Realizing real-time implementation of CO-OFDM receiver with FPGAs

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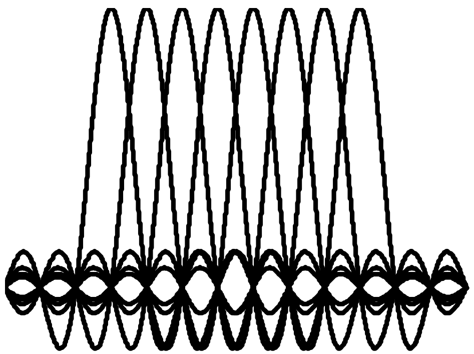
OFDM (Orthogonal Frequency-Division Multiplexing) modulation

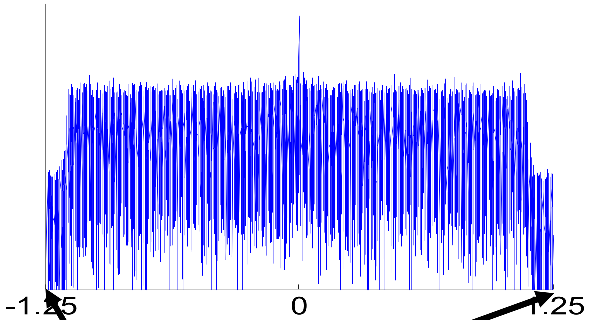


Orthogonal subcarriers

Orthogonal subcarriers allows us to densely populate the spectrum.

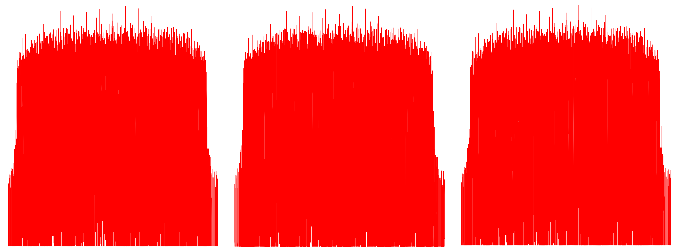
⇩

Efficient spectrum usage



Nyquist frequency

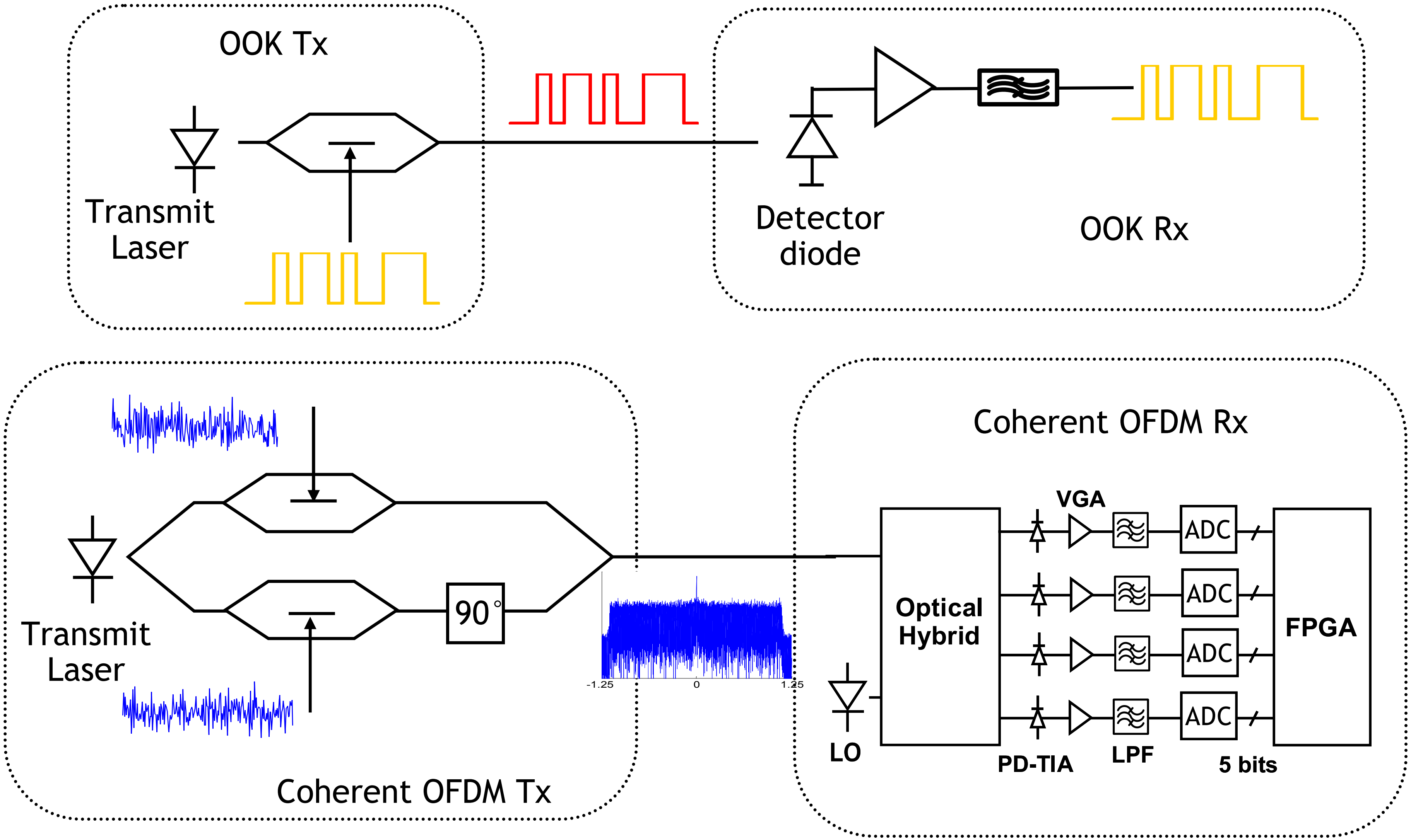
E/O ⇨



OFDM subcarriers can fill in available spectrum close to the Nyquist frequency.

Small or zero frequency guard-band optical OFDM measurements are reported

Coherent Optical OFDM Tx/Rx as opposed to OOK Tx/Rx



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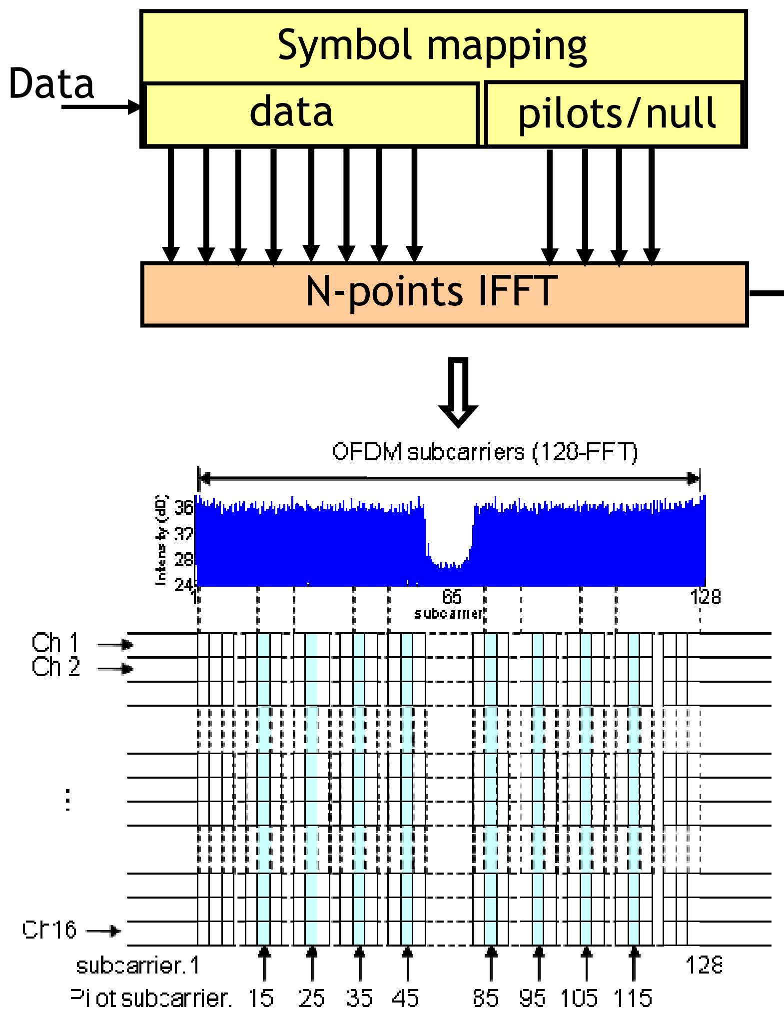
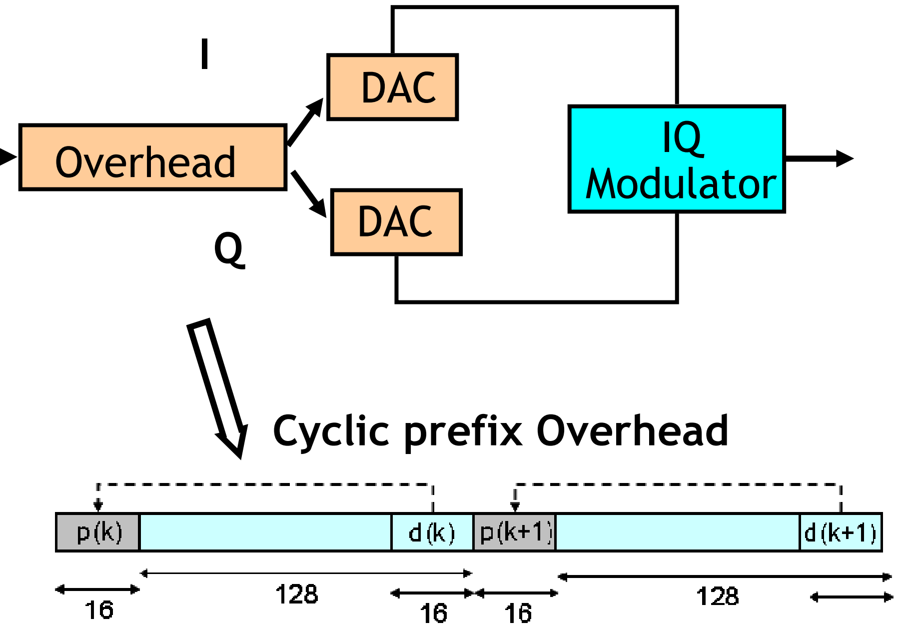
OFDM Tx signal processing diagram





Subcarrier pilots are added in frequency domain prior to IFFT and Cyclic prefix is added in time domain.

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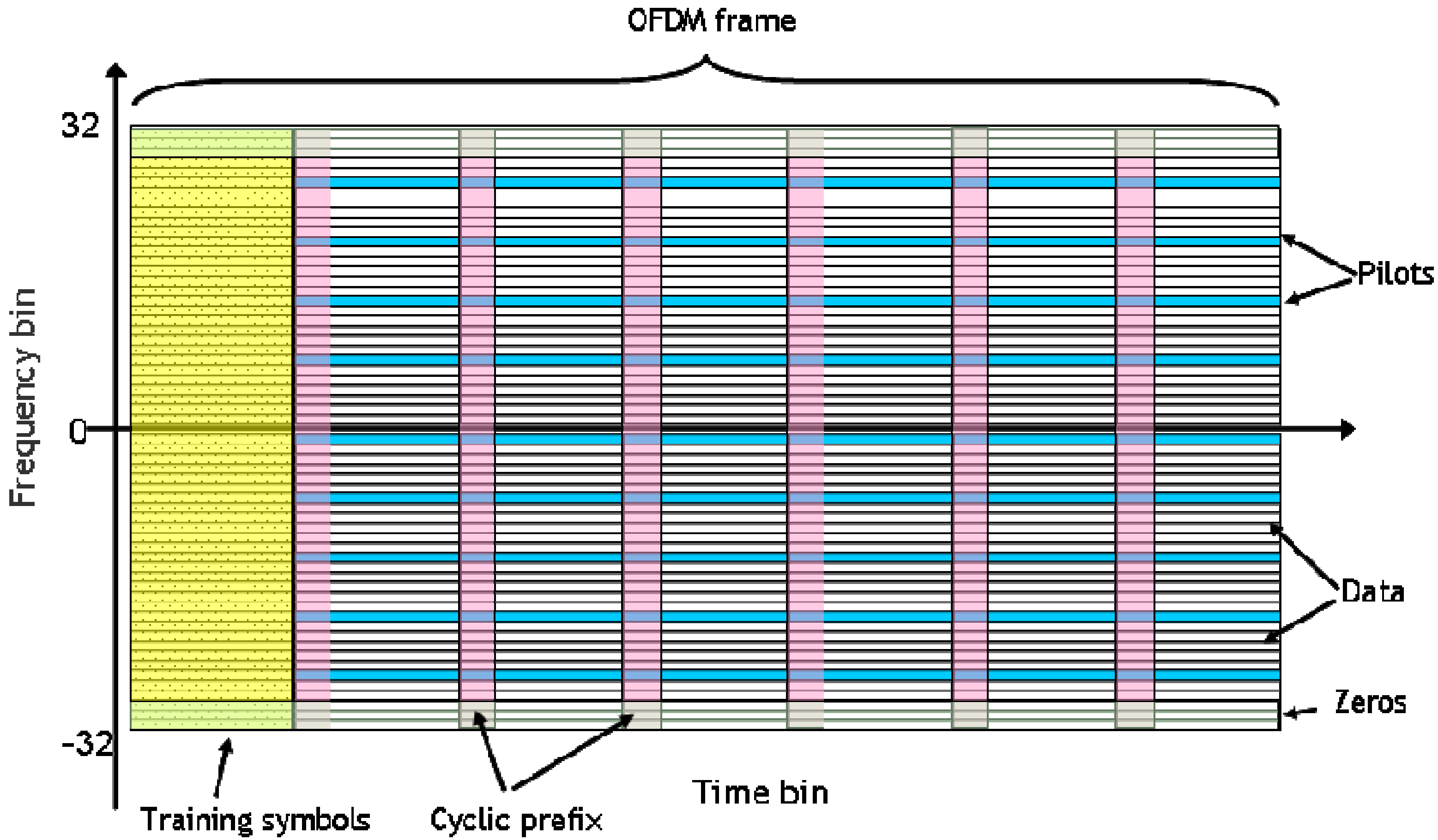
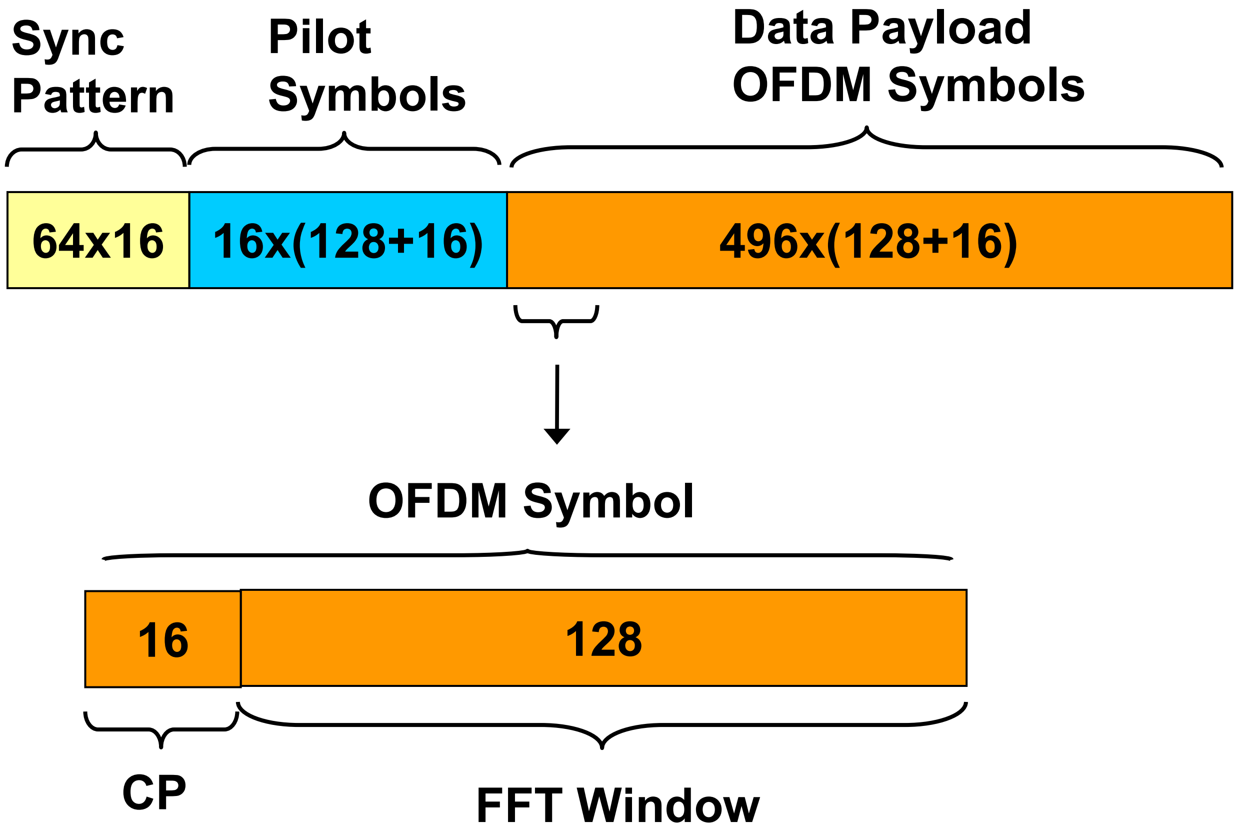
Illustration of OFDM frame in time-frequency profile



OFDM is a time-frequency modulation data format

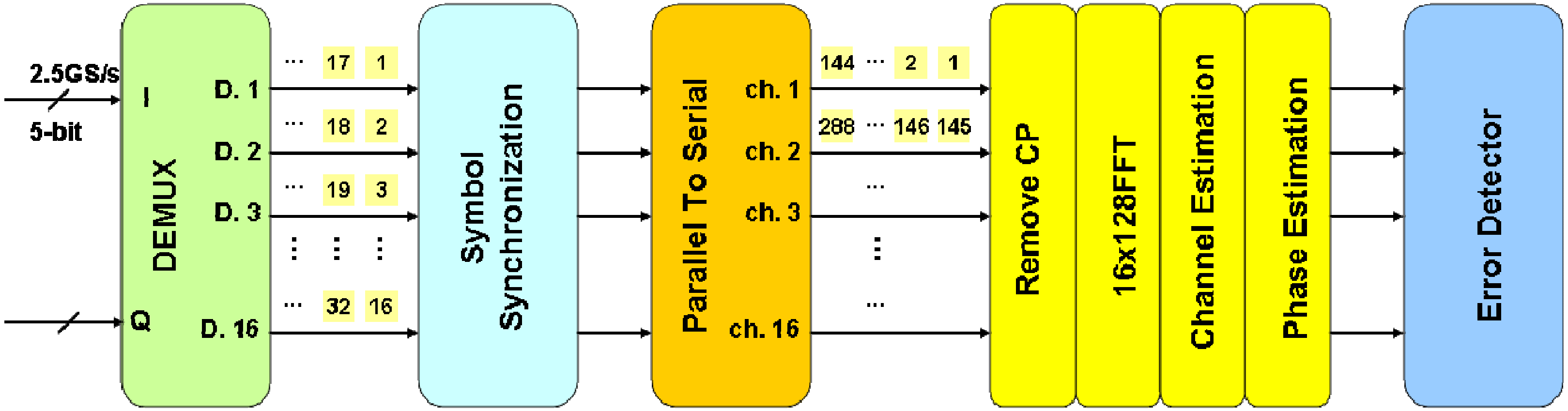
⇨ **More dimensions and freedom for further improvement**

OFDM frame structure for real-time demonstration



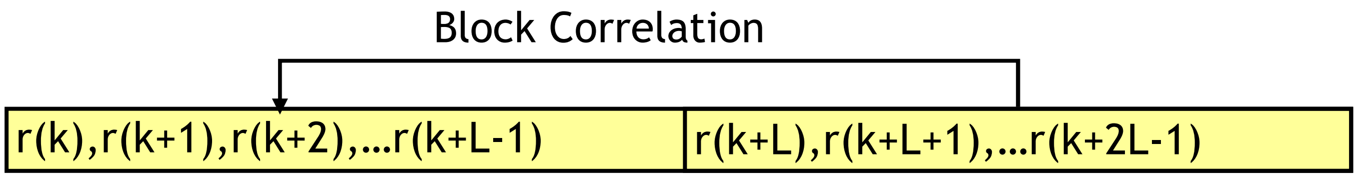
Frame structure is constructed based on the detection methods used for receiver. Frame/symbol synchronization, channel estimate, frequency, phase estimate etc.

DSP diagram for real-time 2.5GS/s OFDM receiver



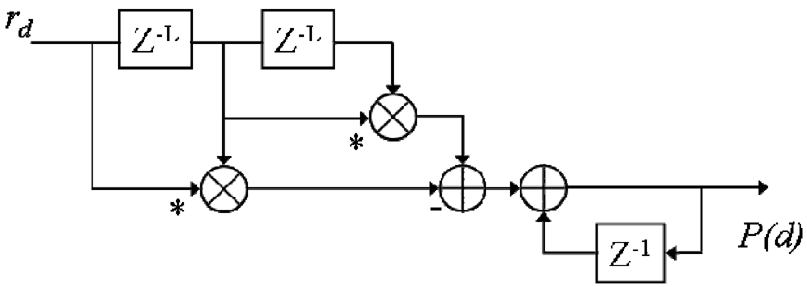
- QPSK modulation.
- 16 channel parallel processing.
- Auto-correlation based (Schmidl and Cox) symbol synchronization for every frame.
- Utilization of serial 128-point FFT.

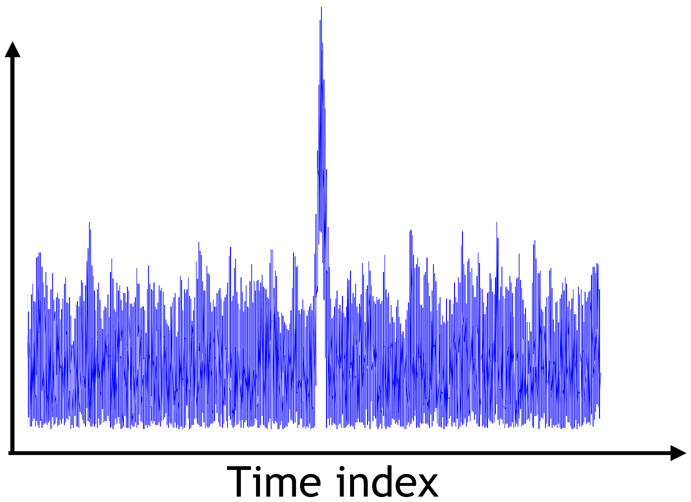
OFDM Symbol Synchronization



Repeated complex preamble pattern

$$P(d+1) = P(d) + r^*_{d+L} r_{d+2L} - r^*_d r_{d+L}$$

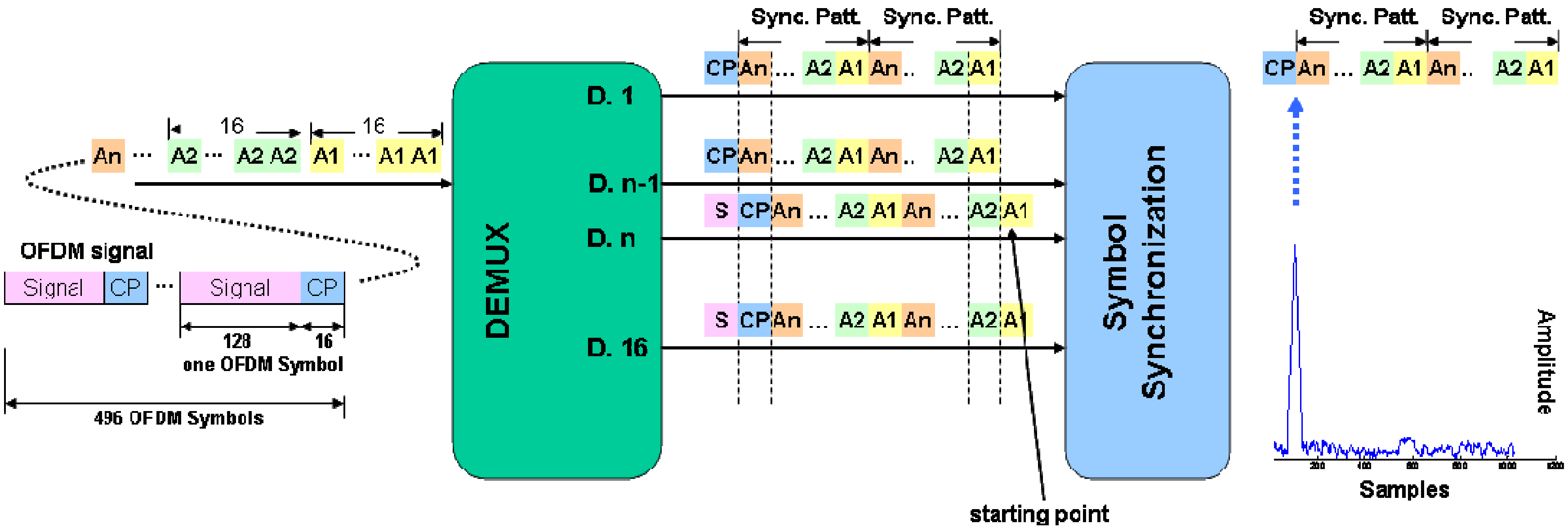




Commonly used synchronization techniques
after Schmidl & Cox

⇨ Resource intensive when parallelized straightforward !

Simple solution for frame synchronization



Synchronization pattern is repeated 16 times thus the conventional auto-correlation can be applied to one of the parallel channel.

- **Pros: Simple and small resource requirement.**
- **Cons: Small frequency offset tolerance.**
  Larger overhead requirement. Loss of CP to timing synchronization.

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OFDM channel and phase estimate

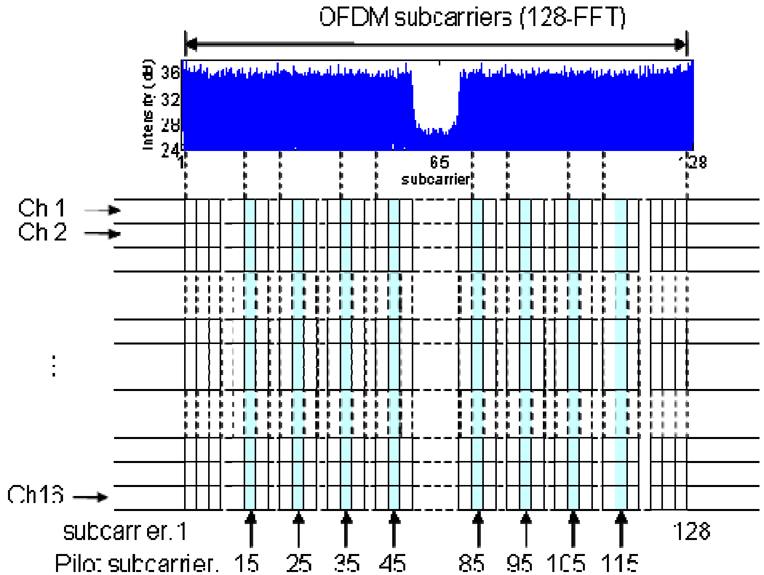
Sync Pattern | **Pilot Symbols** | **Data Payload OFDM Symbols**

64x16	16x(128+16)	496x(128+16)

Channel estimate

Transmitted

Channel estimation
only done for every frame



Phase estimation
done for every pilot of every symbol

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OFDM channel and phase estimate

Received signal in frequency domain

$$R_d\left(k\right) = H\left(k\right)B_d\left(k\right)C_d\left(k\right)$$

Where H and B are the transfer functions for channel and phase

$$\hat{H}^{-1}\left(k\right) = \frac{1}{M}\sum_{d=1}^{M} R_d^{\ *}(k)C_d\left(k\right) \qquad \hat{B}_d^{-1} = \frac{1}{N_p}\sum_{k=1}^{N_p} R_d^{\ *}(k)C_d\left(k\right)$$

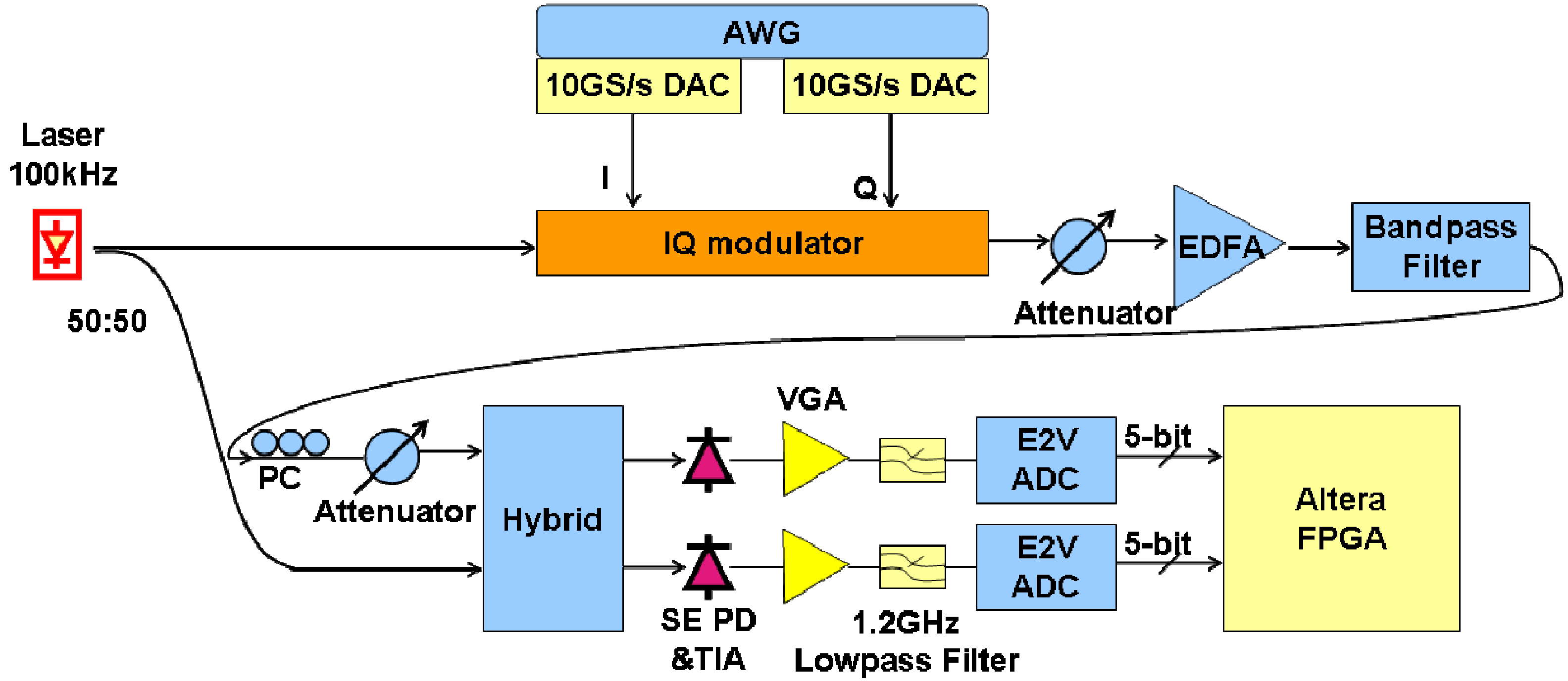
TABLE I
LOOKUP TABLE FOR CHANNEL AND PHASE ESTIMATE

Information symbols of pilot	Modulated symbols of pilot	H^{-1} or B^{-1} real	H^{-1} or B^{-1} imaginary
0	$-1+j$	$-a-b$	$a-b$
1	$-1-j$	$-a+b$	$-a-b$
2	$1+j$	$a-b$	$a+b$
3	$1-j$	$a+b$	$-a+b$

Received signal is $R = a + jb$

Simple lookup table will suffice the complex multiplication for QPSK modulation.

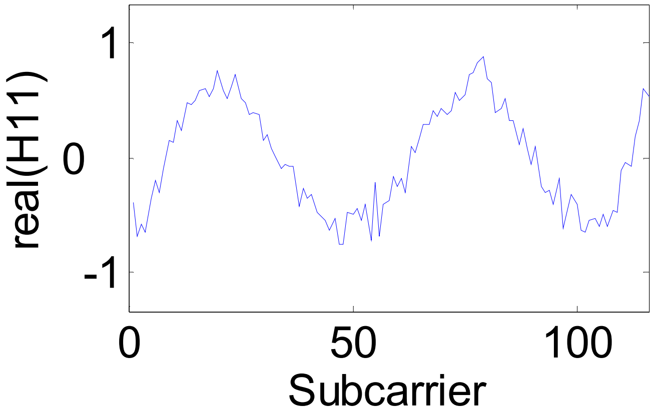
Real-time OFDM receiver experimental setup

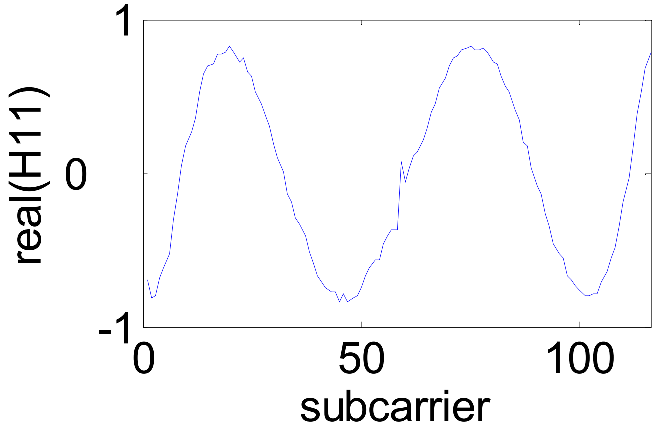


- Arbitrary waveform generator for 128 subcarrier OFDM transmitter.
- 116 subcarriers are filled with QPSK data and pilots.
- 5-bits ADC at 2.5GS/s. Altera Stratix II GX FPGA.
- An external cavity laser is shared for transmit and receive laser.
- Single polarization with polarization control.

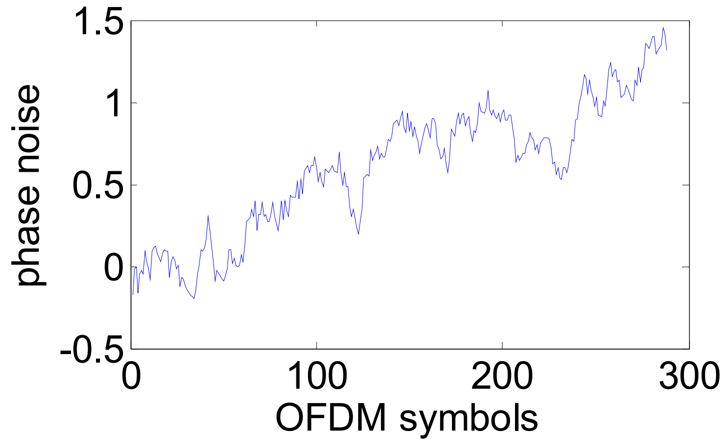
Channel and Phase Estimation

16 out of 512 OFDM symbols are used as pilot symbol for CHANNEL ESTIMATION





8 out of 115 subcarriers are used as pilot subcarriers for PHASE ESTIMATION



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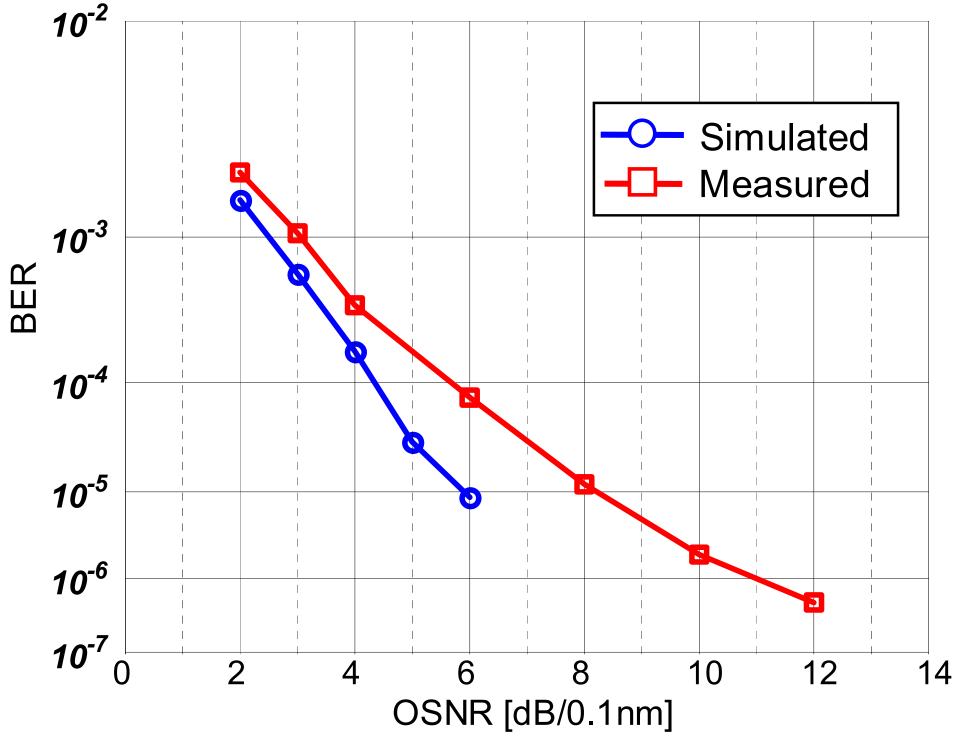
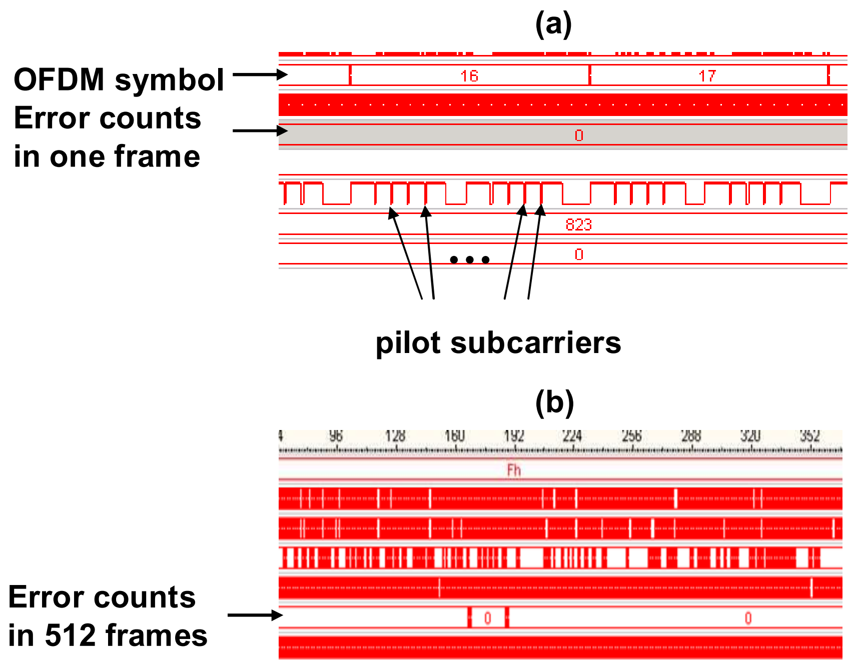
Measurement results: BER vs OSNR



- **Removing all time and frequency overhead, we achieve 3.55Gb/s data rate for 107 data subcarriers.**
- **Errors are counted against transmitted signals locally at FPGA.**
- **Limited resolution in internal processing may be contributing to higher measured BER.**
- **Error floor is not apparent from this plot.**

Measurement results: Error floor verification



Verification of error floor with high OSNR.
The errors were counted for 512 frames (i.e. 496x512 OFDM symbols).
$3.7*10^{-8}$ BER is recorded.

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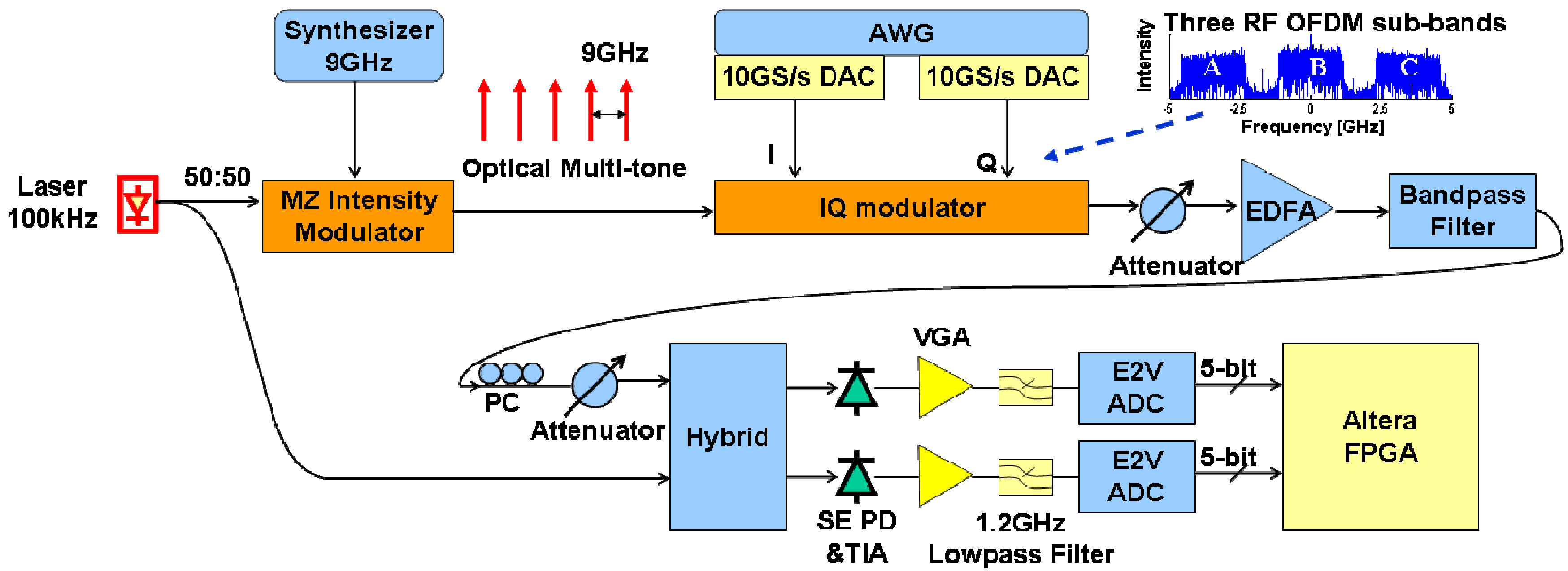
Expanded measurement for 53.3 Gb/s sub-banded OFDM

Fig.1



- Each RF OFDM carries 3.55Gb/s.
- 10GS/s AWG produces three 3.55Gb/s subbands .
- 5 optical tones spaced at 9GHz is generated by overdriving MZ modulator.
- Net rate 53.3Gb/s is achieved.

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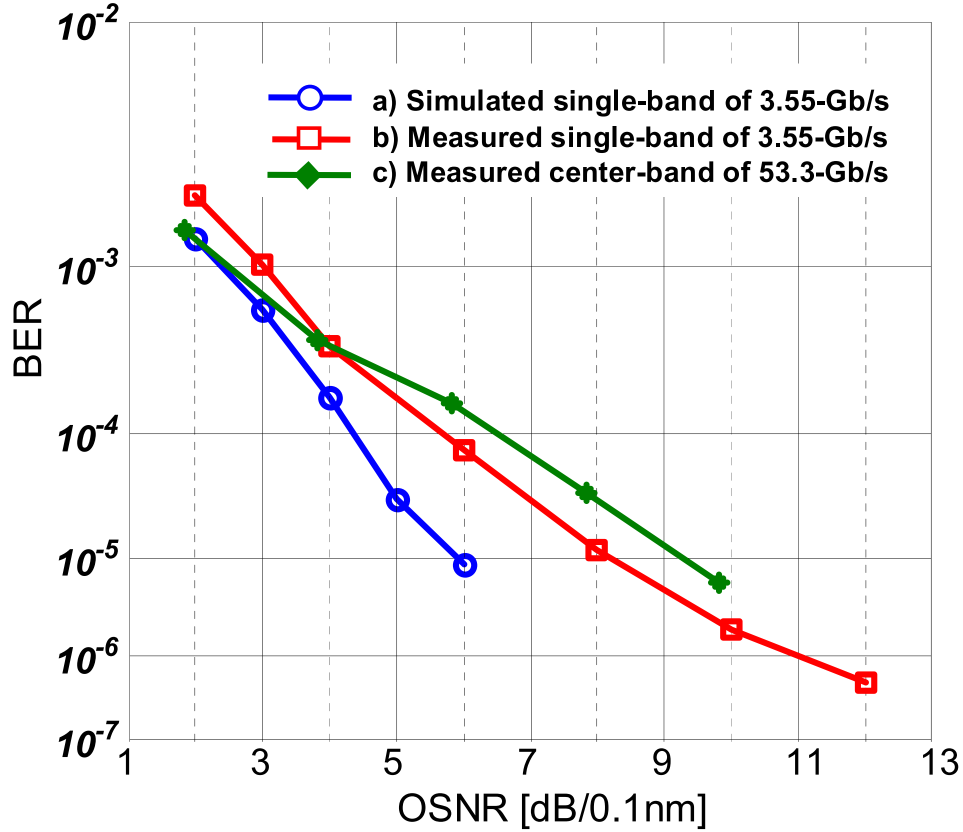
Measurement results: BER vs OSNR



Small penalty for net rate 53.3Gb/s BER is observed at higher OSNR

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