

Nanosecond Electro-optic Switching with Time Synchronisation for Fronthaul TSN Applications

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Abstract: This paper presents a high-speed photonic switching system with time synchronization, enabling nanosecond switching for time-sensitive fronthaul transmission. Fronthaul performance is measured, demonstrating 33ns switch-on latency and supporting 5G/6G dynamic traffic. ©2024 The Author(s)

Introduction

In 5G/6G radio access networks (RANs), fronthaul connections between distributed units (DUs) and remote units (RUs) have stringent timing and latency requirements, posing significant challenges for infrastructure sharing between conventional Ethernet and RAN in the last mile [1]. To address these challenges, IEEE 802.1 Time-Sensitive Networking (TSN) technology was developed to ensure time-deterministic, guaranteed delivery of fronthaul data [2, 3]. TSN operates at the Layer 2 level, prioritizing and scheduling packetized frames.

One of the main contributors to latency is the delay in switching operations, including Layer 2 factors such as store-and-forward time, frame header processing, queuing delay, and reconfiguration time, along with Layer 1 factors like electro-optical conversion, transmission time, clock data recovery, and physical switch fabric delay. Meanwhile, in TSN systems, variability in switching latency can cause disrupt scheduled traffic

delivery and jitter. As the system latency requirement reaches the microsecond level, physical layer delays have become increasingly significant. These systems struggle to handle high-speed data transmission and maintain low latency, especially in dense networks, while also facing challenges in scalability and power consumption. To address these limitations, photonic integrated switches have emerged as a promising solution for dynamic fronthaul traffic routing [4,5], eliminating conversion delays, supporting high-bandwidth, low-latency operations, making them ideal for 5G/6G fronthaul traffic. However, these switches typically lack buffering and header processing capabilities, making them unable to dynamically react to incoming traffic in real time. This creates a risk of packet collision or loss if switching is not perfectly timed. Synchronization is essential to pre-align switch control signals with data bursts, ensuring deterministic and lossless operation in burst-mode and buffer-less environments.

In this paper, we present a novel switching

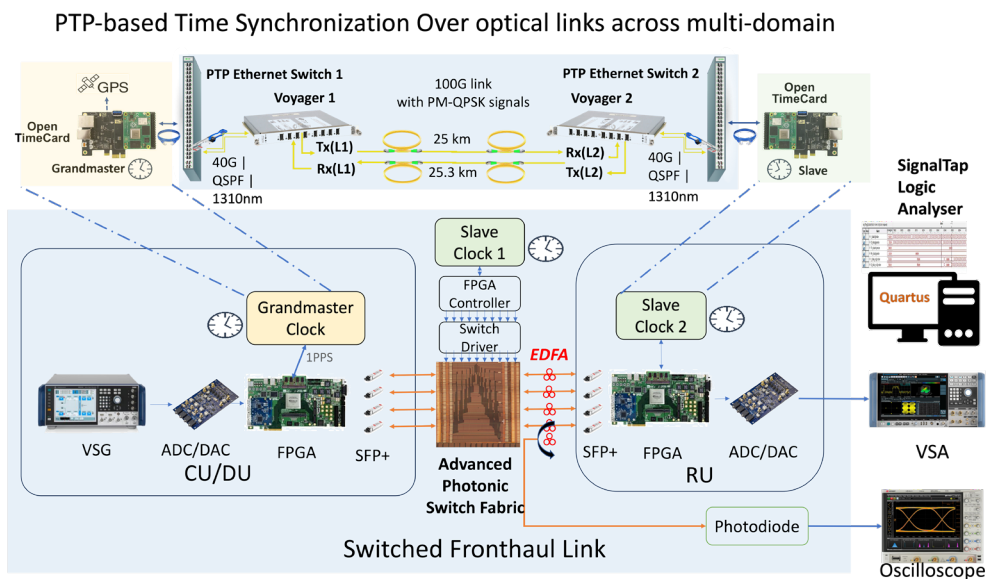


Fig. 1: Synchronized fronthaul with an advanced nanosecond photonic integrated switch.

system, featuring real-time FPGA control and fronthaul switching system using a fully packaged Si-SiN-SiN tri-layer 8×8 optical switch based on electro-optic (EO) microdisks [6]. To showcase the system's performance, we measure the overall system-level switching latency, and fronthaul performance in terms of RF and optical dynamic range using commercial off-the-shelf (COTS) transceivers. This switching system also supports both switching and multicasting functionality using the same chip. A significant milestone of 1-to-4 multicasting is also demonstrated. Using commercial precision time protocol (PTP) time synchronization, nanosecond-level optical switches can be configured and synchronized over existing links. Synchronization across multiple network components can enable time jitter of around 100 nanoseconds, making it suitable for precise control of fast optical switches and synchronization of the fronthaul nodes. The low-jitter synchronization is integrated with the FPGA-based control to enable scheduled switching.

Experimental Setup and Real-time Control

Switched Fronthaul Link

In the experimental setup shown in Figure 1, real-time 5G-compatible and 64-QAM modulated fronthaul IQ data frames running at 8.5 Gb/s are generated using a vector signal generator (VSG), an analogue to digital converter (ADC), and an FPGA, which handles data compression, packetization, and serialisation [7]. Four 1558.17 nm (C24) dense wavelength division multiplexing (DWDM)-compatible small form-factor pluggable (SFP+) optical transceivers, capable of transmitting over distances up to 80 km, performs the E/O conversions and carries the data over the SMF link. The optical switch is edge-coupled with a 10 dB fiber-to-fiber insertion loss, which is compensated for by employing an erbium-doped fiber amplifier (EDFA) at the receiver end. For optical dynamic range testing, we use a variable optical attenuator (VOA) to adjust the optical received power before reaching the Rx SFP+. The received signal is recovered along the reverse path

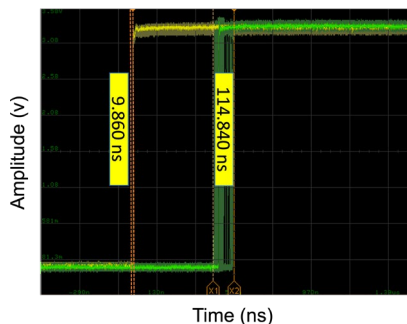


Fig.2: Clock signal jitter (from 9.86 ns to 114 ns) after 25 km transmission across multiple devices.

and then measured using a vector signal analyser (VSA).

To emulate a radio over Ethernet (RoE) frame, a frame header containing source and destination ports number and a repeating K28.5 word alignment preamble, is generated every 1 ms along with the fronthaul payload. At the receiver end, clock data recovery (CDR) is executed on the FPGA to retrieve the transceiver clock at the onset of each frame, facilitating burst mode transmission.

Switch control signals are generated using a simple round-robin scheduling mechanism with equal durations for active frame transmission and idle periods. This setup allows for the measurement of overall delay introduced in each frame relative to the rising edge of the switch control signal for burst mode data recovery. In the multicasting scenario, the control signal enables 1-to-4 broadcasting, allowing a single input to be simultaneously transmitted to all output channels. With an FPGA clock rate of 150 MHz, the switch control is triggered with a precision of 6.67 ns. The control signals are output to the FPGA's GPIO pins, generating an array of alternating 0V or 3V levels. These signals are then attenuated by a switch driver circuit to match the voltage required for controlling the on/off states of the electro-optic microdisks on the switch chip, thereby configuring the optical switching paths.

Time Synchronization

Nanosecond-level optical switching requires precise synchronization across multiple devices, particularly for efficient burst-mode operations. Accurate timing enables high precision switch control without relying on header decoding, which is a major challenge for buffer-less photonic integrated switches, and improves transmission efficiency by maximizing the payload-to-preamble ratio.

To evaluate synchronization accuracy, an Open TimeCard module with GPS timing reference provides local time references in the CU/DU and drive slave TimeCards to synchronize both the FPGA-based real-time switching control and the RUs. The TimeCards are synchronized using a commercial PTP protocol, enabling coordinated and low-jitter timing. These synchronized signals trigger the FPGA to perform simultaneous or scheduled switching, minimizing packet loss and supporting fronthaul system reconfiguration.

In the experiment, a master TimeCard connected to a PTP Ethernet switch, which interfaces with the Voyager 1 transponder via a 40G QSFP interconnect. Voyager is an open, modular coherent optical transponder platform delivering 100–400 Gb/s with Ethernet client interfaces for long-haul and metro fiber networks. Voyager 1 is connected to Voyager 2 through two separate optical

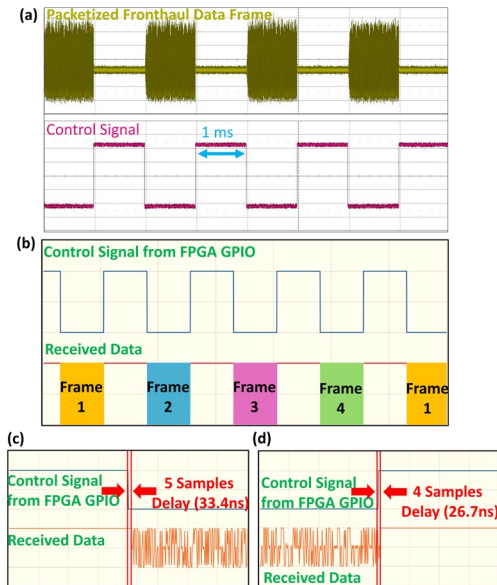


Fig. 3: Frame transmission recorded in (a) Oscilloscope and (b) SignalTap Logic Analyzer. (c) Switch-on and (d) Switch-off latency measurement at the receiver end.

paths: a 25 km transmission (Tx) path and a 25.3 km reception (Rx) path, both operating at 100 Gbit/s using PM-QPSK modulation. Voyager 2 is connected to a second PTP Ethernet switch, which in turn connects to the slave TimeCard. As shown in Figure 2, the measured clock signal jitter increases from 9.86 ns to 114 ns after 25 km transmission across multiple devices. This low jitter, measured over several minutes, confirms the stability of the time synchronization. The synchronized precise time can be used to drive the FPGA-based real-time control to configure two optical switches simultaneously.

Results and Analysis

The switching rise and fall time, measured from 10% to 90%, are 5.9 ns and 2.8 ns [6], respectively, highlighting the nanosecond switching fabric speed. Figure 3(a) and (b) demonstrate the switching performance of the 8.5 Gb/s packetized RF data frame. Four frames from four ports are allocated to each time slot using the simple round-robin mechanism and are monitored and recorded in both oscilloscope and the Altera's SignalTap logic analyser developed for FPGA-level signal probing. Figures 3(c) and (d) are

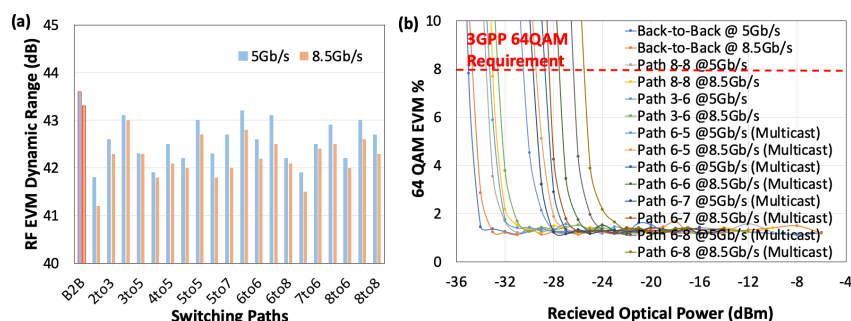


Fig.4: (a) EVM dynamic range vs. switching path. (b) EVM vs. received input power with 10 dBm input power.

zoomed-in view of frame transitions recorded in SingalTap, highlighting the system-level switch on and switch off delays. A comparison of the transmitted control signal and the received data reveals that the system achieves a total switch-on time of 33.4 ns and a switch-off time of 26.7 ns at the receiver end, validating fast and deterministic switching through the optical network.

Figure 4(a) shows the RF input power dynamic range, measured for 5G compatible 64QAM signal, showing less than 8% error vector magnitude (EVM) specified by 3GPP. Measurements were conducted or both back-to-back configuration (which only accounts for edge coupling loss) and transmission across 20 switching paths, at fronthaul rates of 5 Gb/s and 8.5 Gb/s. 8.5Gb/s is the speed limitation of the FPGA transceiver channels, and the results of 5Gb/s were tested as a control group to distinguish the impact of different data transmission rates on EVM. Despite the introduced optical switching losses and crosstalk, the system maintains a dynamic range exceeding 40 dB, with a minimum EVM of less than 1.9% (i.e. no degradation of the RF quality through the switch). Figure 4(b) illustrates the optical dynamic range achieved by adjusting the VOA. Notably, the optical power budget for 1-to-1 channel switching and 1-to-4 channel multicasting exceeds 32 dB and 25 dB, respectively, confirming the system's suitability for high-performance fronthaul applications.

Conclusion

This work demonstrates a high precision, real time optical switching system driven by a fast photonic integrated switch for fronthaul networks. By leveraging GPS-disciplined PTP synchronization, we showcase the capability of achieving fast and accurate switching without the need for header decoding, overcoming a key limitation in burst mode and buffer-less environments. This system shows a system-level switch-on time of 33.4ns and switch-off time of 26.7ns, making it suitable for TSN applications. The system maintains a high dynamic range and low EVM for 64QAM signals. With optical budgets of 32 dB for 1-to-1 switching and 25 dB for 1-to-4 multicasting, this design offers a promising solution for future RAN.

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References

- [1] Andrea Di Giglio and Annachiara Pagano, "Scenarios and Economic Analysis of Fronthaul in 5G Optical Networks," *J. Lightwave Technol.* 37, 585-591 (2019). DOI: [10.1109/JLT.2018.2880050](https://doi.org/10.1109/JLT.2018.2880050)
- [2] N. Finn, "Introduction to Time-Sensitive Networking," in *IEEE Communications Standards Magazine*, vol. 2, no. 2, pp. 22-28, JUNE 2018. DOI: [10.1109/MCOMSTD.2018.1700076](https://doi.org/10.1109/MCOMSTD.2018.1700076)
- [3] J. Farkas, L. L. Bello and C. Gunther, "Time-Sensitive Networking Standards," in *IEEE Communications Standards Magazine*, vol. 2, no. 2, pp. 20-21, JUNE 2018. DOI: [10.1109/MCOMSTD.2018.8412457](https://doi.org/10.1109/MCOMSTD.2018.8412457)
- [4] Qixiang Cheng, Sébastien Rumley, Meisam Bahadori, and Keren Bergman, "Photonic switching in high performance datacenters [Invited]," *Optics Express* 26, 16022-16043 (2018). DOI: [10.1364/OE.26.016022](https://doi.org/10.1364/OE.26.016022)
- [5] R. Sabella, "Silicon Photonics for 5G and Future Networks," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 26, no. 2, pp. 1-11, March-April 2020, Art no. 8301611. DOI: [10.1109/JSTQE.2019.2948501](https://doi.org/10.1109/JSTQE.2019.2948501)
- [6] B. Sun, M. Chen, C. Yao, P. Bao, Z. Zhang, L. Luo, Z. Shi, K. Bergman, R. Penty, and Q. Cheng, "Ultralow-crosstalk, Electro-optic Microdisk Optical Switch Fabric Incorporating Si-SiN-SiN Tri-layer Shuffle," in *ECOC 2024*.
- [7] T. Li, R. V. Penty and I. H. White, "Novel digital radio over fibre for 4G-LTE," 2015 IEEE International Conference on Communication Workshop (ICCW), London, UK, 2015, pp. 312-317. DOI: [10.1109/ICCW.2015.7247197](https://doi.org/10.1109/ICCW.2015.7247197)