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Optimization Model for Dynamic Resource Allocation in DSCM Coherent PON

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***Abstract*—In this paper, we propose an integer linear programming model to dynamically optimize sub-carrier (SC) allocation in the upstream direction of future digital sub-carrier multiplexing (DSCM)-based coherent passive optical networks (PONs). The model incorporates frequency-domain hybrid modulation to account for the varying conditions of optical network units, optimizing resource allocation while minimizing the number of SCs used. Numerical results demonstrate that hybrid modulation increases PON throughput by about 50 Gbps for 32 optical network units.**

***Index Terms*—Coherent passive optical network (PON), digital sub-carrier multiplexing (DSCM), flex-PON, fronthauling, resource allocation.**

I. INTRODUCTION

A passive optical network (PON), with its point-to-multipoint (P2MP) architecture, is widely used for residential fiber-to-the-home (FTTH) services and is emerging as a highly suitable solution for advanced 5G and future 6G fronthauling (FH) deployments [1]. Its widespread geographical coverage and statistical multiplexing capabilities make it particularly well-suited for these applications. ITU-T SG-15 working group is currently working on the next PON standard, targeting 100 and 200 Gbps rates, in which coherent transmission is under consideration including its digital sub-carrier multiplexing (DSCM) variant. The adoption of coherent PON, specifically DSCM coherent PON [2], would introduce an additional layer of flexibility by enabling adaptive line rates tailored to the capacity demands of each end-user in both downstream and upstream directions. Ongoing research on time-frequency division multiplexing (TFDM) in coherent DSCM, combined with burst detection digital signal processing (DSP) design [3], explores the potential of hybrid modulation (HM) in both the time and frequency domains to enhance capacity and flexibility. However, frequency-domain HM is particularly advantageous as it avoids the added DSP complexity associated with time-dependent modulation. Additionally, it supports power and bit loading, making it well-suited for converged metro-access networks and their associated filtering penalties in reconfigurable optical add-drop multiplexer (ROADM) [4]. On the networking side, bandwidth allocation algorithms in PON depend on the underlying network architecture, whether time-division multiplexing (TDM) or time-wavelength division multiplexing (TWDM), as well as the specific requirements of the provided services, such as data and fronthauling. In fixed bandwidth allocation (FBA), the optical line terminal (OLT) distributes bandwidth equally among optical network units (ONUs), ignoring traffic demands, while dynamic bandwidth allocation (DBA) adapts to real-time needs. One approach, status report DBA (SR-DBA) requires ONUs to report queue occupancy, ensuring efficient use but adding latency. Another approach, cooperative DBA (Co-DBA) coordinates PON and radio scheduling, allowing the OLT to predict FH traffic and reduce delays. Both can be deployed simultaneously to support FH and data [5]. Various bandwidth allocation algorithms aim to optimize different performance metrics, including latency, and power consumption [6], [7]. However, resource allocation in coherent DSCM-PON remains an emerging topic, as it is still in the research phase. While it relates to channel bonding in TWDM [8], tuning a laser and adjusting a subcarrier (SC) differ significantly in terms of feasibility, flexibility, and tuning latency. Given that SC adjustment is a DSP operation—bounded by the preamble length of the burst (e.g., 1000 symbols)—it is reasonable to assume that SC adjustment can be performed frequently. In this paper, we propose a SC allocation scheme for future DSCM coherent PONs that considers ONU demands and physical limitations within a simplified clustering constraint. This is formulated in an integer linear programming (ILP) problem to allocate resources based on ONUs demands, incorporating frequency-domain HM (FD-HM) to reflect the physical state of the ONUs. The system supports both data and 5G FH services. The ILP approach is used to obtain the optimal solution that can serve as a reference for future exploration of heuristic algorithms. Moreover, although latency is not addressed in this study, an additional optimization stage could allocate time slots using scheduling information reported from the radio side. The remainder of this paper is organized as follows: Section II presents the system model and optimization problem, while Section III describes the simulation environment and provides numerical results. Finally, we conclude the paper and suggest future research directions.

II. SYSTEM MODEL AND THE PROPOSED DYNAMIC RESOURCE ALLOCATION APPROACH

As discussed in the Introduction, future PONs are anticipated to support diverse data types, each with varying requirements delivered with different physical capabilities. Therefore, a future coherent DSCM PON requires dynamic allocation algorithms that efficiently utilize resources while meeting data demands, latency, and energy constraints. Figure 1 (a) presents a coherent PON scenario with ONUs under different conditions (i.e. different splitter number of outputs and/or access network reach, resulting in a wide range of

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optical distribution network (ODN) loss [9]), while Fig. 1 (b) depicts the proposed SC allocation using frequency-domain HM. The goal of the proposed dynamic resource management approach is to allocate SCs to ONUs based on their demands and physical conditions. Specifically, ONUs that are closer to the OLT and have low splitting ratios can utilize higher-order modulations to achieve higher bitrates with the same allocated SC. In contrast, ONUs located farther away or with higher splitting ratios will experience greater optical distribution loss and thus require a lower modulation order to meet the required bit error rate. To address this, the proposed approach clusters ONUs into groups based on their physical conditions [9], ensuring that ONUs within the same group can benefit from higher modulation orders and, consequently, higher bitrates through frequency-domain HM, while avoiding extra DSP complexity due to time-dependent modulation at the OLT.

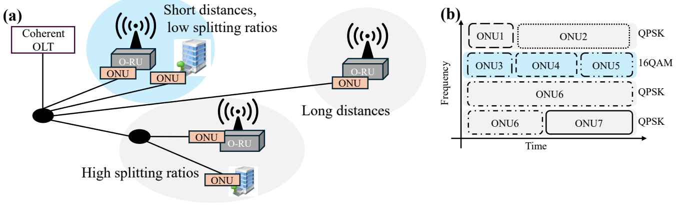

Fig. 1: (a) Coherent PON scenario supporting fronthauling and access services with various distribution losses. (b) Sub-carrier allocation map in a frequency-domain hybrid-modulation coherent DSCM PON.

The considered system is defined by K SCs and M ONUs, where each ONU belongs to one of C clusters, meaning that the set of M ONUs can be partitioned into C subsets depending on their physical conditions. The optimization problem is formulated as a multi-objective integer linear programming problem in which we aim to maximize the delivered demands to ONUs while minimizing the number of SCs used on both the OLT and ONU sides, thus saving energy and enabling the reallocation of unused SCs to other networks, as follows

$$\max\left\{\alpha_1\sum_{i=1}^{M}\sum_{j=1}^{K}x_{ij}-\alpha_2\sum_{j=1}^{K}y_j-\alpha_3\sum_{i=1}^{M}\sum_{j=1}^{K}z_{ij}\right\}. \quad (1)$$

In this multi-objective optimization problem, x_{ij} is the integer decision variable, representing the requested demands from ONU i allocated to SC j. For example, if ONU i has 70 KB in its upstream packet queue before the next allocation interval, $x_{ij} = 70$, means that this demand is allocated to SC j. The variables y_j and z_{ij} are binary decision variables that are dependent on x_{ij}. Specifically, y_j indicates whether SC j is in use, i.e., if the total allocated demand on SC j is greater than zero:

$$y_j = \begin{cases} 1, & \text{if} \quad \sum\limits_{i=1}^{M} x_{ij} > 0, \quad \forall j \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Similarly, z_{ij} is a binary variable indicating whether ONU i is assigned to SC j as follows

$$z_{ij} = \begin{cases} 1, & \text{if} \quad x_{ij} > 0, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Here, α_1, α_2, α_3 are the weighting parameters for the multi-objective optimization, determined through numerical simulations. These weights are chosen to prioritize the first objective; however, a more detailed analysis of their influence and adjustments based on the PON provider's main goal are left for future work. The problem constraints are defined as follows: the first constraint in (4) ensures that resource allocation remains exclusive within each cluster, i.e. if two ONUs belong to different clusters, they cannot be assigned to the same SC

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

The second constraint in (5) enforces that the total allocated resources for ONU i across all SCs does not exceed the demands of ONU i while allowing the ONU to distribute its demand across multiple SCs

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

The third constraint in (6) ensures that the demands allocated to each SC remains within its capacity based on the cluster assignment (i.e. SC-capacity is calculated based on the cluster-based SC bitrate and the allocation interval)

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

III. SIMULATION RESULTS AND DISCUSSION

Considering the system model illustrated in Fig. 1, we assume a coherent DSCM PON operating at a symbol rate of 50 Gbaud and utilizes either 4 or 8 SCs, implementing dual-polarization quadrature phase shift keying (QPSK) or 16-Quadrature amplitude modulation (16QAM), achieving bitrates of 200 Gbps and 400 Gbps, respectively. PON is serving M ONUs, categorized into two clusters based on ODN loss. Therefore, the clusters determine the modulation formats, with cluster 1 supporting QPSK, while cluster 2 supporting 16QAM. Moreover, we assume a 25% of the ONUs support radio FH services with split option 7.2 [1], assuming a radio bandwidth of 100 MHz, 64QAM modulation, 8 MIMO layers, MAC information of 120 Mbps, an IQ bit width of 2×16 bits, 14 symbols, and 1200×5 radio SCs, resulting in a peak FH bitrate of 21.6 Gbps [10]. The remaining ONUs support data services, each with an active number of users of 10 and a peak bitrate of 500 Mbps. Both ONU types generate packets of varying sizes, uniformly distributed between 64 and 1518 bytes. The packet arrival times for all ONUs follow a Poisson process, with λ representing the average packet arrival rate, calculated as the traffic load divided by the average packet length. For all ONUs, the packet interval time is given by $T_i = -1/\lambda \ln(U_i)$, where U_i is a random variable uniformly distributed between 0 and 1 [6]. We simulate the proposed allocation problem in Python modeled with PuLP [11] and solved with CBC [12], running the simulation for 100 iterations while considering a frame length of 125 μs. The OLT computes the allocation map at the beginning of each frame (i.e. 125 μs) based on the reported demands from data ONUs and the predicted demands from the radio controller. The allocation scheme determines the SC assigned to each

ONU, while an additional algorithm is expected to operate alongside this scheme to define time slots, ensuring latency requirements for FH services are met.

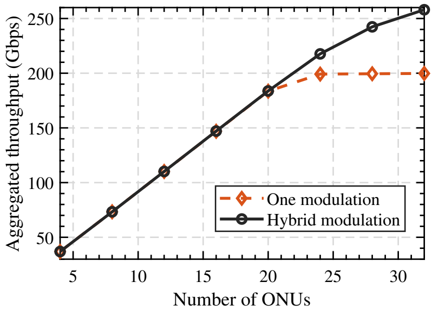

Fig. 2: Aggregated throughput versus number of ONUs with and without HM.

In Fig. 2, we analyze the overall system's aggregated throughput in Gbps as a function of the number of ONUs for the proposed algorithm, both with and without the ONU clustering constraint. This analysis assumes that each ONU operates at its maximum traffic load and that ONUs are randomly assigned to a cluster 1 or a cluster 2 with 4 SCs. The aggregated throughput is then computed by summing the supported demands over the entire simulation period and dividing it by the total simulation time (that is, $100 \times 125\mu s$). As shown, for a low number of ONUs, the aggregated throughput remains the same whether HM is considered or not. However, as the number of ONUs increases, a higher aggregated throughput can be achieved by grouping ONUs with similar conditions on the same SC. This approach enables the aggregated throughput to exceed 200 Gbps, though it does not reach 400 Gbps due to the physical limitations of the ONUs in cluster 1.

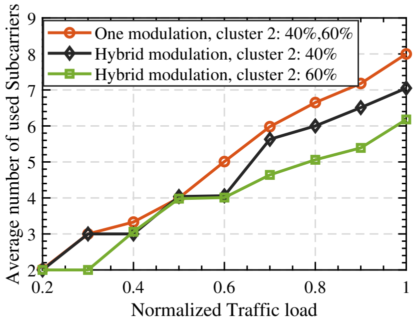

Fig. 3: Average number of utilized sub-carriers versus normalized traffic load, comparing scenarios with and without HM for cluster 2 proportions of 40% and 60%.

In Fig. 3, we examine the number of SCs required to support ONU demands under varying traffic loads, considering both cases with and without HM. In this figure, we assume 8 SCs and 20 ONUs supporting both FH and data services as previously described. The normalized traffic load is varied simultaneously across all ONUs to emulate traffic pattern changes, such as those occurring between day and night across residential and business areas. We vary the percentage of ONUs in cluster 2 to either 40% or 60% of the total ONUs number, including both FH and data service ONUs. As illustrated, deploying HM results in a lower number of required SCs compared to one modulation scheme, and it is more apparent when cluster 2 percentage is higher. This is beneficial for energy savings and potentially enabling the reallocation of SCs to other access network trees.

IV. CONCLUSION

Flexibility in resource allocation, considering varying demands and physical conditions, is addressed by proposing a dynamic SC allocation aimed at maximizing the delivered demands while minimizing the number of SCs used. The results demonstrate that HM enhances the supported aggregated throughput as the number of ONUs increases. Additionally, compared to one modulation scheme, HM improves efficiency by reducing the number of required SCs by 1 under traffic loads higher than 0.6, enabling their potential reallocation. Future work could explore combining flexible modulation with adaptive coding, allowing the system to operate across multiple configurations supporting various net data rates to further maximize throughput and analyzing the scalability of the proposed solution with number of clusters. Additionally, incorporating latency constraints into the optimization problem would help ensure compliance with FH requirements.

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