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Crosstalk in Downlink Carrier Reused WDM-PONs Based on Subcarrier Modulation

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Abstract

We demonstrate that, in carrier reused WDM-PONs based on subcarrier modulation, residual downlink data exists in the reused optical carrier. Both experiments and simulations show that uplink suffers from impairments due to the crosstalk of the residual data.

1 Introduction

Today, wavelength division multiplexed passive optical networks (WDM-PONs) are very attractive due to its potential for future broadband access networks. WDM-PONs do not suffer from power-splitting losses and allow enhanced reliability and privacy because of their virtual point-to-point connections [1]. Centralized light sources of the uplink make WDM-PONs more convenient for wavelength arrangement and upgrade. Some techniques have been proposed to achieve centralized light sources, such as remotely seeding Fabry-Perot lasers [2] and reflective SOAs [3] by spectrum-sliced amplified spontaneous emission (ASE) noise. However, these schemes need two wavelengths arrangement for uplink and downlink, respectively. Recently, subcarrier transmission technique was applied to PONs, where the downlink data was carried on the subcarriers [4, 5]. At each ONU, the subcarriers were filtered out for downlink data detection, while the optical carrier was considered as CW light and remodulated for upstream transmission.

In this paper, we analytically and experimentally investigate the optical subcarrier modulation and show that the reused optical carrier still carries residual baseband data, which cannot be ignored especially for large signal modulation. This residual data degrades the uplink performance when the downlink optical carrier is reused for uplink data encoding. Both simulations and experiment are carried out to examine this degradation

2 Downlink Carrier Reused WDM-PON

In subcarrier modulation (SCM), the baseband data is mixed with a local oscillator (LO) and upconverted to a subcarrier. The mixed signal is then modulated onto a CW light by a Mach-Zehnder modulator (MZM) in amplitude shift keying (ASK) format and transmitted to ONU via a feeder fiber, as shown in Fig. 1. Here only a single channel is considered for principle demonstration. In this system, ONU can have different configurations as shown in Fig 1. In the first two configurations, the carrier and subcarriers are separated by a fiber Bragg grating (FBG) and a circulator. In configuration 3, a delay interferometer (DI) is used to separate the carrier and subcarriers. At each ONU, the subcarriers are detected by downstream receiver and the separated optical carrier is remodulated as uplink light source. In configuration 1, an external modulator is used for data encoding, while the last two schemes use RSOA for data encoding.

Assuming the bias voltage of the MZM is V_b, the downstream output optical field of the modulator is [6]

$$E(t) = E_{in}\exp(j\omega_c t)\left\{\cos\left[\frac{\pi}{V_\pi}\left(V_m(t)\cos(\omega_{rf}t)+V_b\right)\right]\right\} \quad (1)$$

where E_{in} and ω_c are the amplitude and carrier frequency of the input light, respectively, ω_{rf} is the frequency of the local oscillator, V_π is the half-wave voltage of the modulator, and $V_m(t)=\sum_{k=1}^{\infty} b_k A_m f(t), kT_b \le t \le (k+1)T_b$ is the baseband signal voltage, where T_b is the bit duration of the downstream data, b_k=0 or 1is the bit value, and $f_k(\tau)$ is the data waveform.

Expanding Eq.(1) in terms of Bessel functions leads to

$$\begin{aligned} E(t) &= E_{in}\cos(\alpha)J_0(\beta)\exp(j\omega_c t) + \\ & A\cos(\alpha)\sum_{n=1}^{\infty}(-1)^n J_{2n}(\beta)\exp\left[j\left(2n\left(\omega_c \pm \omega_{rf}\right)t\right)\right] \\ & -A\sin(\alpha)\sum_{n=0}^{\infty}(-1)^n J_{2n+1}(\beta)\exp\left[j\left(\omega_c \pm (2n+1)\omega_{rf}t\right)\right] \end{aligned} \quad (2)$$

Here, $\alpha=\pi V_b/V_\pi$ and $\beta(t)=\pi V_m/V_\pi$. Eq. (2) shows that the modulated optical field contains many frequency components, according to $\omega_c \pm i\omega_{rf}$, i=0,1,2… The first

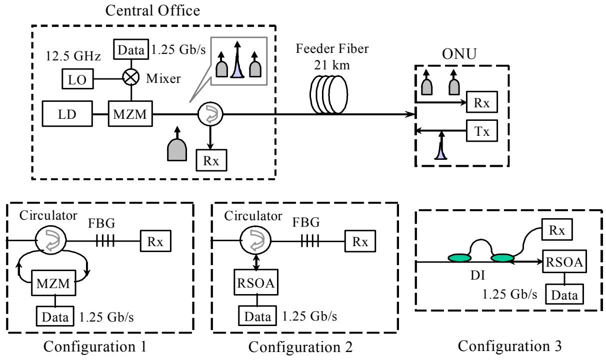
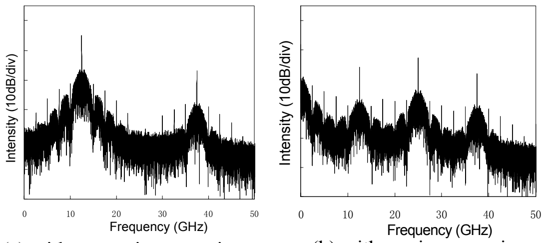


Fig. 1 PON based on downlink optical carrier reusing with different ONU configurations.



(a) without carrier removing (b) with carrier removing

Fig. 2 RF spectra of subcarrier modulated signal.

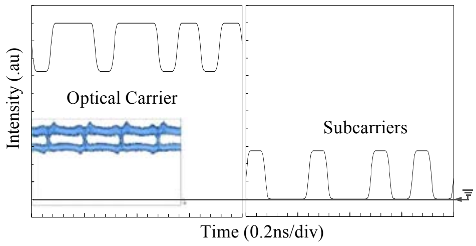


Fig. 3 Waveforms of the optical carrier and subcarriers. $V_b=V_m=V_\pi/4$. Inset: measured eye diagram of optical carrier.

term is the optical carrier and the other terms are the subcarriers of different orders located at $\omega_c \pm i\omega_{rf}$. Depending on the bias condition, the resulting output of the MZM can be different. Generally, the MZM is biased at the quadrature point $V_b=V_\pi/4$ for the purpose of optical carrier reuse. The envelope detection of Eq. (2) gives

$$P(t)=|E(t)|^2=\frac{|E_{in}|^2}{2}\Big\{J_0^2(\beta(t)) \quad 2\sum_{k=1}^{\infty}J_i^2(\beta(t))+\sum_{k=0}^{\infty}J_kJ_{k+1}(\beta(t))\cos(\omega_{rf}t)+\ldots\Big\} \qquad (3)$$

Baseband detection is envelope detection with a low pass filter to remove subcarriers. Using Neumann's addition theorem of Bessel function, baseband detection gives

$$P(t)=\frac{|E_{in}|^2}{2}\left(J_0^2(\beta(t))+2\sum_{k=1}^{\infty}J_k^2(\beta(t))\right)=\text{Constant} \qquad (4)$$

The baseband power of the SCM light is a constant.

If we separate the carrier and subcarriers with an ideal optical filter, we can also get their power from Eq. (2) with $J_0(\beta)=0$ and $J_k(\beta)=0$, respectively, as

$$P_{Ca}(t)=|E_{in}|^2 J_0^2(\beta(t))/2,\ P_{Sub}(t)=|E_{in}|^2\sum_{k=1}^{\infty}J_k^2(\beta(t)) \qquad (5)$$

Fig. 2 shows the RF spectra of the SCM light and subcarriers. Without removing carrier, the SCM light only has DC and no baseband data, which is consistent with Eq. (4). After the carrier is removed, the downlink data exists at baseband, therefore downlink data can be detected by baseband receiver. However, the residual data at optical carrier degrades the uplink performance. Eq. (4) and (5) show that the data carried at the optical carrier is the inverted version of that of the subcarriers as shown in Fig. 3. The subcarrier power of the downlink signal increases with the increase of the downlink RF signal amplitude. While the power fluctuation of the

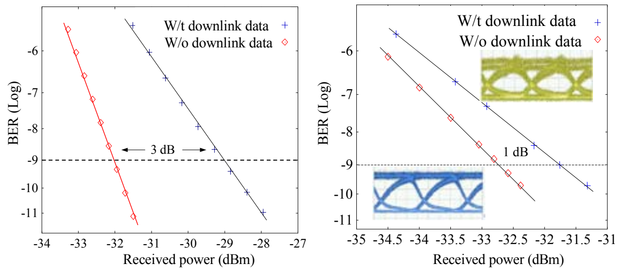


Fig. 4, BER vs. received power of upstream transmission with ONU configuration 1 (left) and configuration 2 (right)

carrier due to the residual data also increases with the RF signal amplitude, which is not desirable. Experimental results shows that when $V_b=A_m \cong V_\pi/4$, the separated downlink optical carrier indeed carries residual baseband data with an extinction of 1.7 dB as shown in the inset of Fig. 3. It introduces crosstalk when the carrier is reused for upstream transmission. In this work, we demonstrated the transmission of the first two ONU configurations, as shown in Fig. 1, to verify the impact of the residual data.

Fig. 4 shows the BER performance of the upstream transmission based on downlink carrier remodulation. Here, both downstream and upstream data rates are 1.25 Gb/s. Local oscillator is 12.5 GHz. The optical carrier to subcarrier ratio (OCSR) is 11 dB. The transmission link is 21 km single mode fiber. In the first configuration, we use an ideal FBG to filter out the optical carrier perfectly and simulate the bidirectional transmission. Considering the receiver sensitivity at 10^{-9}, simulation results showed there was about 3 dB power penalty due to the crosstalk of the residual downlink data. The second configuration was experimentally demonstrated using a simple apodized FBG with a 3 dB bandwidth of 0.15 nm. The OCSR of the seeding light was increased to 18 dB after FBG. The seeding power launched into the RSOA is –20 dBm. Experimental results also show a 1 dB power penalty, which is smaller than the first case. This reduced power penalty is due to the gain saturation of RSOA and the residual subcarriers due to the imperfect filtering.

3 Summary

We have investigated optical subcarrier modulation and demonstrated that the residual downstream data exists in the reused optical carrier. This residual data induces crosstalk and degrades the uplink performance when the downlink optical carrier is reused for uplink data encoding. Simulations and experiments demonstrated there were 3 dB and 1 dB power penalties when the carrier was remodulated by an external modulator and RSOA, respectively.

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