Symmetric Long-Reach 16-QAM Transmission using Lite Coherent Receiver for Next-Generation Optical Access Network

Qi Zhou, Jiale He, Shuyi Shen, Rui Zhang, Shuang Yao, Yahya Alfadhli, You-Wei Chen and Gee-Kung Chang

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA

qi.zhou@gatech.edu

Abstract: We propose and experimentally demonstrate a low-cost symmetric long-reach high-capacity access structure enabled by a lite coherent receiver. 50-Gb/s/λ 16-QAM transmission with 40.1-dB link-budget is achieved to surpass specifications in NG-PON2.

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1. Introduction

Driven by the recent progress in extreme broadband 5G mobile fronthaul, optical broadband services and new attractive applications including super-resolution video, augmented and virtual reality, trigger the demand for higher speed in optical access network. To meet this trend, 10-Gb/s-based passive optical networks (PON) including XG-PON1 and 10G-EPON have recently been deployed and marketized. Following up from this, the ITU-T/Full Service Access Network (FSAN) is actively progressing in the standardization of the next-generation passive optical network stage 2 (NG-PON2). NG-PON2 is a PON system that exploits time- and wavelength- division multiplexing (TWDM). The optical line terminals (OLT) use different wavelength pairs, while each OLT communicates with multiple optical network unit (ONU) via time-division multiple access (TDMA). Also, NG-PON2 is expected to be compatible with the legacy optical distribution network (ODN) with power-splitter based fiber infrastructure. It's envisioned that the NG-PON2 requires 40Gb/s/λ or beyond data rate [1]. To comply with the new standard, approaches using advanced modulation formats such as PAM4, Duobinary and discrete multi-tone (DMT) are proposed [2]. Compared with the conventional non-return-to-zero (NRZ) signal, data rate can be increased with the same bandwidth. However, those intensity-modulation-direction-detection (IMDD) based methods have a comparatively low modulation index and degraded transmission performance due to the creation of optical double sidebands, as well as the fiber/modulator induced dispersion. Also, the optical phase information is lost during square-law detection in the photodetector (PD). Those drawbacks result in low receiver sensitivity ($>$-17dBm), which makes it infeasible to support typical PON link budget requirement. Besides, the IMDD scheme has a very limited fiber dispersion tolerance ($<$30ps/nm), preventing it from being implemented in the desired O+ band ($>$1320 nm) [3]. Optical coherent detection, on the other hand, utilizes an optical local oscillator (OLO) serving as an optical domain downconverter. This method enables linear optical field detection, which offers significant benefits for digital fiber dispersion compensation and electrical/optical components induced impairment mitigation. Also, a huge signal gain is obtained proportional to the magnitude of the OLO. However, the coherent detection hardware is associated with high-cost from the expensive polarization-diversity hybrid, balanced-photodetector array, etc. On top of this, the optical access network is sensitive to cost, which limits the massive deployment of coherent detection in legacy PON.

In this paper, we propose and investigate a novel lite coherent receiver based PON system. The proposed lite coherent receiver consists of only one single PD, one OLO, one analog to digital converter (ADC) and an optical coupler, which significantly simplifies the components and architecture of the conventional coherent receiver. By tuning the wavelength of the OLO, arbitrary wavelength channel selection is feasible. Also, we achieve bits stream I-Q modulation and upconversion digitally, with the optical intensity modulator converting the signal into optical domain, which cuts the high cost and eliminates the I-Q imbalance associated with the optical I-Q modulator. Based on the proposed system built up by 10-G class electrical and optical components, we for the first time, demonstrate a symmetric 50-Gb/s/λ 16-QAM transmission over 100-km standard single mode fiber (SSMF). The prototype inherits the benefits of coherent detection without the high-cost as well as facilitate the realization of promising applications like OLT-less inter-ONU communication [4].

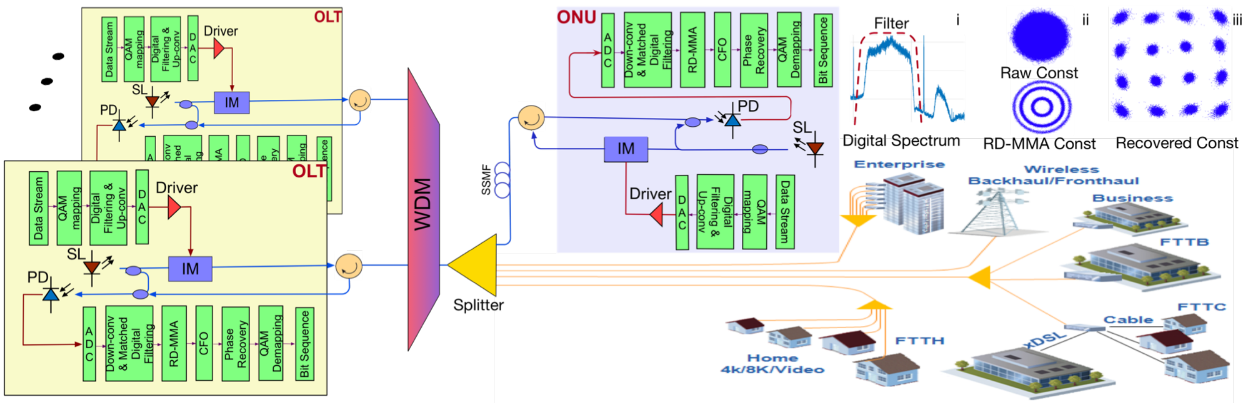

Fig. 1. Experimental setup and framework of the prototype lite coherent access system

2. Principals and Experimental Setup

Fig. 1 demonstrates the framework and experimental setup of the prototype system. An external cavity laser (ECL, PPCL100), refered as ECL1, with 13.5-dBm maximum output power is implemented in the OLT to serve as both the seed light (SL) to the optical intensity modulator for the downlink and as an OLO to the photodetector for the uplink. The OLT is connected to multiple ONUs through some optical power splitters. In the downlink, The PRBS-15 bits sequence is first mapped to 16-QAM constellation using gray coding. We then upconvert the digital I-Q modulated signal to an intermediate frequency (IF) and extract its real part for digital to analog conversion (DAC) using a 65 GSa/s arbitrary waveform generator (AWG, Keysight M8195A). The output of the AWG is amplified by the modulator driver (Picosecond Model 5865) with a 12-GHz 3-dB bandwidth to generate sufficient swing to drive the optical intensity modulator. We bias the JDSU 10-Gb/s intensity modulator to its null point where the best field-wise linearity locates, so that the optical carrier is suppressed while the modulation index is the highest. The modulated optical signal propagates through a 100-km SSMF. At the ONU side, an optical attenuator is implemented in front of the lite coherent receiver to simulate the path loss from power splitters. Another ECL, refered as ECL2 is implemented at the ONU serving the same functionalities as it is in the OLT. The ECL2 is set to be roughly 14-GHz away from the ECL1 and combines with the received optical signal (ROS) using a 3-dB optical coupler for lite coherent detection. After the square law detection in a PD (MITEQ-SLR) with 9.8 GHz 3-dB bandwidth, the ouput photocurrent $I_{PD}(t)$ is proportional to:

$$
\begin{aligned}
I_{PD}(t) &\propto \{E_{OLO}\cdot\cos(\omega_{OLO}\cdot t)+E_{ROS}(t)\cdot\cos[\omega_{ROS}\cdot t+\phi(t)]\}^2 \\
&\propto \frac{1}{2}E_{OLO}^2+\frac{1}{2}E_{ROS}^2(t)+2E_{OLO}\cdot E_{ROS}(t)\cdot\cos(\omega_{OLO}\cdot t)\cdot\cos[\omega_{ROS}\cdot t+\phi(t)] \\
&\propto E_{OLO}\cdot E_{ROS}(t)\cdot\{\cos[\omega_{IF}\cdot t+\phi(t)]+\cos[(\omega_{ROS}+\omega_{OLO})\cdot t+\phi(t)]\}
\end{aligned}
$$

Here, the E_{OLO}^2 is the average DC energy flux filtered out by the PD's internal capacitor. Since the OLO magnitude is much greater than the ROS, the $E_{ROS}^2(t)$ term can be negligible. Besides, the high frequency component at frequency $\omega_{ROS}+\omega_{OLO}$ is out of PD's bandwidth. So the dominant term in photocurrent is $E_{OLO}\cdot E_{ROS}(t)\cdot\cos[\omega_{IF}\cdot t+\phi(t)]$. ω_{IF} is the frequency difference between ω_{ROS} and ω_{OLO}. It can be seen the OLO provides huge gain and enables linear detection of ROS E-field. The ADC function onto the PD's output is performed by an 80 GSa/s oscilloscope (DSOZ254A). The inset (i) shows the spectrum of the digitized samples, where the lower sideband of the signal is filtered out using the minimum-order FIR filter and downconverted to baseband. We design a radius decision based multi-modulus algorithm (RD-MMA) with 30 equalization taps. The constellations before and after the RD-MMA are demonstrated in inset (ii). The carrier frequency offset estimation and compensation is performed through finding the frequency at the maximum of $\left|FFT\left[s^4(t)\right]\right|$. Here, s(t) is the signal after RD-MMA, and FFT is fast-fourier transformation. We apply the phase recovery algorithm afterwards. Since the phase noise frequency is relatively low in our system, we employ 80-symbol length sliding window. In this case, any residual phase components after the fourth power of the constellation points on the center $\sqrt{10}$ radius ring will be eliminated by each other. The recovered constellation is illustrated in inset (iii). After decoding, the BER is calculated by comparing the difference between the original and recovered bits sequences.

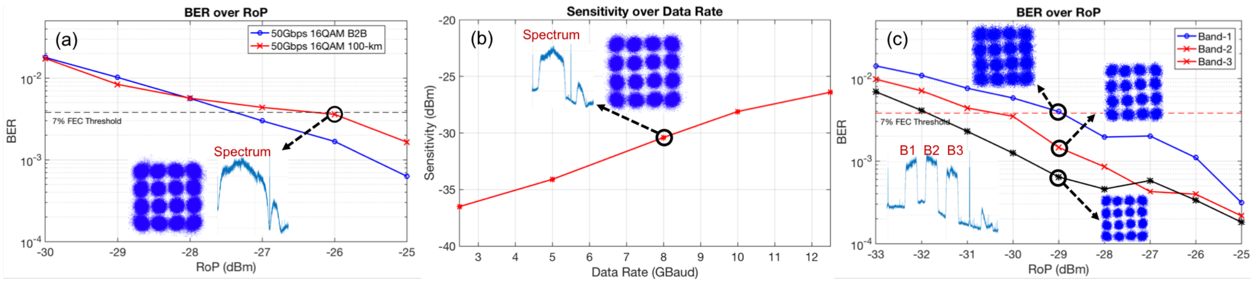

Fig. 2. (a) BER over RoP at 50-Gb/s over 100-km SSMF, (b) sensitivity over data rates, (c) BER over RoP at 2.5-GBaud multi-band transmission over 100-km SSMF

3. Results and Discussion

Fig. 2(a) demonstrates the BER performance over received optical power (RoP), the data rate is set to the fixed 50 Gb/s using 16-QAM modulation. The sensitivity of the prototype reaches -26.4 dBm at 7% forward-error-correction hard decision (FEC-HD) BER threshold. The link-budget reaches 40.1 dB with 13.7 dBm maximum transmitting power at the OLT. We also compare the optical back to back (B2B) with the 100-km transmission performance, and no obvious penalty is observed. The sensitivity over data rate result is shown in Fig.2(b). We choose 2.5-GBaud, 5-GBaud, 8-GBaud, 10-GBaud and 12.5-GBaud as the test points, which correspond to 10-Gb/s to 50-Gb/s using 16-QAM modulation. As observed, The higher sensitivity is obtained at lower data rate, which enables flexible data rate configuration for the ONUs requiring different link budgets. Since the OLTs and ONUs use the same optical/electrical components and architecture, the downlink and uplink transmission are symmetric with identical performance. Besides, the high-capacity OLT-less inter-ONUs communications are feasible based on this prototype, providing ultra low-latency and ultra-reliability compared with over OLT communication. In 5G era, some sets of ONUs will directly connect to wireless backhaul/fronthaul network base stations to provide mobile services within given wireless coverage area [4]. Our prototype also supports this use case as justified in Fig.2(c). Here, 3 bands of upconverted 10-Gb/s 16-QAM signals are generated in the OLT and transmitted through 100-km SSMF. Fig.2(c) demonstrates the BER over RoP for each band after a similar signal detection and recovery processes as described above. The sensitivity for band-1, band-2 and band-3 are -28.9-dBm, -30.3-dBm and -31.8-dBm, respectively. Besides, at the ONU side, the lite coherent receiver output can be further amplified and directly emitted into air through the multi-bandpass sectors antenna to provide carrier aggregated mobile services.

4. Conclusion

We demonstrate a pace-setting symmetric 50 Gb/s/λ 16-QAM transmission over 100-km SSMF with 40.1-dB link budget based on 10G-class electrical/optical components to support the implementation of NG-PON2. The prototype system utilizes a low-cost lite coherent receiver to achieve high receiver sensitivity, flexible wavelength channel selection, and digital dispersion/link impairment compensation. The symmetrical architecture for OLTs and ONUs enables identical downlink/uplink transmission performance. Besides, the prototype lite coherent system system is capable of supporting high-capacity OLT-less inter-ONU communications. Carrier aggregation for 5G wireless services can also be realized through the prototype. Our scheme provides a promising low-cost, high-capacity solution to tackle access networking challenges of NG-PON2 and beyond.

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