Coherent SCM-WDM-PON System using OFDM or Single Carrier with SSB Modulation and Wavelength Reuse

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Abstract: *We propose an SCM-WDM-PON system, suitable for up to 320 users at 1 Gb/s, using SSB modulation and wavelength reuse for colorless ONUs. The experimental results demonstrate the feasibility of this concept, showing increased spectral efficiency at cost of a small penalty for the OFDM case as compared to single carrier DQPSK modulation.*

Introduction

Recently, different architectures for passive optical networks (PON) have been proposed[1] to increase the aggregate bandwidth and the total number of subscribers. A key technology to achieve this goal is the use of wavelength division multiplexing (WDM) together with multiple access techniques per wavelength, including orthogonal frequency division multiplexing (OFDM), subcarrier multiplexing (SCM), or time division multiplexing (TDM). A combination of WDM and OFDM with data rates in the Tbit/s-range was shown by Cvijetic[2]. The feasibility of OFDMA with individual upstream (US) transmitters using the same wavelength was also recently shown[3]. While a simpler approach using direct-detection and re-modulation of the downstream (DS) signal was shown by Fabrega[4], the feasibility of US and DS with 4 ONUs using the same wavelength but different subcarrier frequencies was recently demonstrated[5]. Due to the wavelength reuse of the DS carrier for the US transmission, a high spectral efficiency (SE) as well as low equipment cost can be achieved.

Based on this concept, we investigate the use of OFDM-SCM instead of single carrier DQPSK modulated subcarrier signals (SC-SCM). Due to their rectangular spectra, the frequency spacing of the subcarriers can be reduced and the SE can be further increased. However, a slight sensitivity penalty can be expected due to the higher Peak-to-Average Power Ratio (PAPR). In our concept, each WDM channel carries an optical transmission group (OTG) containing N OFDM signals with a symmetrical data rate of 1 Gb/s each. With typical values of 80 WDM channels and 4 subcarriers per wavelength, 320 independent channels can be realized with an aggregate data rate of 320 Gb/s.

System Concept

A diagram of the proposed PON system is depicted in Fig. 1. Since the SCM-WDM-PON system, using OFDM instead of single carrier DQPSK modulation, is equivalent to our previously proposed system (please refer to Kottke[5]), only a brief system description will be

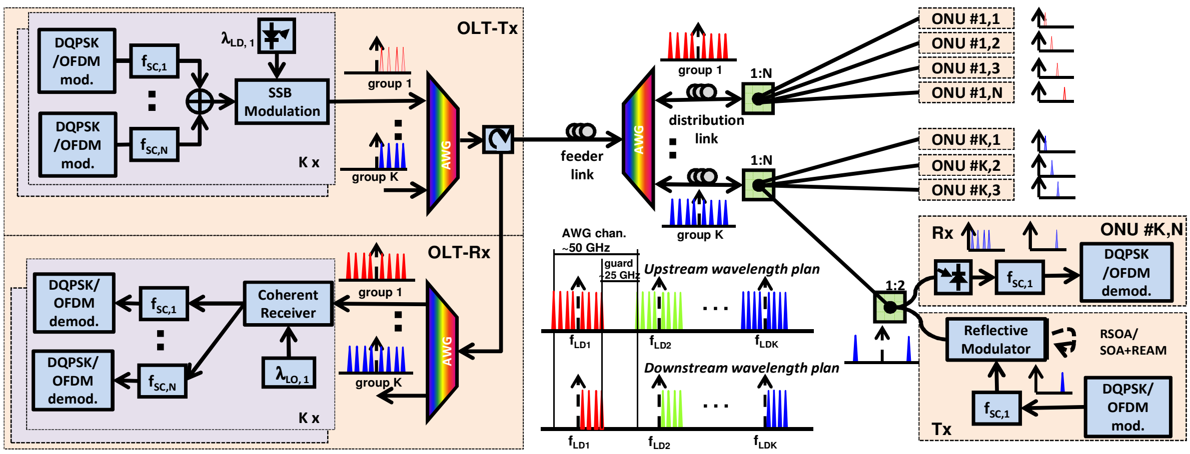

Fig. 1 Proposed SC/OFDM SCM-WDM-PON system with colorless ONUs and single wavelength for up- and downstream transmission.

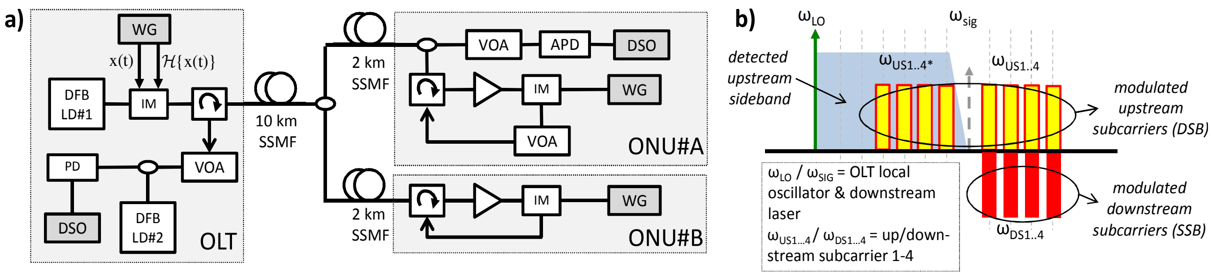

Fig. 2. a) Experimental setup (LD = laser diode, APD/PD = Avalanche/PIN photodetector, VOA = variable optical attenuator, IM = intensity modulator, DSO = digital storage oscilloscope, WG = arbitrary waveform generator) b) Proposed frequency plan at OLT Rx.

given. The OLT transmitter consists of K transmission modules, each of which modulates an optical carrier with the combined signals of N subcarriers, one for each ONU. For the DS, optical SSB modulation and direct-detection (DD) is used. The US signal at each ONU consists of one electrical subcarrier and is generated by simple intensity modulation of the regenerated DS signal. After transmission to the OLT and aggregation of all US signals carried on the same wavelength, heterodyne coherent detection is used there to avoid distortions from the residual DS subcarriers.

Experimental Setup

Fig. 2a shows the experimental setup of the proposed PON architecture. The DS signal was comprised of 4 electrical subcarriers, either OFDM or single carrier DQPSK modulated. In the OFDM case, the signal of each subcarrier consists of 40 orthogonal 4-QAM modulated OFDM-subcarriers. The electrical subcarrier frequencies were set to 1.0, 1.7, 2.4 and 3.1 GHz. With a target data rate of 1 Gb/s on each subcarrier, yielding a bandwidth of 500 MHz, the resulting gap between the subcarriers was ~200 MHz (Fig. 2b). For SC-SCM transmission using DQPSK modulation, more spacing is needed. The subcarriers were located at 1.5, 2.5, 3.5 and 4.5 GHz with a target data rate equivalent to the OFDM-SCM case. To generate the OFDM and SC-SCM signals, we used the previously proposed methods[3,5]. To realize the SSB modulation, a dual-drive Mach-Zehnder-modulator was driven by the aggregated electrical subcarrier signal and its Hilbert transform. Both signals were pre-calculated offline and generated by an arbitrary waveform generator (WG). The optical CW source (see Fig. 2a, DFB LD#1) was a narrow linewidth (100 kHz) DFB laser at 1551 nm. After transmission over 12 km standard single mode fiber (SSMF) and an additional attenuation of 14 dB, emulating the arrayed waveguide grating (AWG) and splitter loss, the DS signal was received by an APD, recorded with a digital storage oscilloscope (DSO) and further processed offline (synchronization, filtering, BER estimation). For US transmission, the DS signal was amplified at each ONU and re-modulated with the corresponding US subcarrier. The subcarrier frequencies and modulation formats were equal to the DS signal. As only two independent ONUs were available to achieve the required 4 US subcarriers for each OTG, the ONU#A generated the subcarrier under test and the ONU#B generated the remaining three subcarriers.

The optical output power for all subcarriers of the OTG was set equal. The electrical US signals were pre-calculated and stored in a WG to drive the optical intensity modulator. After the modulation, the signals were fed back into the fiber, transmitted to the OLT and coherently heterodyne detected. The local oscillator was 8 GHz shifted compared to the respective DS carrier. After optical-to-electrical conversion, the filtered signal was recorded with a DSO and further processed offline.

Experimental Results

Fig. 3 shows the measured BER for the 4 US subcarriers vs. the received optical power from ONU#A at the OLT Rx. For the OFDM-SCM case, the measured BER of a single modulated US subcarrier without any adjacent subcarriers is shown by the square markers. The influence of neighboring subcarriers is shown by the triangles, while the diamonds show the influence of the modulated DS together with neighboring subcarriers. Additionally, to compare the results of OFDM-SCM with the SC-SCM case, the SC-SCM performance with neighbors and modulated DS is shown by the circular markers.

For the OFDM-SCM case, it is observed that the US performance suffers slightly, if adjacent subcarriers are also transmitted (penalty ≤ 1 dB @ 10^{-3}). This penalty is mainly caused by the 2nd order harmonics of the US signal overlapping with neighbor subcarriers. If US and DS are simultaneously transmitted, an additional penalty occurs. This is attributed to a number of effects: First, part of the optical power is no longer available for the US modulation, since it

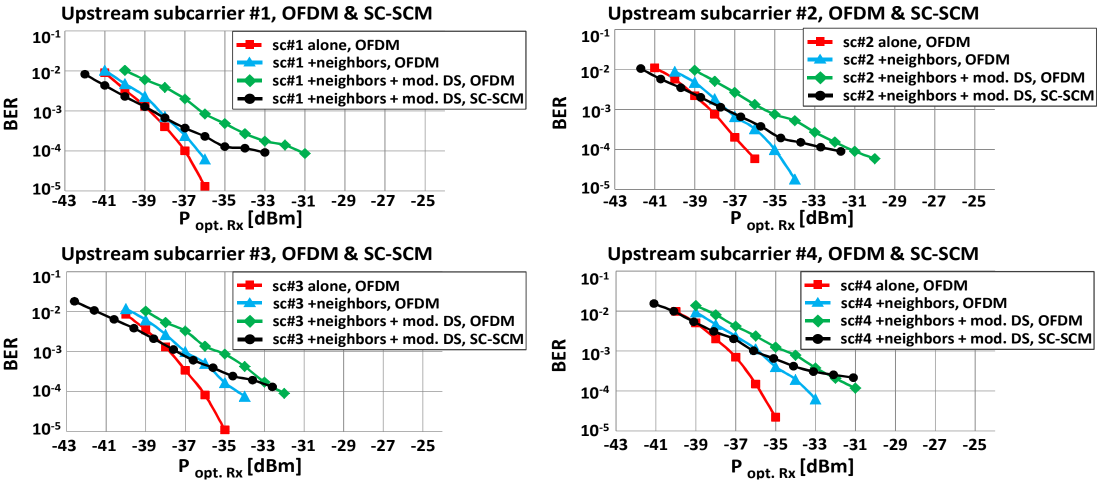

Fig. 3. BER performance of US subcarriers for single transmission (square), with neighbor subcarriers (triangle) and with modulated DS signal for OFDM (diamond) and SC-SCM (circular).

is used for the DS modulation side bands. Second, the imperfect SSB modulation and the unsuppressed harmonics of the DS signal cause distortions of the US signal. Finally, the cross-modulation of the DS subcarriers by the US signal in the ONU results in mixing products, which are partly located in the relevant US sideband and interfere with the US signal. The impact of each effect depends on the modulation index and the frequencies of the DS and US subcarriers.

In addition to these distortions, reduced system performance can be observed for higher US subcarrier frequencies, caused by the overall system frequency response. However, at the target BER of 10^{-3}, corresponding to an error free performance after FEC, a penalty of only ~2.5 dB was measured for all US subcarriers in the OFDM-SCM case.

Compared to the results of the SC-SCM scheme, shown by circular markers, the OFDM-SCM performance is worse at the FEC limit (~2.5 dB penalty @ 10^{-3} BER). This is attributed to the higher PAPR of OFDM signals. However, at BERs below 5×10^{-4}, the error-floor for the OFDM-SCM transmission is lower, compared to SC-SCM. This is due to the localization of the interfering nonlinearities in the frequency gap between the subcarriers in the OFDM-SCM case. For the SC-SCM case, due to the wider modulation spectrum, no frequency gap existed[5], resulting in a lower robustness against the interfering nonlinearities. In addition, if we would use the same modulation spectrum for the OFDM case compared to the SC-SCM, the achieved data rate would be doubled nearly[3], although with further penalties occurring.

The DS performance for both systems was similar, with a measured sensitivity at ONU#A of about -24 dBm (@ 10^{-3} BER). For the DS measurements, the electrical signal power of each subcarrier was adapted to equalize the BERs. Due to this power adjustment, the better PAPR of the SC-SCM scheme was offset by the general system frequency response in combination with a higher necessary signal bandwidth. With a launch power of 0 dBm per user, the measured sensitivity and the proposed splitting ratio, a fiber budget of up to 10 dB (~40 km) is available. This reach compares well with non-amplified state-of-the-art PONs.

Conclusion

We proposed and experimentally verified a subcarrier SCM-WDM-PON architecture using a source-free colorless ONU and OFDM modulation. The simultaneous transmission of DS and US at one wavelength was shown and its influence on the BER performance was investigated. The measured US performance penalty was ~2.5 dB at a BER of 10^{-3}. Compared to our previously published SCM-WDM-PON system, using single carrier DQPSK modulation[5], a similar performance was observed. A penalty for the DS transmission with parallel US was not seen. These results allow a 40 km SCM-WDM-PON, using OFDM, with up to 320 users at 1 Gb/s symmetrical data rate.

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