The Integrated Research Center for Photonic Networks and Technologies (IRCPhoNeT)

Piero Castoldi

Scuola Superiore Sant’Anna, Pisa
November 13th, 2012
Research Group at IRCPhoNeT
(45 InReTe, 18 CNIT)

- 2 Full Professors
- 3 Associate Professors
- 8 Assistant Professors
- 3 Heads of Research
- 6 Senior Researchers
- 5 Junior Researchers
- 1 Senior Technician
- 2 Technicians
- 5 Research Scholars
- 16 Ph.D. Students
- 2 Post-Docs

- 3 Administrative Staff
- 3 Administrative Staff
- 4 Foreign Visiting Students
The “Communication” Research Unit at TeCIP Institute

- Networks and Services (P. Castoldi)
- Optical Communication Systems (E. Ciaramella)
- Optical Communication Theory and Techniques (E. Forestieri)
- Optical Fiber Sensors & Integrated Photonics Subsystems (F. Di Pasquale)
- High-Capacity Optical Communication (L. Potì)
- Digital & Microwave Photonics (A. Bogoni)
- Advanced Technologies for Integrated Photonics (R. Romagnoli)
Networks and Services

- Architectures and algorithms for provisioning, resilience, and QoS support in data networks
- Control plane for optical networks (GMPLS, OpenFlow)
- Architectures of service platforms
- Energy efficiency in data networks
- Optical interconnection networks for DC and HPC: architectures and scheduling
- Industrial networks for railway control applications
- Smart grids for EV fleets
Control of elastic optical networks

- Optical networks exploiting coherent optical systems allows optimization of modulation parameters
  - Bit rate = (Symbol rate) \times (Number of modulation levels) \times (Number of sub-carriers) \times (Number of polarization states)

- Flexible (grid) optical networks are based on:
  - flexible transponders operating with configurable advanced modulation formats
  - bandwidth-variable optical cross-connects (BV-OXCs) with configurable frequency slots

- According to the required optical reach, BV-OXCs, modulation format and baud-rate are dynamically configured by the control plane that explicitly allocate spectral resources to optical path
  - Continuous spectrum is quantized into contiguous frequency slots with appropriate slot width (e.g. frequency slot of 12.5 GHz)
Optical Communication Systems

- Activities on “traditional” WDM systems
  - Numerical simulations
  - Experimental test bed
  - Performance monitoring

- Innovative systems and devices
  - Passive optical networks
  - Free-space outdoor transmission
  - Visible Light Communications (VLC)
  - All optical signal processing
WDM-PON: enhancing capacity and reach

**Self seeded PON**
- simpler TX, using low-cost components

**Low-cost ONU at 10**

10 Gbs NRZ using 1 GHz RSOA

- xWDM - PON

- ngPON

- FTTH ultra dense WDM-PON

- FTTH WDM-TDM-PON

- FTTH XG/G/E-PON

- FTTH PON

- FTTH-PIP

- xDSL

- CATV

- POTs

- ADSL

- COCONUT

- COCONUT

- CAPACITY

- TIME
Optical Communication Theory and Techniques

Transmission techniques
- Modulation formats
- Coding

Performance evaluation
- Analytical methods
- Advanced simulations

Fiber propagation
- Transmission impairments
- Noise accumulation
- Dispersion maps

Detection
- Optical equalization
- Electronic equalization
1 Tb/s Coherent Optical Transmissions

- Coding techniques to improve spectral efficiency
- Impact of nonlinearities on channel capacity
- Linear and nonlinear impairments mitigation via Maximum Likelihood Sequence Detection

\[ |r|^2 \approx \exp \left[ -\frac{4\gamma^2 P_s^2 L}{\pi |\beta_2| B^2} \log N_c \right] \]

\[ C \geq B \log_2 \left( 1 + \frac{|r|^2 P_s}{P_n + (1 - |r|^2) P_s} \right) \]
Optical Fiber Sensors and Integrated Photonic Subsystems

- **Optical fiber-based sensors systems**
  - High performance Raman DTS systems
  - Hybrid fiber optic sensors for simultaneous distributed and dynamic discrete measurements
  - Long-range sub-meter spatial resolution BOTDA systems

- **Integrated Photonic Subsystems**
  - Design of silicon based switching elements based on micro-ring resonators
  - Distributed temperature sensor based on silicon integrated optics
  - Four-port integrated optical circulator based on ultra-low-loss Si$_3$N$_4$ waveguides
Optical Fiber Sensors and Integrated Photonic Subsystems

- **Highly integrated Hybrid Raman/FBG sensor**
- **Tapers**
- **Isolators**
- **High performance Raman DTS systems**
- **FBG Dynamic Interrogation Scheme Based On Pulse Coding**
- **Design of Add/Drop filter**
High-Capacity Optical Communications

• Optical Transmission Systems with Coherent Detection
  – DQPSK/N-QAM systems
  – ultra-short reach to ultra-long haul
  – linear and nonlinear impairment mitigation
  – spectral efficiency optimization
  – flexibility (networking applications)
  – theoretical and experimental activity

• Integrated Terabit transceiver for coherent systems
  – architectures for different apps and technologies
  – system design (before and toward integration)
  – theoretical activity
  (experiments will come after devices fabrication)

• phase and amplitude signal characterization
  – real time and single shot measures
  – theoretical and experimental activity

• In Line tribology
  – oil monitoring
  – theoretical and experimental activity

• Optical tomography
  – experimental activity (collaboration with IFC-CNR)
1 Tb/s DP-QPSK Communication into 200 GHz Bandwidth

- **Time/Frequency packing**
  - powerful coding for faster than Nyquist signaling
  - variable rate for easy adaptation

- **field trial on Telstra network**
  - feasibility study
    - theory and lab experimental activity (done)
  - Sydney to Melbourne 1000 km link field trial
    Feb/March 2013

**Simulation**

<table>
<thead>
<tr>
<th>N° channels</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baud Rate</td>
<td>40 Gbaud</td>
</tr>
<tr>
<td>Total BW</td>
<td>200 GHz</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>25 GHz</td>
</tr>
<tr>
<td>Chirped BW</td>
<td>91 GHz</td>
</tr>
<tr>
<td>Loop Rounds</td>
<td>8</td>
</tr>
<tr>
<td>Fiber spans crossed</td>
<td>16</td>
</tr>
<tr>
<td>Power per Channel</td>
<td>0.5 dBm</td>
</tr>
</tbody>
</table>
Digital & microwave Photonics

Tomorrow optical net

Optical building blocks
- Wavelength converter
- Logic gates
- Add/drop multiplexer
- Regenerator
- Format converter

Optical technologies
- SOA
- Silicon waveguide
- PPLN waveguide
- Chalcogenide glass
- Fiber

Optical XOR for QPSK signals
- Colorless optical PSK phase sum and subtraction
- Multiformat Wavelength Swapping
- Flexible Spacing of ITU-T Grid Adjacent 10Gb/s OOK and 40Gb/s DQPSK Channels
- Optical 224Gb/s PM-16QAM Multicasting
- Optical QPSK Switching for 100G Coherent Syst
- Regenerative Variable Optical Buffer for NRZ and RZ packets
- Photonic two-level transfer function for 40 Gb/s NRZ/RZ regeneration
- Optical 40Gb/s NRZ-DPSK Regeneration
- Regenerative DPSK Wavelength Conversion

- Amplitude modulated (On-Off) signals
- Multilevel phase and amplitude modulated (QAM) signals
Digital & microwave photonics

**PhoDiR project:** Fully digital photonic-based radar systems

**PREPARE project:** Pre-industrial photonic-based radar design

**INSIDE project:** Toward integrated photonic-assisted fully-digital radar transceiver

**SOPHIA project:** Software-defined multicarrier wideband transceiver based on photonic technologies for TLC wireless applications

**motivations**
- low phase now at high frequency
- Multi carrier & ultra-wide band signals
- Fully digital radar system
- Flexibility
- Dual use
- telecom & radar)

**Previous photonic ADCs**

<table>
<thead>
<tr>
<th>ENOB</th>
<th>1 ps</th>
<th>100 fs</th>
<th>10 fs</th>
</tr>
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<tbody>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
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<td></td>
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<td>8</td>
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<td>6</td>
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<td>4</td>
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<td>1</td>
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**Electronic ADCs**

**Our results**

**Prototype specs**

<table>
<thead>
<tr>
<th><strong>TX</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jitter</td>
<td>&lt;10 fs</td>
</tr>
<tr>
<td>SNR</td>
<td>&gt;53 dB</td>
</tr>
<tr>
<td>RF carrier</td>
<td>400 MHz–50 GHz</td>
</tr>
<tr>
<td>Inst band</td>
<td>Up to 1 GHz</td>
</tr>
<tr>
<td>Modulation formats</td>
<td>Amplitude and phase coding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>RX</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ENOB</td>
<td>&gt; 7</td>
</tr>
<tr>
<td>carrier</td>
<td>400 MHz–40 GHz</td>
</tr>
<tr>
<td>Inst band</td>
<td>Up to 1 GHz</td>
</tr>
</tbody>
</table>
Advanced Technologies for Integrated Photonics

Dr. Marco Romagnoli joined the TeCIP as Advanced Technologies Area Leader

A PIC Design Center has been recently opened for external users (Companies and other research bodies)

PIC manufacturing
- in III/V (mostly InP) at TU/e (JePPix) and Oclaro (PARADIGM)
- in Silicon for passive devices at IMEC (ePIXFab)
- in Silicon for active devices using OPSIS platform
- Hybrid integration collaborations with Ghent and UCSB
Clean-Room for PIC manufacturing: state of the project

700 sqm Building – 500 sqm Clean Room

Now

End of 2013
Major Active Projects

- ERC StG PHODIR, “PHOtonic-based full Digtal Radar”, Dr. Antonella Bogoni
- FP7 ACEPLAN, “Active plasmonics and lossless metamaterials”, Dr. Antonella Bogoni
- FP7 GOSPEL, “Governing the speed of light”, Dr. Antonella Bogoni
- ERC PoC PPREPARE project: Pre-industrial photonic-based radar design, Dr. Antonella Bogoni
- FP7 SOPHIA project: Software-defined multicarrier wideband transceiver based on photonic technologies for TLC wireless applications, Dr. Antonella Bogoni
- FP7 INSIDE project: Toward integrated photonic-assisted fully-digital radar transceiver Dr. Antonella Bogoni
- FP7 STRONGEST “Scalable, Tunable and Resilient Optical Networks Guaranteeing Extremely-high Speed Transport”, (ending), Prof. Piero Castoldi
- FP7 IDEALIST “Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks” (starting), Ing. Filippo Cugini
- FP7 OFELIA “OpenFlow In Europe –Linking Infrastructure and Applications”, Prof. Piero Castoldi
- Company sponsored (ENEL), “In line tribology measurements”, Dr. Luca Potì
- Company sponsored (RFI) “Temperature sensors based on optical fibers”, Prof. Fabrizio Di Pasquale
- Company sponsored (RFI) “Reliability of AV/AC Networks”, Prof. Piero Castoldi
- Company sponsored (Ericsson), “Optical Networks and technologies”, research lines led by area leaders, resp. Prof. Giancarlo Prati,
- MIUR National project FIRB, “Advance techniques for coherent demodulation”, Dr. Marco Secondini
- Regional project SR SECURE, “Radio System to improve railway circulation safety”, Prof. Piero Castoldi
- Regional project ARNO, “Architectures of Networks and optical nodes for high-capacity transmission, the access-metro-core transport based integrated photonic technologies”, Prof. Giancarlo Prati, Prof. Piero Castoldi
- Regional project PIC, “Photonic Integrated Circuits”, Prof. Giancarlo Prati
- FP7 STREP COCONUT, COst-effective COhereNt ultra-dense-WDM-PON for lambda-To-the-user access, Prof Ernesto Ciaramella (coord.)
- PRIN ROAD, Rete Ottica di Accesso a Divisione di frequenza e/o lunghezza d’onda per soluzioni Next Generation Network, Prof Ernesto Ciaramella
- FP7 ITN INFIERI, INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry, Prof Giancarlo Prati, Prof. Ernesto Ciaramella
### Courses offered in academic year 2012/13 – (1)

<table>
<thead>
<tr>
<th>COURSE</th>
<th>Abbreviation</th>
<th>TEACHER(S)</th>
<th>Sem.</th>
<th>Credits</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication networks</td>
<td>CN</td>
<td>Luca Valcarenghi</td>
<td>1</td>
<td>4</td>
<td>The course will introduce the fundamentals of communication networks with regards to all network layers. Packet vs circuit switching will be described as well as fundamentals of networking.</td>
</tr>
<tr>
<td>Sensor Networks</td>
<td>SN</td>
<td>Paolo Pagano</td>
<td>2</td>
<td>3</td>
<td>This course will introduce the fundamentals of sensors networks, with special emphasis on wireless sensor networks.</td>
</tr>
<tr>
<td>Communication theory and digital transmission</td>
<td>CTDT</td>
<td>Enrico Forestieri</td>
<td>1</td>
<td>4</td>
<td>This course module will introduce the students to the fundamental principles of communication theory and data transmission with emphasis on performance, spectral characteristics, and complexity.</td>
</tr>
<tr>
<td>Fundamentals of applied optics</td>
<td>FAO</td>
<td>Ernesto Ciaramella</td>
<td>2</td>
<td>4</td>
<td>The course provides basic information about the nature of lightwave, its physical descriptions and the current applications of optics science.</td>
</tr>
<tr>
<td>Electromagnetic fields and propagation</td>
<td>EFP</td>
<td>Fabrizio Di Pasquale</td>
<td>1-2</td>
<td>2+2</td>
<td>Focusing on the design of optical fiber and waveguide based optical components this course will offer students an introduction to the fundamental concepts related to electromagnetic theory and will then be specifically focused on transmission line theory, propagation in dielectric optical waveguides, fiber and waveguide amplifiers and lasers.</td>
</tr>
<tr>
<td>Design of access, metro and core networks</td>
<td>AMCN</td>
<td>Castoldi, inc. Andrioli</td>
<td>2</td>
<td>4</td>
<td>The course will cover network hierarchy, access segments, metro segments, core segments with special emphasis on optical network technologies.</td>
</tr>
<tr>
<td>Wireless communication networks</td>
<td>WCN</td>
<td>Castoldi, inc. Cerutti</td>
<td>2</td>
<td>2</td>
<td>The course will overview wireless transmissions, wireless networks and introduces relevant protocols.</td>
</tr>
<tr>
<td>Network optimization</td>
<td>NO</td>
<td>Castoldi, inc. Cerutti</td>
<td>2</td>
<td>3</td>
<td>The aim of this course is to introduce the modeling and mathematical methods for network optimization. The course will cover the mathematical methods and algorithms used for network optimization.</td>
</tr>
</tbody>
</table>
Courses offered in academic year 2010/11 - (2)

<table>
<thead>
<tr>
<th>COURSE</th>
<th>Abbreviation</th>
<th>TEACHER(S)</th>
<th>Type</th>
<th>Credits</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamentals of optical communications</td>
<td>FOC</td>
<td>Forestieri, inc. Secondini</td>
<td>2</td>
<td>3</td>
<td>This course provides an overview on the field of optical communication systems. The fundamentals of photonics and optical modulation are presented on an introductory level.</td>
</tr>
<tr>
<td>Design of optical systems</td>
<td>DOS</td>
<td>Ernesto Ciaramella</td>
<td>1</td>
<td>3</td>
<td>The course reviews the most common transmission impairments that must be considered when designing today high capacity optical systems.</td>
</tr>
<tr>
<td>Optical amplification and fibre-optic sensing</td>
<td>OAS</td>
<td>Oton-Nieto</td>
<td>1</td>
<td>3</td>
<td>This course will mainly provide an overview on optical amplification and other fundamental photonic components such as lasers, photodiodes and passive devices. In its last part, the course will outline some novel applications of optical fibers, such as optical fiber sensors.</td>
</tr>
<tr>
<td>Lab of photonic amplification and components</td>
<td>LAB-PAC</td>
<td>Oton-Nieto</td>
<td>1</td>
<td>4</td>
<td>The course provides a general overview to common fiber optic measurement techniques used in photonics, as well as an introduction to fiber optic sensors.</td>
</tr>
<tr>
<td>Photonic Technologies</td>
<td>PT</td>
<td>Prati, inc. Porzi, Contestabile</td>
<td>2</td>
<td>3</td>
<td>Semiconductors for Photonics, Photonic Passive and Functional Integrated Devices, Deposition and Compound Semiconductors Growth Techniques, Processing/Manufacturing Devices</td>
</tr>
<tr>
<td>Lab of photonic switching</td>
<td>LAB-PSW</td>
<td>Prati, inc. Pot', Bogoni, Scaffardi</td>
<td>1</td>
<td>6</td>
<td>The course will give most basics for photonic switching with strong emphasys to nonlinear fibres and devices. Laboratory practice will be provided.</td>
</tr>
<tr>
<td>Performance evaluation of communication systems</td>
<td>PECS</td>
<td>Enrico Forestieri</td>
<td>1</td>
<td>6</td>
<td>This course module will cover the most used mathematical methods for evaluating the performance of a communication system through both analytical approaches and simulations.</td>
</tr>
<tr>
<td>Lab of Network software</td>
<td>LAB-NS</td>
<td>Castoldi, inc. Andriolli</td>
<td>2</td>
<td>3</td>
<td>Network modeling and simulation: introduction to OPNET</td>
</tr>
<tr>
<td>Lab of Traffic Engineering</td>
<td>LAB-TE</td>
<td>Castoldi, inc. Valcarenghi</td>
<td>2</td>
<td>3</td>
<td>This course reviews Traffic Engineering issues in optical transport networks that support the Internet Protocol.</td>
</tr>
<tr>
<td>Photonic integrated systems</td>
<td>PIC</td>
<td>Jonathan Klamkin</td>
<td>2</td>
<td>3</td>
<td>This course will introduce Photonic Integrated Circuits, which are photonic circuits whose components are fabricated on a common substrate. Emphasis will be on design and fabrication.</td>
</tr>
<tr>
<td>Lab of photonic systems</td>
<td>LAB-PSY</td>
<td>Ciaramella, inc. Presi</td>
<td>2</td>
<td>6</td>
<td>This course will review optical transmitters, optical receivers and multichannel lightwave systems from an experimental perspective.</td>
</tr>
</tbody>
</table>
Thank you!

Q&A

castoldi@sssup.it