WDM extended reach passive optical networks using OFDM-QAM

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Abstract: In order to reduce the cost for delivering future broadband services, network operators are inclined to simplify the network architectures by integrating the metro and access networks into a single system. Hence, extended reach passive optical networks (ER-PONs) have been proposed. ER-PON usually has four new features: high data rate in both upstream and downstream signals (>1 Gb/s); reach extension to >100 km; a high split ratio (>100); and using wavelength division multiplexing (WDM). In this work, we propose and demonstrate a highly spectral efficient ER-PON using 4 Gb/s OFDM-QAM for both upstream and downstream signals, while achieving a high split-ratio of 256. The ER-PON employs optical components optimized for GPON (bandwidth of ~1GHz) and reaches 100 km without dispersion compensation. Numerical analysis using 16, 64 and 256-QAM OFDM are also performed to study the back-to-back receiver sensitivities and power penalties at different electrical driving ratios.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications.

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1. Introduction

In order to deliver future broadband services economically, service providers have to reduce the cost in order to sustain profit margins. One possible way to achieve this is to simplify the network architecture; hence the number of equipment interfaces and network elements, e.g. electronic switches and routers, can be reduced. Extended reach (ER) access network has been proposed to achieve this [1-3]. The ER access network makes use of a high capacity, high split-ratio passive optical network (PON), with a reach of more than 100 km, to combine optical access and metro into a single system [3]. The local exchange [between the head-end office and the customer optical networking units (ONUs)] would contain a small amount of compact, low power physical layer elements, such as optical amplifiers and temperature-controlled arrayed waveguide gratings for wavelength multiplexing and demultiplexing. The higher layer networking equipments would be located in a small number of head-end offices (also called centralized major service nodes).

Gigabit PONs (GPONs) are now standardized and commercially available. They typically provide a split-ratio of 32 via passive optical splitters using time division multiplexing (TDM), over a reach of up to 20 km. They offer 1 to 2.5 Gb/s downstream and ~1 Gb/s upstream data rate. The proposed ER-PON usually requires four new features: (1) high data rate in both upstream and downstream directions (> 1 Gb/s); (2) reach extension to ~100 km; (3) a high split ratio (> 100); and (4) using wavelength division multiplexing (WDM).

It is viable to directly use 10 Gb/s system in these ER-PONs. This would require the adoption of relatively expensive 10 GHz optical components (if on-off-keying modulation is used), such as optical modulator or semiconductor optical amplifier (SOA), in the cost sensitivity ONU. The cost of the ONU is not shared as it is, for example, the cost of optical line terminal (OLT). In this work, we propose and demonstrate WDM ER-PONs that make use of orthogonal frequency division multiplexing (OFDM). Due to the highly spectral efficiency of the M-quadrature amplitude modulation (QAM) in each subcarrier of the OFDM signal, low-bandwidth optical components can still be used. This means we can directly increase the data rate of the system while using the existing optical components developed for GPONs. Besides, the inherent advantage of OFDM frequency diversity transmission allows simple equalization of frequency response by baseband digital signal processing (DSP) [4]. These characteristics can be used to mitigate fiber chromatic dispersion [5, 6] which is one of the major impairments in ER-PONs). The proposed approach also solves the frequency ripple problem caused by low-cost components. High split-ratio of 256 and 100 km reach without dispersion compensation are achieved. Here we experimentally demonstrate 16-QAM. Simulations of 16, 64 and 256-QAM are conducted to study the back-to-back receiver (Rx) sensitivities and power penalties at different electrical driving ratios.

2. OFDM-QAM signal description and experiment

Figure 1 shows the experimental setup of the WDM ER-PON. We used a baseband DSP and a digital to analog converter (DAC), which is an arbitrary waveform generator with 4 GHz sampling rate to generate the OFDM-QAM signal. The incoming bit streams were packed into 16 subcarrier symbols, each subcarrier symbol was in a 16-QAM format. By using inverse fast Fourier transform (IFFT), these subcarrier symbols were converted to a real-valued time-domain waveform, called an OFDM symbol. Then the DAC converted the digital data to an analog signal.

In the downstream experiment (from the head-end office to the ONU), this OFDM signal was applied to an electro-absorption modulator (EAM) with proper bias via a bias-tee. The dc-bias was 0.98 V and the driving amplitude was about 2 V peak-to-peak. The downstream signal was at a wavelength of 1560 nm with average optical power of 3 dBm measured at the output of the EAM. The signal was then launched into a 100 km standard single mode fiber (SMF) (dispersion parameter = 17 ps/nm/km) without dispersion compensation. In the local exchange, an erbium doped fiber amplifier (EDFA) with saturated output power of 21 dBm and noise figure of 6 dB was used to amplify the signal. A temperature-controlled wavelength

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demultiplexer (Gaussian shaped arrayed waveguide grating with channel separation of 100 GHz and 3-dB bandwidth of 50 GHz) is also located in the local exchange. In the ONU, the analog to digital converter (ADC), which is a real-time 10 GHz sampling oscilloscope, converted the downstream signal detected by the optically pre-amplified Rx to digital signals for demodulation. The optically pre-amplified Rx consisted of an EDFA with saturated output power of 15 dBm and noise figure of 5 dB, and an optical bandpass filter with 3-dB bandwidth of 50 GHz to remove the out-of-band amplified spontaneous emission (ASE) noise. The synchronizer extracted the carrier phase and aligned the OFDM symbol boundaries. The time- to frequency-domain translation was performed with fast Fourier transform (FFT). A QAM decoder analyzed the symbol on each subcarrier to make the final decision.

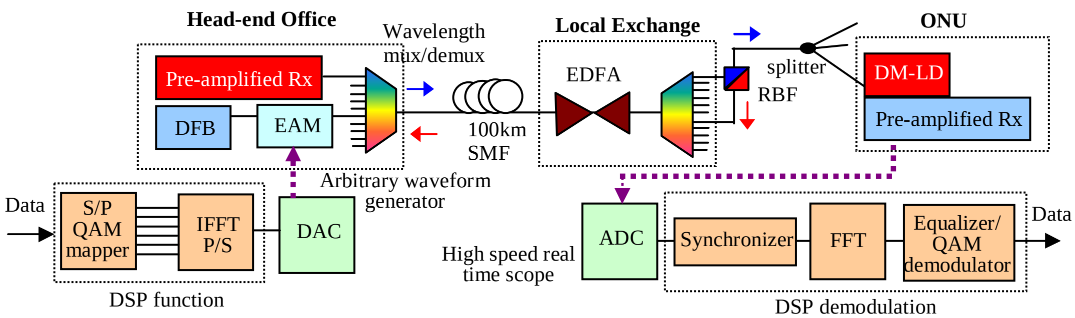

Fig. 1. Schematic of OFDM-QAM over WDM ER-PON. S/P: serial to parallel, P/S: parallel to serial, IFFT: inverse fast Fourier transform, FFT: fast Fourier transform, DAC: digital analog converter, ADC: analog digital converter, EAM: electroabsorption modulator, SMF: single mode fiber.

The 1 G symbol/s OFDM signal occupied the spectrum from 62.5 MHz to 1125 MHz, with data pattern consisted of 8192 OFDM symbols. We calculated the bit error rate (BER) performance from the measured error vector magnitude (EVM) [7]. In the upstream experiment, the DAC was connected to a distributed feedback (DFB) laser diode (LD) operating at a nominal wavelength of 1543nm, for direct modulation; while the ADC was connected to the pre-amplified Rx at head-end office. The DFB-LD was commercially available. It was biased at 30 mA, and directly modulated with output power and driving bandwidth of 3 dBm and 1 GHz respectively. The upstream optical signal was sent back through the 100 km SMF to the Rx at the head-end office via a red-blue-filter (RBF).

3. Results and discussion

Figure 2 shows the BER measurements of both upstream and downstream OFDM 16-QAM signals. About 2 dB power penalty was observed at the back-to-back between the upstream signal generated by the directly modulated LD and the downstream signal generated by the EAM. The power penalty is due to the increased noise generated by the direct modulation of the DFB-LD. Negligible penalty was observed in both upstream and downstream signals after 0, 50 and 100 km SMF transmissions, respectively, without dispersion compensation. Measurement results show that the OFDM signal is especially good for ER-PONs, since the ER-PONs cannot be fully dispersion compensated due to different distances between the head-end office and the ONUs. Inset of Fig. 2 shows the radio-frequency (RF) spectrum of the OFDM QAM signal at back-to-back, measured by an RF spectrum analyzer with resolution of 1 MHz. The 4 Gb/s OFDM signal consists of 16 subcarriers occupying about 1 GHz bandwidth. Hence, optical components optimized for GPON can be used. The measured constellation diagrams of the downstream and upstream signals after transmission of 100 km SMF are shown in Fig. 3(a) and (b), respectively. We can observe that each constellation point is condensed with good separation among others. This verifies that successful baseband frequency domain equalizations have been achieved by the DSP.

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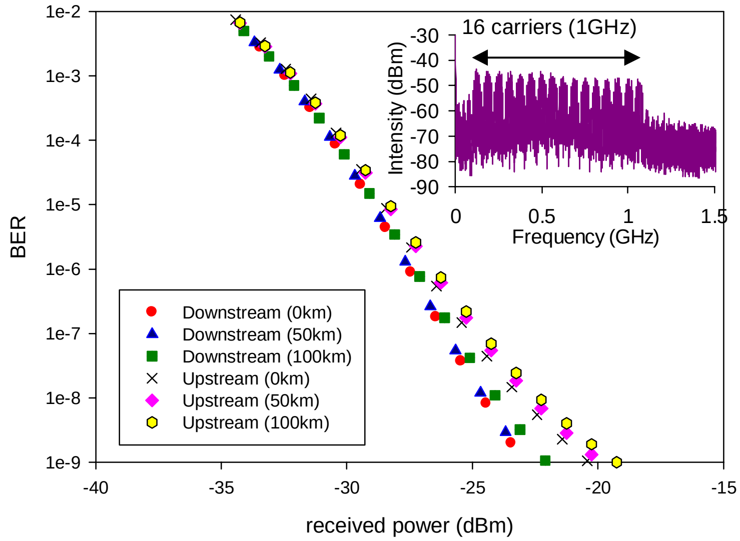

Fig. 2. Measured BER of downstream and upstream OFDM-QAM signals at different transmission distances. Inset: measured RF spectrum of the 4Gb/s OFDM-QAM signal, occupying 1GHz bandwidth.

A variable optical attenuator (VOA) was placed between the ONU and the RBF to emulate different PON split-ratios in the proposed architecture (Fig. 1). In Fig. 4, we show that 1024 and 256 PON split-ratios can be achieved in downstream and upstream signals, respectively, in the 100 km transmission. The lower upstream split-ratio is attributed to the fact that signal is highly attenuated (by the splitting) before amplified by the EDFA in the local exchange. Higher upstream split-ratio may be achieved if higher optical output power LD could be used in the ONU.

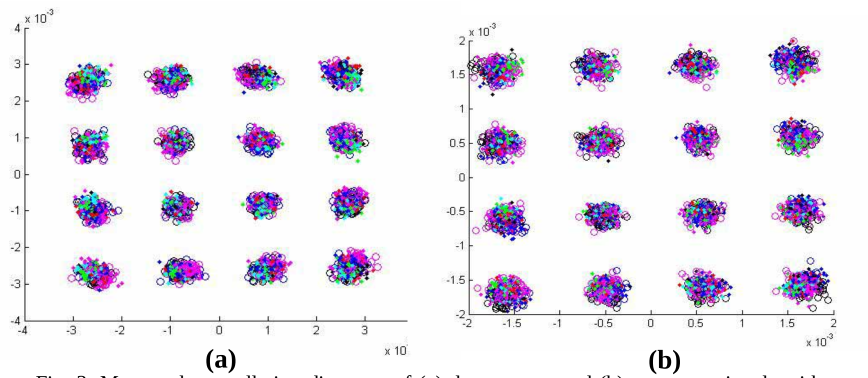

Fig. 3. Measured constellation diagrams of (a) downstream and (b) upstream signals with 100km SMF transmission without dispersion compensation.

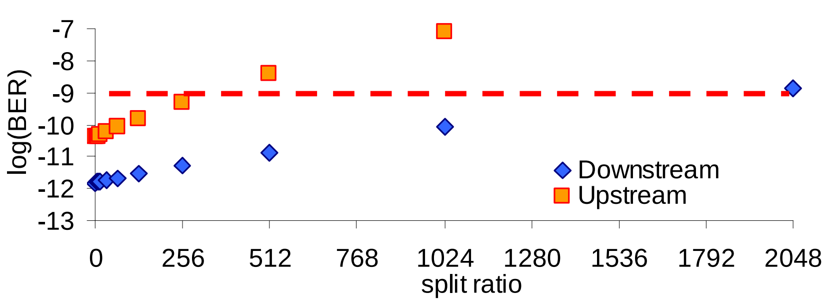

Fig. 4. Measured BER at different PON split ratio for upstream and downstream signals.

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4. Numerical analysis

Numerical analysis using OFDM 16-QAM was performed, showing there is a good match in terms of transmission penalty and split-ratio. Figure 5 shows the simulation results of the back-to-back Rx sensitivities of 16, 64 and 256-QAM signals with different OFDM subcarriers. 16, 64 and 256-QAM represent aggregated data rates of 4 Gb/s, 6 Gb/s and 8 Gb/s respectively. By using 32 subcarriers in the OFDM signal, while keeping the total data rates of 4 Gb/s, 6 Gb/s and 8 Gb/s in the 16, 64 and 256-QAM signals respectively, we can improve the Rx sensitivities by 2-3 dB. The tradeoff, however, is that optical components with higher bandwidth (2 GHz) should be used. Higher data rate using higher level of QAM maybe possible if the split-ratio and reach can be relaxed in the system architecture.

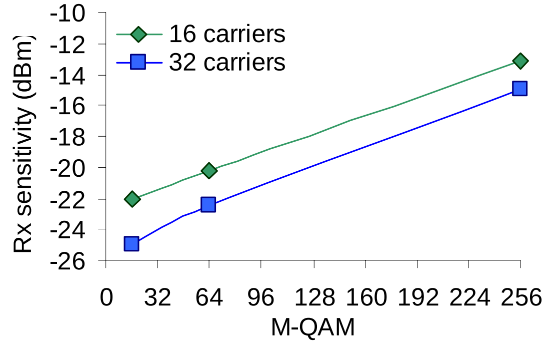

Fig. 5. Simulated Rx sensitivity of different OFDM-QAM. The aggregated data rates of 16, 64 and 256-QAM OFDM signals are 4 Gb/s, 6 Gb/s and 8 Gb/s respectively for both 16 and 32 subcarriers.

As the waveform of the OFDM signal presents a high peak-to-average-ratio, resembling noise, high driving amplitude to the EAM or LD could cause the signal to fall occasionally outside the linear transmission region and create signal clipping. Using low driving amplitude prevents the signal clipping but the system suffers from poor power efficiency. Figure 6 shows the power penalty of the 16, 64, 256-QAM (using 16 carriers) under different driving voltage ratios (V_{appl}/V_{linear}, defined as the ratio of applied voltage to the linear driving range of the EAM). The results indicate an asymmetric response to the driving voltage ratio: the signal works well up to a regime for which it is slightly clipped but suffers high penalty when the clipping increases.

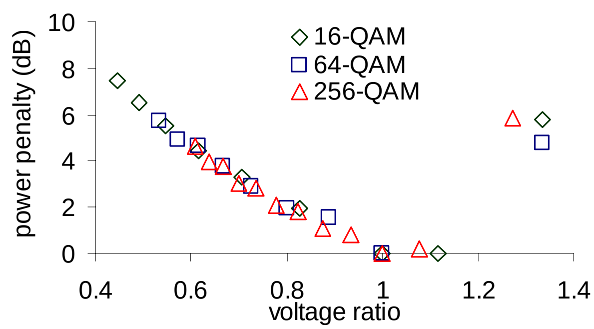

Fig. 6. Simulated power penalty at different V_{appl}/V_{linear}.

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5. Conclusion

We proposed and experimentally demonstrated a highly spectral efficient ER-PON (100km) using 4 Gb/s OFDM QAM for both upstream and downstream signals. We can achieve a high split-ratio of 256 in the upstream signal and 1024 in the downstream signal. The ER-PON is constructed by using optical components optimized for GPON (~1 GHz). Numerical analysis using 16, 64 and 256-QAM OFDM were also performed to study the trade-off between the Rx sensitivities, number of level of QAM and the number of subcarrier. Simulation results show that by using 32 subcarriers, we can improve the Rx sensitivities by 2-3 dB, however, higher bandwidth (2GHz) optical components should be used. Using higher level of QAM can increase the aggregated data rate while keeping the data bandwidth the same, i.e., using the same number of OFDM subcarriers, however, Rx sensitivities increase due to the reduced decision margins in the EVM calculations. As the waveform of OFDM signal presents a high peak-to-average-ratio, different electrical driving ratios were applied to the EAM. The simulation results show that slightly clipped signals work well. Further increase in clipping will result in high penalty. Since data converters with resolution higher than 2 GHz are commercially available recently, and OFDM offers the prospect of integrating forward error correction (FEC) to improve transmission, we believe that the proposed architecture could be a practical candidate for upgrading optical access networks in the future.

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