Symmetric 2.5 Gb/s RSOA-Based WDM-PON with Electronic Equalization and Overlapped-Subcarrier Multiplexing

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***Abstract*—The performance benefits of electronic equalization are investigated in a symmetric WDM-PON architecture using 100% overlapped-SCM and a bandwidth-limited RSOA. A power budget improvement of $\sim 4.5\,\mathrm{dB}$ is demonstrated for error free operation at realistic launch powers.**

I. Introduction

To meet the increasing bandwidth demands of consumer Internet traffic, it is well accepted that the progression toward wavelength-division multiplexing (WDM) in access networks is the most promising step for next-generation passive optical network (PON) deployments. To ensure the success of WDM on PONs, colourless optical network units (ONUs) are essential to reduce the cost and complexity of transceivers at the customer premises [1]. The reflective semiconductor optical amplifier (RSOA), which can be seeded with either continuous wave light or simply the downstream signal, is one of the most investigated candidates for this purpose.

In a single feeder configuration, radio-frequency (RF) subcarrier multiplexing is a simple and low cost means to reduce the severe impact of Rayleigh backscattering on the PON's performance [2]. The authors' previous research demonstrated an overlapped-subcarrier multiplexing (O-SCM) technique that mitigates these effects while maximizing spectrum use in bandwidth-limited ($\sim 2\,\mathrm{GHz}$) RSOAs [3]. In the literature, a number of techniques have proven successful at further increasing the transmission bit rate, such as the use of complex modulation formats, narrow optical filters, device optimization (i.e. increasing length of gain channel), integrated modulators, and electronic equalization [4]–[8]. Accounting for the system's cost and complexity, electronic equalization with digital signal processing (DSP) was selected for this investigation as the most practical approach to increase the modulation bandwidth of the commercially available RSOA.

II. Overlapped Subcarrier Multiplexing with Electronic Equalization

A. Physical Architecture

The WDM-PON architecture used existing infrastructure constraints, and is illustrated in Fig. 1. At the optical line terminal (OLT), the transmitter consisted of an electro-absorption modulated laser (EML) centred at $1549.36\,\mathrm{nm}$ and directly modulated at $2.5\,\mathrm{Gb/s}$ with a $2^{15}-1$ nonreturn-to-zero (NRZ) pseudo-random binary sequence (PRBS) with an extinction ratio (ER) $\sim 2.4\,\mathrm{dB}$ $(1\,\mathrm{V_{p-p}}, V_{off} = -0.25\,\mathrm{V}, I_D = 50\,\mathrm{mA})$. Following the EML, a booster EDFA and VOA controlled the launch power for the subsequent measurements. At the ONU, a $70/30$ coupler tapped off the received downstream signal while the remainder seeded the RSOA [3]. The RSOA, biased at $3.35\,\mathrm{V}$, was directly modulated with a $2.5\,\mathrm{Gb/s}$ up-converted $(f_{sc} = 2.5\,\mathrm{GHz})$ PRBS-based bit sequence with $4\,\mathrm{V_{p-p}}$ $(ER \gg 2.4\,\mathrm{dB})$. Due to the RF up-conversion, $\sim 5\,\mathrm{GHz}$ of the RSOA's modulation bandwidth was used. The OLT receiver comprised an optical bandpass filter $(BW = 0.4\,\mathrm{nm})$, a *p-i-n* photoreceiver, RF down-conversion circuit, and a low pass filter $(BW \sim 1.875\,\mathrm{GHz})$.

B. Offline Processing Approach

The electronic equalization of the upstream signal using offline DSP was facilitated by a real-time oscilloscope (Agilent: DSA90804A) which captured the bit sequences at $4\,\mathrm{Sample/bit}$ to a maximum of $20.5\,\mathrm{MSample}$. The inset of Fig. 1 illustrates the data frame sequence's structure. To begin, a $2^{23}-1$ PRBS was generated and segmented into 16 frames $311,500$ bits in length. We placed a replica of the first $1000\,\mathrm{bits}$ at each frame's beginning to create a unique preamble, thus allowing us to identify each frame in the received sequence using cross-correlation. The preamble size was selected to be large enough to maintain the uniqueness for cross-correlation, but smaller than $1024\,\mathrm{bits}$ to reduce the memory footprint of the calculations. This preamble size results in $\sim 0.3\%$ overhead, which we considered acceptable. The total frame size of $312,500\,\mathrm{bits}$ at $2.5\,\mathrm{Gb/s}$ is compatible with the $125\,\mu\mathrm{s}$ upstream frame duration in existing gigabit-capable PON (G-PON) standards [9].

The technique provides two advantages: (1) each frame can be uniquely identified and extracted from the received sequence to facilitate the use of training symbols; (2) each frame's start can be resynchronized for a comparison with the transmitted bits, analogous to clock-synchronization in deployed G-PON systems. A 16 frame set ensured that at least 15 complete frames were recorded within the maximum memory of the real-time scope. After the received frames were aligned and extracted, the $1000\,\mathrm{bit}$ preamble was removed with the incomplete frame in order to maintain the statistical significance of the $2^{23}-1$ PRBS. The system's performance

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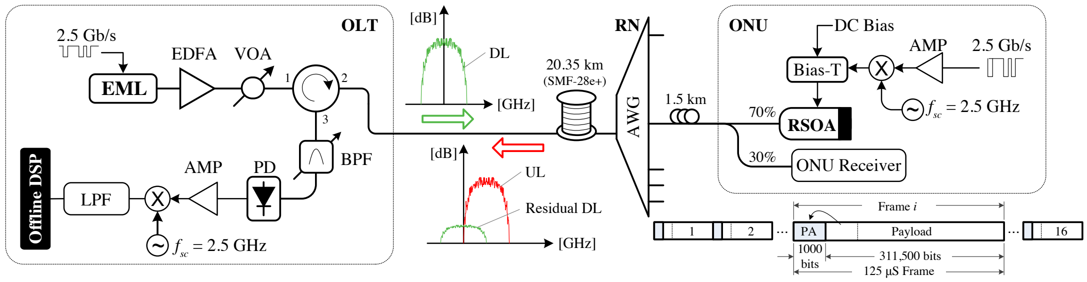

Fig. 1. Experimental setup. (AMP: amplifier, AWG: arrayed waveguide grating (100 GHz), BPF: 0.4 nm band pass filter, DC: direct current, DL: downlink, EDFA: erbium-doped fiber amplifier, f_{sc}: subcarrier frequency, EML: electro-absorption modulated laser (CyOptics E4560), LPF: low pass filter, PA: preamble, PD: photodiode, RF: radio frequency, RN: remote node, UL: uplink, VOA: variable optical attenuator). Mixers: Marki Microwave M10208MP. Inset: Each of the 16 transmitted data frames was composed of a 1000 bit preamble and a 311, 500 bit payload.

was measured using quality (Q) factor rather than bit-error rate (BER) because the captured sequence's length was limited to $\sim 4.67 \times 10^6$ bits.

III. Results and Discussion

The recorded data was first analyzed by optimizing the bit sampling point and threshold voltage, and accomplished by minimizing the number of detected errors when compared to the transmitted sequence. The Q factor was calculated at this sampling location using the mean and standard deviation of the bit level histograms [10].

The smooth roll-off of the RSOA's frequency response coupled with its linear modulation response make it ideal for electronic equalization using a decision-feedback equalizer (DFE) [8], [11]. To perform the offline DSP, we used a quarter-symbol-spaced DFE with 16 forward and 2 backward taps. These tap numbers were deemed optimal for the launch power range of interest. Analogous to a system startup, the initial tap weights were set using a training sequence of received data one frame in length. The tap values were dynamically adjusted using the least-mean squared adaptive algorithm throughout the equalization stage [11]. After equalization the Q factor was calculated using histograms, as described above.

The Q factor improvement from electronic equalization is demonstrated in Fig. 2. At launch powers greater than 0 dBm, the equalization process created a significant Q factor improvement. Furthermore, at launch powers below the 10^{-3} forward-error correction (FEC) threshold, the signal to noise ratio appeared to be too low to show any appreciable gain from the DSP. Using the BER threshold of 10^{-10}, the equivalent error free launch power after equalization was $\sim$ 2.1 dBm, demonstrating a launch power reduction of $\sim$ 4.5 dB as compared to the unequalized case. The additional margin in the power budget could potentially increase capacity and/or extend the reach of the PON. The link margin could further increase through FEC code use, which will be mandatory in next-generation PONs.

IV. Conclusion

In this investigation we demonstrated a symmetric 2.5 Gb/s RSOA-based bidirectional WDM-PON with electronic equalization and 100% O-SCM on the upstream signal. Through the use of electronic equalization at the OLT receiver, we demonstrated a power budget increase of 4.5 dB, allowing for an error free uplink transmission with realistic launch powers of 2.1 dBm over a 20.35 km feeder without FEC use. Future investigations will focus on increasing the data bit rate and reducing the sampling frequency closer to the Nyquist rate.

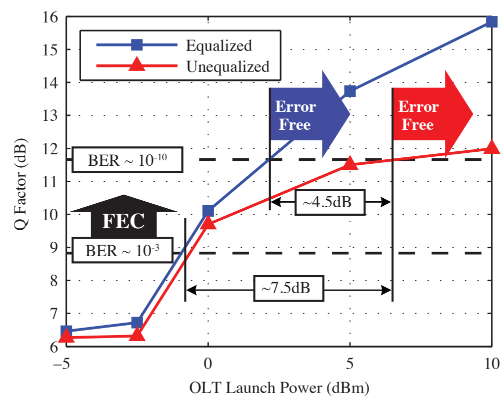

Fig. 2. The Q factor of the upstream data sequence for various OLT launch powers before (red) and after (blue) electronic equalization. Equivalent Q factor thresholds for BER rates of 10^{-10} (error free operation) and 10^{-3} (FEC) were determined through system characterization. A 4.5 dB benefit from equalization was found for error free operation, which could be further increased by > 7 dB using FEC codes.

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