Multipoint-to-point data aggregation using a single receiver and frequency-multiplexed intensity-modulated ONUs

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Abstract: We demonstrate 2.5-GHz-spaced frequency multiplexing capable of aggregating 64 intensity-modulated end-users using low-speed electronic and optoelectronic components. All optical network units (ONUs) achieved high per-user capacity with dedicated optical bands, enabling future low latency applications.

1. Introduction

The emerging edge cloud and latency sensitive services (e.g., 5G, tactile internet, autonomous vehicles, virtual reality) require low and stable latency connectivity between the cloud and end-users [1, 2]. Such networks should be scalable to support a large number of end-users, e.g., for internet of things [3]. Importantly, these requirements should be met using deployed legacy fiber links, which are primarily multipoint-to-point (MP2P) passive optical networks (PON), to deliver these services at low cost. In such systems, the main technical challenge is providing dedicated, low and stable latency upstream connection from each end-user (e.g., optical network unit, ONU) without time or frequency domain collision [4]. The existing standardized time division multiplexing (TDM) approach, such as Ethernet PON or Gigabit PON, requires time scheduling and a large gap between consecutive optical bursts to avoid collisions at the remote splitter and consequently, cannot provide dedicated, low and stable latency services to all end-users [4]. In addition, all TDM ONUs need to operate at the full rate while the effective per-user upstream capacity is only a factor 1/N (where N is the number of ONUs [5]), resulting in limited per-user upstream capacity. For example, considering a 50 Gb/s TDM PON with 64 end-users [5], each ONU needs to use a 50-Gb/s burst-mode transceiver for an effective upstream rate of 781.25Mb/s. Alternatively, wavelength division multiplexing (WDM) offers a dedicated frequency channel for each ONU and promises high per-user capacity as well as low and stable latency [6]. Nevertheless, it requires changing existing infrastructure (e.g., change the splitters at remote note to wavelength multiplexers), which significantly increase capital and operating expenses. Combined WDM-TDM approaches have lowered cost versus WDM, but the use of TDM still prevents low and stable latency. To provide dedicated frequency channels (and thus low latency) at low cost, multiple ONUs were multiplexed using sub-carrier modulation and detected by a single coherent receiver [7]. Analysis shows that it can significantly lower the capital cost [8]. Nevertheless, the demonstration of this concept only showed up to four upstream end-users [7] and the scheme is expensive to scale up due to the use of expensive external cavity lasers locked to their own individual etalons.

In this work, we propose an economical and scalable route to providing dedicated, low and stable latency optical access using frequency multiplexed (FDM) subcarrier channels. The low-cost FDM is enabled by frequency-locking ONU's CW light to a tone of a reference frequency comb sent an optical line terminal (OLT). Since only frequency locking (as compared to optical phase locking) is needed and a small frequency deviation (e.g., a few MHz) has a minimum impact on system performance, low-speed and low-cost electronics can be used for the frequency locking. Further, the ONUs are color-less and only requiring intensity modulation using low-bandwidth electronics (as oppose to the full rate of TDM ONUs) for each upstream channel, resulting in capital and operation cost saving. The conceptual diagram of the proposed system is shown in Fig.1a. All ONU upstream signals in our configuration are passively combined through a remote splitter and are detected simultaneously using a single coherent receiver. Using

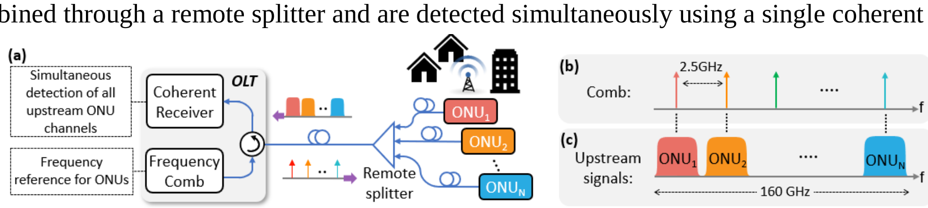

Fig. 1: Conceptual diagram of the proposed FDM upstream aggregation: (a) system architecture; (b) frequency comb sent to the ONUs; (c) upstream ONU signals detected by a single coherent receiver.

the 2.5-GHz-spacing frequency comb as reference (Fig.1b), the FDM ONUs are 2.5-GHz apart from each other, enabling closely-spaced FDM ONU upstream channels for high spectral efficiency (Fig.1c). The ONUs use the same type of low-cost single-wavelength lasers, which can be flexibly and stably locked to any of the 64 channels across a 160 GHz (1.2 nm in wavelength) optical bandwidth. Using <2.5 GHz electronics and subcarrier modulation intensity modulation (SCM), a per-user upstream data rate of up to 4.29 Gb/s is achieved, resulting in an aggregated data rate of 253 Gb/s.

2. Experimental setup

Fig. 2 shows the experimental setup. The system consisted of an OLT, a 25 km SMF-28 distributing fiber, a 1:64 remote splitting node and three branches of feeder fibers of 1 km, 4 km and 20 m length to ONU1-3, respectively. The remote node was emulated by using two splitters and a 9-dB-loss optical attenuator (VOA2). The total loss of the 25 km link and the remote splitting was 24 dB. The OLT used a 30-kHz-linewidth laser emitting a 13 dBm continuous wave (CW) signal at 1550.08 nm as both the local oscillator (LO) for coherent detection of the upstream signals and the seed light for the downstream frequency comb, via a 70:30 splitter. 64 comb lines with 2.5-GHz spacing were generated by driving a cavity-enhanced modulator with a 2.5-GHz RF signal [9]. Subsequently, the comb was amplified by an erbium doped fiber amplifier (EDFA1), scrambled by a polarization scrambler, and attenuated before being sent to the ONUs as optical frequency references (Fig.3a).

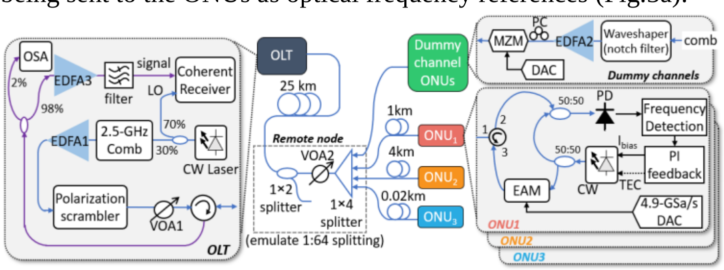

Fig. 2: Experimental setup; Three ONUs are used in this proof-of-concept experiment; the rest of the optical bandwidth is populated using the dummy channels.

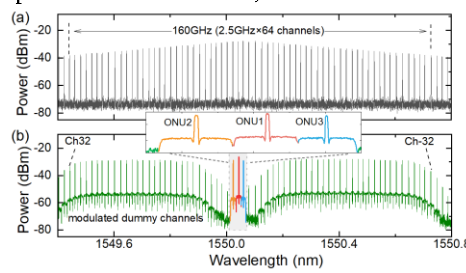

Fig. 3: Optical spectra of (a) frequency comb received at ONUs; (b) upstream ONU signals received at the OLT: red (ONU1 locked at Ch2), orange (ONU2) and blue (ONU3). Green lines show the modulated dummy channels.

We implemented three live ONUs using the same model of single-wavelength low-cost lasers outputting 8 dBm CW [10]. The CW light was split by a 50:50 coupler and mixed with the downstream frequency comb to generate a beat note corresponding to the frequency difference between the CW and the selected reference tone for feedback current control, using a proportional integral (PI) controller. In this proof-of-concept experiment, the ONU CW lasers were tuned to the target frequency channels using thermoelectric coolers (TECs). In temperature uncontrolled environment, uncooled tunable laser can be used as the upstream CW source [11]. The ONUs were frequency locked to three neighboring comb tones (2.5 GHz apart). For performance validation, we tuned the ONUs across the whole 160 GHz range. The upstream signals were generated by modulating an electroabsorption modulator (EAM) driven with 1.072 GBaud SCM-QAM signals, generated using 4.9 GSa/s digital-to-analog converters (DACs). The digital SCM-QAM signals were generated offline using a PRBS sequence of 2^{14}-1 length, mapped to QAM symbols, shaped by a root-raise-cosine filter with a 0.01 roll-off factor, and upconverted to a carrier frequency of 0.635 GHz to generate real-value SCM-QAM signals. 4/8/16 QAM was used to achieve a per-user data rate of 2.14, 3.22 and 4.3 Gbit/s, respectively. The power of the upstream signals reaching the remote splitter was -3, -5 and -6 dBm for ONU1, ONU2 and ONU3, respectively, due to different losses of the EAMs and the feeder fiber links.

We employed dummy channels to populate the rest of the upstream channels to emulate the simultaneous transmission and detection of 64 ONUs. The dummy channels were generated by modulating a frequency comb using a Mach-Zehnder modulator (MZM) driven with 1.072 GBaud intensity-modulated SCM-QAM signals with a carrier-signal-to-power ratio of about 14 dB, which is similar to that of the ONUs' outputs. The comb for the dummy channels was tapped from EDFA1 and filtered using a waveshaper, configured to generate a flat comb with a 30 GHz bandwidth notch centered at the ONUs' frequency band. The modulated dummy channels are shown as green lines in Fig.3b. The combined upstream signals were sent to the OLT, pre-amplified by EDFA3 (noise figure of ~5 dB), then filtered and detected by a 70 GHz bandwidth dual-polarization coherent receiver. The waveforms were subsequently captured by a 100-GHz-bandwidth 256-GSa/s real-time oscilloscope before performing offline DSP, in which only the three ONU channels were demodulation. No dispersion compensation was required due to the low per-user bandwidth.

3. Results and Discussion

Fig.4 shows the BER measured with regard to per-channel power for the three live ONUs when they are locked to neighboring channels at the center (channel 1-3, closed markers) and the edge (channel 29-31, open markers) of the optical bandwidth. Their frequency offset to center wavelength (i.e., the LO wavelength) is Δf = i ×2.5GHz, where i is the channel ID. ONU1 exhibited about 4 dB higher sensitivity than ONU2&3 irrespective of modulation format because the EAM for ONU1 was optimized for 1550 nm, whilst the EAMs for ONU2&3 were optimized for shorter wavelength. Considering ONU1, the sensitivities for the SCM formats of 4, 8 and 16 QAM at the hard-decision forward error correction (HD-FEC) threshold of 4.4e-3 (6.7% overhead [12]) were -44, -35 and -29 dBm, respectively.

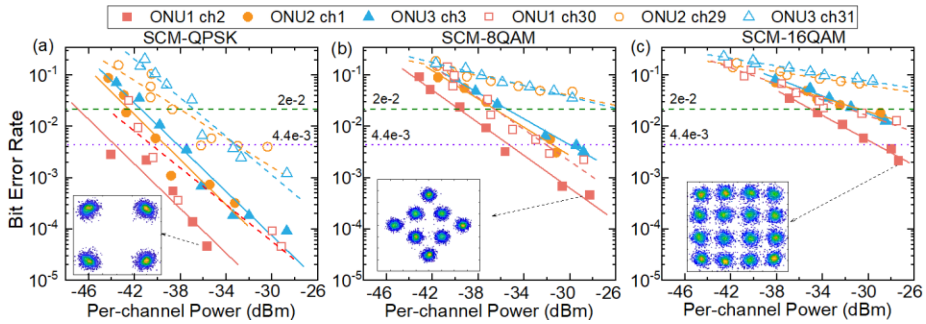

Fig. 4: BER sensitivities of the ONUs locked at the center (solid markers, channel 1-3) and the edge (open markers, channel 29-31) of the receiver bandwidth using different SCM formats (a) 4 QAM; (b) 8 QAM; (c) 16 QAM.

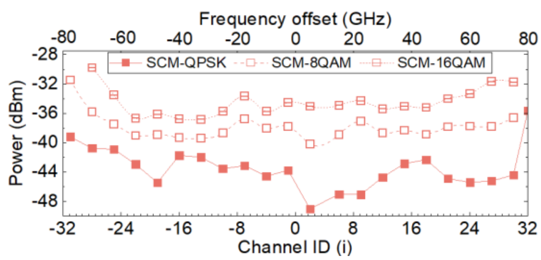

Fig. 5: Upstream power sensitivity for SD-FEC threshold (BER of 2e-2). Power measured using OSA before the pre-amplifier (EDFA3) of the coherent receiver. The relationship between the channel ID (i) and the frequency offset to center wavelength is Δf = i×2.5 GHz.

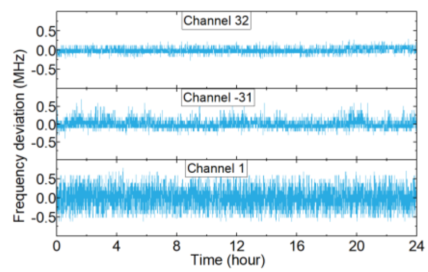

Fig. 6: Measured frequency deviation range over 24 hours for ONUs locked at different channels.

The sensitivities at the soft-decision (SD) threshold of 2e-2 (15.3% overhead [13]) were -47, -40 and -35 dBm, respectively, for the SCM with formats of 4/8/16QAM. The BER performance across the whole 160 GHz bandwidth was tested by tuning the live ONUs from -80 GHz frequency offset (Ch -32) to 80 GHz (Ch 32). Fig. 5 shows the sensitivities of ONU1 over 160 GHz for the SD-FEC threshold. All 64 channels achieved sub-SD-FEC BER for 4 QAM, but only 62 channels (Ch -31 to 30) for 8 QAM and 59 channels (Ch -28 to 30) for 16 QAM, primarily due to the high frequency roll-off of the coherent receiver. The average sensitivities for the SD-FEC threshold for the SCM-4/8/16QAM formats are about -44, -38 and -34 dBm, respectively. The BER degradation at the edge of the optical band was primarily due to the receiver frequency roll-off. We then calculated the aggregate upstream capacity over the whole bandwidth assuming optimized EAM (ONU1) was used, resulting in raw data rates of 137.2, 202.6, and 253 Gb/s for the SCM formats of 4, 8 and 16QAM, respectively. Finally, we studied the long-term frequency stability of the locked ONUs by measuring frequency deviation over 24 hours. As shown in Fig.6, the maximum frequency deviation was < 1.5 MHz, allowing only a small guard band to be used between neighboring channels.

4. Conclusion

We demonstrated 2.5-GHz-spacing FDM MP2P data aggregation, providing a record high number of end-users with dedicated frequency channels for low and stable latency access. All channels are simultaneous detected by a single coherent receiver, providing up to a 253 Gb/s aggregate data rate for intensity-modulated colorless ONUs. Only low-speed, low-cost electronic and optoelectronic is required, promising cost-effective scalability for MP2P connection.

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