OFDM for Optical Access

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Th1H.1
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Optical Access Networks

Optical Access Network → Passive Optical Network (PON)

Goal: Increase data rate, reach, subscriber (ONU) count
Goals for Future Optical Access Networks

- Increase data rate
  - Introduce WDM, increase data rate per \( \lambda \)
- Increase subscriber count
  - WDM + multiple access (MA) techniques on each wavelength:
    - TDMA, CDMA, FDMA, OFDMA

Advantages of OFDMA:

- Flexibility in time and frequency domain
- Continuous operation (instead of burst operation)
- Efficient equalization

... however, there are challenges!
Aspects of OFDM in Optical Access Networks

Our Perspective on OFDM

High Data Rate

Sync. Aspects

Field Trial

Cost Reductions

Real-Time Experiments

Downstream + Upstream

WDM DSP
Outline

• Basics of Optical OFDM
• Principles of OFDM in PON: Downstream
• Principles of OFDM in PON: Upstream
  - Concepts with multiple optical sources
  - Concepts with single optical source
  - Multiple access
• Field Trial
• Further Advances of OFDM in Access
• Summary and Outlook
Basics of Optical OFDM: Introduction

Orthogonal Frequency Division Multiplexing (OFDM)

- **Parallel** transmission of narrow-band data streams
- Different (sub-)carrier frequencies $f_0, \ldots, f_{N-1}$
- **Partially overlapping** in frequency domain
- **Orthogonal**

![Diagram of OFDM Transmitter and Receiver](diagram.png)
Basics of Optical OFDM: Introduction

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- **Parallel** transmission of narrow-band data streams
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![Diagram of OFDM Transmitter and Receiver](image)
Basics of Optical OFDM: Introduction

Orthogonal Frequency Division Multiplexing (OFDM)

- **Parallel** transmission of **narrow-band** data streams
- **Different** (sub-)carrier frequencies \( f_0, \ldots, f_{N-1} \)
- **Partially overlapping** in frequency domain
- **Orthogonal**

Required:
- sync. frequency
- sync. timing
Basics of Optical OFDM:
All-Optical Realization

- All-Optical OFDM: Many optical modulators → Long-haul
Basics of Optical OFDM:
Analog-Electrical Realization

- **All-Optical OFDM:** Many optical modulators → Long-haul
- **Analog-Electrical OFDM:** Many analog-electrical modulators
Basics of Optical OFDM:
DSP-Based Realization

- **All-Optical OFDM:** Many optical modulators → Long-haul
- **Analog-Electrical OFDM:** Many analog-electrical modulators
- **DSP-based OFDM:** Many digital multipliers in DSP → Access, metro
Basics of Optical OFDM:
DSP-Based (IFFT) Realization

- **All-Optical OFDM**: Many optical modulators → Long-haul
- **Analog-Electrical OFDM**: Many analog-electrical modulators
- **DSP-based OFDM**: IFFT/FFT in DSP → Access, metro

![Diagram](Image)

**OFDM-Transmitter**
- S/P
- Data
- S/P
- P/S
- IFFT
- $d_0(i)$
- $d_k(i)$
- $d_{N-1}(i)$

**Channel**
- DAC
- ADC
- S/P
- FFT
- P/S

**OFDM-Receiver**
- S/P
- Data
Basics of Optical OFDM:
Advanced Elements of DSP-based OFDM

- **Mapping** for higher-order modulation formats
- **Synchronization** of OFDM-symbols required
- **CP** to avoid ISI
- Efficient **channel equalization**
- **Phase noise (PN)-compensation** (with coherent detection)
Basics of Optical OFDM:
Optical Modulation/Detection

Optical spectrum

**IM-DD DSB**

\[ S_1^* \quad \quad \quad C \quad \quad \quad S_1 \]

**IM-DD SSB**

\[ C \quad \quad \quad S_1 \]

**IM-CO DSB**

\[ S_1^* \quad S_1 \]

Dispersion

\[ |E|^2 \]

Electrical spectrum

**IM-DD DSB**

\[ C^2 \quad S_1^* + S_1^2 \quad C \cdot S_1 + C \cdot S_1^* \]

**IM-DD SSB**

\[ C^2 \quad S_1^2 \quad C \cdot S_1 \]

**IM-CO DSB**

\[ LO^2 \quad LO \cdot S_1^* \quad LO \cdot S_1 \]

\[ S_1^2 + S_1^{*2} \]

as in OFC’14 Short Course, OFC’12 Tutorial by Sander Jansen
Aspects of OFDM in Optical Access Networks

- High Data Rate
- Field Trial
- Cost Reductions
- Real-Time Experiments
- WDM
- Synchron. Aspects
- DSP
- +

Downstream
Upstream
Principles of OFDM in PON: Downstream (DS)

OFDM $\rightarrow$ OFDMA (OFD Multiple Access)

Example with 4 ONUs

Groups of OFDM subcarriers assigned to ONU 1 … ONU 4

Downstream: Point-to-Multi-Point (P2MP)
### OFDMA-DS: Optics

**Detection**

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Direct Detection</th>
<th>Coherent Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IM DSB</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>DAC</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>IM</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>Cost efficiency</td>
<td>Cost efficiency</td>
</tr>
<tr>
<td></td>
<td>+ +</td>
<td>– –</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Sensitivity</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>+ +</td>
</tr>
<tr>
<td></td>
<td>Reach</td>
<td>Reach</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>+ +</td>
</tr>
<tr>
<td><strong>IM SSB</strong></td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td>DAC</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
</tr>
<tr>
<td>IM</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>Cost efficiency</td>
<td>Cost efficiency</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>– –</td>
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<td>+ +</td>
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<td></td>
<td>Reach</td>
<td>Reach</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>+ +</td>
</tr>
</tbody>
</table>
OFDMA-DS: Concept with IM/DD

OFDM signal generation at OLT
- Orthogonal subcarrier groups → OFDMA possible

Electrical IQ modulation
- Real valued signal
- Frequency gap
- Intensity modulation and direct detection possible
**OFDMA-DS: Effort Reduction** *(Kiel, OFC’12)*

**Concept**

OFDM signal generation at OLT
- Orthogonal subcarrier groups → OFDMA possible

**Processing of small subcarrier group at each ONU**
- Reduction of ADC-speed, DSP-speed and DSP-complexity possible: Cost ↓
- Tunable electrical LO frequency → access every section of DS-spectrum
**OFDMA-DS: Effort Reduction** (Kiel, OFC’12)

**Experimental Setup**

**Single Tx (OLT):**
- Offline processing
- SSB-filtering to avoid power fading
- Full data rate: 12 Gb/s (net)
- 8-QAM mapping

**Single Rx → Emulate multiple Rx (ONU):**
- Different LO-frequencies
- Different reduction factors \( r \)
  - \( 50 \text{ GS/s} \rightarrow 10 \text{ GS/s} , \ldots , 2.5 \text{ GS/s} \)
  - Full / half / quarter data rate

---

**Diagram:**

OLT

```
OLT
```

**ONU**

```
ONU
```

v. Hoyningen-Huene et al., OFC 2012, OW4B.
OFDMA-DS: Effort Reduction (Kiel, OFC’12)

Experimental Setup

Single Tx (OLT):
• Offline processing
• SSB-filtering to avoid power fading
• Full data rate: 12 Gb/s (net)
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Single Rx → Emulate multiple Rx (ONU):
• Different LO-frequencies
• Different reduction factors ($r$)
→ 50 GS/s → 10 GS/s , ... , 2.5 GS/s
→ Full / half / quarter data rate

Experimental Setup Diagram:

OLT

- Offline processing
- SSB-filtering to avoid power fading
- Full data rate: 12 Gb/s (net)
- 8-QAM mapping

ONU

- Different LO-frequencies
- Different reduction factors ($r$)

 disparity in processing rates: 50 GS/s → 10 GS/s , ... , 2.5 GS/s
- Full / half / quarter data rate
OFDMA-DS: Effort Reduction (Kiel, OFC’12)
Experimental Results

\( r = 1, \approx 12 \text{ Gb/s} \)

\( r = 2, \approx 6 \text{ Gb/s} \)

\( r = 4, \approx 3 \text{ Gb/s} \)

OSNR [dB]

log\(_{10}\)(BER)

Full bandwidth

Half bandwidth

Quarter bandwidth

f [GHz]
11.25 Gb/s real-time experiment with clock synchronization

Further P2P experiments with OFDM:
W. Yan et al. (Fujitsu), OFC 2014: 80 km, IM-DD, 100 Gb/s on single \( \lambda \), offline DSP
X. Xiao et al. (ZTE), OFC 2014 PDP, : 200 km, IQ-CO, 100 Gb/s on single \( \lambda \), real-time DSP

\( \rightarrow \) OFDM(A)-downstream in PON is feasible (P2P \( \rightarrow \) P2MP)
Aspects of OFDM in Optical Access Networks

High Data Rate
Sync. Aspects
Field Trial
Cost Reductions
Real-Time Experiments
WDM
DSP
Downstream + Upstream

Chair for Communications
Duplex of Downstream and Upstream

- Different fibers
  - Simple concept, relatively expensive

- Common fiber, different wavelengths
  - Separation with WDM components
  - Small interference of US and DS
  - NEC, CAU Kiel, etc.

- Common fiber, single wavelength
  - Remodulation of downlink signal
  - Technion, HHI Berlin, NEC, etc.
Upstream: Multi-Point-to-Point (MP2P)

OLT

ONU 1

ONU 2

ONU 3

ONU 4
Principles of OFDM in PON:
Upstream (US)

Upstream: Multi-Point-to-Point

Challenges:
• Carrier frequency offset
Principles of OFDM in PON: Upstream (US)

Upstream: Multi-Point-to-Point

Challenges:
• Carrier frequency offset
• Different path lengths
• Different states of polarization
• Different optical phase
OFDMA-US: Multiple Optical Sources
Different Wavelength, Direct Detection

Optical spectrum

Electrical spectrum

Desired parts

Intermodulation products
OFDMA-US: Multiple Optical Sources
Different Wavelength, Direct Detection

Optical spectrum

Electrical spectrum

- Insensitive to carrier frequency offset
- Insensitive to pol./phase mismatch
- Large optical bandwidth required
OFDMA-US: Multiple Optical Sources ($M-\lambda$)
Proof of Concept

ONU:
- DMLs
- 2 ONUs
- SC/$N_{\text{FFT}}$: 2x128 / 256
- Guard band

PON:
- Passive splitter 4:1
- Single fiber 20 km

OLT:
- DD
- OFDMA
- 10 Gb/s

Proof of concept:

D. Qian et al., ECOC 2007, paper 5.4.1 (NEC)
OFDMA-US: Multiple Optical Sources ($M$-$\lambda$)
Real-Time Experiment

**ONU:**
- DML & VCSEL
- DAC 4 GS/s
- $N_{\text{FFT}}$/SC/CP: 32/15/8
- Modulation: 64 QAM
- FPGA clock: 100 MHz

**PON:**
- Passive splitter 2:1
- Single fiber 26.4 km
- $N_{\text{FFT}}$/SC/CP: 32/15/8
- Modulation: 64 QAM
- FPGA clock: 100 MHz

**OLT:**
- DD 4 GS/s ADC
- OFDMA with DBA
- 11.25 Gb/s (gross)

Real-time experiment upstream:

X.Q. Jin et al., Opt Exp. 2011, (Bangor)
Aspects of OFDM in Optical Access Networks

- High Data Rate
- Sync. Aspects
- Field Trial
- Cost Reductions
- Real-Time Experiments
- WDM
- Downstream + Upstream

Chair for Communications
OFDMA-US: Single Optical Source (1-\(\lambda\))
Common Wavelength, Direct Detection

Optical spectrum

\[ f_1, A \lambda_1 \]

Electrical spectrum

\[ |E|^2 \]
### OFDMA-US: Optical Tx/Rx
Common Wavelength, Direct Detection

- Equal carrier frequencies required → Synchronize optical carriers
  → Carrier distributed from OLT to all ONUs

#### Optical spectrum

\[ f_i = \lambda_i \]

#### Electrical spectrum

\[ |E|^2 \]

Carrier frequency error → Crosstalk
OFDMA-US: Single Optical Source (1-λ)
Common Wavelength, Direct Detection

- Equal carrier frequencies required
- Destructive beating of carriers possible
  → Loss of sub-signals
  → Direct detection not robust enough
OFDMA-US: Single Optical Source (1-λ)
Common Wavelength, Coherent Detection

- Equal carrier frequencies required
- Carrier suppression at transmitter
- Coherent detection of both polarizations
### OFDMA-US: Single Optical Source (1-λ)

**ONU Tx / OLT Rx**

<table>
<thead>
<tr>
<th>Modulation ONU</th>
<th>Detection OLT</th>
<th>Direct Detection</th>
<th>Coherent Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity Modulation</strong>&lt;br&gt;Local laser sources&lt;br&gt;Multiple wavelengths (M-λ)</td>
<td></td>
<td>Cost efficiency ++&lt;br&gt;Sensitivity –&lt;br&gt;WDM –&lt;br&gt;Groups: NEC, Bangor, Orange</td>
<td>Cost efficiency – (M⋅Rx)&lt;br&gt;Sensitivity ++&lt;br&gt;WDM –</td>
</tr>
<tr>
<td><strong>Intensity Modulation</strong>&lt;br&gt;Central laser source&lt;br&gt;Common wavelength (1-λ)</td>
<td></td>
<td><strong>Beating</strong></td>
<td>Cost efficiency – (shared)&lt;br&gt;Sensitivity ++&lt;br&gt;Groups: NEC, Kiel, Accordance, HHI</td>
</tr>
<tr>
<td><strong>Optical IQ-Modulator</strong>&lt;br&gt;Central laser source&lt;br&gt;Common wavelength (1-λ)</td>
<td></td>
<td><strong>Beating</strong></td>
<td>Cost efficiency – (shared)&lt;br&gt;Sensitivity ++&lt;br&gt;Higher SE&lt;br&gt;Groups: Technion</td>
</tr>
<tr>
<td><strong>Optical IQ-Modulator</strong>&lt;br&gt;Local laser sources&lt;br&gt;Carrier synchronization (“1”-λ)</td>
<td></td>
<td><strong>Beating</strong></td>
<td>Cost efficiency – (M Lasers)&lt;br&gt;Sensitivity ++&lt;br&gt;Higher SE&lt;br&gt;Groups: Osaka</td>
</tr>
</tbody>
</table>
OFDMA-US: Single Optical Source (1-\(\lambda\))

Setup

1-\(\lambda\) US

- Distributed optical modulation (multiple transmitters) \(\rightarrow\) 1-\(\lambda\) US
  - Broadcast US-carrier from OLT / remodulation at ONU
  - Common wavelength \(\rightarrow\) Frequency offset problem solved

- Multiple access
  - Subcarriers
  - Time slots
# OFDMA-US:
## Multiple Access Schemes

<table>
<thead>
<tr>
<th>MA Schemes</th>
<th>Spectrum</th>
<th>Pro/Con</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(0) OFDM-TDMA</strong></td>
<td><img src="image" alt="FFT-window" /></td>
<td><strong>Cost eff.:</strong> ++ (free running lasers)</td>
</tr>
<tr>
<td><em>(IM/DD IM/CO)</em></td>
<td></td>
<td><strong>Timing:</strong> – sync/guard</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Rx/Tx:</strong> – burst mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Granularity:</strong> – (only time)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Groups:</strong> NTT</td>
</tr>
<tr>
<td><strong>(1) OFDM-FDMA</strong></td>
<td><img src="image" alt="FFT-window" /></td>
<td><strong>Cost eff.:</strong> ++ (Co Rx shared)</td>
</tr>
<tr>
<td><em>(IM/CO)</em></td>
<td></td>
<td><strong>Timing:</strong> + robust</td>
</tr>
<tr>
<td><strong>Individual FFT</strong></td>
<td></td>
<td><strong>Granularity:</strong> +</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Groups:</strong> NEC, Kiel, Orange</td>
</tr>
<tr>
<td><strong>(2) OFDMA</strong></td>
<td><img src="image" alt="FFT-window" /></td>
<td><strong>Cost eff.:</strong> +/- (Co Rx shared)</td>
</tr>
<tr>
<td><em>(IM/CO)</em></td>
<td></td>
<td><strong>Timing:</strong> – sync required</td>
</tr>
<tr>
<td><strong>Common FFT</strong></td>
<td></td>
<td><strong>– common clock</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Granularity:</strong> ++ (comb. TDMA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Groups:</strong> NEC, Kiel, Technion</td>
</tr>
</tbody>
</table>
Aspects of OFDM in Optical Access Networks

- High Data Rate
- Sync. Aspects
- Field Trial
- Cost Reductions
- Real-Time Experiments
- WDM
- DSP

Downstream + Upstream
OFDMA-US: (1)FDMA
Experiments (NEC, ECOC’09)

OLT:
- Common US-carrier
- Coherent Rx (Dual pol.)
- DSP individual Rx (DFTs)

PON:
- Duplex with 2 fibers
- Optical interleaver

ONU (3):
- DD/IM + el. IQ
- 10 Gbit/s
- Carrier suppression

DSP:
- \( N_{\text{DFT}} \): 800
- SC/ONU: 200/240
- Guard band: 500 MHz

D. Qian et al., ECOC 2009, paper 8.5.1
Aspects of OFDM in Optical Access Networks

Christian-Albrechts-Universität zu Kiel

High Data Rate

Sync. Aspects

Field Trial

Cost Reductions

Real-Time Experiments

WDM

Downstream + Upstream

DSP

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OFDMA-US: Individual FFT(1) vs. Common FFT(2)

- No carrier frequency offset \( \rightarrow 1-\lambda \)
- Synchronization, timing and clock

![Diagram showing OFDMA-US: Individual FFT(1) vs. Common FFT(2)]

Common DSP

Individual DSP

\( \Delta \tau = 2 \text{ns} \)

\( \tau_1 \rightarrow L_1 \)

\( \tau_2 + \Delta \tau \rightarrow L_2 \)

\( \tau_3 \rightarrow L_3 \)

\( \tau_4 \rightarrow L_4 \)

\( \rightarrow \) Control symbol timing

\( \rightarrow \) Common clock

Subcarrier index

EVM in %

OLT

ONU 1

ONU 2

ONU 3

ONU 4
**OFDMA-US:**
Experiments (Kiel, OFC’14)

**ONUs (Tx):**
- Generation of 4 real-valued OFDM signals

**PON:**
- Distribution fibers different lengths
- **Bidirectional** feeder fiber

**OLT (Rx):**
- Coherent detection (dual pol.)
  1) DSP with individual FFTs
  2) DSP with common FFT

---

von Hoyningen-Huene et al., OFC 2014, Tu2F.4.
**OFDMA-US: Experiments (Kiel, OFC’14)**

Optical Spectra

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**Graphs and Diagrams:**

- X-pol. and Y-pol. spectra showing optical signals across different wavelengths.
- Diagram illustrating the signal flow from TX DSP to DAC, through 25 km of fiber, and to downstream components like VOA, CO RX, ADC, OFDMA Rx DSP, ECL, and OLT.

**Text:**

- von Hoyningen-Huene et al., OFC 2014, Tu2F.4.
**OFDMA-US:**
DSP for US Receiver (OLT)

**US-DSP:**
- ✓ Frame Synchronization
- ✓ Timing Advance
- ✗ FFT-size, CP duration
- ✗ EQ Adaption to polarization diversity receiver
- ✗ PN estimation and compensation

Dual Pol. Co-Rx → ADC → ADC → ADC → ADC

Sync. → S/P → - CP → FFT → EQ (SIMO) → PN-Comp → Demapping → P/S

Common vs. Individual → we have full control over timing.
OFDMA-US: Experiments (Kiel, OFC’14)
Individual FFTs (1)

2.25 Gb/s per ONU
Individual FFT (1)

OFDM-FDMA

Delay wrt. to neighboring ONUs $\Delta t/T_{OFDM}$

von Hoyningen-Huene et al., OFC 2014, Tu2F.4.
2.25 Gb/s per ONU
Common FFT (2)

OFDMA-US: Experiments (Kiel, OFC’14)
Common FFT (2)

Delay of ONU3 $\Delta t/T_{OFDM}$

EVM per SC

Subcarrier index

0
0.1
0.2
0.3
0.4
0.5

0
0.1
0.2
0.3
0.4

-5
-4
-3
-2
-1

ONU 1
ONU 2
ONU 3
ONU 4

FFTW-window

$\exp(-j2\pi f_0 t)$

von Hoyningen-Huene et al., OFC 2014, Tu2F.4.

Chair for Communications
1. Initialization:
Cross-correlation with individual synchronization symbols:

\[ \Delta \tau_3 \Delta \tau_4 \Delta \tau_2 \Delta \tau_1 \]

\[ \rightarrow \text{Estimation: } \Delta \tau_3 \Delta \tau_4 \Delta \tau_2 \Delta \tau_1 \]

\[ \rightarrow \text{timing advance (TA)} \]

C. Ruprecht et al., ACP 2013, AF1G.4
2. Fine tuning and tracking:

One-tap equalizer coefficients:

\[ H_{\text{offset}}(f_k) = |H(f_k)| \cdot \exp(j \cdot \phi_k + j \cdot 2\cdot \pi \cdot \tau \cdot f_k) \]  
Subcarrier index \( k = 1\ldots196 \)

Linear deviation of phase

\[ \rightarrow \text{TA update} \]
**OFDMA-US: Synchronization (Kiel, ACP’13)**

**Tracking Experiment**

**OLT**
- ECL, linewidth 5 kHz

**PON:**
- Bidirectional distribution fiber
- Amplifier at remote node

**Result:**
→ Tracked delay change of 29…39 ns
294…392 samples

**ONU1..4 @ 10 GS/s**
- TS/EQ/Data = 1/1/40
- FFT/CP = 512/8

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C. Ruprecht et al., ACP 2013, AF1G.4

Chair for Communications
Aspects of OFDM in Optical Access Networks

Field Trial Experiment

- High Data Rate
- WDM
- Sync. Aspects
- Downstream + Upstream
- DSP
- Field Trial
- Cost Reductions
- Real-Time Experiments
Field Trial: OFDMA-PON (Kiel, OFC’14)

Scenario

• US and DS including 1 OLT and 4 ONUs
• Optical attenuator → emulate 32 ONUs
• 37.5 km field deployed feeder fiber
• DS: 20 Gbit/s (FFT 1024, 8-QAM)
• US: 6.5 Gbit/s (FFT 512, 4-QAM)
**Field Trial:** OFDMA-PON (Kiel, OFC’14)

**Setup**

Succesfully realised:
20 Gbit/s DS and 6.5 Gbit/s in US
37.5 km supporting 32 ONUs (Trellis)

Polarization dependent!!
Field Trial: OFDMA-PON (Kiel, OFC’14)
Flexible Subcarrier Allocation

Synchronized US $\to$ orthogonal subcarriers at OLT receiver
Flexible subcarrier allocation possible

OLT: assigns different number of subcarriers (different data rate)
OLT: assigns different subcarriers (same data rate)

$\rightarrow$ Flexible subcarrier allocation (per ONU) possible without penalty

Upstream ONUs:
- **ONU 1:** 2.29 Gbit/s
- **ONU 2:** 0.96 Gbit/s
- **ONU 3:** 1.29 Gbit/s
- **ONU 4:** 1.96 Gbit/s

C. Ruprecht et al., OFC 2014, T3G.5
Field Trial: OFDMA-PON (Kiel, OFC’14)
Flexible Subcarrier Allocation

Synchronized US → orthogonal subcarriers at OLT receiver
Flexible subcarrier allocation possible

![Graph showing EVM and PSD for different subcarrier allocations]

- **Upstream ONUs:**
  - **ONU 1:** 2.29 Gbit/s
  - **ONU 2:** 0.96 Gbit/s
  - **ONU 3:** 1.29 Gbit/s
  - **ONU 4:** 1.96 Gbit/s

→ **Flexible subcarrier allocation (per ONU) possible without penalty**

C. Ruprecht et al., OFC 2014, T3G.5

Chair for Communications
Aspects of OFDM in Optical Access Networks

Further Advances of OFDM in Access

- High Data Rate
- WDM
- Downstream + Upstream
- Sync. Aspects
- Field Trial
- Cost Reductions
- Real-Time Experiments
- DSP
1.2 Tb/s (1 Tb/s after overhead) symmetric WDM-OFDMA-PON

Advances:
- High data rate: 25 x 40 Gb/s
- Long reach: 90 km

Further steps:
- DS and US: bidirectional fiber
- Generation of data at different ONUs
- Less optical amplifiers

N. Cvijetic et al., OFC 2011, PDPD7
Further Advances of OFDM in Access

- High Data Rate
- Sync. Aspects
- Field Trial
- Cost Reductions
- Real-Time Experiments
- WDM + Downstream DSP Upstream
Real-Time Upstream (Bangor, OptExp’12)
First Steps Towards 1-λ

OLT:
• DD
• Remote Laser (1-λ possible)

PON:
• Single fiber: 25 km

ONU:
• REAM
• 1 ONU @ 10Gb/s
• Bidirectional Amplifier

Advances:
• Polarization independent
• Bidirectional
• Colorless

“Further steps”:
• Multiple ONU
• Co-Rx at OLT
• Less amplifier

E. Hugues-Salas al., Optics Express 20(19), 2012
Aspects of OFDM in Optical Access Networks

Further Advances of OFDM in Access

- High Data Rate
- Sync. Aspects
- Field Trial
- Cost Reductions
- Downstream + Upstream
- WDM
- DSP
- Real-Time Experiments
**ONU Integration:** (Technion, OFC’13)
First Steps OTONES Concept Class I

**ONU:**
- Colorless
- $1-\lambda$
- Polarization independent mod.
- Photonic integrated circuit
- Low speed ADC/DAC
- Tune into 1 of 10 streams (1Gbit/s)
- 16 QAM

**Concept:** A. Agmon et al., OFC 2013, OTh3A.6

**Bidirectional Modulator:** P.C. Schindler et al. ECOC 2014

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Further Advances of OFDM in Access

- High Data Rate
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Aspects of OFDM in Optical Access Networks
Co-OFDMA-PON (Osaka, ECOC’14, OFC’15)
CFO Compensation

OFDMA US with CFO compensation using feedback from OLT
• 3 kHz linewidth ECL
• 400 ms feedback delay

Advances:
• ONUs with individual sources
• CFO compensation for 100 kHz ECL
• Real-time ONU in US
• MUI cancelation implemented at OLT

Further steps:
• SC spacing 187 MHz → scalability difficult
• Higher data rate
• Larger linewidth ECL used at other ONUs

Y. Yoshida et al., JLT 33(8), 2015,
Summary

• OFDMA for flexible capacity allocation among ONUs

• Downstream direction: “Straight forward”
  Simple optics, real-time DSP, high speed experiments,

• Upstream direction: “Challenging but possible”
  Proof of concept: MA, optical modulation schemes and synchronization
What is still Missing?

• Cost reduction (DAC/ADC, DSP, optics)
• Real-time DSP experiments
  + more ONUs @ high data rate (upstream!)
    + advanced optics
      + bidirectional
      + WDM

Realistic OFDMA-PON experiment
“... put the puzzle together”
What is still missing?

- Cost reduction (DAC/ADC, DSP, optics)
- Real-time DSP experiments
  - more ONUs @ high data rate (upstream!)
    - advanced optics
    - bidirectional
    - WDM

Realistic OFDMA-PON experiment
“... put the puzzle together”
Thank You!

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• W. Yan et al., 80 km IM-DD Transmission for 100 Gb/s per Lane Enabled by DMT and Nonlinearity Management., OFC 2014, M2I.4

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