Burst-Mode Clock and [redacted] and Fast Phase Acq[redacted] Correctio[redacted]

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***Abstract*—We demonstrate experimentally for the first time t[redacted] impact of forward error correction (FEC) on the performance [redacted] 622/1244 Mb/s burst-mode clock and data recovery (BM-CD[redacted] with instantaneous phase acquisition (0 bit) for any phase st[redacted] ($\pm 2\pi$ rads) for gigabit-capable passive optical network (GPO[redacted] optical line terminator (OLT) applications with (255, 239) Ree[redacted] Solomon (*R-S*) codes. Our design is based on commercial[redacted] available SONET CDRs operated in 2× over sampling mod[redacted] This burst-mode receiver (BM-RX) provides a $\sim$ 5 dB codi[redacted] gain at bit error ratio (BER) of 10^{-10}. We also show that th[redacted] novel technique of employing FEC on BM-CDRs with fast pha[redacted] acquisition time, provides a solution for fast burst-error corre[redacted] tion giving reliable and predictable BERs in bursty-channe[redacted] The BM-RX meets the GPON physical media dependent lay[redacted] specifications defined in the ITU-T G.984.2 recommendation. T[redacted] coding gain can be used to increase the optical link budget [redacted] specified in the ITU-T G.984.3 standard, that is, support high[redacted] bit rates, achieve longer physical reach between the OLT and t[redacted] optical network units (ONUs), as well as increase the number [redacted] splits per single PON tree.**

I. Introduction

PONs are an emerging access network technology th[redacted] provide a low-cost method of deploying fiber-to-the-hom[redacted] Fig. 1 shows an example of a PON network. In the u[redacted] stream direction, the network is point-to-multipoint. Becau[redacted] upstream packets can vary in phase and amplitude due [redacted] optical path differences, the OLT requires a BM-RX and [redacted] BM-CDR. Within the OLT, the BM-RX is responsible f[redacted] amplitude recovery, whereas the BM-CDR is responsible for phase recovery. This paper is about the design of a BM-CDR.

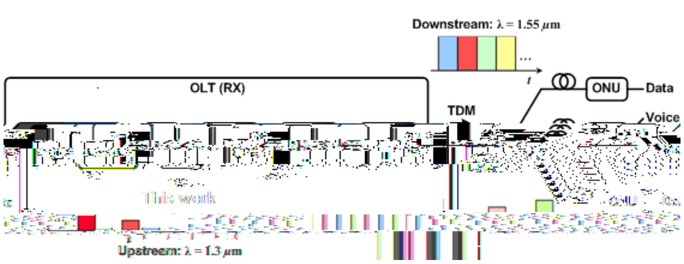

Fig. 1. Generic GPON network architecture for FTTx scenarios showing the work in context. OLT: optical line terminator; RX: receiver; LT: line terminator; FEC: forward error correction; DES: deserializer; APD: avalanche photodiode; TIA: transimpedance amplifier; TDM: time division multiplexing; TDMA: time division multiple access; ONU: optical network unit.

[redacted]employ Fabry-Perot (FP) lasers, a [redacted]MLM) device, at the ONU, as it [redacted]e solution for meeting the PON [redacted]power required for a 20 km reach in [redacted]e [1]. However, performance of the [redacted]npaired by the mode partition ratio [redacted]upled with the chromatic dispersion [redacted]sion fiber. Thus, MPN introduces a [redacted] the optical link.

[redacted]lem is that of burst-errors (clustered [redacted]arise in GPON channels because of [redacted]ess by BM-CDRs for bursty data. [redacted]asurements unreliable and unpre- [redacted] a true BER representation. There [redacted]s. Firstly, at a particular SNR, the [redacted]because of the presence of burst- [redacted]et. Thus, the BER will change from [redacted]nent for the same SNR. Secondly, [redacted]or packets with different phases at [redacted] phase acquisition time of the CDR [redacted]e phase between two packets.

[redacted]on (*R-S*) codes is useful for burst- [redacted]ned as *R-S*(n, k), *R-S* codes are [redacted]de a codeword of n symbols into [redacted]mbols of data and

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II. Experimental Setup

To test the BM-CDR with FEC and *R-S* decoding, we use the custom burst-mode test setup (BM-TS)[1] as depicted in Fig. 2 [11]. The BM-TS has two main functionalities. First, it can generate alternating packets with adjustable amplitude and phase to emulate PON traffic. Second, it can perform BER measurements. Consequently, the BER measurements can also be used to determine the amplitude/phase acquisition times, and the number of consecutive identical digits (CIDs) supported by the BM-CDR.

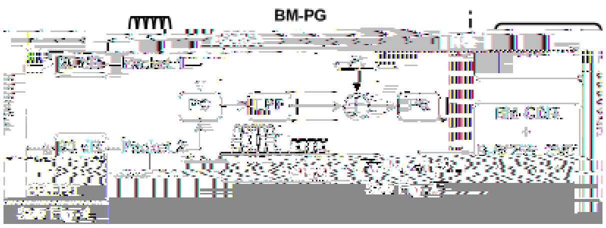

Fig. 2. Burst-mode packet generator. The burst-mode packet generator is on the left of the dashed line. When performing the BER measurements, the two packets are set to have the same amplitude. BM-PG: burst-mode pattern generator; PC: power combiner; LPF: low-pass filter (4th order Bessel-Thomson); NG: Gaussian noise generator; PS: power splitter; Osc: oscilloscope; BM-CDR: burst-mode clock and data recovery; R-S: Reed-Solomon; BBERT: burst bit error rate tester.

The BM-PG generates the upstream traffic shown in Fig. 3. Packet #1 serves as a dummy packet to force the BM-CDR to lock to a certain phase (ϕ_1) before the arrival of packet #2. The BER and phase acquisition times measurements are performed on packet #2, which consists of guard bits (16), preamble bits (0 to 2^{15}), delimiter bits (20), payload bits (2^{15}), comma bits (48), and a '1010 . . .' pattern that can be circularly shifted in front of the delimiter to increase the preamble length. The guard, preamble, and delimiter bits correspond to the physical-layer upstream burst-mode overhead specified by the ITU-T G.984.2 standard [10]. The guard bits provide distance between two consecutive packets to avoid collisions. The preamble is used to perform amplitude and phase recovery. The delimiter is a unique pattern indicating the start of the packet to perform byte synchronization. Likewise, the comma is a unique pattern to indicate the end of the payload. The payload is an *R-S* encoded $2^{15}-1$ PRBS with a zero appended at the end. The packet loss ratio (PLR) and the BER are measured on the payload bits only. The lock acquisition time corresponds to the number of bits that need to be circularly shifted in front of the delimiter in order to get a PLR of zero for over three minutes at 622.08 Mb/s ($>10^6$ packets received) and a BER $< 10^{-10}$.

As shown in Fig. 3, the preamble is split into two fields, a threshold determination field (TDF) for amplitude recovery and a CPA field for clock-phase recovery. In order to generate this pattern, we use two ports of an *HP80000* pattern generator

[1]The BM-TS can go up to 1 Gb/s. This limitation, which comes from the *HP80000*, explains why the design of the BM-CDR with FEC can only be experimentally verified at 622.08 Mb/s.

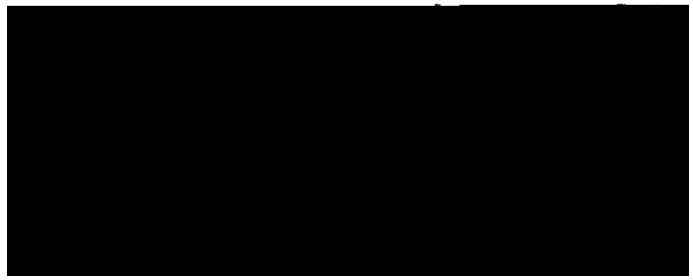

Fig. 3. Test signal and specification of the upstream burst-mode overhead. When performing BER measurements and testing the phase acquisition time, the two packets are set to have the same amplitude. TDF: threshold determination field; CPA: clock phase alignment; PRBS: pseudo-random binary sequence.

(see Fig. 2). The two packets are combined on the same line using an RF power combiner, which emulates the optical power combiner of a PON network (see Fig. 1). We use 20-dB attenuators to control the maximum amplitude of the packets and minimize reflections [12]. To test the FEC and BM-CDR under stringent conditions, we stress the input pattern in two different ways. First, we slow down the edges of the input pattern with a 4th-order Bessel-Thomson filter having a -3-dB bandwidth of 467 MHz (

This receiver architecture is built upon the novel burst-mode clock phase aligner (BM-CPA) [11] based on commercially available SONET CDRs operated in 2$\times$ over sampling mode,

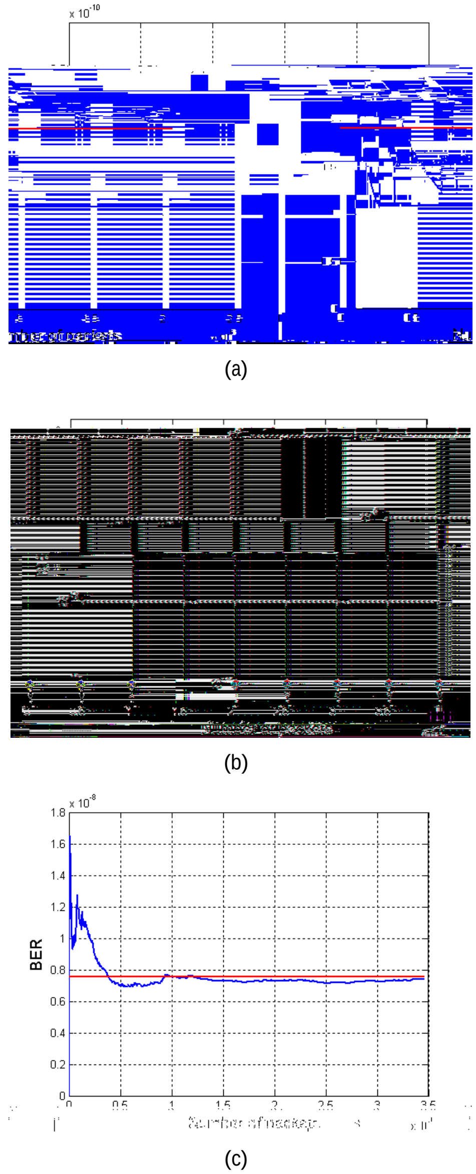

Fig. 6. BER as a function of time (number of packets received by the BM-CDR). (a) Without FEC (burst-errors and no BER convergence). (b) Error free operation with FEC and BM-CPA enabled for the same input power, $P_o = -28$ dBm as (a). (c) With FEC and BM-CPA enabled for a lower SNR ($P_o = -33$ dBm, elimination of burst-errors and fast BER convergence). The straight line shows the average BER over the period of packet reception. Measurements made with preamble length set to zero.

It can be observed from Fig. 5 that the experimental BER with FEC lies within these bounds for BER $< 10^{-4}$ and lies outside these bounds for BER $> 10^{-4}$. The reason for this is based on the fact the BER performance is a function of intrinsic and extrinsic effects of the channel, that is, the presence of random and deterministic jitter will affect the error correcting capability of the *R-S* codes. Since (2) and (3) assume *purely random* bit errors, the channel BER with FEC is overestimated for BER $> 10^{-4}$. This is attributed to the fact that as the SNR is increased, the presence of random jitter is attenuated relative to the presence of deterministic jitter. Consequently, for BER $> 10^{-4}$, deterministic jitter is the dominating factor.

V. Conclusion

We have successfully demonstrated a 622/1244 Mb/s BM-CDR with FEC and *R-S* codes for GPON OLT applications that meets the G.984.2 and G.984.3 specifications. This receiver provides for fast burst-error correction in bursty channels and also achieves an instantaneous phase acquisition. The coding gain obtained verifies the claim of the increased link budget by the G.984.3 standard. The coding gain can be used to reduce the minimum and maximum transmitter power by 5 dB or increase the minimum receiver sensitivity by the same amount. Alternatively, it can be used to achieve a longer physical reach or a higher split ratio when using a MLM laser in the ONU to reduce the penalty due to MPN. A novel technique for fast burst-error correction for bursty channels is also presented. This is achieved by employing FEC on BM-CDRs with fast phase acquisition time.

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