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MODERN MODULATION METHODS

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Explanatory Notes

Definition

Interesting

Note

Example

Summary

Advantage

Disadvantage

ANNOTATION

A modulation format is necessary to suit the information to a form that can be transmitted over an optical fibre. In addition, achieving high bit rates and significant information capacities of transmission systems is associated with the use of appropriate modulation formats. Every modulation performs in a different way and is suitable for different transmission scenario. For this reason, it is necessary to familiarize students with principles of advanced modulation formats, which are part of any optimization processes within modern high-speed optical transmission networks.

OBJECTIVES

The goal of this teaching material is to present the overview of digital modulation formats, including amplitude, phase, a multilevel or advances formats combining more parameters. The description includes principle of particular modulations, their benefits and certain disadvantages. A reader should be able to consider which modulation format is suitable for a given application area (in terms of suitable fibre lengths, information capacity, spacing between frequency channels, among others).

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1 Digital intensity modulations: Alternate Mark Inversion, Duobinary Modulation, Carrier Suppressed Return to Zero

1.1 Basic classification of digital optical modulations

Information can be transmitted in an optical communication system in a form of optical symbols that are created by modulating a source of optical radiation.

Goals

- The primary goal of modulation is to suit the information signal to a form that is acceptable for transmission.
- Another goal is to reduce chromatic dispersion causing different speed of each frequency components contained in an optical pulse.
- And finally the goal is to avoid the problem of long string of the same binary symbols, i.e. long strings of logical 0s or logical 1s that can potentially cause problems with timing.

Classification

There are many modulation formats used in fibre-optic communication systems. They can be classified based on whether they modulate the signal's amplitude or phase:

- Intensity modulation formats:
  - **OOK** – *On-Off Keying*
  - **AMI** – *Alternate Mark Inversion*
  - **DB** – *Duobinary Modulation*
  - **CRZ** – *Chirp Return to Zero*
  - **CSRZ** – *Carrier Suppressed Return to Zero*
- Frequency modulation formats:
  - **OFDM** – *Orthogonal Frequency-Division Multiplexing*
  - **VDMT** – *Vectored Discrete Multi-Tone*
- Phase modulation formats:

- **PSK** – *Phase Shift Keying*
- **BPSK** – *Binary Phase Shift Keying*
- **DPSK** – *Differential Phase Shift Keying*
- **QPSK** – *Quadrature Phase Shift Keying*

- Formats combining amplitude, phase, polarization of a signal:
  - **PM-QPSK** – *Polarization Multiplexing QPSK*
  - **QAM** – *Quadrature Amplitude Modulation*
  - 16-QAM, 64-QAM, etc.
- *Multi-Carrier Modulations* (**MCM**):
  - **OFDM** – *Orthogonal Frequency Division Multiplexing*
  - **DMT** – *Discrete Multi-Tone*
  - **VDMT** – *Vectored Discrete Multi-Tone*

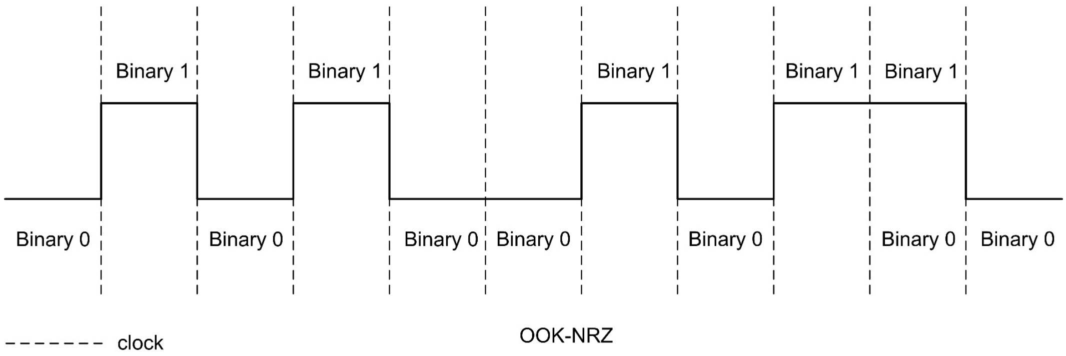
These are selected modulation formats (among many others) that are widely used in optical communications and are promising for high-speed transmission systems.

One of the most used formats is OOK, where binary 1 is assigned certain power level of a laser. Binary 0 is represented by absence of laser power. An optical symbol can last the entire clock period dedicated for a bit, then it is a *Non-Return to Zero* (**NRZ**) signal or some part of the bit slot, then it is a *Return to Zero* (**RZ**). One of the examples is that a symbol starts with the rising edge and returns to zero during the clock period, e.g. in the half of the bit slot.

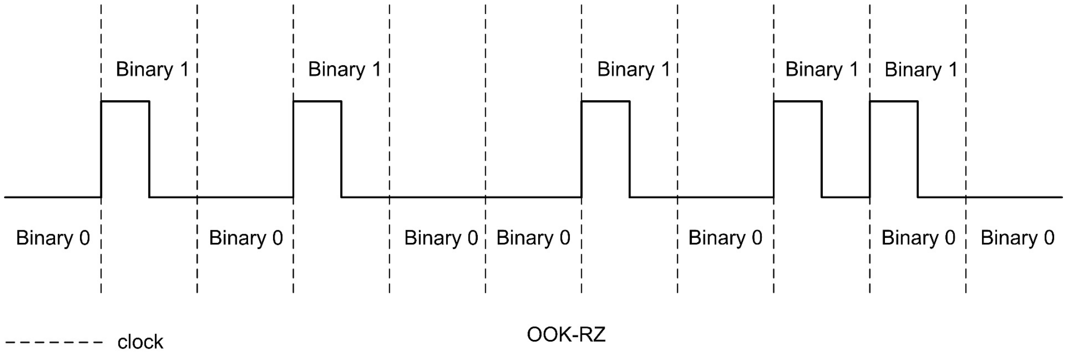
However, this is just one of the cases of NRZ and the symbols do not have to last exactly half of the period and start/end exactly at the edge.

+

The main benefit of having shorter symbols is greater immunity to their dispersion (spread due to different speed of particular components of which a laser pulse is composed, i.e. frequencies, modes, etc.) that leads to *Inter-Symbol Interference* (**ISI**).



The principle of OOK-NRZ modulation.



The principle of OOK-RZ modulation.

1.2 Carrier-Suppressed Return to Zero

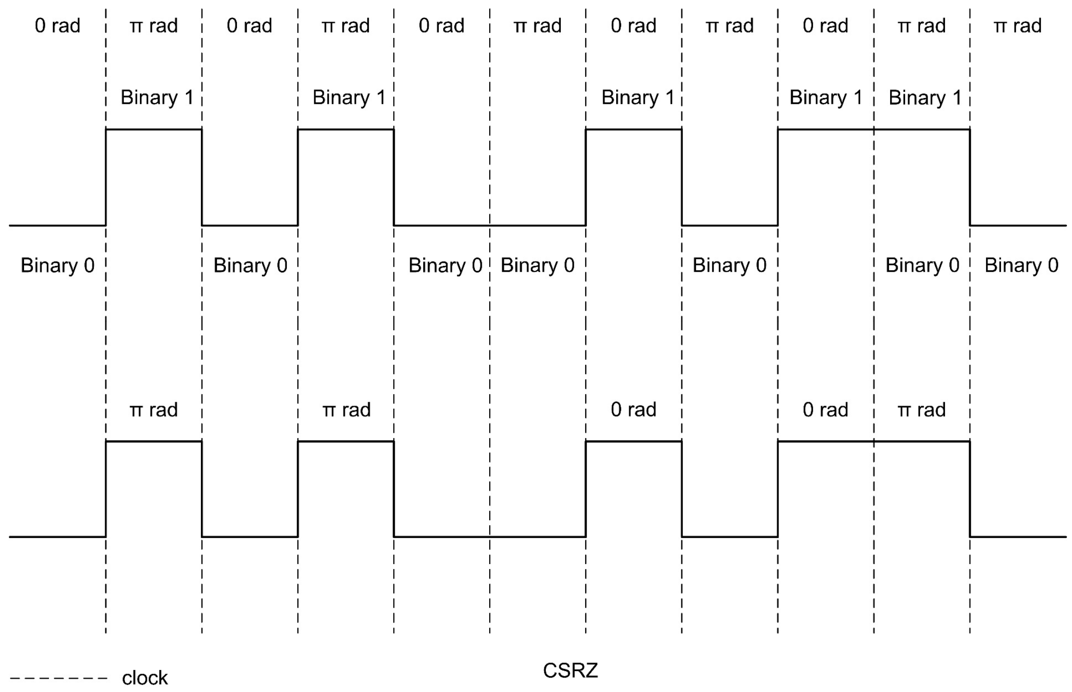
The principle

In *Carrier-Suppressed Return-to-Zero* (**CSRZ**), phase of optical carrier is changed by π every bit regardless of the data traffic, no matter if it's 0 or 1. The altered phase results in suppressing the carrier frequency of the source of optical radiation, generating the optical pulses.

The phases of a given binary sequence will be subtracted, the central peak at the carrier frequency is suppressed and this reduced power will be distributed in other parts of spectrum where real traffic is carried. The field intensity drops to zero between consecutive bits (RZ), and the field phase alternates by π between neighbouring bits, so that if the phase of the signal is e.g. 0 in even bits (bit number 2n), the phase in odd bit slots (bit number 2n+1) will be π, the phase alternation amplitude.

Main benefits

- Compared to standard RZ-OOK, the CSRZ-OOK is considered to be more tolerant to filtering and chromatic dispersion, thanks to its narrower spectrum.
- CSRZ signal are those to have a spectrum where no peak is present at the carrier and power is ideally zero at the carrier frequency.



The principle of CSRZ modulation.

1.3 Transceivers for optical modulations

A transceiver is a device composed of a transmitter and a receiver, which are combined and share common circuits or/and common housing. Transceivers are placed at the input of a network to launch modulated, encoded information to transmission medium (e.g. optical fibres) – a transceiver works as a transmitter, and at the termination of the network to decode, demodulate the signal – it operates as a receiver.

In case of transmission in both directions (e.g. duplex transmission), each transceiver transmits and receives data (e.g. alternately or at the same time in duplex).

A transmitter part can use lasers as a source of symbols in optical networks; a receiver contains a photodiode that converts an optical signal to electrical signal, which is further processed e.g. by a *digital signal processor* (**DSP**).

Transceivers for CSRZ modulation

Each following binary symbol has phase shifted by π. A *Mach-Zehnder modulator* (**MZM**) is used to create the binary string, where pulses have the same shape and altered phase. The speed of this signal is the same as the speed of an information signal.

The information signal in a form of electronic pulses is sent to the modulator, and based on this "control" signal, the pulses with altering phase produced in the modulator are released or suppressed. The output signal is then a certain product of those two signals.

- The NRZ transmitter is based on a continuous wave laser externally modulated with a Mach-Zehnder modulator. We set parameters, such as bit rate, laser frequency, full width at half maximum, output power of the laser, loss inserted by the modulator, etc.
- Unlike NRZ, we set the RZ raised cosine format in the electrical signal generator.
- For the CSRZ type, a NRZ optical generated signal is subsequently modulated by a second MZM, which is driven by a sinusoidal signal with a frequency half of the bit rate.
- Any two adjacent bits will have a π phase shift and it is possible to suppress the carrier and generate a CSRZ modulated signal.

- For NRZ, RZ and CSRZ, we use a compound receiver which models a photodetector, an electrical amplifier and an electrical filter.

1.4 Alternate Mark Inversion

In telecommunication, a paired disparity code is a line code in which at least one of the data characters is represented by two code words of opposite disparity that are used in sequence so as to minimize the total disparity of a longer sequence of digits.

The principle

The simplest example of a paired disparity code is *Alternate Mark Inversion* (**AMI**). It uses three logical levels corresponding to two bipolar levels: +,-, and zero.

E=m·c²

A binary 0 is encoded as absence of power during the bit interval (zero voltage), while a binary 1 is encoded alternately as a positive voltage or a negative voltage. A binary 1 is referred to as a mark, while a binary 0 is known as a space.

Main benefits

General benefits of using a line code with bipolar encoding:

+

- The use of a bipolar code prevents a significant build-up of DC, the cable may then be used for longer distances.
- AMI helps to maintain synchronization between the transmitter and receiver, especially in case of long strings of binary 1 symbols, which are problematic for NRZ. An additional transmission medium for the clock signal is not necessary.
- Error detection. AMI signal is regenerated at regular intervals. A signal with low *Signal to Noise Ratio* (**SNR**) can exhibit errors, as for example a mark can be interpreted as zero, or zero as positive or negative mark. AMI has the ability to detect single errors, which violate the rule of bipolarity (every following non-zero mark is different).

Disadvantages

–

- Long sequences of binary zero are problematic in terms of synchronization.

i

The solution is to add a binary 1 after seven binary zeros to maintain synchronization. On the decoder side, this extra symbol is removed.

1.5 Duobinary modulation

The principle

Duobinary modulation (**DB**) is implemented in optical communications by using three logical states, where:

A binary zero is represented by the absence of a laser pulse; binary 1s can be represented by a laser pulse with altered phase, based on the previous symbols in the following manner.

Phase of a binary symbol is shifted by π if there is an odd number of binary 0 between two binary 1.

It can be combined with RZ or NRZ rule.

- *Non-return-to-zero* (**NRZ**) assigns a laser pulse for the binary 1 for the entire bit interval, while zeros are represented by the absence of a laser pulse.
- *Return-to-zero* (**RZ**) assigns a laser pulse for the binary 1 for some part of the bit interval, while zeros are represented by the absence of a laser pulse.

Making the pulse length shorter than the duration of a logical symbol 1 causes the power falling to zero between two (or more) logical 1s. For data containing long chains of binary 1, it is a practical solution for synchronization issues.

Main benefits

Advantages of DB:

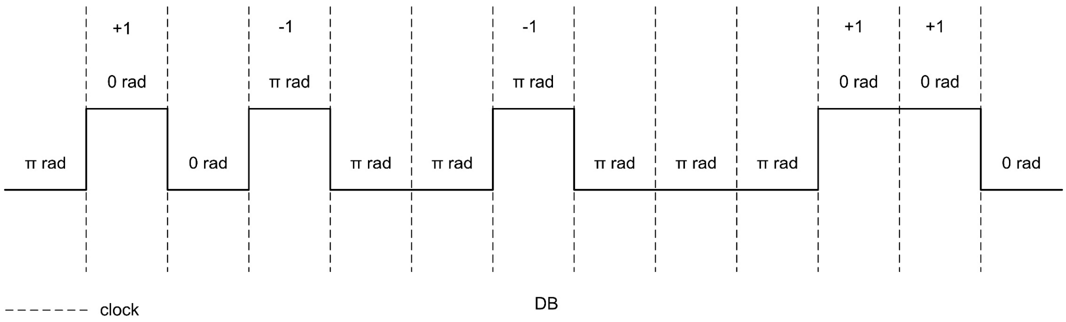
- High tolerance to *chromatic dispersion* (**CD**)
- Easy narrow-band filtering , (DB's narrow bandwidth could handle similar to the performance of *Differential Quadrature Phase Shift Keying* (**DQPSK**) format also a 12.5 GHz DWDM grid
- DB is the only intensity format which is still stable even for a 130 km long transmission and its system performance is quite similar to that of phase modulations, e.g. DQPSK.
- DB can be even more efficient than NRZ-DQPSK and CSRZ-DQPSK in terms of transmitter's design and implementation cost.

Transceiver's construction:

The DB transmitter consists of an amplitude dual-arm MZM with two electrical inputs:

- the first one is the standard electrical signal achieved by pseudorandom binary sequence signals passing through a NRZ driver a low-pass filter
- the second input by performing a bitwise logical NOT operation on the logical input which again travels through a driver and an electrical filter
- Similarly as for NRZ, a continuous wave laser is used as a light source.

In the following figure, +1 corresponds to phase 0 and -1 corresponds to phase π or its odd multiples.



The principle of DB modulation – symbol's phase is shifted by π radians if there is odd number of binary zeros (1, 3, 5...).

2 Phase modulations: Differential Phase-Shift Keying, Quadrature Phase-Shift Keying

2.1 Differential Phase-Shift Keying

The principle

Similarly as for OOK, DPSK can be implemented as RZ and NRZ.

E=m·c²

It is a type of phase modulation that conveys data by changing the phase of the carrier wave. All subsequent information is coded as 180° phase reversals of the carrier frequency.

- A 180-degree carrier phase reversal preceding a chip shall characterize that chip as a binary 1.
- The absence of a preceding phase reversal shall denote a binary 0.

Main benefits

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The main advantage of DPSK is the 3-dB improvement it offers in the receiver sensitivity compared to OOK.

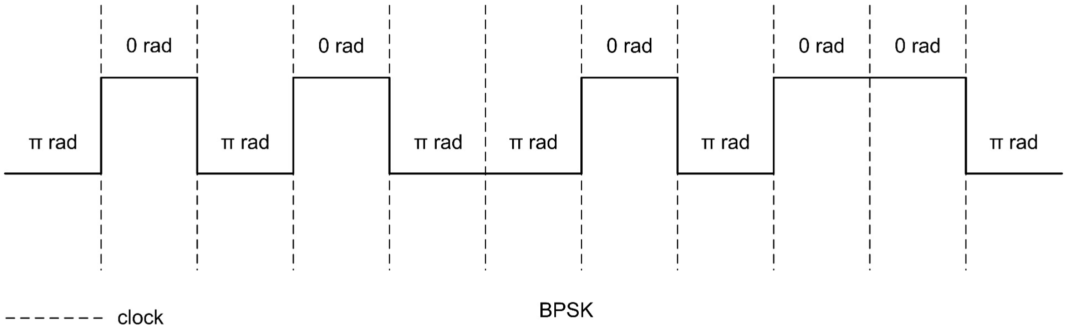
The difference in results between NRZ-DPSK and RZ-DPSK is primarily related to the wider spectrum of RZ-DPSK format.

Transceivers for DPSK

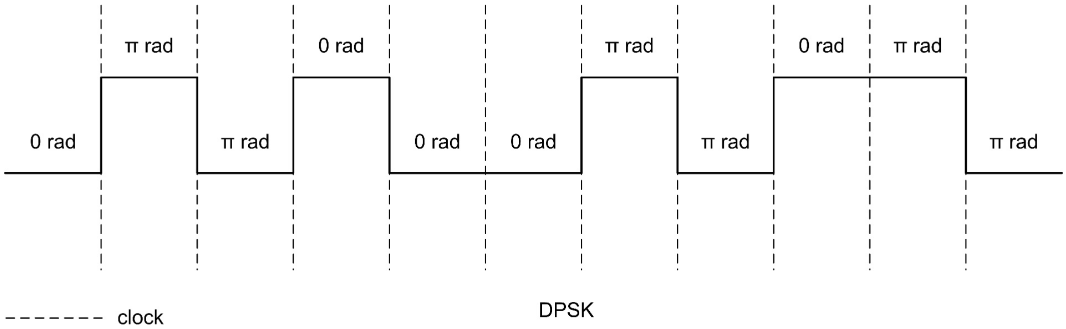
Transceiver's construction:

i

- NRZ-DPSK transmitter's design is similar to that of NRZ, but instead of the MZM, a phase modulator with 180° phase shift is deployed.
- A low-pass filter is used between the driver and modulator to include the impact of a non-ideal binary to electrical signal conversion.
- The RZ-DPSK transmitter includes additionally among others a second modulator to generate RZ output pulses.
- A DPSK receiver consists of a delay interferometer for decoding purposes and a balanced receiver modelled using two regular compound receivers, where the electrical output of the first one is added to the second's inverted output.



The principle of BPSK modulation – binary zeros and ones are represented by phase states shifted by π from each other, e.g. binary zero is assigned phase π and binary one, phase 0 radians.



The principle of DPSK modulation – a binary one shifts the symbol's phase by π, binary zero does not shift the phases.

2.2 Quadrature Phase-Shift Keying and Differential Quadrature Phase-Shift Keying

The principle

Differential Quadrature Phase-Shift Keying (**DQPSK**) is a multilevel format.

E=m·c²

QPSK is effectively two independent BPSK systems, and therefore exhibits the same performance but twice the bandwidth efficiency.

- Pairs of bits are assigned a specific phase, as for example:
  - 00 → 45°
  - 01 → 135°
  - 10 → 315°
  - 11 → 225°

i

There are many options of QPSK – the pairs of bits can be assigned different phase and different pairs can be the neighbour pairs, which can be observed in the following constellation diagrams.

E=m·c²

- In DQPSK, the pairs of bits correspond to a given phase shift from a reference (initial) phase, or, in other words, by 90° between the neighbour symbols.
- The initial phase can be 0° or non-zero.
  - 00 → shift by 0° from the initial phase.
  - 01 → shift by 90° from the initial phase.
  - 10 → shift by 180° from the initial phase.
  - 11 → shift by 270° from the initial phase.

Main benefits

+

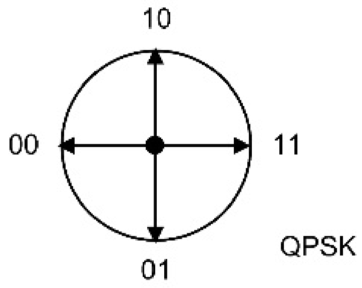
- Symbol rate is 2x slower than the bit rate
- DQPSK benefits in good optical signal to noise ratio
- robustness against polarization mode dispersion due to its longer symbol duration

- compression in frequency
- increased tolerance to chromatic dispersion
- narrow optical spectrum
- NRZ-DQPSK is promising even for terabit transmission
- DQPSK can also perform well at 40 Gbps
- RZ-DQPSK enables the longest optical reach
- RZ-DPSK offers the largest nonlinearity tolerance for a single 160 Gbps channel
- Among DQPSK formats, the highest values of Q-factors for each optical channel can be achieved for RZ-DQPSK.

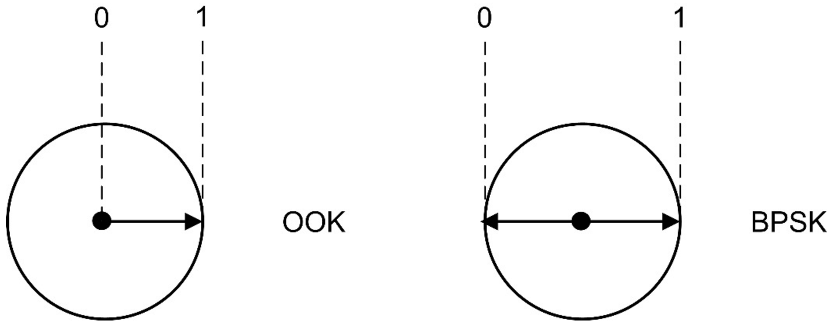
Transceivers

Transceiver's construction:

- In a NRZ-DQPSK transmitter, the two input encoded in-phase and quadrature binary signals are converted into electrical waveforms which drive two MZMs.
- A continuous laser source is used for both MZMs. The output of one of the modulators travels through a phase modulator used to obtain an additional phase shift of 90°, which is required for the quadrature component.
- Signals are then combined together to generate a single DQPSK modulated signal.
- Additional components include two low pass filters between electrical signal generators and MZMs to consider also the non-ideal binary to electrical signal conversion.
- For RZ-DQPSK, an additional MZM is used to create the RZ output pulses.
- DQPSK receiver is modelled using two balanced 2DPSK receivers for the in-phase and quadrature signals, each composed of a tunable Mach Zehnder interferometer and two PIN photodetectors.



The principle of QPSK modulation. Sample constellation diagram. Pairs of bits are assigned particular symbols; since there are four combinations of the pairs, the modulation has four states (levels).



Sample constellation diagrams for OOK and BPSK for comparison purposes. Phase and amplitude expressed by a constellation diagram.

3 Advanced aspects of optical modulations in achieving high bit rates and immunity to signal degradation

3.1 Polarization multiplexing in QPSK for terabit transmission

The idea of multiplexing modulation states based on polarization

Polarization Division Multiplexing (**PDM**) has been widely denoted either by polarization multiplexing, polarization division multiplexing, dual polarization or orthogonal polarization. PDM-QPSK is primarily designed for 100 Gbps channel systems.

PDM-QPSK combined with coherent detection (demodulation). In case of coherent demodulation carrier used for demodulation purpose is in phase and frequency synchronism with carrier used for modulation purpose. For non-coherent demodulation it is not in synchronism. Coherent light is a light in which the electromagnetic waves maintain a fixed and predictable phase relationship with each other over a period of time.

Main benefits

Advantages:

- spectral efficiency as it can halve the symbol rate
- PDM-QPSK has been the main candidate for 100 Gbps transponders, due to its high tolerance against signal distortions
- PDM-QPSK is better than DPQSK at the cost of implementation complexity
- it can also be efficient at 100 Gbps with 50 GHz spacing, where it can enable hundreds of km by using appropriate dispersion compensation techniques, inline amplifiers, etc.

Disadvantages

Disadvantages and limits:

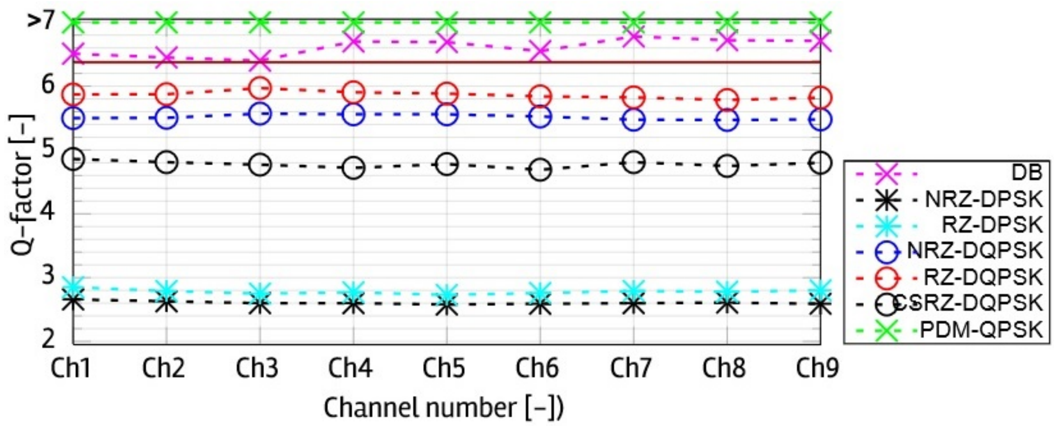
- cost of implementation complexity

- need for higher power consumption
- faster digital signal processing circuits
- analogue to digital converters

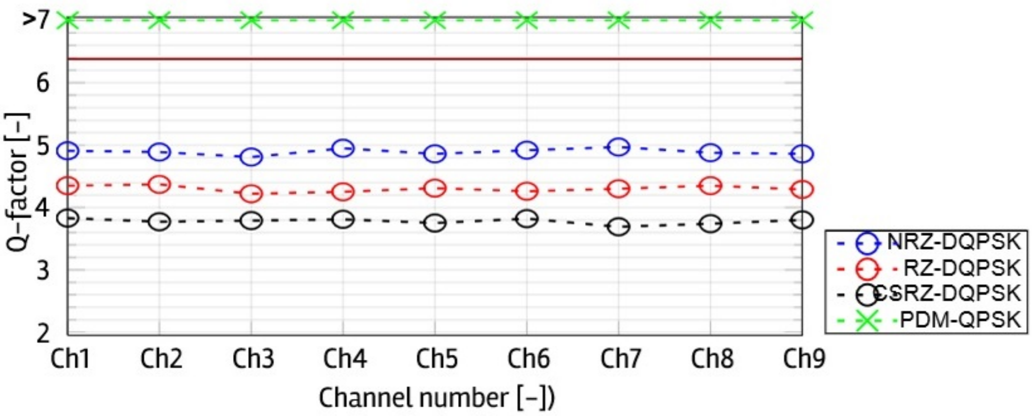
Transceivers

Transceiver's construction:

- In a PDM-QPSK transmitter we have to deal with four signal components for the in-phase respectively quadrature signals and for the two polarizations.
- Similarly as in previous formats, the binary to electrical signal conversion is performed,
- Low-pass Bessel filters are used again to consider the impact of a non-ideal conversion.
- The four electrical signals are then launched to two QPSK modulators, two per each.
- The output signal of one of the modulators travels through a polarization rotator and then it is combined with the output from the second QPSK modulator to obtain a single PDM-QPSK modulated signal.
- The PDM-QPSK receiver includes many components such as a single ended 90° hybrid with local oscillator and four PIN photodiodes to enable the coherent detection; trans-impedance amplifiers, electrical filters, electronic dispersion compensator and in the end a memoryless blind receiver to separate the in-phase and quadrature components and orthogonal polarizations.



40 Gbps transmission with 100 GHz channel spacing over sample 12-km long SMF. Notice the best performance of PDM-QPSK format [2].



40 Gbps transmission with 50 GHz channel spacing over sample 12-km long SMF. Notice the best performance of PDM-QPSK format [2].

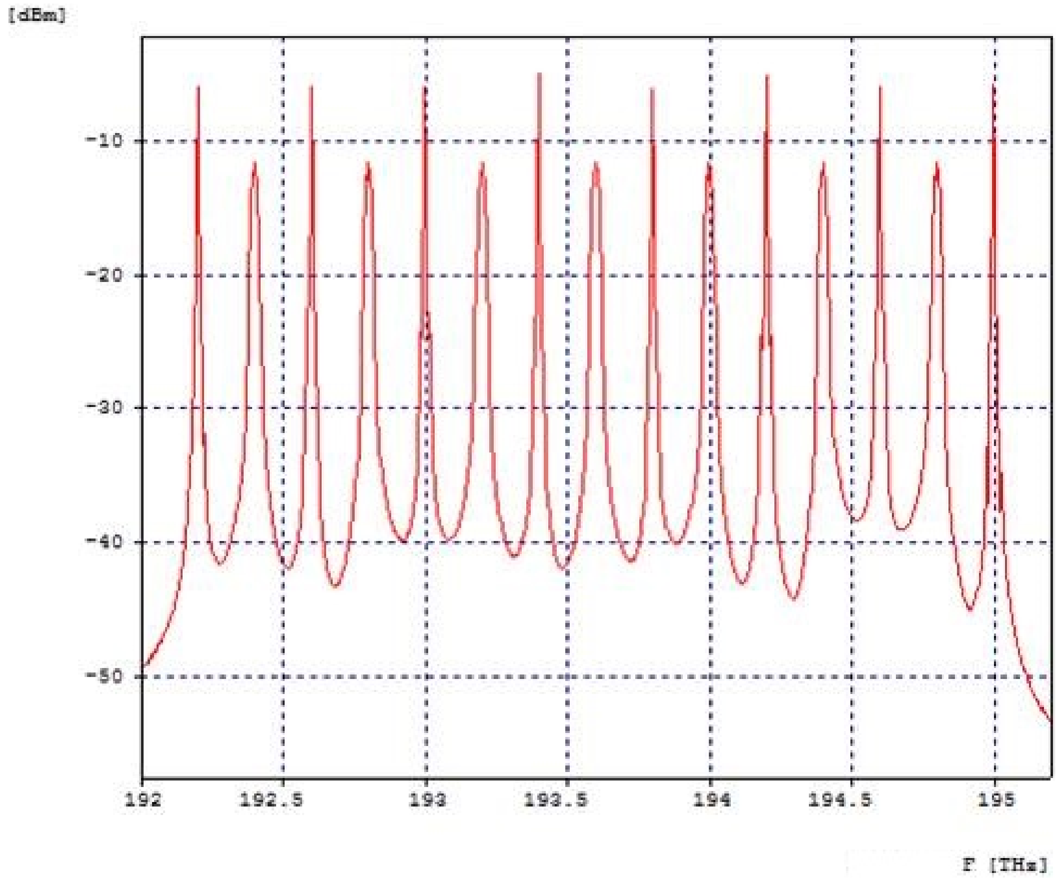
3.2 Convergence of networks: coexistence of amplitude and phase modulations in one fibre

Demand for higher information capacity and bit rates require upgrading existing optical systems or running more systems on one fibre. Then, new systems are added to existing systems and the fibre bandwidth is used in more efficient way. The coexistence of optical systems refers mainly to:

- *Coarse Wavelength Division Multiplexing* system (**CWDM**)
- *Dense Wavelength Division Multiplexing* system (**DWDM**)

In many cases, each system running in a fibre uses different modulation format.

- Example: Hybrid 10G/40G DWDM
  - Initially 10G DWDM system
  - 15x10 Gbps, NRZ-OOK, 50 GHz spacing.
  - 6x80km SSMF (dual phase amplifiers, post-compensation).
- Hybrid DWDM 10G/40G with channel interleaving
  - Combining with 7x40 Gbps system.
  - Duobinary modulation, P-DPSK, RZ-DQPSK modulation formats.
  - Influence of 10 Gbps channels on 40 Gbps channels.
  - *Cross Phase Modulation* (**XPM**) problem.



Optical spectrum of DWDM with channel interleaving.

3.3 Cross phase modulation caused by phase modulation over amplitude modulation

Running two or more systems over one optical fibre is not arbitrary. It can happen that an existing system uses amplitude modulation and a new system will use much more modern modulation format, which is considered to be one of the phase or multilevel phase modulation formats. The old and the new channels can be interleaving or each would occupy its dedicated band. The result can be origination of crosstalk from amplitude modulation channels to frequency modulation channels. The crosstalk is known as *Cross-phase modulation* (**XPM**).

It is associated with much higher energy transmitted by amplitude modulation formats, which can be transferred to other channels of the wavelength multiplex.

Cross-phase modulation (**XPM**) is the change in the optical phase of optical radiation at a certain wavelength caused by the interaction with radiation at another wavelength in a nonlinear medium.

It can be achieved by:

- the Kerr effect, (causes modification of the refractive index of a material in response to applied electric field, i.e. intense radiation, in fibre optics tens f dBm)
- the changes in refractive index via the carrier density in a *Semiconductor Optical Amplifier* (**SOA**)

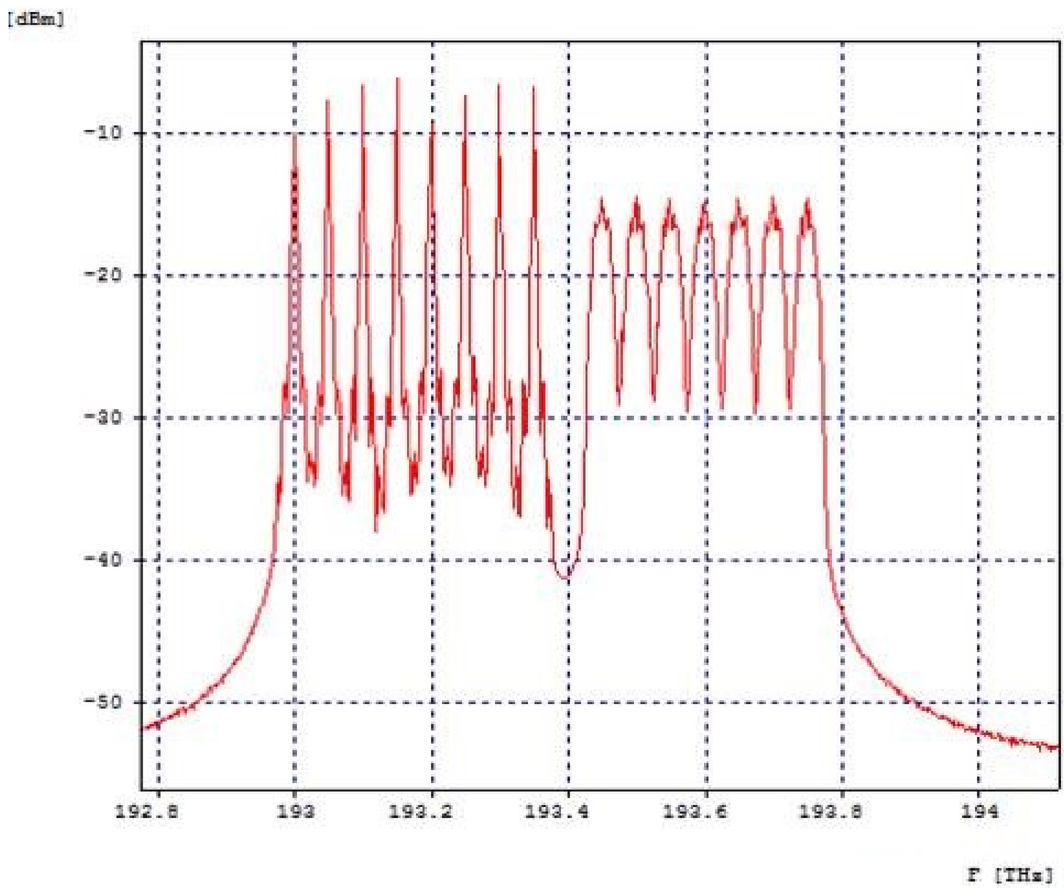
3.4 Avoidance of nonlinear effects caused by advanced modulations

XPM is a non-desired phenomenon in telecommunication systems using WDM, since it can damage transmission. XPM leads to inter-channel crosstalk (wavelength conversion) in DWDM systems.

One of the solutions to the XPM effect is to separate wavelength bands used for each modulation format running in a fibre and set appropriate safety bands:

- Hybrid DWDM 10G/40G with safety band

Spectral split of 10G and 40G by safety band can help reducing the cross phase modulation from the 10G system.



Safety band (100 GHz) splitting two systems (RZ-DQPSK and P-DPSK 40G channels).

3.5 Immunity of digital modulations to dispersion effects at high speeds

- Another goal is to reduce chromatic dispersion causing different speed of each frequency components contained in an optical pulse.
- Compared to NRZ formats, RZ is considered to be more tolerant to filtering and chromatic dispersion, thanks to its narrower spectrum.

3.6 OFDM – multicarrier modulation – principle, applications

The principle of orthogonal multiplexing

Orthogonal Frequency Division Multiplexing (**OFDM**) is a method of encoding digital data multiplexed carrier frequencies. It belongs to *Multi-Carrier Modulations* (**MCM**). In other words, it is a modulation with more frequency carriers.

OFDM channels are orthogonal. Then, the spectral distribution of each channel do not interfere with each other, even if they seemingly overlap (orthogonal components cannot be added).

A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. Each sub-carrier is modulated using a conventional modulation method (e.g. PSK or QAM) at a low symbol rate, similar to single-carrier modulation.

Source data are additionally encoded by a convolution code to increase errorless reception. OFDM is implemented by a DSP.

Applications

- *Long Term Evolution* (**LTE**)
  - Bandwidth 1 MHz up to 20 MHz
  - Compression MPEG2 or MPEG 4
  - Transmission rate ~300 Mb/s (downlink) and 50 Mb/s (uplink)
- *Digital Video Broadcasting - Terrestrial* (**DVB-T**)
  - Number of sub-channels 6817
  - Channel spacing 1116 Hz
  - TV bandwidth 8 MHz
  - Modulation in sub-channels 4-PSK, 16-QAM, 64-QAM
  - Transmission rate 19 to 25 Mbps
- *Wireless LAN* (**WLAN**)
- *Digital Audio Broadcasting* (**DAB**)

3.7 OFDM – multicarrier modulation – parameters, benefits and limits

Parameters

- Available bandwidth B is split into N sub-channels.
- The width of each sub-channel is then $\Delta f = B/N$.
- Modulation rate is $\Delta f = 1/T$, where T is duration of one symbol.

Main benefits

- Spectral efficiency gives as the ratio of transmission rate and bandwidth
- By increasing the number of sub-channels, while keeping the same overall transmission rate, one can potentially reduce the modulation speed in particular sub-channels and extend the symbol duration.
- It allows reducing *Inter-Symbol Interference* (**ISI**)

Disadvantages

- It is necessary to maintain and monitor spacing between sub-channels
- In case the spacing between adjacent channels is not constant – this case is known as jitter – the principle of orthogonal channels is affected and as a result, *Inter-symbol Interference* (**ISI**) and *Inter-Channel Interference* (**ICI**) are observed.
- The above can lead to increased *bit error rate* (*BER*).

3.8 VDMT – advanced vectored modulation – principle, application

The principle

Discrete Multi-Tone (**DMT**) is a multicarrier modulation. It is implemented by a DSP. Sub-channels widely use PSK or QAM, similarly to OFDM. On the contrary to OFDM, DMT however allows using different modulation schemes or even modulation types in each sub-channel of orthogonal multiplex.

Application

- Telecommunications *Digital Subscriber Line* (**xDSL**), using metallic wires:
  - *Asymmetric Digital Subscriber Line 2+* (**ADSL2+**) – bandwidth 2.2 MHz, number of sub-channels 512, channel spacing 4.3kHz, modulation – QAM, max. overall bit rate 30.72 Mbps
  - *Very High Speed DSL 2* (**VDSL2**) – bandwidth 30 MHz, number of sub-channels 3479, channel spacing 8.625 kHz, modulation – QAM, max. overall bit rate 417 Mbps

Vectored Discrete Multi-Tone (**VDMT**)

For downstream, VDMT in *Digital Subscriber Line Access Multiplexer* (**DSLAM**) is common for xDSL lines in a metallic cable.

- In DSLAM there is information about all the symbols to be sent to the metallic line (there is a vector of the DMT symbols – the term "Vector DMT" is created after this fact).
- In DSLAM, there is information about the parameters of particular symmetric pairs and crosstalk relations between them; it is then possible to adjust the DMT symbols based on the environment in which they are to be transmitted.
- Synchronisation of all DMT symbols is necessary.
- In the upstream direction, it is possible to adjust the transmitted symbols at the terminal equipment of a user.

Advantages

- VDMT is extension of DMT, it solves the problem of *Multiple Input Multiple Output* (**MIMO**) processes and eliminates *Far End Crosstalk* (**FEXT**).
- *Near End Crosstalk* (**NEXT**) is eliminated due to frequency multiplexing.

3.9 Conclusion

- The most widely used formats are intensity (e.g. OOK, DB, CSRZ) and phase (e.g. BPSK, DPSK) modulation formats.
  - Compared to intensity formats, phase-based modulation formats can perform better at the cost of increased transceiver's complexity.
  - Above 10 Gbps, the only intensity format which can be potentially a good match between the transceiver complexity and system performance is DB. This format could for example transmit 40 Gbps data traffic even for 0.8 nm DWDM grid. Phase formats can perform well even for denser DWDM grids (0.4nm–0.1 nm spacing).
- However, multistage modulations using more than two levels (e.g. QPSK) or modulations based combining phase and intensity (e.g. QAM) or phase and polarization (e.g. PM-QPSK) become more promising for high-speed and/or long-haul systems.
  - Formats using polarization multiplexing can benefit from higher spectral efficiency, optical reaches, optical to signal noise ratio and chromatic dispersion tolerances.
  - The most promising format even for terabit transmission which can substantially be used in upgrading the current fibre infrastructure to higher bit rates than 40 Gbps is PDM-QPSK.
- The latest development is multicarrier modulations, such as OFDM and VDMT that found the application in digital television or LTE.