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TECHNICAL REPORT

Fibre optic communication system design guidelines –
Part 16: Coherent receivers and transmitters with high-speed digital signal processing

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Part 16: Coherent receivers and transmitters with high-speed digital signal processing

FOREWORD

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IEC 61282-16 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is a Technical Report.

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Draft	Report on voting
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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 61282 series, published under the general title *Fibre optic communication system design guidelines*, can be found on the IEC website.

Future documents in this series will carry the new general title as cited above. Titles of existing documents in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

Coherent optical receivers are widely used in long-haul fibre optic communication systems, especially in systems that transmit optical carriers at data rates of 100 Gbit/s and higher. While the principle of coherent detection is very similar to that of super-heterodyne (or homodyne) detection in radio and microwave receivers, its implementation is significantly more challenging. The main reason is that optical frequencies are substantially higher than radio frequencies, so it becomes more difficult to match the local oscillator frequency in the coherent receiver to the frequency of the transmitted optical signal. Furthermore, optical signals tend to be highly polarized, which means that the amplitude of a coherently received signal can be substantially reduced or even vanish if the polarization state of the local oscillator light does not match the polarization state of the received optical signal. This polarization matching is particularly difficult to achieve in fibre optic communications systems, which usually do not preserve the launched state of polarization of the transmitted signal. To overcome these problems, modern coherent receivers typically consist of four parallel coherent optical mixers that provide phase and polarization diversity, and they rely on high-speed digital signal processors to retrieve the transmitted data from the four received electrical signals.

This rather complex coherent receiver architecture is further justified by the fact that it allows the receiver to mitigate various types of signal impairments introduced in the fibre optic link (or in the receiver itself) simply by means of additional electronic signal processing. Most notably, it is possible to substantially reduce the signal distortions caused by polarization-mode dispersion (PMD) or uncompensated chromatic dispersion (CD) in the fibre link, without requiring additional optical PMD or CD compensators. For this reason, coherent optical communication systems generally allow signal transmission at much higher data rates than communication systems using direct-detection receivers. Furthermore, coherent detection with subsequent digital signal processing facilitates the decoding of complex vector-modulated signals, such as quadrature-amplitude modulated signals (QAM) and polarization-multiplexed (PM) signals, and thereby the transmission of higher data rates.

Aside from fibre optic communications systems, coherent optical receivers are also used in various test and measurement instrumentation. Most notable examples are optical modulation analysers (OMAs) and high-resolution optical spectrum analysers (HR-OSAs). Optical modulation analysers are high-performance optical reference receivers and are used to assess the signal quality of complex vector-modulated optical signals. They are typically composed of a carefully calibrated coherent receiver and a high-speed real-time digitizing oscilloscope to record the coherently received signals, which are then analysed with the help of a software-based digital signal processor.

High-resolution optical spectrum analysers are often used to analyse narrowband features of the optical spectrum of a modulated signal, such as a residual optical carrier or other spectral lines. In contrast to OMAs, they typically employ a low-speed coherent receiver, so as to utilize the frequency-selectivity of coherent detection. The key component in these instruments is a continuously tuneable local oscillator, which is scanned over the frequency range of the signal to be analysed while the total power of the coherently received signal is recorded. The spectral resolution of these instruments can be of the order of a few MHz. Other examples of coherent optical test instruments include in-service PMD analysers and in-band optical signal-to-noise ratio analysers for polarization-multiplexed signals.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDELINES –

Part 16: Coherent receivers and transmitters with high-speed digital signal processing

1 Scope

This part of IEC 61282 is a technical report on coherent optical receiver and transmitter technologies that are employed in fibre optic communication systems as well as in optical test and measurement equipment. This document describes the principle of operation and functional capabilities of coherent optical receivers as well as the operation of optical transmitters used to generate complex vector-modulated signals. It is intended to serve as a technical foundation for other IEC documents and standards related to coherent optical transmission techniques.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-731, *International Electrotechnical Vocabulary (IEV) – Part 731: Optical fibre communication* (available at www.electropedia.org)

IEC TR 61931, *Fibre optic – Terminology*

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-731 and IEC TR 61931 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.2 Abbreviated terms

ABC	adaptive bias control
ADC	analogue-to-digital converter
AM	amplitude modulation
ASIC	application-specific integrated circuit
ASK	amplitude-shift keying
BER	bit-error ratio
BPSK	binary phase-shift keying
CD	chromatic dispersion
CFP	C form-factor pluggable
CMA	constant modulus algorithm

CMRR	common-mode-rejection ratio
COSA	coherent optical subassembly
CW	continuous wave
DAC	digital-to-analogue converter
DD-LMS	decision-directed least-mean-square
DGD	differential group delay
DSP	digital signal processor
DWDM	dense wavelength-division multiplexing
EDFA	erbium-doped fibre amplifier
ENOB	effective number of bits
EVM	error-vector magnitude
ER	extinction ratio
EQL	equalizer filter
FEC	forward error correction
FFT	fast Fourier transform
FIR	finite impulse response
FSE	fractionally spaced equalizer
FWM	four-wave mixing
GS	geometrically shaped
GVD	group velocity dispersion
HB-CDM	high-bandwidth coherent driver modulator
HR-OSA	high-resolution optical spectrum analyser
LO	local oscillator
LPF	low-pass filter
MAP	maximum a posteriori
MMA	multi-modulus algorithm
MMI	multi-mode interference
MZM	Mach-Zehnder modulator
NLFT	nonlinear Fourier transform
NLPN	nonlinear phase noise
I	in-phase component
IA	implementation agreement
ICR	intradyne coherent receiver
IC-TROSA	integrated coherent transmit-receive optical subassembly
iFFT	inverse fast Fourier transform
Im	imaginary part
InP	indium phosphide
ITLA	integrable tuneable laser assembly
OFDM	orthogonal frequency-division multiplexing
OMA	optical modulation analyser
OOK	on-off keying
OSA	optical spectrum analyser
OSNR	optical signal-to-noise ratio

OTN	optical transport network
PAM	pulse-amplitude modulation
PBC	polarization beam combiner
PBS	polarization beam splitter
PC	polarization controller
PD	photodiodes, photo detectors
PDL	polarization-dependent loss
PLC	planar lightwave circuit
PMD	polarization-mode dispersion
PM	polarization multiplexed
PM-QPSK	polarization multiplexed QPSK
PR	polarization rotator
PRBS	pseudo-random binary sequence
PS-QPSK	polarization switched QPSK
PSK	phase-shift keying
Q	quadrature component
QAM	quadrature amplitude modulation
QASK	quaternary amplitude-shift keying
QPSK	quaternary phase-shift keying
RAM	random access memory
RDE	radius-directed equalizer
Re	real part
RF	radio frequency
RMS	root-mean-square
ROADM	reconfigurable optical add-drop multiplexer
RRC	root-raised-cosine
SiPh	silicon photonics
SNR	signal-to-noise ratio
SPM	self-phase modulation
SSB	single-sideband
TDE	time-domain equalizer
TEF	transversal electrical filter
TIA	transimpedance amplifier
TROSA	transmit-receive optical subassembly
VCO	voltage-controlled oscillator
WDM	wavelength-division multiplexing
X	X-polarized component
XI	in-phase component of X-polarized signal
XPM	cross-phase modulation
XQ	quadrature component of X-polarized signal
Y	Y-polarized component
YI	in-phase component of Y-polarized signal
YQ	quadrature component of Y-polarized signal

4 Background

The development of coherent optical receivers started in the late 1980s and was driven by the desire to improve the sensitivity of optical receivers in order to increase the reach of fibre-optic communication systems [1][1]. In addition, coherent receivers were expected to facilitate decoding of phase-shift-keyed signals (PSKs) and to serve as narrow-band frequency selectors in wavelength-division multiplexed systems. However, the interest in coherent receivers diminished rapidly after practical Erbium-doped fibre amplifiers (EDFAs) became available just a few years later, because these optical amplifiers enabled repeater-less transmission of optical signals over very long distances without the need for coherent detection. Besides, coherent receivers at that time were still not mature enough to be deployed in practical fibre optic communication systems, because coherent detection was very sensitive to the polarization state of the received signals and, in addition, required transmitter and local-oscillator lasers with very high phase stability [2].

The interest in coherent optical receiver technology revived in the late 2000s, when high-speed analogue-to-digital converters (ADCs) and high-speed digital signal processors (DSPs) became available. These high-speed ADCs sample the received electrical signals at or above the symbol rate of the transmitted signals and deliver the digitized signals to a DSP, which then processes the sampled electrical signals in real time to retrieve the transmitted digital or analogue information [3]. It turned out that the combination of linear signal detection in coherent receivers and signal processing in high-speed DSPs not only solved the technical problems of early-generation coherent receivers, but also enabled electronic mitigation of linear (and even nonlinear) signal distortions encountered in the optical communication link [4]. Most importantly, coherent reception with subsequent digital signal processing allows adaptive mitigation of undesired impairments caused by polarization-mode dispersion (PMD) and uncompensated chromatic dispersion (CD) in the transmission fibre, either of which can severely distort the waveforms of optical signals at data rates of 10 Gbit/s or higher [6]. Modern coherent receivers are often capable of accommodating large amounts of PMD and CD and, as a result, allow signal transmission at much higher modulation rates and/or over much longer distances than direct-detection receivers [5]. Moreover, the DSP used in coherent receivers can even mitigate signal distortions resulting from non-ideal optical and electronic components in the coherent receiver itself, such as signal skew, amplitude imbalance, and other deviations from the desired frequency response, as described in more detail in Clause 5 of this document.

Coherent receivers also facilitate the decoding of complex vector-modulated signals, such as M-ary PSK or quadrature-amplitude modulation (M-QAM), which can carry several times the information of binary on-off-keyed (OOK) signals of the same symbol rate [7]. Moreover, modern coherent receivers are capable of decoding polarization-multiplexed (PM) signals, which can carry up to twice the information of corresponding single-polarized signals [7], [8]. In fact, the first commercially deployed fibre optic communication systems with coherent detection transmitted polarization-multiplexed quaternary phase-shift-keyed (PM-QPSK) signals at symbol rates of 10 GBd, yielding a total transmission rate of 40 Gbit/s per optical carrier [9]. Just a few years later, a second generation of coherent receivers was introduced allowing transmission of single-carrier PM-QPSK signals at 100 Gbit/s [10]. Subsequent development of transmitters with linear modulation response then enabled transmission of polarization-multiplexed 16QAM signals at 200 Gbit/s and even 400 Gbit/s [11]. Moreover, transmission of 32QAM and 64QAM signals under practical conditions has been demonstrated, and the feasibility of transmitting of even higher-order QAM signals is under investigation [13], [14], [15].

The generation of higher-order optical QAM signals usually requires linear modulators and driver amplifiers as well as careful equalization of non-ideal transmitter characteristics introduced by the optical and electronic transmitter components, including frequency roll-off, skew, and nonlinear response. This equalization can be achieved by employing digital signal processing in the transmitter to facilitate adjustable pre-distortion of the electrical signals applied to the optical modulator [2]. Therefore, as soon as fast high-speed digital-to-analogue

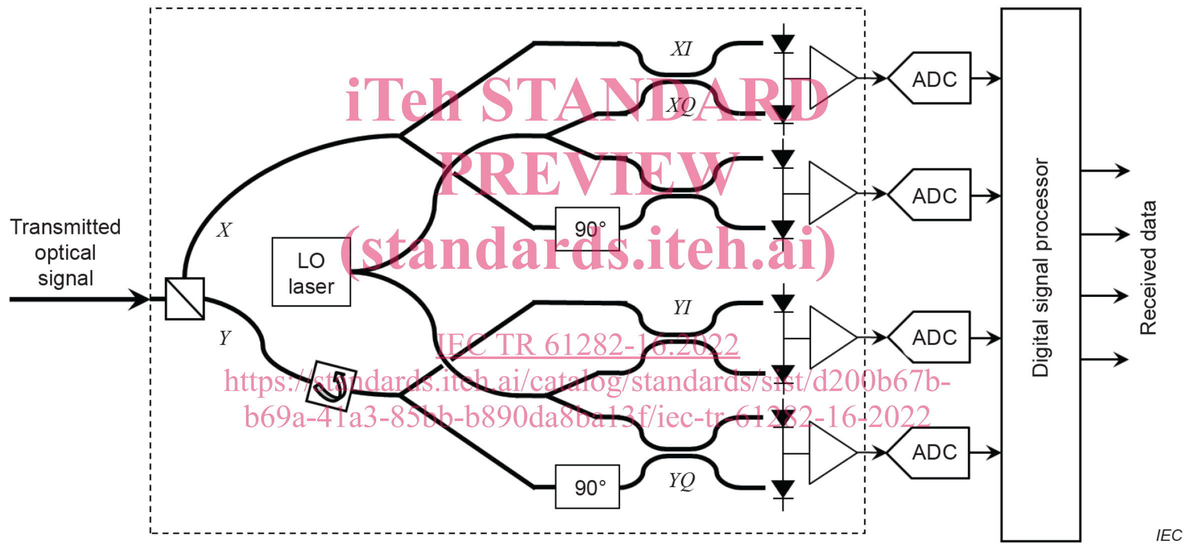
[1] Numbers in square brackets refer to the Bibliography.

converters (DACs) became commercially available, high-speed DSPs were also introduced in optical transmitters. In addition to equalization, the transmitter DSPs are frequently used to spectrally shape the electrical drive signals applied to the optical modulator in order to generate optical signals with the desired optical spectrum [12]. Transmitter DSPs also facilitate electronic pre-compensation of chromatic dispersion in the transmission fibre [6], [15]. Clause 8 describes the generation of optical signals with complex modulation formats and the functions of transmitter DSPs.

5 Coherent transmission of vector-modulated signals

5.1 Typical receiver architecture

As mentioned in Clause 4, modern coherent receivers for fibre optic communication systems usually employ four parallel coherent mixers that are configured in such a way that they detect the optical amplitude, phase, and polarization state of the received signal. Figure 1 displays a typical arrangement of these four mixers, which are labelled *XI*, *XQ*, *YI*, and *YQ* [16]. The mixers thus generate four analogue electrical signals, which are then converted to digital signals via high-speed analogue to digital converters (ADCs) and further processed in a high-speed digital signal processor (DSP).



Key

ADC Analogue-to-digital converter

LO Local oscillator

X *X*-polarized signal

Y *Y*-polarized signal

XI In-phase component of *X*-polarized signal

XQ Quadrature component of *X*-polarized signal

YI In-phase component of *Y*-polarized signal

YQ Quadrature component of *Y*-polarized signal

Figure 1 – Coherent optical receiver

The operation of these mixers and their capabilities will be discussed in more detail in Clause 6. It is important to note that the arrangement shown in Figure 1 makes the coherent receiver insensitive to time-varying fluctuations in the optical phase and polarization state of the received signal, which is a highly desirable feature for practical applications in fibre optic communication systems [1]. Moreover, it also allows the receiver to decode complex vector-modulated signals in which amplitude, phase, and polarization state are independently modulated [8], [17]. As described in more detail in 5.3, these vector-modulated signals can carry several times more