CDMA IN OPTICS

Invited paper
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Abstract As spectrum spreading and CDMA proved themselves as very efficient in radio communication CDMA application in optical communication seemed to be reasonable as well. Research in this field started two decades ago or so and is still flourishing. In this tutorial paper – after giving a brief listing of relevant concepts in optical communications – concepts of optical spectrum spreading, techniques of temporal and spectral coding are described, possibilities of long-haul application and some networking issues are discussed.

1. Introduction

In optical networks Wavelength Division Multiplexing (WDM) and its dense version (Dense WDM, DWDM) are the basic methods in maximizing the capacity of optical fibers and in solving various networking tasks. In our days WDM/DWDM technology is rather well evolved and nation-wide WDM networks are operating in several parts of the world; also, this is a hot topic in telecommunication research and as a result, technology becomes more and more evolved.

While WDM is very likely the most evolved and so the best approach in realizing wide range optical networks it is less favorable in Local Area Networks (LANs), (belonging rather to the category of multiple access than to multiplex networks). The main reason of this is that WDM networks are not very much flexible and scalable – being basic requirements in LANs – and also, in most realizations they require significant central control and command.

On the other hand as Code Division Multiple Access (CDMA) proved itself to be very successful in wireless networks – note that this is applied in UMTS, the third generation of mobile networks. Based on these results and also on special characteristics of fiber optics an intensive research work was started in optical CDMA (OCDMA) for LAN and similar applications, some fifteen-to-twenty years ago. This work, of course, led to significant results in OCDMA theory, techniques and fields of application. In particular, the extremely wide band available in the optical frequency band makes it apt to use code division technique, in spite of the fact that some basic characteristics are less suited than the RF band. As an interesting point it is noted right here that some of the devices specially developed for application in WDM systems find application in OCDMA as well; lasers operating at multiple frequencies are one example. It is also mentioned that OCDMA became more general than its original application, i.e. application in LANs and wide-area applications exist as well.

2. A few points from the techniques of optical communications

2.1 E/O and O/E conversion, modulation

In optical communications information bearing electrical signal is converted into the optical domain. It is transmitted through the optical transmission medium. And then – maybe, after optical processing – it is reconverted into the electrical domain. Roughly viewing this process we can say that the electrical domain is characterized by elementary particles electrons while the optical domain by photons. Thus in E/O (Electrical-to-Optical) conversion electrons generate photons while the O/E conversion (Optical-to-Electrical) is characterized by the inverse operation. Thus in the most plausible optical modulation scheme optical power is proportional to the electrical signal, leading to Intensity Modulation (IM) as the basic modulation method. Really, in optical communications nearly exclusively IM is applied. While current can be positive or negative, nonzero intensity is definitely positive. Thus for OCDMA strictly positive spectrum spreading codes must be found with good correlation properties. A significant result of recent researches is the possibility of applying bipolar codes in this basically unipolar medium.

2.2 The transmission medium

Transmission medium is the optical fiber. As it is well known, optical fiber has very low loss and very wide transmission band. Its main adverse characteristics – of course, not being free of these – are listed in what follows.

Loss is minimal in standard glass fiber in three windows around 850, 1300 and 1550 nm wavelength. Loss of single-mode fiber in the band of 1.5 \( \mu \)m is a few tenths of a dB per km.

Dispersion (i.e. nonlinear dependence of the phase constant on frequency) causes linear distortion. Pulse broadening, modulation suppression are examples of the effects of dispersion.

Nonlinearity may have various effects. Self-Phase Modulation (SPM) is one of these. Due to SPM intensity-modulated light becomes phase modulated. Nonlinear scattering is another example of nonlinear effects.
Birefringence may cause random variation of light polarization.

2.3 Noise sources

Like in RF CDMA one source of disturbance – maybe the most harmful one – is Multi-User Interference (MUI) in OCDMA as well. MUI is much dependent on the spectrum spreading codes, as we shall see in the sequel.

Shot-noise – mainly due to quantized character of light radiation – causes noise in the photo-detected current. Average magnitude of the shot-noise current is

$$E[I^2] = 2eIB$$

(1)

with $e$ the electron charge,
$I$ the DC current
and $B$ the bandwidth

Mean square magnitude of the Relative Intensity Noise (RIN) current is

$$E[I^2] = KI^2(1 + P^2)\tau_cB$$

(2)

with $\tau_c$ coherence time of the light source,
$P$ the degree of its polarization and
$K$ a constant depending on the light source; $K=1$ for thermal sources but can attain values up to 8 in various light sources.

Beat noise or Phase Induced Intensity Noise (PIIN) is due to interference if fields of partially coherent light sources are added; mean square noise current is

$$E[I^2] = \frac{1}{2} I^2(1 + P^2)\tau_cB$$

(3)

i.e. it has a form nearly the same as (2). Of course, if the sources are fully uncorrelated (i.e. if $\tau_c=0$) they are exactly power-additive, without any interference. However, 0 coherence time would require infinite bandwidth, which is not the case. As it will be seen in some OCDMA cases PIIN is the main noise source.

Shot noise due to photodetector dark current is nonzero but usually negligible.

Thermal noise is nonexistent in the optical frequency band. However, post(photo)detector thermal noise can be non-negligible.

2.4 Some basic optical components

A star coupler is the component to form an optical broadcast network. In our discussions this will be the basic component to form an optical LAN.

A wideband optical signal can spatially be decomposed by a diffraction grating. This is one means for spectrally processing or manipulating a signal. A diffraction grating can be applied also to recombine a spatially decomposed signal.

Once spatially decomposed a wideband signal can be processed by a Spatial Light Modulator (SLM). An SLM contains a large number of pixels. Pixels can attenuate, transmit or absorb/reflect light or change its phase or its polarization state. Transmission, phase or polarization characteristic of individual pixels can be adjusted by addressable voltages. SLMs are liquid crystal or MEMS devices.

3 Concepts in optical spectrum spreading

3.1 Temporal coding

To spread the spectrum of an intensity-modulated optical field, the self-evident solution is the application of on-off keying (OOK). I.e.: the signature sequence should be composed of 0-s and 1-s, (i.e. of short pulses, pulses of duration $T_c$, called chip-time), superimposed on the data modulation. Thus in the spread spectrum signal an information bit “0” corresponds usually to 0-intensity, an information bit “1” corresponds to the spectrum spreading code. Processing gain is thus $T/T_c$. Each user (normally: each sink) has a distinct signature code.

3.2 Spectral coding

In spectral coding an unmodulated wide-band signal is generated and spectrally decomposed. In the coding process amplitude or phase of the spectral components is modulated according to the appropriate code.

3.3 On-off vs. Pulse Position Modulation

While in OCDMA the basic modulation principle is OOK, M-ary PPM can have advantages over simple OOK. With this $n = \log_2 M$ bits are united into one symbol. The M-ary symbol contains the signature sequence in the appropriate position. So an orthogonal signal set is formed.

3.4 Two- and three-D modulation

In 2D time and frequency are modulated. In 3D parts of the 2D signal are transmitted through more than one fiber.

4 Temporal coding: basic systems and Optical Orthogonal Codes

4.1 General

An OCDMA system is shown in Fig. 1. Being a broadcast system sinks receive all source signals – as is normal in the case of CDMA. The advantage of this scheme is self-evident: it doesn’t require any central control. The price to be paid for this is that signals of various users are directly connected to each other, interfering with each other. Therefore it is the task of the spectrum spreading codes to mitigate this interference.
To go a little bit into details, a code is a periodic sequence of 0-s and 1-s, with the spectrum spreading sequence:

\[ x(t) = \frac{1}{T_c} \sum_{k=-\infty}^{\infty} a_k P(t - kT_c), \quad x(t) = x(t + nT_c), n = 0, \pm 1, \ldots \]  

(4)

with \( T \) and \( T_c \) the bit time and the chip time, respectively. \( x_k = 0 \) or 1, according to the signature sequence \( P(t) \) (the intensity) pulse.

Thus, while voltage can be positive or negative, current or field strength), in optics it is power (or intensity). Thus, while in RF systems what is modulated is voltage (or current), in optics it is power (or intensity). So spectrum-spreading codes, composed of positive elements must be found, having appropriate correlation properties.

Of course, \( a = 0 \) and \( x_k = 0 \); this is not possible; however OOC-s can be constructed with \( \lambda_a = \lambda_c = 1 \); usually these are called strict OOCs. Usually an OOC is designated by the quadruple of names, prime codes (if \( p \) is a prime the code size is \( p-1 \)).

Note that sequences having low auto- and cross-correlation magnitudes are of very low weight. This has at least three unfavorable consequences. For appropriate performance the peak-to-average ratio must be rather high, its magnitude being \( F/w \). The number \( N \) of sequences (and consequently the maximal number of users in a network) is rather low; as it can be shown, for an \( (F, w, 1, 1) \) code \( N \leq (F-1)/w(w-1) \). Finally, as a consequence of that, for an acceptable number of users the spectrum-spreading ratio \( F \) must be very high; this means that the per-user bit-rate must be relatively low and consequently the total system capacity is also low.

In Fig. 2a and 2b an OOC spectrum spreader and a de-spreader, respectively, are shown. These are the so-called “passive” versions. For sake of completeness the “active” de-spreader is shown in Fig. 3. One of the main differences between the passive and the active version is that in the former the electrical circuits must have the spread bandwidth while in the latter the un-spread bandwidth of the information signal is sufficient.

Data demodulator is a threshold device. As intensity is a definitely positive quantity MUI can cause decision errors only in the “0” information bits. And this happens if the sum of interfering intensities exceeds the threshold.
much poorer characteristics than bipolar codes applied in RF spread spectrum systems.

\[ c_1 + c_2 \]

Fig. 4 Forming of MUI in OCDMA with OOC

4.2 Synchronous OCDMA

Until now user terminals were assumed to be completely asynchronous. The possibility to operate in an asynchronous way is one of the main advantages of CDMA under general conditions. However, in a LAN of rather limited geographical size it is not too difficult to achieve synchronism: a pulsed optical source, serving as “chip-generator” can be located centrally, sending pulse trains to each user. If the users are connected to this pulse generator with appropriate delays, appropriate synchronism is insured. This makes code construction significantly easier: if synchronization information needs not to be extracted from the CDMA signal itself, time-shifted autocorrelation magnitudes \( O_a \) may have magnitude even of \( w \), i.e. the zero-shifted autocorrelation. (As: the only reason for requiring a low time-shifted autocorrelation is the need of easy synchronizability.) This ease results in an increased code size and also in an increased number of simultaneous users.

5 Spectral coding OCDMA

According to the view of this author a 1995 paper of Kavehrad, Zaccarin brought real breakthrough in OCDMA techniques. While OOCs operating with very narrow pulses need expensive (like mode locked) laser light sources, cheap LEDs or superluminescent diodes (SLDs) yield non-coherent i.e. noise like wideband light. Fig. 5 shows the basic principle of a spectral amplitude encoder.

The SLM is adjusted according to the code: pixels transmit or attenuate appropriate parts of the spectrum, realizing thus spectral “1”s and “0”s.

A second breakthrough is the recognition: a certain sort of differential decoding makes possible the application of unipolar version of bipolar codes. For this purpose one of the best codes is formed of rows of an \( N \times N \) Hadamard matrix; these are composed of \( N/2 \) 0-s and 1-s. A relevant coder and decoder are shown in Fig. 6 a and b.

In these “0”s and “1”s are represented by a Hadamard code and its complement, respectively. Thus the integrator output current is \( \pm R.P.N/2 \) if the input is a “0” or a “1”, respectively of code \( k \). (Here \( R \) is the photodetector responsivity and \( P \) the optical power.) However, any input of code of subscript different from \( k \) results in output 0: equal currents are outputted from the upper and the lower photodetectors of Fig. 5b, their difference being so zero.

Thus this system has various advantages. It operates with cheap light-sources. The number of available codes is higher than that of OOCs. And (under ideal conditions) there is no MUI.

To conclude this section note that a different spectral coding principle also exists. In that rather than a noise-like light-source, a femtosecond pulse is the wideband signal to be decomposed spectrally. Of course, this needs an expensive light source; otherwise its operation can be the same as discussed above. On the other hand, in this case spectral phase modulation is also possible.

As seen above, a MUI-free operation is possible. In its absence the main source of malfunctioning is PIIN, see point 2.3 and Eq (3).
6 Two- and three-dimensional codes; OCDMA in long-haul networks

Application of OCDMA rather than DWDM in long haul networks would be more than justified if similar techniques to those in DWDM could be applied. As, number of codes – although limited – is significantly higher than number of frequencies available for DWDM, and in addition OCDMA is much more flexible. While the systems discussed in previous sections are well applicable in LANs and similar short range networks they are less favorable in long haul applications. This is due to the dispersion of the fibers: signals of much wider spectrum would undergo much heavier distortion and would require more complex dispersion compensation than DWDM.

A method to solve this problem is to apply so-called “2-dimensional” or matrix codes i.e. to encode the optical signal in time and in frequency. The basic principle is the following: the code-sequence (either temporal or spectral) of “1”s and “0”s is ordered into an \( m \times n \) matrix. In the realization rows correspond to wavelengths and the columns to chip time-slots; thus “1”s correspond to pulses at the relevant frequencies. The total number of matrix elements, \( m \times n \) is equal to the code length (with possible “0”s added). Thus the spectrum spreading applied in one wavelength equals to the number of elements in one row – rather than the total spectrum spreading of \( F \).

As an example take the OOC code-word (1010011) (i.e. \( F=7, w=4 \)). This is organized into a \( 3 \times 3 \) matrix by folding the code word (with two additional zeros), resulting in

\[
\begin{bmatrix}
1 & 0 & 1 \\
0 & 0 & 1 \\
1 & 1 & 1
\end{bmatrix}
\]

That means that the transmitted sequence contains a \( \lambda_1 \) and a \( \lambda_3 \) pulse in time-slot 1, a \( \lambda_3 \) pulse in time slot 2 and a \( \lambda_1 \) pulse in time slot 3. A sequence like that can be generated by applying multi-wavelength lasers; these, originally designed for WDM systems, are available commercially.

A further advantage of matrix codes is: by down-shifting rows of the matrix new codes are generated with equal correlation characteristics increasing cardinality.

As a 3rd dimension space can also be included in the coding operation. In that case codes are ordered in a 3D \( m \times n \times p \) matrix and multiwavelength signal streams are transmitted over \( p \) fibers.

Or, in a version of 2D, \( m \times p \) is also proposed. In Eq. (6) a spectral amplitude/space M-matrix code is shown, generated from two (in the example: identical) M-sequences.

![M-matrix codes](image)

Fig. 7 Comparison of WDMA, and CDMA; a) utilization vs. offered load; b) retransmission number vs. utilization

Performance comparison of OCDMA and DWDM LANs shows an advantage in favor of the former – as seen in Fig. 7. 2D prime codes were used with \( p \), chips/frequency.

7 Higher-than-physical layer studies

Although investigations in codes and systems do not decrease during the years studies in network issues are intensifying in recent years. Some results are briefly mentioned in this section.
Bibliography

A rather complete bibliography of papers before 2002 is http://www.co.it.pt/~slug/research/optical_CDM A/final_report/final_report.html

In what follows not too much from this period will be listed.

One of the first papers in two parts (among others, defining OOCs) are


Basic papers dealing with spectral coding


A paper on synchronous OCDMA


Papers on 2D codes and applications


Papers on PPM-OCMDA


Papers on higher-than-physical layer


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