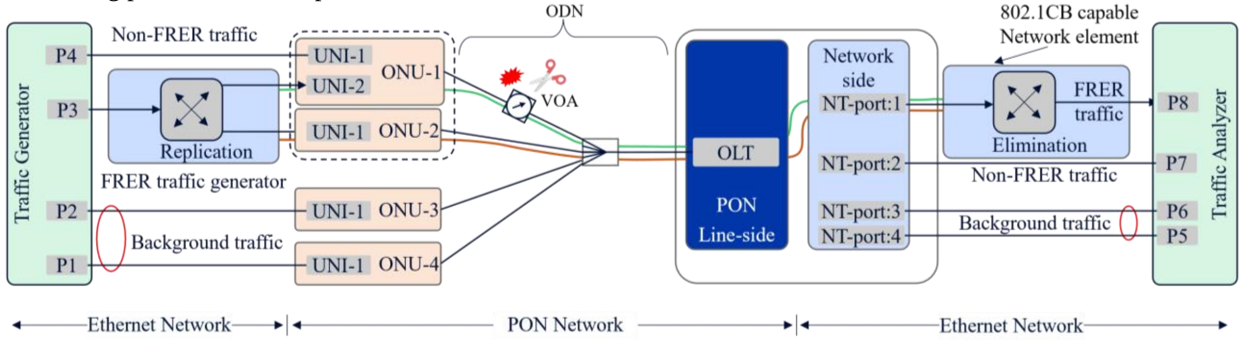

Fig. 2: The experimental setup: TDM-PON supporting IEEE-802.1CB FRER TSN.

4. Experimental Results

Fig. 3-(a) compares packet loss in FRER and non-FRER traffic during an emulated link fault associated with ONU-1, induced by increasing the VOA attenuation over 30 seconds (50-80s). The non-FRER traffic first experiences partial loss (~10% at 60s) and then complete failure (~80s), while the FRER traffic remains unaffected. Fig. 3-(b) shows L2 upstream latency as a function of the Received Optical Power (ROP) at the OLT, where non-FRER traffic faces high latency (~50ms at -28.5 to -29 dBm) and ceases beyond -30 dBm. The FRER traffic remains stable due to the still active path via ONU-2 (-24 dBm). Notably, Fig. 3-(b) reveals a slight latency increase (~55 µs) when ONU-1 fails, as FRER packets reroute through ONU-2, which is scheduled later at the OLT. Once the fault resolves, latency returns to normal as ONU-1 resumes primary transmission, eliminating duplicate packets from ONU-2. Figs. 3-(c) and (d) illustrate the effect of real-world faults induced via fiber tampering (bending/releasing) on both transmission paths with (c) showing ROP over time and (d) showing the corresponding packet loss. The FRER traffic remains unaffected as long as one path is operational, whereas non-FRER traffic is blocked as soon as path-1 (via ONU-1) fails.

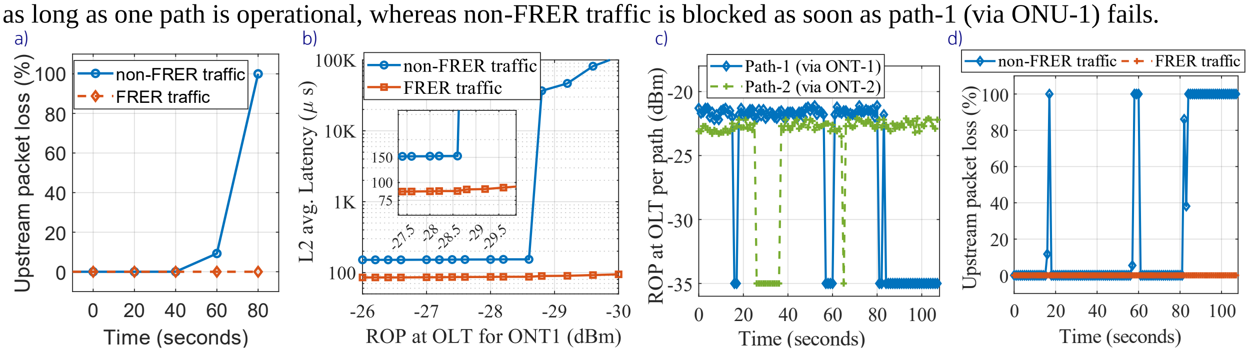

Fig. 3. Comparison of performance between FRER and non-FRER traffic: (a) Upstream packet loss over time during a link fault at ONU-1 access ODN branch (b) Corresponding application-level latency vs. the upstream ROP for ONT-1 measured at OLT-Rx, (d, e) Performance of FRER vs non-FRER traffic during real-time induced fault (fiber bend, cut and tamper) on different paths.

5. Conclusions

In this paper, we proposed a novel TDM-PON scheme and configuration that supports IEEE802.1CB-FRER for enhancing reliability in TSN for industrial applications. We presented the first demonstration of IEEE802.1CB-FRER-supporting TDM-PON indicating the viability of our scheme. The result shows that PON is a perfect fit for supporting FRER transport in industrial TSN scenarios and can serve as a great alternative to its point-to-point copper or fiber-based Ethernet TSN counterpart.

6. References.

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