Dual Architecture Uplink Demonstration of a 7×622 Mbps SAC-OCDMA PON Using a Burst-Mode Receiver

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Abstract: We demonstrate experimentally the uplink of an incoherent spectral amplitude-coded optical code-division multiple-access passive optical network (PON) using a burst-mode receiver. Error free transmission is achieved for local sources and centralized sources PON architectures.

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1. Introduction

Spectral amplitude-coded (SAC) optical code-division multiple-access (OCDMA) offers cost savings over other OCDMA techniques as it requires electronics operating at only the bit rate and it enjoys excellent multiple access interference (MAI) rejection due to balanced detection [1]. Furthermore, advances in writing fiber Bragg gratings (FBGs) make possible the design of low cost and compact passive encoders/decoders well adapted to passive optical networks (PONs). OCDMA combines the large bandwidth of the fiber medium with the flexibility of the CDMA to achieve high-speed connectivity. SAC-OCDMA is suitable for PON applications, where cost and performance are critical. In this paper we examine for the first time to our knowledge SAC-OCDMA with local sources (LS) and centralized light source (CLS) PON architectures. An inexpensive incoherent light source is placed at each optical network unit (ONU) for LS architectures; a single high power light source is placed at the optical line terminal (OLT) for the CLS architectures.

Most research in OCDMA focuses on optical design, and assumes the availability of compatible electronics [1],[2]. Emerging research is concerned with the electronic design of receivers for optical access networks, featuring post-processing functionalities [3]. Previous electronic receivers were reported in the literature for fast-frequency hop (FFH) OCDMA and PON systems [4], [5]. FFH-OCDMA requires electronics that operate at the chip rate rather than the bit rate. In this paper we demonstrate experimentally burst-mode reception of an incoherent SAC-OCDMA PON uplink supporting seven asynchronous users at 622 Mbps (FFH results were at 155 Mbps data rate) with no global clock, using a standalone receiver with a commercial SONET clock-and-data recovery (CDR). The receiver also features clock-and-phase alignment (CPA), forward-error correction (FEC), and a custom bit error rate tester (BERT), all implemented on a field programmable gate array (FPGA). We measure the performance of the proposed PONs in terms of bit error rate (BER) and packet loss ratio (PLR). We quantify the increase in soft capacity via FEC, while working with a nonideal recovered clock that provides realistic, achievable sampling.

2. SAC-OCDMA PON physical architectures and burst-mode receiver functionalities

Tree architectures are widely deployed for PONs, and both two-feeder and single-feeder versions have been studied [6]. In two-feeder architectures, uplink and downlink traffic are sent on separate feeders; a single-feeder architecture carries both uplink and downlink on one fiber feeder. Fig. 1(a) shows our proposed SAC-OCDMA PON architectures. Both LS architectures (a source at each ONU) and CLS architectures (one source at the OLT) can exist with two-feeder and single-feeder topologies (shown within the optical distribution network). In the LS architecture an inexpensive light emitting diode (LED) is directly or externally modulated and located at each ONU. A CLS architecture places a single powerful light source at the OLT, with remote external modulation of that source at each ONU. In CLS PONs, coarse wavelength-division multiplexed (WDM) filters are needed at the OLT and ONU, as shown in Fig. 1(a), to separate the continuous wave light for the uplink from the modulated downlink. The remote node (RN) consists of passive combiners and splitters, as in existing TDM PONs, so there is no need to upgrade the PON infrastructure; for WDM PONs the couplers must be replaced by arrayed waveguide gratings (AWGs). At the OLT a multi-user transceiver is used to communicate with all users, optical amplifiers may be used to boost the signal prior to transmission and/or reception. Recall that the optimum receiver for a SAC-OCDMA PON at the OLT and ONUs is the conventional balanced receiver, where a 1×2 coupler, a decoder (DEC), a complementary decoder, and a balanced photodiode are used. Although our OCDMA PON architectures offer the flexibility of adopting both two-feeder and single-feeder architectures, we test only the two-feeder architecture. The effect of Rayleigh backscattering, which is reduced in two-feeder architectures, is not addressed.

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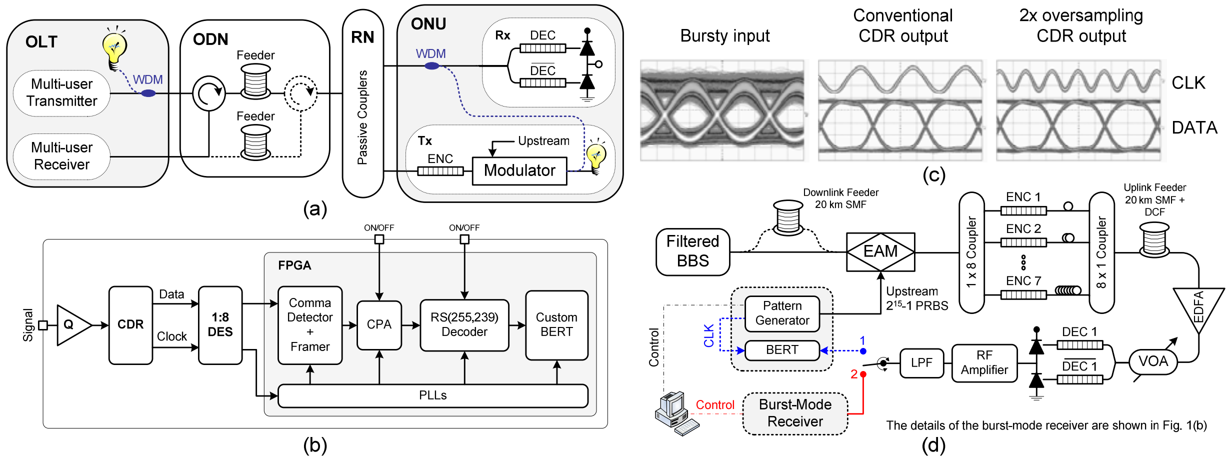


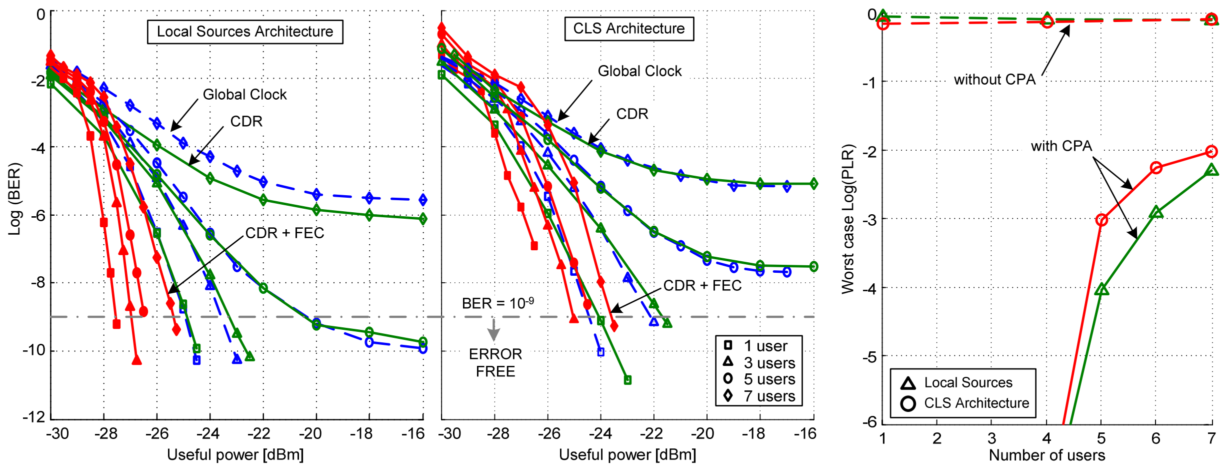
Fig. 1. (a) SAC-OCDMA physical PON architectures (ENC: encoder, ODN: optical distribution network), (b) OLT SAC-OCDMA burst-mode receiver block diagram (PLL: phase-locked loop), (c) Typical eye diagrams (CLK: clock), and (d) 7×622 Mbps SAC-OCDMA PON uplink experimental setup (LPF: low pass filter, RF: radio frequency).

Because of the bursty nature of the upstream, the OLT receives packets from active ONUs with different amplitude levels and phases. Fig. 1(b) illustrates the main building blocks of our burst-mode receiver. The receiver is similar to that in [4], but without a return-to-zero (RZ) to non-return-to-zero (NRZ) converter required for FFH-OCDMA. The quantizer (Q) is used before the multi-rate CDR to apply a threshold (manually adjusted) to the incoming signal to filter out intensity noise [refer to Fig. 1(c)]. The CDR then recovers the clock and data from the incoming signal. It is operated at either 622 Mbps or 666.43 Mbps (to account for the 15/14 FEC overhead) depending on whether the FEC module is OFF or ON, respectively. A 1:8 deserializer (DES) is then used to reduce the frequency for processing by digital logic. A framer and a comma detector, a CPA, PLLs, and a Reed Solomon RS(255,239) decoder, are implemented on an FPGA alongside with a custom BERT. The CPA module makes use of the phase picking algorithm in [3] and the CDR operated in the 2× over sampling mode shown in Fig. 1(c). The CPA is turned ON for the PLR measurements with phase acquisition, otherwise it is bypassed.

3. Experimental results and discussion

The experimental setup illustrated in Fig. 1(d) is used to test the uplink of the LS and CLS SAC-OCDMA PON architectures shown in Fig. 1(a). A single incoherent broadband source (BBS) is filtered around 1542.5 nm providing a 9.6 nm band, and serves to test both the CLS and LS architectures. An NRZ 2^{15}-1 pseudo random binary sequence (PRBS) is input to a single electro-absorption modulator (EAM) that, in conjunction with appropriate decorrelating delay lines, represents independent data streams each modulated externally at a distinct ONU. For the CLS architecture, the single powerful BBS is sent over the 20km downlink feeder and split by a 1×8 coupler representing the RN. For the LS architecture, the 20 km single mode fiber (SMF) is not present and the 1×8 coupler is not part of the network, but rather an experimental trick to simulate eight separate, low power incoherent sources. The balance of the setup is interpreted as seven ONUs each with a distinct CDMA encoder, followed by a 1×8 coupler representing the RN and 20 km SMF for the uplink in the two-feeder architecture. At the OLT an appropriate dispersion compensation fiber (DCF) is used, and the signal is amplified by an erbium-doped fiber amplifier (EDFA) and detected in a balanced receiver. A variable optical attenuator (VOA) serves to control the received power. After photodetection, the electrical signal is amplified and low-pass filtered. Measurements are performed with either a global clock, or through our OCDMA burst-mode receiver, corresponding to switch position 1 or 2, respectively. The spectral coding is achieved by FBGs working in transmission; balanced incomplete block design (BIBD) codes with length 7 and weight 3 are used as in [1].

Fig. 2(a) presents the BER versus useful power (received power from the desired user) for both the LS (left) and CLS (right) architectures. Ignoring for a moment the solid curves with filled markers (FEC results), we focus our attention on the set of curves for the global clock using the BERT (dashed) versus using the CDR module on the burst-mode receiver (solid + unfilled markers). Starting from a single user we see a classic waterfall curve; as we go to a fully charged system of seven users BER floors begin to appear, starting from five users. The penalty added by the CDR with respect to the global clock is less than 0.25 dB, as we can see by the proximity of the CDR and global clock curves. When adding the FEC to the CDR operation, we see that all BER floors disappear and we return to the classic waterfall close to the single user performance.



(a) (b)

Fig. 2. (a) BER vs. power for LS and CLS PON architectures for different number of users, and (b) worst case PLR (at π phase shift) vs. number of users for LS and CLS architectures, with and without CPA.

In Fig. 2(b) we plot the worst case PLR versus the number of users, with and without CPA (at -18 dBm received power). The worst case PLR is the PLR measured at π phase shift between packets, *i.e.*, half the bit period. At this phase shift, the CDR samples exactly at the edge of the eye diagram. We consider that all packets are correctly received when PLR<10^{-6} corresponding to a BER<10^{-10} as in [3]. Packets have zero preamble bits; use of a preamble would improve PLR, but at the cost of reduced throughput. In the case of CDR without CPA, the worst case PLR is near 1. In contrast, the phase picking algorithm samples each bit twice and significantly enhances the performance. Therefore, we achieve a zero PLR for up to four users, and two orders of magnitude improvement for a fully loaded system despite the nonideal sampling of the CDR. There is degradation in performance passing from LS to CLS architecture. This is easily explained by the corresponding degradation in the BER, since packets are declared lost either if the payload is incorrectly received (poor BER performance) or if the delimiters are not received properly.

The power budget of a PON is an important parameter in the design, as it helps the fiber-to-the-home (FTTH) service providers to select appropriate light sources and convenient receivers. Splitting is the major source of losses in TDM and OCDMA PONs. In LS architectures, the uplink signal travels only from the ONU to the OLT, therefore, for N ONUs we have 10log(N) dB splitting losses. In the CLS architecture, the uplink signal travels from the OLT to the ONU and then back to the OLT after modulation, therefore a CLS PON experiences twice the splitting losses as a similar LS architecture PON. Obviously, the propagation losses for the upstream direction are also doubled in CLS architectures compared to LS architectures. For a 1:8 splitting ratio and for a 20 km reach PON, the total uplink losses in the LS and CLS configurations were roughly 39 dB (excluding the losses through the 1×8 splitter incurred for LS experimental convenience) and 52 dB, respectively. The 13 dB difference is the contribution of an additional 9 dB coupling loss, and an extra 4 dB propagation loss over the 20 km link.

4. Conclusion

We achieved error free transmission for an incoherent 7×622 Mbps uplink of LS and CLS SAC-OCDMA PONs using a standalone burst-mode receiver providing a coding gain of more than 2.5 dB at BER = 10^{-9}. We reported a zero PLR for up to four simultaneous users (for any phase difference between packets), and more than two orders of magnitude improvement for a fully loaded system when using the CPA module. In LS architectures, splitting losses are only in one direction, whereas in CLS architectures, there are splitting losses in both directions. Therefore, doubling the number of users while maintaining the same distance and source power imposes an additional 3 dB loss in LS architectures, whereas doing the same for CLS architectures imposes an extra 6 dB loss.

5. References

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