Optical Access Networking using OFDM Tones

The OTONES project addresses next generation optical access networking on the basis of Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Multiple Access (OFDMA), with special provision for reduced complexity and signal processing aspects of the subscriber side terminals (ONUs).

1. Design Targets:

- 1Gbps+ subscriber connectivity over passive optical networks
- Optical-source-less ONUs, colorless operation
- 40Gbps+ shared capacity per PON wavelength channel
- Network Scalability with DWDM technology
- Asymmetrical OLT and ONU processing loads
- Class B+ passive optical budget capability to fit G.983 PONs
- Metro/Access network level integration with active remote node and spectral filtering
- High power efficiency

2. Project Objectives:

- Optimization of system level concept with respect to cost and reach/splitting
- Leverage of OFDM and related technologies to realize a cost-effective access system
- Use of Si-photonics technologies for cost-effective ONU
- ONU integration of all optical components in a compact package
- Develop and enhance digital signal processing algorithms improving network performance at high capacity
- Investigate novel analog circuitry to reduce requirements for digital electronics: ONU DAC/ADC rate reduction and improve overall energy efficiency
- Develop and fabricate a fine-wavelength, Metro-to-PON demultiplexer, [25/12.5 GHz 2port or 50/12.5GHz 4port]
- Proof of concept in a test-bed, modeling deployed PONs

3. Topology and System Concept:

The use of OFDM based multiplexing and multiple access is investigated for increasing the capacity of optical access network systems from current 10 Gbps to 40 Gbps aggregate capacity and multiples thereof. The OTONES approach targets long-reach access networks with a transparent interconnection of the metro and the access network layer. Passive optical networks are the medium to be utilized in the access layer. Dense wavelength multiplexing (DWDM) is considered a necessity for future high-capacity, long-reach access.
At 40Gbps line-rate, the impact of single mode fiber chromatic dispersion from the metro links is already a limiting factor. Optical bandwidth reduction by higher modulation constellations and use of many subcarriers in OFDM are means introduced to mitigate this effect. There is an increasing need to decouple signal processing bandwidths in the distributed subscriber terminals from the aggregate rate. Spectrally efficient metro network layer transport and the opportunity to slice fiber-level aggregate broad spectra prior to electronic processing into smaller fractions makes OFDM an interesting option in this context.

Subscriber and traffic multiplexing is performed in the wavelength domain on the metro feeder link (up to 40 km) and by means of OFDM/A on the passive optical network in the access layer.

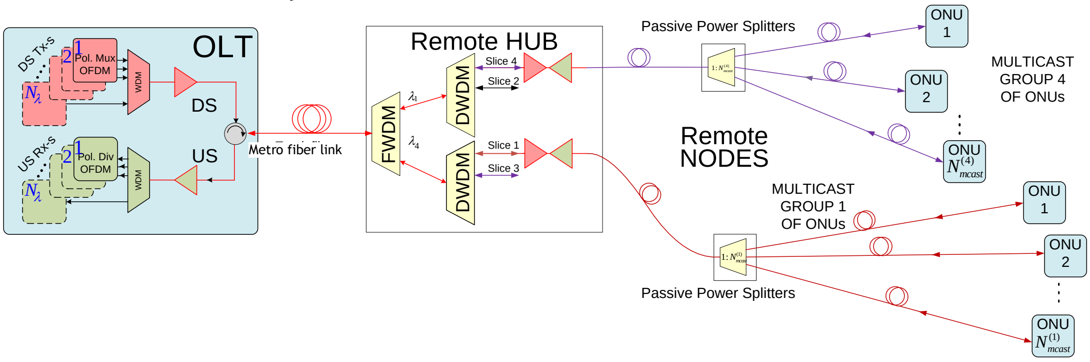

Figure 1: OTONES target topology

A unique "PUDG" spectral design is employed, characterized by a recurrent spectral slot sequence of pilot (P), upstream data (U), downstream (D) and guardband (G) sections. This spectral structure enables optical envelope detection in the ONUs, with concurrent transmission of a seed component, constraining post-detection bandwidth in the electrical domain to a fraction of only the optical channel bandwidth and providing an absorption range for spurious modulation. Moreover, non-ideal optical filtering is supported. The evolution of the spectral components along the downstream (DS) and upstream (US) transmission chain is depicted below.

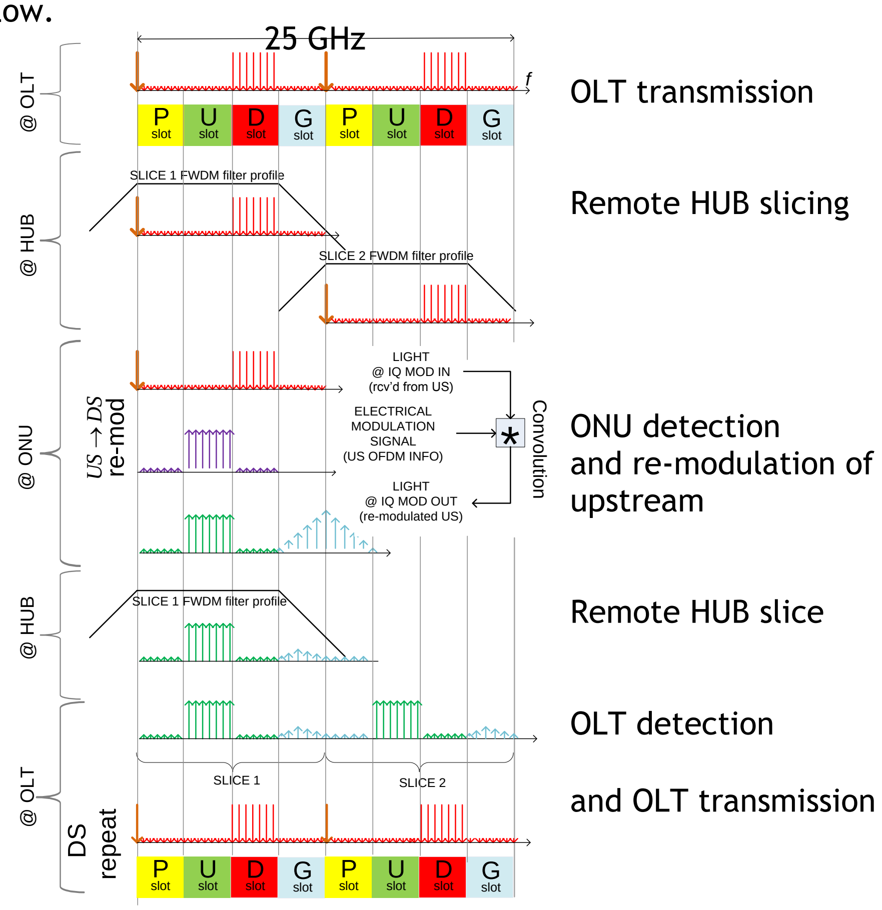

Figure 2: OTONES engineered US/DS-interleaving-spectral design

A key requirement is to have colorless subscriber terminals (ONUs) which have a common structure for all possible wavelength channels. It is also beneficial to eliminate tunable lasers and tunable optical receivers in the subscriber units. Therefore, all wavelength precision and wavelength selectivity is confined to the shared central OLT and the remote HUB location. With the projected optical field modulated OFDM approach, a compact optical spectrum can be created, which enables moderate electrical bandwidths in the terminals by using higher modulation levels (16-64 QAM) even in presence of significant fiber dispersion over the metro and access links.

Our preferred detection method employs remote-heterodyne reception of DS signals in the ONUs to the benefit of cost-effective ONU optics and electronics. In the DS direction, polarization multiplexing (pol-mux) accommodates highest aggregate data capacities with moderate electrical bandwidth requirements. An optical carrier signal (pilot) to be used for remote-heterodyne detection is weaved into the downstream spectrum and also is reused as wavelength seed for the upstream direction, enabling to a laser-less DWDM ONU.

This approach shows high resilience against laser phase noise and is a prerequisite for the use of a coherent receiver in the OLT for upstream detection. Any frequency offset potentially created by ONUs is eliminated. Optical beat interference, often observed in multipoint-to-point subcarrier networks, is thus prevented. For upstream modulation of the pilot seed component an integrated optical IQ modulator is provisioned in the ONUs. The upstream modulation is associated with a frequency shift for the upstream spectrum away from the DS induced reflection and strong seed component, filtering Rayleigh backscatter.

Within the specially tailored spectral design (Figure 1), precaution is taken to properly control spurious spectral components and to provide minimal guard bands for signal separation.

In terms of multiple access schemes, either subcarrier-domain or time-domain based combining can be used. A combination of both methods is also possible in order to achieve fine granularity of the data capacity.

4. Key Technologies:

Remote-heterodyne detection (using a remotely transmitted pilot) will preferably be used in ONU receivers. No local optical source is required in the ONU. As a fallback solution, it is also considered to employ either **coherent detection, with a local oscillator laser, or a self-coherent homodyne scheme with delay-lines**, should remote-heterodyne reception prove too challenging or provide inferior performance.

Wavelength control is c**entralized in** the OLT, engineering the optical spectrum by dense interleaving of DS/US/carrier/seeding. The tiered wavelength grid on the metro level is 25 GHz. A fraction thereof is forwarded to the access layer, e.g. 12.5 GHz width per optical distribution network.

To make OFDM processing as efficient and low-cost as possible, the OFDM/A scheme may be optionally augmented by **SC-OFDM/OFDMA** techniques, enabling significant complexity reduction in the fractional capacity ONU transmitters.

The ONU will be based on a **Photonic Integrated Circuit (PIC)** realized in the preferred **Silicon-on-Insulator (SOI)** technology. This technology, used for several years, now featuring under the headline of Silicon Photonics, is a promising candidate for the co-integration of optics and electronics on a single chip. This project will primarily benefit from the low-cost mass-production of the ONU-PIC.

Long-reach capability and ONU-side colorless and laser-less operation is enabled by the use of optical amplification. In the remote node, the attenuation of metro links and the wavelength handling losses are compensated by **bidirectional optical amplification** of densely interleaved optical spectra. Also in the ONUs the optical gain element is concurrently exploited for both transceive directions, sharing the cost intensive element for the prevalent functions.

To dilute the preferably high aggregate bandwidths on the metro and feeder layer into finer spectral fractions thereof, for processing in the numerous ONUs, **spectral fine filtering** is applied. This had not been previously usable in access networks. Now a bridge can be built between datarate capacities known from long-haul networks and the restricted processing capabilities affordable in a subscriber located terminal.

5. System-level Key Figures:

The performance parameters targeted for the OTONES proof of concept system are summarized in Table 1 below.

Optical Channel Width	Slices per Channel	Slots per Slice	Modul. level DS	Payload pol. modes DS	Modul. level US	Aggregate Bitrate/ Slice DS	Aggregate Bitrate/ Slice US
25 GHz	**2**	**4**	**16 QAM**	**2**	**16 QAM**	**20**	**10 Gbps**
Passive Power budget	Active Power budget ODN	Active Power budget OTL	Spectral Density DS	Spectral Density US	ONU ADC rate	ONU DAC rate	
29 dB	**29 dB**	**6 dB**	**1.6** bps/Hz	**0.8** bps/Hz	**< 0.5** GSym/sec	**< 0.8** GSym/sec	

Table 1: Key OTONES performance parameter

6. Electrical Energy Efficiency

Innovative concepts leveraging the OFDM platform for improved energy efficiency in high-speed shared optical access networks are pursued in OTONES.
The OFDM spectral structure lends itself to slicing down for finer bandwidth distribution without loss of signal integrity. An OTONES objective is to investigate the options enabled by OFDM/A to adapt processing depth to traffic and capacity demands and to support fast-wake-up sleep-modes.

7. Optical Network Unit

ONUs are the most cost-sensitive components in an optical access system. It is an OTONES target to support multi-gigabit capacity per ONU wavelength channel in multi-tens of gigabits aggregated capacity multi-point network without resorting to cumbersome 40 Gbps time-division multiplexed signal detection and 40 GHz regeneration. Functions and grouping foreseen in OTONES ONUs are depicted below. The design strives to reuse optical functions for multiple purposes (both transmit and receive) and to avoid tunable laser sources or optical filters still providing tapping capability for a reasonable fraction of a Terabit-per-second aggregated downstream signal while restricting the ONU signal processing to the fraction of data dedicated to the respective terminal.

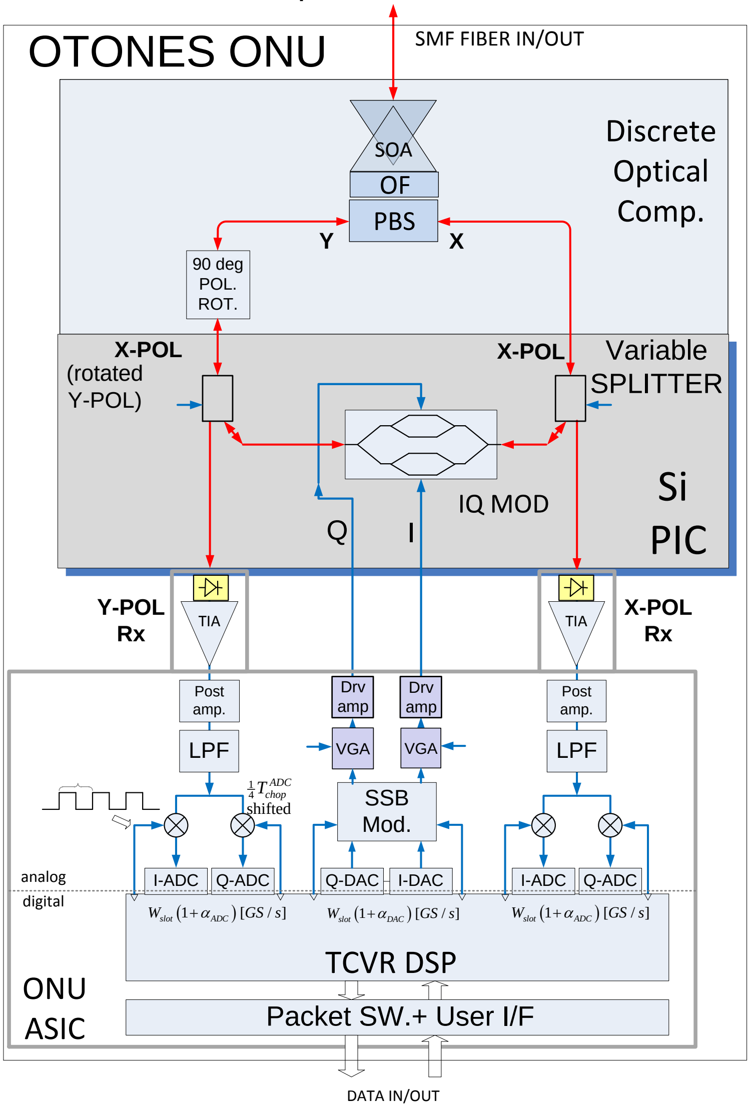

Figure 3: OTONES ONU functions with PIC frontend

Glossary:

ONU	Optical Network Unit
ASIC	Application Specific (Electronic) Circuit
SW	Switch
I/F	Interface
ADC	Analog-to-Digital Converter
DAC	Digital-to-Analog Converter
I/Q	Inphase/Quadrature Phase Signal Component
TCVR	Transceiver
DSP	Digital Signal Processing
LPF	Lowpass Filter
TIA	Trans-Impedance Amplifier
SOA	Semiconductor Optical Amplifier
SMF	Single Mode Fiber
PBS	Polarization Beam Splitter
OF	Optical Filter
OFDM	Orthogonal Frequency Division Multiplexing
QAM	Quadrature Amplitude Modulation
DWDM	Dense Wavelength Divison Multiplexing
OLT	Optical Line Termination

8. Partners:

The OTONES consortium partners are:

Karlsruhe Institute of Technology	KIT	Germany
Alcatel-Lucent Deutschland	Alcatel·Lucent	Germany
Finisar With subcontractors Israel Institute of Technology and Hebrew University of Jerusalem	Finisar TECHNION Israel Institute of Technology The Hebrew University of Jerusalem	Israel
MultiPhy	MultiPhy	Israel
Compound Semiconductor Technologies	Compound Semiconductor Technologies	United Kingdom
OptoCap	optocap	United Kingdom
University College London	UCL	United Kingdom

9. Project Timeline:

The OTONES project is planned for a three years timeframe from 05/2011 to 04/2014.

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More info and updates can be found on the project website www.ict-otones.eu