Direct-detection optical OFDM superchannel for long-reach PON using pilot regeneration

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Abstract: We demonstrate a novel long-reach PON downstream scheme based on the regenerated pilot assisted direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM) superchannel transmission. We use the optical comb source to form DDO-OFDM superchannel, and reserve the center carrier as a seed pilot. The seed pilot is further tracked and reused to generate multiple optical carriers at the local exchange. Each regenerated pilot carrier is selected to beat with an adjacent OFDM sub-band at ONU, so that the electrical bandwidth limitation can be much released compared to the conventional DDO-OFDM superchannel detection. With the proposed proof-of-concept architecture, we experimentally demonstrated a 116.7 Gb/s superchannel OFDM-PON system with transmission reach of 100 km, and 1:64 splitting ratio. We analyze the impact of carrier-to-sideband power ratio (CSPR) on system performance. The experiment result shows that, 5 dB power margin is still remained at ONU using such technique.

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References and links


1. Introduction

The long-reach passive optical network (LR-PON) enables network operators and service providers to deliver wide-bandwidth traffic to a vast number of end users at a low cost by exploiting optical amplification in combination with wavelength division multiplexing (WDM). The consolidation of metro/access networks reduces the number of active optical network interfaces and elements in the field, thus minimizes network planning. This in turn lowers capital expenditure (CAPEX) and operational expenditure (OPEX) of the integrated network [1–3].

As a technique well employed in wired and wireless communications, orthogonal frequency division multiplexing (OFDM) has recently attracted many research focuses in the optical communications and access networks. The direct-detection optical OFDM (DDO-OFDM) [4–8] is thought to be one of the most promising candidates for next-generation optical access due to several advantages, such as low cost, resistance to dispersion, and modulation/spectra flexibility. J. M. Tang et al. demonstrated a real-time 10.375 Gb/s optical OFDM-PON upstream transmission with adaptive dynamic bandwidth allocation (DBA) and colorless ONUs in IM/DD architectures [9]. D. Y. Qian et al. proposed and experimentally demonstrated a single-side band 43.6-Gb/s downstream OFDMA-PON using 64/32/16QAM signals and direct detection [10]. J. H. Yan et al. proposed a double-sided DDO-OFDM downstream scheme, which transmitted an aggregated data rate of 120 Gb/s using less than 25 GHz single-end receiver [11].

In this paper, we conduct a proof-of-concept experiment of a regenerated pilot assisted DDO-OFDM superchannel LR-PON downstream system. We firstly employ the optical comb source to form an OFDM superchannel loading with high data rate optical signal. Unlike the works in [12–14], we reserve one carrier unloaded so that we can reuse it at local exchange to generate multiple pilot sources. The pilot sources are then beat with corresponding modulated sub-bands at ONUs. In such manners, the bandwidth requirement of the photo detectors (PDs) at ONUs can be greatly reduced. We experimentally demonstrate a 116.7-Gb/s downstream transmission of 100 km reach and 1:64 splitting ratio using the proposed scheme. More than 5 dB power margin is obtained at ONUs under an optimized carrier-to-sideband power ratio (CSPR). Our demonstration shows that the proposed regenerated pilot assisted OFDM-PON would be a feasible solution for the future LR-PON configuration.

2. Principle

Figure 1 illustrates the system architecture of the proposed DDO-OFDM superchannel downstream scheme based on the optical comb regeneration technique. At OLT, a laser source is firstly fed into the optical comb generator to produce \( n \) optical carriers (wavelength of \( \lambda(i,\ldots,n) \)) with frequency spacing of \( \Delta f \). Then, an arrayed waveguide grating (AWG), which is denoted as AWG1, is employed to separate the optical combs. Except for the central carrier (\( \lambda_c \)), all the others are used to carry the OFDM signals. The central carrier (\( \lambda_c \)) is reserved as the seed carrier for further comb regeneration. Such seed carrier and the modulated

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optical OFDM signals are combined by AWG2, as shown in Fig. 1(a), and then sent to the local exchange through the feeder fiber. Since the seed carrier ($\lambda_c$) is un-modulated, it could be extracted and reused to produce the optical pilots using another comb generator at the local exchange. Before the multi-band signal is relatively de-multiplexed into $n$ channels by AWG3, a polarization tracking is indispensable to align the polarization state of the seed carrier with the following comb generator, and also maintain the polarization states of the regenerated carriers the same as that of the modulated sub-bands. The comb regenerator is also driven with the same radio frequency ($\Delta f$) and produce $n$ optical carriers with wavelength of $\lambda_i (i = 2,...,n+1)$. The wavelength of the regenerated carrier is one carrier spacing shifted compared to the comb source at OLT. The regenerated comb sources are separated by AWG4. Each comb source is then coupled with a corresponding OFDM sub-band to satisfy the pilot assisted single side band (SSB) DDO-OFDM configuration, as illustrated in Fig. 1(b). Supposed that the bandwidth of each OFDM sub-band is $B$, the minimum electrical bandwidth requirement of each photo-detector at ONUs is only $2 \cdot B$ [10, 15], as shown in Fig. 1(c). Each coupled pilot carrier and sub-band is fed into a distribution path. Furthermore, each distribution path is split to support multiple ONUs. The main advantages of such proposed scheme come from two aspects: i) The superchannel configuration is used to carry high data rate signal; ii) Compared to the conventional method [11], the electrical bandwidth limitation for each photo-detector is only related to the bandwidth of each sub-band, instead of the entire superchannel. Based on the proposed method, much more ONUs could be supported by one set of devices. Although the cost of local exchange is increased slightly, the overall cost has been well reduced from the aspect of CAPEX and OPEX. Additionally, the cost of devices in local exchange can be further reduced by employing integration technology such as silicon photonics [16].

![Fig. 1. System architecture of the proposed DDO-OFDM LR-PON downstream scheme. (a) Optical spectrum of the generated DDO-OFDM superchannel; (b) coupling scheme for the filtered pilot-carriers and sub-bands; (c) the coupled signal transmitted to ONUs. BPF: Band Pass Filter.](image)

3. Experimental setup

The experimental setup of the proposed 116.7 Gb/s DDO-OFDM superchannel transmission for LR-PON is shown in Fig. 2. At OLT, an external cavity laser (ECL) with 100 kHz linewidth operating at 1549.6 nm is firstly split into two tributaries by a 3 dB optical coupler. The upper branch is fed into an optical phase modulator, which is driven by strong RF sine wave (~1.5 W)
at 15 GHz. A programmable wavelength selective switch (WSS) is then used to select and reshape 6 optical carriers, while the central optical carrier is suppressed. All of the 6 optical carriers are modulated with OFDM-QPSK signal using the optical IQ modulator (IQM). The lower branch is directly coupled with the upper path via a variable optical attenuator (VOA). The optical spectrum of the coupled signal is shown in Fig. 2(a). The OFDM-QPSK signal is generated from a high speed digital-to-analog converter (DAC) of 10 GS/s sampling rate with a resolution of 6 bits. The inverse fast Fourier transform (IFFT) size is 512, in which 498 subcarriers are filled with payload. Cyclic prefix with length of 1/32 FFT size per OFDM symbol is adopted to avoid the inter-symbol interference. Each sub-band has a line rate of 19.45 Gb/s. The data rate of the superchannel is 116.7-Gb/s.

The feeder fiber between OLT and local exchange consists of a single span of 80 km standard single mode fiber (SSMF). At the local exchange, an Agilent N7788 polarization analyzer is used to track and align the polarization status of the seed pilot carrier with the subsequent optical phase modulator to regenerate the pilot carriers. Currently, the polarization tracking modules/devices have been well designed and commercialized supporting up to 140 krad/s polarization variation rate [17]. The optical signal is then split into two tributaries by a 3 dB optical coupler. In the upper path, a tunable optical filters (TOF) is used to filter the seed

Fig. 2. Experimental setup of the proposed 116.7-Gb/s DDO-OFDM superchannel transmission for LR-PON. VOA: Variable Optical Attenuator; WSS: Wavelength Selective Switch; TOF: Tunable Optical Filters; PM: Phase Modulator; IQM: IQ Modulator; ECL: External Cavity Laser.

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carrier, and then feed it into another phase modulator (driven by the same 15 GHz RF frequency source). The spectrum of the regenerated comb source, without any optical shaping, is shown in Fig. 2(b). Two WSSs are used to flatten the regenerated carriers, and also perform the function of the AWG3 and AWG4 as described in the Section II. The selected sub-band and pilot carrier are coupled by the proposed criterion, as shown in Figs. 2(c) and 2(d), and then fed into the distribution path. Note that all the devices at local exchange should be polarization maintained.

The distribution path consists of a 20 km SSMF and a VOA, in which VOA is used to emulate the optical split. At the ONU, a single-end photo detector (U2T photo receiver, XPRV2021) of 40 GHz bandwidth is used to detect the optical signal. The RF signal is then fed into a Tektronix real-time scope, sampled at 50 GS/s, and processed off-line.

4. Results and discussion

Firstly, we conduct the back-to-back and 80 km transmission measurements, as shown in Fig. 3. The optimum Q factor in the back-to-back measurement is 15.6 dB at a CSPR of ~7 dB. After 80 km transmission, the optimum Q factor reaches 14.4 dB at a CSPR of ~6.5 dB. The launch power into the feeder fiber is fixed at 0 dBm. Compared to back-to-back, there is about 1.2 dB degradation for the optimum Q factor, which is mainly due to the increased amplified spontaneous emission (ASE) noise from the EDFA. Additionally, the optimum CSPR after transmission decreases slightly, which agrees with the results reported in [13]. Note that, the CSPR in this paper is obviously greater than those in the reported papers [12, 13], because only one sub-band is supported by each regenerated pilot carrier.

The distribution path is composed of a 20 km SSMF and a VOA. The VOA is set to 18 dB to emulate the 1:64 split. Since no amplifier is allowed at the ONU side, it is crucial to find the optimum launch power for the distribution path, which will determine the maximum achievable optical power budget between local exchange and ONUs. The measurement is taken under three different CSPRs (2, 7, and 12 dB), and the results are shown in Fig. 4. The maximum Q factor is ~13.7 dB, which is achieved when CSPR is 7 dB and launch power is ~12.5 dBm. With a lower CSPR of 2 dB, the optimum launch power is found to be similar and the optimum Q factor has ~1 dB degradation relative to that of CSPR of 7 dB. A further increase in CSPR (i.e. CSPR = 12 dB) would sacrifice the signal quality with a drastically enhanced optimum launch power.

![Fig. 3. The impact of CSPR on system performance for back-to-back and 80 km transmission.](image)
The receiver sensitivity at the ONU is also investigated by tuning the VOA, as shown in Fig. 5. The VOA is located right after the 20 km distribution fiber. According to the previous results, CSPR is set to 7 dB and launch power is set to 12.5 dBm. Firstly, the VOA is set to 18 dB (1:64 split), and the corresponding Q factor is about 13 dB. With the consideration of 7% FEC limit [18], a maximum receiver sensitivity of about $-16$ dBm could be achieved. After the transmission of 100 km length with 1:64 split, more than 5 dB system power margin is achieved using the proposed method.

We further measure the performances of all the 6 sub-bands with the same experiment setting (CSPR be 7 dB, launch power be 12.5 dBm). As shown in Fig. 6, the average Q factor of each sub-band has a 4.5 dB margin above the FEC limit, which indicates that higher data rate signal or longer reaches could be potentially achieved.
5. Conclusion

We proposed a novel downstream transmission scheme using DDO-OFDM superchannel for LR-PON. The superchannel is composed of multiple sub-bands and one pilot-carrier, which is then used as the seed for comb regeneration at the local exchange. The regenerated pilot carriers are assigned to beat with the adjacent sub-band at the ONU side. Our demonstration showed an excellent and low cost PON architecture with significant Q factor margin (~4.5 dB) to the FEC limit under an appropriate CSPR, which would be a feasible solution for the future LR-PON.

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Fig. 6. The measured performance of each sub-band when CSPR is 7 dB and launch power is 12.5 dBm.