Experimental Demonstration of Demand-Driven PON Configuration for Fixed-Mobile Convergence

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Abstract *Here, we address fixed-mobile convergence using an SDN-enabled PON with dynamic T-CONT configuration. Sub-millisecond PON latency is demonstrated for mobile traffic while reducing bandwidth usage by up to 80% during off-peak periods. We also compare different network configuration approaches with a Random Forest prediction model.*

Introduction

Mobile and fixed access networks have historically evolved along separate technological paths in terms of optical connectivity. However, increasing demands for ubiquitous connectivity, network consolidation, along with the need to reduce fiber deployment costs and simplify site maintenance, have recently pushed both domains towards shared architectural approaches. This Fixed-Mobile Convergence (FMC) manifests from simple sharing of Optical Line Termination (OLT), augmented with point-to-point (PtP) line cards, to more disruptive mutualization of optical channels in the same Optical Distribution Network (ODN) of a point-to-multipoint (PtMP) topology. The key advantage of FMC within the access network lies in leveraging pre-existing Fiber-to-the-Home (FTTH) networks whenever and wherever needed, reducing deployment costs and accelerating mobile coverage. Unlike traditional PtP optical fiber systems, which offer superior performance but at high deployment costs, PtMP architectures could provide cost-effective alternatives in more opportunistic connectivity scenarios. The densification requirements of 5G networks could further accelerate this convergence, prompting cost-effective deployment strategies for small cells. Although Gigabit-capable Passive Optical Networks (G-PON) are now considered a legacy standard for access networks with lower throughputs compared to newer technologies, its widespread global deployment[1] represents a significant opportunity for infrastructure reuse.

However, 5G and beyond (B5G) networks will have to comply with stringent needs such as ultra-low latency (0.1 - 1 ms) while also ensuring improved throughput and other capabilities[2]–[4]. Thus, while FMC aims to optimize resource utilization and ensure service continuity, transmitting all 5G verticals or xhaul interfaces over shared optical infrastructures presents several challenges, namely in terms of bit-rate, latency and fairness between fixed and mobile usages. Proper bandwidth allocation could thus prove to be a viable solution for the transmission of certain interfaces and services of the Radio Access Network (RAN), especially for small cells provisioning, service-specific offloading and link redundancy use-cases (Fig.1).

Various works have tackled FMC by modifying PON dynamic bandwidth allocation (DBA) algorithms[5]–[9]. However, these were mainly vendor-centric solutions as DBA algorithms typically operate as black-boxes, preventing any sort of modification by the operators. Adaptive DBA traffic container (T-CONT) configuration has also been investigated in a link redundancy use-case[10] but only with 2 optical network units (ONU), which limited the assessment of the impact on and from the mobile traffic. Finally, user traffic profiling should also be taken into account when evaluating FMC. Dynamic service level agreement (SLA) optimization for G-PON based on field traffic patterns was suggested in the past[11], but focused on user clustering without addressing latency issues.

Our study leverages a commercial G-PON platform with software-defined networking (SDN) and orchestration for dynamic T-CONT configuration, enabling traffic-adaptive uplink resource allocation in a FMC context, with a higher number of ONUs and without any need for changes of the DBA algorithm. We compare different approaches for network configuration with different ONU traffic profiles using a Machine Learning prediction model which allows for sub-millisecond latency for mobile traffic while ensuring global bandwidth reduction by up to 80% during off-peak periods. This approach could be seamlessly used in newer, higher-throughput PON generations.

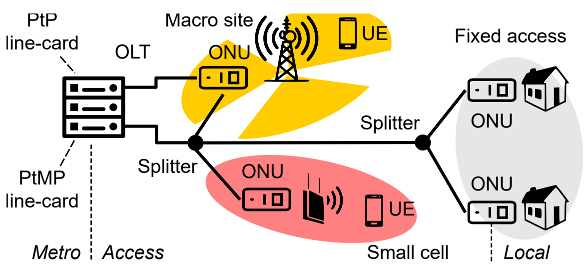

Fig. 1: FMC use-cases. Top: Macro site dual-homing with selective offloading. Bottom: opportunistic small cell link.

Experimental Setup

The physical network functions in our experimental setup, shown in Fig.2, include a commercial G-PON platform with an OLT and 16 ONUs, an Ethernet traffic generator for generation and analyses of upstream and downstream data flows, switches for the aggregation of ONU traffic and for an out-of-band control plane (CP) and a server hosting all SDN and orchestration functionalities. One ONU handled Fiber-to-the-Antenna (FTTA) traffic, while 15 ONUs served fixed clients, i.e., FTTH.

Our SDN controller abstracts the optical access network via CLI over Telnet (southbound) and RESTCONF/YANG (northbound). An orchestration layer automates experimental measurements, service definition, model calculations, and training using the acquired datasets.

Traffic patterns were created based on literature documenting 24-hour cycles, as shown in Fig.3. Fixed users showed minimal usage at 3 a.m., peaking at 21 hs.[12]–[14], while mobile traffic peaked at 15 hs before declining as users switch to Wi-Fi[15]. The mobile traffic in Fig.3 could be associated with a small cell or with part of the traffic from a dual-homed Macro site that is offloaded using a nearby PON. Also, the 15 fixed clients representing Fiber-to-the-Home (FTTH) connections were classified into heavy, medium and low usage groups.

Through our SDN controller, we collected more than 44k measurement points over two weeks focusing on two types of T-CONTs: T-CONT type 1 for mobile traffic, defined by the fixed-information-rate (FIR) parameter and T-CONT type 3 for fixed clients, defined by the peak-information-rate (PIR) and committed-information-rate (CIR). Even if we consider here a relatively simple scenario with only one type of service for each of the FTTA and FTTH users, our choice of T-CONTs should allow deterministic packet jitter for mobile clients and bandwidth reallocation between fixed-users while guaranteeing them a minimum SLA. All 15 FTTH clients were always guaranteed 1 Mbps and shared the same PIR value in each measurement scenario. Multiple FIR-PIR combinations were tested throughout the data collection period. Our objective is thus to reduce the impacts of the fixed

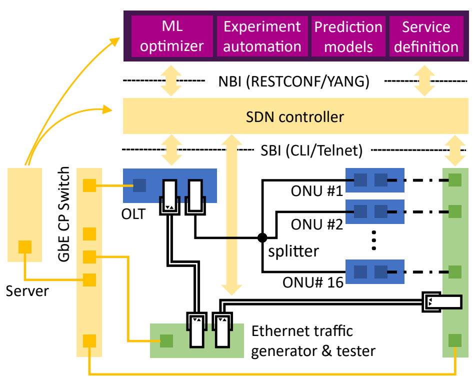

Fig. 2: Experimental setup.

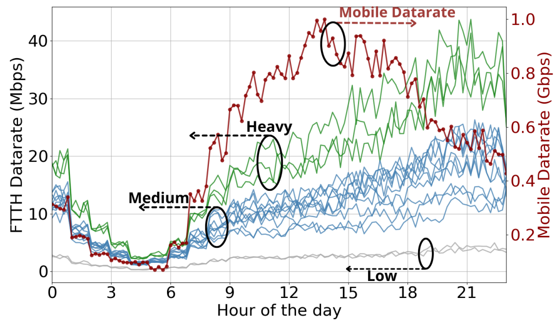

Fig. 3: Assumed traffic profiles for a weekday. Client types: mobile (red), fixed (low: grey, medium: blue, heavy: green).

bandwidth allocation of the FTTA ONU on the remaining FTTH users while ensuring the needed performances in terms of latency for the former, at different times of the day.

Prediction Models

Accurate forecasting models are essential for characterizing PON behavior and optimizing bandwidth allocation parameters, especially when dealing with such a high number of dimensions. We thus trained models using a limited set of acquired experimental data that allow us to interpolate results for other T-CONT configurations and predict congestion and delays.

We implemented Random Forest algorithms with two models for each FTTH ONU: one detecting congestion (delay > 1 ms) and another identifying low congestion (1 - 5 ms), along with a delay prediction model for FTTA, using the upstream delay as reference. Each model used eighteen input features including T-CONT configuration parameters and throughputs of all flows.

As expected, analysis of the mobile prediction model (Tab. 1) revealed that delay is primarily impacted by the FTTA FIR since longer guaranteed upstream time slots results in shorter waiting times. Mobile data volume also impacts delay performances whenever transmitted bit-rates overcome the FIR value. Interestingly, however, we notice that the FTTH PIR parameter and the fixed client data rates, while not directly related to FTTA traffic, also, exert some influence on its delay. We believe this occurs because of non-negligible PIR values and active fixed traffic generating increased queuing at OLT, thus degrading overall performances.

Tab. 1: Feature importance in mobile delay prediction. DR = Datarate; "FTTH DR" aggregates all 15 FTTH clients.

FTTA FIR	FTTH PIR	FTTA DR	FTTH DR
81.92%	1.77%	14.41%	1.81%

Fig. 4 displays the delay behavior for several FIR-PIR combinations, with colors indicating different traffic categories. During mobile traffic peak hours (12 hs - 16 hs), bandwidth demands increase significantly. However, even with large but

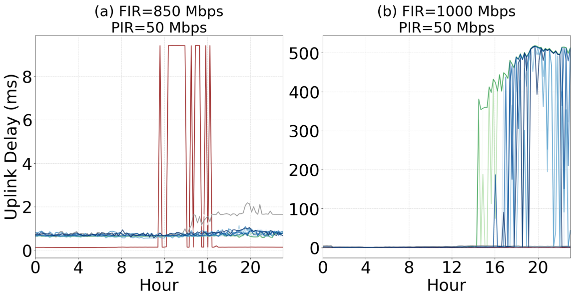

Fig. 4: 24-hour delay for FIR-PIR combinations. Colors match client types from Fig.3.

static bandwidth allocations, inadequate FIR settings relative to traffic load lead to delays of approximately 9 ms (see Fig. 4 left)—unacceptable under 5G requirements. Results show that no static configuration can maintain uncongested FTTA and low congestion for FTTH during the entire 24-hour period, which is why dynamic PON parameters adjustment is essential for optimal FMC.

We performed a grid search over PIR-FIR combinations for each hour, evaluating each pair with our congestion models. For FTTA, we kept only configurations with delay $<$ 1 ms; for FTTH, we allowed low congestion only if no combination avoided it while meeting FTTA constraints. We're supposing here that FTTH services can be assumed more tolerant to higher latency values within 5 ms. We then defined four T-CONT configuration policies:

- **Minimum FTTA Delay**: dynamically selects the combination with lowest predicted FTTA delay.
- **Minimum Assigned Bit-rate**: minimizes FIR $+$ $15 \times (\text{CIR} + \text{PIR})$, CIR $=$ 1 Mbps.
- **Balanced**: among combinations of the minimum FTTA delays, picks the one allowing the lowest total bandwidth usage (i.e., the sum of bandwidth used by all ONUs).
- **Fixed Policy**: used as a baseline for static T-CONT use-cases, defined with 600 Mbps FIR and 40 Mbps PIR on the full dataset.

Results

Figs. 5a and 5b demonstrate the performance trade-offs between delay minimization and total bandwidth usage across our four distinct optimization policies. The three dynamic policies have no congestion for FTTA traffic. For FTTH, only 16 of 120 points (13%) show low congestion.

In Fig. 5a, the Minimum FTTA Delay Policy consistently maintains low latency (120-140 μs), while the Fixed Policy experiences congestion during peak hours. The Minimum Reserved Capacity Policy shows higher delay variability, with peaks reaching 350 μs during off-peak hours.

Fig. 5b reveals the corresponding bandwidth requirements, where the Fixed Policy maintains a constant 1.22 Gbps allocation, while the Minimum Reserved Capacity Policy achieves significant reductions (down to 150 Mbps) during low-traffic periods. The Balanced Policy effectively mediates between these extremes, preserving acceptable delay performance while achieving substantial bandwidth savings during off-peak hours. These results confirm that dynamic PON parameter optimization can simultaneously satisfy latency requirements of some 5G FTTA services and improve network resource efficiency compared to static configurations.

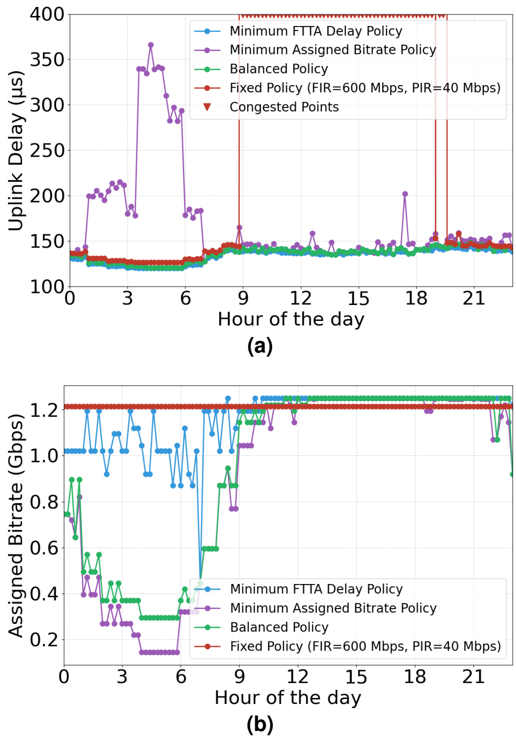

Fig. 5: Comparison of different policies.

Conclusions

In this work, we have demonstrated the viability of G-PON networks for supporting both fixed and mobile traffic in FMC scenarios. Our experimental setup, employing SDN-enabled dynamic T-CONT configuration, confirms that adaptive parameter optimization can effectively balance the competing requirements of bandwidth efficiency and low-latency service delivery. The comprehensive analysis across multiple FIR-PIR combinations reveals that static configurations inevitably lead to either congestion during peak hours or bandwidth wastage during off-peak periods.

The proposed Machine Learning approach, using Random Forest models, provides accurate delay predictions, enabling proactive network reconfiguration. Our results show that the Balanced Policy achieves a practical compromise between FTTA minimal delay requirements and bandwidth conservation, with significant resource savings (up to 80% compared to the reference fixed allocation) during low-traffic periods while keeping performances acceptable for all users.

These results, which could be easily declined to newer PON generations, support the feasibility of reuse of PON infrastructures for selected 5G services, especially small cell backhaul, alongside plain FTTH services, offering operators a solution to a better use of network resources without compromising service quality.

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