In-band 16-QAM and multi-carrier SCM modulation to label DPSK payload signals for IP packet routing

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Abstract: We present an experimental demonstration of the feasibility of in-band subcarrier multiplexing (SCM) for labeling of differential phase shift keying (DPSK) payload signals. We show that by proper selection of the value of the subcarrier frequency the effect of the superimposed SCM label on the performance of the DPSK signal is minimized. Furthermore, we show experimentally the advantages of using alternative modulation formats such as 16-QAM and multi-carrier SCM for optical labeling of a 10 Gb/s DPSK payload signal.

OCIS codes: (060.4510) Optical communications; (060.5060) Phase modulation; (060.2360) Fiber optics links and subsystems; (060.4080) Modulation

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1. Introduction

Subcarrier multiplexing (SCM) schemes to label payload signals are considered a promising technique for optical label switching [1].Conventional SCM labeling schemes use subcarrier frequencies above the spectral band of the payload signal. For example, for 10 Gb/s payload signals, SCM frequencies at least of 14 GHz [1] are commonly used in order to effectively separate the payload and label spectral contents. Migration to higher bit-rates for the payload signal will require more bandwidth and high speed SCM technology. Therefore operating with lower subcarrier frequencies, even within the payload data bandwidth, is desirable to reduce the complexity of the electronics involved in label generation, detection and processing.

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In this paper we propose an in-band SCM labeling scheme for DPSK payload signals. In-band amplitude shift keying (ASK) [2] and polarization shift-keying (PolSK) [3] modulation schemes to label DPSK payload signals have been proposed and demonstrated earlier; however, SCM labeling offers additional advantages such as the possibility of adding to the payload signal multi-SCM tones for label stacking or signaling purposes. Mathematical analysis and computer simulations show that the crosstalk between the SCM label and the DPSK payload is minimized when the label is centered at a subcarrier frequency equal to half the bit rate of the DPSK signal. We validate as well this finding experimentally for a system operating at 10 Gb/s with two different in-band SCM label schemes, namely a 16-QAM label and a multi-carrier (10 MHz spaced carriers) label. The results show the feasibility of the proposed in-band SCM label schemes at frequency of 5 GHz with the lowest measured power penalty on the performance of the DPSK payload signal. This paper is organized as follows. In section 2 we introduce the in-band SCM labeling scheme while section 3 presents the experimental validation. Finally, section 4 presents summary conclusions.

2. In-band sub-carrier labeling scheme for DPSK signals

The optical field of the in-band SCM labeled DPSK payload signal can be described as:

$$E(t)=\sqrt{P_0[1+m\times label(t)\sin(\omega_s t)]}\,e^{i\phi_k} \tag{1}$$

where: m is the intensity modulation index, *label(t)* is the label data, $\omega_s = 2\cdot\pi f_s$ is the sub-carrier frequency, $e^{j\cdot\phi_k}$ is the DPSK phase information and P_o is the optical peak power. DPSK signal are commonly demodulated by using a one-bit delay Mach-Zehnder interferometer (MZI) [4]. The electric field at each output port of the MZI demodulator can be written as $E_{cons}(t)=\frac{1}{2}\left[E_{in}(t-\tau)-E_{in}(t)\right]$ for the constructive port and as $E_{des}(t)=\frac{j}{2}\left[E_{in}(t-\tau)+E_{in}(t)\right]$ for the destructive port, respectively; where τ is the one-bit delay. Considering a balanced photodetector receiver, the resultant photocurrent (after subtraction of the constructive and destructive MZI port contributions) can be expressed as

$$I(t)\propto\frac{P_0}{2}\cos(\phi_{k-1}-\phi_k)\left[2+m\times label(t)\{\sin(\omega_s(t-\tau))+\sin(\omega_s t)\}\right] \tag{2}$$

where a small modulation index m approximation has been used. We can see from expression (2) that for a value of $\omega_s\cdot\tau=\pi \quad \Rightarrow \quad f_s=\frac{1}{2\cdot\tau}=\frac{BitRateDPSK}{2}$, the crosstalk from the label signal on the resultant photocurrent is minimized.

To confirm the above finding we have simulated a 10 Gb/s DPSK system with a superimposed, in-band subcarrier frequency ranging from 2 GHz to 7 GHz with a value of $m = 0.4$. Fig. 2 shows the simulation results for the power penalty at a bit-error rate (BER) of 10^{-9}. The power penalty is computed with reference to the case of absence of the SCM tone (open markers in Fig. 2). We can observe that the minimum power penalty takes place for a value of SCM equal to 5 GHz. This is confirmed as well by the measurement explained in the next section. As the value of the subcarrier frequency approaches 10 GHz and beyond, the power penalty becomes negligible as the SCM spectrum will fall outside the spectral band of the DPSK signal. Therefore, in-band SCM of DPSK will allow for using relatively low frequency subcarrier signals while minimizing the crosstalk on the DPSK payload.

3. Experimental demonstration

The proposed DPSK payload and in-band SCM labeling scheme has been experimentally assessed, as depicted in Fig. 1. A distributed feedback laser source (DFB) with an integrated electro-absorption modulator (EAM) is used for generating the lightwave carrier and to insert the SCM signal, respectively. The EAM section was reversed biased at 1.06 V. The label data signal was derived from a vector signal generator. A $LiNbO_3$ phase modulator was used to impose the DPSK modulation at 10 Gbit/s. The electrical signal was a 2^{31}-1 pseudo-random binary sequence (PRBS) pulse pattern. The average optical power after the phase modulator (PM) was set to - 6 dBm. An erbium-doped fiber amplifier (EDFA) was used to amplify the signal up to a value of 0 dBm followed by an optical band-pass filter in order to reject the amplified spontaneous emission (ASE) noise.

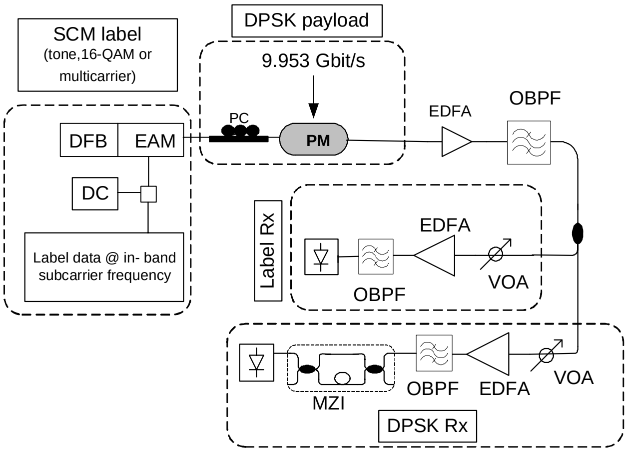

Fig. 1. Experimental setup. DFB: distributed feedback laser. EAM: electro-absorption modulator. DC: voltage generator. PM: phase modulator. PC: polarization controller. EDFA: erbium-doped fiber amplifier. OBPF: optical band-pass filter. VOA: variable optical attenuator. MZI: Mach-Zehnder interferometer.

At the receiver side, the incoming signal was split into two parts for payload and label detection purposes, respectively. To study the performance of the detected label signal (the SCM signal), a variable optical attenuator (VOA) and an EDFA followed by an optical band-pass filter (OBPF) were used before the photodetector. The recovered label signal was then analyzed by a RF vector analyzer. The payload detection was performed by demodulating the DPSK signal by using a one-bit-delay MZI. An optical preamplifier stage was used, composed of a VOA, an EDFA and an OBPF. The detected payload signal was fed into a data and clock recovery (DCR) unit for bit-error rate (BER) measurements.

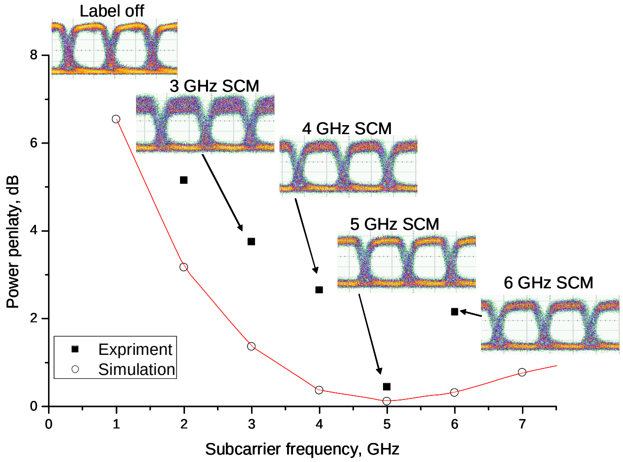

Fig. 2. Power penalty, with reference to the case of no label at a BER of 10^{-9}, for the DPSK payload signal in presence of SCM tones at different frequencies. Open markers: simulation results. Solid markers: measurements. Insets: eye-diagrams of the detected DPSK signal, 50 ps/div.

3.1 DPSK payload performance

Firstly, we investigate the performance of the payload DPSK signal in presence of a single sub-carrier frequency tone at different frequencies. The power penalty at a BER of 10^{-9} with respect to the case of no SCM being present is shown in Fig. 2 by the solid markers. The modulation index m was measured to be 0.4. The insets show the detected DPSK eye diagrams for a single photodetector receiver. As it can be observed, when the carrier frequency is at half of the DPSK bitrate, a power penalty of less than 0.5 dB is observed, as predicted by simulations (open markers). When the frequency tone is shifted to a lower or higher frequency with respect to the 5 GHz value the power penalty increases. This confirms that a proper in-band frequency value for the SCM signal should be equal to half the DPSK bit-rate.

Secondly, we study the performance of the DPSK payload signal when a 16-QAM in-band SCM labeling is applied. The use of a QAM format is introduced to reduce the net modulation bandwidth of the SCM label signal and therefore to minimize the crosstalk on the DPSK payload. A 16-QAM SCM modulation format on a 5GHz subcarrier frequency is chosen for the experiment (50Mbps, 12.5MHz symbol rate, and 0.5 roll-off factor). Figure 3 (left) presents the measured BER for the DPSK signal without SCM, with a SCM tone at 5 GHz, and with 16-QAM modulation, respectively. As it can be observed, the superposition of a frequency tone at 5GHz does not affect the performance of the DPSK signal significantly. However, when the subcarrier is modulated with a16-QAM data signal, a power penalty of less than 2 dB measured at a BER of 10^{-9} is observed.

Thirdly, the DPSK performance was evaluated with a multi-carrier modulation scheme centered at 5 GHz, with carrier spacing equal to 10 MHz. Each carrier represents one information bit, and hence, the labeling information is performed by means of on/off keying (present/not present) of the multi-carrier tones. A common 32-bit long label of the multiprotocol label switching (MPLS) format may be conveyed by using *5* multi-carrier frequencies. This SCM scheme offers the possibility of narrow SCM modulation bandwidth and allows for parallel processing of the label information. The BER performance of the DPSK with superposition of such a multi-carrier labeling technique is shown in Figure 3 (right). As it can be observed, the introduction of the 5 carriers at 5 GHz does not affect the performance of the DPSK signal significantly. However, when 7 carriers are introduced, the performance of the DPSK shows a power penalty of 2 dB for a BER of 10^{-9}.

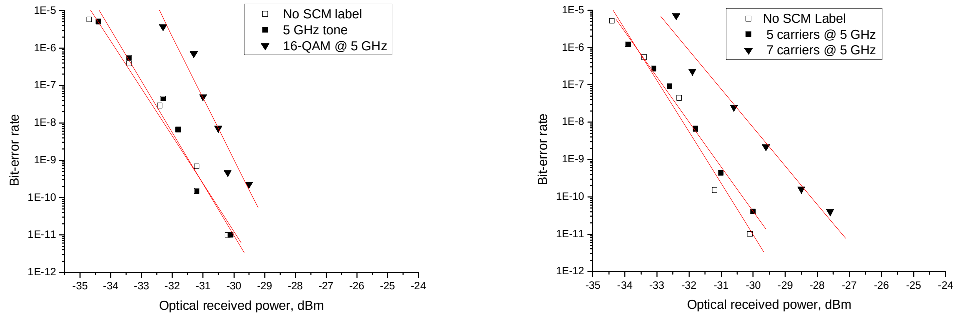

Figure 3. BER as function of received optical power. Left: back-to-back case, presence of a single frequency tone at 5GHz and with 16-QAM, respectively. Right: back-to-back case, in presence of 5, and 7 carriers (10 MHz spacing), respectively.

3.2 In-band SCM label performance

The performance of the 16-QAM and multi-carrier SCM schemes was studied for the case of absence and presence of the DPSK signal. Fig. 4 shows the performance of the 16-QAM label signal at 5GHz (50Mbps, 12.5MHz symbol rate, and 0.5 roll-off factor) for different values of the received optical power. The signal-to-noise ratio (SNR) is measured after photodection by the signal vector analyzer. The insets show the IQ diagram of the 16-QAM label for values of the optical received power set to -30 dBm and -2.3 dBm, respectively. The penalty curve presented in Fig. 4 is the resultant SNR penalty due to the presence of the DPSK signal. As it can be observed from Fig. 4, the SNR penalty increases above 3 dB for values of the optical received power lower than -5 dBm. However, the measured values of SNR are above 20 dB (for receiver power levels larger that -25 dBm) indicating good signal quality for reception of the 16-QAM label signal [7].

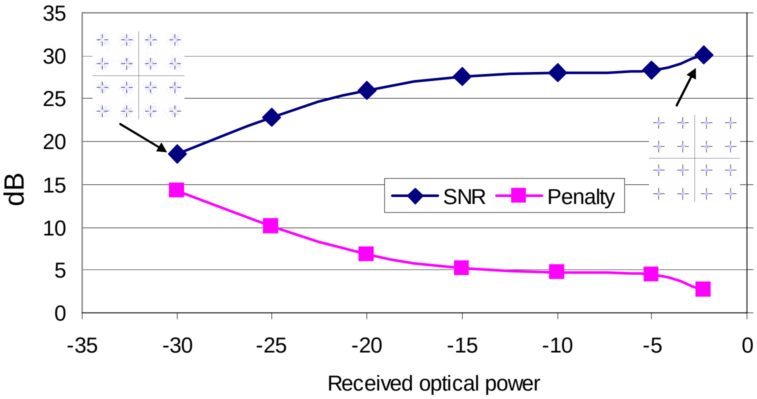

Fig. 4. 16 QAM, 50 Mbps label performance in presence of DPSK payload. SNR and penalty (due to the presence of the DPSK signal) as a function of the optical received power. Insets: IQ diagrams for -30 dBm and - 2.3 dBm of optical received power.

Similarly, the performance of the multi-carrier SCM scheme was studied. Fig. 5 shows the spectrum of the 5 GHz single frequency tone, a 5 and 7 multi-carrier label (both centered at 5 GHz and with 10MHz carrier spacing) in the absence (DPSK off) and presence (DPSK on) of the DPSK payload, respectively. As it can be seen, the carrier power level remains unaltered in the presence of the payload signal, whereas the noise level increases approximately by 4dB when the DPSK payload is on; this results in a 4 dB penalty of the carrier-to-noise ratio (CNR). However, the measured value of the CNR was larger that 34 dB for optical receiver in the range form -30 dBm to -2.3 dBm indicating that data recovery is feasible for the multi-carrier SCM schemes[7].

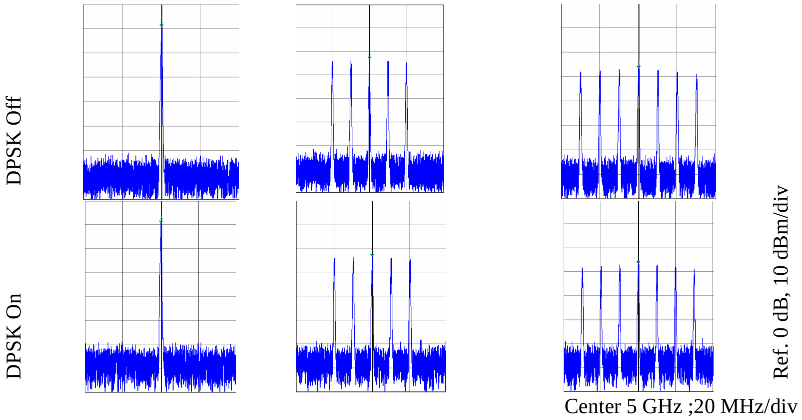

Fig. 5. Label performance at 5 GHz in absence and presence of DPSK payload: single carrier, 5 and 7 multi-carrier schemes (carrier spacing = 10MHz).

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4. Conclusion

We have demonstrated that an in-band SCM labeling scheme can be used to label DPSK payload signal, achieving a minimum penalty on the DPSK performance when the subcarrier frequency is chosen to be equal to half the DPSK bit-rate. In our experimental set-up, power penalties of around 2 dB are observed when the 10 Gb/s DPSK signal is labeled with a 16-QAM or 7 multi-carries (spaced at 10 MHz from each other) SCM scheme at 5 GHz. We expect that the performance can be improved by using an analog optical modulator for insertion of the SCM label with superior linear and chirp properties than the EAM section of an integrated DFB-EAM laser used in the present experiment. However, for the case of 5-multi-carrier SCM or a single tone no substantial performance degradation is observed. It suggest that in-band SCM labeling of DPSK is feasible with low crosstalk provided the label data bandwidth is narrow, what can be accomplished by using a QAM or multi-carrier modulation format. The label performance of the multi-carrier and 16-QAM SCM label schemes has been investigated as well. Although both the 5 and 7 multi-carrier and the 16-QAM SCM labeling signal suffer from SNR degradation due to the presence of the DPSK signal, their performance is satisfactory for proper label detection.

The reported optical signal labeling technique using SCM and DPSK modulation schemes offers a few advantageous features for IP packet/burst routing:

- The subcarrier frequency may be chosen within the frequency band of the payload data, which is appropriate for spectral efficiency while keeping the complexity of the RF signal generation and detection low.
- Multilevel and/or multi-carrier SCM modulation format may be used resulting in a narrow SCM modulation bandwidth. A multi-carrier SCM schemes allows for bit-parallel processing of the label data.
- DPSK modulation format is a promising candidate for future optical networking due to its tolerance to chromatic dispersion, polarization mode dispersion (PMD), and cross-phase modulation (XPM) effects during fiber transmission [4,5].

For reliable transmission of the SCM labeled signal over optical fibers, measures should be implemented to avoid the radio-frequency (RF) fading effect stemming from the interaction between the RF subcarrier and chromatic dispersion. However, it has been shown that optical-frequency-domain filtering techniques eliminate the fading effects [1,6]. Moreover, system design measures should be taken to prevent non-linearities in the transmission link that may cause inter-modulation distortions, resulting in interference into other multi-carrier frequencies [1]. Label swapping and propagation issues for a SCM labeled DPSK signal should be studied to assess its performance and scalability for optical label switching networking. Label erasure of intensity modulation (IM) labeled signals have been reported by using a semiconductor optical amplifier (SOA) in deep saturation [2] with a measured 3 dB improvement of the a 10 Gb/s DPSK payload signal receiver sensitivity, at a BER of 10^{-9}, after label erasure.

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