Dynamic Resource Allocation in Coherent DSCM PON for Mobile Fronthaul with Different Functional Splits

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***Abstract*—Considering the expected heterogeneity of future mobile fronthauling scenarios in terms of capacity, latency, and geographical density, flexibility becomes a crucial factor in utilizing network resources. Therefore, we propose an integer linear programming model for the dynamic allocation of subcarriers in the upstream coherent passive optical networks, by leveraging digital subcarrier multiplexing to accommodate 5G/6G mobile fronthauling demands. The model specifically considers the requirements of the low-layer functional splits 7.1 and 7.2, while integrating frequency-domain hybrid-modulation to accommodate the varying conditions of optical network units. This approach enables efficient and flexible resource allocation in heterogeneous fronthauling environments.**

***Index Terms*—Coherent PON, digital subcarrier multiplexing, flexible PON, fronthauling, functional split, resource allocation.**

I. Introduction

Advancements in 5G and upcoming 6G technologies, targeting higher data rates and denser cells, combined with the wide geographical coverage of the point-to-multipoint (P2MP) architecture of passive optical networks (PON), make PON an ideal solution for future mobile fronthauling (FH) deployments [1]. This is further supported by ongoing standardization efforts for next-generation PON, aimed at 100 and/or 200 Gbps, in which coherent transmission is under consideration including its digital subcarrier multiplexing (DSCM) variant [2], enabling time-frequency division multiplexing for a greater flexibility and supporting hybrid-modulation (HM) across both domains. FH also plays a role in dynamic bandwidth allocation (DBA) schemes in PON, which are controlled by the optical line terminal (OLT) and designed based on the network architecture while also considering the specific requirements of services such as data and FH. Various schemes exist, including status-report DBA, which relies on optical network units (ONUs) queue-occupancy reports for efficient allocation but introduces latency, and cooperative DBA, which reports on the FH traffic arrival to reduce allocation delays. These approaches can be combined to support both FH and data services [3]. The study of optimal and flexible resource allocation algorithms is becoming interesting for DSCM-coherent PON. We thus propose a subcarrier (SC) allocation scheme for future DSCM-coherent PONs that considers ONU demands and physical limitations within a simplified clustering constraint. This study builds on the optimization model introduced in [4], which initially assumed that ONUs could access all available SCs, with the goal of minimizing the number of SCs used on both the OLT and ONU sides. In contrast, the key contribution of the present work is introducing additional constraints, restricting the ONUs to a maximum of two consecutive SCs. This constraint allows the use of low-bandwidth digital-to-analog converters (DACs) at the ONU side, where hardware cost is a key issue. The constraint on using only two consecutive SCs reduces not only DAC requirements but also the speed requirements for all following receiver DSP functions. Furthermore, this study investigates various functional splits (FSs) and assesses the impact of high-bitrate radio FS, such as split 7.1, in conjunction with its ONU physical characteristics. Although latency is not addressed in this study, a supplementary optimization stage could incorporate time-slot allocation using scheduling information from the radio side. The remainder of this paper is structured as follows: Section II outlines the system model and optimization problem, while Section III describes the simulation setup and presents numerical results.

II. Proposed system model

In this section, we describe the proposed coherent PON architecture, as illustrated in Fig. 1(b). We consider a converged metro-access coherent uplink consisting of two PON trees optically connected to the metro section through reconfigurable optical add-drop multiplexers (ROADMs) utilizing DSCM. Both PON trees operate on the same upstream wavelength λ_{US} and use proper time and SC multiplexing. On the radio side, 3GPP standards define eight possible FS options. Among these, FS 7.2 and FS 7.1 are the most promising options for

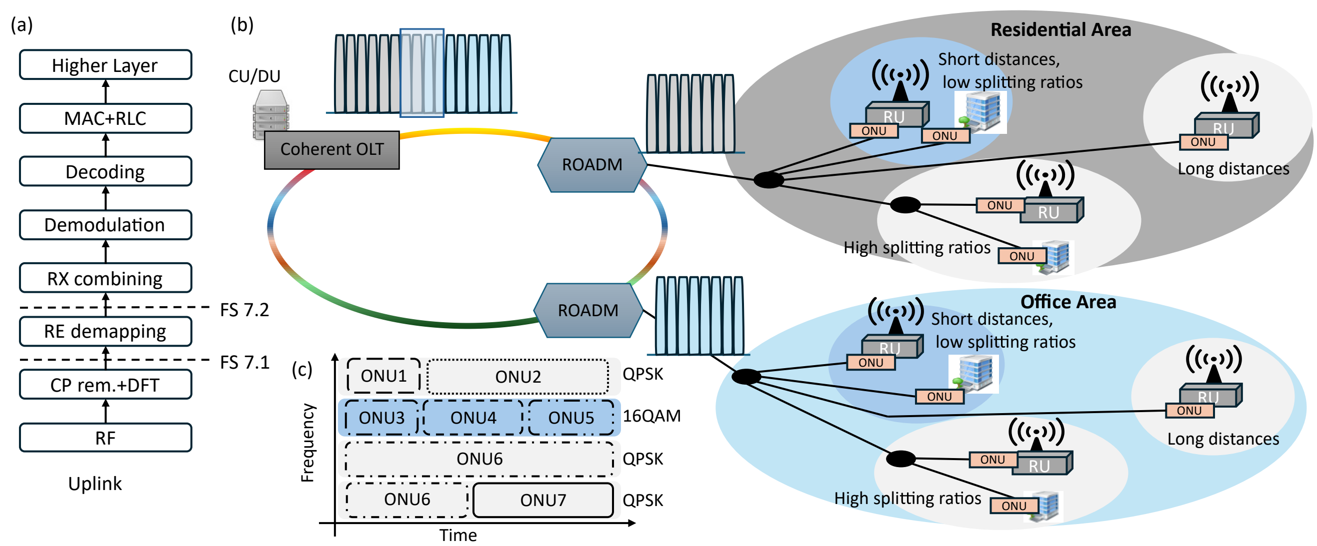

Fig. 1. (a) Uplink radio processing blocks with the functional splits addressed, as defined by the 3GPP standard. (b) Converged coherent metro-access passive optical network (PON) supporting both fronthauling and access services while accounting for various distribution losses. (c) Subcarrier (SC) allocation map based on frequency-domain hybrid-modulation in a coherent digital SC multiplexed PON.

uplink integration, as illustrated in Fig. 1(a), and are therefore the focus of this study. Our objective is to integrate the high and constant bitrate demands of FS 7.1 with the moderate and variable demands of FS 7.2 within the future P2MP infrastructure [5]. We assume that each PON tree consists of a set of M ONUs, categorized into three groups based on traffic type: FS 7.1, FS 7.2, and residential access. In addition to this classification, we define a set of clusters $C = \{c1, c2\}$, where each cluster groups a subset of ONUs based on their optical distribution network (ODN) loss [6]. Specifically, cluster $c1$ includes ONUs with high ODN loss, characterized by a higher number of splitters or longer distances, while cluster $c2$ represents ONUs experiencing low ODN loss, corresponding to fewer splitters or shorter distances. In our Monte Carlo simulations, each ONU i is randomly assigned to one of these two clusters such that $c(i) \in C$. Moreover, we assume that each PON tree is assigned a set of K SCs deploying frequency-domain HM, where ONUs can share a SC only if they belong to the same cluster. This approach allows ONUs with low ODN loss to utilize high-order modulation formats while avoiding the need for time-dependent signal processing at the OLT, required in time-domain HM. We formulate the SC assignment to ONUs as a multi-objective linear programming problem, with the goal of maximizing the allocated demands while minimizing the number of occupied SCs at the OLT. This proposed algorithm considers several inputs, including the number of ONUs, the number of available SCs, the type of traffic associated with each ONU, and the ODN loss cluster of the ONUs. We define x_{ij} as a decision variable that represents the demands assigned from i^{th} ONU to j^{th} SC and consequently the variables z_{ij} and y_j are binary decision variables that depend on x_{ij}. Specifically, z_{ij} defined in (1) indicates whether ONU i is assigned to SC j:

$$z_{ij} = \begin{cases} 1, & \text{if} \quad x_{ij} > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

and y_j in (2) indicates whether SC j is in use, i.e., if the total allocated demands across all ONUs on SC j is greater than zero, as follows:

$$y_j = \begin{cases} 1, & \text{if} \quad \sum_{i=1}^{M} x_{ij} > 0, \quad \forall j \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Consequently, the optimization objective for each PON tree is formulated as follows:

$$\max \left\{ \alpha_1 \sum_{i=1}^{M} \sum_{j=1}^{K} x_{ij} - \alpha_2 \sum_{j=1}^{K} y_j \right\}. \tag{3}$$

Here, α_1 and α_2 are the weighting parameters for the multi-objective optimization, determined through numerical simulations. The problem constraints are defined as follows: the first constraint in (4) ensures that resource allocation remains exclusive within each cluster, meaning that ONUs belonging to different clusters cannot be assigned to the same SC:

$$z_{ij} + z_{mj} \neq 1, \quad \text{if} \quad c\,(i) \neq c\,(m)\,, \quad \forall j. \tag{4}$$

Additionally, the constraint in (5) ensures that the total resources allocated to ONU i across all SCs do not exceed its demand while allowing the ONU to distribute its demand among multiple SCs:

$$\sum_{j=1}^{K} x_{ij} \leq demands\_ONU(i), \quad \forall i, \tag{5}$$

whereas the constraint in (6) ensures that the demands assigned to each SC does not exceed its capacity, as follows:

$$\sum_{i}^{M} x_{ij} \leq SC\_capacity(c), \quad \text{for} \quad \forall j, \quad \forall c \in C. \tag{6}$$

Here, the SC capacity is determined considering the cluster-specific SC bitrate and the frame size. Finally, we define a subset of N ONUs that is restricted to using a maximum of two SCs, as specified in (7).

$$\sum_{j=1}^{K} z_{ij} \leq 2, \quad \forall i \in N \tag{7}$$

Additionally, we introduce a constraint to ensure that the assigned SCs are consecutive, i.e adjacent in the spectral allocation, thereby limiting the bandwidth requirements of the DAC at the ONU, as outlined in (8):

$$\sum_{j=1}^{K-1} \left| z_{ij} - z_{i(j+1)} \right| \leq 2, \quad \forall i \in N \tag{8}$$

The remaining ONUs ($M - N$), such as the FS 7.1 ONUs with extremely high bitrate requirements, are granted access to the full available symbol rate, allowing them to utilize all SCs.

III. Simulation Results and Discussion

We consider the architecture depicted in Fig. 1(b), where each PON tree serves M ONUs using a coherent DSCM system operating at a global symbol rate of 50 Gbaud with 8 SCs. The system employs dual-polarization quadrature phase shift keying (QPSK) for cluster $c1$ (high ODN loss) and 16-quadrature amplitude modulation (16QAM) for cluster $c2$ (low ODN loss), achieving bitrates of 25 and 50 Gbps per SC, respectively. Additionally, we assume that 25% of the ONUs support FH services with FS 7.2, while only a single ONU operates with FS 7.1. The remaining ONUs are designated as regular data ONUs. Moreover, we assume that FH ONUs support a radio bandwidth of 100 MHz, 64QAM modulation, 32 antenna ports, 8 MIMO layers, MAC information of 120 Mbps and 80 Mbps for FS 7.2 and 7.1, respectively, an IQ bit width of 2×16 bits, 14 symbols, and 1200×5 radio SCs. This configuration results in a peak FH bitrate of 21.6 Gbps for FS 7.2 and 86.1 Gbps for FS 7.1 [7]. Each data (residential) ONU serves 10 active users, each with a peak bitrate of 500 Mbps. FS 7.1 operates at a constant bitrate, independent of user traffic. Therefore, we assume a fixed packet size of 1518 bytes, with inter-arrival times determined by the bitrate. In contrast, variable bitrate FS 7.2 and data ONUs generate packets of varying sizes, uniformly distributed between 64 and 1518 bytes, as their bitrates depend on user traffic. The packet arrival times for FS 7.2 and data ONUs follow a Poisson process, where average packet arrival rate, λ, is computed as the total traffic load divided by the average packet length. The packet inter-arrival time is then given by $T_i = -\frac{1}{\lambda} \ln(U_i)$, where U_i is a uniformly distributed random variable in the range $[0, 1]$. To evaluate the performance of the proposed optimization algorithm, we compare it with two baseline algorithms: (i) *Sequential allocation*, where ONUs are assigned SCs one at a time until their demands are met or the available capacity is fully utilized, after which allocation proceeds to the next ONU demands or the next SC, and (ii) *Fixed bandwidth allocation*, where the total bandwidth is evenly divided among ONUs without considering their individual demands or physical state, and then assigned to SCs sequentially. The proposed optimization approach is implemented in Python using PuLP [8] and solved with CBC [9]. At the beginning of each upstream frame size of 125 μs, the OLT determines the allocation map based on FH demands stated by the radio controller and demands reported from other ONUs, and then each ONU is assigned one or more SCs along with transmission duration in bytes. Simulations are conducted over 100 iterations, i.e 100 upstream frames.

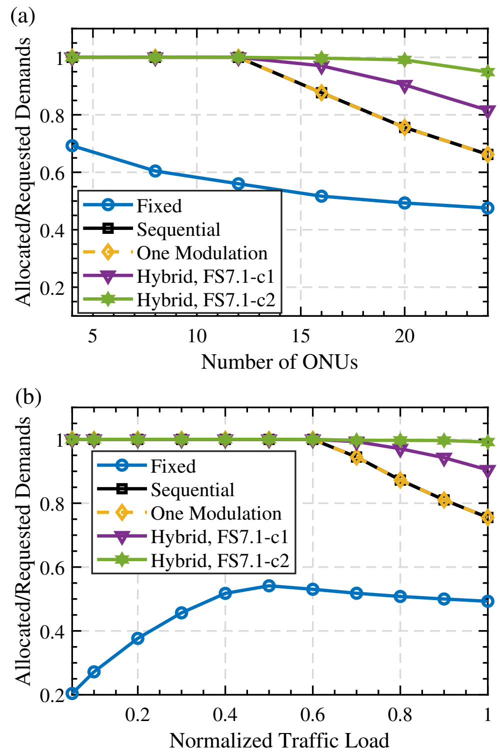

Fig. 2. The ratio of the total allocated demands to the requested demands considering the discussed allocation approaches versus (a) number of ONUs, and (b) normalized traffic load considering 20 ONU.

Figure 2(a) illustrates the ratio of total allocated demands to requested demands as a function of the number of ONUs under full load. Meanwhile, Fig. 2(b) depicts the same ratio but plotted against the normalized traffic load for a set of 20 ONUs. The results are presented for the different allocation approaches: fixed, sequential, one modulation (i.e., the same optimization function but without considering HM clustering), and hybrid (representing the proposed optimization algorithm, with the high bitrate ONU FS 7.1 classified as either c1 or c2). As seen in Fig. 2(a), deploying the allocation scheme that considers clustering with HM outperforms the other algorithms. When the ONU with FS 7.1 is assigned to the cluster with higher modulation and consequently higher SC bitrate, the PON can fully allocate the requested demands for up to 20 ONUs. However, when it is assigned to the other cluster, about 14 ONUs can be fully supported. Without considering HM and with FS 7.1's high required bitrate, the PON can support about

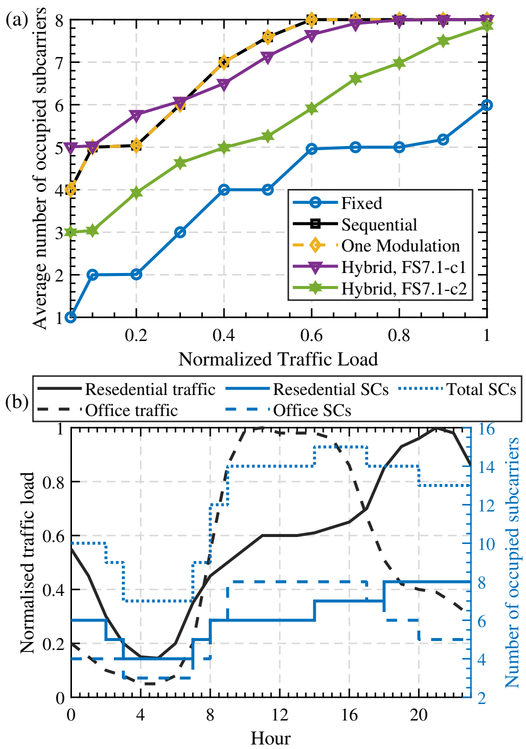

Fig. 3. The number of allocated subcarriers as a function of (a) normalized traffic load for 20 ONUs, and (b) time-based traffic load for two PON trees [10] sharing subcarriers in a converged metro-access network.

12-13 ONUs. Since the fixed bandwidth allocation assigns bandwidth to all ONUs irrespective of their demands, the bandwidth allocated to FS 7.1 is the same as that allocated to data ONUs, resulting in a low ratio, even for a small number of ONUs. Moreover, this ratio decreases as the number of ONUs increases, since the share for FS 7.1 becomes even smaller. However, if we consider the traffic load of the ONUs, as illustrated in Fig. 2(b), which is applied only to user-dependent ONUs (specifically FS 7.2 and data ONUs), the PON can fully support up to 1 FS 7.1 ONU (user-independent) and 19 other ONUs with a traffic load of 0.6, whether HM is used or not. For traffic loads higher than 0.6, such as 1, the ODN loss for the FS 7.1 ONU, $c1$ or $c2$, determines whether 0.9 or 1 of the requested traffic demands can be fully allocated, respectively. Figure 3(a) illustrates the average number of utilized SCs as a function of the normalized traffic load for 20 ONUs for the studied algorithms. As shown, the fixed allocation approach requires the fewest SCs; however, this comes at the expense of unallocated demands. In contrast, the proposed optimization model achieves a reduction in the number of SCs while still fulfilling the requested demands, as demonstrated in Fig. 2(b). It is important to note that the SC-saving of the proposed model is dependent on the ODN loss associated with the FS 7.1 ONU, which requires a substantial portion of the system's capacity. Specifically, if the FS 7.1 ONU is assigned to cluster $c1$, the application of HM will not result in the same reduction in the number of SCs.

In Fig. 3(b), we present the hourly-based normalized traffic in two PON areas, residential and office, which are estimated based on typical mobile traffic patterns [10]. Using the proposed optimization algorithm, we compute the required number of SCs for 20 ONUs in each PON tree with one FS 7.1 ONU in cluster 2. In Fig. 3(a), we retain the average number of SCs in our results to maintain granularity for potential future scenarios with a higher number of SCs, benefiting from the evolution of a converged metro-access network. In contrast, in Fig. 3(b), we round up the required number of SCs to establish an upper bound. As observed, when considering both PON trees together, the maximum number of required SCs is 15, although individually, they each require 8 SCs. This indicates that one SC can be shared and dynamically redirected between the two PON trees, corresponding to time-based traffic variations, thus enhancing the flexibility and efficiency of the future converged metro-access network.

IV. Conclusion

We propose and evaluate an optimization model for dynamic SC allocation to ONUs with diverse physical characteristics and service requirements. The model ensures demand satisfaction while minimizing the number of allocated SCs, allowing for efficient resource utilization and enabling the possible dynamic redirection of SCs between different PON trees.

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