Maximizing Flexibility and Coverage of a 400G Point-to-Multi-Point IM-DD System by Simplified OFDMA Entropy Loading with Subcarrier Grouping Per-User Basis

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Abstract *We propose subcarrier grouping to simplify the entropy loading for OFDMA, where each user only treats one probabilistic-shaping format. We reveal a diversity gain of OFDMA for the first time over the rate-adaptive TDM in a 400G-class point-to-multipoint IM-DD system. ©2023 The Author(s)*

Introduction

The ever-increasing access speed demand has pushed the fiber closer to end users, calling for a faster and more cost-efficient point-to-multi-point (P2MP) fiber network [1]. As the most popular P2MP fiber architecture, passive optical networks (PON), having adopted intensity-modulation (IM) direct-detection (DD) since it born till the latest generation at 50G [2], may stick to IM-DD due to the cost-sensitive nature of end users. With the coherent technique being penetrated to shorter reach point-to-point (P2P) links to <20 km, future P2MP IM-DD networks face relaxed requirement on distance but more on flexibility. The need of flexibility arises from the user diversity of various rate demand and link quality [3]. In particular, future P2MP networks are expected to support a variety of user types with large disparity like mobile X-Haul [4], fiber-to-the-X (FTTx) and cable access convergence. The current PON provides a fixed (aggregated) rate imposed by the worst-case user in the network regardless of user diversity, leading to a waste of network capacity [5,6]. This motivates proposals of adding rate adaptation to existing PON [5-11]. A simple way is to enable multiple formats like PAM-2/4/8 with an integer rate granularity [5]. The step change of rate between adjacent formats can be mitigated by multi-rate forward error correction (FEC) [6] or probabilistic shaping (PS) [7]. Besides flexibility, an IM-DD system aiming at higher throughput tends to push the hardware towards its bandwidth limit. Orthogonal frequency division multiplexing (OFDM) is known to maximize the rate flexibility and meanwhile approach the bandwidth-limited channel capacity by adaptive bit loading (BL). In a P2MP system, OFDM can serve multiple users by time division multiplexing (TDM) and each user fully occupies the spectrum like the TDM-PON. Moreover, OFDM can allocate subcarriers (SC) to different users for an enhanced flexibility, known as orthogonal frequency division multiple access (OFDMA). OFDMA has been adopted in a variety of broadband access standards like DOCSIS 3.1 [12], 4G/5G cellular and Wi-Fi 6. It was proposed [13] for PON decades ago but was not commercialized due to its high complexity.

In this paper, we propose an OFDMA-based P2MP technique by entropy loading (EL) [14] and use SC grouping (SCG) to greatly reduce the complexity for end users. Using SCG, each user is assigned with a group of SCs having a unique PS format. Namely, each user treats one format only instead of a variety of formats for all the SCs in OFDM-TDM (with per-SC based BL [8] or EL [14]). A main concern would be if such coarse format adaptation in frequency domain reduces the system capacity. This is indeed an issue for BL, but we will reveal that the SCG penalty is marginal when it is combined with EL owing to the fine rate granularity of PS. Since EL approaches the capacity of a bandwidth limited system and can outperform flexible-rate PS-PAM (as will be proven in the experiment), EL-SCG can also be regarded as a capacity-approaching scheme but with a greatly reduced complexity. Moreover, we reveal a diversity gain of the proposed scheme over common flexible TDM schemes based on PAM [6] or OFDM [11]. This enables a network to serve outliner users with exceptionally worse link quality than other users to extend the network coverage, and fundamentally differentiates itself from the TDM-based OFDM-EL as demonstrated recently [15]. These findings are verified in a 400G-class P2MP IM-DD system.

Entropy Loading with Subcarrier Grouping

Though SCG [16] has been proposed for OFDMA BL, its combination with EL greatly simplifies the adaptive loading. Assuming hard-decision (HD) FEC, we use bit error rate (BER) as the loading target and generalized mutual information under binary HD decoding (hGMI) as the system metric,

$$hGMI = \mathbb{H}(X) - \log_2|\mathcal{X}| \cdot \mathbb{H}_2(\epsilon)$$

where $\mathbb{H}(X)$ is the entropy of signal X and $\mathbb{H}_2(\cdot)$ is the binary entropy function, ϵ is the bit error probability and $|\mathcal{X}|$ is the size of modulation alphabet [17]. Using a rate-c binary HD-FEC code, the net bit rate $\mathbb{R}$ is calculated as

$$\mathbb{R} = \mathbb{H}(X) - \log_2|\mathcal{X}| \cdot (1 - c)$$

$\mathbb{R}$ is upper bounded by hGMI and $\mathbb{R} = hGMI$ for an ideal HD-FEC that corrects ϵ with a code rate $1 - \mathbb{H}_2(\epsilon)$. The algorithm below fits for a network with both an identical and diverse link conditions. We initialize $\mathcal{S}$ as the set of all available SCs.

(1) Pre-loading by an EL algorithm (*e.g.* the look-up table based one in [14]) to determine $\mathbb{H}$ and $\mathbb{R}$ for *each SC* and *each link condition*

For the m^{th} user with a rate target of $T(m)$:

(2) Sorting the SCs in $\mathcal{S}$ by a descending order based on $\mathbb{R}$ under m^{th}-user link condition

(3) Grouping SCs in the sorted order till $T(m)$ is met, and remove these SCs from $\mathcal{S}$

(4) Assigning a uniform $\mathbb{H}(m)$ to the SC group in step (3) with the number of SCs $N(m)$

$$\mathbb{H}(m) = T(m)/N(m) + \log_2|\mathcal{X}(m)| \cdot (1-c)$$

and then evaluate the average BER

(5) If the BER is larger than the target, add one more SC to the group and go back to (4)

Step (2) aims to minimizes the ΔSNR within a group to avoid extra power loading. The potential iteration from step (4) to (5) is not needed in most cases as the rate gap between EL-SCG and EL is marginal, as will be revealed in the experiment.

If all the users have the same link condition, it doesn't matter who gets the priority for assigning SCs. However, for a P2MP system with diversity, the user priority is crucial to determine the aggregated multiuser capacity, because once an SC is assigned to one user, it cannot be occupied by another with a different link condition. It is not a trivial task to find the optimum user order, and we propose a sub-optimum user sorting strategy:

- Sorting user (clusters) in an ascending order based on $\sum_i \mathbb{R}(i)$ (where i is the SC index)

Namely, the user (cluster) quality is defined by its total achievable rate, and worse-case users get higher priority to be assigned with better SCs. EL-SCG supports arbitrary rate per user. Without loss of generality, we set an identical rate target for all OFDMA users and try to maximize it. We use OFDM-TDM as the baseline for comparison, namely, we first calculate $\sum_i \mathbb{R}(i)$ for each user, and then calculate the identical per-user TDM rate by the harmonic average among all users.

Experiment Setup

We use an IM-DD setup with 100 GHz end-to-end bandwidth in Fig. 1(a) as detailed in [18]. We test downstream only without considering the optical beat interference issue in upstream [19,20]. Like the "user grouping" concept in FLCS-PON [6], we divide users into several "clusters" (each cluster contains users with the same link condition) in our study to simplify our setup.We use a 1:4 power splitter to emulate 4 link conditions where each branch consists of a standard single-mode fiber (SSMF) spool (0 to 600 m with a step of 60 m) to add chromatic dispersion (CD) (17 ps/nm/km at 1550 nm, ~1 ps/nm every 60 m) and a variable optical attenuator (VOA) to add extra optical path loss (OPL). The conditions are not mapped to an existing PON specification (*e.g.* wavelength plan, reach) but to emulate general P2MP features like bandwidth limit, spectral fading and link disparity.

The OFDM signal has a DFT size of 2048 and a SC spacing of 0.125 GHz, with totally 800 data-carrying SCs in 100-GHz bandwidth. Each OFDM symbol has 16-point cyclic prefix. As comparison, the 200-GBd PS-PAM signal is pulse-shaped by a 0.01 roll-off root-raised cosine (RRC) filter with variable PAM orders (up to PAM-8) and entropies for rate adaptation. Because both the strong pre-equalization and the sharp RRC filtering greatly enhance the signal peak, it is the most effective to use Maxwell-Boltzmann distributions [18,21, 22] for PS gain. The receiver uses a 1-tap per SC equalizer for OFDM and a 2048-tap equalizer for PAM, to have the same equalizer time duration.

EL Gain in the Bandwidth-Limited System

We first demonstrate the EL advantage over BL and PS-PAM under bandwidth limit, and reveal the SCG penalty is trivial. We choose a link with

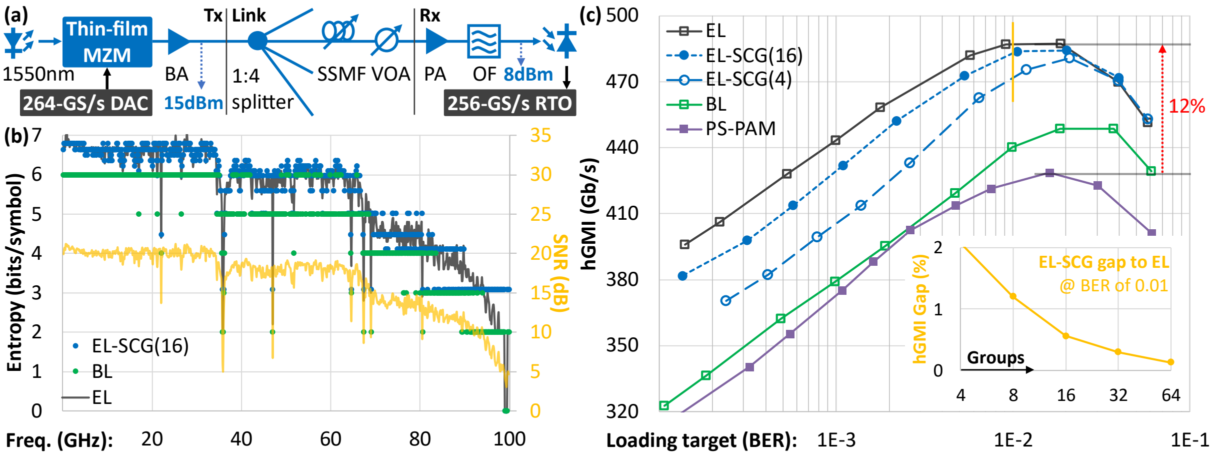

Fig. 1: (a) Experimental setup [18]; the 264-GS/s D/A converter (DAC) is made by digital-band interleaving (DBI) of 3×88-GS/s DACs; BA/PA: booster-/pre-amplifier; RTO: real-time oscilloscope. Rate comparison with a fixed link condition (5-ps CD, 8-dBm received optical power): (b) SNR and entropy profiles, (c) hGMI; (c-inset) shows the gap of EL-SCG to EL.

5-ps CD whose frequency response is limited by both the electronic transmitter and the frequency selective fading due to CD. Fig.1(b) shows the SNR and the loaded entropy of EL, BL, and 16-group EL-SCG. EL is expected to be superior to other modulation schemes owing to (i) the PS gain [21] and (ii) the precise entropy adaptation per SC. This is clearly verified by the hGMI curve on the top of Fig. 1(c). Without the PS gain, the maximum hGMI drops by 8% using BL; and without the frequency domain adaptation, the highest hGMI of PS-PAM is 12% away from EL (red line with arrow). EL-SCG exhibits an hGMI gap to EL especially for small number of groups in Fig. 1(c), but the gap quickly narrows down at higher BER target. Considering the 50G-PON [2] has adopted a high HD BER threshold of 0.01, we show the SCG penalties at this BER with variable number of groups in the inset of Fig. 1(c). Encouragingly, the penalty is below 0.6% when the SC group (*i.e.* user) number is 16 (or above).

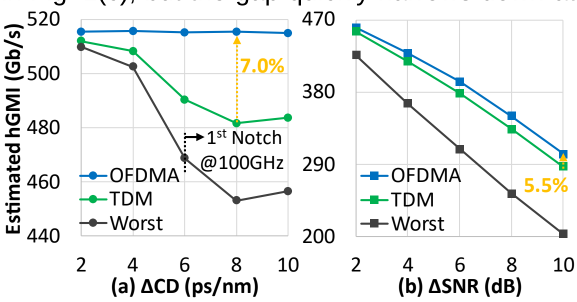

Fig. 2: hGMI with different (a) CD and (b) OPL. The 1st CD fading notch appears at 100 GHz when CD≈6ps/nm; "Worst": all the users operate at the worst case without rate adaptation.

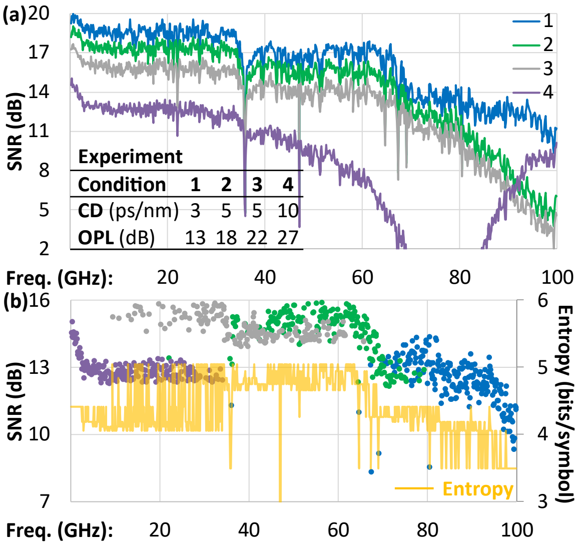

Fig. 3: Link diversity experiment: (a) the 4 link conditions and their SNR profiles; (b) SC allocations per cluster of users by EL-SCG and the overall entropy profile of all subcarriers.

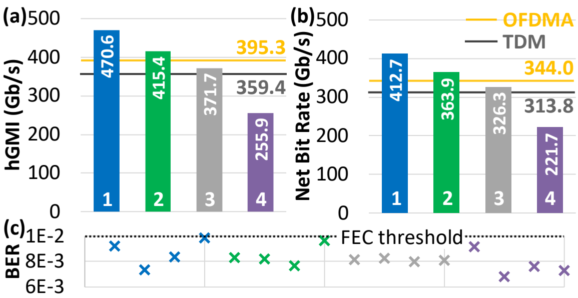

Fig. 4: Achievable rates for each link condition (bars) and the aggregated rates of all users evaluated by (a) hGMI and (b) net bit rate after a 20% HD-FEC; (c) the BER is below the threshold of 0.01 for all 16 OFDMA users.

OFDMA Multiuser Diversity Gain over TDM

In a P2MP IM-DD system, the link conditions are mainly diversified in CD and OPL which represent two types of diversity - a colored (*i.e.*, frequency dependent) SNR difference by CD and a white one (*i.e.*, the same SNR variation for all SCs) by OPL. We first use simulation to show the impact of the two separately and then experimentally demonstrate a practical case where the two types of diversity co-exist. The reference TDM system uses OFDM-EL. The diversity gain in this section is claimed on top of the EL gain shown in Fig. 1.

The simulation uses experimentally measured SNR profiles and evaluates the hGMI with a BER target of 0.01. We assume 2 user clusters (each with 8 users) to simplify our analysis. For the CD case, the reference cluster fixes its CD as 0 ps and the others have various CD values up to 10 ps; for the OPL case, the reference is the SNR profile in Fig. 1(b), and the others have a white SNR reduction (ΔSNR). As indicated in Fig. 2(a), it is easy to understand the capability of OFDMA to avoid CD degradations, because bad users with CD-induced fading get the priority to occupy good SCs which are not affected by fading. Moreover, OFDMA exhibits gain over TDM in Fig. 2(b) even with a white ΔSNR. This is because bad users with high OPLs are first assigned with good SCs. Consequently, they occupy a smaller number of SCs for the same rate target, leaving more available SCs for good users.

Finally, we demonstrate a practical scenario with 4 user clusters as in Fig. 3(a) each having 4 users. Fig. 3(b) shows how EL-SCG assigns SCs per cluster as well as the overall EL map. As the baseline, hGMI for each link condition is shown (as bars) in Fig. 4(a). The flexible TDM improves the rate over the worst condition (purple), and OFDMA gets 10% extra gain on top of it. We also evaluate the net bit rate in Fig. 4(b) by using a 20% HD-FEC (BER limit of 0.01) in the PON standard [2]. Fig. 4(c) shows all the 16 OFDMA users achieve the BER below the FEC threshold.

Conclusions

We propose a greatly simplified OFDMA scheme for P2MP networks by EL-SCG and demonstrate two types of gain over the common flexible-rate TDM in a bandwidth-limited 400G P2MP IM-DD system: the EL gain (~12%) and the diversity gain (~10%). EL-SCG will support higher throughput and larger disparity for future P2MP networks.

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