Optisches OFDM – Eine neue Technik für die optischen Datenübertragung

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Outline

- Einleitung
- Grundlagen – OFDM
- O-OFDM Systeme und deren Eigenschaften
- Realisierungsaspekte
- Zusammenfassung

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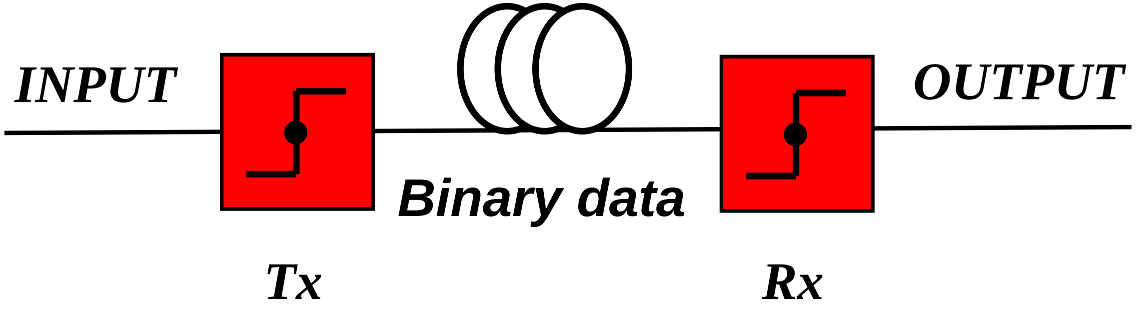
Einleitung

Typisches optisches Übertragungssystem



- Bitraten: 155 Mb/s … 40 Gb/s
- Bei 10 Gb/s mußte die chromatische Dispersion berücksichtigt werden, teilweise auch PMD
- Bei 40 Gb/s muß die chromatische Dispersion nach Anwendung von Kompensationsfasern berücksichtigt werden, sowie PMD in weiteren Anwendungen
- Verzerrungen (**CD und PMD**) begrenzen Einsetzbarkeit von Systemen höherer Symbolrate
- **Spektrale Effizienz** erlaubt keine weitere Erhöhung der Bitrate im 50 GHz Raster
- **Empfindlichkeit** der Systeme muß stetig verbessert werden

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Einleitung

- Bitraten über 40 Gb/s sind nachgefragt, 100 Gb/s ist nächste Stufe
- Derzeit in Diskussion:
  - DQPSK bei 50 Gbaud
  - Kohärentes QPSK
  - Kohärentes O-OFDM
- Kohärente Systeme ermöglichen die Übertragung der gesamten Feldinformation in die elektrische Ebene
- Dabei wird erstmal massiv DSP in physikalischer Ebene eingesetzt, es sind ADCs (und DACs) erforderlich
- PMD und CD können dann vollständig elektrisch kompensiert werden
- System- und Implementierungsaspekte von kohärentem O-OFDM sind weniger umfassend untersucht

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Grundlagen von optischem OFDM

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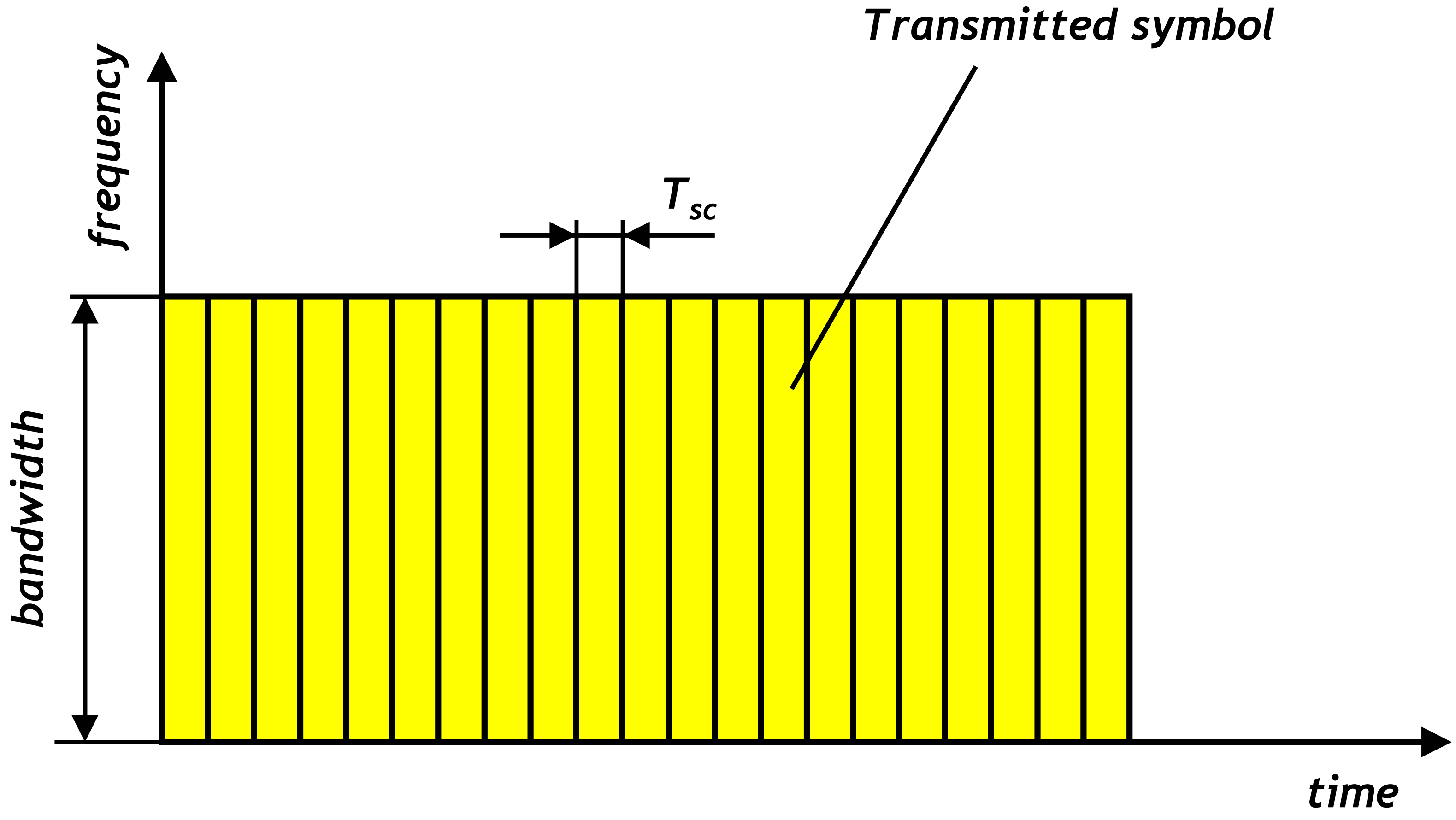
Prinzip von OFDM: Vergleich zwischen Einzelträger und Mehrträgerverfahren (1)

- **Einzelträgerverfahren**:
  - Einzelnes Trägerband welches die gesamte Kanalbandbreite belegt
  - Serielle Übertragung der Daten
  - Störanfällig für Intersymbolinterferenz



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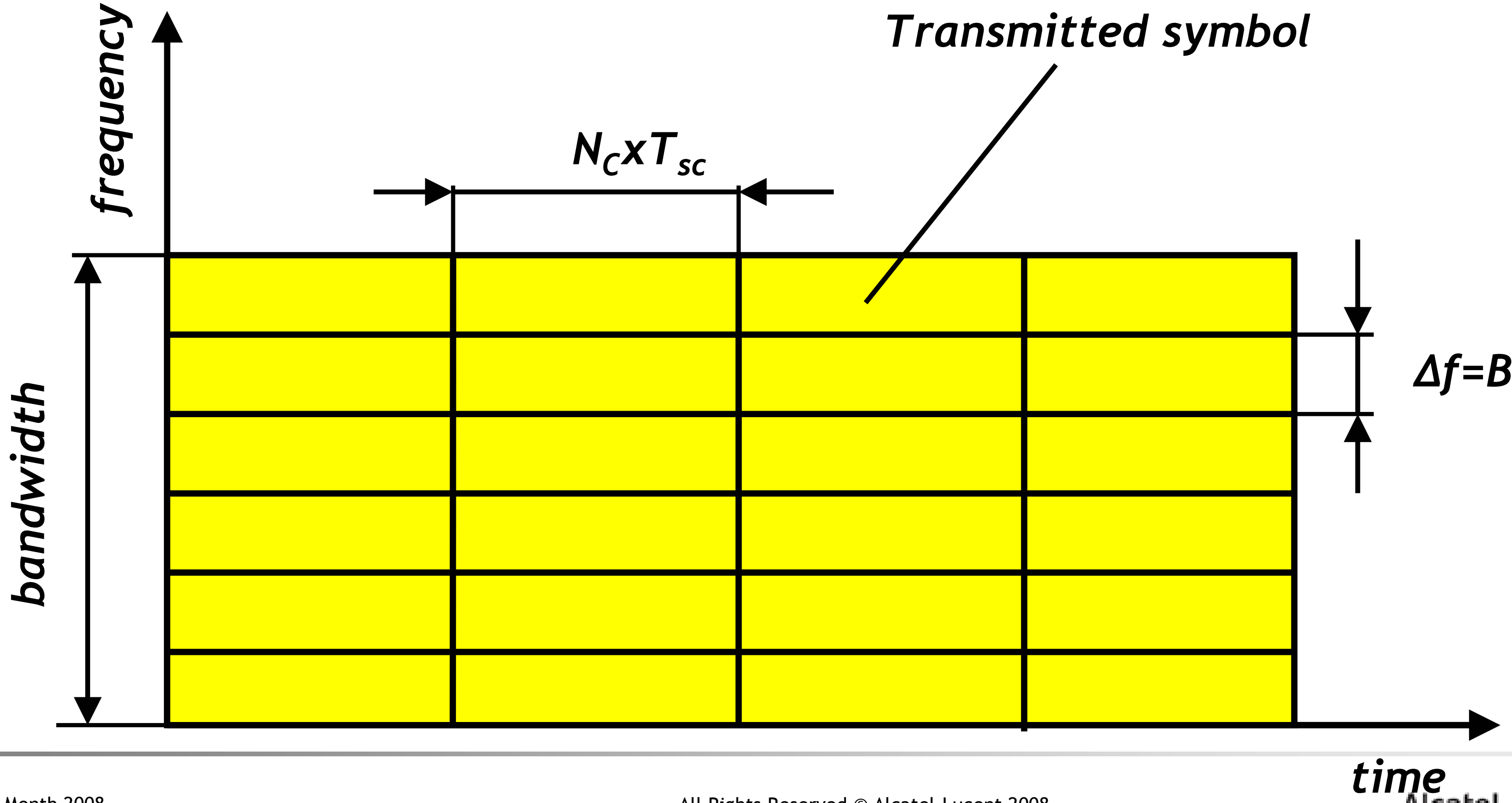
Prinzip von OFDM: Vergleich zwischen Einzelträger und Mehrträgerverfahren (2)

- **Mehrträgerverfahren**:
  - Aufteilung der Kanalbandbreite in Unterkanäle
  - Serieller Datenstrom wird parallelisiert und auf Unterkanäle aufgeteilt
  - beliebiges Modulationsverfahren für jeden Unterkanal
  - Symboldauer verlängert sich um Faktor N_C gegenüber Einzelträgerverfahren

  → weniger anfällig für Störung durch ISI



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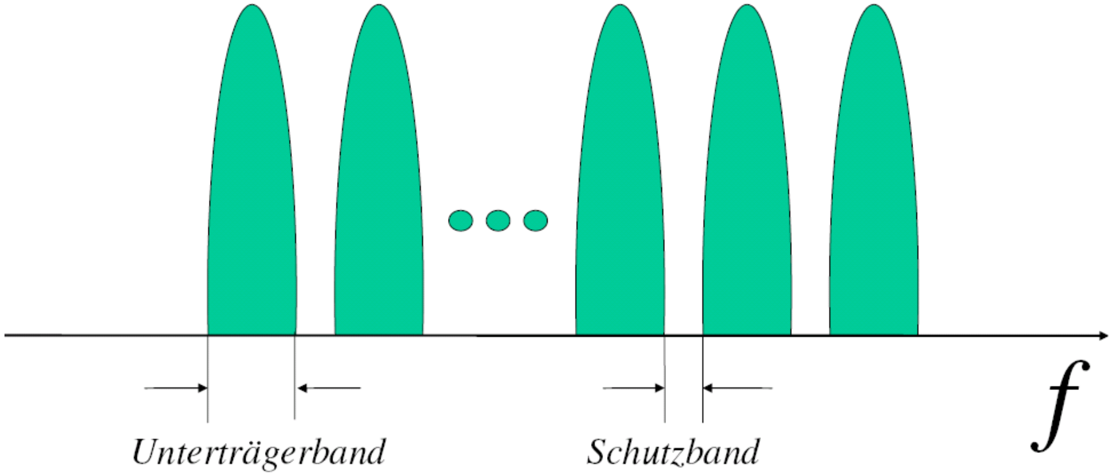
Prinzip von OFDM: Frequency Division Multiplexing

- Schutzbänder zwischen den einzelnen Kanälen nötig
  - zur Vermeidung von Kanalübersprechen (Inter Channel Interference, ICI)
  - zur Rückgewinnung der Kanäle mittels Filtern

→ Dadurch schlechte Bandbreiteneffizienz

Abhilfe: Orthogonal Frequency Division Multiplexing



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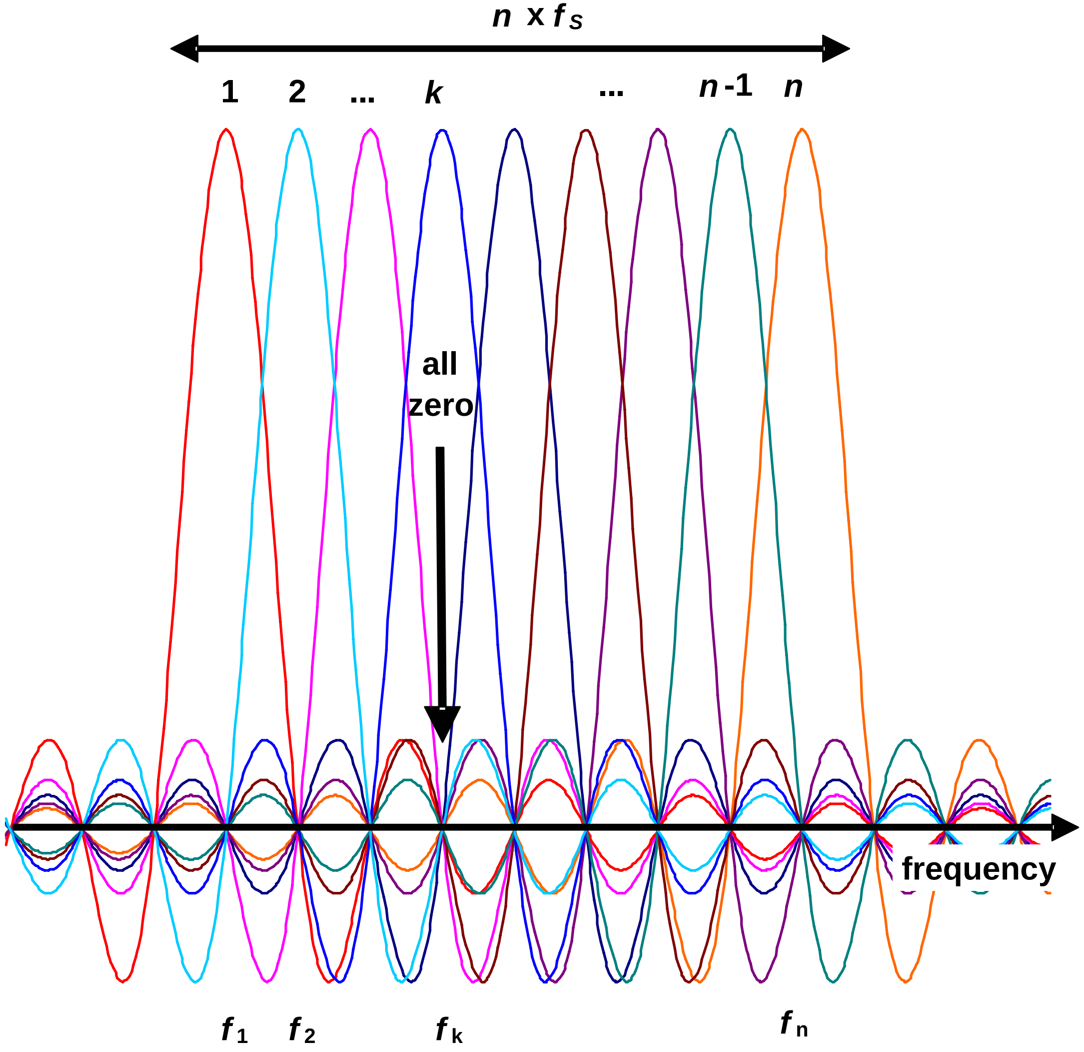
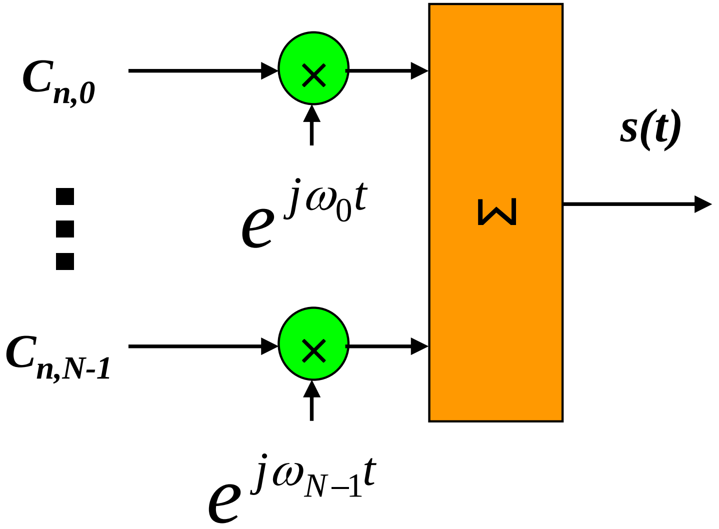
Prinzip von OFDM

- **Mehrträgerverfahren:**
  - OFDM – Unterträgerbänder überlappen

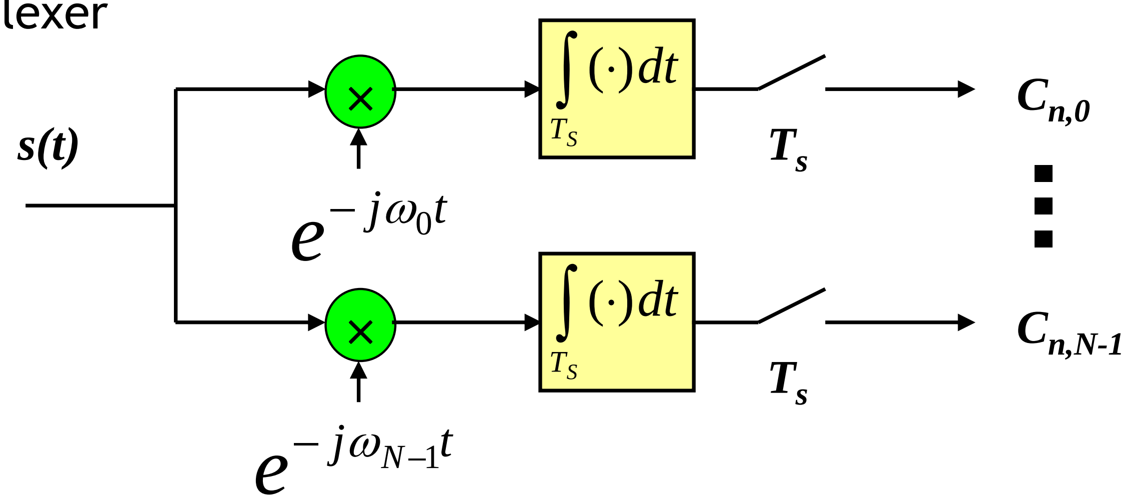


Prinzip von OFDM

→ OFDM modulator/multiplexer



→ OFDM demodulator/demultiplexer



Basic requirement: use of orthogonal basefunctions

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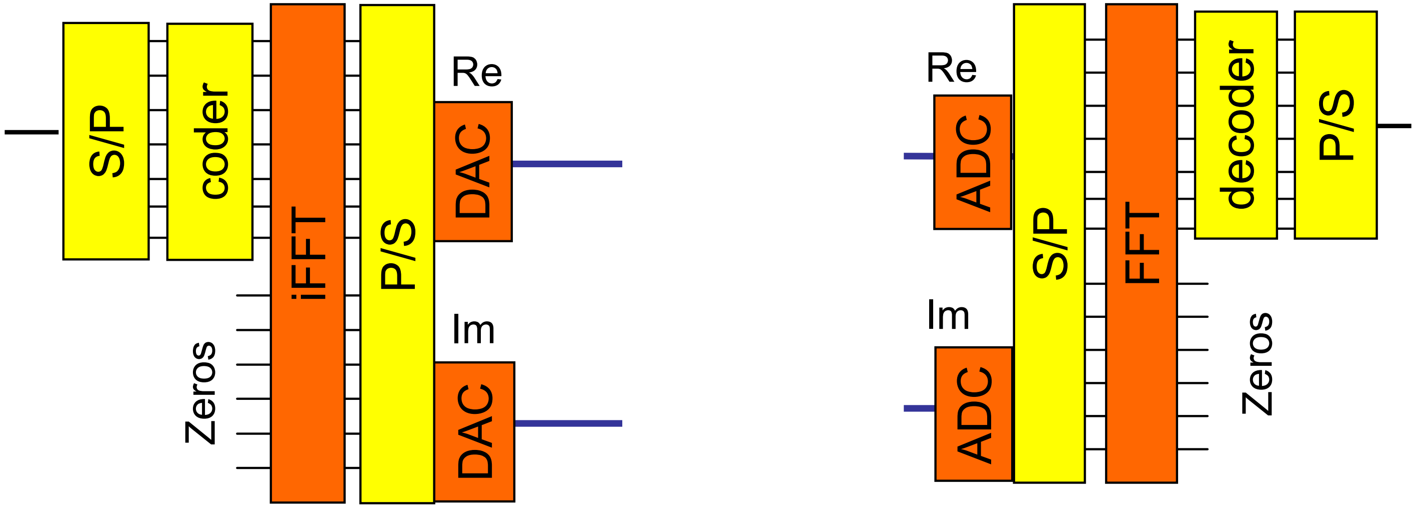
OFDM: Sender und Empfänger

→ targeted function is relialized by DFT



OFDM signals are in general complex valued

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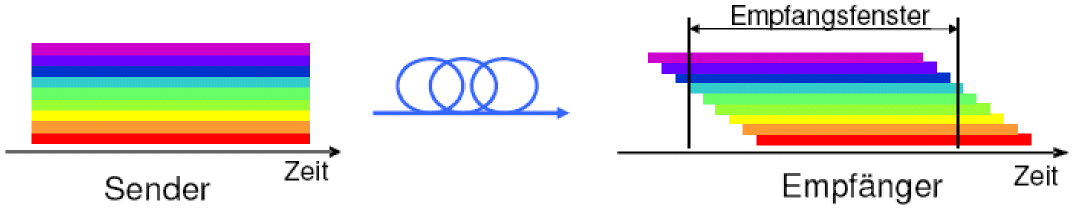
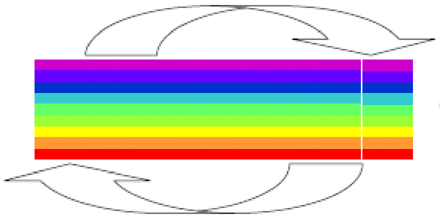
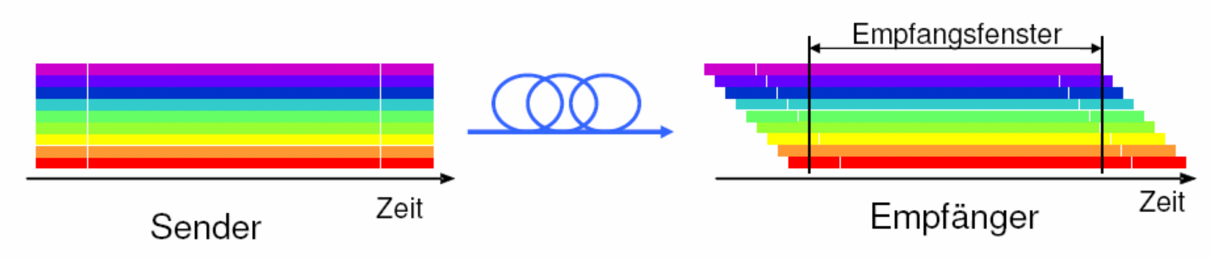
Prinzip von OFDM: Guard Interval

- Zyklische Erweiterung des OFDM-Signals
  - Im Empfangsfenster muß immer volständige Peride jedes Unterträgers vorhanden sein
  - Erweiterung reduziert Nettodatenrate





Guardband kopieren



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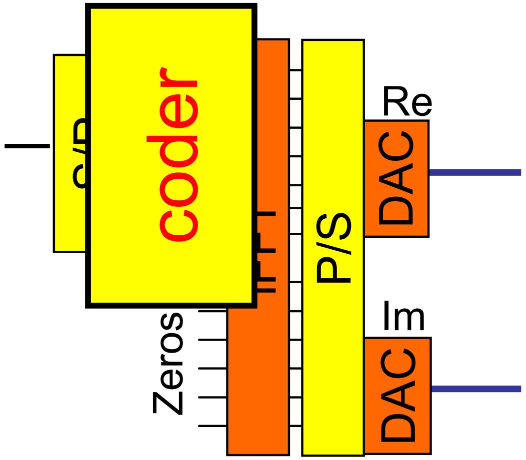
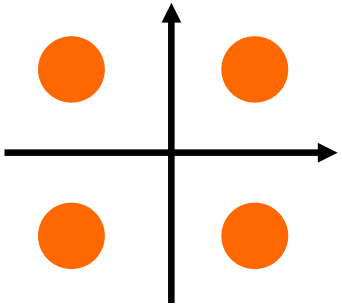
Prinzip von OFDM: Subcarrier modulation





QPSK is efficient scheme for high sensitivity

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Subcarrier modulation

Investigated schemes

- QPSK – 2 bit per subcarrier 10 Gb/s
- QAM16 – 4 bit per subcarrier 20 Gb/s
- QAM64 – 6 bit per subcarrier 30 Gb/s

Increase of number of bit per subcarrier leads to drastic decrease of distance between adjacent states in the constellation

Reduction of SNR	**-6.9 dB**	**-13.1 dB**
Conv. schemes, e.g. NRZ	**-3 dB**	**-4.8 dB**

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Comparison of subcarrier modulation schemes

	QPSK	QAM16	QAM64
Data rate [Gb/s]	10	20	30
Req. OSNR @ 1E-3 [dB]	7.9	15.0	22.7
Sensitivity below 10Gb/s [dB]		7.1	15.8
Comp. to NRZ [dB]		3.0	4.8
Red. In sensitivity [dB] vs. QPSK		4.1	11.0
Spectral efficiency [bit/Hz]	0.8	1.6	2.4

Makes higher level subcarrier modulation sence?

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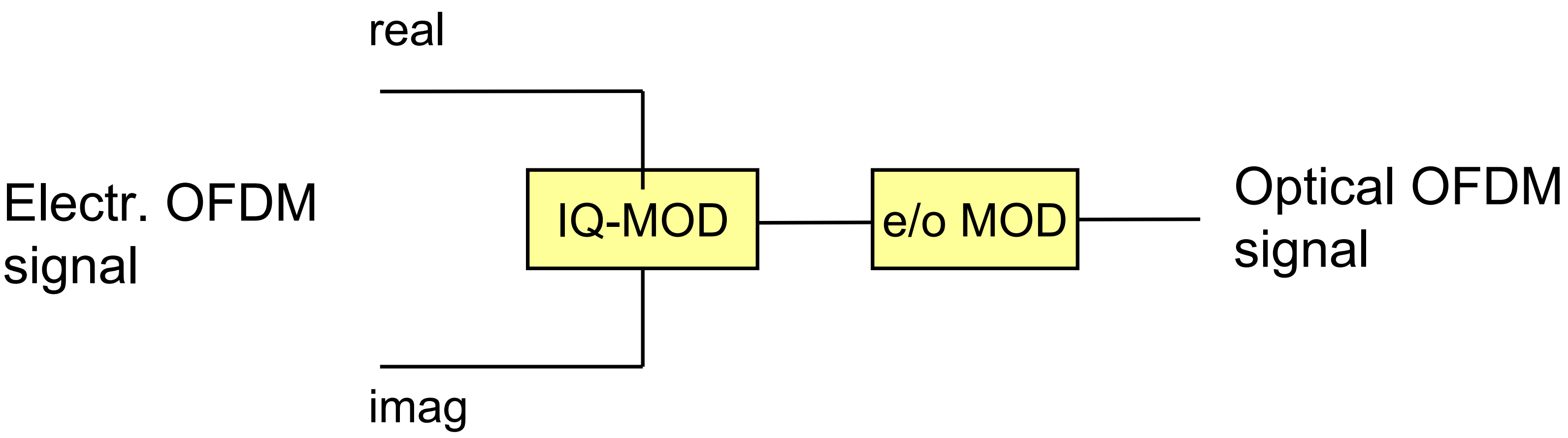
O-OFDM transmitter



real

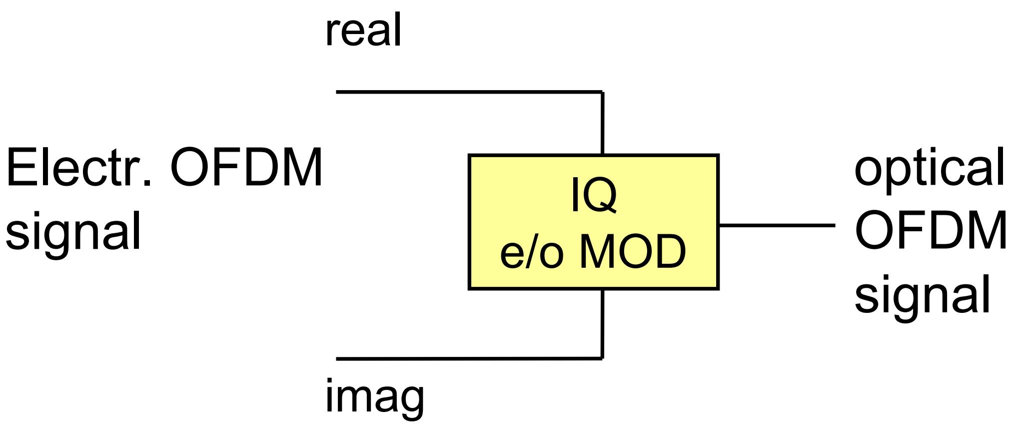
Electr. OFDM
signal

IQ-MOD

e/o MOD

Optical OFDM
signal

imag



real

Electr. OFDM
signal

IQ
e/o MOD

optical
OFDM
signal

imag

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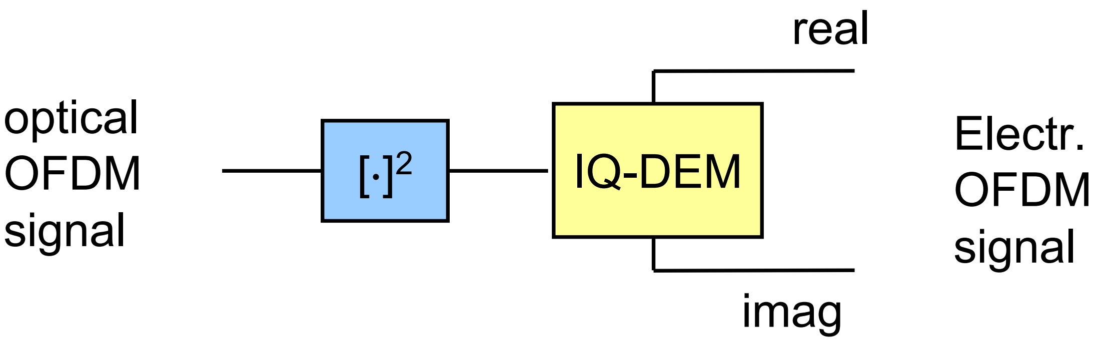
O-OFDM receivers

Direct detection



optical OFDM signal

$[\cdot]^2$

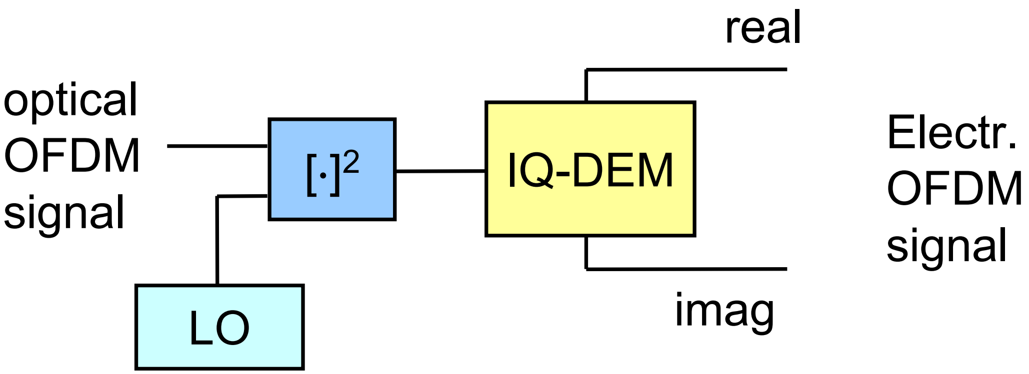
IQ-DEM

real

imag

Electr. OFDM signal

Coherent



optical OFDM signal

$[\cdot]^2$

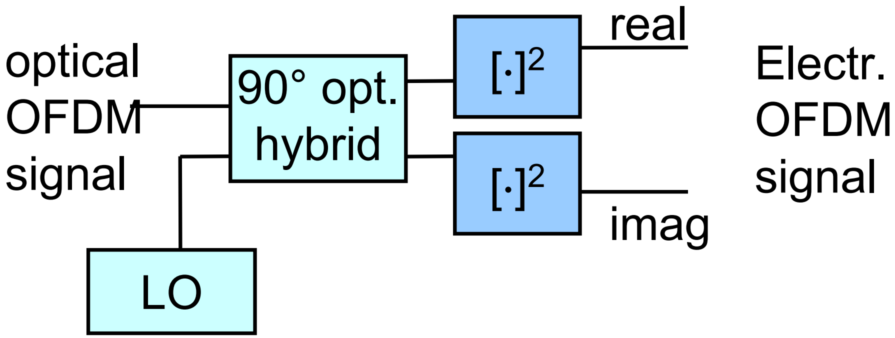
LO

IQ-DEM

real

imag

Electr. OFDM signal



optical OFDM signal

90° opt. hybrid

LO

$[\cdot]^2$

$[\cdot]^2$

real

imag

Electr. OFDM signal

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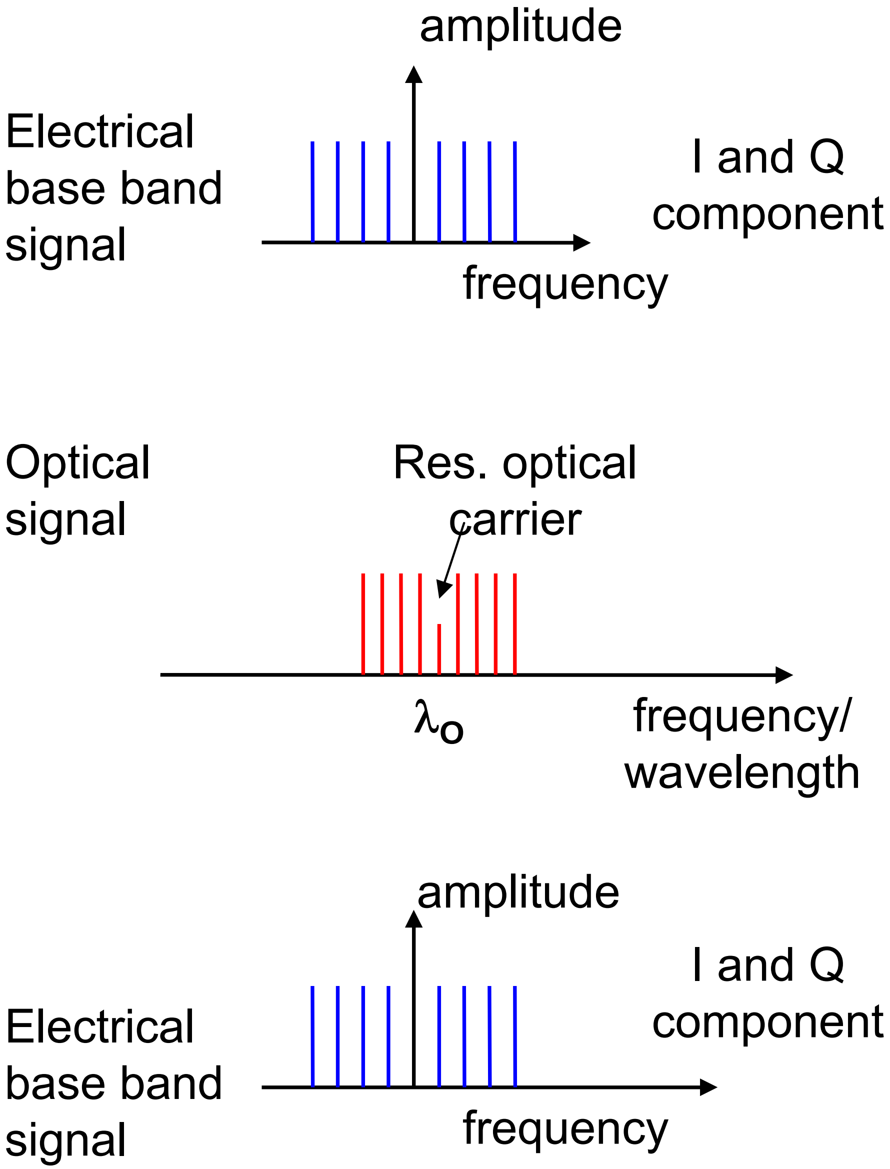
O-OFDM spectra



amplitude

Electrical
base band
signal

I and Q
component

frequency

Optical
signal

Res. optical
carrier

λ_o

frequency/
wavelength

amplitude

I and Q
component

Electrical
base band
signal

frequency

**nahezu
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Spektren**

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O-OFDM Systeme und deren Eigenschaften

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Scaling OFDM towards higher bitrates – first estimation

Optical channel

Data rate	Subcarrier modulation	Optical bandwidth	Spectral efficiency	req. OSNR [dB](*)
10G	QPSK	< 8 GHz	1.4 bit/Hz	6.0
20G	QAM16	< 8 GHz	2.8 bit/Hz	13.1
40G	QAM16	< 16 GHz	2.8 bit/Hz	16.1
50G	QAM16	< 20 GHz	2.8 bit/Hz	17.1
PM 2x50G=100G	QAM16 (2x)	< 20 GHz	5.6 bit/Hz	20.1
50G	QPSK	< 40 GHz	1.4 bit/Hz	13.0
PM 2x50G=100G	QPSK (2x)	< 40 GHz	2.8 bit/Hz	16.0

(*) BER 10^{-3}

CO-OFDM transmitter (similar for receiver)

Data rate	Subcarrier modulation	DAC/ADC rate	DAC/ADC bandw.	Resol.	Interconnect
10G	QPSK	10GSa/s	< 4 GHz	6 bit	2x60Gb/s
20G	QAM16	10GSa/s	< 4 GHz	8 bit	2x80Gb/s
40G	QAM16	20GSa/s	< 8 GHz	8 bit	2x160Gb/s
50G	QAM16	25GSa/s	< 10 GHz	8 bit	2x200Gb/s
PM 2x50G=100G	QAM16 (2x)	25GSa/s	< 10 GHz	8 bit	4x200Gb/s
50G	QPSK	50GSa/s	< 20 GHz	6 bit	2x300Gb/s
PM 2x50G=100G	QPSK (2x)	50GSa/s	< 20 GHz	6 bit	4x300Gb/s

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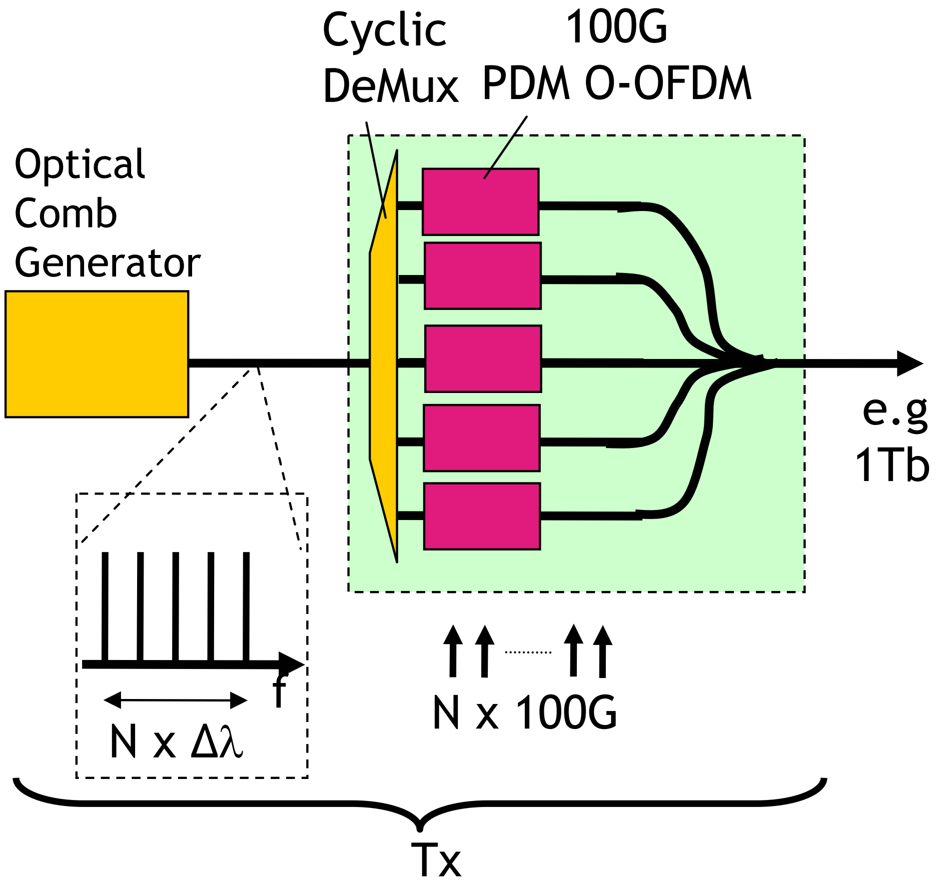
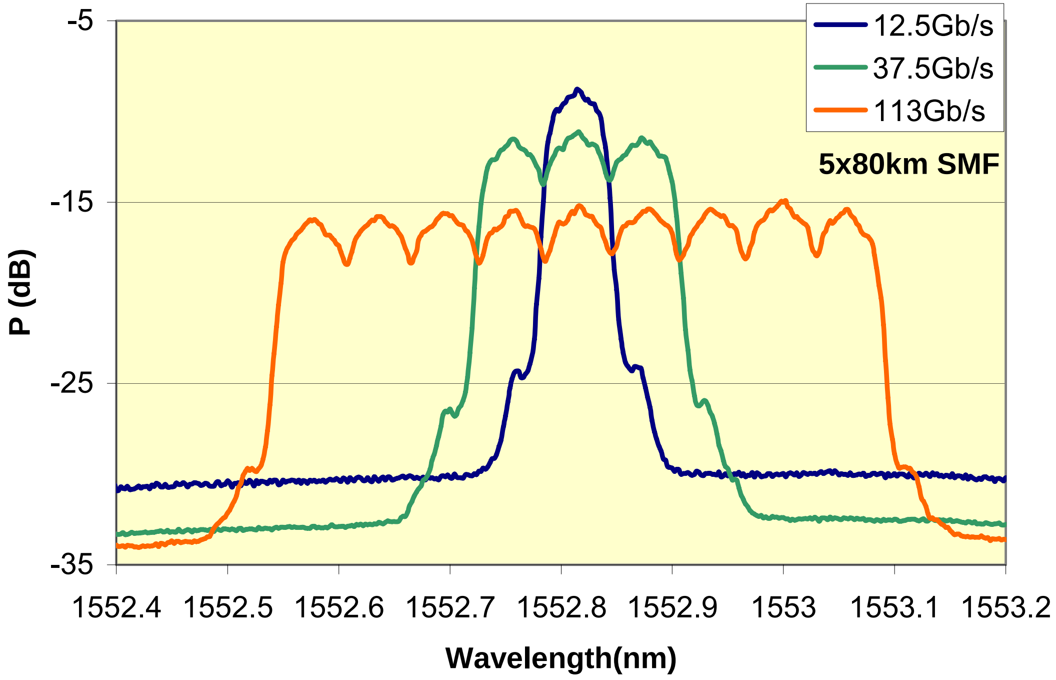
+100Gb/s OFDM scenario



Experimental result

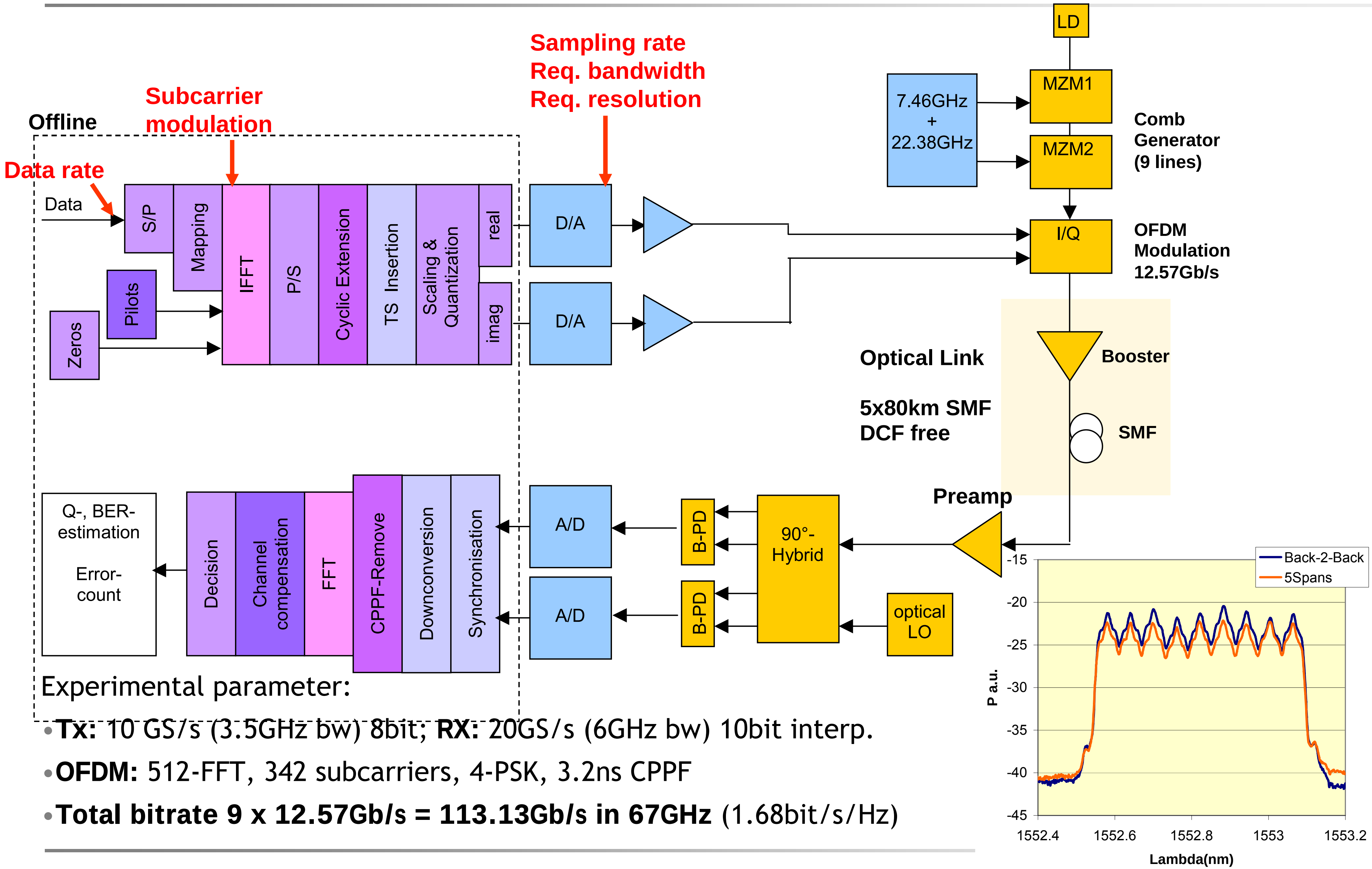
9x12.5Gb/s in 7.5GHz spacing

113 Gb/s in 67GHz bandwidth



- multiplexing of OFDM sub bands
- spectral shaping of sub bands is suitable for narrow wavelength spacing
- demux of sub bands using comb lines aligned to each sub band
- high capacity scenario without WDM grid
- highest spectral efficiencies achievable w/o. WDM grid (e.g. 1.7 b/s/Hz for 9x12.5 Gb/s)

Setup of 113Gb/s OFDM-System



Experimental parameter:

- **Tx:** 10 GS/s (3.5GHz bw) 8bit; **RX:** 20GS/s (6GHz bw) 10bit interp.
- **OFDM:** 512-FFT, 342 subcarriers, 4-PSK, 3.2ns CPPF
- **Total bitrate 9 x 12.57Gb/s = 113.13Gb/s in 67GHz** (1.68bit/s/Hz)

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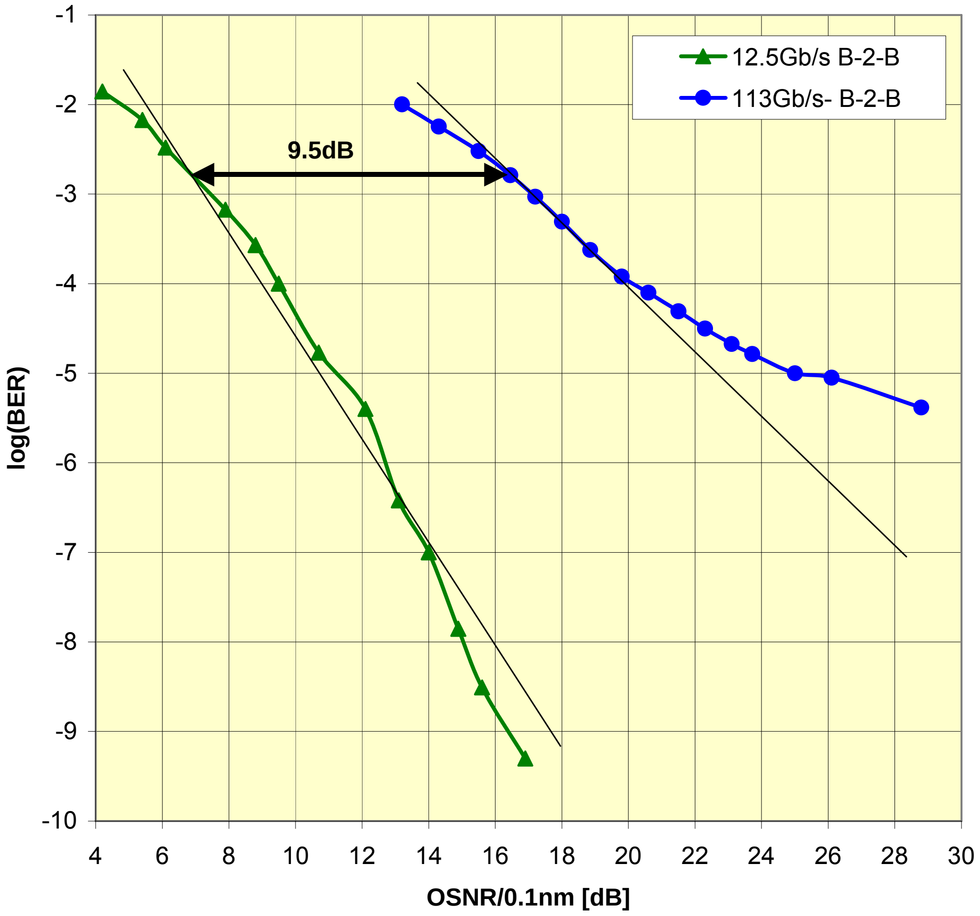
System performance: Back-2-Back

Increase of datarate x9 => 9.5dB penalty (= 10 log 9)



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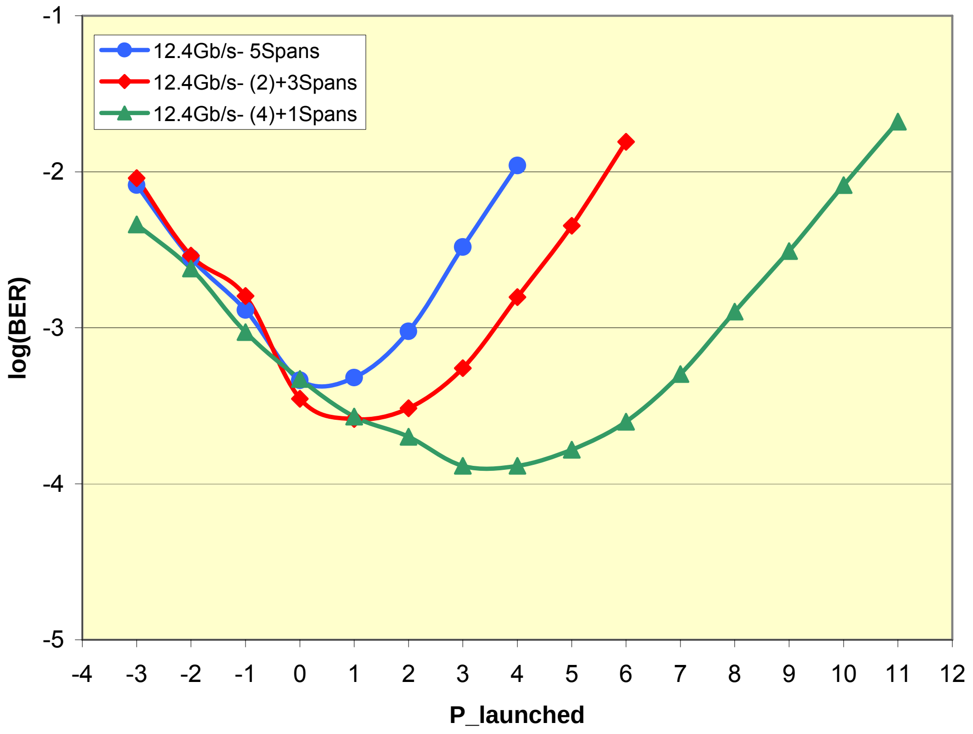
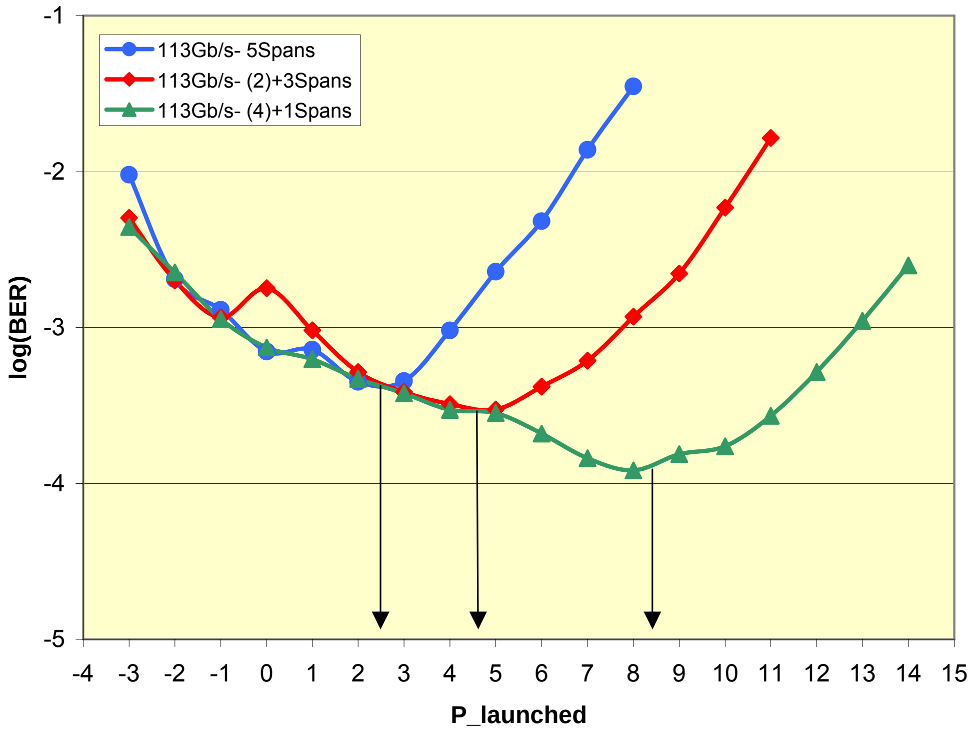
Measurement of Non-linear-threshold

Transmission over 5 Spans 80km SMF





12.4Gb/s
NLT 1Span: 4dBm

113Gb/s
NLT 1Span 8.5dBm

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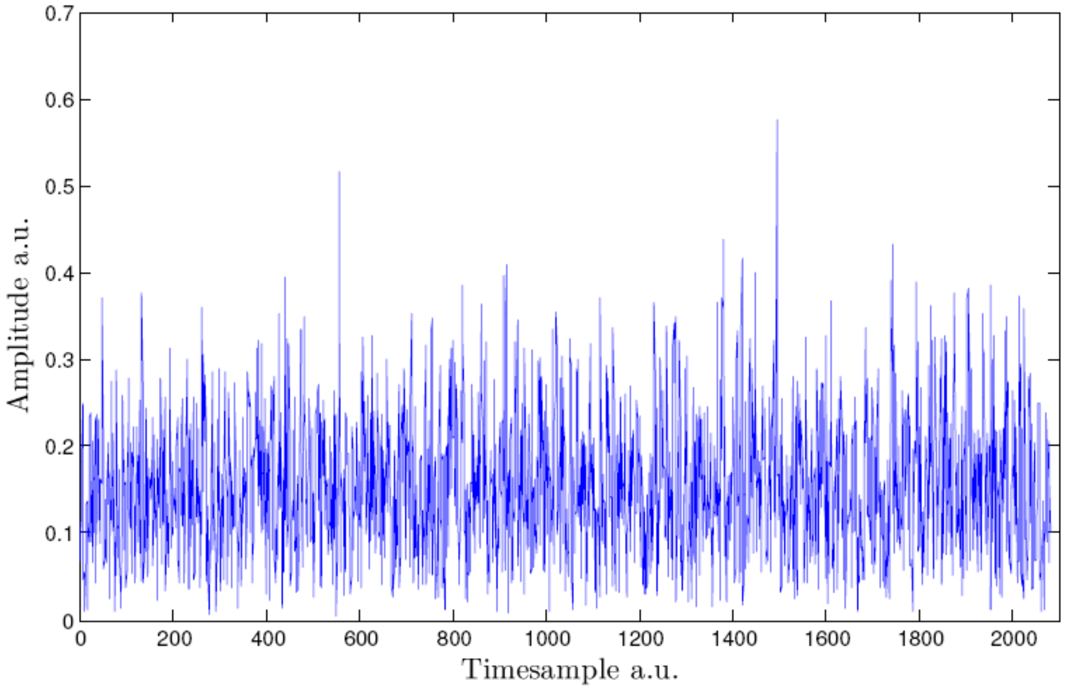
Signalcharakteristik von OFDM-Signalen: Signal to Average Ratio

- Hohe Peakwerte sind problematisch
  - Nichtlineare Effekte sind leistungsabhängig
  - Signalverfälschung
- Charakterisierung von Peaks bzw. SAR and PAR
  - Amplitude des Peaks wird auf mittlere Amplitude des Signals normiert
  - i.d.R. Angabe in dB

$$SAR(t_1) = 20 \cdot \log \frac{|s(t_1)|}{\overline{|s(t)|}}$$



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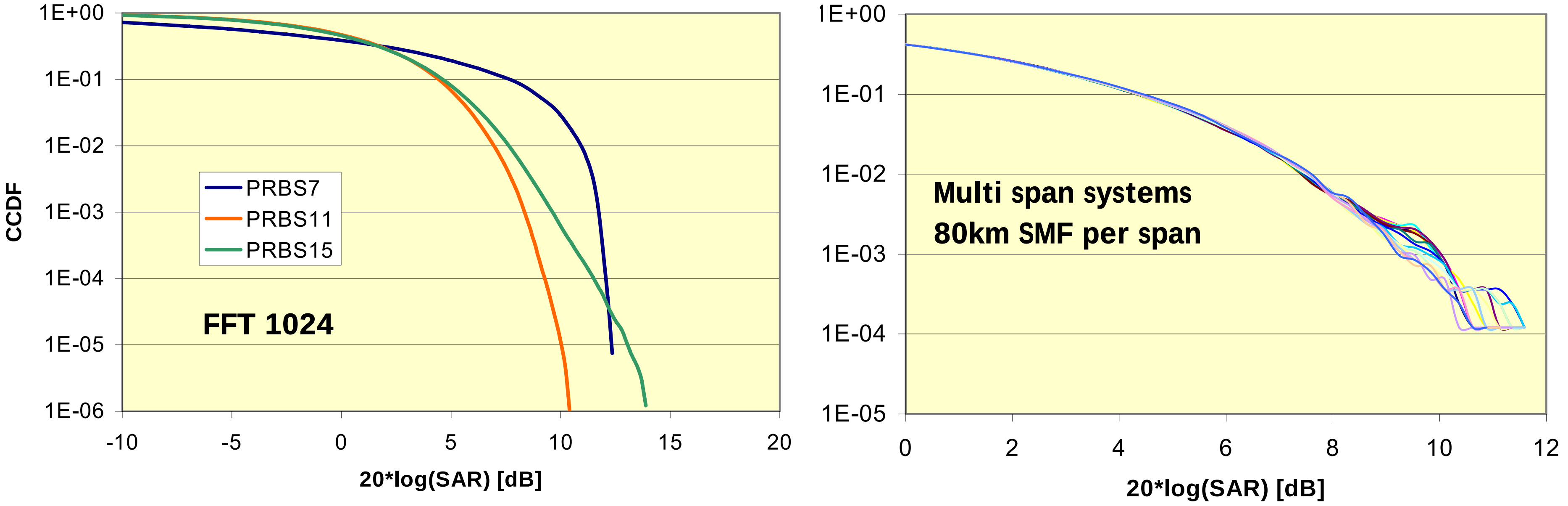
Investigation of signal power distribution

Description of optical signal

- PAPR: Ratio of max. power to average
  but: 'density' of peak values not regarded
- CCDF: Complementary Cumulative Distribution Function
  ⇒ Probability for power (amplitude) exceeds given value



- OFDM has statistical distribution of signal amplitudes already at Tx
- Statistics is not influenced by CD

➢**Similar distributions are present in conventional transmission systems w/o. DCF (fiber acts as Fourier transformer)**

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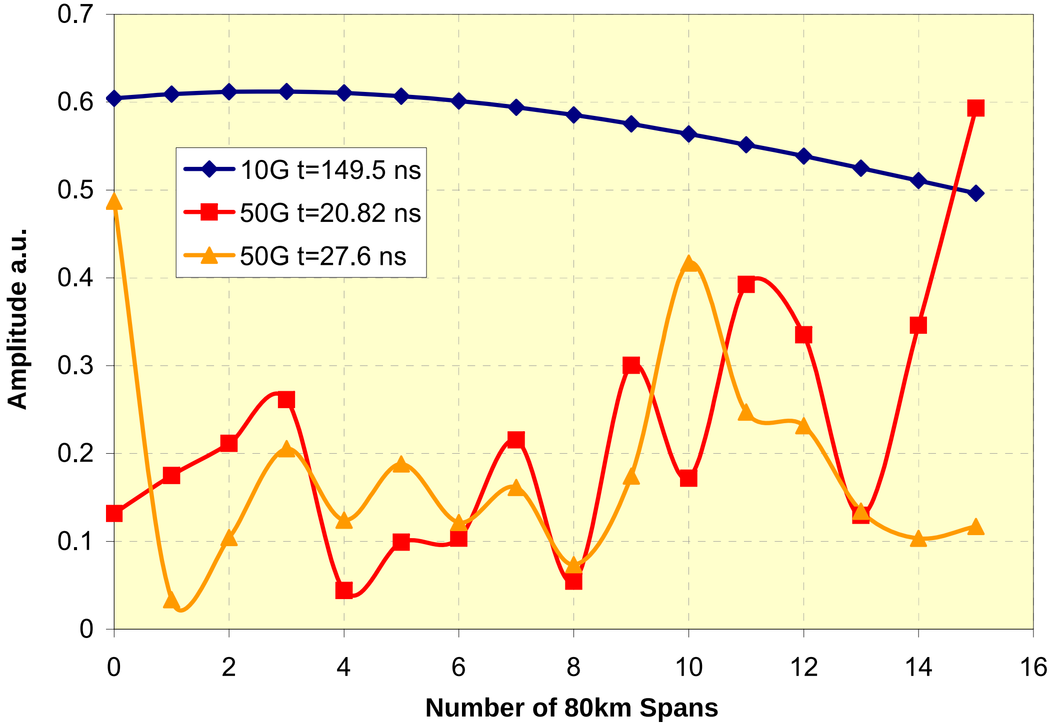
Transmission on SSMF

Comparison of 10 Gb/s with a 50 Gb/s scenario

- Evaluation of peak values from span to span



- 10G: dispersion is low wrt. bandwidth consumption
  - peaks survive over several spans
  - same peaks meet nonlinear degradation after optical amplification
- 50G: peak values arise and vanish from span to span
  - different peaks meet nonlinear degradation after optical amplification

- In 16 span simulations: NLT rises from 11 to 16 dBm integrated power while increasing the bit rate from 10 to 50 Gb/s

OFDM has high and competitive nonlinear tolerances in high bit rate systems without DCMs

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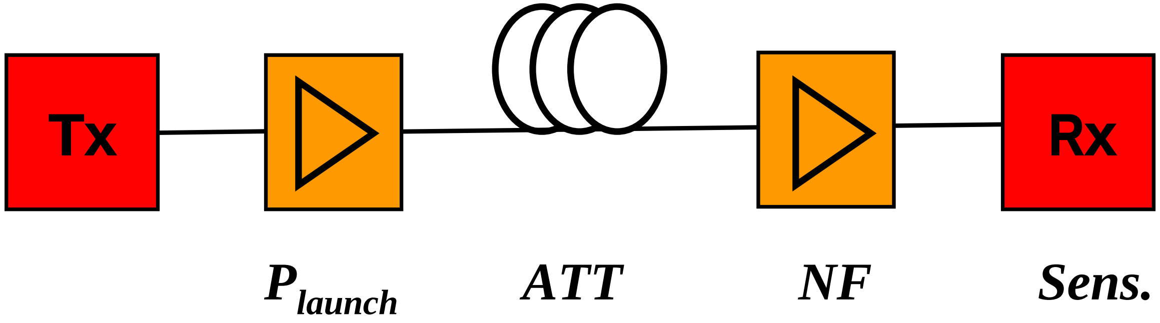
Power budget - nonlinear threshold

Investigation of power budget

- Maximum launch power
- Maximum link attenuation
- Preamp noise figure
- Receiver sensitivity



OSNR at the receiver is given by

$$OSNR = P_{launch} - ATT - NF + 58 \text{ dB}$$

To achieve high $OSNR$ highest P_{launch} is required, which is limited by nonlinear effects

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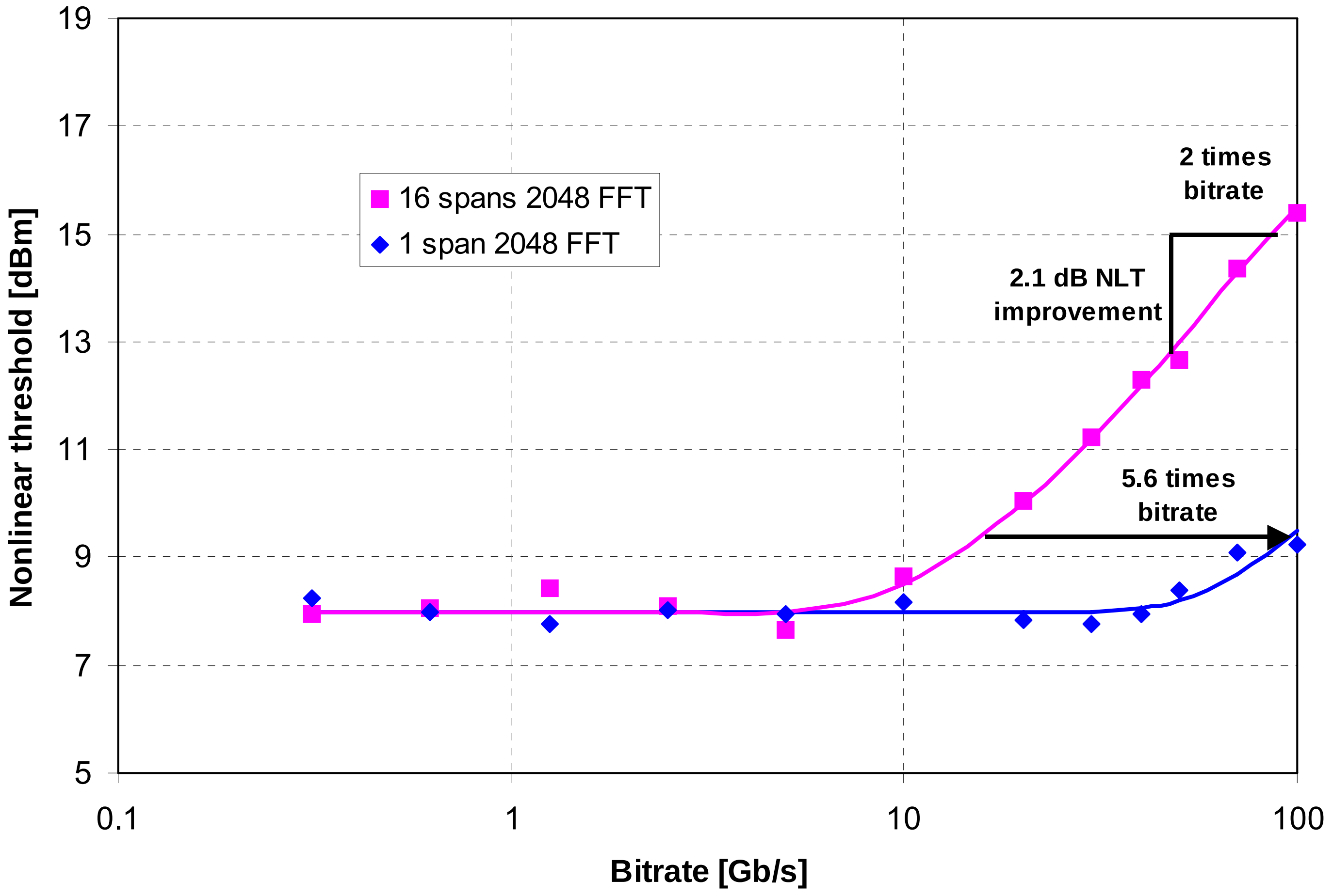
Nonlinear thresholds



→High nonlinear thresholds support OFDM at highest data rates

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Realisierungsaspekte

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Realization aspects

- → Investigation of DSP, ADC and DAC
- → for 100Gb/s 50 GSa/s components are required
- → Interface rate beyond 1Tb/s
- → due to high interface rates integrated converter – DSP chips are first choice
- → Investigation of DSP complexity

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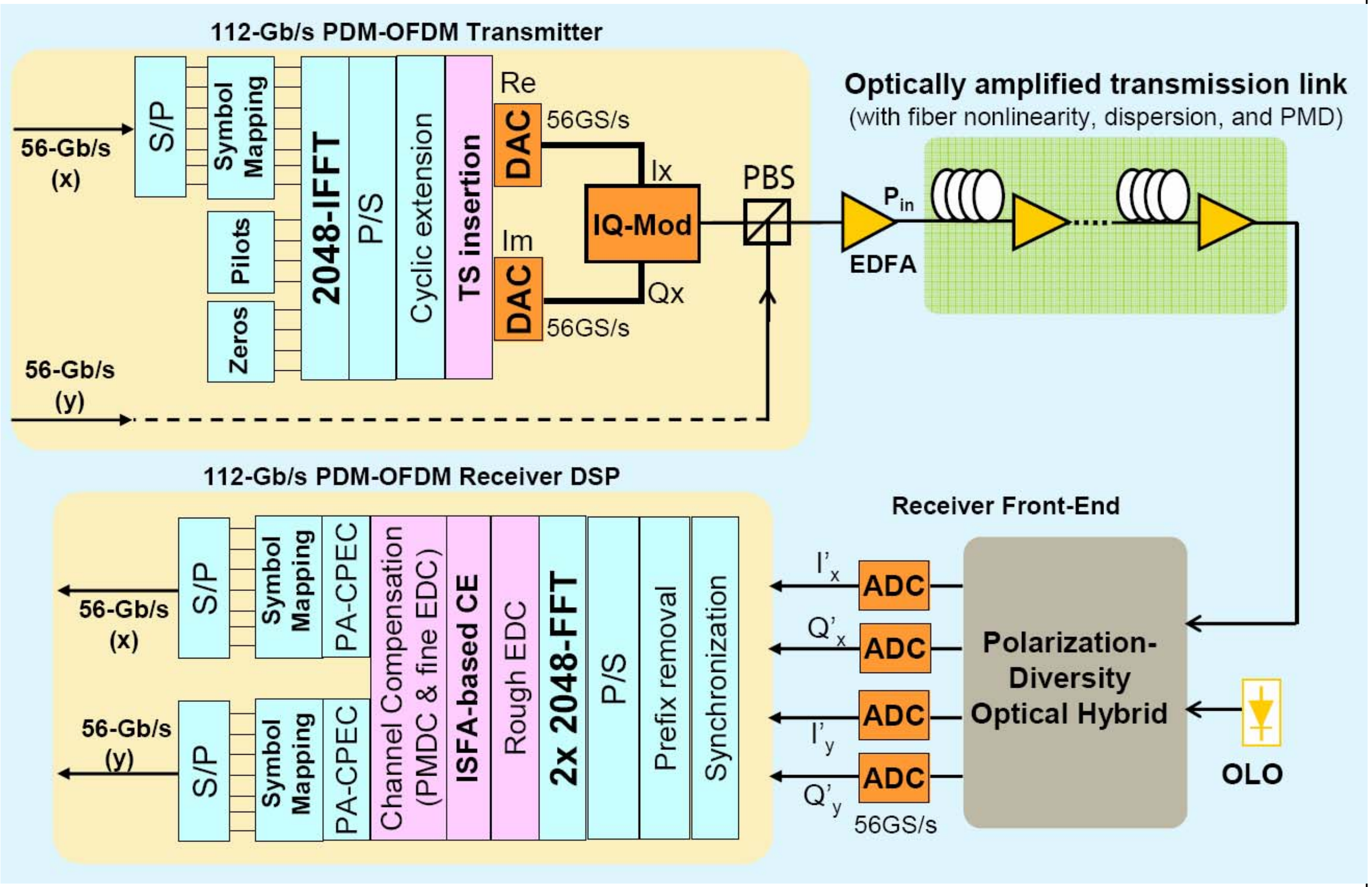
Setup of 113Gb/s OFDM-System

DSP: Tx

- IFFT

DSP: Rx

- synchronization
- Frequency offset compensation
- FFT
- channel equalization
- polarization demux



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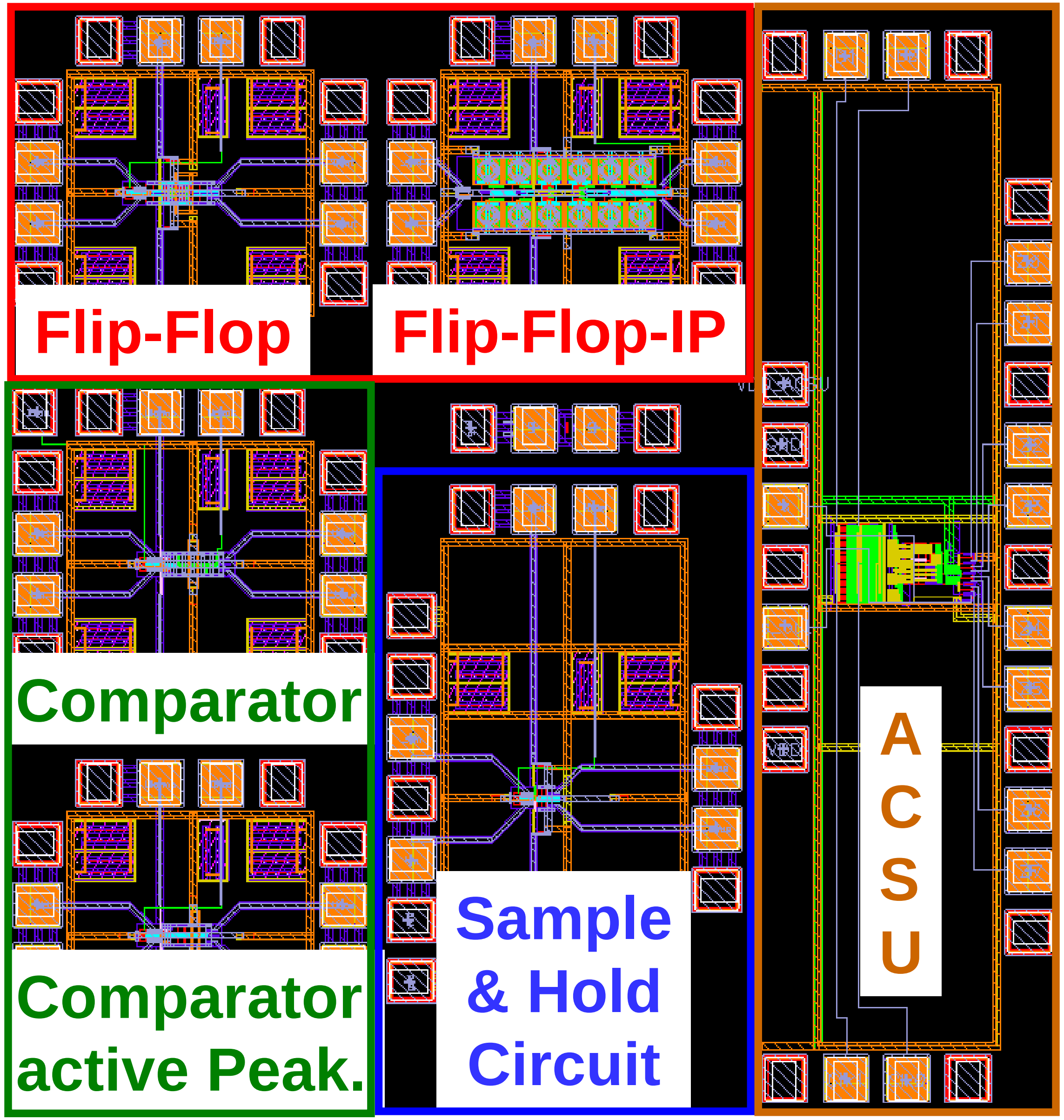
CMOS building blocks

Investigation of CMOS building blocks

- CMOS S&H as key element for ADCs
- ACS unit as key element for VE
- Testchip realized in 90nm CMOS



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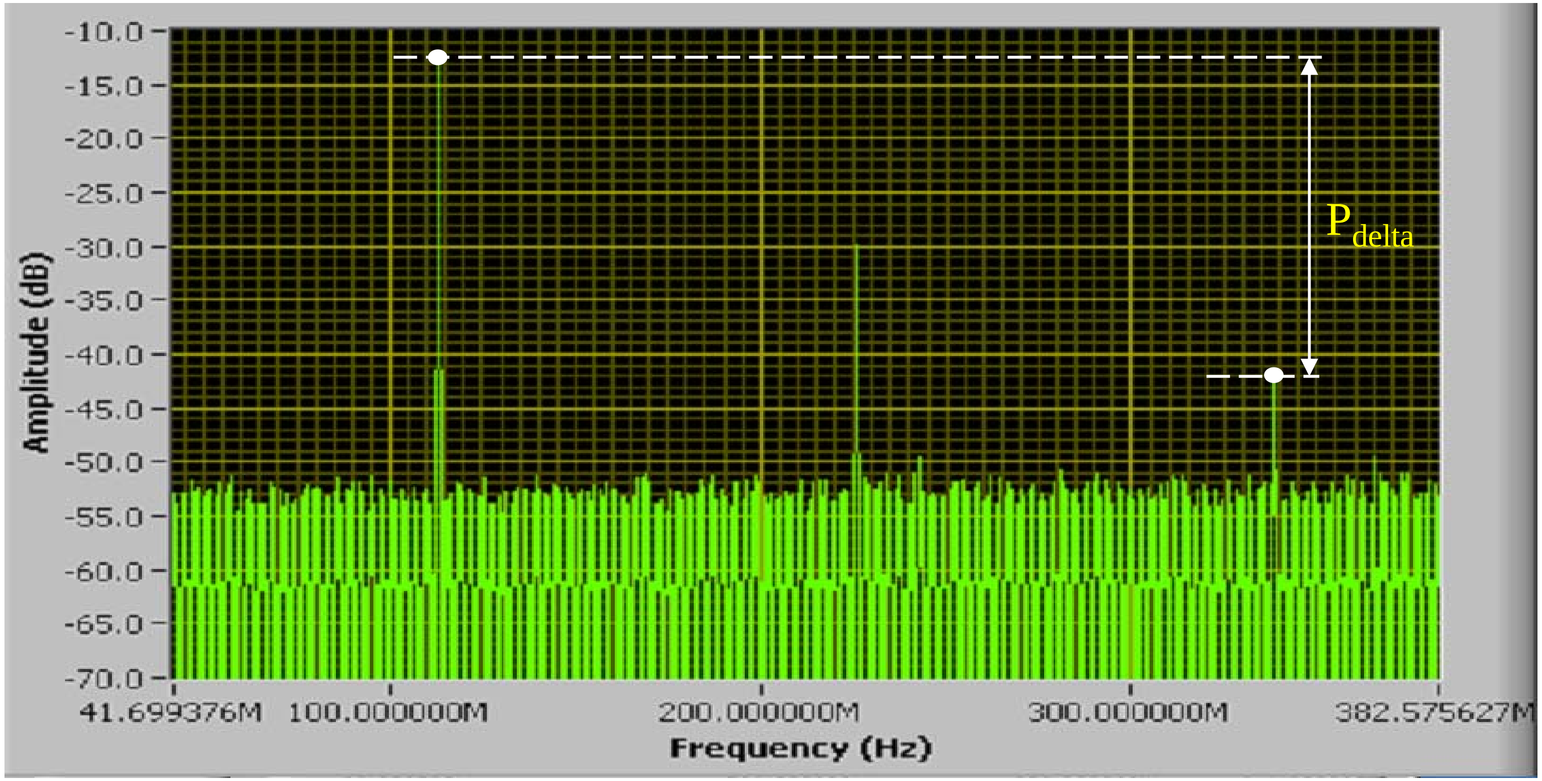
Equalizer building blocks: test of S&H resolution



Marker Delta
f_{delta}=230 MHz
P_{delta}= –28dB

$freq_{Data}$ =19.9 GHz
P_{Data} = 5 dBm
$freq_{clk}$ = 20 GHz
Amp_{clk} = 1.2Vpp

The corresponding ENOB

$$= \frac{SINAD - 1.76dB}{6.02}$$

$$= 4.36\,bits$$

- Beat frequency test: 4.36 bit resolution
- BER method @ 10 GHz: 4.0 bit resolution

90nm CMOS is suitable for low resolution 40 GSa/s ADCs

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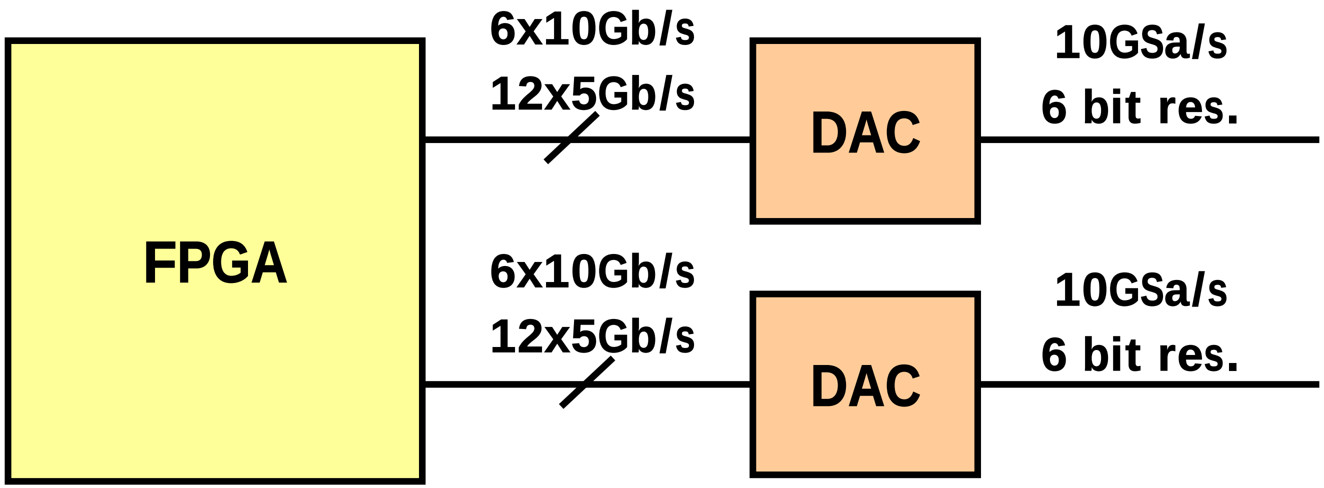
Feasibility-check for real time system

- No dedicated DSPs for O-OFDM available today
- Real time systems should base on FPGAs with subsequent DACs or ADCs

Assuming DAC with 10 GSa/s, 6 bit resolution (faster DACs are available)



- FPGAs (e.g. Xilinx) have high speed interconnects with <10 Gb/s rate,
- 5 Gb/s rate is highest alternative: 24 interconnects are required for setup
- Highest complex FPGAs have 24 high speed interconnects

Today no significant increase for base data rates beyond 10Gb/s possible

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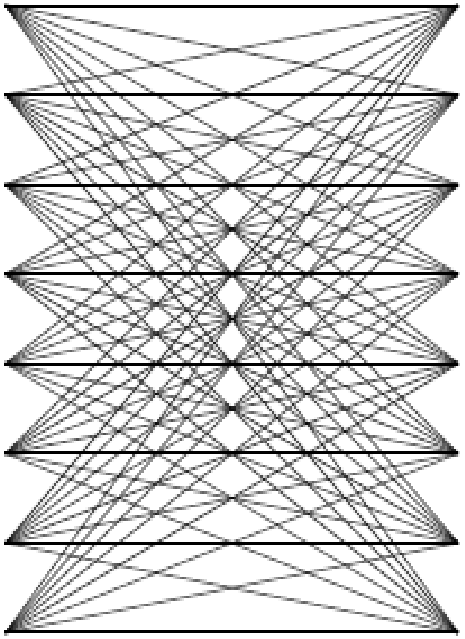
Feasibility-check for real time system

OFDM Tx implementation in FPGA

- Data rate 10 Gb/s, QPSK modulation
- Input word length: 6 bit
- FFT is highest complexity block in Tx
- Radix-8 assumed as an efficient realization

Radix-8 FFT



Utilization of FPGA resources for 512-FFT

FPGA type for investigations: XCE4VFX140

- Flip Flops: 8 %
- LUTs: 68%!!

Conclusions

- Implementation of OFDM Tx for 10 Gb/s using FPGA is feasible
- Increase of data rate or FFT size is limited by FPGA
  - in logic resources
  - interconnection resources to ADC and DAC

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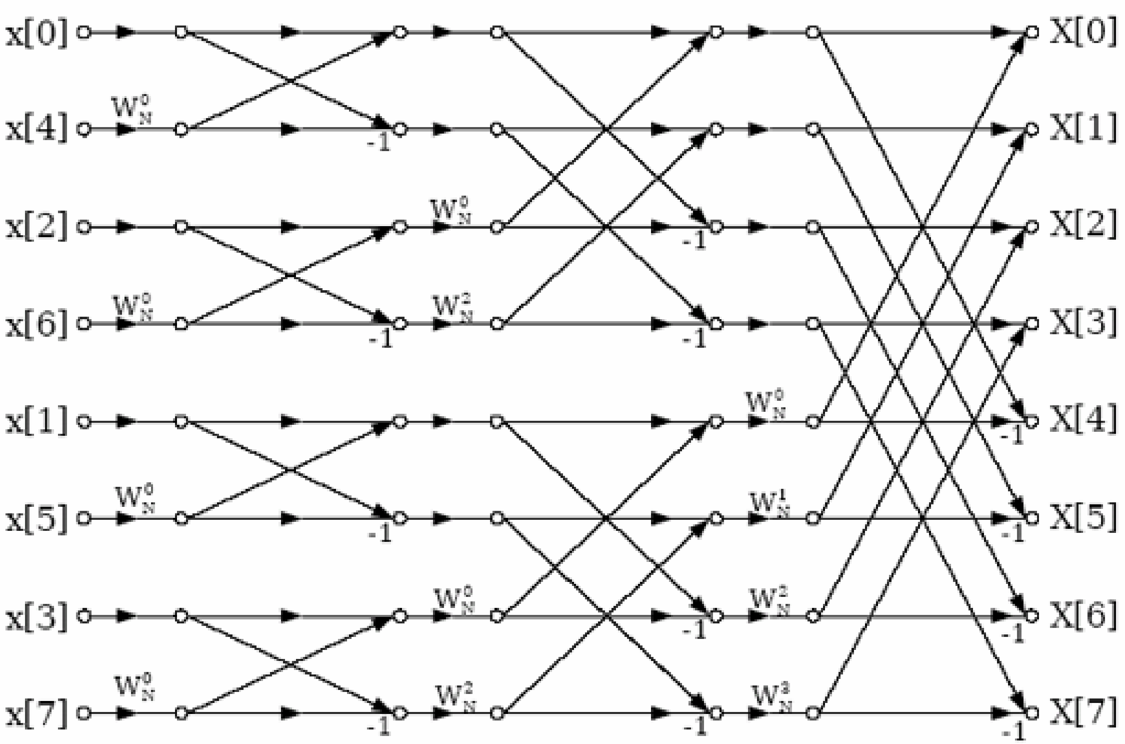
Potential hardware implementation: FFT

FFT implementation



- **FFT is highest effort block within algorithm**
- Butterfly is most important sub-structure

- Loading of data into a parallel structure
- 50GSa, FFT256: 200 MHz processing in a pipelined FFT, 50 MHz @ FFT1024
- Very suitable for subrate processing, further parallelization or pipelining possible
- Structure is same as proposed for frequency domain CD compensation for coh. QPSK, but for whole data stream required (complexity roughly times 4)

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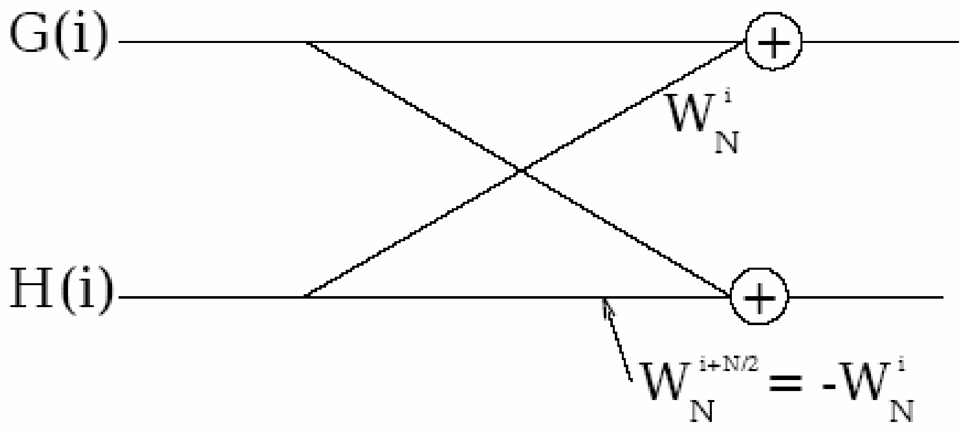
Potential hardware implementation: FFT

FFT implementation



- Each butterfly consists of 1 complex mul and 2 add
- Number of stages 128 @ FFT256, 512 @ FFT1024
- Number of butterflys 1024 @ FFT256, 5120 @ FFT1024
- In sum 4x4.7Mgates = 19 Mgates are required, but distributed to Tx and Rx (half each)

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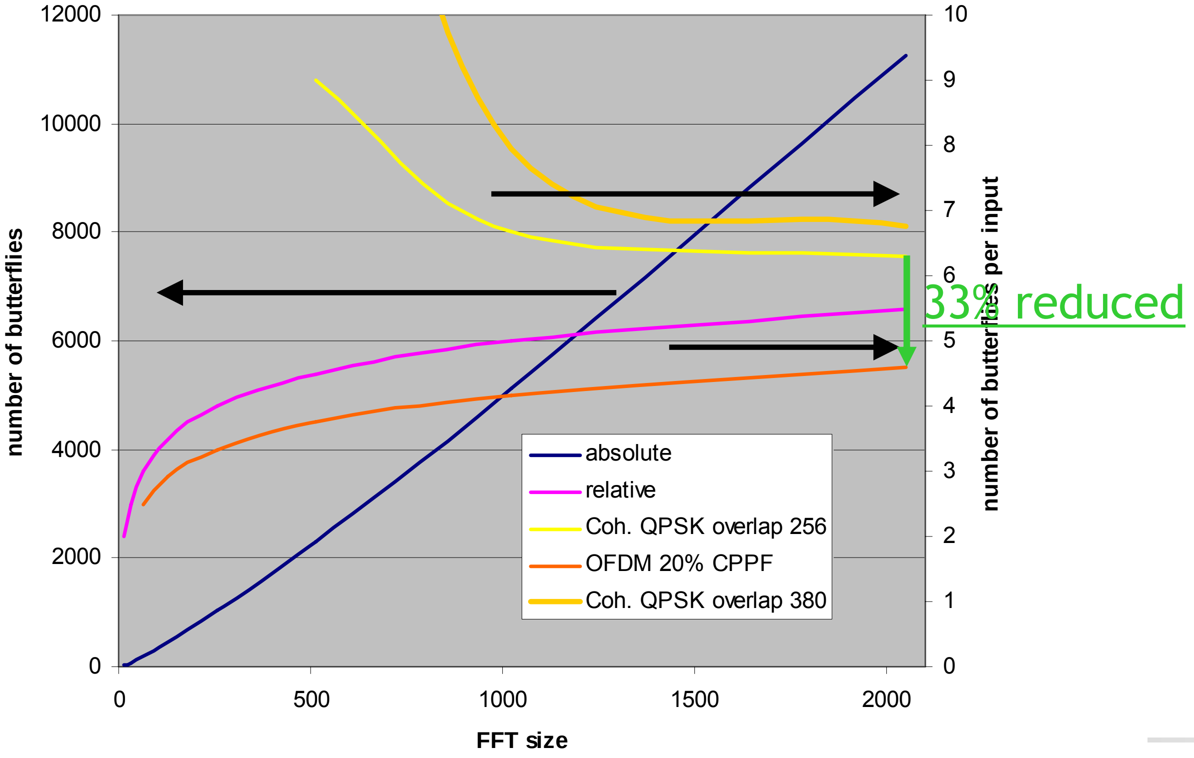
DSP complexity comparison – 1: FFT

FFT complexity

- Small relative increase in hardware with FFT increase
  - OFDM: processing of reduced number of samples
  - Comp. To QPSK: overlap requires higher number of samples, FFT is more complex (bases on Carlos inputs)



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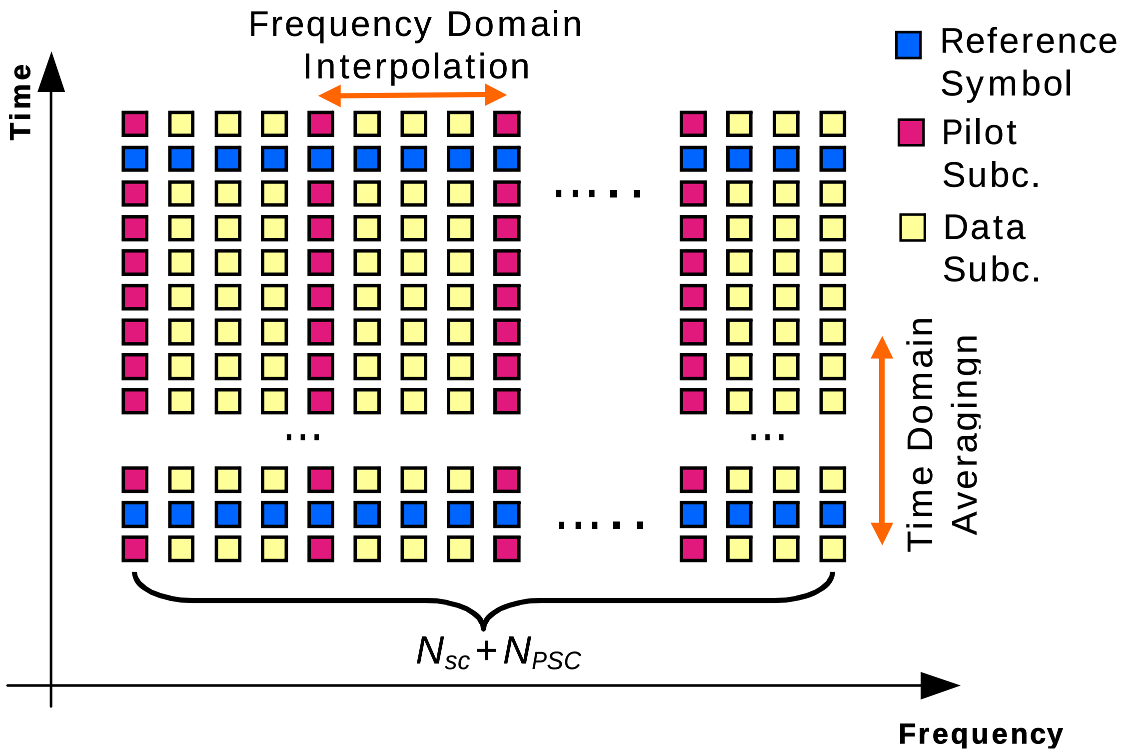
Potential hardware implementation: Channel equalization



Application of pilot signals within the OFDM signal

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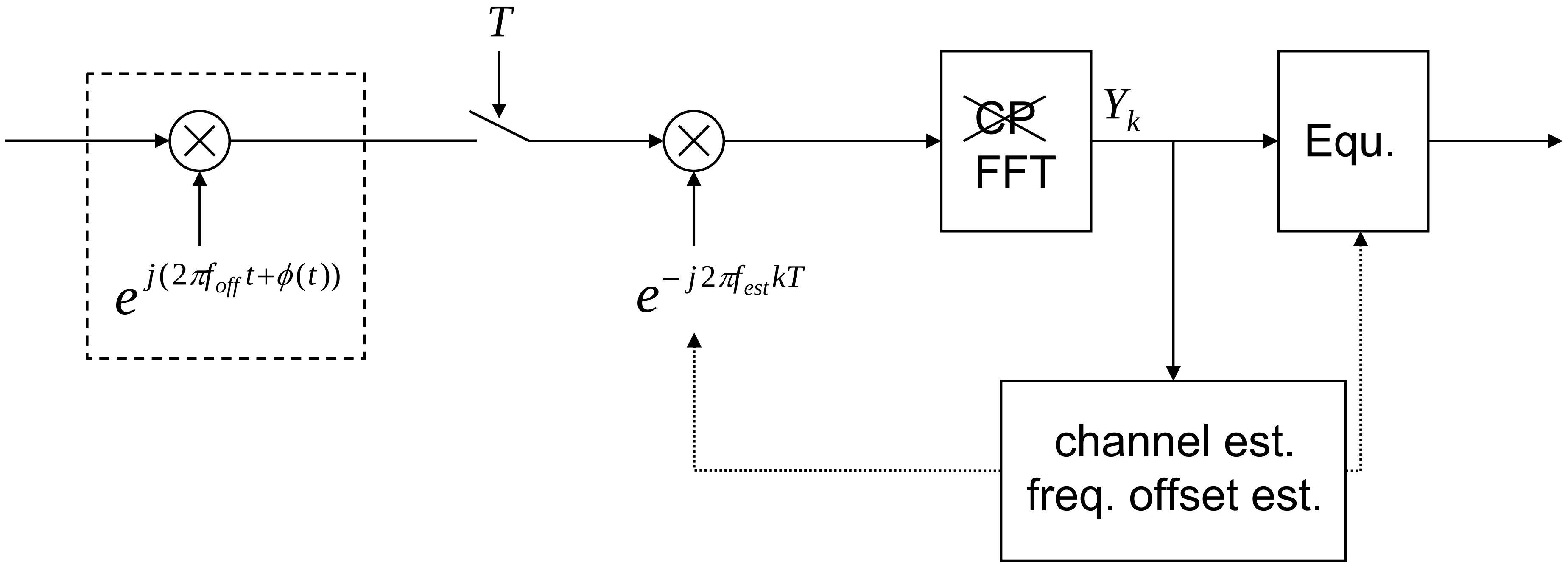
Potential hardware implementation: LO offset estimation and correction

Coherent RX with LO freq. offset + phase noise

Estimation + Compensation of LO offset



LO offset correction is a simple complex multiplication of time domain samples

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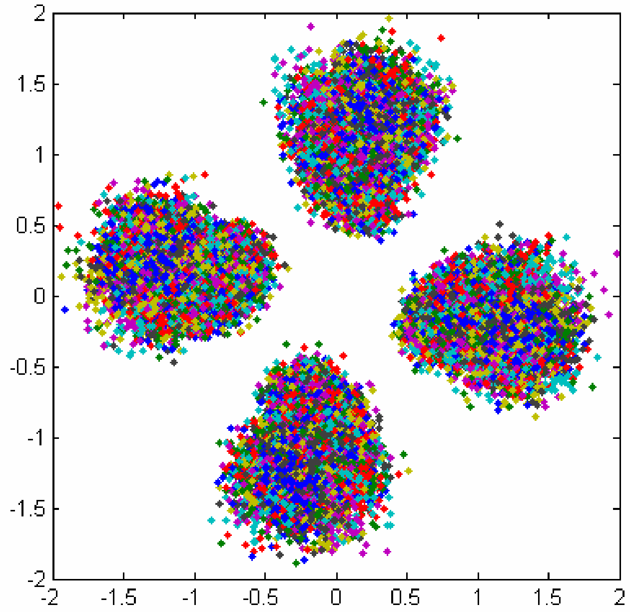
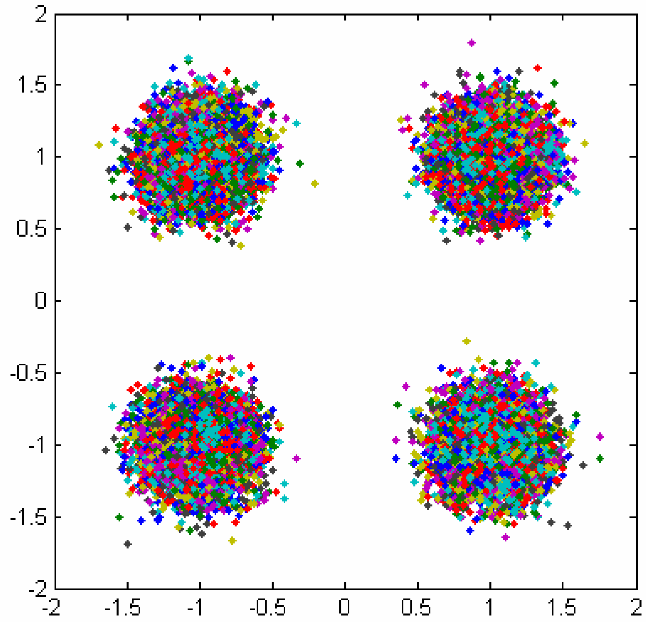
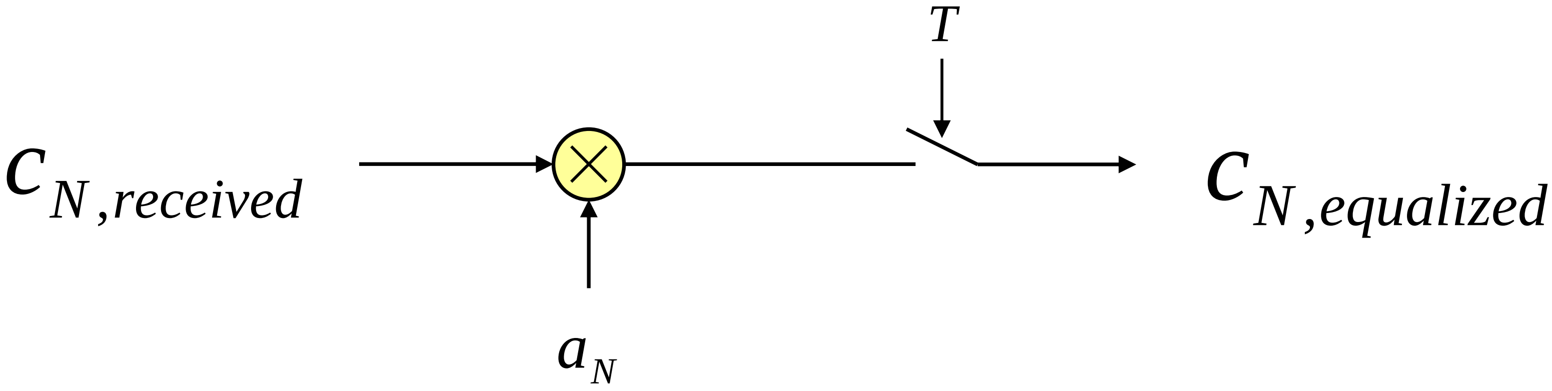
Potential hardware implementation: Channel equalization







$c_{N,received}$

T

$c_{N,equalized}$

a_N

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Potential hardware implementation: Channel equalization

- → Mathmatical operations for OFDM are very simple and very few
- → Adaptation of system is performed by pilot signals and pilot subcarriers, no blind adaptation required

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Comparison QPSK - OFDM

- ECOC 2008, We2E4, B. Spinnler, “Adaptive equalizer complexity in coherent optical receivers”

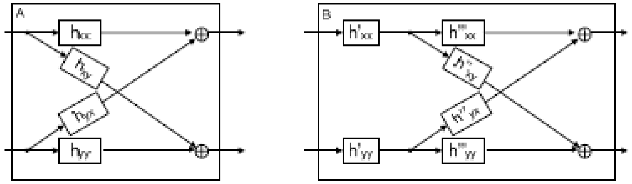


Figure 1: Pure butterfly equalizer (A) and butterfly equalizer with split-off pol. independent part (B).

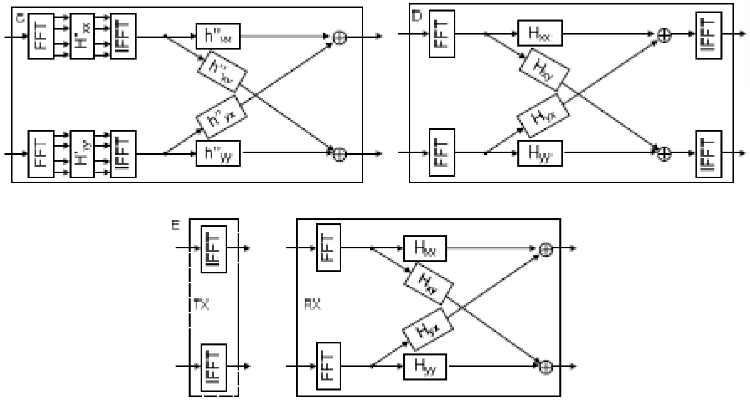
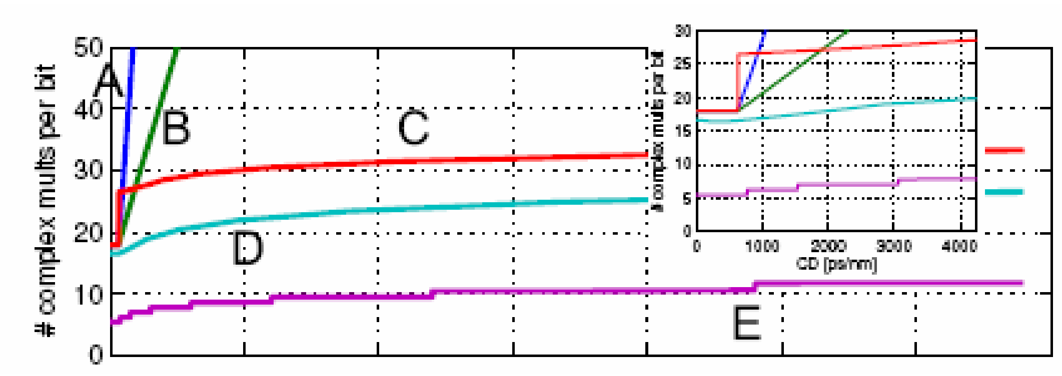


Figure 2: Hybrid TD/FD equalizer (C), FD equalizer (D), and OFDM one-tap equalizer (E).



- Similar/comparable approaches for QPSK and OFDM
- Time domain processing is more complex
- QPSK: full frequency domain processing challenging
  - monitor channel advantageous for adaptation
- In sum: OFDM has half complexity

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Schlußfolgerung

- O-OFDM untersucht
- Definition von Szenarios für 100 Gb/s Systeme
- Diese haben eine gute Empfindlichkeit und hohe nichtlineare Schwellen, sodass das OSNR Budget ein flexibles Systemdesign erlaubt
- Erfordert 50 GSa/s DACs und ADCs, Testchips lieferten ermutigende Ergebnisse
- Erfordert DSP in Tx und Rx, Gesamtaufwand ist vergleichsweise gering

- O-OFDM ist attraktive Technik für optische Systeme bei höheren Datenraten.

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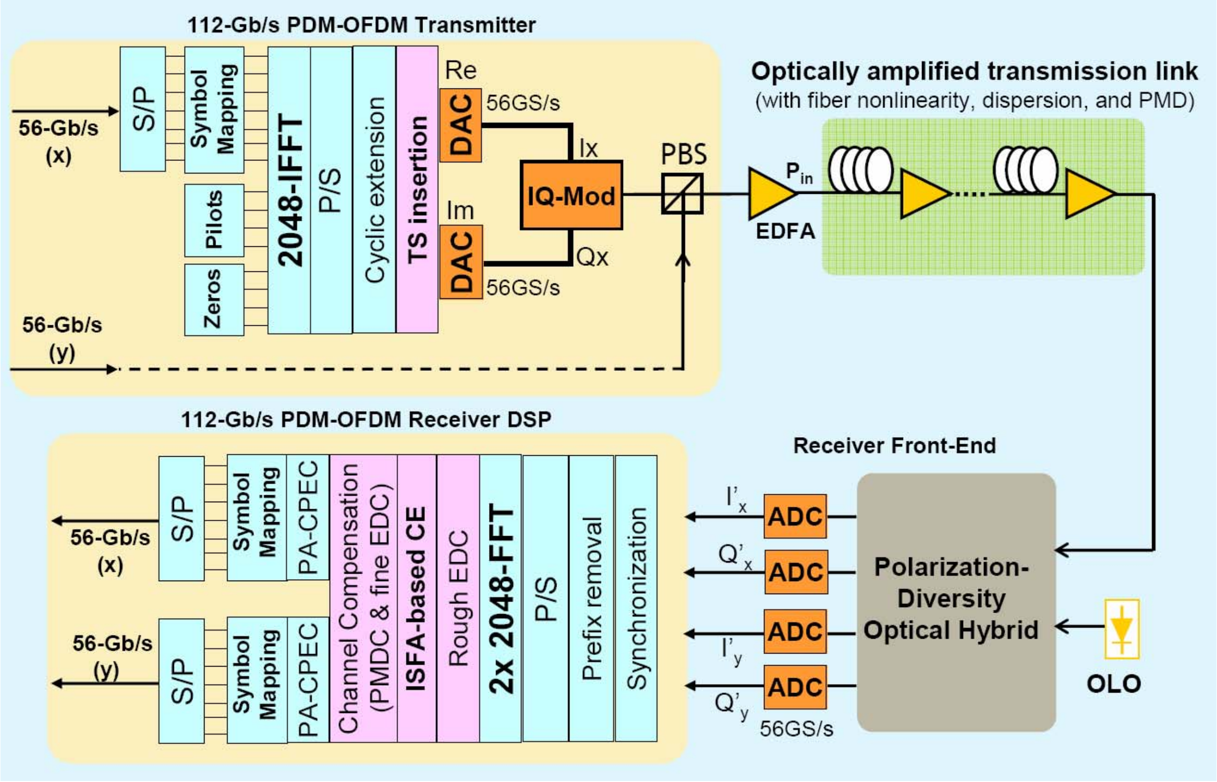
Figure 10: Schematic of a 112-Gb/s PDM-OFDM transceiver architecture. PMDC: PMD compensation. EDC: electronic dispersion compensation. PA-CPEC: pilot-assisted common phase error compensation. DAC: digital-to-analog converter. ADC: analog-to-digital converter.



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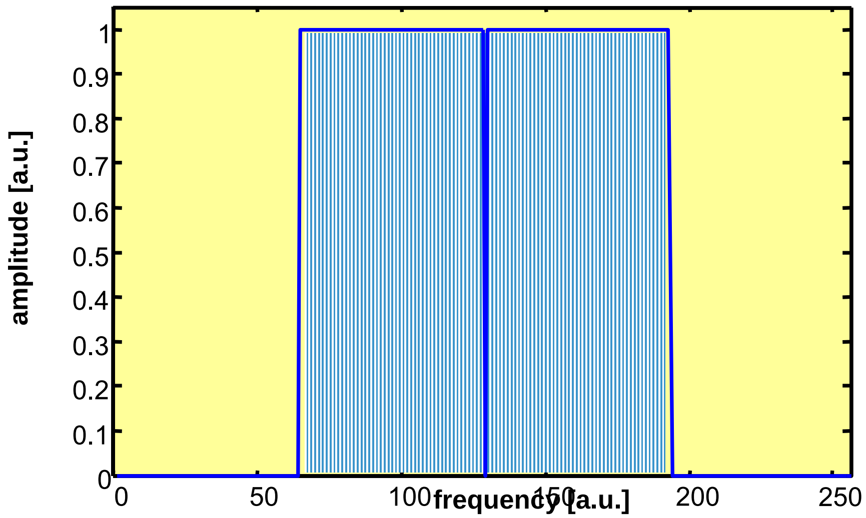
OFDM signal characteristic

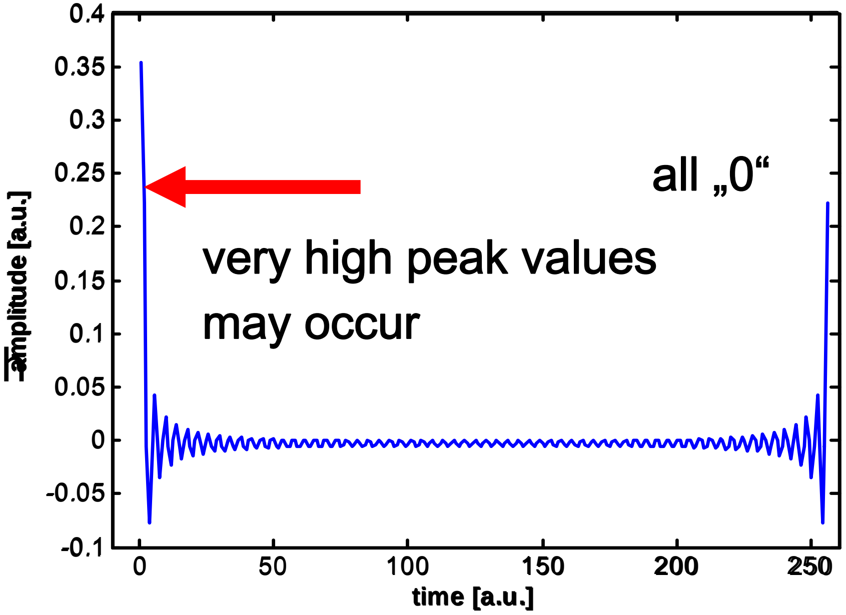
Frequency domain

- QPSK modulated subcarriers (128 subcarriers)
- All have same power
- Information is coded in phase



Time domain

- no constant amplitude (envelope)
- critical data pattern leading to high signal peak power (PRBS7 and all “0”)
- probability of amplitudes depend on FFT length and data pattern (e.g. PRBS length)


all „0“

very high peak values may occur

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