Novel Results on the Coexistence of Spectrally Phase-Encoded OCDMA and DWDM

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Abstract(1) **–We propose and experimentally validate a novel method for transmitting several OCDMA channels in the unused bandwidth of a single WDM channel, thus allowing the OCDMA and SONET signals to share the same WDM channel. The theoretical justification of this new modulation scheme is based on a powerful property of spectrally phase-encoded OCDMA signals which is reported and proved for the first time: the operation of spectral phase encoding allows us to convey broadband signals over a disjoint (non-contiguous) frequency support. Remarkably, this property does not impair signal orthogonality so that it can be exploited both in synchronous and asynchronous OCDMA.**

I. 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 [1]-[5]. 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 [6]. Therefore, it is important to understand the compatibility of newly developed OCDMA technologies within this type of networking environment.

In contrast to other proposed optical CDMA systems based on the phase encoding of ultra-short pulses [7] or on time-domain chips [8], we have developed a novel phase-frequency approach to OCDMA that is compatible with existing transparent reconfigurable optical networks and has high spectral efficiency [9], [12]. Coding and decoding is based on modifying the relative spectral phases of each individual spectral line 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, individually shifting their phases, and recombining all the frequency components to produce the coded signal.

In [10], 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 [9], [10] and [12], 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*. Phase-encoded CDMA offers the *unique* capability of efficiently 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 simultaneously 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.

II. Description of the Proposed OCDMA System

Phase-locked multiple lines are generated by a MLL. In our experiments, we use two disjoint sets of 8 lines each out of a set of 20 lines spaced at 5 GHz in a total optical bandwidth of 100 GHz. The lines are the longitudinal modes of the MLL and are separated by a frequency interval equal to the temporal pulse repetition rate. Their phase-locked addition generates the mode-locked pulse train at a repetition rate with a pulse width inversely proportional to the total frequency window.

The electric field $m(t)$ output of our MLL is a set of N equi-amplitude phase-locked laser lines:

$$m(t) = A\sum_{i=1}^{N} e^{j(2\pi f_i t+\phi)} \tag{1}$$

where f_i = ~193THz + $(i\text{-}1)\Delta f$ are equally spaced frequencies. Signal $m(t)$ is a periodic signal constituting a train of pulses spaced $1/\Delta f$ seconds apart and each pulse has a width equal to $1/(N\Delta f)$ seconds. We can also express (1) as:

$$m(t) = \sum_{k} p(t-kT) \tag{2}$$

where $p(t)$ represents a pulse of duration $T=1/\Delta f$ whose energy is mostly confined in the main lobe of width $1/(N\Delta f)$.

In its idealized form, the hyperfine encoder for user i acts as a phase-mask filter with frequency response $E^{(i)}(f)$:

$$E^{(i)}(f) = \sum_{j=1}^{N} c_j^{(i)} RECT_{\Delta f}\left(f - f_j\right) \tag{3}$$

where $c_j^{(i)}$ are complex symbols indicating the j-th ($1\le j\le N$) element of the i-th code $\underline{c}^{(i)}$ ($1\le i\le M$), and the function $RECT_W(f)$ denotes the rectangle function of unitary amplitude and width W defined as:

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$$RECT_W(f) = \begin{cases} 1, |f| < W/2 \\ 0, \text{ otherwise} \end{cases} \quad (4)$$

Although in principle the elements of code $\underline{c}^{(i)}$ can take any complex value, the phase mask currently employed allows only for unitary amplitude and binary phase values:

$$c_j^{(i)} = e^{j\alpha_j^{(i)}}, \text{ with } \alpha_j^{(i)} \in \{0, \pi\} \Rightarrow c_j^{(i)} \in \{-1, 1\} \quad (5)$$

Ideally, all the spectral components of the unencoded signal would emerge from the encoder unchanged in amplitude but, in some cases, flipped in phase. The effect of phase encoding is to *spread in time* the narrow MLL pulses of width $1/(N\Delta f)$ seconds across the whole bit-interval. Therefore, the proposed phase-encoded OCDMA can be considered as the dual version of conventional direct sequence CDMA (DS-CDMA) based on *frequency* spreading.

Due to the bin edge effects in the Hyperfine mask (see [12] for more details on this issue), the OOK modulation rate must be chosen so that the spectrum broadening of each of the N spectral lines is confined to $\Delta f/2$ Hz. OOK modulation at a rate of $R_b=\Delta f/2$ bits/sec that uses a pair of pulses from the MLL to represent a single bit satisfies this physical restriction. 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.

Therefore, after modulation the temporal expression of the signal pertaining to the i-th user can be written as follows:

$$b^{(i)}(t) = \sum_k a_k^{(i)} p(t - kT) \quad (6)$$

where $a_k^{(i)} \in \{0,1\}$ is the sequence of information bits of user i. After phase encoding, we obtain:

$$s^{(i)}(t) = b^{(i)}(t) * e^{(i)}(t) = \sum_k a_k^{(i)} q^{(i)}(t - kT) \quad (7)$$

where $e^{(i)}(t) = FT^{-1}\{E^{(i)}(f)\}$ is the impulse response of the spectral phase encoder $E^{(i)}(f)$ as defined in (3); FT^{-1} is the Inverse Fourier Transform (IFT) operator; $q^{(i)}(t)=p(t)*e^{(i)}(t)$ represents the pulse shape of user i after encoding. If we neglect the effects of the pulse output by the MLL, the shape of the pulse is governed by the phase mask.

The users’ signals are optically combined prior to transmission over the fiber link:

$$x(t) = \sum_{i=1}^{M} s^{(i)}(t - \tau^{(i)}) \quad (8)$$

where $\tau^{(i)}$ is the random delay of user i.

For the sake of simplicity, we assume that fiber propagation is ideal. Therefore, discrimination of the i-th user is performed using a decoding filter $d^{(i)}(t)$ at the receiver matched to the encoder filter only (single user matched filtering). This is achieved by employing at the receiver side a decoder equal to the conjugate of the phase mask used at the transmitter side:

$$y^{(i)}(t) = x(t) * d^{(i)}(t) \quad (9)$$

where $d^{(i)}(t)$ is the impulse response of the matched filter

$$d^{(i)}(t) = e^{*(i)}(-t) \Leftrightarrow D^{(i)}(f) = E^{*(i)}(f) \quad (10)$$

The output of the filter matched to the desired user i can be expressed as follows (assuming $\tau^{(i)}=0$):

$$y^{(i)}(t) = b^{(i)}(t) * AC_i(t) + \sum_{j=1, j\neq i}^{M} b^{(j)} * CC_{j,i}(t - \tau^{(j)}) \quad (11)$$

where we have defined as $AC_i(t) = e^{(i)}(t) * e^{*(i)}(-t)$ and as $CC_{ji}(t) = e^{(j)}(t) * e^{*(i)}(-t)$ the autocorrelations (ACs) and the crosscorrelations (CCs) of the impulse responses of the phase masks, respectively. The ACs and CCs are a function of the IFT of the sequences used as phase masks. It is important to point out that, as opposed to the case of conventional CDMA based on DS spreading, correlations are between the IFT of codes, not between the codes themselves [12].

The effect of a matched phase decoder is to restore the original narrow pulses of width $1/(N\Delta f)$ seconds that were originally spread in time by the phase encoder. The effect of a mismatched phase decoder is to turn interfering signals into a noise-like signal. It is worth pointing out that when orthogonal codes are employed, as opposed to conventional OCDMA, *true* orthogonality is achieved here and no Multiple Access Interference (MAI) is present at the ideal sampling time.

On the basis of our experiments, we have ascertained that an effective way to reduce MAI is to introduce time-gating prior to intensity detection. In our experiments, we use a SOA-based interferometric optical time gate (OTG). The OTG filters out MAI by temporally extracting only the desired user. In addition, time gating allows us to utilize receivers with a bandwidth equal to the de-spread signal (Δf) instead of the full bandwidth of the signal ($N\Delta f$).

III. Novel Coding Pproperties of a Spectrally Phase-Encoded OCDMA System

Let us now recast the time domain model in (11) in the frequency domain by writing the power spectral density (PSD) of the received signal at the output of the ith decoder:

$$P_{y^{(i)}}(f) = P_{b^{(i)}}(f) \left|E^{(i)}(f)\right|^2 + \\ + \sum_{j=1, j\neq i}^{M} P_{b^{(j)}}(f) E^{(j)}(f) E^{*(i)}(f) e^{-j2\pi f \tau^{(j)}} \quad (12)$$

Ideally, Multiple Access (MA) codes should have a Dirac-shaped AC, and zero CC for all lags. In practice, however, MA codes do not have these ideal properties so that MAI is always present in the decoded signal. It is worth pointing out that, if orthogonal codes such as the Hadamard ones are used, we can also obtain true orthogonality between users at the optimal sampling time:

$$IFT\left\{E^{(i)}(f) E^{*(j)}(f)\right\}_{t=t^*} = \begin{cases} 1, i = j \\ 0, i \neq j \end{cases} \quad (13)$$

where $IFT\{A\}_{t=t^*}$ indicates the IFT of A computed at the t^* time instant. Therefore, matched decoding allows us to recover the original MLL pulses while mismatched decoding results in exactly zero MAI at optimum sampling time t^*. With appropriate synchronization between coded transmitters, a receiver can discriminate its matching coded signal from the (N-1) other signals by sampling the decoded signal at integer multiples of *the bit-rate* where the desired signal is maximized and the interfering signals are zero. To the best of the Authors' knowledge, except for spectrally phase-encoded ODMA, there is no other OCDMA implementation that achieves true orthogonality between users.

As (13) shows, the effects of matched and mismatched decoding of the received signal are governed by the product of the transfer function of the phase encoders. By looking at eqs.(3)-(5), it is also possible to say that the effects of matched and mismatched decoding are governed by the Schur-Hadamard product, i.e. element-by-element product, of the discrete sequences used as phase masks. This dependence of the MA properties on the Schur-Hadamard product of the discrete sequences used as phase masks, which are the equivalent of the spreading codes used in conventional DS-based spreading, is unique to spectrally phase-encoded signals and has no counterpart in other CDMA implementations. As will be shown below, this unique property can be exploited to convey broadband signals over disjoint frequency bands.

Let us assume that we have three disjoint frequency bands available for transmission, as shown in Figure 1.

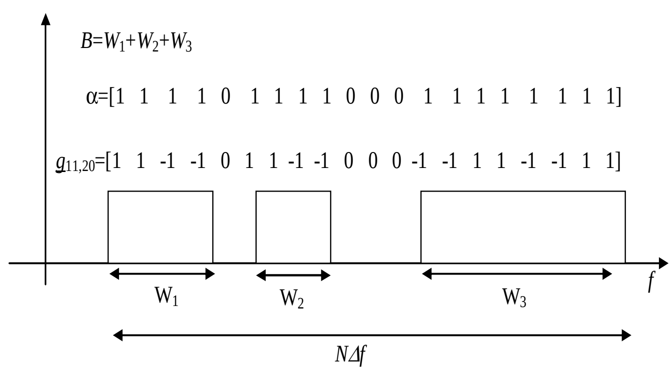

Figure 1: Example of three disjoint bands, with total available bandwidth $B=W_1+W_2+W_3$. A zero-padded Hadamard code 11 is used to spectrally phase encode a user over the disjoint frequency bands.

We will show here that a spectrally phase-encoded CDMA signal can be conveyed simultaneously over all the available bandwidth even if disjoint and that, at the same time, a spreading gain proportional to the *total occupied bandwidth* $B=W_1+W_2+W_3$ is also achieved.

Let us now recall the iterative definition of the Sylvester type Hadamard matrix $\mathbf{H}_N$ of size (N,N):

$$\mathbf{H}_{2N} = \begin{bmatrix} \mathbf{H}_N & \mathbf{H}_N \\ \mathbf{H}_N & -\mathbf{H}_N \end{bmatrix} \tag{14}$$

where the recursion starts by posing $\mathbf{H}_1$=1. $\mathbf{H}_N$ satisfies the following orthogonality condition:

$$\mathbf{H}'_N \mathbf{H}_N = N\mathbf{I}_N \tag{15}$$

where $'$ indicates the Hilbert operator, and $\mathbf{I}_N$ represents the identity matrix of order N. Let us also define as $\underline{h}_{i,N}$ the ith column of $\mathbf{H}_N$ that represents Hadamard code i. Then, the following relationship holds (here $\circ$ denotes the Schur-Hadamard product):

$$\underline{h}_{i,N} \circ \underline{h}_{j,N} = \underline{h}_{j,N} \circ \underline{h}_{i,N} = \underline{h}_{k,N} \tag{16}$$

where k=1 iff i=j, and k=i (k=j) iff j=1 (i=1) (see [13] for recent results on the closure of the Hadamard set with respect to the Schur-Hadamard product).

If disjoint frequency slivers of bandwidth are available, it is possible to use a phase sequence together with a simple binary {0,1} amplitude modulation:

$$E^{(i)}(f) = \sum_{j=1}^{N} a_j^{(i)} RECT_{\Delta f}\left(f - f_j\right) \tag{17}$$

where, as opposed to (5) where the elements of $\underline{c}^{(i)}$ could assume only unitary values, here $\alpha \in \{0,1\}$, $a_j^{(i)} = \alpha e^{j\beta_j^{(i)}}$, and $a_j^{(i)} \in \{-1, 0, 1\}$. Basically, the parameter α is equal to 1 in the slivers of spectrum available for transmission and is equal to zero, otherwise (see Figure 1).

It is easy to recognize that an amplitude/phase mask as in (17) corresponds, in the domain of the spreading sequences, to a suitably zero-padded version of the Hadamard sequence originally used for spreading. For example, let us consider the case where a user needs to transmit over the three disjoint bands in Figure 1 with the Hadamard code $\underline{h}_{11,16}$ of length N=16. The spectral amplitude/phase mask spans a free range of $N\Delta f$ Hz (see eq.(17)), and the Hadamard code is split in three sub-sequences of length 4, 4, 8, and then zero padded in between the sub-sequences.

Let us now define the zero padded version of the Hadamard sequence $\underline{h}_{i,N}$ as $\underline{g}_{i,N'}$, and as $\mathbf{G}_{N'}$=[$\underline{g}_{1,N'}$; $\underline{g}_{2,N'}$; …; $\underline{g}_{N',N'}$] the matrix containing the zero-padded Hadamard codeset; $N'=N+M$, where M is the number of zeros added to each sequences in the codeset. Referring to the example in Figure 1, N=16 and M=4. If we apply the orthogonality test in (15) to matrix $\mathbf{G}_{N'}$ we then obtain the following:

$$\mathbf{G}'_{N'}\mathbf{G}_{N'} = \begin{vmatrix} N\mathbf{I}_{L_1} & \mathbf{0} & \cdots & \cdots & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0}_{L_2} & \ddots & & & \vdots \\ \vdots & \ddots & N\mathbf{I}_{L_3} & \ddots & & \vdots \\ \vdots & & \ddots & \mathbf{0}_{L_4} & \ddots & \vdots \\ \vdots & & & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \cdots & \cdots & \mathbf{0} & N\mathbf{I}_{L_P} \end{vmatrix} \tag{18}$$

where P is the number of sub-sequences, L_i (i=1, …, P) is the length of the ith sub-sequence, $\mathbf{0}_{Li}$ is the all-zero element matrix of size (L_i, L_i), and $N'=L_1+\ldots+L_P$. Referring to the example in Figure 1, we have P=5, L_1=4, L_2=1, L_3=4, L_4=4, and L_5=8. As eq.(18) shows, orthogonality is maintained across all the utilized bandwidth spanning $N\Delta f$ Hz.

This notable property of spectrally amplitude/phase-encoded OCDMA gives us many more degrees of freedom than in the conventional DS-based spreading for ensuring co-existence between OCDMA users and other modulation formats. Moreover, the considerations made here apply to any spreading sequence used as a phase code, not only the Hadamard one, and thus to both synchronous and asynchronous systems. However, only the orthogonal and synchronous case will be experimentally validated in the next Section, where we will show a possible exploitation of the property proven here.

IV. Experimental Results

In our previous experiments [9], [10], [12] 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 [11]. Hadamard codes are converted to phase codes by assigning to -1's and +1's phase shifts of 0 and π, respectively. For our experiments, we suitably modified the Essex *Hyperfine* phase mask in order to also allow for simple on-off amplitude encoding of the MLL spectral lines.

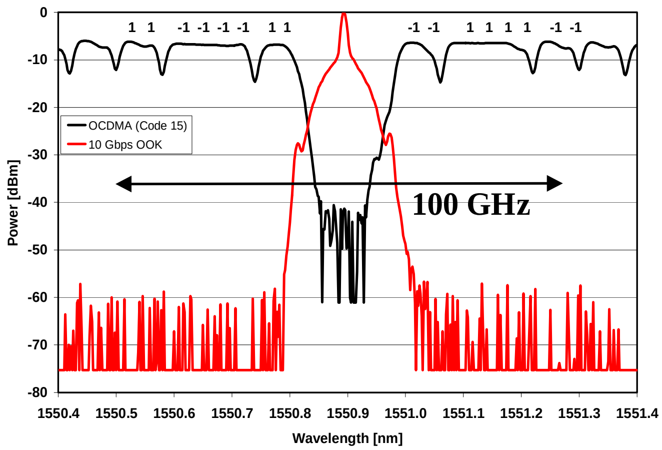

Figure 2: Measured optical spectra: 2.5 Gbps OCDMA signal spanning two disjoint frequency bands and phase encoded with the 15th Hadamard code of length 16, plus a suitably centered 10 Gbps OOK signal.

In particular, we modified the phase mask in order to allow for: 1) 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 0-padded Hadamard codes of length 16; 3) *notching* of the 4 central MLL lines. As shown by the frequency response of one of the encoder/decoders in the top curve of Figure 2, this allowed us to create a 20 GHz "spectral hole" in the middle of the OCDMA band. The purpose of creating this "spectral hole" is to allow for the insertion of a 10 Gbps OOK signal. It is worth emphasizing that our OCDMA system is actually spectrally spreading OCDMA users over a band characterized by a non-contiguous frequency range.

In Figure 3, 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.

The modulated signals are encoded using two different spectral phase encoders (SPEs) and, with filtering and amplification, are combined with a standard 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 OC-192 receiver while a spectral phase decoder (SPD) and optical time gate (OTG) isolates one of the OCDMA signals for reception at a SONET OC-48 receiver.

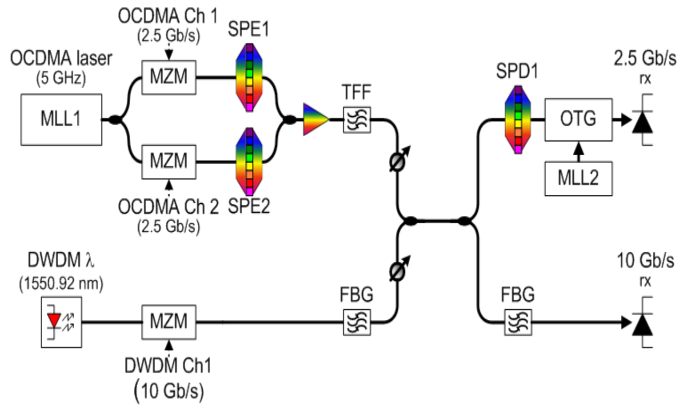

Figure 3: Experimental set-up.

Figure 4 shows the BER performance obtained decoding one of the OCDMA users (code 14) in the presence of the second OCDMA user (code 15) and the OOK signal. Figure 5 reports the OOK BER in four cases: when only the one 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 when the OCDMA signal is received at the same (or lower) power than the OC-192 signal.

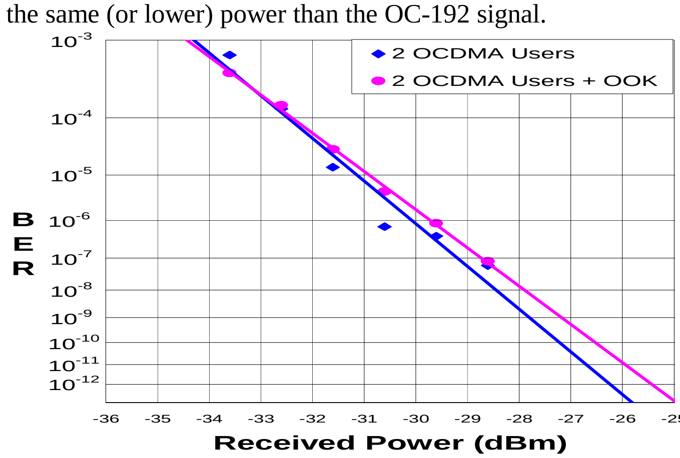

Figure 4: OCDMA performance with and without the SONET channel.

V. 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 paper shows that properly designed OCDMA signals can indeed co-exist with conventional WDM signals thus providing *both* additional transport capability to existing WDM systems *and* co-existence capability with legacy systems.

As opposed to other OCDMA schemes that represent an alternative technology to existing WDM-based systems, the OCDMA scheme originally proposed in [9] represents an effort in the direction of enabling co-existence of these two different technologies as a means of providing additional capacity within the same WDM channel and not only as a means of enabling multiple access. Finally, the possibility of transmitting over disjoint frequency bands can be exploited for insertion of a concurrent optical clock and/or optically generated RF signal for injection locking experiments.

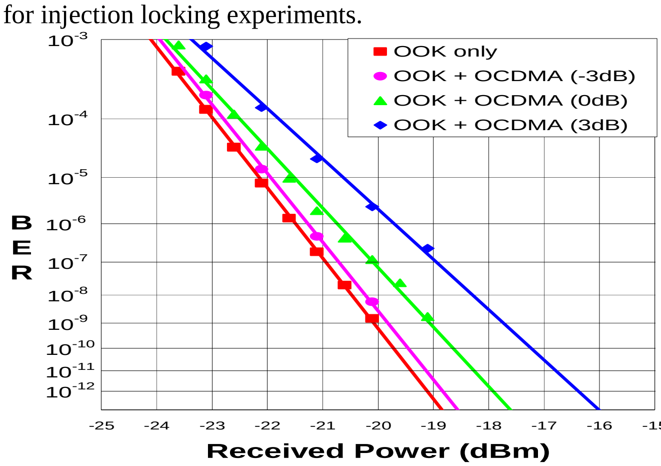

Figure 5: OC-192 OOK channel performance with and w/o the two OCDMA channels present at different power ratios.

A useful consequence of the property reported here is the possibility of transforming the original DWDM-compatible synchronous[(2)] (orthogonal) system described in [9] into an asynchronous DWDM-compatible one. In fact, spreading over disjoint frequency bands is also possible if quasi-orthogonal codes are used. Therefore, we are now able to spread over all the ITU windows in the C-band, notching all the frequencies outside the ITU windows, and using quasi-orthogonal codes since now we have the availability of much longer codes that allow for asynchronous access as shown in Figure 6.

As a final comment, we would like to point out that the considerations made here for OCDMA still apply to other modulations such as Ultra-Wide Band (UWB) and to other domains, such as wireless or power line communications [14]. In particular, phase encoding may be a spectrally efficient technique for allocating a scarce resource such as the RF spectrum. The current method of assigning spectrum to different radio systems is a fixed allocation scheme; however, this is inefficient since bands show local heavy, medium, and sparse activity so that transient "opportunity holes" (not necessarily contiguous) in the spectrum arise. Therefore we face a true paradox: the radio spectrum, whilst being a scarce and valuable commodity, is often underused or idle at certain times or in certain areas. We believe that spectral phase-encoding represents an appealing solution to this problem since it allows for adaptive "waveform morphing" on the basis of the available spectrum. In fact, transmitting signals over disjoint frequency support allows for the opportunistic exploitation of the available slivers of spectrum, which may indeed not be contiguous.

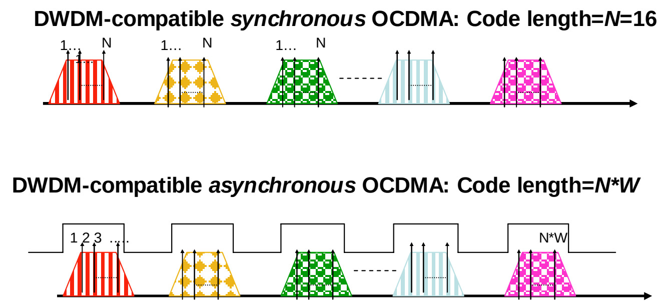

Figure 6: Exploitation of the possibility of spreading over disjoint frequency bands, allowing us to use long codes of length *N*W*, where *W* is the number of ITU windows in the C-band, for asynchronous multiple access.

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(2) The current generation of phase encoders allows access to at most N=32 frequency bins; therefore, since we cannot rely on long codes to mitigate interference, we were forced to use orthogonal codes.