High-Performance Preamble Design and Upstream Burst-Mode Detection in 100 -Gb/s/λ TDM Coherent-PON

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Abstract: We propose robust, high-efficient preamble design and signal processing for upstream burst-mode detection in 100-Gb/s/λ TDM Coherent-PON. Using a 71.68-ns preamble, we achieve 36-dB power budget after50-km SMF and 20-dB dynamic range. ©2020 The Author(s)

1. Introductions

Driven by 5G mobile Internet, cloud networking, and HD video streaming services, the bandwidth requirements in optical access network have grown tremendously in recent years. It is envisioned that 25/50 Gb/s and even 100 Gb/s PON will be required [1-5]. However, 100G PON via wavelength multiplexing and IM/DD of four 25 Gb/s or two 50Gb/s channels are viewed as too challenging due to limited power budget and complicated wavelength resource management [1-2]. To solve these problems, 100-Gb/s single wavelength TDM coherent PON is an atttractive solution. Thanks to the high sensitivity and the advancement of digital signal processing (DSP), coherent PON can provide much higher access capacity and longer coverage reach [2-5]. However, there are still several challenges and one of the key issues is how to efficiently and robustly achieve upstream burst-mode coherent detections [3].

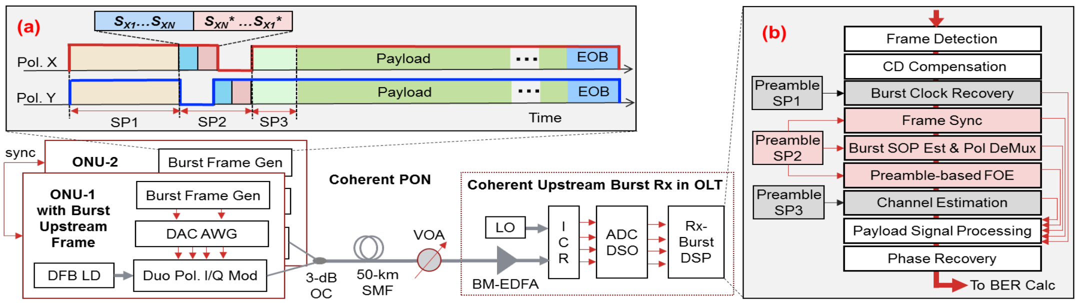
Conventional continuous-mode coherent detection used in point-to-point links, which is mainly based on blind or feed-back type equalizations, is not suitable for burst-mode detection as it takes long acquisition time for signal recovery [5-6]. Several studies have been reported to solve this issue by using special designed preambles. For instance, 20-Gbps QPSK coherent burst-mode detection with fast state-of-polarization (SOP) estimation is realized by 1.3-us preamble [3]; fast I/Q imbalance compensation is demonstrated for 100G PDM-QPSK burst detection with 826-ns preamble [4]. However, there are few studies on the overall preamble design, burst-mode signal processing performance and most importantly preamble length reduction and optimization for 100G TDM coherent PON.

In this paper, we propose and demonstrate robust, high-efficient preamble design and burst-mode DSP for the coherent upstream burst-mode detection in 100-Gb/s/λ TDM Coherent-PON. The preamble length is reduced by sharing the preamble unit for multiple DSP functions. We also confirmed the robust performance in large frequency-offset and long-time running. Using preamble of only 71.68-ns, we achieve coherent upstream burst-mode detection of 100Gb/s PDM-QPSK with 36-dB power budget after 50-km SMF transmission, with 20-dB dynamic range.

2. Experimental Setup, Preamble Design Principle, and Data-aided Burst-Mode Signal Processing

Fig. 1 shows the experimental setup of coherent upstream burst detection in 100-Gb/s/λ TDM coherent PON. To evaluate the performance of upstream burst signal detection, two synced ONUs are running separately. At the ONU-side, the burst frames of 25-GBaud PDM-QPSK are generated by the 80-GSa/s arbitrary waveform generators (AWGs), and then fed into the dual-polarization I/Q modulators for signal modulation. Here, we use a tunable DFB laser at 1550-nm wavelength with a linewidth of ~1-MHz as the laser source. After modulation, the burst signals from ONU-1 is combined with a dummy signal from ONU-2 by a 3-dB optical coupler (OC). To avoid collision, the burst frames from two ONUs with same setup are staggered. Through the automatic bias-control, the burst signal from one ONU is only coupled with the null signal from the other ONU. The combined burst signals are then transmitted over 50-km single-mode fiber. The received optical power is controlled by a variable optical attenuator (VOA) for BER test. At the OLT-side, a burst-mode EDFA is used for signal pre-amplification. The pre-amplified signal is mixed with local oscillator (LO) in an integrated coherent receiver (ICR) for coherent detection. A tunable external-cavity-laser (ECL) at 1550m-nm is used as LO in OLT, and its linewidth is < 100-kHz. After coherent detection, the received signals are sampled by an 80-GSa/s scope and then processed via offline burst-mode DSP.

The upstream frame structure with designed preamble for burst transmission is shown in Fig. 1 (a) and the corresponding burst-mode DSP is shown in Fig.1 (b). The overall DSP flow is designed in feed-forward structure to reduce the processing latency and shorten the burst preamble length. Following the non-data-aided chromatic dispersion (CD) compensation, five essential data-aided DSP functions are performed as shown in Fig. 1 (b) based on three sync patterns (SP) SP1, SP2 and SP3. Here, SP1 is used for burst-clock-recovery (and additional burst gain control if needed) based on DC-balanced, state near-equally distributed QPSK symbols. Correspondingly, the fast square-timing-recovery algorithm [7] is applied based on received symbols within SP1 section.



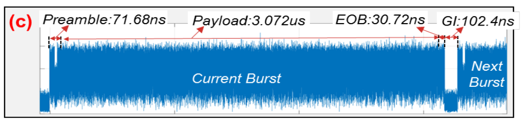


Table I. Summary of Preamble Type, Length and Functions

Preamble	Length (Symbols)	Functions
SP1	1024	Burst Clock Recovery
SP2	512	Frame Sync, Pol DeMux, FOE
SP3	256	Channel Estimation

Fig. 1 The experimental setup, with (a) the preamble design for dual polarization upstream burst frame, including three sync-patterns SP1, SP2 and SP3; (b) the burst-mode DSP at the OLT; (c) the detailed configuration of burst frame and Table I summary of preamble.

In our designed preamble structure, the most notable unit is SP2, which is specially designed to perform three key data-aided DSP functions, including frame synchronization, SOP estimation and frequency-offset estimation (FOE). Therefore, the overall preamble length is reduced by sharing the same preamble unit. Here, $4N$ symbols are used in SP2, including $2N$ conjugate symmetric symbols and $2N$ zeros on each polarization. As such, the pattern [$\boldsymbol{S_X}$, $\boldsymbol{0}$; $\boldsymbol{0}$, $\boldsymbol{S_Y}$] is transmitted. Here, $\boldsymbol{S_X}=[s_{x1},...,s_{xN}, s_{xN}^*,...,s_{x1}^*]$, and $\boldsymbol{S_Y}=[s_{y1}...s_{yN}, s_{yN}^*,...,s_{y1}^*]$. Accurate frame synchronization is realized by a sliding window with auto-correlation process. Here we propose a combining scheme to improve the tolerance to polarization rotations:

$$C_{x,y}(m)=\sum_{k=0}^{N-1} r_{x,y}(m+k) r_{x,y}(m+2N+k-1)/P_{total}\,,\ C(m)=W_x C_x + W_y C_y \qquad (1)$$

here, [$\boldsymbol{r_x}$;$\boldsymbol{r_y}$] are the received signals from X and Y polarization. $\boldsymbol{C_x}$ and $\boldsymbol{C_y}$ are normalized auto-correlation function on each polarization, and $\boldsymbol{C(m)}$ is the combined function for peak search. W_x and W_y are defined as the power ratio of each polarization. For instance, $W_x=P_x/(P_x+P_y)$. By doing so, the exact location of the SP2 symbols is found from the received signal. Assuming [$\boldsymbol{r_{x1}},\boldsymbol{r_{x2}}$;$\boldsymbol{r_{y1}},\boldsymbol{r_{y2}}$] are the received SP2 symbols, the SOP can be instantly estimated from the received SP2 symbols. Extending the single polarization case in [3], the inverse Jones Matrix can be estimated as

$$H=[\sqrt{\alpha_2}e^{-j\gamma_2},\sqrt{(1-\alpha_2)}\ ;-\sqrt{(1-\alpha_1)},\sqrt{\alpha_1}e^{j\gamma_1}] \qquad (2)$$

here, $\alpha_1=|\boldsymbol{r_{x1}}|^2/(|\boldsymbol{r_{x1}}|^2+|\boldsymbol{r_{y1}}|^2)$, $\gamma_1=arg(\boldsymbol{r_{x1}}/\boldsymbol{r_{y1}})$, and a_2 and γ_2 can also be obtained by the second half SP2 symbols.

Based on the inverse of Jones Matrix, polarization demultiplexing is performed. After separating the two polarizations, frequency-offset is estimated based on the training symbols in SP2. To achieve fast and accurate FOE, the maximum likelihood (ML) criteria FOE algorithm [8] is modified by taking into two-polarizations to estimate the carrier frequency-offset. Finally, SP3 is designed with QPSK symbols for channel estimation based on constant modulus algorithm (CMA) in DSP [6]. All information obtained from preamble is then applied to the following payload process, which would greatly simplify the payload demodulation process and reduce the convergence time. After phase recovery, the BER calculation is applied to measure the performance.

The detected power waveform of burst frame is shown in Fig. 1(c) with the detailed configuration, and the summary of preamble unit length and functions is shown in Table I. SP1, SP2 and SP3 have 1024, 512 and 256 symbols, respectively. Therefore, each burst frame contains a total preamble length of 71.68 ns (1792 symbols), a payload of 3.072µs, an end of burst (EOB) of 30.72 ns. A guard interval time of 102.4 ns is used to separate bursts.

3. Experimental Results

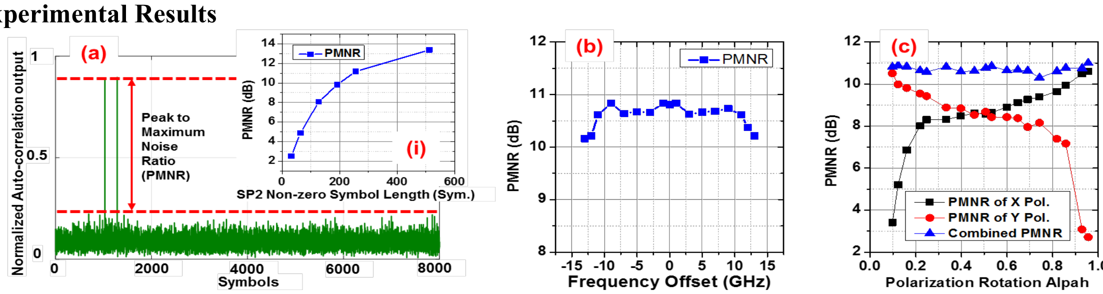


Fig. 2 (a) the normalized auto-correlation output for peak search; (b) PMNR vs frequency-offset; (c) PMNR vs polarization rotations; inset (i) the PMNR vs SP2 non-zero symbols length.

We test the performance of preamble unit SP2 for frame synchronization, SOP estimation and FOE, respectively. The performance of frame synchronization is shown in Fig. 2. Fig. 2(a) shows the combined auto-correlation $\boldsymbol{C(m)}$.

The sync-peak locations represent the start of non-zero SP2 symbols in the received signals. The peak-to-maximum-noise ratio (PMNR) is defined here to show the quality of sync-peaks compared with noise peaks. The PMNR versus training symbol length is shown in inset (i). It is seen that 256 non-zero symbols per polarization in SP2 (in total 512 symbols in SP2 with 256 zeros) provide over 10-dB PMNR, showing very high-quality peaks. The PMNR tolerance to large frequency-offset is also verified from the results in Fig. 2(b). Over 10-dB PMNR can still be achieve with 25GHz offset range (-12.5 to 12.5 GHz). The tolerance to polarization rotation is confirmed from results in Fig. 2(c). The PMNR from one polarization is polarization-dependent, however, the combined PMNR is independent.

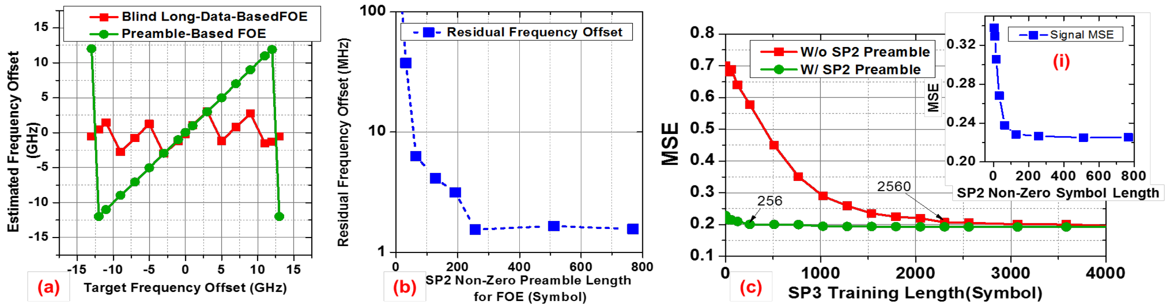


Fig. 3. The results of (a) estimated frequency offset v.s target frequency offset; (b) residual offset v.s. SP2 non-zero symbols length; (c) MSE v.s. SP3 length. Inset (i) MSE v.s. SP2 non-zero symbols length

The FOE performance of proposed preamble and DSP scheme is shown in Fig. 3 (a). It is seen that our proposed preamble-based FOE method outperforms the blind long-data based method with much larger estimation range from -12.5 to 12.5 GHz. Here blind FOE using 2500 symbols, while we only use 512 SP2 symbols. The performance of FOE versus the SP2 non-zero training symbol length is depicted in Fig. 3(b). We confirm that 256 non-zero symbols per polarization in SP2 would be accurate enough to achieve <2-MHz residual offset. The performance of SOP estimation as well as its impact on the required SP3 symbol length for channel estimation is shown in Fig. 3 (c). Without SP2 for SOP estimation, the CMA process for channel equalization needs long convergence time. By using proposed method for SOP estimation, we reduce the convergence time (SP3 training symbols) from 2560 symbols to only 256 symbols. We also confirm the required SP2 symbols for SOP estimation as shown in inset (i) of Fig. 3. It is also seen that 512 symbols (256 non-zero symbols) in SP2 on each polarization would be accurate enough.

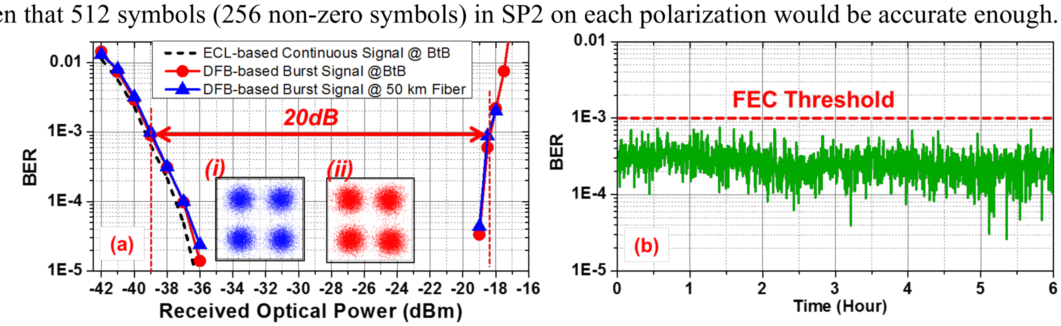


Fig. 4. The BER performance versus the received optical power; (b) the long-term BER test over time up to 6 hours.

The signal BER performance with received optical power is shown in Fig. 4 (a). After 50-km fiber transmission, the require optical power at average BER of 1×10^{-3} is -39 dBm, and the constellations at -39 dBm are shown here. There is less than 0.3-dB penalty for DFB laser-based burst signal compared with ECL-based continuous signals in ONU-side. Without changing the receiver setup in OLT-side (same BM-EDFA current and ICR setup), about 20-dB dynamic range of received power is verified for burst signals. Finally, the BER performance is tested in long-term running. Here 1-dB margin is reserved while the received optical power is fixed at -38 dBm. The BERs in 6-hour running are all below the FEC threshold of BER at 1×10^{-3}. The stability of upstream burst-mod coherent detection is confirmed. With -2-dBm output power from ONU, the achieved power budget is 36 dB (1-dB margin included).

4. Conclusions

We propose a robust, high-efficient preamble structure and burst-mode signal processing for upstream detection in 100-Gb/s/λ TDM Coherent-PON. The preamble length is reduced by sharing the preamble unit for multiple DSP functions. Using a 71.68-ns preamble, we achieve 36-dB power budget after 50-km SMF and 20-dB dynamic range.

5. References

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