Synchronized XGPON - WiFi Convergence in Fiber to the Room (FTTR) Networks

Kaustubh Venkatesh*, Christian Bluemm*, Cristian Bermudez Serna†, and Carmen Mas-Machuca†
*Huawei Technologies Duesseldorf GmbH, Munich Research Center, Munich, Germany
†Chair of Communication Networks, University of the Bundeswehr Munich (UniBW), Neubiberg, Germany
{kaustubh.venkatesh1, christian.bluemm}@huawei.com, {cristian.bermudez, cmas}@unibw.de

Abstract—**As demand for fast and reliable in-building connectivity increases, Fiber To The Room (FTTR) has emerged as a key technology to improve network performance and scalability. The preferred FTTR variant corresponds to a point-to-multipoint topology, where a centrally located Main FTTR Unit (MFU) connects to Sub FTTR Units (SFUs) in each room. Both the MFU and the SFUs integrate a WiFi Access Point (AP), implementing an IEEE 802.11 standard. Today's typical choice for the optical link is 10-Gigabit Passive Optical Network (XGPON). One challenge with this cascaded optical-wireless design is the increased system delay resulting from poor synchronization and mismatched segmentation. To solve this issue, the study proposes novel modifications to the XGPON physical layer. Notably, to enable accurate synchronization with WiFi MAC timings and procedures, we propose reducing the XGPON frame duration to $5.2\,\mu s$ and increasing the optical line rate to $25\,\mathrm{Gbps}$. End-to-end simulations with ns-3 verify that our proposals lead to improved synchronization between XGPON and WiFi. Specifically, it is demonstrated that the mean delay is reduced by approximately 11% for downstream and 9% for upstream transmissions.**

Index Terms—**Fiber To The Room, Passive Optical Networks, Optical-Wireless Convergence**

I. INTRODUCTION

Today, more than 80% of data traffic is consumed and generated indoors, while average data consumption grows rapidly. While the last transmission span towards consumer devices is typically wireless, the effectiveness of indoor communication comes with a well-matched combination of all network elements. Fiber To The Room (FTTR) connects multiple wireless Access Points (APs) with optical links, bringing fiber connections closer to end devices. This comes with the advantages of highly reliable and scalable capacity, improved network throughput, and reduced latency and jitter [1]. As in other network domains, optical connectivity can reduce the cost and energy consumption per bit compared to copper solutions and cellular connections. With the highest link rates, optical networks are future-proof to converge with emerging wireless technologies, such as the upcoming IEEE 802.11bn (WiFi 8) standard.

ITU-T Q3/SG15 has standardized multiple FTTR technologies, including G.9940 for the system architecture [2]. The preferred architecture, called G.fin (shown in Fig. 1), defines a Main FTTR Unit (MFU), which terminates the classical access network. It interfaces towards the in-building side as the Optical Line Terminal (OLT) by linking to multiple Sub FTTR Units (SFUs) in each room. Each SFU combines an Optical Network Unit (ONU) and a WiFi AP. The latest FTTR deployments implement a 10-Gigabit Passive Optical Network (XGPON), cascaded with a WiFi 6 (IEEE 802.11ax) or WiFi 7 (IEEE 802.11be) AP [1].

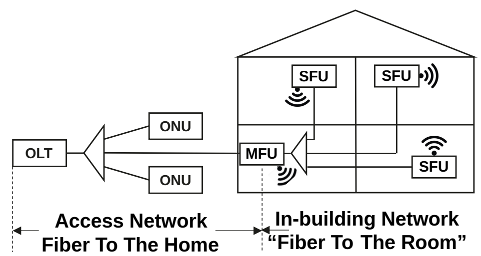

Fig. 1. G.fin Fiber To The Room Point-to-Multi-Point (P2MP) architecture.

Although this point-to-multipoint architecture is centralized, the Medium Access Control (MAC) and Physical (PHY) layers of the optical transport and WiFi air interfaces remain fully decoupled, with their respective protocols simply being cascaded. This lack of integration between the two domains constrains the overall system performance in several ways:

- Increased latency and jitter due to poor timing synchronization and buffering delays.
- Reduced throughput due to scheduling mismatches and misaligned frame segmentation between the two MAC protocols.
- Redundant header fields across the protocols, leading to processing overhead and reduced capacity.

Existing studies [3] fail to adequately address these issues, as they primarily focus on the wireless aspects of FTTR without considering possible improvements to the XGPON protocol. In particular, [4] provides some analysis of timing synchronizations, but simply bridges XGPON procedures with WiFi for better integration. Other works address the cross-link scheduling problem but overlook timing synchronization between the two domains [5, 6]. However, as wireless standards achieve higher peak data rates, the XGPON link becomes a key bottleneck in the system [7].

To address these issues, this study makes the following contributions:

- WiFi-specific enhancements to the XGPON PHY layer, enabling efficient synchronized operation in the heavily loaded downstream direction.

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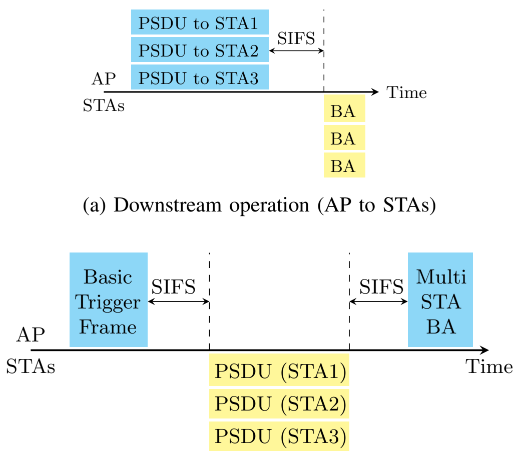
- A comprehensive End-to-End (E2E) ns-3 simulation testbed for FTTR, allowing accurate system-level evaluations.
- Analysis of latency and throughput improvements under the proposed scheme.

II. Synchronized Convergence for FTTR

In XGPON, the MFU (OLT) controls scheduling in the downstream and resource allocation in the upstream. Each SFU (ONU) requests bandwidth from the MFU via the upstream buffer occupancy frame. The MFU includes the Dynamic Bandwidth Allocation (DBA) for each SFU in the subsequent downstream frame. In IEEE 802.11ax [8], the AP arbitrates Multi-user (MU) trigger-based transmissions, depicted in Fig. 2. To avoid collisions, the devices wait for Short Inter-frame Spacing (SIFS), defined to be $10\,\mu s$ in the $2.4\,GHz$ band and $16\,\mu s$ in the $5\,GHz$ band. In the downstream, the AP performs a MU transmission to all the STAtions (STAs), which reply with a Block Acknowledgment (BA). Once the AP receives the BA, it schedules a MU upstream transmission by sending basic trigger frames to the STAs.



(a) Downstream operation (AP to STAs)

(b) Upstream operation (STAs to AP)

Fig. 2. Multi-user down- and upstream operation in IEEE 802.11ax.

Fig. 3 shows the sequence diagram of the converged network, where each XGPON frame has a fixed duration of $125\,\mu s$. It takes three frame cycles to complete the DBA procedure and to receive a new downstream frame at the SFU. Thus, the SFU (AP) must wait for $3 \times 125\,\mu s$ before it can access the wireless channel for a downstream transmission. The WiFi MAC at the SFU must then wait for the channel to be free, while buffering any data to be sent in the upstream. This timing mismatch causes buffer overflows, leading to retransmissions and increased delays. However, if these three cycles are completed before the SIFS timer expires, the SFU can transmit packets in the downstream and take control of the channel before any STA, improving latency.

By reducing the XGPON frame duration to approximately $5.2\,\mu s$ (a third of the maximum SIFS duration), we achieve synchronization between the XGPON and WiFi MAC layers. To ensure sufficient payload capacity for the XGPON header and data bits, the optical line rate is increased to $25\,Gbps$. Studies [9, 10] show that such an increase requires no significant upgrade from classical 10G optical components. With appropriate signal processing techniques (duo-binary encoding and feed-forward equalization), these components can support the required rate for a range of $25\,km$. Compared to these studies, the need for signal processing techniques to realize $25\,Gbps$ with 10G optical components is much more relaxed in FTTR environments due to significantly lower range requirements of only up to $200\,m$ in residential scenarios according to ITU-T G.9940.

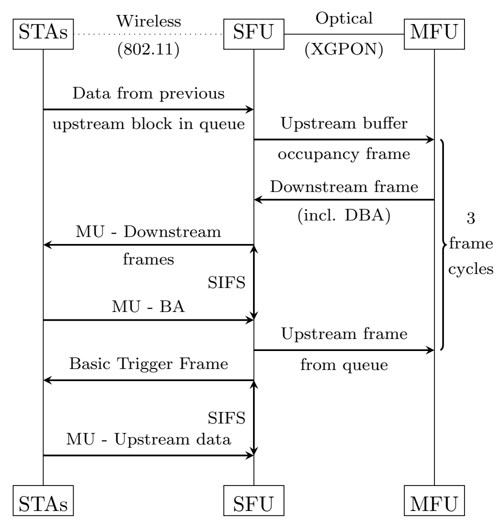


Fig. 3. Sequence diagram of the converged network.

III. Simulations with NS-3

The network simulator ns-3 is used to simulate and analyze an FTTR system. The default ns-3 distribution includes a WiFi module based on IEEE 802.11ax. This study uses a standard-compliant XGPON module contributed by the authors of [11].

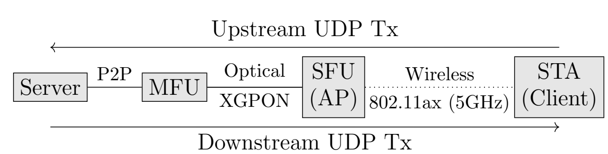
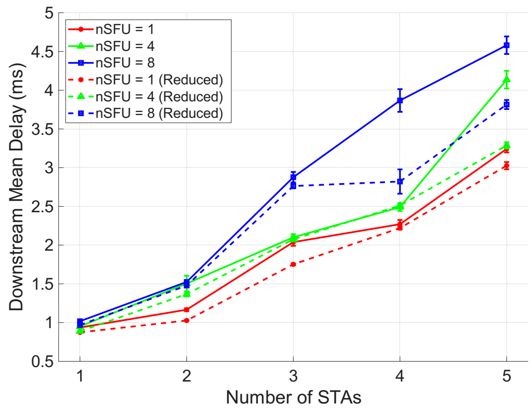
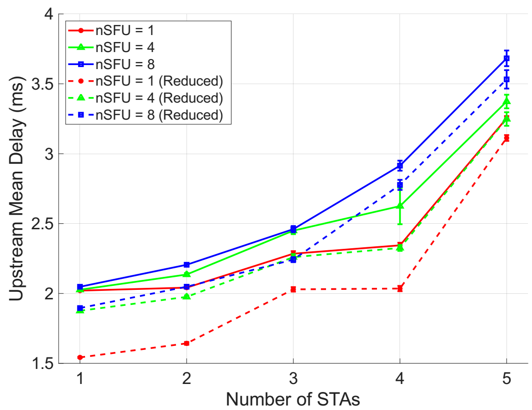


Fig. 4. ns-3 setup for the FTTR simulator.

An FTTR setup is implemented in ns-3 by interfacing various classes of the XGPON and WiFi modules. The simulation models both home and commercial deployments, where the nodes have static positions. To simulate network traffic, UDP packets are generated with client applications on the STAs. Fig. 4 shows the packet transmission setup. Each client generates data traffic at the rate of 25 Mbps, where the active and idle periods are modeled with independent exponentially distributed random variables with $\lambda = 1.5\,s$. This study evaluates the mean E2E packet delay between the client (STA) and the server, while keeping throughput constant.



(a) Downstream mean delay statistics



(b) Upstream mean delay statistics

Fig. 5. Delay statistics for End-to-End FTTR simulation.

IV. Results & Evaluation

This section presents ns-3 simulation results to demonstrate the performance improvement that can be achieved with our proposals. The setup described in the previous section is executed 30 independent times for 30 s with different seed values, and the statistics are averaged. In Fig. 5a and 5b, the mean delay, along with 99% confidence intervals for down- and upstream transmissions, is illustrated, respectively. They depict the statistics for the baseline and reduced frame setups for different numbers of SFUs (nSFU), each connected to multiple STAs, shown on the x-axis.

From the plots, it is clear that the reduced frame setup offers improved delay, especially in dense scenarios with a large number of STAs (≥ 4 per AP). Overall, the downstream delay improves by about 11% for the reduced frame setup, whereas the reduction is about 9% for the upstream. This is attributed to better converged timing synchronization, which reduces the mean buffering delay in the downstream and scheduling delay in the upstream. Shrinking the XGPON cycle ensures that the fiber backhaul is not the dominant delay component, significantly lowering the overall E2E system latency.

However, for setups with more than 8 STAs, the reduced frame size of $5.2\,\mu s$ becomes insufficient to accommodate XGPON headers and data. This results in higher overhead, segmentation, and abnormal delays. However, the reduction in the effective payload per frame is an acceptable trade-off for the improvement in latency, especially for real-time traffic applications. This scaling issue can be solved with optimized scheduling and load balancing schemes in the downstream, or by further increasing the optical link data rate.

V. Conclusion

Though FTTR offers substantial improvements in coverage, throughput and scalability, poor network synchronization between the cascaded XGPON and WiFi protocols leads to increased latency and jitter. To optimize converged network operation, this paper proposes reducing the XGPON frame duration to $5.2\,\mu s$ such that the XGPON DBA procedure and downstream frame cycles at the SFU are synchronized with the WiFi MAC. To support this, the optical line rate is increased to 25 Gbps, which is feasible with existing XGPON components, when applied to relaxed link budget scenarios like FTTR. Simulations with ns-3 show that reductions in queuing and scheduling delays improve E2E delay by $\approx 11\%$ in the downstream and $\approx 9\%$ in the upstream.

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