# Demonstration of Point-to-Multipoint Diversity Gain in a 1.6-Tb/s-Class Subcarrier-Multiplexed Coherent System

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**Abstract:** We reveal a diversity gain in point-to-multipoint systems when the end points experience various channel conditions. We demonstrate rate improvement over the conventional time-division multiple access in an 18×10-GBaud subcarrier-multiplexed coherent system. © 2024 The Author(s)

## 1. Introduction

Digital subcarrier multiplexing (SCM) has been implemented in commercial coherent optical transponders since the 800G generation [1]. Compared with the conventional single-carrier QAM system, SCM owns unique advantages for long-haul transmissions, like a lower complexity for dispersion compensation [1] and better tolerances to equalization enhanced phase noise (EEPN) [2] and fiber nonlinearity [3-5]. Moreover, for a colored signal-to-noise ratio (SNR) channel, (*e.g.*, due to reconfigurable optical add/drop multiplexer (ROADM) filter narrowing, transceiver bandwidth limit), SCM can improve the achievable information rate (AIR) by entropy loading (EL) [6-8] that adaptively assigns a probabilistically shaped (PS) format to each subcarrier with a fractionally adjustable entropy matching its SNR.

Besides the advantages in point-to-point (P2P) transmissions above, SCM is a promising technique of simplifying the architecture of a point-to-multipoint (P2MP) network [9,10]. It brings cost saving by sharing one high-capacity transceiver with multiple low-capacity ones at the end points (EPs), where each EP is equipped with a tunable laser capable of accessing one or a batch of subcarriers in a colorless manner to enable potential bypass of ROADMs [10]. In this paper, we demonstrate a novel SCM advantage in P2MP optical networks named diversity gain, that can be achieved when the EPs go through different channel conditions. The diversity gain was demonstrated in a discrete-multitone (DMT) intensity-modulation direct-detection (IM-DD) system suffering from various degrees of frequency-selective fading due to chromatic dispersion (CD) [11]. This paper further reveals that the diversity gain remains even when the EP disparity is frequency independent (*e.g.*, from different levels of amplified spontaneous emission (ASE) noise). The findings are experimentally verified in a 1.6-Tb/s class coherent SCM system.

## 2. P2MP diversity gain

A prerequisite of the diversity gain is that the hub point (*i.e.*, with a high-capacity transceiver) induces a colored SNR across the spectrum occupied by the P2MP system. Such frequency-dependent SNR may be inevitable in future high-bandwidth coherent systems due to various transceiver impairments that tend to be severer at higher frequencies, like the finite efficient number of bits (ENoB) of digital-to-analog converter (DAC), component bandwidth limits and I/Q imbalance. According to Shannon's theorem, a colored SNR leads to a colored spectral efficiency (SE) as illustrated in Fig. 1(a). Each EP has its unique SNR (or SE) curve measured by sweeping its tunable laser frequency across the available bandwidth. There exist a variety of factors that induce disparity among EPs. In a coherent system, they can be different optical SNR (OSNR), ROADM filtering, received optical power (ROP) in an amplifier-less system, laser linewidth, digital signal processing (DSP) complexity, and so on. The EP disparity can be categorized into white and colored types. A white disparity means the SNR "*difference*" is frequency independent like the example shown in Fig. 1(b), and vice versa for a colored one in Fig. 1(c). Since the diversity gain with colored disparity has been demonstrated in an IM-DD P2MP link with various CD [11], we mainly focus on the white disparity in this paper. The findings can be easily extended to a coherent system with colored disparity (*e.g.*, ROADM filtering). The diversity gain relies on the fact that the subcarrier assignment plan to EPs influences the aggregated network AIR. A toy example to explain

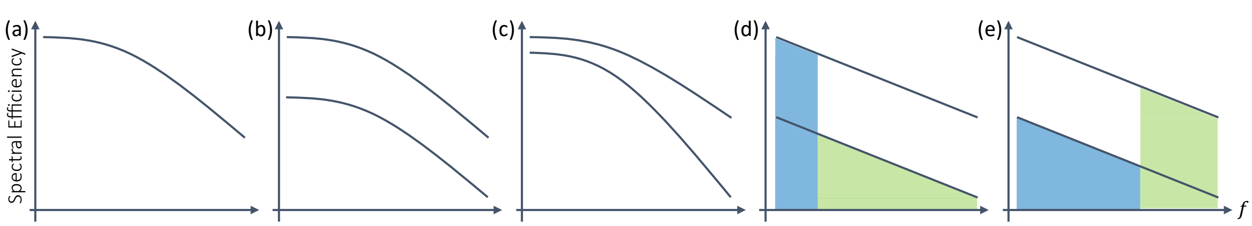


Fig. 1. Illustrations of (a) a colored SNR channel, (b) 2 channels with a white spectral efficiency (SE) gap, (c) 2 channels with a colored SE gap, and (d-e) comparisons between 2 bandwidth assignment schemes, targeting the same data rate for the 2 EPs (denoted by blue and green colors).

such a fact is shown in Fig. 1(d-e) where two EPs share the spectrum and target the same AIR. Since AIR is the integral of SE, the shaded areas in Fig. 1(d-e) represent the aggregated AIR. Apparently, the spectrum assignment in (e) achieves a wider area than that in (d). This is because if the "bad" EP (with low SNR) is assigned with the high-frequency region in (d), it needs more bandwidth to match its AIR to the "good" EP (with high SNR), which wastes the bandwidth resource; in other words, it is more efficient for the good EP to use the high-frequency region. In a real-world system, given the SNR profiles and AIR targets of all EPs, the optimum subcarrier assignment is a mathematical problem that can be solved by optimization algorithms. A rule-of-thumb (and a suboptimal solution) is to assign good subcarriers to bad EPs as shown in Fig. 1(e), and we will use an algorithm [11] following this idea in the experiment.

## 3. Experimental setup

We demonstrate the P2MP diversity gain in a state-of-the-art coherent optical experiment with the setup shown in Fig. 2. The electrical signal is generated by a 2-channel 256-GSa/s arbitrary waveform generator (AWG) (Keysight 8199B) with an analog bandwidth of about 80 GHz. The AWG outputs drive a single-polarization $LiNbO_3$ I/Q Mach-Zehnder modulator (MZM) with a 3-dB bandwidth of about 35 GHz and a smooth frequency response decay. The light source is an external cavity laser (ECL) tuned at 1550.1 nm with <100-kHz linewidth, whose output is amplified by an erbium doped fiber amplifier (EDFA) to feed the modulator with 20-dBm optical power. The dual-polarization (DP) signal is emulated by combining the single-polarization signal with its decorrelated copy after 10-m single-mode fiber (SMF) delay with a polarization beam combiner (PBC). We choose to vary the OSNR condition as a typical example of EP disparities, by loading different amount of ASE noise on the DP signal. Fixing the ROP, signals with various OSNR are back-to-back (b2b) detected by a DP coherent receiver consisting of a local oscillator same as the transmitter laser, a DP 90° optical hybrid and four 100-GHz balanced photodiodes (BPD). The BPD outputs are digitized by a 4-channel 113-GHz real-time oscilloscope (RTO) sampling at 256 GSa/s.

The optical signal is SCM-modulated with 18 10-GBaud DP subcarriers. For every OSNR condition, we measure its SNR profile (*i.e.*, SNR of all subcarriers) by sending a probe signal with a format of 5.2-bit/symbol PS 64-QAM. Without loss of generality, we set an identical AIR target for EPs and try to maximize the aggregated AIR to be quoted when we claim the diversity gain. For each AIR comparison, we only assume two EPs with two OSNR conditions to simplify our analysis, which can be straightforward generalized to multiple EPs. Given the SNR profiles and rate targets, the subcarriers are assigned by a suboptimal algorithm [11] shown in Fig. 2(i). The modulation format of each subcarrier is then determined by a lookup table based EL algorithm [12]. As only one coherent receiver is available, the experiment setup is a P2P link. To measure the P2MP performance, the full-band optical EL signal is detected twice at two OSNR conditions to emulate two EPs; and during each time, only the subcarriers that correspond to the EP of interest are demodulated. The subcarrier assignment is essentially a frequency-division multiple access (FDMA) technique. To claim the P2MP diversity gain, we choose SCM-based time-division multiple access (TDMA) as the baseline, namely, we assume each EP occupies the entire spectrum with SCM-EL modulation and time-shares the bandwidth resource. Since the EPs have an identical rate target, the TDMA rate is calculated by the harmonic average of AIRs between the two EPs. Note that most TDMA-based P2MP applications like passive optical networks (PON) [13] use single-carrier formats. Therefore, the gain claimed here is on top of the EL gain in a bandwidth-limited system as demonstrated in [7]. Besides the subcarrier assignment plan in Fig. 2(i), we also take into account a bad assignment plan with the rule opposite to the one suggested at the end of Sec. 2, namely, assigning bad subcarriers to the bad EP like in Fig. 1(d). In the experiment, we use normalized generalized mutual information (NGMI) as the system metric and net data rate $NDR = H - (1 - c) \cdot \log_2 M$ for AIR evaluations, where $H$ is the PS-QAM entropy, $c$ is the forward error correction (FEC) code rate, and $M$ is the QAM order. We choose a concatenated FEC scheme [14] ($c = 0.8262$) with an NGMI threshold (NGMI*) of 0.8714. Correspondingly, the EL algorithm takes NGMI as the loading target.

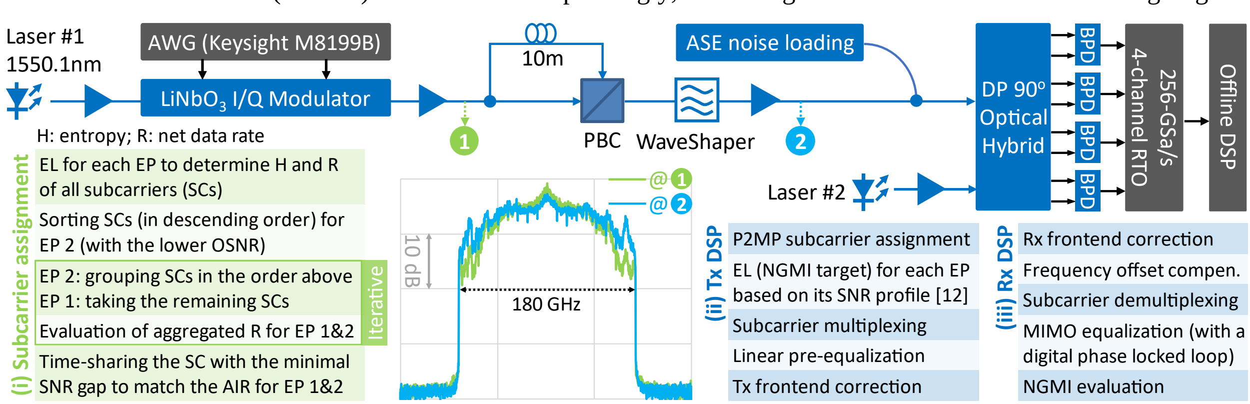

Fig. 2. Experimental setup. Inset (i): a subcarrier assignment scheme for 2 EPs; the algorithm for an arbitrary number of EPs can be found in [11].

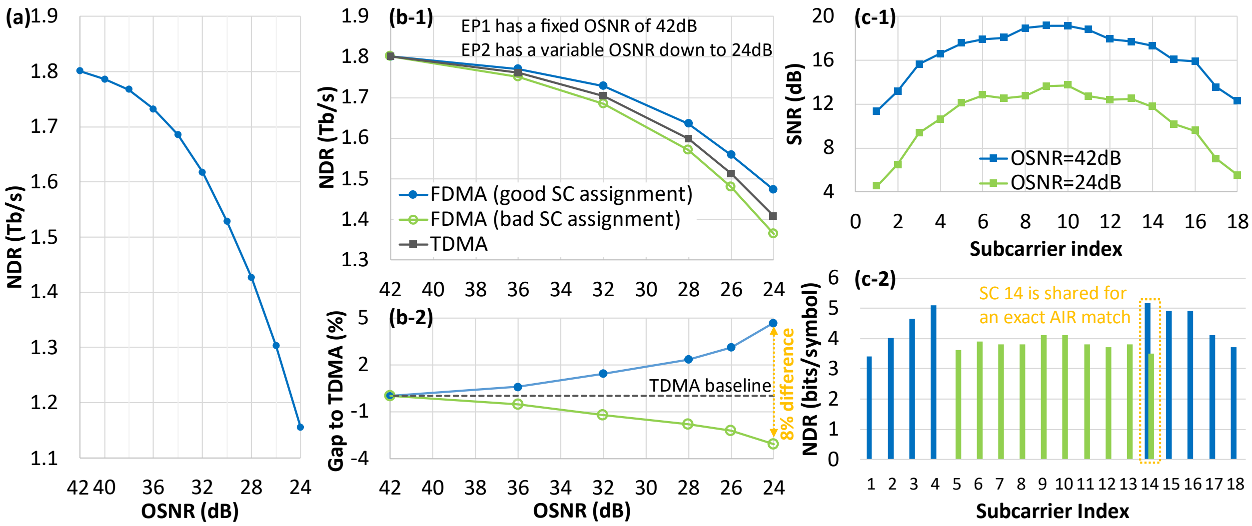


Fig. 3. Experimental results. (a) System AIR at various OSNRs; (b) FDMA diversity gain/penalty with respect to TDMA using 2 subcarrier (SC) assignment schemes; (c) an example of subcarrier assignment (using the scheme shown in Fig. 2(i)) for 2 EPs with OSNRs of 42 and 24 dB.

## 4. Results and extended discussions

To provide references for the P2MP results, we first evaluate the P2P system NDR at different OSNRs as shown in Fig. 3(a), with the maximum NDR of 1.8 Tb/s at 42-dB OSNR. Then, we fix the OSNR of one EP as 42 dB and reduce the OSNR of the other one to evaluate the aggregated P2MP AIR, as shown in Fig. 3(b). Using the FDMA algorithm in Fig. 2(i), the diversity gain with respect to TDMA gradually increases when the OSNR difference is higher, and approaches 5% when the 2$^{nd}$-EP's OSNR reaches 24 dB. More critically, if a wrong subcarrier assignment is applied, FDMA shows a diversity penalty with an absolute value close to the gain. This indicates a proper subcarrier assignment is crucial in a P2MP system with EP disparity. Fig. 3(c) shows the subcarrier assignment taking the OSNR pair of 42 and 24 dB as an example. Note that the blue EP is assigned with two non-adjacent subcarrier groups, which cannot be detected by a single-wavelength LO. Such a non-practical case is mainly because only 2 EPs are considered in this proof-of-concept demonstration, and can be avoided in a real-world P2MP network with more EPs. Furthermore, this SCM-based FDMA technique can be combined with TDMA (*i.e.*, TFDMA) to support a much bigger number of EPs.

The diversity gain increases with the degree of diversity. In our experiment, the maximum SNR gap is about 6 dB as shown in Fig. 3(c-1), given by the OSNR pair of 42 and 24 dB. A practical P2MP link may have even higher SNR disparity due to various factors besides OSNR, like ROP (in optical-amplifier-less systems) and DSP complexity. For instance, a mining on the PON field data shows the SNR difference can be at the order of 10 dB [15]. Moreover, the diversity gain can be higher given a more colored channel response (*e.g.*, due to stronger component bandwidth limit).

## 5. Conclusions

We demonstrate the P2MP gain in a 1.6-Tb/s class system with OSNR disparity while showing an improper subcarrier assignment can induce a P2MP penalty. The findings may be critical for future coherent P2MP networks targeting a wide range of coverage, where a large amount of disparity among EPs becomes inevitable.

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