Reflective FDMA-PON with 32 Gbps upstream capacity per wavelength and more than 32 dB ODN loss

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Outline

- The EU project FABULOUS: proposed architecture
  - Focus of the paper: upstream physical layer
- Optimization of several transmission parameters
- Experimental results
- Conclusion
FP7-ICT-2011-8 – Objective 3.5: Core and disruptive photonic technologies

“Application-specific photonic components and subsystems”

“For access networks, the goal is affordable technology enabling 1-10 Gb/s data-rate per client”
System architecture
Frequency division multiplexed (FDMA) PON

- PON based on electrical subcarrier
- FDM/FDMA in both directions
- This presentation: focus on upstream

OLT

\( \lambda_{CW} \)

ONU

\( f_i \)

\( f_j \)

\( B_i \)

\( B_j \)

Electric signal OUT

Self-coherent receiver

Electric signal IN

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**Detail on the ONU**

One of the main purposes of the project is to integrate the required reflective ONU on a Silicon Photonics platform.
Self-coherent detection at OLT

- Self-coherent detection at OLT enables high ODN loss achievements even in a reflective architecture
  - Intrinsic Faraday rotation at R-ONU allows simplified single polarization coherent detection at the OLT

![Diagram showing self-coherent detection at OLT](image-url)

**ECL CW laser**

**PBS**

**PM fiber**

**PM fiber**

**Local Oscillator**

**Signal**

**Single Polarization Coherent Receiver**

**Towards OLT**

**SMF fiber**

**x**

**y**

**Towards OLT**

**DSP**
Novelty of this work

The novelty of this work compared to previous papers of the FABULOUS project consortium is related to:

- Focus on **maximum possible ODN loss**
  - To be compliant with ITU-T ODN loss classes
  - **high bit rate per user** (all users at 1 Gbps)

- **Optimization** of several ONU free parameters
System Upstream Experiments
Main physical layer parameters

- **Data rate per user fixed at 1 Gbps**
  - (net data rate, giving a gross rate of 1.2 Gbps including FEC, overhead and line coding)

- **Modulation format fixed at 16-QAM**
  - Raised cosine spectrum, roll-off=0.1
  - Requires $B \sim 330$ MHz per user

- **32 users per wavelength**
  - the modulator has 11 GHz cut-off

Electrical spectrum

Approximately 11 GHz total required bandwidth

$B = 330$ MHz

$f_{1, RF}$ $f_{2, RF}$ $f_{3, RF}$ $\ldots$ $f_{N, RF}$ $f_{el}$
Parameters to be optimized

- Modulation index \( MI = \frac{V_p}{V_\pi} \)
  - Peak voltage of the electrical signal
  - \( V_p \) of the Mach-Zehender modulator

- Electrical channel allocation \( f_1 \ldots f_N \)

- Electrical frequency spacing \( \Delta f = f_{i+1} - f_i \)

- SOA biasing current \( I_{bias} \)
Optical spectrum (high resolution OSA)

Electrical subcarrier at $f_i=2\text{GHz}$

For different modulation indexes

One modulated ONU at electrical subcarrier frequency $f_i=2\text{GHz}$

Modulation index from 0.1 to 0.4

Second harmonic at $2f_i=4\text{GHz}$

Power spectral density [dBm/Hz]

Frequency [GHz]
Minimizing the nonlinear effects

- The second harmonic can generate crosstalk on a higher frequency useful subcarrier, used by another ONU

- We thus theoretically and experimentally found:
  - An optimized modulation index
  - An optimized position for the comb of subcarriers
Optimizing the modulation index

Simulation using realistic system parameters

32 channels modulate using 16-QAM

EVM (%) vs. $m_{\text{index}}$

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Subcarrier frequency allocation

Best frequency allocation:
second harmonic falls exactly
at in the middle of two
another modulated channels

Worst frequency allocation:
second harmonic falls exactly
at the center of another
modulated channel
Upstream setup – 2 active ONUs

OLT

\[ \lambda_{US} \]

90/10

PBS

+9dBm

ODN

37km

VOA

PM Fiber

R-MZM

1x2

ABC

16QAM

37km

R-MZM

16QAM

PM Fiber

PM Fiber

PM Fiber

100GHz PM-filter

VOA PM

EDFA PM

EDFA PM

Noise Loading

EDFA

Filter

EDFA

VOA

Real Fiber Testbed

Real-time FPGA 4 S/symb (1 GS/s)

RX

16QAM

ONU i

IQ MOD

16QAM

ONU j

IQ MOD

f_i

f_j

VOA

EDFA

Filter

EDFA

Real Fiber Testbed

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16
Electrical channel spacing optimization

At 330 MHz spacing, the penalty becomes negligible.
SOA biasing current optimization

Bit Error Rate vs. SOA bias current [mA]

- MI=20%
- MI=40%

SOA bias optimization (as a function of MI and ODN Loss)

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SOA biasing current optimization vs. ODN loss
Choice of the Forward Error Correction

As a starting point for our reference, we considered two FEC with correction ability for BER post-FEC of $10^{-15}$

- A FEC defined in ITU-T G.975.1 for high bit rate DWDM submarine systems (FEC 1)
- A third generation code featuring concatenated FEC with soft decision (FEC 2)

<table>
<thead>
<tr>
<th>FEC</th>
<th>Code</th>
<th>Overhead</th>
<th>BER pre-FEC threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEC 1</td>
<td>RS(1023,1007) + BCH(2047,1952)</td>
<td>6.69%</td>
<td>$2.17 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>FEC 2</td>
<td>RS(992,956) + LDPC(9216,7936)</td>
<td>20.5%</td>
<td>$1.0 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>

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BER vs. ODN loss and modulation index

BER contour plots

Small inaccuracy in the title (we are slightly below 32 dB) … our fault!

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N1 class
N2 class
Conclusions

We demonstrated

- with a launched power of $P_F=9dBm$ (same as in TWDM-PON highest classes)
- using an installed metropolitan fiber network

that the **FABULOUS** upstream reflective FDMA PON supports:

- a total capacity of **32 Gbps** per wavelength
- more than **31 dB** of ODN loss (satisfying N2-class of TWDM-PON standard)
32 Gbps net capacity upstream is significantly better than what is today envisioned for the first implementations of TWDM-PON (4λx2.5 Gbps)

This is **WITHOUT requiring WDM**, but only single wavelength operation

DSP is required at ONU, but at very reasonable speed (<1Gsample/s)

- In fact, the Orange Lab Demo at this conference implemented this DSP using consumer electronic chipsets coming from wireless-USB applications
Acknowledgments

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n°318704, titled:

**FABULOUS: “FDMA Access By Using Low-cost Optical Network Units in Silicon Photonics”**

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