Digital dual-rate burst-mode receiver for 10G and 1G coexistence in optical access networks

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Abstract: A digital dual-rate burst-mode receiver, intended to support 10 and 1 Gb/s coexistence in optical access networks, is proposed and experimentally characterized. The receiver employs a standard DC-coupled photoreceiver followed by a 20 GS/s digitizer and the detection of the packet presence and line-rate is implemented in the digital domain. A polyphase, 2 samples-per-bit digital signal processing algorithm is then used for efficient clock and data recovery of the 10/1.25 Gb/s packets. The receiver performance is characterized in terms of sensitivity and dynamic range under burst-mode operation for 10/1.25 Gb/s intensity modulated data in terms of both the packet error rate (PER) and the payload bit error rate (pBER). The impact of packet preamble lengths of 16, 32, 48, and 64 bits, at 10 Gb/s, on the receiver performance is investigated. We show that there is a trade-off between pBER and PER that is limited by electrical noise and digitizer clipping at low and high received powers, respectively, and that a 16/2-bit preamble at 10/1.25 Gb/s is sufficient to reliably detect packets at both line-rates over a burst-to-burst dynamic range of 14,5dB with a sensitivity of −18.5dBm at 10 Gb/s.

OCIS codes: (060.4510) Optical Communications; (060.4259) Networks, packet-switched.

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1. Introduction

To tackle the increasing bandwidth demand of access networks, Gigabit Ethernet Passive Optical Networks (1G-EPON) are already being deployed, and 10G-EPON has been recently standardized [1]. From an upgrade and cost point of view, such networks will need to support 10G and lower line-rates concurrently. This can be achieved in the downstream direction by using separated wavelength bands. However, in the upstream direction a burst-mode (BM) receiver capable of receiving multiple line-rates will be essential to terminate both 10G and legacy 1G users at the central office. In current PONs, analog BM receivers are typically used [2,3], however, these do not readily lend themselves to multirate operation. Nakagawa et al. [4] recently demonstrated a dual-rate receiver that uses two separate electrical front-ends for 10G and 1.25G and employs 8x oversampling for BM clock recovery. In this paper, we demonstrate for the first time a complete digital dual-rate burst-mode receiver (DDBMRx), using a DC-coupled PIN front-end, followed by a digitizer that samples the signal at the Nyquist rate for 10G and performs all the BM clock and data recovery (CDR) in the digital domain. This architecture has the advantage that the required sampling rate of the digitizer is only 20GS/s rather than the 80GS/s required in [4]. In addition the receiver employs clipping of the signal in the high power operating regime to increase the dynamic range of the receiver.

The paper is organized as follows. In section 2, we describe the hardware and software architecture of the DDBMRx and the experimental setup for optical packet generation. The operation of the DDBMRx in continuous-mode (CM) and BM is experimentally characterized in section 3 in order to optimize the digitizer range and offset values. Finally, the receiver performance is characterized in terms of both PER and pBER.

2. Digital dual-rate receiver design and experimental setup

2.1 Digital dual-rate receiver description

The DDBMRx, shown in Fig. 1(a), consists of a DC-coupled PIN photodiode with integrated transimpedance amplifier (TIA), and is followed by a Tektronix DPO72004 scope used as digitizer. There is no electrical filtering between the TIA and the digitizer to maintain the maximum signal bandwidth and thus minimize the penalty introduced by signal clipping at high input powers. The first DSP step was to precondition the captured signal by ideally resampling from the scope imposed sampling rate of 25GS/s to 20GS/s (the Nyquist rate at 10G). This and all subsequent DSP is done offline with MATLAB.

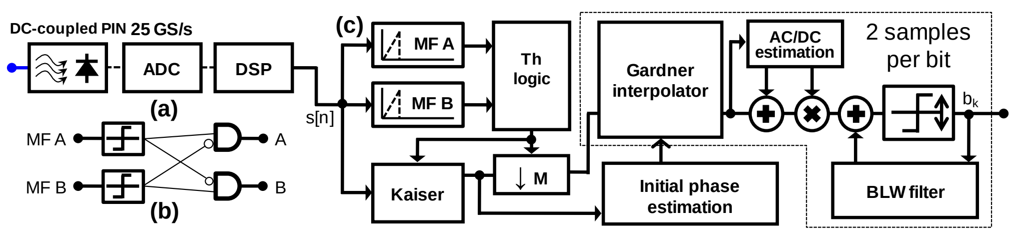

Fig. 1. (a) Experimental receiver. (b) Threshold logic detailed diagram. (c) DDBMRx architecture.

The digital dual-rate receiver architecture is presented in Fig. 1(c). The two principal functions a digital multirate receiver must carry out are, firstly, detect both the presence and the line-rate of incoming optical packets, and secondly, perform CDR (and possibly other impairment mitigation such as correcting for base-line wander (BLW)). Our approach follows a polyphase design, in which the first function is carried out at 20 GS/s independently of the incoming line-rate, whilst the second is always done at 2 samples-per-bit for all line-rates. The packet and line-rate detection is realized with two complex matched filters (MFs) whose outputs are fed to a digital threshold-logic block. We chose a preamble of alternating ones and zeros which produces a spectral component at a frequency of half the line-rate. Thus, the MF kernels consist of the appropriate discrete-time Fourier coefficients at 5GHz and 0.625GHz

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for 10G and 1.25G line-rates, respectively. By exploiting the orthogonality of these frequencies among different line-rates, the output of the MF matched to the incoming packet is maximized, whilst the output of the other MF is minimized [5]. The digital threshold-logic block, depicted in Fig. 1(b), uses this property and detects an incoming packet/line-rate only if one MF output is high and the other low. For simplicity, in this work an 800 ps threshold window centered about the MF peak was used when obtaining the PER measurements. This window length was chosen to be half of the 1.6 ns separation between the undesired periodic peaks in the unmatched output of the 10G MF [5]. However, in practice to remove the need for precise timing information at the receiver, the peak output from the MF would be determined using a peak search algorithm and the threshold logic applied at this point. The output decision from the presence and line-rate detector controls a programmable resampler, consisting of an anti-aliasing Kaiser filter followed by a decimator. Inside the dotted line in Fig. 1(c) is the CDR section, which works at 2 samples-per-bit independently of the line-rate. Firstly, the incoming samples are interpolated using the linear Gardner algorithm [6]. The phase delay for the interpolator is estimated using the 2 sample-per-bit algorithm described in [7] for 10G, and [8] for lower line-rates where 16 samples per bit are available, thus increasing the robustness of the receiver. After the interpolator, the packet offset and amplitude is estimated in order to normalize the interpolated samples. In all cases, the estimation is done over a range of 128 bits, independently of the line-rate. This estimation length is equal to the PRBS period, and thus the number of ones and zeros are balanced to ensure that the results are not biased. After this stage, a BLW correction coefficient is added, and samples are sliced using a variable-threshold decisor [9].

2.2 Experimental setup description

Figure 2(a) shows a diagram of the experimental setup used to simulate two optical network unit (ONU) transmitters, labeled A and B, in a dual-rate PON. It consists of two DFB lasers, which are coupled together with a 50/50 coupler and externally modulated using a single Mach-Zehnder modulator. The DFB laser currents are independently driven with rectangular pulses to generate optical packets of 1.63μs duration. Optical attenuators in each branch allow the transmit power of each ONU to be varied. Whilst in practice each ONU transmitter would be modulated independently, which could have an impact on the orthogonality of the preambles, as a result of transmitter clock frequency drift, and extinction ratio variations, in this work a single modulator is used to modulate both lasers to ensure that the performance of the transmitters is identical.

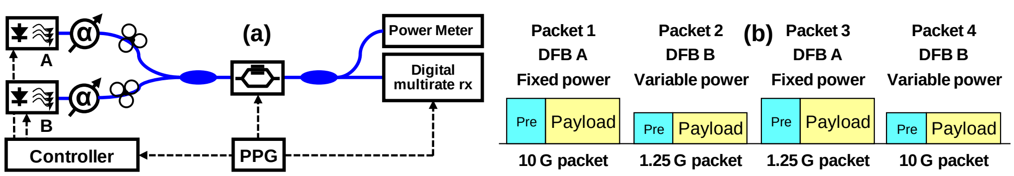

Fig. 2. (a) Experimental setup for generating optical packets. (b) Diagram of the generated optical packets.

The generated optical signal, shown in Fig. 2(b), consists of 4 optical packets, each having a 6.4ns preamble followed by a 1.47μs payload, and a 153.6ns gap band, which correspond to 64/8, 14784/1848 and 1536/192 bits at 10/1.25G, respectively. The PPG is programmed to produce a repeating packet sequence consisting of a 10G packet followed by two 1.25G packets and then a 10G packet, labeled packet 1-4, respectively. When characterizing the receiver, packets 1 and 3, generated by branch A, are set to have a constant power of −18.5dBm, corresponding to the 10G sensitivity of the receiver at a BER = 10^{-3}, while packets 2 and 4, generated by branch B, are swept over a range from + 2.5dBm to −30dBm.

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3. Receiver experimental characterization

The key performance requirements of a BM receiver are the sensitivity and packet-to-packet dynamic range. In order to fully explore these requirements the DDBMRx was characterized in terms of both pBER and PER, as a function of the optical received power, where the PER is defined as the probability of incorrectly detecting the arrival and/or line-rate of a packet. In previous work [9], we have shown that the sensitivity and dynamic range of an AC-coupled digital BM receiver is limited by the resolution of the digitizer to about 7dB when the received signal is maintained within the digitizer range. In this work we look to increase the dynamic range by letting the high power or loud packets exceed the range of the digitizer such that they are nonlinearly clipped by the digitizer. This clipping technique necessitates the use of a DC-coupled receiver front end, to avoid BLW which would result in the complete loss of part of the packets, and thus the performance of the receiver will depend not only on the digitizer range but also on the digitizer DC offset.

To investigate the optimum digitizer range and offset we, firstly, characterized the impact of the digitizer range (in mV) on the sensitivity of the digital receiver under CM operation for 10G and 1.25G line-rates. Secondly, we assessed the pBER in a BM experiment, using the optimum range obtained in the previous step, and assessed the impact of the digitizer offset due to residual BLW. Once the optimal range and offset has been determined it is then necessary to optimize the packet and line-rate detector thresholds in order to maximize both the sensitivity and dynamic range. Finally, the packet and line-rate performance of the digital receiver is characterized when the packet and line-rate detector thresholds are optimized to match the payload to a sensitivity equal to BER = 10^{-3}.

3.1 Digital receiver continuous-mode characterization

Using one of the branches of the setup shown in Fig. 2(a), we generated a set of continuous bit streams, each having 100 kSamples. The optical power was swept from + 2.5 to –30dBm in 1dB steps. The traces were processed with the same digital receiver described in section 2.1 without the burst and line-rate detection section. Figure 3(a) shows the BER characterization for 10G and 1.25G, for digitizer ranges of 100, 200, 300 and 400 mV.

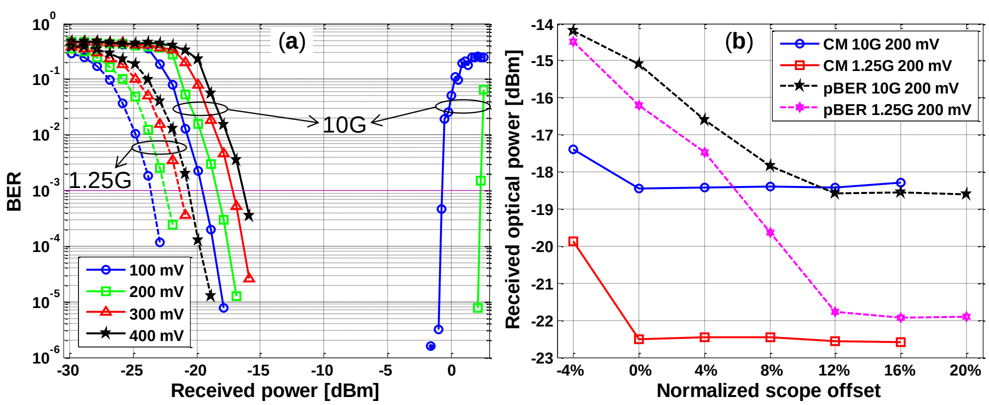

Fig. 3. (a) CM sensitivity and overshoot as a function of received power for digitizer ranges of 100, 200, 300, and 400 mV. (b) Receiver sensitivity for a BER = 10^{-3} and a digitizer range of 200 mV as a function of the normalized scope offset under continuous and burst operation.

For both line-rates, we observe, as expected, an increased sensitivity for lower digitizer ranges. In addition, due to digital filtering of out of band noise by the Kaiser filter, there is an extra sensitivity gain of 4.06dB for the 1.25G line-rate. PON receivers operate in a loss limited regime and are dominated by the electrical Johnson-Nyquist noise of the photodiode + TIA and the electrical noise of the digitizer [10], and so the Q-factor is inversely proportional to the square root of the bandwidth for a constant received optical power, thus for the 1.25 G

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signal where the filter bandwidth is reduced by 8 times a theoretical sensitivity improvement of 4.51dB is expected. Figure 3(a) also shows the receiver performance degradation that occurs at high powers due to clipping of the signal as the input signal power significantly exceeds the range of the digitizer. This effect is shown to occur at an input power of −1dBm for the 100mV range and 2dBm for the 200mV range. We note that for the 100 and 200mV ranges the onset of clipping occurs at received powers of −9 and −6dBm, respectively. Thus, clipping increases the dynamic range by 8dB under CM operation. As a result of the reduced bandwidth requirements for the 1.25G signal the effects of clipping on the receiver performance are not observed up to the maximum received power of 2.5dBm that was used in this experiment. As a compromise between sensitivity and dynamic range, we chose to use a digitizer range of 200mV for the subsequent experiments which gives rise to a sensitivity and dynamic range of −18.5dB and 20.5dB, respectively.

3.2 Payload BER performance and digitizer offset optimization

Given a fixed digitizer range chosen to meet a particular sensitivity, the digitizer DC-offset should be optimized in order to minimize the receiver clipping at high received powers whilst allowing for error free operation at low powers. In addition, the DC-coupled receiver introduces a small BLW when operating in BM which will affect the performance for low power bursts. In order to both quantify this penalty and to optimize the digitizer offset, the pBER was measured in BM operation by capturing a trace containing the worst case in terms of residual BLW, that is, a high-power packet followed by a low-power packet. In order to neglect effects that may arise from packet detection in this experiment the pBER of the variable-power packets was measured by simply chopping out the payload using the known packet timing. The payload amplitude and offset was then determined by averaging across the entire payload in order to get the best possible estimation of these values.

Figure 3(b) shows the sensitivity of the variable-power packet, in CM and BM, defined as the required received power for a BER/pBER better than 10^{-3}, for a digitizer range of 200 mV. A normalized offset of 0% corresponds to setting the offset equal to the bottom rail of the digitizer, with negative values falling below the screen. The impact of BLW under BM operation is minimized if the offset is chosen to be 12% or higher. Under BM operation, the 10G performance is equivalent to the continuous performance, however, at 1.25G a degradation of 1dB with respect to the continuous performance is observed as a result of BLW. The BLW compensator updates at the baud rate and thus the tracking performance depends on the ratio of the baud rate to the associated BLW time constant which is the same for both line-rates and thus is not as effective at lower line-rates.

3.3 Packet and line-rate detector performance

Figure 4(a) shows the average MF output for matched and unmatched packets, corresponding A to 10Gb/s and B to 1.25Gb/s, as a function of the input packet power for packet header lengths of 16, 32, 48 and 64 bits at 10Gb/s. As expected, for a normalized MF the matched output is independent of both the line-rate and the header length, so here we show the averaged result for clarity. For the unmatched outputs we only show the output of the 10G MF when a 1.25G packet is input as this represents the worse case performance, as the 1.25G MF output when a 10G packet is input is always lower. Firstly, we see that increasing the header length reduces the noise floor of the unmatched output as the longer correlator more effectively filters out the noise. Secondly, we observe that signal clipping in the digitizer, which occurs for input powers greater than −6dBm (as indicated by the grey shaded region) significantly affects the 10G line-rate detector performance. This occurs because the nonlinear clipping process generates harmonics of the clock tone that the correlator is detecting, and particularly affects the performance of the 10G MF as the 8th harmonic of the 1.25G preamble matches that of the 10G MF.

The packet and line-rate detector described in section 2 requires optimization of the two thresholds after each MF in order to maximize the sensitivity and dynamic range of the

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receiver. To achieve this it is first necessary to choose a soft power-level (P_{low}) for the matched burst and a loud power-level (P_{high}) for the unmatched burst and then using the mean and variance of the correlator outputs at these two power levels the optimal threshold can be calculated using Eq. (4.5.9) in [11]. Once the thresholds are determined then the packet receiver performance can be characterized in terms of PER and pBER. An example of this is shown in Fig. 4(b), where we define the PER sensitivity as the lowest received power where no errors were recorded, the PER overshoot as the highest received power where errors start, and the PER dynamic range as the difference of these two points. In this work the PER is estimated using 2048 packets which results in a packet error in the interval [2.5×10^{-3}, 4×10^{-4}] with 95% confidence.

To investigate the impact of the choice of optimization powers on the receiver performance we scanned all possible combinations of P_{high} and P_{low} on a 1dB grid, and then, firstly, chose only those that met the sensitivity criteria (in this case a sensitivity better than −20dBm to ensure that the PER performance exceeds that of the pBER) and, secondly, chose the points, from this first subset, that maximized the dynamic range. The best performance using this exhaustive search was a PER sensitivity of −23dBm and a dynamic range of 19dB for a preamble of 64 bits at 10G. Figure 4(a) shows that the PER sensitivity may be improved by increasing the preamble length, however we find that the PER overshoot is limited by clipping regardless of the preamble length as a result of the nonlinear harmonics generated by the clipping process. Thus, we find that a 16 bit preamble, at 10G, is enough to reliably detect the packet line-rate over a 16dB dynamic range, and an overall dynamic range of 14.5dB with a guaranteed pBER better than 10^{-3}.

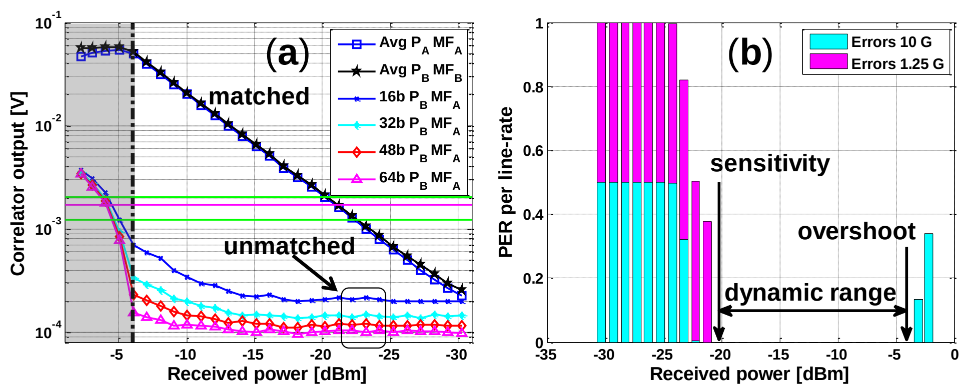

Fig. 4. (a) Average MF output at the optimum time sampling point. (b) PER for $L_{high} = -4.02$ dBm and $L_{low} = -20.19$ dBm and a preamble of 64 bits.

4. Conclusions

A digital dual-rate burst-mode receiver suitable for 10G-EPON and 1G-EPON coexistence has been developed. The PIN based receiver provides a sensitivity of −18.5dBm at 10Gb/s for a pBER = 10^{-3} and shows a 4.06dB sensitivity gain when receiving 1.25G line-rates. Clipping has been used to increase the burst-to-burst dynamic range to 20.5dB in CM, an 8dB improvement over that when clipping is not used. Under BM operation a digitizer offset of 12% is required to minimize the penalty that arises from residual BLW and results in a penalty of 0dB at 10G and 0.6dB at 1.25G compared to continuous operation.

Clipping introduces an upper limit on the received power that is independent of the preamble length as a result of nonlinearly generated harmonics which degrade the performance of the packet presence and line-rate detector. Nevertheless, the combination of both DC-coupling and clipping offers a significant improvement in terms of dynamic range for a given digitizer resolution. Hence a 16/2 bit preamble for 10/1.25G line-rates is sufficient

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to reliably receive dual-rate optical packets at a pBER better than 10^{-3} over a 14.5dB dynamic range using a digitizer range of 200mV and 5 effective bits of resolution.

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