Final system results from the EU FP7 project FABULOUS

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Outline

- General introduction to the EU FABULOUS project
- Implementation of the reflective-ONU in a silicon Photonic integrated chip
- Latest results on flexibility in terms of:
  - Bit rate
  - Number of users
  - Achievable ODN loss
EU STREP project - FP7-ICT-2011-8

FDMA Access By Using Low-cost Optical Network Units in Silicon photonics

The project started in October 2012 and ended at the beginning of 2016.
The proposed Passive Optical Network (PON)

- **Electrical FDMA** in both US and DS
- A higher level of multiplexing using **WDM**
- **Targeting bit rate per wavelength well above 10 Gbps**

For time limitation, this presentation focuses only on the upstream, that is characterized by:

- **Reflective modulation at ONU**
  - No need for tunable lasers at ONU
  - Implemented using an ad-hoc **silicon photonic chip**

- **Self-coherent detection at OLT**
  - Implemented in **real-time on an FPGA platform**
The system concept for the upstream

- The required upstream wavelengths are generated at the **Central Office by CW lasers** and sent downstream.

- Each ONU:
  - Selects one wavelength
  - Modulates it in reflection using electrical QAM over a given electrical subcarrier

- The OLT receives all the Frequency Division Multiplexed signals with a self-coherent receiver.
An R-ONU suitable for Silicon Photonic

Purpose of the project is to modulate the subcarrier QAM and performs 90° polarization rotation (allowing single pol. RX)

This R-MZM structure is independent from input polarization but internally requires only single polarization waveguides

Particularly suitable for Photonic Integration

FDMA Access By Using Low-cost Optical Network Units in Silicon photonics

FP7-ICT-2011-8 Challenge 3.5 – STREP project n. 318704 – FABULOUS
Optical Distribution Network (ODN)

- ITU-T compliant ODN
- Splitter-based PON
- Targeting high ODN losses

Compared to ITU-T and IEEE standards our proposal is thus:
- “in the mainstream” for the ODN
- “highly alternative” for the ONU and OLT
**PROs AND CONs vs. TWDM-PON (NG-PON2)**

**PROs**

Most of WDM complexity and cost left at the OLT

No tunable lasers at ONU and thus NO uncontrolled wavelength problems at ONU switch-on

Continuous data-stream, no burst mode thanks to FDMA

Thus strong FEC, M-QAM and easier DSP compared to burst-mode systems

Higher bit rate per wavelength

Using electrical frequency up/down converters

DSP can work at low sampling rate at baseband

**CONs**

Modulator and tunable optical filter and SOA at the ONU

Need for a photonic integrated chip

Linear optoelectronics at both TX and RX

DSP-based, so that DAC and ADC required
BENCHMARKING WITH COMMERCIAL AND DISCRETE OPTOELECTRONIC COMPONENTS

A Single Wavelength 25-Gb/s Symmetric FDMA PON
Aurelien Lebreton, Benoît Charbonnier, and Jérôme Le Masson

Optimization of Reflective FDMA-PON Architecture to Achieve 32 Gb/s Per Upstream Wavelength Over 31 dB ODN Loss
Stefano Straullu, Paolo Savio, Joana Chang, Valter Ferrero, Member, IEEE, Antonino Nespoli, Roberto Gaudino, and Silvio Abrate

Overview of the FABULOUS EU Project: Final System Performance Assessment With Discrete Components
Silvio Abrate, Senior Member, IEEE, Stefano Straullu, Antonino Nespoli, Paolo Savio, Joana Chang, Valter Ferrero, Benoît Charbonnier, and Roberto Gaudino, Senior Member, IEEE
### BENCHMARKING WITH DISCRETE COMPONENTS

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>Electrical bandwidth per channel</th>
<th>Net bit-rate per user</th>
<th>Maximum ODN loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>64-QAM</td>
<td>660 MHz</td>
<td>3 Gbps</td>
<td>23.0 dB</td>
</tr>
<tr>
<td>64-QAM</td>
<td>1320 MHz</td>
<td>6 Gbps</td>
<td>23.0 dB</td>
</tr>
<tr>
<td><strong>16-QAM</strong></td>
<td><strong>330 MHz</strong></td>
<td><strong>1 Gbps</strong></td>
<td><strong>31.0 dB</strong></td>
</tr>
<tr>
<td>16-QAM</td>
<td>1650 MHz</td>
<td>5 Gbps</td>
<td>30.5 dB</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3300 MHz</td>
<td>10 Gbps</td>
<td>28.0 dB</td>
</tr>
<tr>
<td>QPSK</td>
<td>1650 MHz</td>
<td>100 Mbps</td>
<td>41.0 dB</td>
</tr>
<tr>
<td>QPSK</td>
<td>3300 MHz</td>
<td>500 Mbps</td>
<td>38.0 dB</td>
</tr>
<tr>
<td>BPSK</td>
<td>330 MHz</td>
<td>250 Mbps</td>
<td>40.5 dB</td>
</tr>
<tr>
<td>OOK</td>
<td>6250 MHz</td>
<td>10 Gbps</td>
<td>38.5 dB</td>
</tr>
</tbody>
</table>

32 users per lambda

= 32 Gbps US per lambda

**Fig. 2.** Performance of the upstream transmission in terms of BER vs ODN loss with two active ONUs (32 emulated channels per wavelength using optical noise loading). It is evident that the simplified setup totally emulates the meaningful interferences.
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THE INTEGRATED R-MZM IN SILICON PHOTONONICS

Transmitter Made up of a Silicon Photonic IC and its Flip-Chipped CMOS IC Driver Targeting Implementation in FDMA-PON

Sylvie Menezo, Member, IEEE, Enrico Temporiti, Junsu Lee, Olivier Dubray, Maryse Fournier, Stéphane Bernabé, Member, IEEE, Daniele Baldi, Benjamin Blampey, Gabriele Minoia, Matteo Repossi, André Myko, Sonia Messaoudène, Lee Carroll, Silvio Abrate, Member, IEEE, Roberto Gaudino, Senior Member, IEEE, Peter O’Brien, and Benoit Charbonnier

Grating coupler with PBS
Segmented MZ modulator
CMOS electrical driver flip-chipped on top
Low driving voltage and power consumption (6W including DSP)
BW~5GHz in current version
Insertion loss ~ 20dB (fiber to fiber)
R-MZM Fully-packaged for system tests and demo

Integrated on a test-board for system experiments with an external SOA placed before the chip.
16QAM BACK-TO-BACK at 1 Gbps per user

- $f_{ch} = 2$ GHz
- Back-to-back
- EVM = 11%
- BER = $2 \cdot 10^{-3}$
QPSK BACK-TO-BACK at 500 Mbps per user

- $f_{ch} = 2$ GHz
- Back-to-back
- EVM = 12%
- BER < 10^{-6}

Sampled Demod Output (2 SpS)

Equalized Signal (Blind Equalizer)

Signal after CPE

Normalized PSD [dB/Hz]

Frequency [GHz]
**EXPERIMENTAL SETUP**

**FULL vertical integration at ONU side:**
- Photonic chip
- Electronic driver
- Real time DSP
- Final demonstration carrying bidirectional Ethernet Traffic

**REAL TIME DSPs programmed on FGPA platforms**
XILINX Virtex4 at ONU, Virtex 7 at OLT

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FDMA Access By Using Low-cost Optical Network Units in Silicon photonics
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REAL-TIME BER VS. ODN-LOSS

- QPSK
- 500 Mbps
- $f_{ch} = 2\,\text{GHz}$
- 25 km SMF
- 1550 nm

The “missing” 7 dB between the silicon photonic setup and the discrete components one mostly come from the higher insertion loss of the current prototype.

FEC RS(992,956)+LDPC(9216,7936)

FEC implemented on FPGA

BER

ODN LOSS [dB]

Real-time
Post-processing

FEC implemented on FPGA

16 17 18 19 20 21 22 23 24 25

10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
IS THE FULL ONU LOW COST?

Techno-economic study carried out in project. Considering:

>1,000,000 pieces/year, size of the SiP chip, SOA, electrical driver, commercial FDM IC

ABOUT 80$ (70% DUE TO PACKAGING)

Review and comparative assessment of FDMA-PON vs. TDMA-PON for next-generation optical access networks

Silvio Abrate a, Roberto Gaudino b,*

FDMA-PON and NG-PON2: Performance and Cost Comparison

Power Consumption Estimation for the Silicon-Photonics Reflective ONU Conceived within the FABULOUS European Project

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FDMA Access By Using Low-cost Optical Network Units in Silicon photonics

Some of the techno-economic figures were taken from the EU project OASE
http://www.ict-oase.eu/
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- General introduction to the FABULOUS project

- Implementation of the reflective-ONU in a silicon Photonic integrated chip

- Latest results on flexibility in terms of:
  - Bit rate
  - Number of users
  - Achievable ODN loss
Introducing flexibility in our architecture

- Most of the work during the duration of the project was focused on
  - 1 Gbit/s per user in the upstream
  - 16-QAM modulation on each subcarrier
  - 32 users per wavelength
  - ITU-T Class N1 ODN loss

- The architecture is potentially very flexible in terms of
  - Bit rate per user
  - Number of user per wavelength
  - Achievable ODN loss

Mostly thanks to the DSP-based transmission platform AND FDMA approach
Increasing the bit rate per user

- Different bit rates and number of user per wavelength

![Graph showing BER vs ODN Loss for different bit rates and number of users.]
Increasing the achievable ODN loss

- Moving from 16-QAM to more resilient QPSK

![Graph showing the relationship between ODN loss and BER for different data rates and ONUs counts.](image)

- FEC (Forward Error Correction) point
- ODN LOSS [dB]
- BER
- 500 Mbps, 32 ONUs
- 2.5 Gbps, 6 ONUs
- 5 Gbps, 3 ONUs

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FDMA Access By Using Low-cost Optical Network Units in Silicon photonics
Going to even higher ODN loss

- Comparison of different modulation formats: BPSK, QPSK and 16-QAM

![Graph showing BER vs. ODN loss for different modulation formats](image)

- BPSK, 250 Mbps
- QPSK, 500 Mbps
- 16QAM, 1 Gbps

**FEC**
Increasing the bit rate per user AND the ODN loss

- even using a single OOK stream, single user at 10 Gbps
Conclusion

We have demonstrated:

- The effectiveness of a self-coherent reflective FDMA PON architecture in complying to ODN loss standard requirements.
- The feasibility of the required Photonic Integrated Circuits and Real-time DSP.

+ Flexibility in the Architecture

FP7-ICT-2011-8 Challenge 3.5 – STREP project n. 318704 – FABULOUS
FDMA Access By Using Low-cost Optical Network Units in Silicon photonics
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”

**WEB site:**
www.fabulous-project.eu

**To contact us:**
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roberto.gaudino@polito.it
PIC FABRICATION

- Processed at CEA-LETI clean room
- 200 mm wafers (8 inches)
- Used Substrate: HR-SOI with 2µm Buried Oxide and 220 nm Silicon
- Devices E/O characterizations on Cascade Elite wafer probers

Couplers
- footprint < 500mm²

Waveguide Specifications
- propagation loss < 1.2dB/cm

Heater R: 2.2 K ohms

- Grating Coupler etching
- PN junction implantation
- Rib waveguide etching
- Heater & via
- Electrodes

Mach Zehnder modulators
Electronic driver flip-chip processed on the Silicon Photonic platform

20 μm Copper Pillar
SnAgCu Solder Cap
SIMPLIFIED COHERENT DETECTION

Faraday rotation at ONU allows simplified coherent detection at the OLT

ECL CW laser

PM fiber

PBS

PM fiber

Faraday rotation at ONU allows simplified coherent detection at the OLT

Digital Signal Processing (DSP)

Single Polarization Coherent Receiver

Local Oscillator

Signal
System experiments using discrete optoelectronics

- Main achievements for what concerns 1 Gbps per user experiments
  - 32 Gbps per wavelength for 32 users
  - Up to 31 dB of ODN loss
  - Demonstration of four-lambdas WDM

- A joint demo including both Orange Labs and ISMB hardware prototypes was finally assembled, "massive" experimental setup with 5 ONUs.

Fig. 1. Full off-line processing experimental setup with installed fiber, two active ONUs and reconfigurable optical network units, RTO: real time oscilloscope, SOA: semiconductor optical amplifier, ABM: amorphous bulk modulator, REAM: reflective electro absorption modulator.

Fig. 2. Performance of the upstream transmission in terms of BER vs ODN loss with two active ONUs (32 emulated channels per wavelength using optical noise loading). It is evident that the simplified setup totally emulates the meaningful interferences.
### ONU power consumption

<table>
<thead>
<tr>
<th>Device</th>
<th>Power consumption [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic chipset for modulation (Rx and Tx)</td>
<td>1.1</td>
</tr>
<tr>
<td>Optoelectronic receiver</td>
<td>1.0</td>
</tr>
<tr>
<td>R-MZM driver</td>
<td>1.4</td>
</tr>
<tr>
<td>Photonic integrated circuit (R-MZM)</td>
<td>0.5</td>
</tr>
<tr>
<td>SOA</td>
<td>0.5</td>
</tr>
<tr>
<td>Tuneable optical filters</td>
<td>0.5</td>
</tr>
<tr>
<td>TEC</td>
<td>3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>8 Watt</strong></td>
</tr>
</tbody>
</table>

**Post-deliverable news:** the actual required power for the TEC in the final release of the PIC is significantly less

- The new estimate is 1 W to stabilize the PIC to 25 C
- The total power consumption of the ONU would thus decrease to 6 W
Bill-of-Material costs: two scenarios

**SCENARIO #1**: Medium-term scenario in which the NG-PON implementation is based on TWDM-PON using 4 wavelengths per direction for an aggregated capacity of 40 Gbps DS and 10 Gbps US.

<table>
<thead>
<tr>
<th></th>
<th>FABULOUS</th>
<th>TWDM PON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLT</td>
<td>ONU</td>
</tr>
<tr>
<td>Cost</td>
<td>1620 US$</td>
<td>78 US$</td>
</tr>
<tr>
<td>Power consumption</td>
<td>88 W</td>
<td>8 W</td>
</tr>
</tbody>
</table>

**SCENARIO #2**: Long-term scenario in which the NG-PON implementation is based on TWDM-PON using 16 wavelengths per direction for an aggregated capacity of at least 160 Gbps DS and 40 Gbps US.

<table>
<thead>
<tr>
<th></th>
<th>FABULOUS</th>
<th>TWDM PON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLT</td>
<td>ONU</td>
</tr>
<tr>
<td>Cost</td>
<td>6026 US$</td>
<td>78 US$</td>
</tr>
<tr>
<td>Power consumption</td>
<td>329 W</td>
<td>8 W</td>
</tr>
</tbody>
</table>