

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.

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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 $|\Delta| = 2$ 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 ~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 2x oversampling mode. The CPA is tur-

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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 ~ 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 $\Delta = 0$ rad, and the number of preamble bits required without the BMRx when $\Delta = 0$ 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 8x 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

PLR <
$$\sum_{i=1}^{a} P(i)$$
 where $P(x) = \left(\frac{d}{2\pi} p_{i}^{x} (1 - p_{e})^{d-x} (1)\right)$

and P(j) 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 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 ~2 dB at 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 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 $_{mpn} = k/2[1 - exp(-)^2]$, where = BDL , 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 is the spectrum width of the laser source. The resulting power penalty caused by MPN, is then $_{mpn} = -5 \log (1 - Q^2 r_{mpn}^2)$, where Q is the effective signal-to-noise ratio determined by the BER $p_e = 0.5 \text{ erfc } (Q/$