Experimental Results on the Simultaneous Transmission of Two 2.5 Gbps Optical-CDMA Channels and a 10 Gbps OOK Channel Within the Same WDM Window

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Abstract[1]: *We propose and experimentally validate a novel coding technique that allows the simultaneous transmission of several OCDMA channels and a SONET channel in the same WDM window, thus obtaining a truly OCDMA-overlaid WDM system.*

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems.

1. Introduction.

Recently, there has been a renewed interest in OCDMA due to its potential for offering increased levels of security at ultra-high data rates as well as simplifying key networking functions such as user code assignment and code conversion. Much of the research done in this area has focused on homogeneous OCDMA networking, where it is assumed that the fiber bandwidth is used strictly for OCDMA signals only. On the other hand, emerging networks that are optically transparent can, in principle, allow for a variety of signal types, modulation formats, and bit rates to be transported over a common infrastructure [1]. Therefore, it is important to understand the compatibility of newly developed OCDMA technologies within this type of transparent networking environment.

In contrast to other proposed optical CDMA systems based on the phase encoding of ultra-short pulses [2] or on time-domain chips [3], we have developed a novel phase-frequency approach to OCDMA that is compatible with existing transparent reconfigurable optical networks and has high spectral efficiency [4]. Coding and decoding is based on modifying the relative spectral phases of the set of well defined phase-locked frequencies that are the output of a mode-locked laser (MLL). Encoding consists of separating each of these frequency bins, shifting their phase, as prescribed by the choice of code, and recombining the frequency bins to produce the coded signal.

In [5], we report the first experimental demonstration of the transmission of two spectrally phase-encoded OCDMA signals through a single ITU channel of a transparent reconfigurable optical network while conventional DWDM signals occupy *other* channel passbands of a metro-scale transparent optical network. In the present paper, we extend the work in [4] and [5], and report experimental results that show that our OCDMA system allows us to *simultaneously* transmit multiple OCDMA channels *and* a conventional OC-192 OOK channel *within the same ITU window*. An amplitude/phase encoded CDMA offers the *unique* capability of conveying broadband signals over non-contiguous frequency bands, thus allowing the transmission of several OCDMA channels in the unused bandwidth of a single WDM channel when the SONET signal is actually present. This is the first contribution reporting the experimental confirmation that spread spectrum signals can be conveyed over disjoint frequency bands, and the exploitation of this capability to obtain a *truly* OCDMA-overlaid WDM system.

2. Key Technologies and a Novel Coding Scheme

As described in more detail in [4], our OCDMA approach requires a stable source of closely spaced phase-locked frequencies such as the longitudinal modes of an MLL with a frequency spacing equal to the pulse repetition rate. Phase coding of the individual spectral components requires a demultiplexer with sufficient resolution to resolve individual lines.

In our previous experiments [4], [5], we have phase encoded *16 contiguous MLL lines* contained in an 80 GHz window with Hadamard codes of length 16 using an Essex *Hyperfine* optical coder [6]. Hadamard codes are converted to phase codes by assigning to -1's and +1's phase shifts of 0 and π, respectively. For the experiments reported here, we suitably modified the Essex *Hyperfine* phase mask in order to also allow for simple on-off amplitude encoding of the MLL spectral lines. In particular, we modified the phase mask in order to allow for: 1)

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de-multiplexing of 20 MLL lines (a total passband of 100 GHz); 2) phase encoding of the *first 8 and the last 8 MLL lines* using Hadamard codes of length 16; 3) *notching* of the 4 central MLL lines.

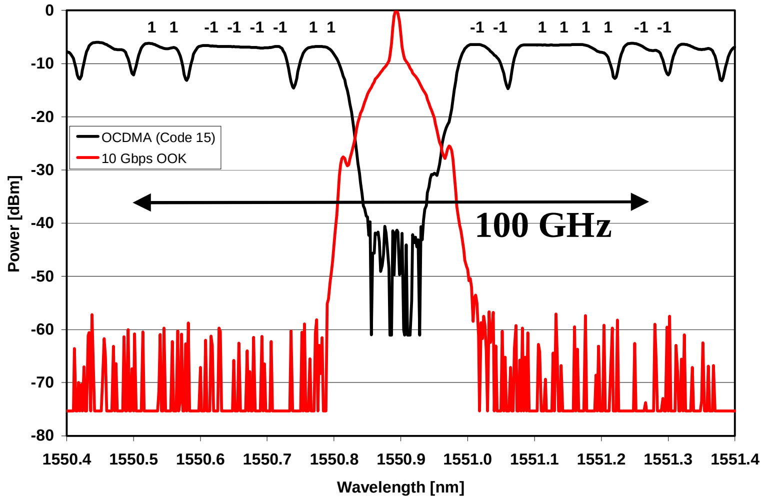

Fig. 1: Measured optical spectra: 2.5 Gbps OCDMA signal spanning two disjoint frequency bands and phase encoded with the 15th Hadamard code of length 16, plus a suitably centered 10 Gbps OOK signal.

As shown by the frequency response of one of the encoder/decoders in the top curve of Fig. 1, this allowed us to create a 20 GHz "spectral hole" in the middle of the OCDMA band. The short dips in the frequency response are from destructive interference caused where two adjacent frequency bins have phase changes of 0 and π. This "bin-edge effect" can be avoided by modulating the pulses output by the MLL at a lower rate, e.g. by sending multiple pulses per bit. As an alternative, using duobinary encoding and then modulating at the full rate $R_b=\Delta f$ bits/sec ensures that the spectral constituents of the data-modulated signal stay within their respective Δf–wide frequency bins. In principle, if no bin-edge effect were present as in the case of multi-phase codes with no 0-π phase transitions, full rate modulation would be possible even without line coding.

The purpose of creating this "spectral hole" is to allow for the insertion of a 10 Gbps OOK signal. It is worth pointing out that our OCDMA system is actually spectrally spreading users over a band characterized by a non-contiguous frequency range. It is also worth noting that, despite the disjoint frequency range, the orthogonality of the Hadamard codes is fully preserved (see [7] for the mathematical proof of this behavior).

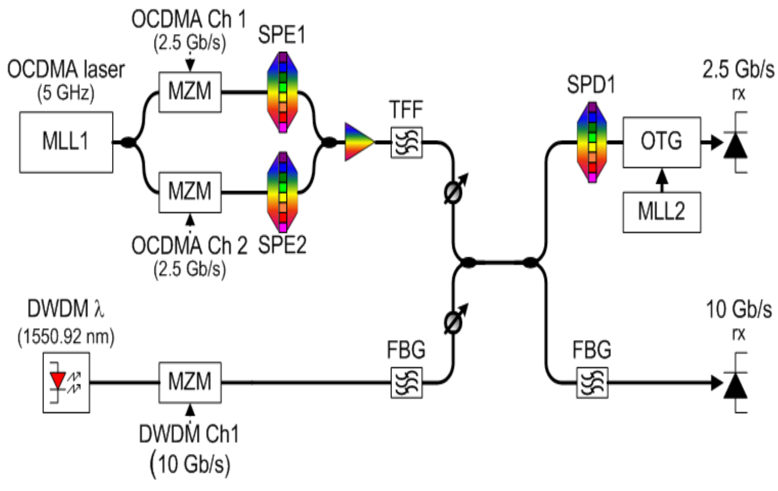

Fig. 2: Experimental setup.

3. Experimental Results

In Fig. 2, we illustrate the experimental setup of our system demonstration. At the top left, the MLL produces a pulse train with 5-GHz repetition rate that is split to two Mach-Zehnder modulators (MZM) that impress independent PRBS data at OC-48 rate (2.5 Gb/s). Note that a single data bit is sent as a pair of pulses to cope with the bin edge effect described in the previous Section.

The modulated signals are encoded using two different spectral phase encoders (SPEs) and, with filtering and amplification, are combined with a standard OOK OC-192 signal and launched over a short length of fiber. At the receiver end, the two OCDMA signals and the OOK signal are separated by optical filters. The OOK signal is recovered with a standard SONET receiver while a spectral phase decoder (SPD) and optical time gate (OTG) isolates one of the two OCDMA signals which is then received by a commercial OC-48 receiver.

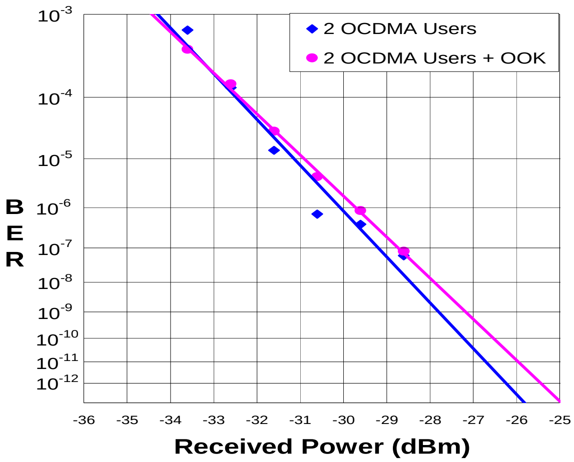

Fig. 3: OCDMA performance with and without the 10 Gbps OOK channel present.

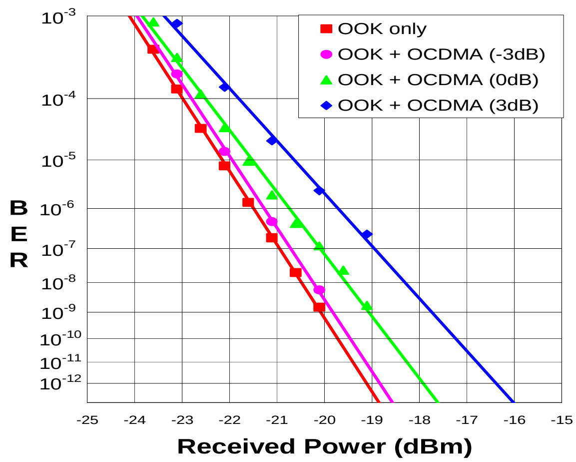

Fig. 4: OC-192 OOK channel performance with and w/o the two OCDMA channels present at different power ratios.

Fig. 3 shows the performance obtained decoding one of the OCDMA users (code 14) in the presence of the second OCDMA user (code 15) and of the OOK signal. Fig. 4 reports the OOK BER in four cases: when only the OOK channel is present, and when both the OOK and the two-user OCDMA channel are present with three different power levels. We considered the cases when the total power of the two OCDMA signal is equal to the OOK signal (0 dB curve) or at ±3 dB. Note that curve labeled "-3 dB" corresponds to the case where all three users (two OCDMA plus one SONET) exhibit the same received optical power. The experiments confirm that both the OCDMA and OC-192 channels exhibit a power penalty limited to 1 dB at a Bit Error rate (BER) of 10^{-9} when the OCDMA signal is received at the same (or lower) power than the OC-192 signal.

4. Conclusions.

For the first time, we report experimental results that confirm the possibility of overlaying suitably amplitude/phase encoded OCDMA channels over conventional WDM signals *within the same ITU window*. This was accomplished by recognizing that spectrally phase encoded OCDMA signals allow us to convey broadband signals over a disjoint (non-contiguous) frequency support, a powerful property reported here for the first time. Remarkably, this property does not impair signal orthogonality so that it can be exploited both in synchronous and asynchronous OCDMA [7].

As opposed to other OCDMA schemes that represent an alternative technology to existing WDM-based systems, the OCDMA scheme proposed in [4] represents an effort in the direction of enabling the co-existence of these two very different technologies. This coexistence allows us not only to exploit the benefits of OCDMA as a means for multiple access, but also to provide additional transport capability by conveying SONET and OCDMA signals within the same WDM channel.

5. References

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