

# Experimental Investigation of Packet Loss Ratio Performance of Burst-Mode Receivers in GPON

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**Abstract**—We experimentally study the packet-loss ratio performance of burst-mode receivers in GPON as a function of phase step, mode-partition noise, and BER. We assess tradeoffs in power penalty, preamble length, and pattern correlator error resistance.

## I. INTRODUCTION

Passive optical networks (PONs) provide a low-cost method of deploying fiber-to-the-home to enable new multimedia services. In the uplink, the network is point-to-multipoint, making PON traffic from multiple optical network units (ONUs) bursty in nature with phase and amplitude variations. To deal with this, the optical line terminal (OLT) at the central office requires a burst-mode receiver (BMRx).

Recently, we demonstrated standalone receivers for PON applications [1], [2]. In this paper, we investigate the packet loss ratio (PLR) performance of a BMRx in a 622 Mb/s 20-km GPON uplink, and quantify it as a function of the phase step between consecutive packets, received signal power, consecutive identical digit (CID) immunity, bit-error rate (BER), and mode-partition noise (MPN) penalty. We also assess the tradeoffs in power penalty, preamble length, and pattern correlator error resistance. These results will help refine theoretical models of BMRx and PONs, and provide input for establishing realistic power budgets.

## II. EXPERIMENTAL RESULTS

A block diagram of the GPON uplink experimental setup is shown in Fig. 1. A burst controller is used to generate bursty upstream PON traffic by inserting phase steps  $|\Delta\phi| \leq 2\pi$  rads, and  $m$  CIDs between alternating packets from two programmable ports of a pattern generator, which are then concatenated via a power combiner (PC) and used to drive a modulator (MOD) [2]. These packets are formed from 16 guard bits, 0 to 28 preamble bits, 20 delimiter bits,  $2^{15} - 1$  PRBS payload bits, and 48 comma bits [3]. A 1310-nm laser is then modulated with the PON traffic and the signal is then sent through 20 km of uplink fiber. Prior to photodetection, a variable optical attenuator (VOA) serves to control the received power level. The output of the photodetector is then low-pass filtered (LPF) by a fourth-order Bessel-Thomson filter whose  $-3$ -dB cutoff frequency is 467 MHz.

The BMRx as in [1] includes a multi-rate CDR, a 1:8 deserializer, and a CPA and a forward error correction (FEC) Reed-Solomon (RS) (255, 239) decoder implemented on a FPGA. The CDR recovers the clock and data from the incoming signal. The CDR supports the following frequencies of interest: 622 Mb/s, 666.43 Mb/s with FEC to account for the  $\sim 15/14$  overhead introduced by RS(255, 239) codes, and 1.25 Gb/s for burst-mode operation. The lower rate parallel data is then sent to the FPGA for further processing. Automatic detection of the payload is implemented on the FPGA through a framer and a comma detector. The CPA makes use of a phase picking algorithm [2] and the CDR operated in  $2\times$  oversampling mode. The CPA is tur-

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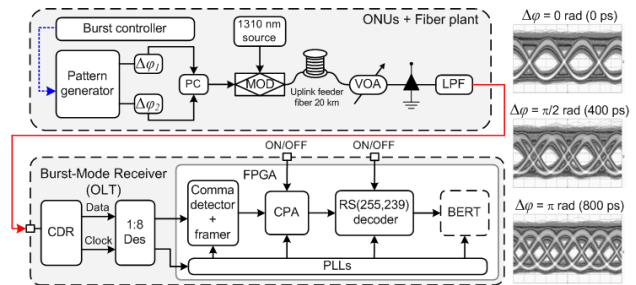


Fig. 1. Block diagram of the 622 Mb/s GPON uplink experimental setup with the BMRx (Des: deserializer; PLL: phase-locked loop; BERT: BER tester).

ned on for the PLR measurements with phase acquisition otherwise it is by-passed. The realigned data is then sent to the RS decoder which is turned on for BER measurements with FEC.

## III. RESULTS AND DISCUSSION

Fig. 2(a) shows the PLR performance of the GPON uplink as a function of phase step between consecutive packets for a back-to-back configuration (without fiber), with only the CDR and the CPA turned off. The reason for a bell-shaped curve centered at 800 ps is that it represents the half bit period corresponding to the worst-case phase step at  $\pi$  rads, and therefore, the CDR is sampling exactly at the edge of the eye diagram. Preamble bits (“1010...” pattern) can be inserted at the beginning of the packets to help the CDR acquire lock. However, the use of the preamble reduces the effective throughput and increases delay. As the preamble length is increased, there is an improvement in the PLR. We observe error-free operation ( $PLR < 10^{-6}$  and  $BER = 10^{-10}$ ) for any phase step after 32 preamble bits. This does not satisfy the 28-bit requirement specified in the G.984.2 standard. With the introduction of the 20-km fiber, there is degradation in the PLR performance as depicted in Fig. 2(a). However, by switching on the burst-mode functionality of the receiver with the CPA, we observe error-free operation in both configurations for any phase step with *no* preamble bits, allowing for instantaneous phase acquisition—well below the 28-bit specification. We note that a sensitivity penalty results from the quick extraction of the decision threshold and clock phase from a short preamble at the start of each packet [4]. However, by reducing the length of the CPA field, more bits are left for amplitude recovery, thus reducing the burst-mode sensitivity penalty.

To determine the burst-mode penalty of the receiver, we plot the PLR as a function of the received signal power in Fig. 2(b). The PLR performance of the CDR sampling continuous data at the bit rate with no phase difference is compared to the PLR performance of the BMRx sampling bursty data with a worst-case phase difference. Both measurements are made for a 0-bit preamble. We observe a power penalty of less than 1 dB due to faster electronics. If there does exist a worst-case phase difference between the consecutive packets, the CDR will not be able to recover any packets, regardless of the signal power,

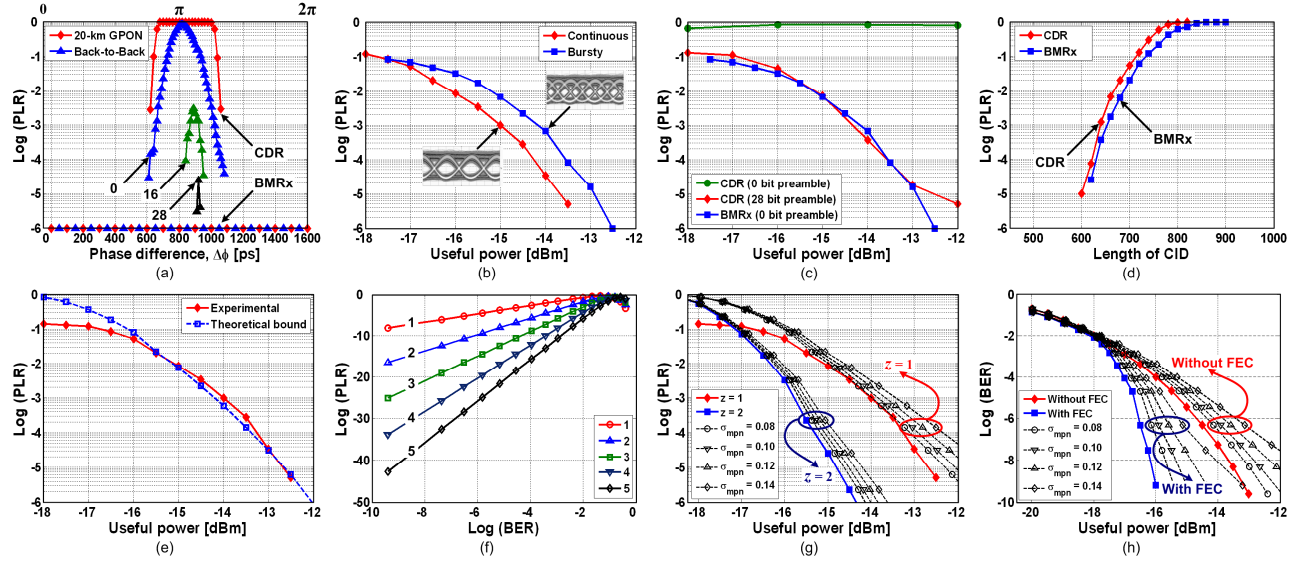


Fig. 2. (a) PLR vs. phase step for different preamble lengths. (b) Burst-mode penalty. (c) Preamble length penalty. (d) PLR vs. CID immunity. (e) Simulated vs. measured PLR. (f) PLR vs. BER performance as a function of pattern correlator error resistance. (g) Effect of MPN on PLR. (h) Effect of MPN on BER.

in a worst-case PLR  $\sim 1$  as shown in Fig. 2(c). However, if the 28 preamble bit specification is complied with, the PLR performance of the CDR is then comparable to the PLR performance obtained by the BMRx with zero preamble bits. Hence, there is a tradeoff between the power penalty with the BMRx oversampling when  $\Delta\varphi = 0$  rad, and the number of preamble bits required without the BMRx when  $\Delta\varphi \neq 0$  rad. Since phase steps in the GPON uplink are inevitable, the 1-dB power penalty may be a small price to pay than not receiving any packets. Fig. 2(d) shows the CID immunity of the BMRx. The receiver can support up to 600 CIDs with error-free operation, which is  $8\times$  more than the minimum 72 CIDs specified in G.984.2.

A delimiter of a packet that cannot be detected correctly will lead to the packet being lost. The error resistance of the delimiter depends not only on its length, but also on the exact implementation of the pattern correlator. If the pattern correlator has an error resistance of  $z$  bits in a  $d$ -bit delimiter, then the PLR at a given BER of  $p_e$  can be estimated as

$$\text{PLR} \leq \sum_{j=z+1}^d P(j) \text{ where } P(x) = \binom{d}{x} p_e^x (1-p_e)^{d-x} \quad (1)$$

and  $P(j) \approx P(z+1)$  for  $p_e \ll 1$ . Simulation versus measurement of the PLR performance is depicted in Fig. 2(e); the experimental results and theoretical predictions concur. The complexity of the pattern correlator depends on an acceptable error resistance of the delimiter. Fig. 2(f) shows the PLR performance as a function of the BER for various error resistance values of the delimiter. Even with a simple pattern correlator having  $z = 1$  bit error resistance, we obtain error-free operation at  $\text{BER} = 10^{-10}$ . Furthermore, by increasing the pattern correlator error resistance to  $z = 2$  bits, we obtain improvement in the PLR performance by eight orders of magnitude. In addition, we observe a coding gain  $\sim 2$  dB at  $\text{PLR} = 10^{-6}$  from Fig. 2(g)—compensating the 1-dB burst-mode penalty.

Current PON systems employ Fabry-Perot (FP) lasers at the ONU to minimize the cost per subscriber. However, the BER and the PLR performance of the system may be severely impaired by the MPN of a FP laser. Thus, G.984.2 proposes the use of FEC to reduce the associated penalty. To measure the impact of FEC on the optical link budget, we plot the BER performance with and

without FEC, as a function of the received signal power as shown in Fig. 2(h). We observe a coding gain of  $\sim 3$  dB at  $\text{BER} = 10^{-10}$ .

The power penalty caused by MPN in 1330-nm lightwave systems has been analyzed in [5]. Suppose the time average spectrum of the laser source is Gaussian, then the mean square variance of MPN  $\sigma_{mpn} = k/\sqrt{2}[1 - \exp(-\beta)^2]$ , where  $\beta = \pi BDL\sigma_s$ ,  $k$  is the mode partition coefficient,  $B$  is the bit rate,  $D$  is the fiber delay dispersion per unit length per unit wavelength,  $L$  is the fiber length, and  $\sigma_s$  is the spectrum width of the laser source. The resulting power penalty caused by MPN, is then  $\delta_{mpn} = -5 \log(1 - Q^2\sigma_{mpn}^2)$ , where  $Q$  is the effective signal-to-noise ratio determined by the BER  $p_e = 0.5 \text{erfc}(Q/\sqrt{2})$ . In Fig. 2(g) and (h), we plot the PLR and BER performance of the system as a function of  $\sigma_{mpn}$ , respectively. As expected, the system performance degrades with an increase in  $\sigma_{mpn}$ . The MPN penalty on the BER and PLR performance can be compensated by employing FEC and increasing the pattern correlator error resistance, respectively. Alternatively, the effective coding gain can be used to reduce transmitter power, increase receiver sensitivity, achieve a longer physical reach, or support more splits per single PON tree.

#### IV. CONCLUSION

We experimentally investigated the effect of channel impairments on the performance of a BMRx in a 622 Mb/s 20-km GPON uplink. Specifically, we performed PLR measurements and quantified it as a function of the phase steps between packets, signal power, CID immunity, BER, and MPN penalty, while also assessing tradeoffs in power penalty, preamble length, and pattern correlator error resistance. The receiver features instantaneous (0 bit) phase acquisition for any phase step ( $\pm 2\pi$  rads) between consecutive packets with a 1-dB power penalty. The BMRx supports up to 600 CIDs and accomplishes a 2-dB PLR and 3-dB BER coding gain. The experimental results are in line with the theoretical predictions.

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