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

N. Kaneda\textsuperscript{1}, Q. Yang\textsuperscript{3}, X. Liu\textsuperscript{2}, W. Shieh\textsuperscript{3}, and Y.K. Chen\textsuperscript{1}

\textsuperscript{1}: Bell Laboratories, Alcatel-Lucent, 600-700 Mountain Avenue, Murray Hill, NJ 07974, USA
\textsuperscript{2}: Bell Laboratories, Alcatel-Lucent, 791 Holmdel-Keyport Road, Holmdel, NJ 07733, USA
\textsuperscript{3}: Department of Electrical and Electronic Engineering, The University of Melbourne, VIC 3010, Australia

Email: kaneda@alcatel-lucent.com
OFDM (Orthogonal Frequency-Division Multiplexing) modulation

Orthogonal subcarriers allows us to densely populate the spectrum.

Efficient spectrum usage

Orthogonal 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

OOK Tx
- Transmit Laser
- Detector diode
- OOK Rx

Coherent OFDM Tx
- Transmit Laser
- 90°
- Coherent OFDM Rx
- Optical Hybrid
- VGA
- ADC
- PD-TIA
- LPF
- ADC
- FPGA
- 5 bits
OFDM Tx signal processing diagram

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

Received signal in frequency domain

\[ R_d(k) = H(k)B_d(k)C_d(k) \]

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

\[ H^{-1}(k) = \frac{1}{M} \sum_{d=1}^{M} R_d^{*}(k)C_d(k) \]

\[ B_d^{-1} = \frac{1}{N_p} \sum_{k=1}^{N_p} R_d^{*}(k)C_d(k) \]

| TABLE I
Look up table for channel and phase estimate |
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Information</td>
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<tr>
<td></td>
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<tr>
<td>Informat.</td>
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<tr>
<td>H⁻¹ or B⁻¹</td>
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<td>2</td>
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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
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.
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.
Measurement results: BER vs OSNR

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