On Real-time Optical Subcarrier Management in P2MP Networks with Mixed-strategy Gaming

Qian Wang[1], H. Shakespear-Miles[2], Xiaoliang Chen[1], Marc Ruiz[2], Zhaohui Li[1,3], and Luis Velasco[2]

1. Guangdong Provincial Key Labratory of Optoelectronic Information Processing Chips and Systems, School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou, China
2. Optical Communications Group (GCO), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
3. Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, China
xlichen@ieee.org, luis.velasco@upc.edu

Abstract: We developed a mixed-strategy gaming approach for distributed and real-time optical subscarrier management in point-to-multipoint networks, achieving traffic loss rates close to those by ILP-based centralized optimization.

1. Introduction

Digital Subcarrier Multiplexing (DSCM) optical technology has shown the potential to reduce energy consumption because of its ability to activate/deactivate each subcarrier (SC) independently, thus adapting the capacity of optical connections to the actual traffic [1]. DSCM shows great potential in 5G/6G scenarios. Since it supports point to multi-point (P2MP) configurations; in P2MP connectivity, one single transponder installed in the hub node can serve several transponders in the leaves, which reduces capital expenditures.

The authors in [2] proposed a centralized module running in the Software Defined Networking (SDN) controller to dynamically manage SCs based on the traffic observed at the leaves of a P2MP connection. These results showed the potential of dynamic allocation to increase the number of leaves supported by the hub node, increasing the number of demands serviced while avoiding traffic loss. However, such a solution demands near real-time operation in the SDN controller. A much more scalable solution was proposed in [3], by allowing the agents controlling the optical transponders to communicate each other and moving the real-time operation to the agent in the hub node. In this paper, we extend the concept of multi-agent system (MAS) in [3] by incorporating distributed SC management. We first detail the architecture of the P2MP connectivity and the operation principle of a leaf agent. Then, the problem is formally modeled as a noncooperative mixed-strategy game and solved by a time-efficient algorithm. Finally, the performance of the proposed method is evaluated and benchmarked with a centralized element solving an Integer Linear Program (ILP) model, and a dynamic SC allocation heuristic.

2. Operation Principle

Fig. 1(a) illustrates P2MP connectivity based on DSCM, where a high-speed hub node communicates with a set of low data rate leaf nodes $\mathbb{V}$ through a passive splitter/combiner. Each leaf node can transmit up to N optical subcarriers (SCs), while the hub node operates in M SCs, leading to an oversubscription ratio of $\theta:1$, i.e., $N\cdot|\mathbb{V}|=\theta\cdot M$. The allocation of SCs to leaf nodes can be optimized on-the-fly, based on the their actual data rate requirements for maximized system throughput.

Dynamic SC management can be realized using a centralized element for the P2MP connection, as represented in Fig. 1(b), and produce a global optimal solution. However, as such an element needs to work in real time, it has to be replicated for every P2MP connection in the network. A different approach is depicted in Fig. 1(c), where node intelligent agents in every leaf and hub node collaborate to find solutions without any centralized element.

In this paper, we leverage game theory to realize distributed SC management. Fig. 1(d) shows the operation principle of a leaf agent. Specifically, each agent $v\in\mathbb{V}$ constantly monitors the traffic dynamics on the client side by collecting traffic statistics or interacting with client equipment (*step 1*). At the beginning of each provisioning period, agent v first forecasts its bandwidth requirement b_v with a machine learning traffic estimator (*step 2*) and advertises b_v to its peers (*step 3*). Upon receiving the bandwidth forecasts from all its peers, the capacity scheduler of agent v invokes a gaming strategy to determine a set of consecutive SCs that will request from the hub node (*step 4*). The hub node then, adopts a simple admission rule to accept or reject the request for an SC, i.e., randomly pick a winner if multiple agents compete for the SC (*step 5*). Finally, agent v reconfigures its Tx and Rx (if necessary) through its equipment controller (*step 6*).

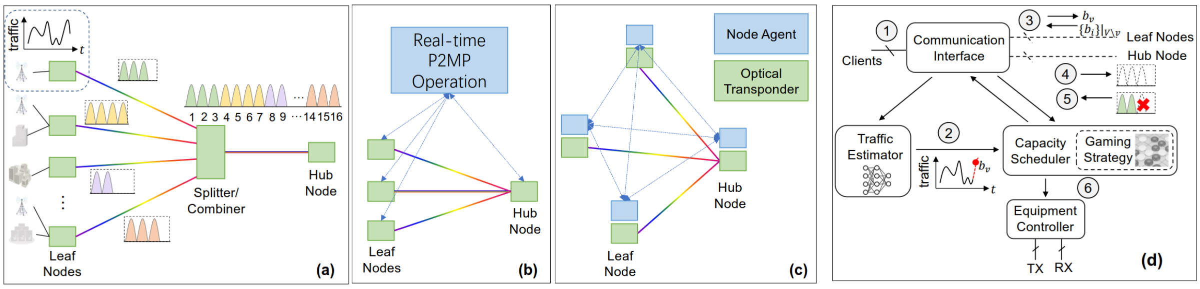

Fig. 1: (a) Illustration of P2MP communication based on DSCM, (b) real-time P2MP operation, (c) node intelligent agents centralized operation, and (d) operation principle of a leaf agent.

3. Game-theoretic Design

We model the distributed SC allocation problem as a non-cooperative mixed-strategy game, with leaf nodes being the players. Let F_v denote the set of indices that the SC allocation of leaf node v can start with, i.e., F_v is the strategy space. Then, for each strategy $f \in F_v$, $\mathbb{S}_{v,f} = \{f, \cdots, f + \lceil b_v/B \rceil - 1\}$ signifies the set of SCs v that will request if f is chosen, and B represents the capacity of an SC. In other words, v requests for just enough SCs. Then, each leaf node needs to decide a probability distribution x_v over F_v to minimize the misalignment between b_v and the acquired bandwidth. To this end, we define the utility function for each v as,

$$u_v(x) = -\sum_{f \in F_v} x_{v,f} \cdot \max\{b_v - B \cdot \sum_{s \in \mathbb{S}_{v,f}} p_{v,s}, 0\}/b_v, \quad p_{v,s} = 1/(1 + \sum_{u \in \mathbb{V} \setminus v} \sum_{f \in F_u} x_{u,f} \cdot h_{u,f,s}), \tag{1}$$

where $p_{v,s}$ represents the likelihood of the request for s being accepted, and $h_{u,f,s}$ is a Boolean parameter indicating whether $s \in \mathbb{S}_{u,f}$. A natural solution for non-cooperative games is finding the Nash equilibria, which correspond to conditions where no player can improve its utility by unilateral deviations. For the proposed mixed-strategy game, this translates to $x^* = (x_1^*, \cdots, x_{|\mathbb{V}|}^*)$ leading to,

$$u_{v,f}(x^*) = u_{v,f'}(x^*), \forall v \in \mathbb{V}, f, f' \in F_v. \tag{2}$$

Note that, mixed-strategy Nash equilibria are guaranteed to exist for games with finite numbers of players and strategy spaces [4]. Table 1 summarizes the procedures of finding approximate mixed-strategy Nash equilibria for the proposed game. In *step 1*, we first calculate the utility supremum and infimum for each strategy of each leaf node by identifying the best and worst-case game outcomes when the strategy is adopted. Then, with *step 2*, we obtain the support set for each leaf node by deleting strategies whose utility supremum is lower than the infimum of one of others because they certainly violate the condition in Eq. 2. Finally, *step 4* calculates an approximate Nash equilibrium with the algorithm proposed in [5], which iteratively adjusts $x_{v,f}$ by a small step δ to approximate Eq. 2. More specifically, we increase the probability of every possible strategy from others that overlaps with $\mathbb{S}_{v,f}$ (i.e., compete for SCs) when $u_{v,f}$ is larger than the average, and vice versa. The algorithm converges when the utility differences between strategies are below a threshold.

step 1: calculate $\sup u_{v,f}$ and $\inf u_{v,f}$ for each strategy f of each leaf node $v \in \mathbb{V}$;
step 2: delete f from F_v if $\sup u_{v,f} < \inf u_{v,f'}, \exists f' \in F_v$;
step 3: repeat **steps 1-2** until the condition in **step 2** is eliminated;
step 4: initialize x_v with equal probabilities for each v and ontain x^* by iteratively adjusting $x_{v,f}$ with the algorithm in [5] until $\frac{|u_{v,f} - \bar{u}_v|}{|\bar{u}_v|} < \eta, \forall v, f$ holds, where $\bar{u}_v = \frac{1}{|F_v|} \sum u_{v,f}$;

Table 1: Procedure for finding approximate mixed-strategy Nash equilibria for the proposed game.

4. Evaluations

We assessed performance of the proposed design with numerical simulations under different numbers of leaf nodes and traffic intensities. Each leaf node could support up to 4 SCs with the hub node supporting 16 SCs in total. We assume that each SC has a capacity of 25 Gb/s. Various traffic intensities were considered with the lowest simultaneous traffic load of 0.5, up to the largest load of 1 (fully loaded). Each of these traffic scenarios were tested with leaf nodes varying from 5 to 8. We compared the mixed-strategy gaming approach presented in Section 3 with an ILP method proposed in [2], a fixed SC allocation scheme, and a dynamic SC allocation heuristic that serves leaf nodes sequentially and performs bandwidth expansion for each leaf node by left shifting the original starting index of SC.

Figs. 2(a), (b), and (c) show the traffic loss results for each method with 5,6 and 7 leaf nodes, respectively. From Fig. 2 it is clear that, the mixed-strategy gaming and the ILP strategy are able to reduce the amount of traffic loss

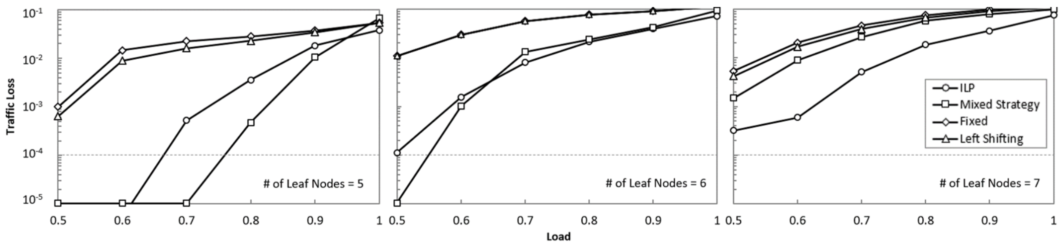

Fig. 2: Percent traffic loss for (a) 5 leaf nodes, (b) 6 leaf nodes, and (c) 7 leaf nodes.

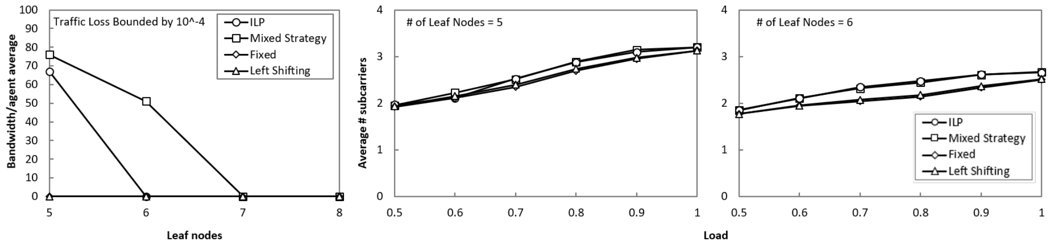

Fig. 3: a) Average bandwidth supported by a leaf node with loss below 10^{-4}. Average number of occupied SCs per leaf for (b) 5 leaf nodes, (c) 6 leaf nodes.

through dynamic allocation. This reduction is more pronounced for 5 leaf nodes such as Fig. 2(a) and it reduces as more leaf nodes are introduced, as in Figs. 2(b) and (c). It can also be seen in Fig. 2(a) that for a lower number of leaf nodes, mixed-strategy gaming outperforms the ILP method at certain traffic loads. When there are 6 leaf nodes (Fig. 2(b)), the results from mixed-strategy gaming and ILP are very similar, and in Fig. 2(c) the ILP method outperforms the mixed-strategy gaming. This could suggest that the mixed-strategy gaming design is better suited for lower subscription, while the ILP strategy is better suited when there are a greater number of leaf nodes.

Number of Leaf Nodes	5	6	7
Distributed Scheme	8640	12096	161280
Centralized Scheme	2880	3456	40320

Table 2: Number of messages sent per day.

Fig. 3(a) shows the average bandwidth per leaf node at 10^{-4} traffic loss for the different number of leaf nodes considered. With 5 leafs nodes, there is a relatively small difference between mixed-strategy gaming and ILP with the gaming approach being able to offer more bandwidth. For 6 leaf nodes, this difference is increased significantly as the ILP method is no longer able to provide traffic loss below 10^{-4}, while mixed-strategy gaming is able to support around half. With 7 and 8 leaf nodes, both methods are unable to realize traffic loss below 10^{-4}.

The average number of SCs used by each leaf node was also explored in Figs. 3(b) and (c) for 5 and 6 leaf nodes, respectively. In both cases, mixed-strategy gaming and ILP are able to support more SCs on average than the rest two baselines, resulting in less traffic losses, as seen in Fig. 2. Additionally, both mixed-strategy gaming and ILP use a very similar number of SCs on average, suggesting that mixed-strategy gaming can provide very similar power savings to the ILP method.

Finally, we count the number of messages in a day assuming a decision interval of five minutes and summarize the results in Table 2. We can see that, while the distributed scheme facilitates better scalability, it requires sending more messages (introducing a larger overhead) compared with the centralized one. Thus, the decision interval should be carefully chosen taking into account both the time scale of traffic variarion and system costs.

5. Summary

This paper proposes a noncooperative mixed-strategy gaming approach for distributed SC allocation in P2MP networks. Numerical results show that the proposed approach could achieve traffic loss rates and SC utilization comparable to those from the ILP method.

References

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