ICTON 2017
19th International Conference on Transparent Optical Networks

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Alternative Solutions for Fronthauling based on DSP-assisted Radio-over-Fiber

P. Torres-Ferrera[1], S. Straullu[2], S. Abrate[2] and R. Gaudino[3]
[1] *Institute of Engineering, Universidad Nacional Autónoma de México, UNAM, 04510 Mexico City - Mexico, ptorresf@ii.unam.mx*
[2] *ISMB, Istituto Superiore Mario Boella, Via P.C. Boggio 61, Torino (TO), Italy, straullu@ismb.it*
[3] *Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino (TO), Italy, roberto.gaudino@polito.it*

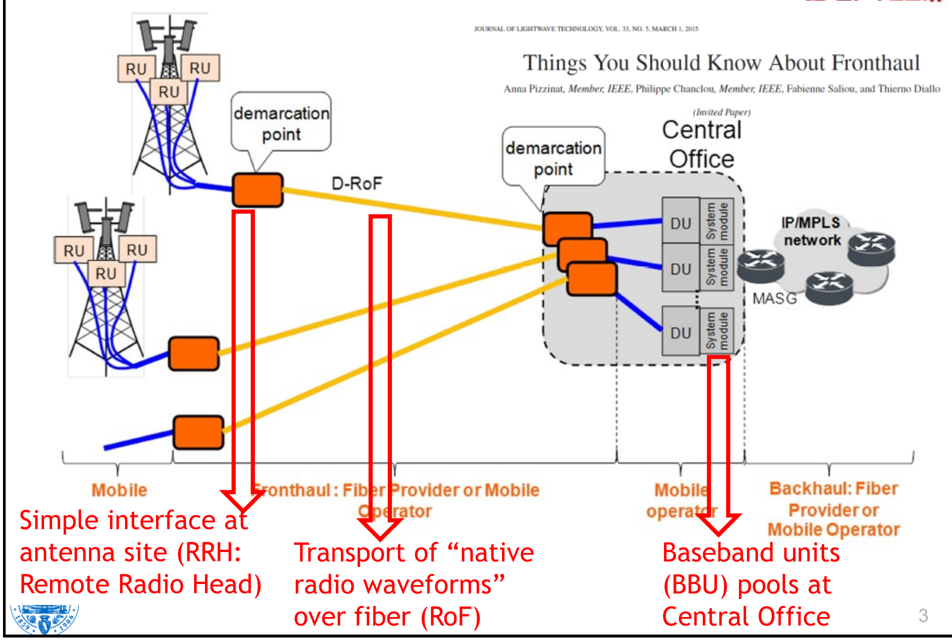
OPTCOM - Dipartimento di Elettronica
Politecnico di Torino - Torino - Italy
www.optcom.polito.it

Presentation outline for Invited Paper

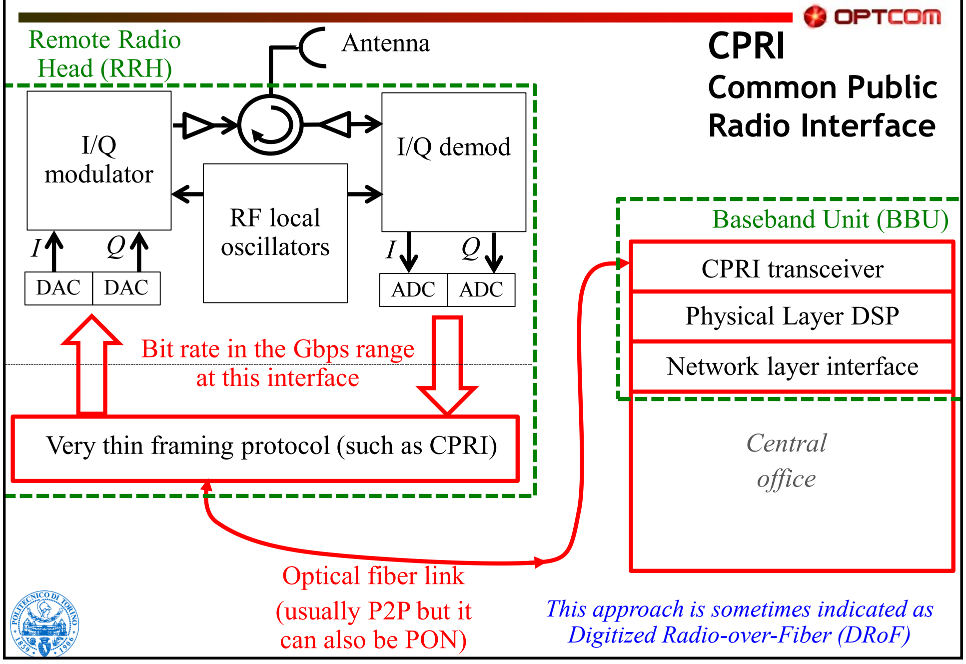
- A short introduction on Fronthauling for CRAN
  - Mainstream architectures:
    - CPRI
  - Alternative architectures
    - DSP-Assisted analog Radio over Fiber (RoF)
- Our recent results on the optimization of DSP-Assisted RoF Fronthauling Solutions

- *This work was partially sponsored by CISCO in the framework of RFP 2015 «5G-PON»*
- *We also would like to thank Tektronix for lending us the instruments*

The Fronthauling architecture



Fronthauling using Digitized Radio over Fiber



Digitizing one 20-MHz LTE channel

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- To “digitize” a 20-MHz LTE-A radio signal one needs:
  - Two I/Q DACs
  - Each of the them runs at 30.72 Msamples/s
  - The number of bits per sample is 15 (or higher)
    - The OFDM signal in radio should be generated in an “almost perfect” way, there is no possibility for clipping, since it would distort the radio spectrum, generating unwanted spurious radio frequencies
- The resulting bit rate to be carried using a “digitized” approach is thus:
  - 30.72 Msamples/s x 2 x 15 = **921.6 Mbit/s**
- CPRI adds some control words (overhead 16/15) and a line code (8B/10B) thus generating in the end a bit rate for each 20 MHz LTE channel equal to **1.23 Gbit/s**

An “advanced” future antenna site

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- In a near future, each antenna site may :
  - More than 3 “angular” sectors
    - Today typically there are 3 sectors at 120 degrees each)
  - More than one 20 MHz band on each sector
  - *NxM* MIMO
- Assuming (just as an “advanced” example):
  - six sectors
  - three 20 MHz bands
  - 8x8 MIMO
- one gets 144 “bands”, giving rise using CPRI to an enormous bit rate per antenna site equal to

177 Gbit/s

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AN ALTERNATIVE APPROACH:

DSP-AGGREGATED FDMA-BASED FRONTHAULING

Aggregation by Frequency Division Multiplexing

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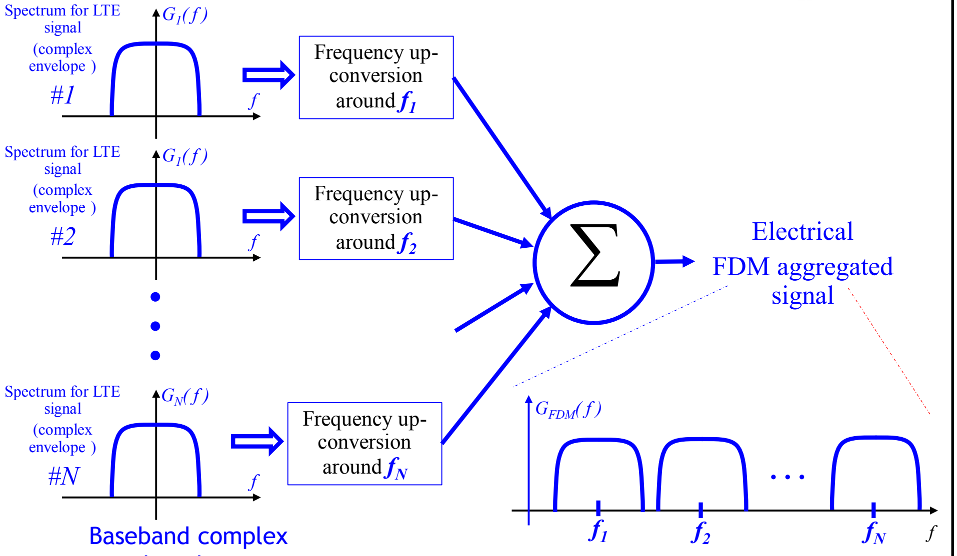
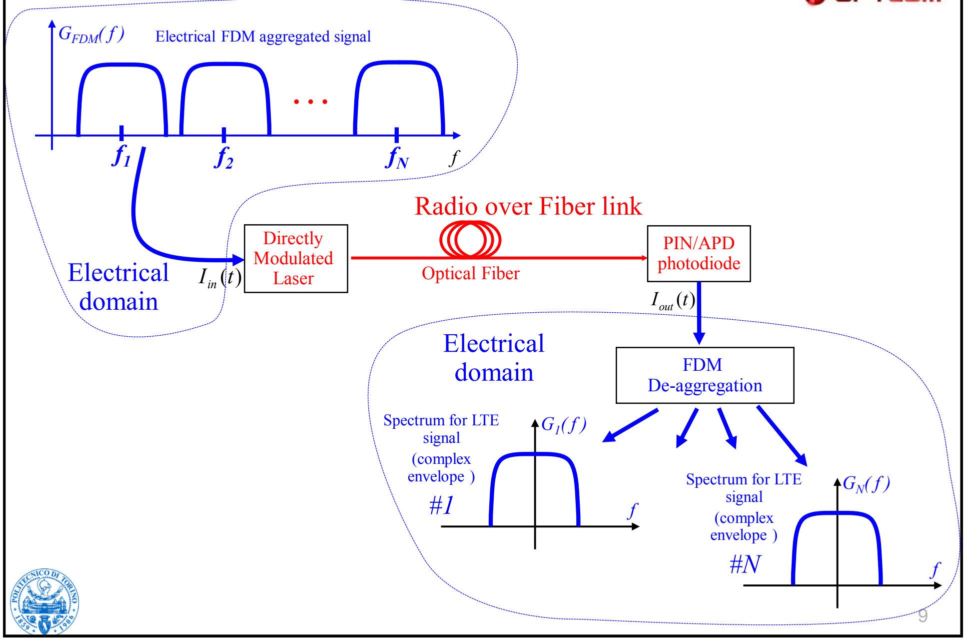
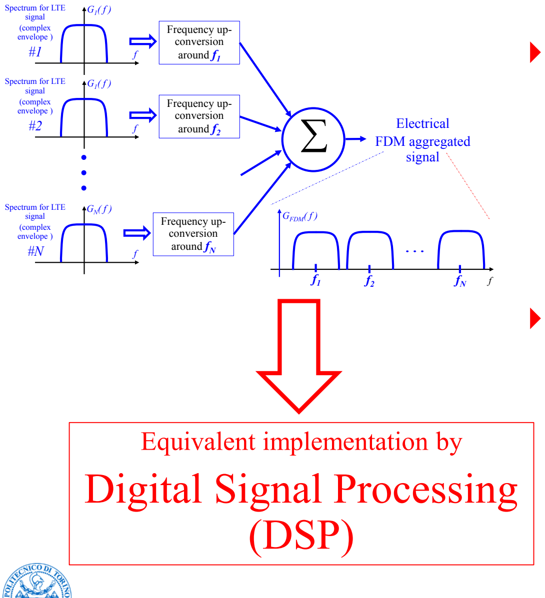


Baseband complex signals to be delivered to the RRH

Basically… an updated version of Radio over Fiber (RoF)



How to perform aggregation?



- The FDM aggregation can be in principle obtained by using hardware radio-frequency (RF) electrical I/Q modulators
- Anyway, if the target is aggregating tens of signal, the resulting electronic would be too expensive

DSP-aggregated Fronthauling

Experimental Demonstration of High-Throughput Low-Latency Mobile Fronthaul Supporting 48 20-MHz LTE Signals with 59-Gb/s CPRI-Equivalent Rate and 2-µs Processing Latency

ECOC 2015

Xiang Liu, Huaiyu Zeng, Naresh Chand, and Frank Effenberger
Futurewei Technologies, Huawei R&D USA, Bridgewater, NJ 08807, USA

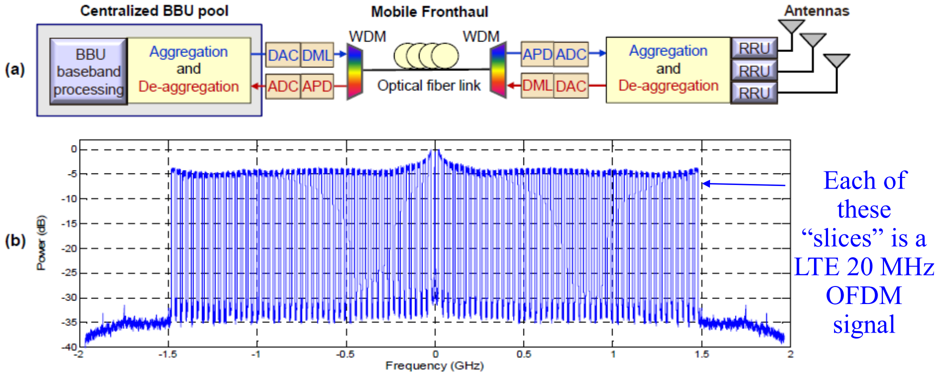


Fig. 1: (a) Schematic of the mobile fronthaul architecture with DSP-based channel aggregation and de-aggregation in the frequency domain; (b) Experimentally measured spectrum of 48 20-MHz LTE signals (and their images due to Hermitian symmetry) that are aggregated using seamless channel mapping and transmitted over 5-km SSMF with -6 dBm received signal power. The signal center wavelength is 1550 nm. DML: directly modulated laser; APD: avalanche photodiode.

The DSP-aggregation principle

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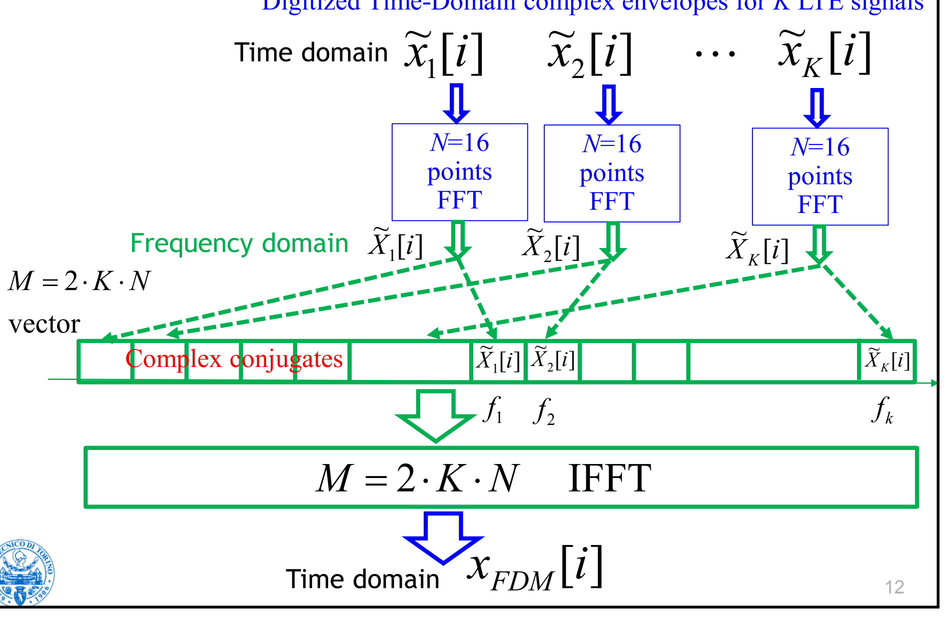

Comparison of CPRI and G.RoF

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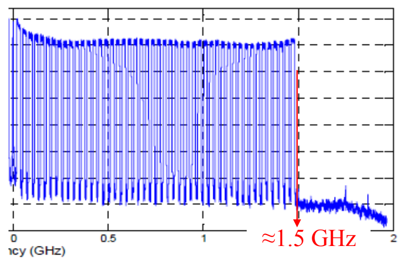
- In the original Huawei ECOC2015 experiment, 48 LTE signals were carried over approx. 1.5 GHz of electrical analog bandwidth



- The CPRI approach would have required approximately 48x1.23Gbit/s ≈ 60 Gbit/s
- This is the clear advantage of the new proposal

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OUR EXPERIMENTS ON DSP-AGGREGATED FDMA FRONTHAULING

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OPTIMIZATION OF THE SYSTEM PARAMETERS

Off-line processing experimental setup

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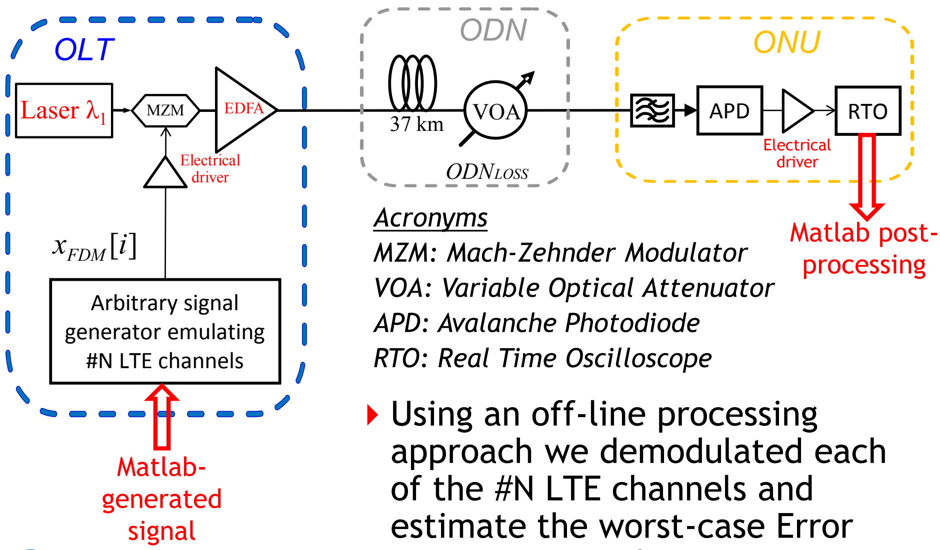

Acronyms

MZM: Mach-Zehnder Modulator

VOA: Variable Optical Attenuator

APD: Avalanche Photodiode

RTO: Real Time Oscilloscope

- Using an off-line processing approach we demodulated each of the #N LTE channels and estimate the worst-case Error Vector Magnitude (EVM)

EVM vs. ODN loss and optical power

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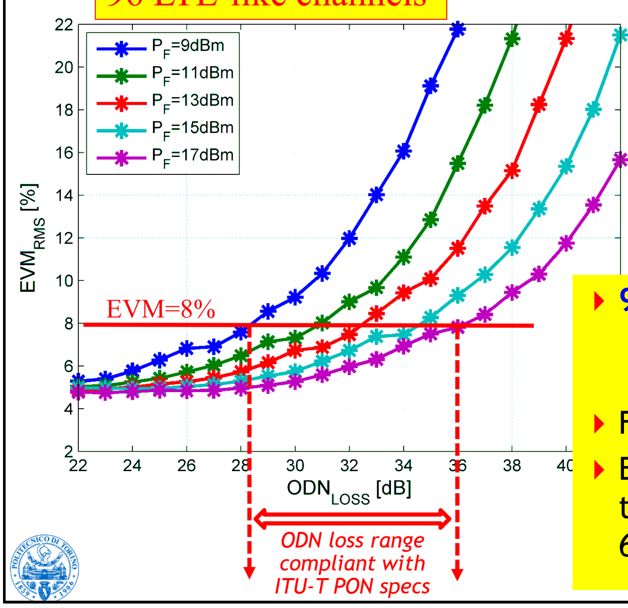
96 LTE-like channels



Our presentation at ECOC 2016 - Dusseldorf

Same conditions used in this ICTON paper

- **96 LTE channels**
  - **20 MHz,**
  - **OFDM 64-QAM**
- Fiber length = 37 km
- EVM=8% is required by the LTE standard on 64-QAM

Parameters to be optimized

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In order to obtain the result presented at ECOC 2016 we had to optimize several system parameters, and in particular:

1. Clipping factor to reduce signal Peak-to-Average-Power Ratio (PAPR)
2. Simple nonlinearity compensation
3. Channels power equalization

- Our ICTON paper is focused on these optimizations
  - Which were not presented at ECOC 2016

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How to properly clip the signal

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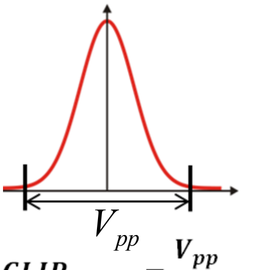
- The resulting DSP-aggregated signal has an amplitude distribution that is very close to a Gaussian probability density function
  - Being the sum of many (such as 96) OFDM channels
    - That are already Gaussian-shaped
- We define here the clipping factor as:
  - Where:
    - σ_s is the standard deviation of the DSP-aggregated Gaussian-like signal
    - V_{pp} is the peak to peak amplitude of the signal AFTER clipping



$$CLIP_{factor} = \frac{V_{pp}}{\sigma_s}$$

The clipping factor was the first parameter we optimized

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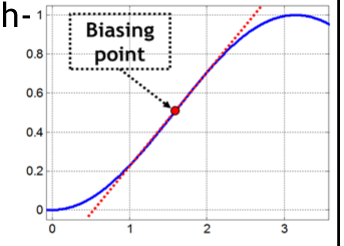
How to compensate for the link nonlinearity

- The link we used, being based on Mach-Zehnder modulator (MZM) and direct-detection, was intrinsically (mildly) nonlinear, due to the $cos^2(\cdot)$ instantaneous response of the MZM
- We want to introduce a correction of the nonlinearity in the DSP domain
  - But we want to keep it simple, avoiding Volterra's series approach
- We found that a simple cubic relation in DSP can highly reduce the impact of nonlinearities



$$x_{corr} = x + CF \cdot x^3$$

The nonlinear *CF* factor was the second parameter we optimized

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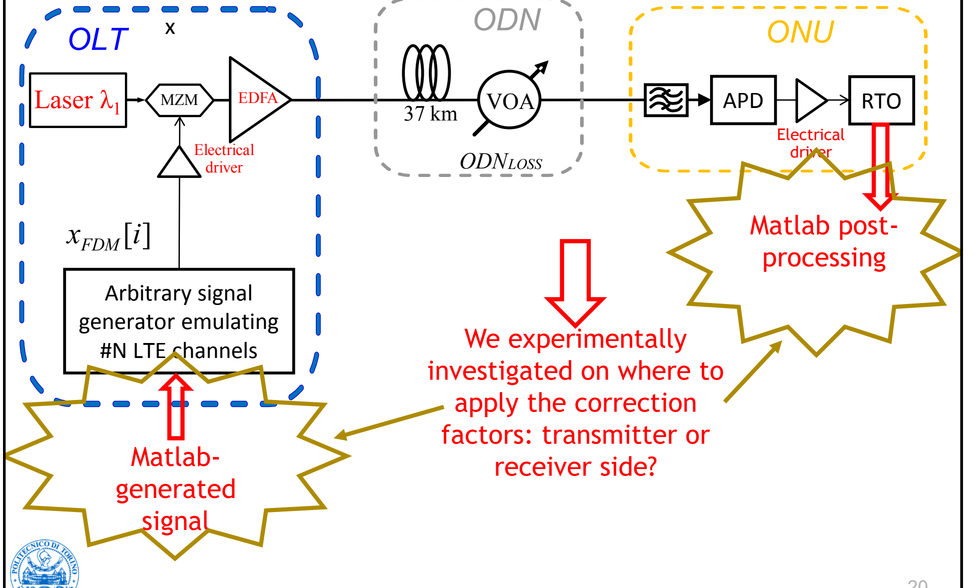
Clipping and nonlinearity compensation: WHERE?



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CLIPPING and nonlinearity comp at TX or RX?

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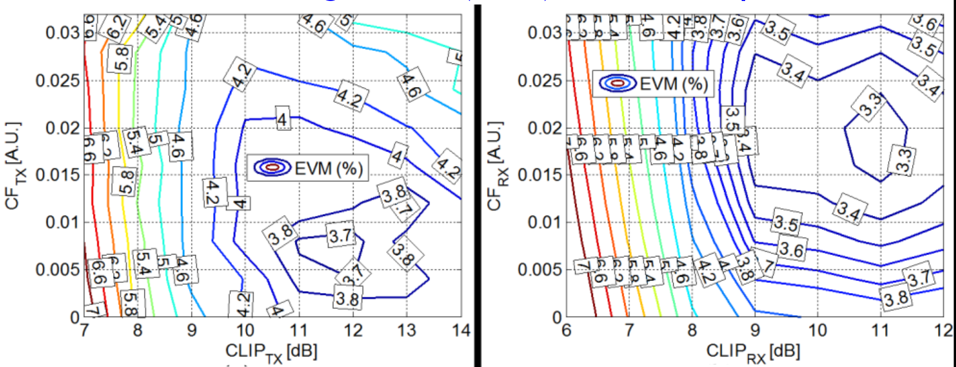
Error Vector Magnitude (EVM) on the output channels



[redacted] Transmitter side [redacted] Receiver side (with 12 dB clipping also at TX)

- Conclusion: <u>the compensation at the RX gave better results</u>, and we thus performed all our further experiments in this condition

Optimized EVM vs. Optical Path Loss

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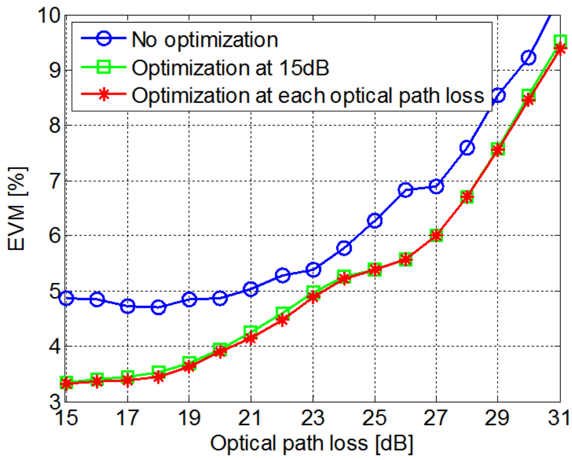
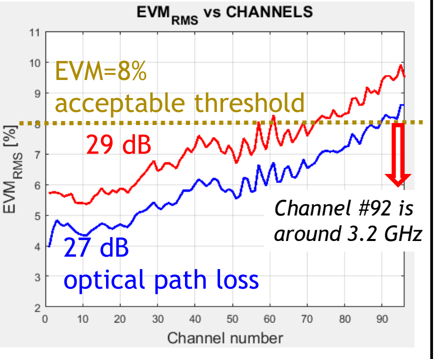


- **96 LTE channels,**
- **20 MHz, OFDM 64-QAM**
- Fiber length = 37 km
- +9dBm optical launched power

- Conclusion: optimization can be done at a given (reasonable) optical path loss, and then kept for all other operating conditions

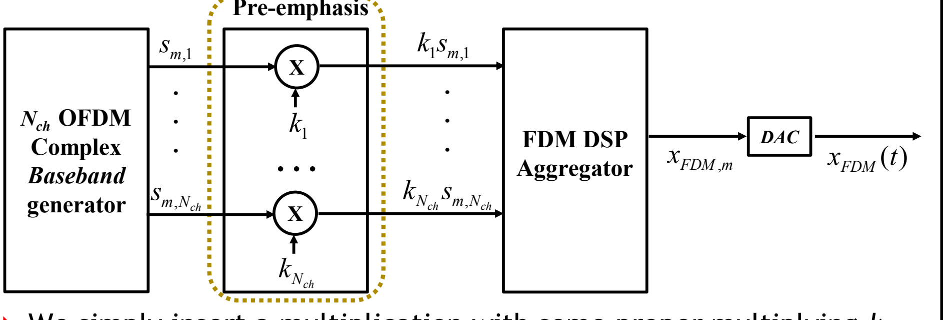
Compensation of frequency dependence

- Particularly for the high number of channels, the aggregated FDM signal can occupy a large bandwidth, over which the direct-detection channel is not flat in terms of:
  - Frequency transfer function
  - Receiver noise power spectral density
- The resulting SNR (and thus EVM) per channel can be significantly different



- We need to perform a power equalization at the transmitter
- … and again, keep it simple!

Proposed approach: DSP-based pre-emphasis



- We simply insert a multiplication with some proper multiplying k_i coefficients in the TX DSP aggregator block diagram
- The coefficient were evaluated using a min-max algorithm
  - Minimization of the worst-case EVM_i among all received channels

$$k_i = \frac{\mathrm{EVM}_i^{out,no-pre}}{\mathrm{EVM}_{\mathrm{target}}^{out}}$$

$$G_{DS}(\mathrm{EVM}_{\mathrm{target}}^{out}) = \frac{1}{N_{ch}}\sum_{i=1}^{N_{ch}} k_i^2 = \frac{1}{N_{ch}}\sum_{i=1}^{N_{ch}}\left(\frac{\mathrm{EVM}_i^{out,no-pre}}{\mathrm{EVM}_{\mathrm{target}}^{out}}\right)^2 = 1$$

Proposed approach: DSP-based pre-emphasis

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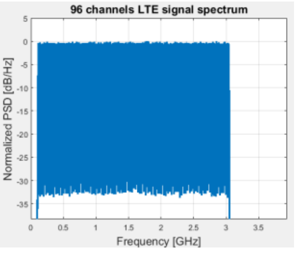
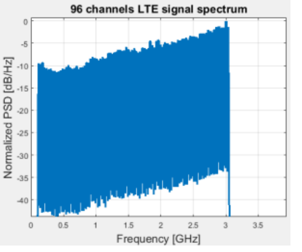
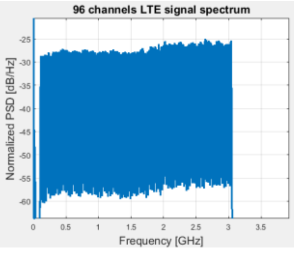


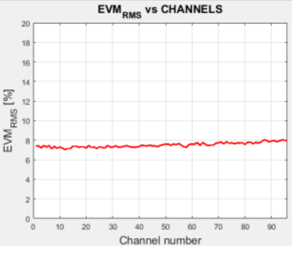
Tx PSD without Pre-emphasis



Tx PSD with Pre-emphasis



Rx PSD with Pre-emphasis



Rx EVM with Pre-emphasis

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Example of application

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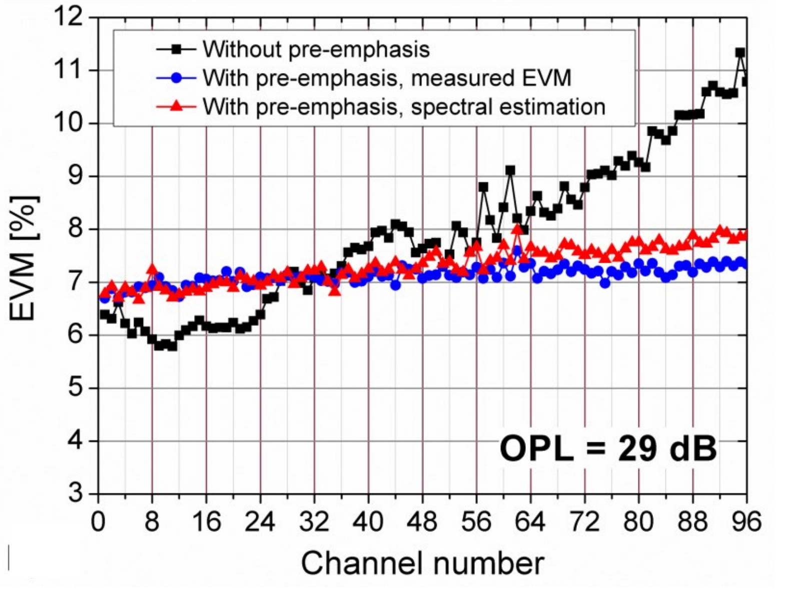

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Comments and Conclusion

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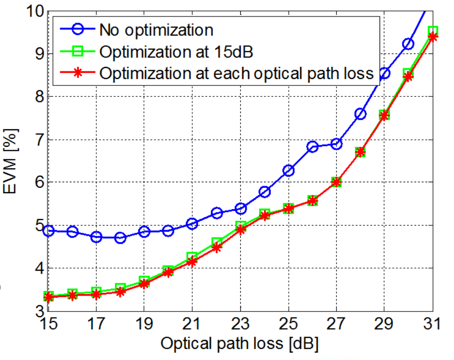
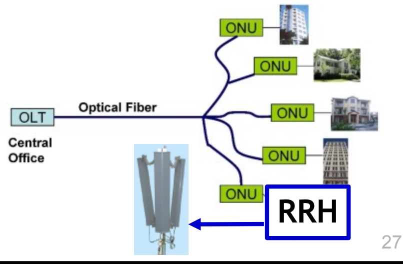
- We described the optimization procedure we inserted in a DSP-assisted FDM-aggregated fronthauling architecture

- The obtained results (for 96 aggregated channels) allow to envision transmission up to optical path losses (29dB) that are compliant with ITU-T class N1 for Passive Optical Network (PON)





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