Fotonica 2017 AEIT

19ª Edition - Convegno Italiano delle Tecnologie Fotoniche

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Up to 4x192 LTE-A Radio Waveforms Transmission in a Point to Multipoint architecture for Massive Fronthauling Solutions

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Presentation outline for Invited Paper

- A short tutorial on Fronthauling for CRAN
  - Mainstream architectures:
    - CPRI
    - Functional-split
  - Alternative architectures
    - DSP-Assisted analog Radio over Fiber (RoF)
- Our recent results DSP-Assisted RoF towards Massive Fronthauling Solutions based on multi-output EDFA

- *This work was partially sponsored by CISCO in the framework of RFP 2015 «5G-PON»*
  - *In particular, we would like to thanks Cisco Allentown team for the multi-output EDFA*
  - *We also would like to thank Tektronix for lending us the instruments*

Traditional solution: Backhauling

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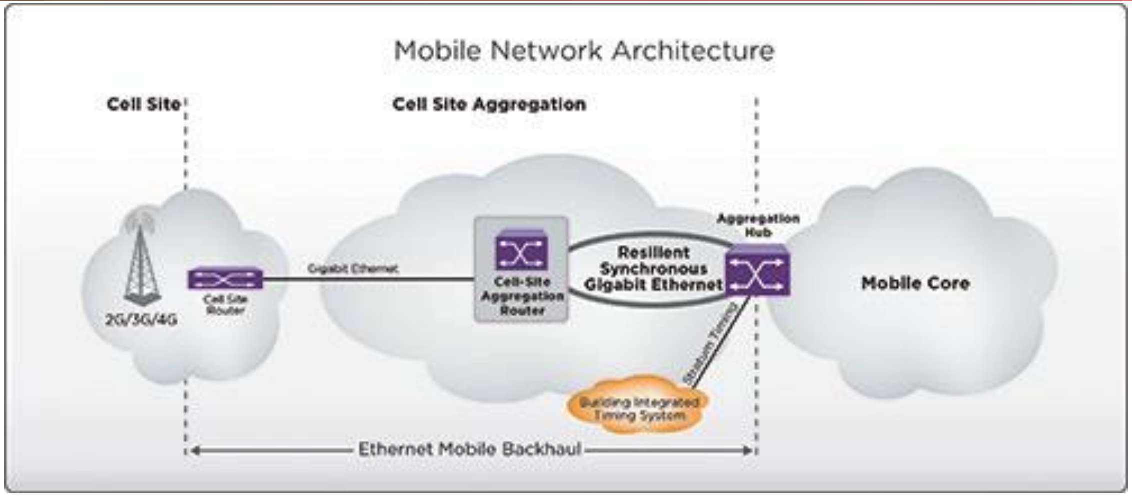


http://www.telecomengine.com/sites/default/files/temp/MobileNetworkArch_Small.jpg

- Traditional mobile networks implement most of the <u>"wireless-related" protocol in the base stations</u>, that are located at the antenna sites
- <u>Backhaul</u>: link between the base station and the core network
  - Backhaul transports the "information" going to/from the mobile network (basically, IP data packets)

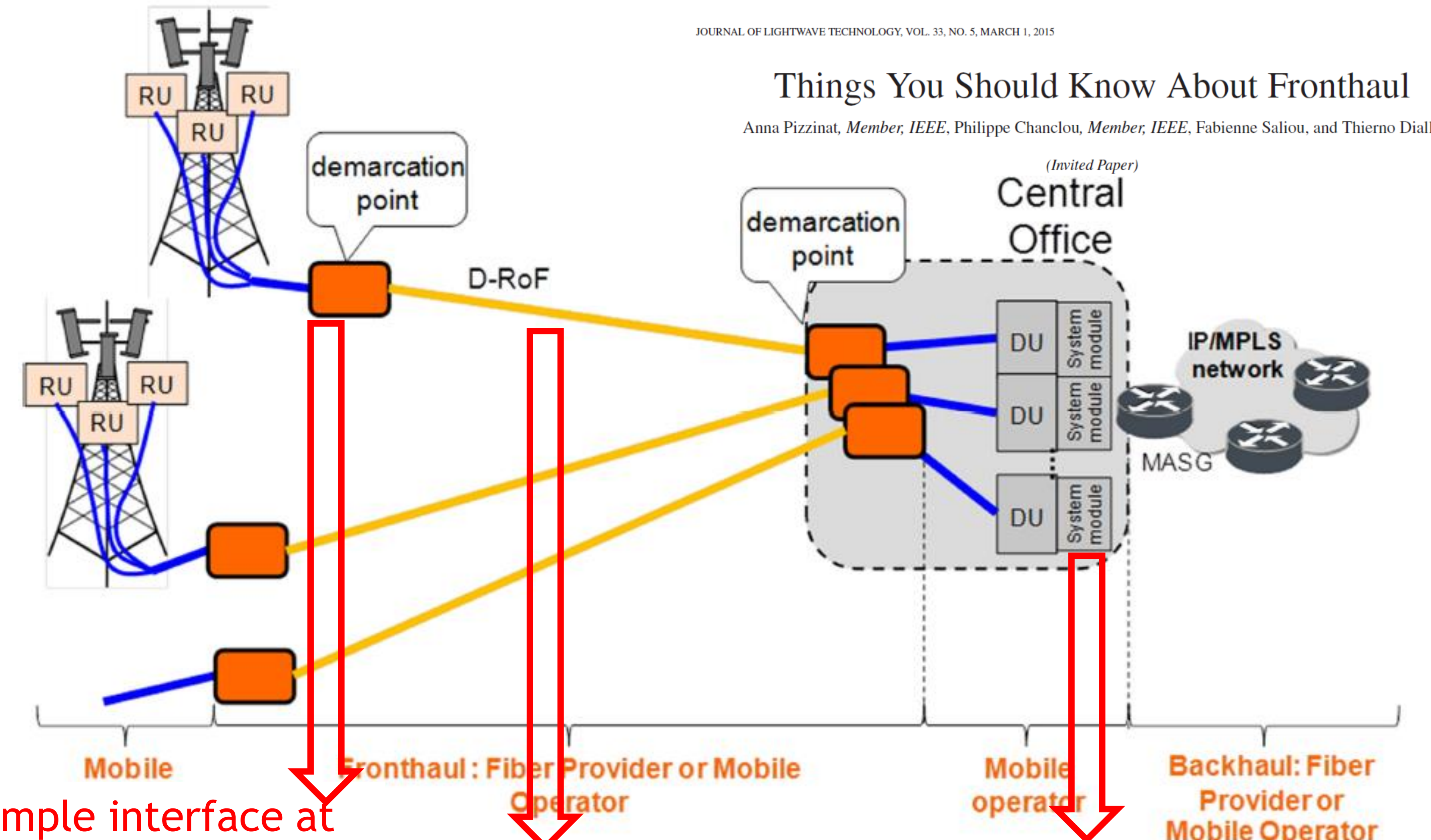
The new scenario: Fronthauling

- Key principle: highly simplified antenna site, most of the protocols complexity centralized in the first central office connected to the antenna sites

- Fibers used instead of microwave links

- This new paradigm is going to be more and more common for LTE-Advanced
  - Moreover, it is perceived to be a must for next-generation 5G

The Fronthauling architecture



Simple interface at antenna site (RRH: Remote Radio Head)

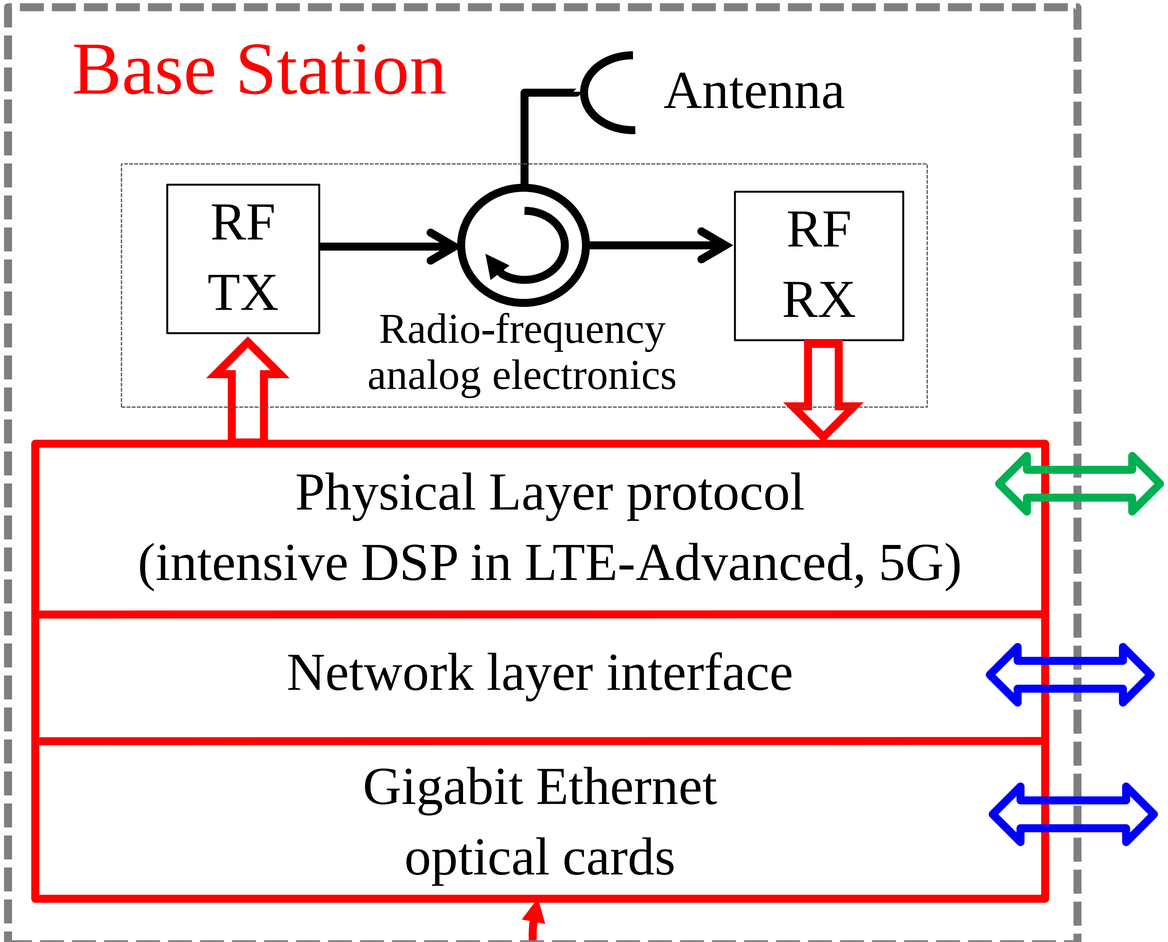
Transport of “native radio waveforms” over fiber (RoF)

Baseband units (BBU) pools at Central Office

The “Front-hauling” approach

- PROS:
  - The antenna unit (or Remote Radio Head RRH) is greatly simplified
  - The degree of software-defined re-configurability is much higher
    - Ready for network cloudification and virtualization
    - In the longer term: CRAN: Cloud Radio Access Networks
  - The aggregation of Baseband Units (BBU) coming from different antennas in the same Central Office can increase coordination capabilities:
    - Cognitive radio,
    - LTE CoMP (Coordinated Multipoint)
- CONS:
  - The “mainstream” fronthauling solutions requires very high bit rates per antenna (as detailed later)
    - The existing standard for front-hauling (called CPRI) requires 10 Gbps today for its highest rate
  - Very stringent requirements on latency

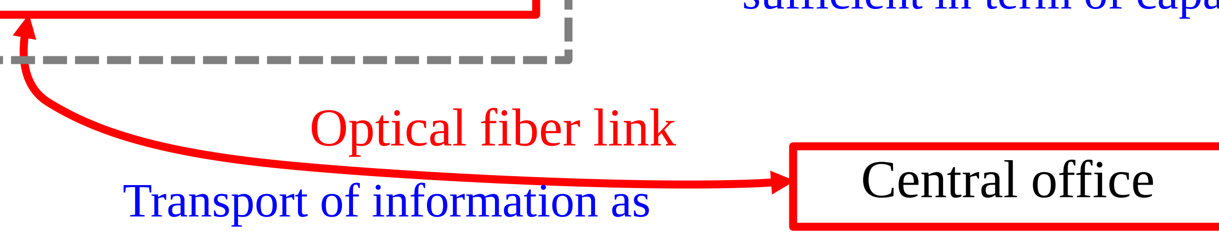
Simplified view of backhaul architectures



This layers has to handle ALL the very complex physical layer of 4G-LTE (or previously 3G-UMTS), requiring intensive digital signal processing

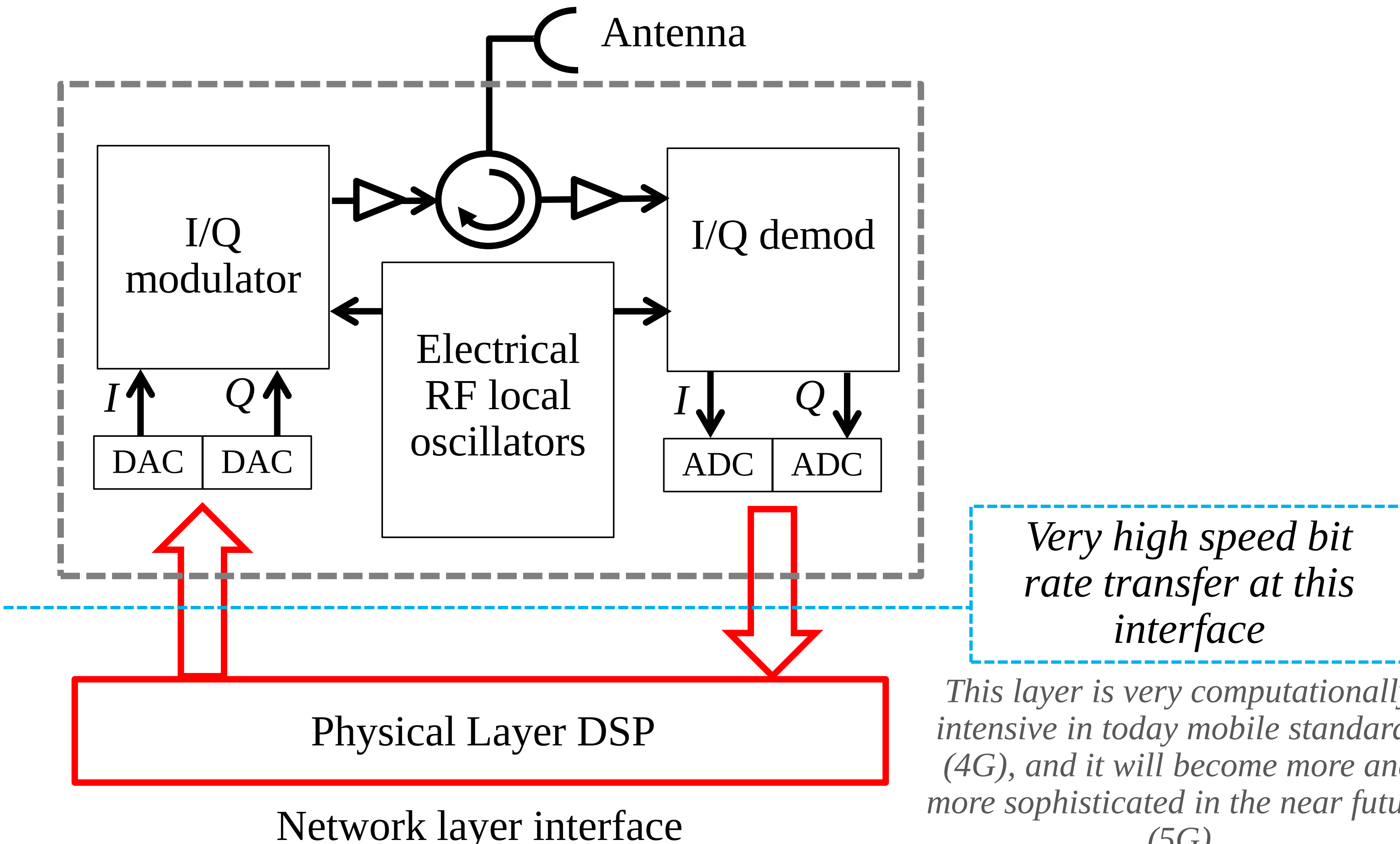
Ethernet is usually introduced to transport IP packets.

A Gigabit/s interface is thus sufficient in term of capacity



Transport of information as IP packets

«Zooming in» at the physical layer



This layer is very computationally intensive in today mobile standards (4G), and it will become more and more sophisticated in the near future (5G)

Digitizing one 20-MHz LTE channel

- The DACs that generate a 20-MHz LTE-A radio signal are as follows:
  - Two I/Q DACs followed by an electrical I/Q modulator
  - Each of the two DACs 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**

The new vision: Digitized Radio over Fiber (DRoF)

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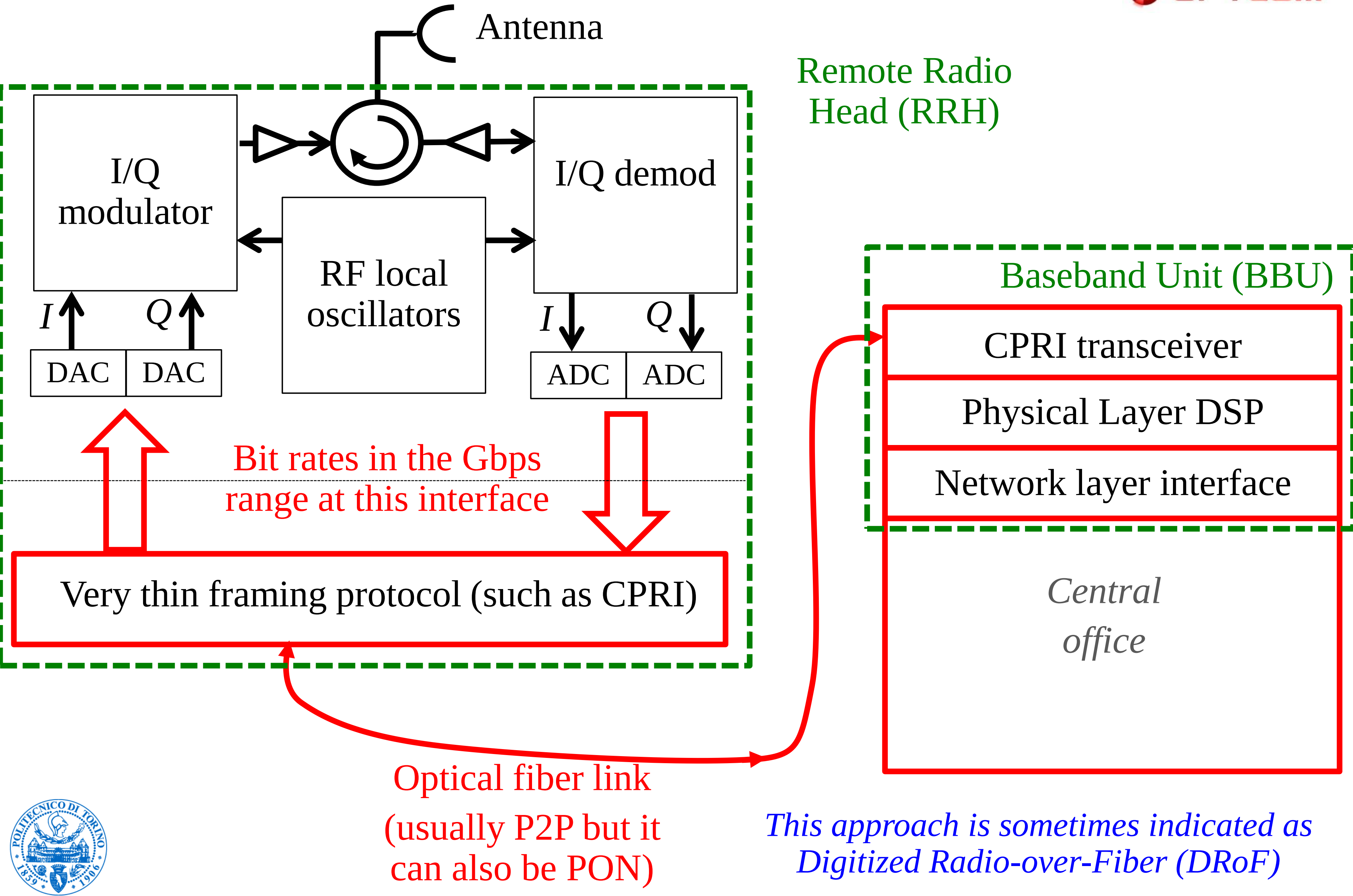

This approach is sometimes indicated as Digitized Radio-over-Fiber (DRoF)

Common Public Radio Interface (CPRI)

- CPRI current data rates

4.2. Physical Layer (Layer 1) Specification

4.2.1. Line Bit Rate

In order to achieve the required flexibility and cost efficiency, several different line bit rates are defined. Therefore, the CPRI line bit rate may be selected from the following option list:

- CPRI line bit rate option 1: 614.4 Mbit/s
- CPRI line bit rate option 2: 1228.8 Mbit/s (2 x 614.4 Mbit/s)
- CPRI line bit rate option 3: 2457.6 Mbit/s (4 x 614.4 Mbit/s)
- CPRI line bit rate option 4: 3072.0 Mbit/s (5 x 614.4 Mbit/s)
- CPRI line bit rate option 5: 4915.2 Mbit/s (8 x 614.4 Mbit/s)
- CPRI line bit rate option 6: 6144.0 Mbit/s (10 x 614.4 Mbit/s)
- CPRI line bit rate option 7: 9830.4 Mbit/s (16 x 614.4 Mbit/s)

- The bit rates in the CPRI standard includes signaling and control information on top of the "raw" DRoF bit stream

The bit rate expansion issue in DRoF

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- 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
- But the actual traffic for the final user carried by one 20 MHz LTE signal is about 100 Mbit/s (gross data rate using 64-QAM)
- This is the well-know "bit-rate expansion" problem in CPRI
  - The "multiplication" factor is more 10x
  - This is the price to be paid when comparing CPRI fronthauling with traditional backhauling

An "advanced" future antenna site

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- Let's assume that each antenna site has:
  - 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

A RECENT NEW TREND:

FUNCTIONAL-SPLIT FRONTHAULING

Functional-split fronthauling

- Key idea: a flexible protocol architecture in which some of the protocol functions are left at the CO, others are moved to the RRH
  - The result is a "suite" of options giving a tradeoff between:
    - Increasing the amount of functionalities moved to the RRH
    - Increasing the resulting bit rate to be carried on the fronthauling link

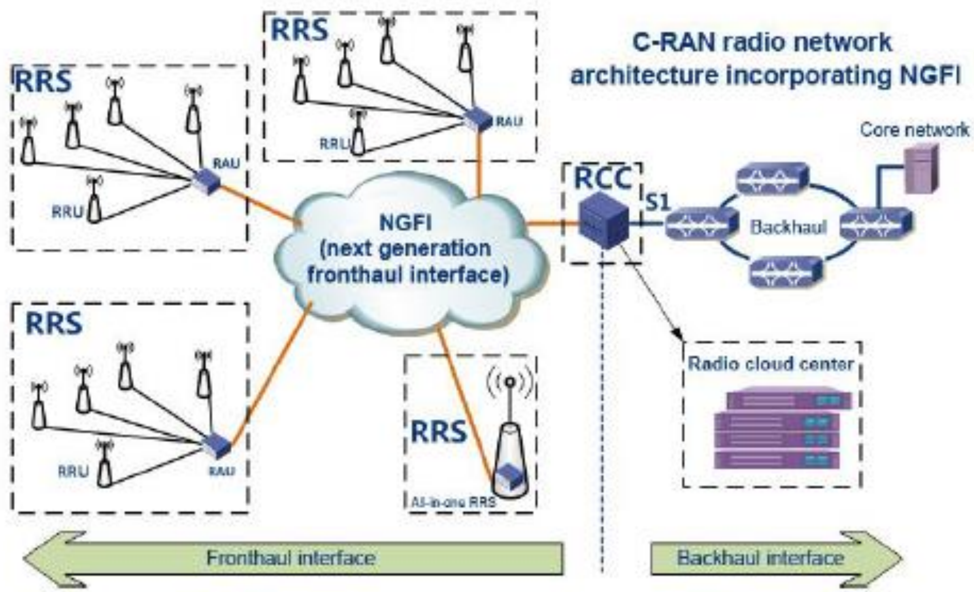


Figure 2-1: C-RAN Radio Network Architecture Based on NGFI

China Mobile Research Institute
Alcatel-Lucent
Nokia Networks
ZTE Corporation
Broadcom Corporation
Intel China Research Center

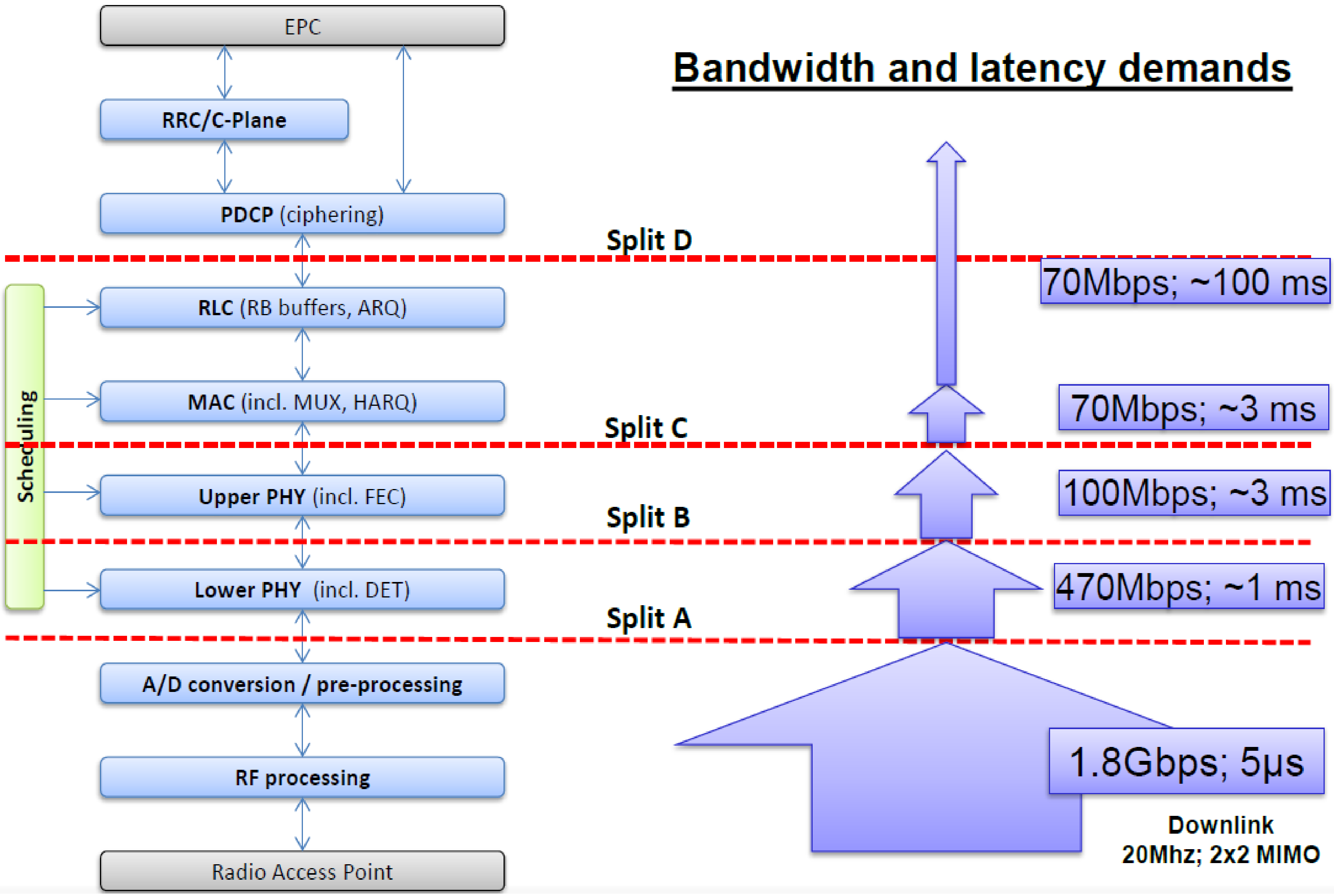
White Paper of

Next Generation Fronthaul Interface

Version 1.0

June 4, 2015

Resulting bit rates



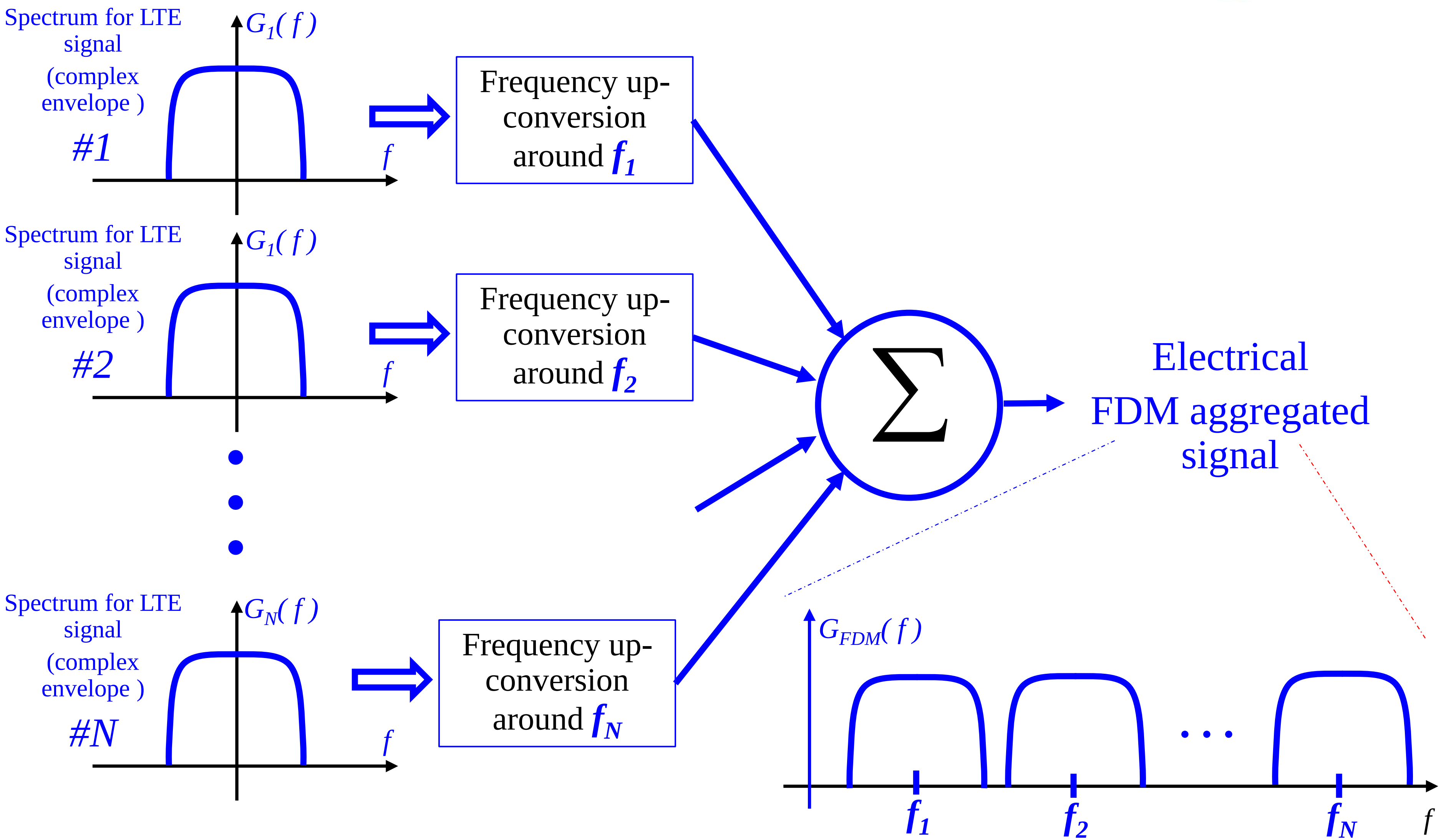
Towards a Flexible Functional Split for Cloud-RAN Networks

Andreas Maeder[1], Massissa Lalam[2], Antonio De Domenico[3], Emmanouil Pateromichelakis[4], Dirk Wübben[5], Jens Bartelt[6], Richard Fritzsche[6], Peter Rost[1]
[1]NEC Laboratories Europe, [2]Sagemcom Broadband, [3]CEA-LETI, [4]University of Surrey, [5]University of Bremen, [6]Technical University of Dresden

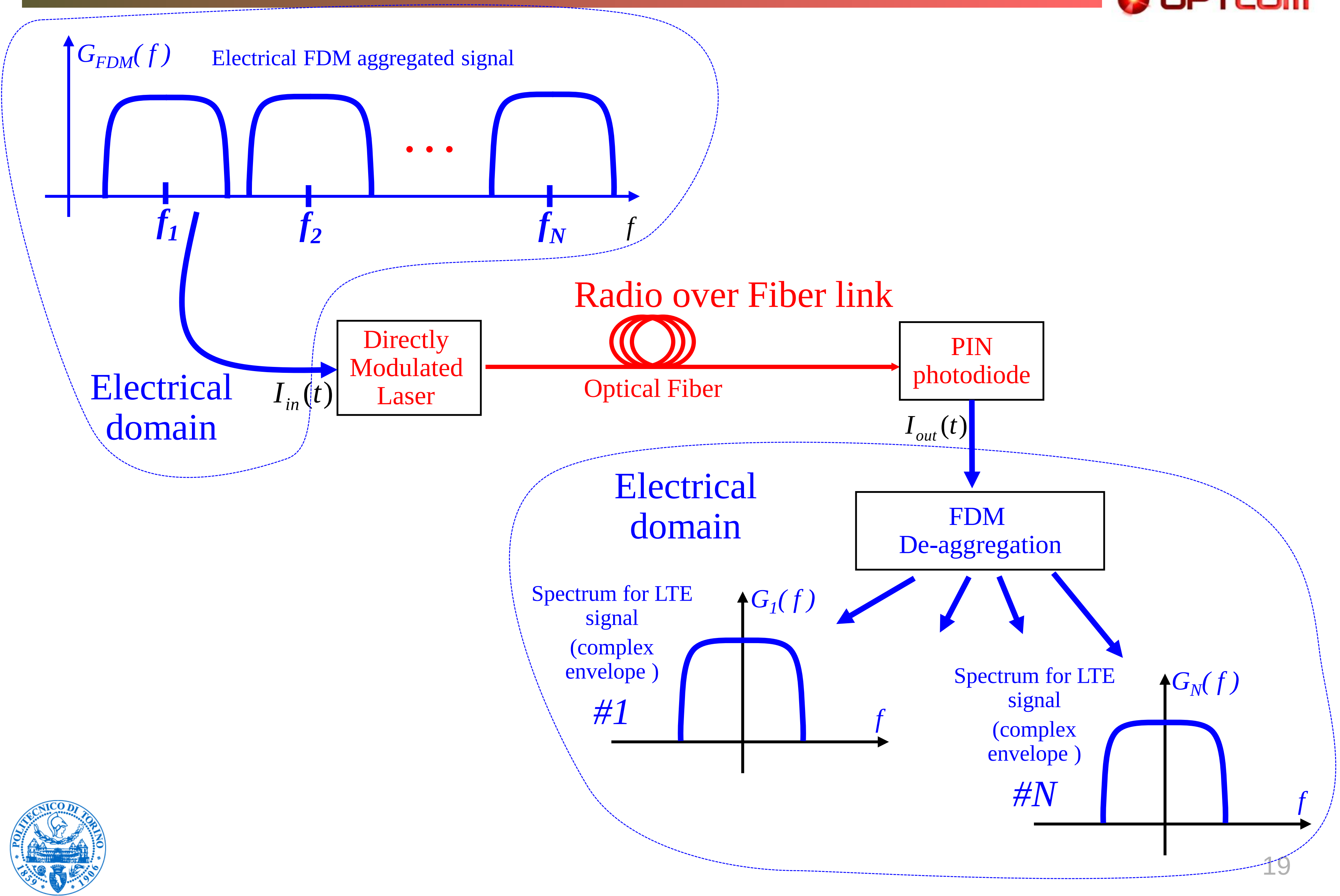
AN ALTERNATIVE APPROACH:

DSP-AGGREGATED FDMA-BASED FRONTHAULING

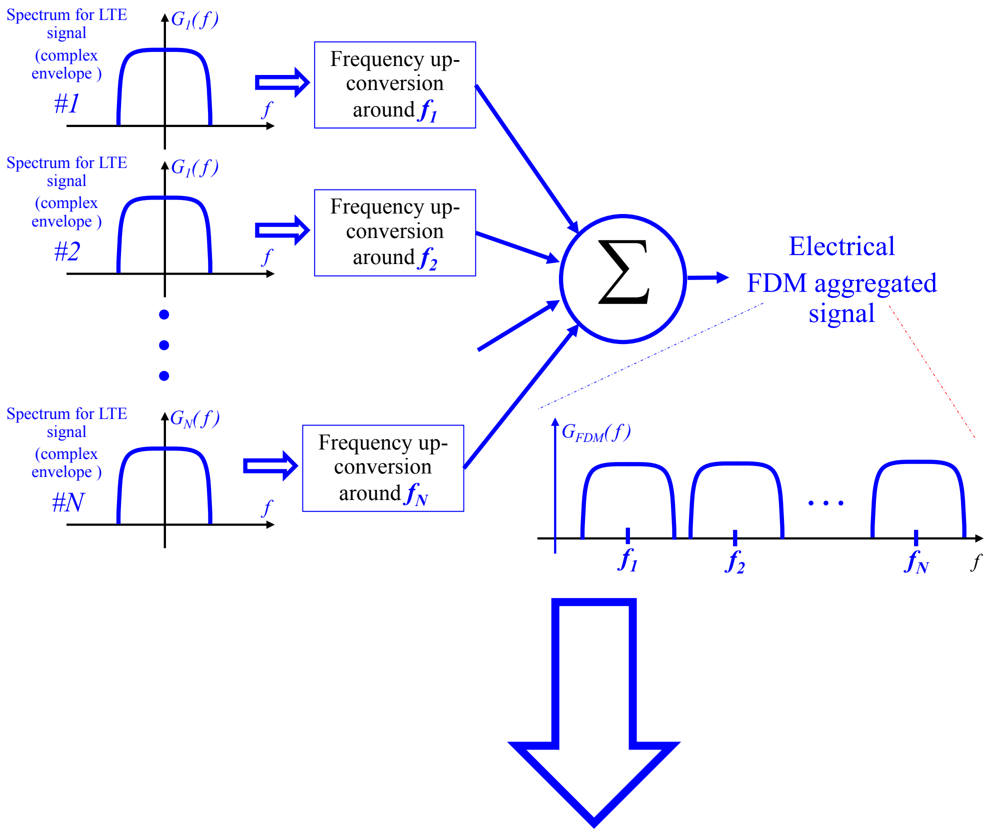
Aggregation by FDM - functional schematic



Aggregation by FDM – functional schematic



How to perform aggregation?



Equivalent implementation by

Digital Signal Processing (DSP)

- 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

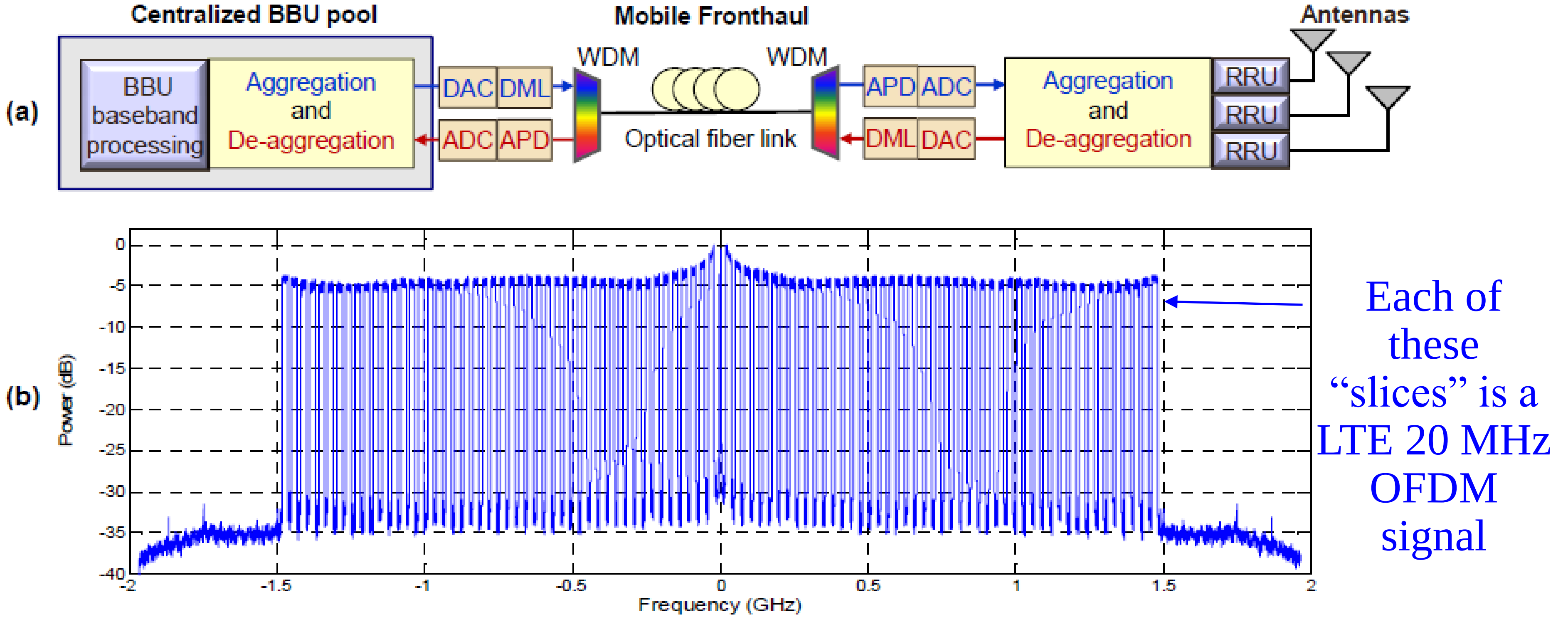
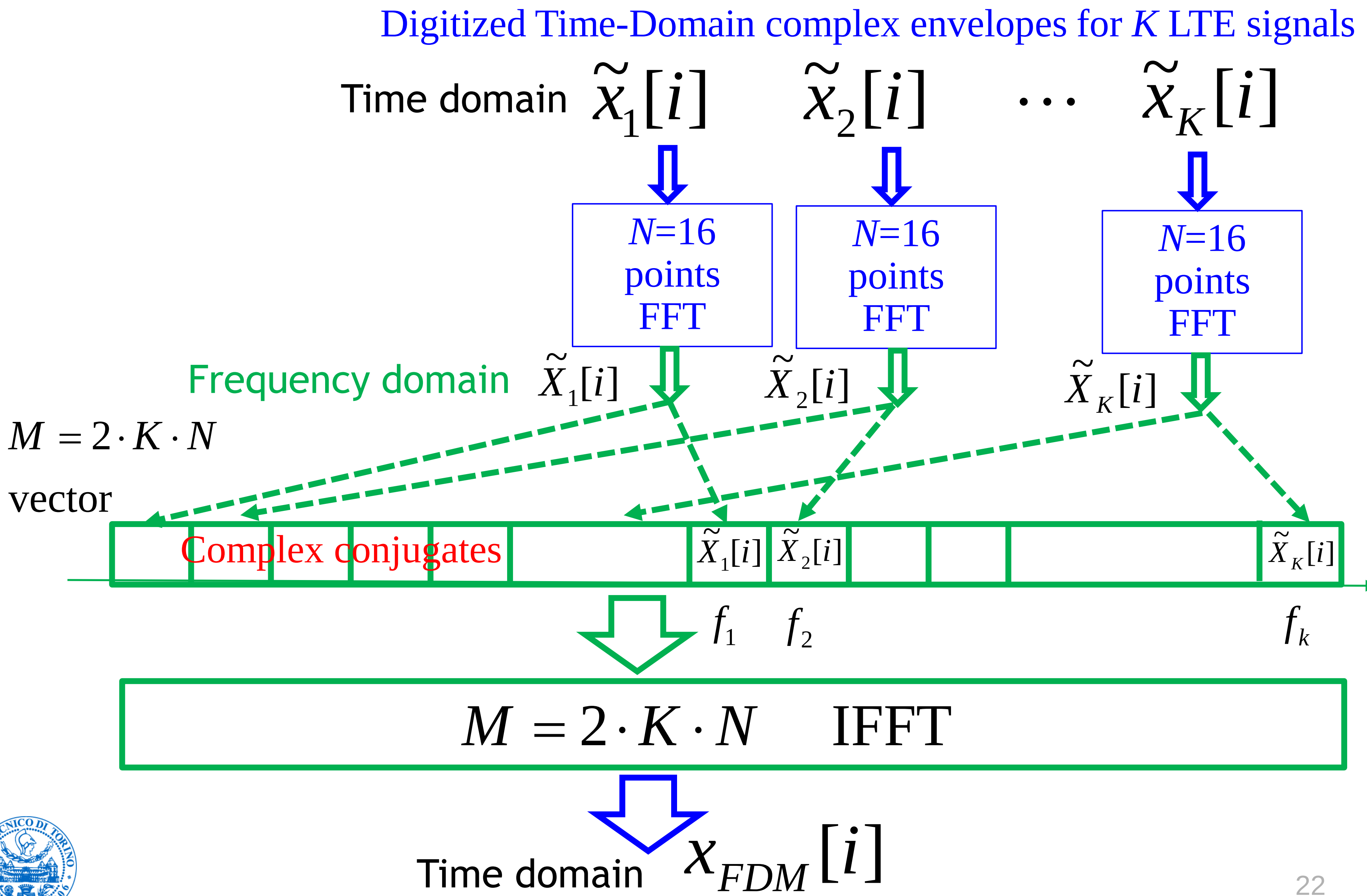


Fig. 1: (a) Schematic of the mobile fronthaul architecture with DSP-based channel aggregation and de-aggregation in the frequency domain; (b) Experimentally measured spectrum of 48 20-MHz LTE signals (and their images due to Hermitian symmetry) that are aggregated using seamless channel mapping and transmitted 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



- Variants of this architecture are under consideration in ITU-T FSAN
  - Recommendation ITU-T G.RoF

Series G

Supplement 55

(07/2015)

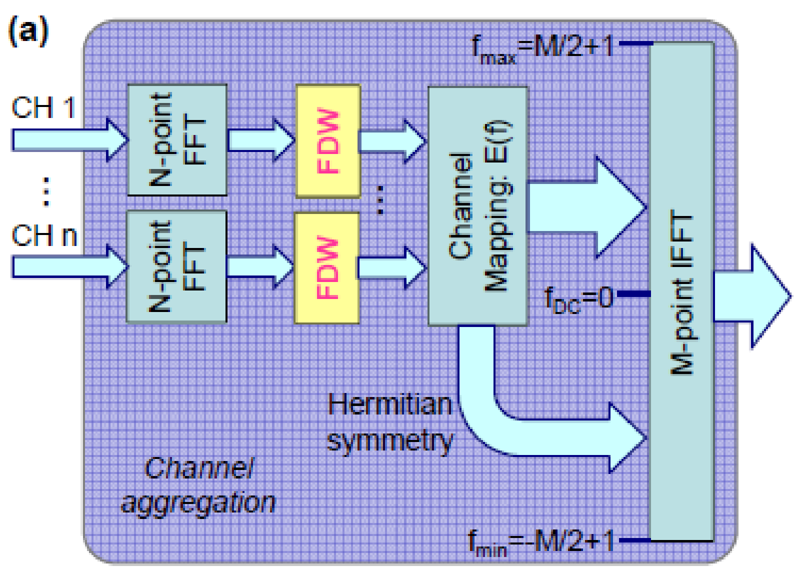
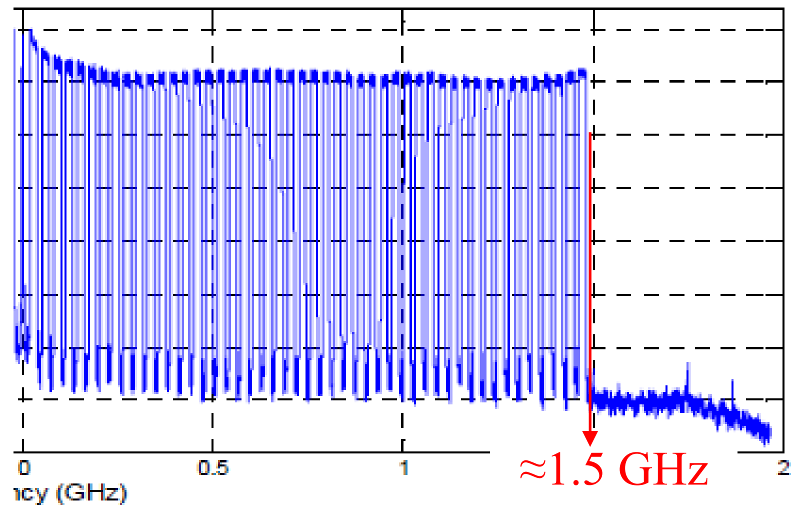


Fig. 2: Schematic of the DSP blocks for FFT/IFFT-based channel aggregation (a) and de-aggregation (b), both with the use of frequency-domain windowing (FDW) to reduce the DSP processing latency.

Comparison of CPRI and G.RoF

- 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

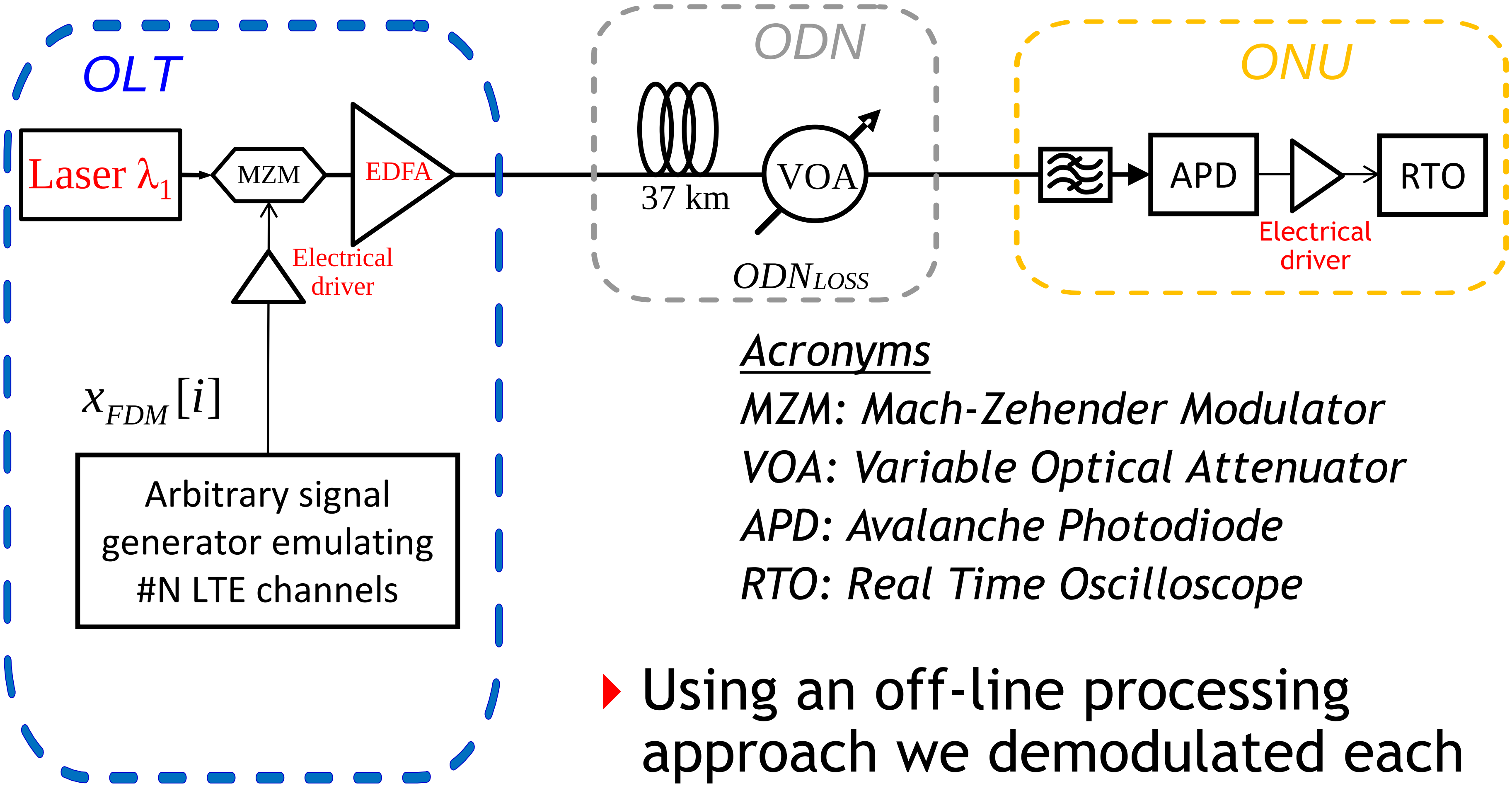
OUR EXPERIMENTS ON DSP-AGGREGATED FDMA FRONTHAULING

MAIN TARGET

MASSIVE FRONTHAULING

INCREASING THE NUMBER OF LTE CHANNELS PER FIBER

Off-line processing experimental setup



Acronyms

MZM: Mach-Zehender 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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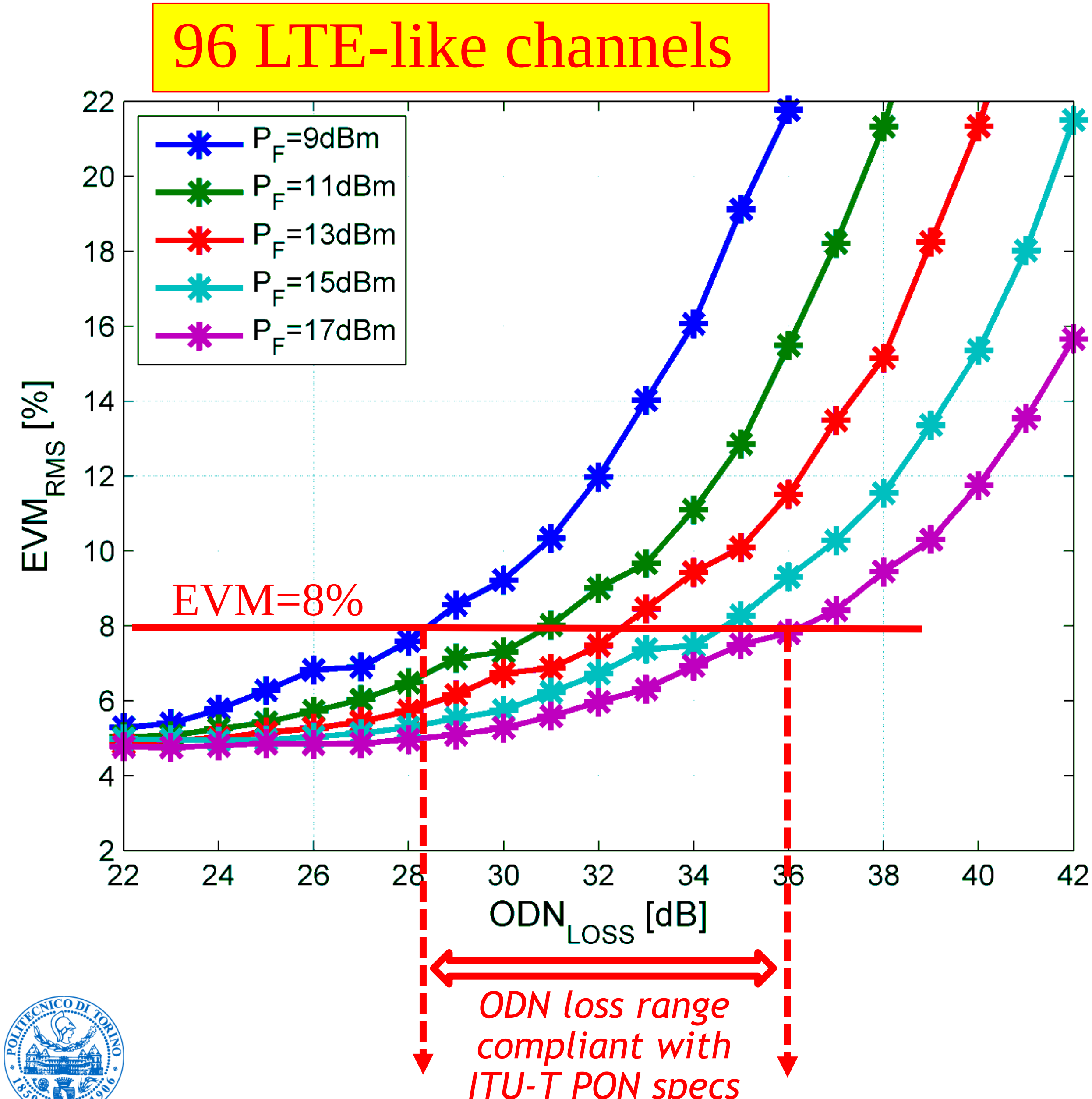

Our presentation at ECOC 2016 - Dusseldorf

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

Our new work for FOTONICA 2017

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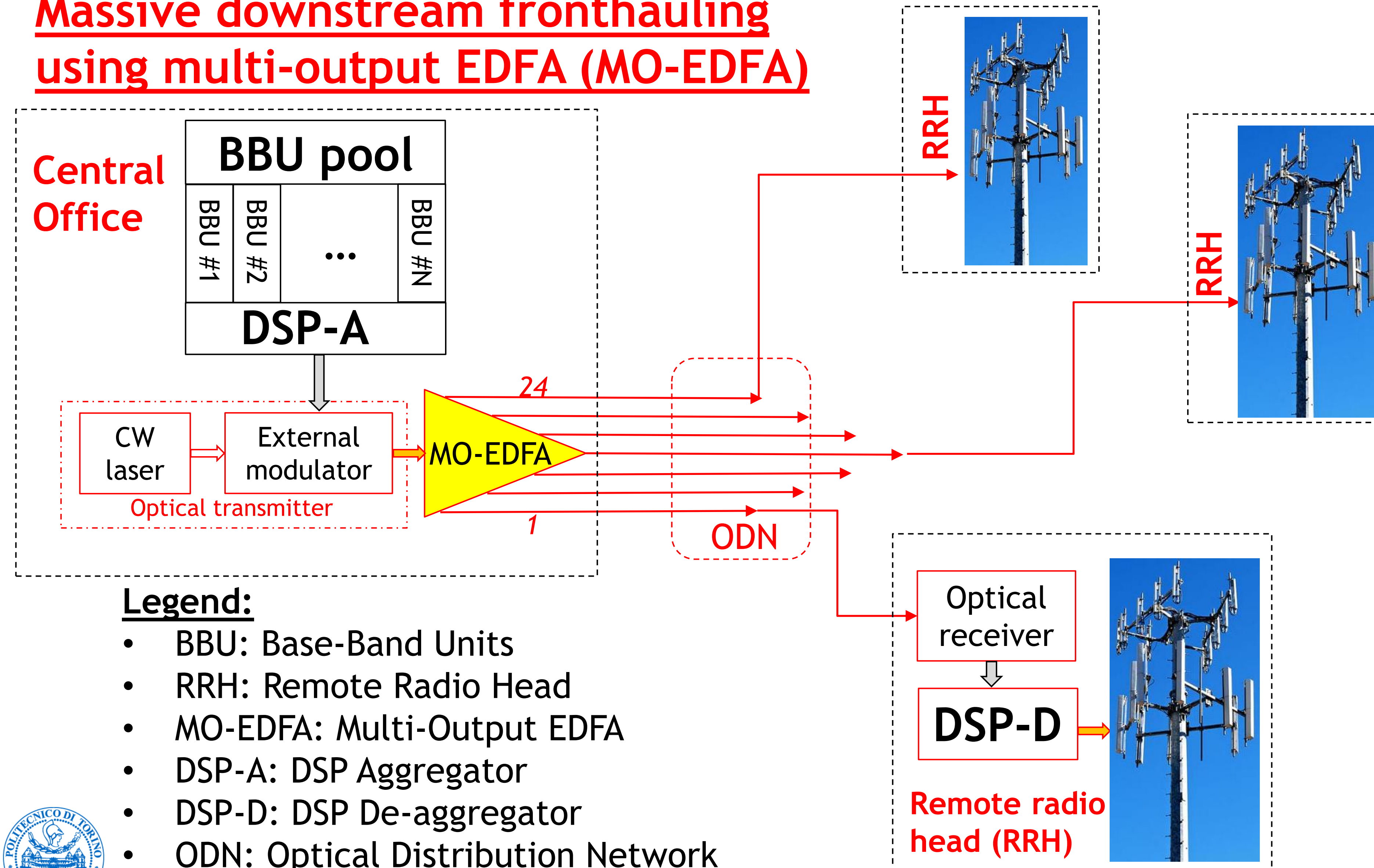
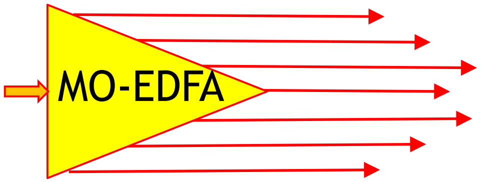
Massive downstream fronthauling using multi-output EDFA (MO-EDFA)



Legend:

- BBU: Base-Band Units
- RRH: Remote Radio Head
- MO-EDFA: Multi-Output EDFA
- DSP-A: DSP Aggregator
- DSP-D: DSP De-aggregator
- ODN: Optical Distribution Network

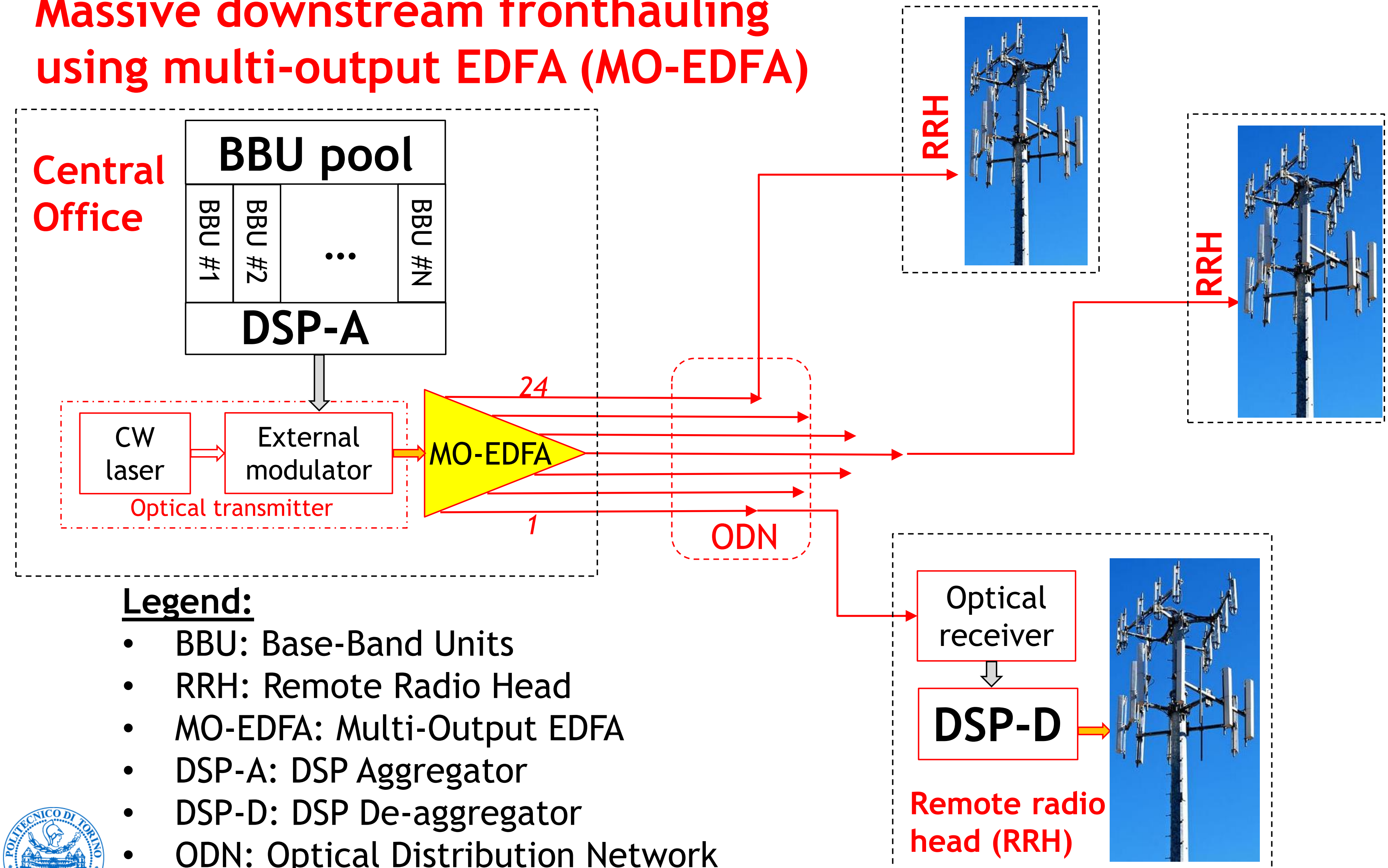
A few words on MO-EDFA



- MO-EDFA are commercial devices that amplifies the same input optical signal towards many output fibers
  - up to 24 in commercial devices
- These optical amplifiers are today used in CATV downstream distribution over fibers
  - The same optical signal (carrying the Video-overly signal typically at 1550 nm) needs to be distributed over many output fibers
  - Moreover, the power per fiber in video-overly is usually very high
    - at least +14 dBm

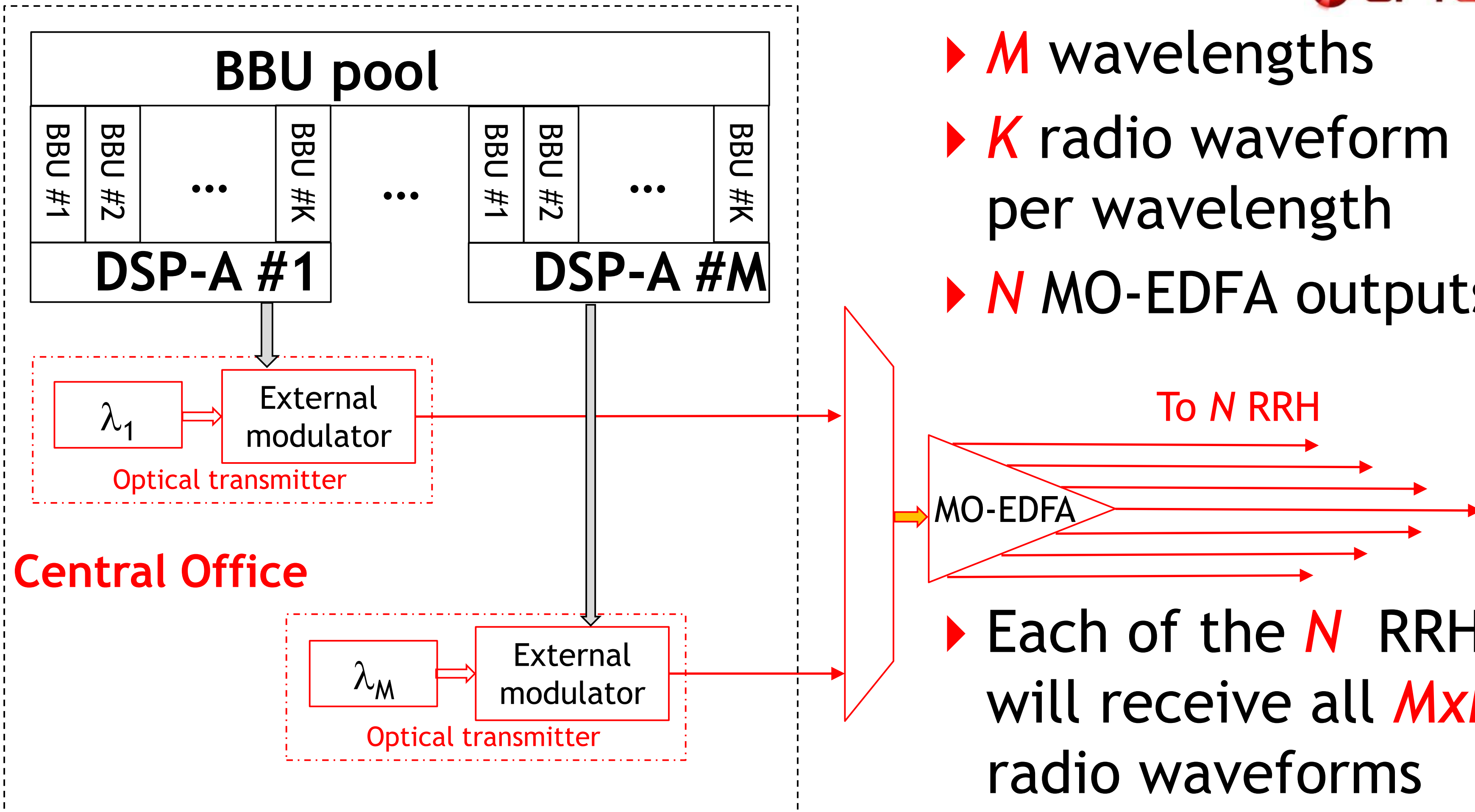
Our new work for FOTONICA 2017

Massive downstream fronthauling using multi-output EDFA (MO-EDFA)



Legend:
- BBU: Base-Band Units
- RRH: Remote Radio Head
- MO-EDFA: Multi-Output EDFA
- DSP-A: DSP Aggregator
- DSP-D: DSP De-aggregator
- ODN: Optical Distribution Network

Multi-lambda CWDM version

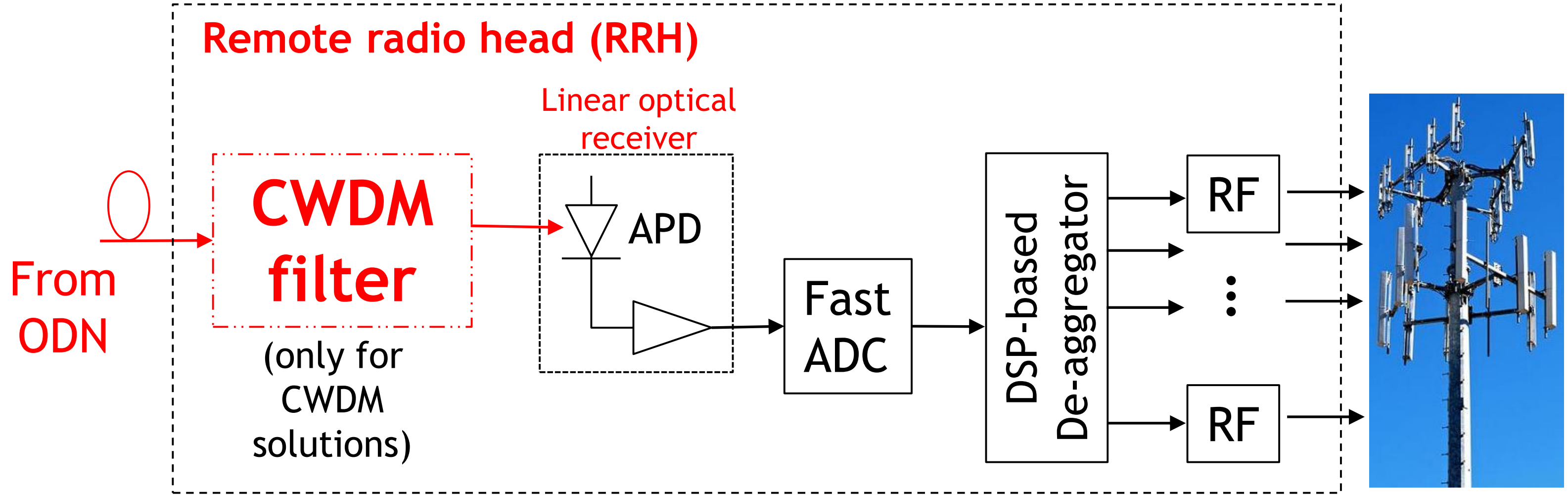


- *M* wavelengths
- *K* radio waveform per wavelength
- *N* MO-EDFA outputs
- Each of the *N* RRHs will receive all *MxK* radio waveforms

In our experiments:

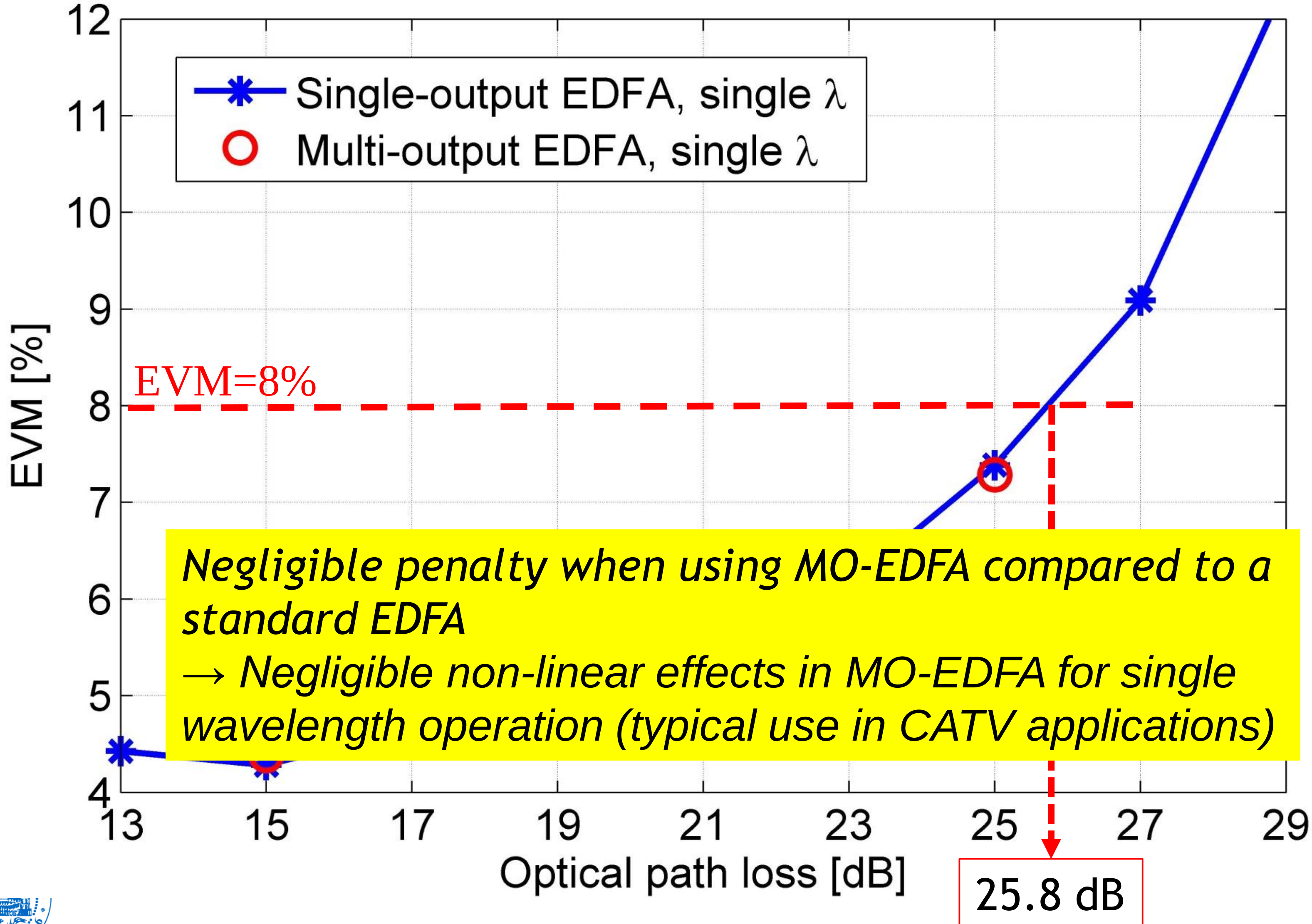
- *M=4* wavelengths
- *K=192* radio waveforms per wavelength
- *N=24* RRHs

Structure of the remote radio head



- Using a tunable optical filter and proper DSP-de-aggregation, each of the *N* RRH can select an arbitrary subset of the *MxK* radio waveforms generated by the BBU pool at the central office
  - High number of delivered radio waveforms
  - High level of network flexibility

192 radio-waveforms on a single wavelength



Negligible penalty when using MO-EDFA compared to a standard EDFA
→ Negligible non-linear effects in MO-EDFA for single wavelength operation (typical use in CATV applications)

Multi-output EDFA, CWDM, ODN = 21dB

- Performances as a function of WDM channel spacing

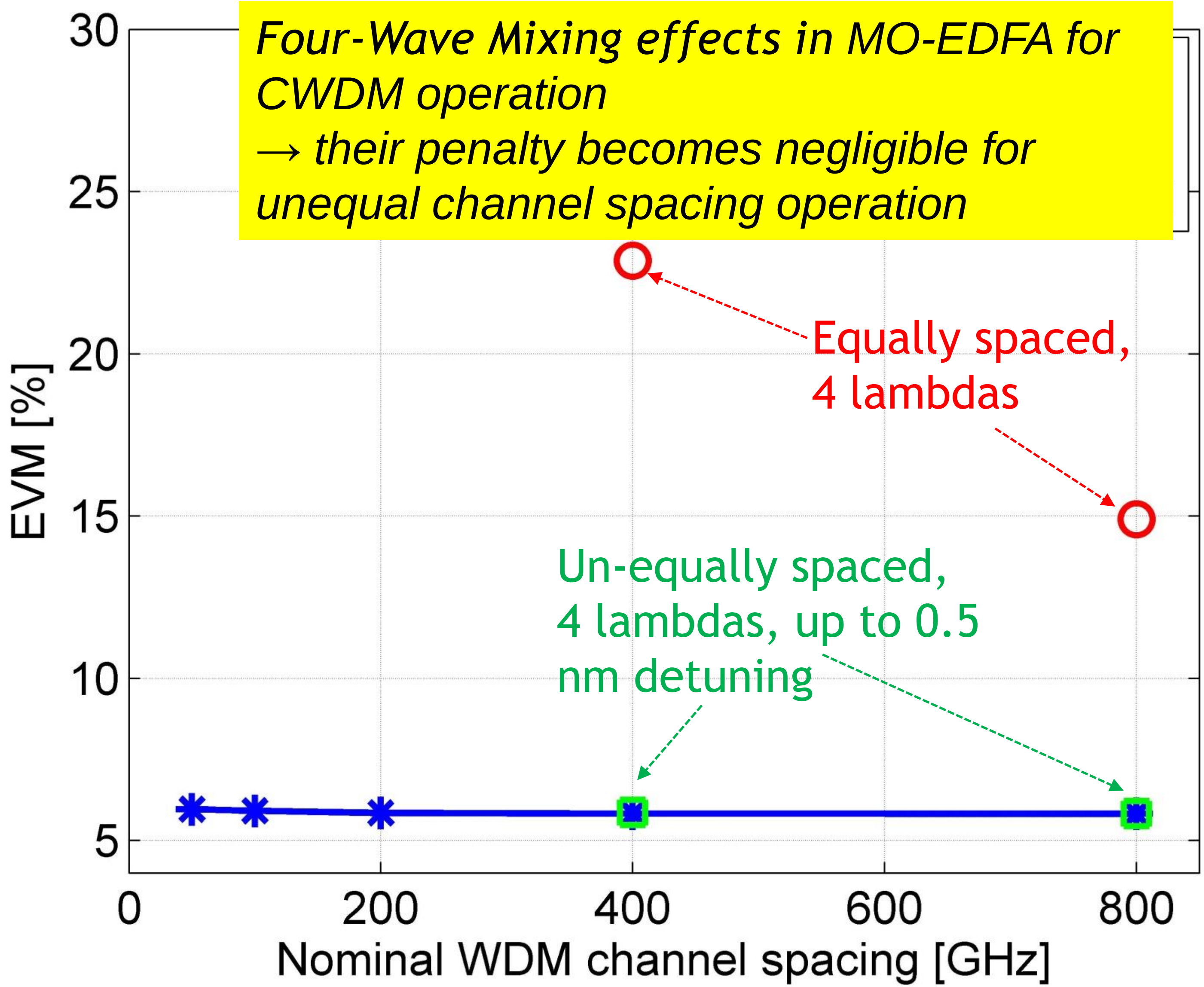
Four equally spaced λs @400GHz

- *1547.711 nm*
- *1550.918 nm*
- *1554.125 nm*
- *1557.332 nm*

Four unequally spaced λs

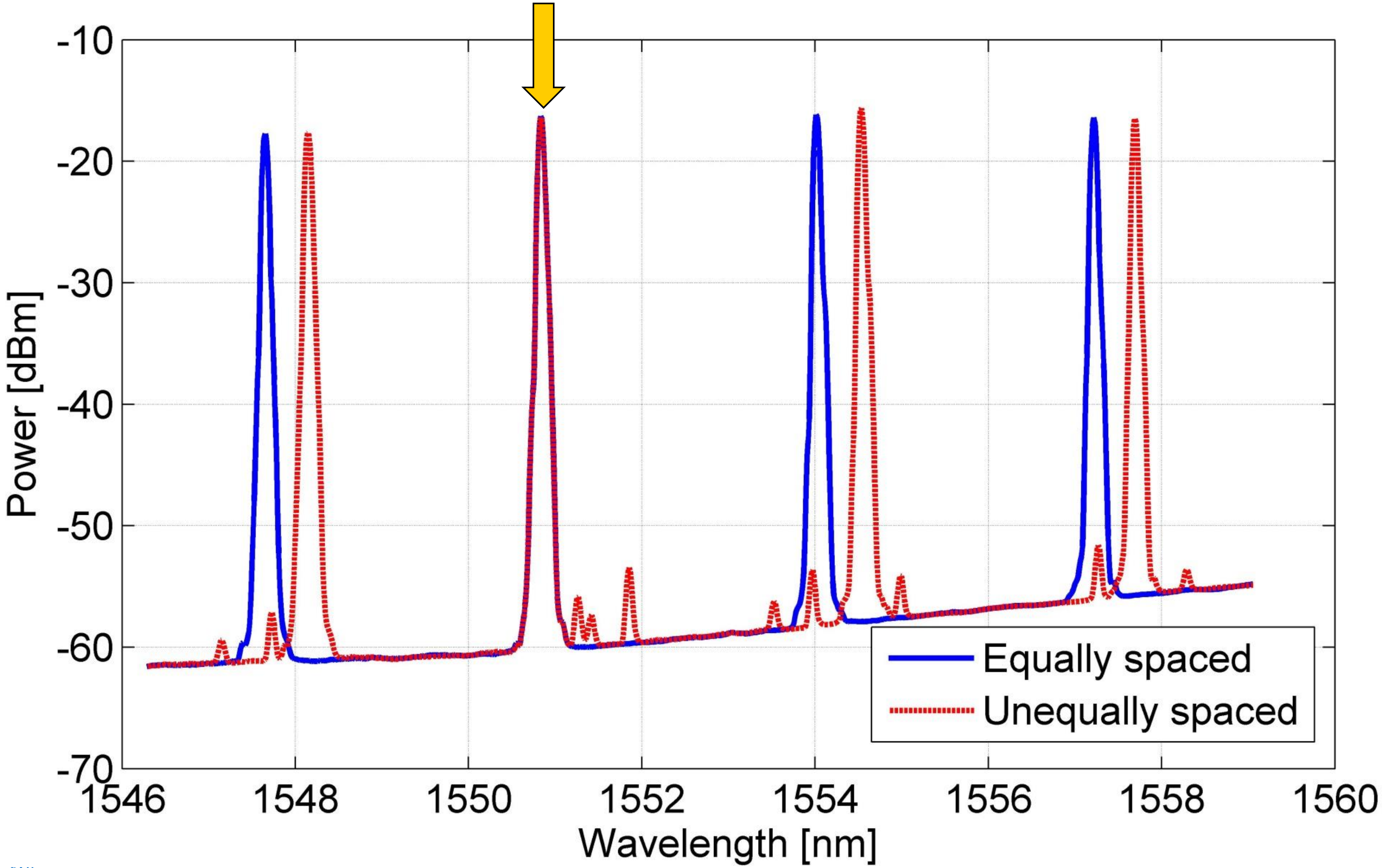
- *1548.211 nm*
- *1550.918 nm*
- *1554.625 nm*
- *1557.832 nm*

Four-Wave Mixing effects in MO-EDFA for CWDM operation
→ their penalty becomes negligible for unequal channel spacing operation

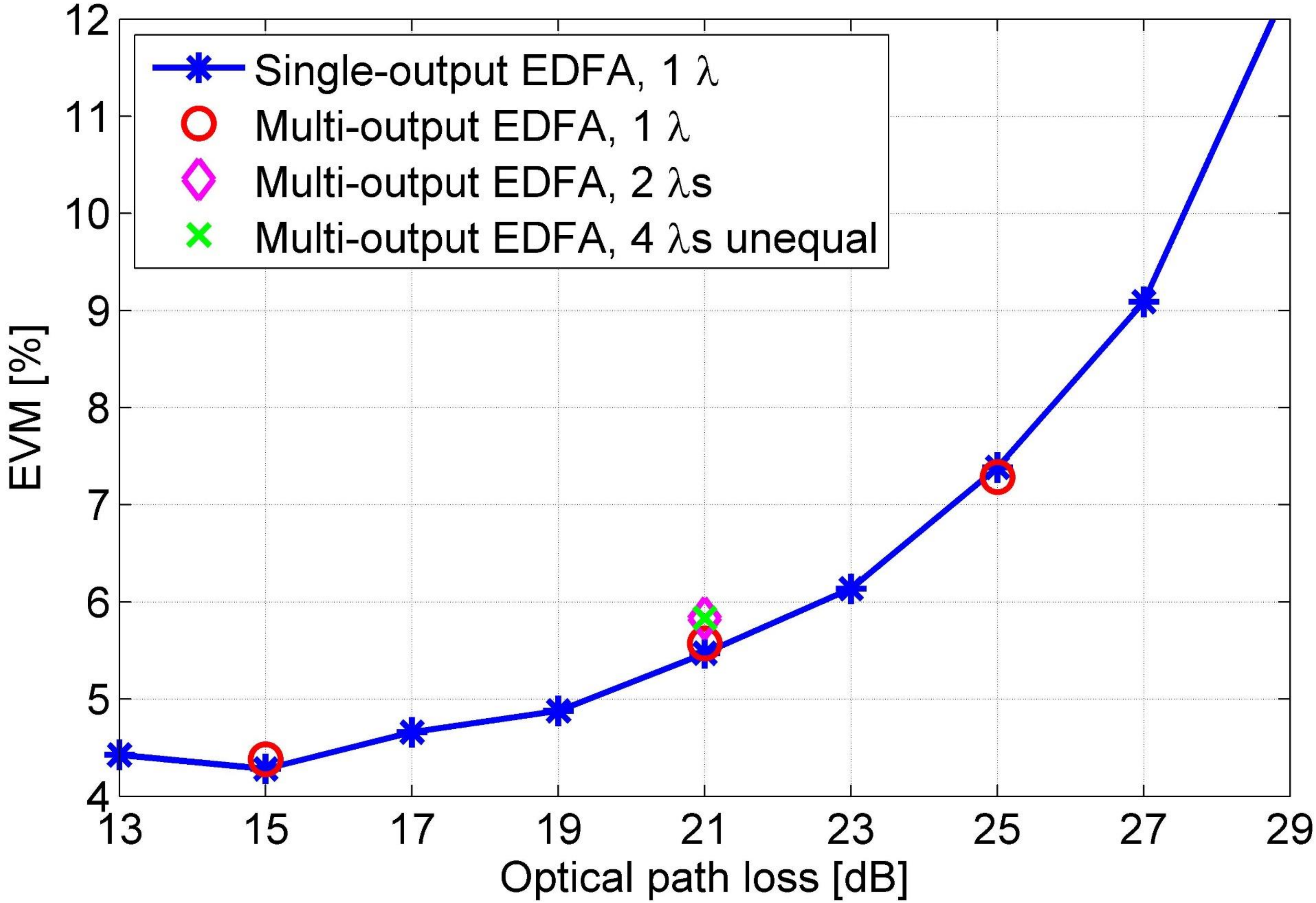


WDM spectrum at MC-EDFA output
Δf = 400GHz

Measured wavelength
at 1550.92 nm



Using up to four wavelenghts



Conclusions

- We proposed a new architecture to deliver massive DSP-aggregated FDMA fronthauling taking advantage of MO-EDFA
  - For WDM operation, nonlinear effect in MO-EDFA requires unequal WDM channel spacing
- We were able to deliver 4x192 radio waveforms to up to 24 different RRHs
  - The total bit rate that would be required using CPRI would be around 944 Gbit/s

Up to 4x192 LTE-A Radio Waveforms Transmission in a Point to Multipoint architecture for Massive Fronthauling Solutions

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[3] Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino (TO), Italy, roberto.gaudino@polito.it

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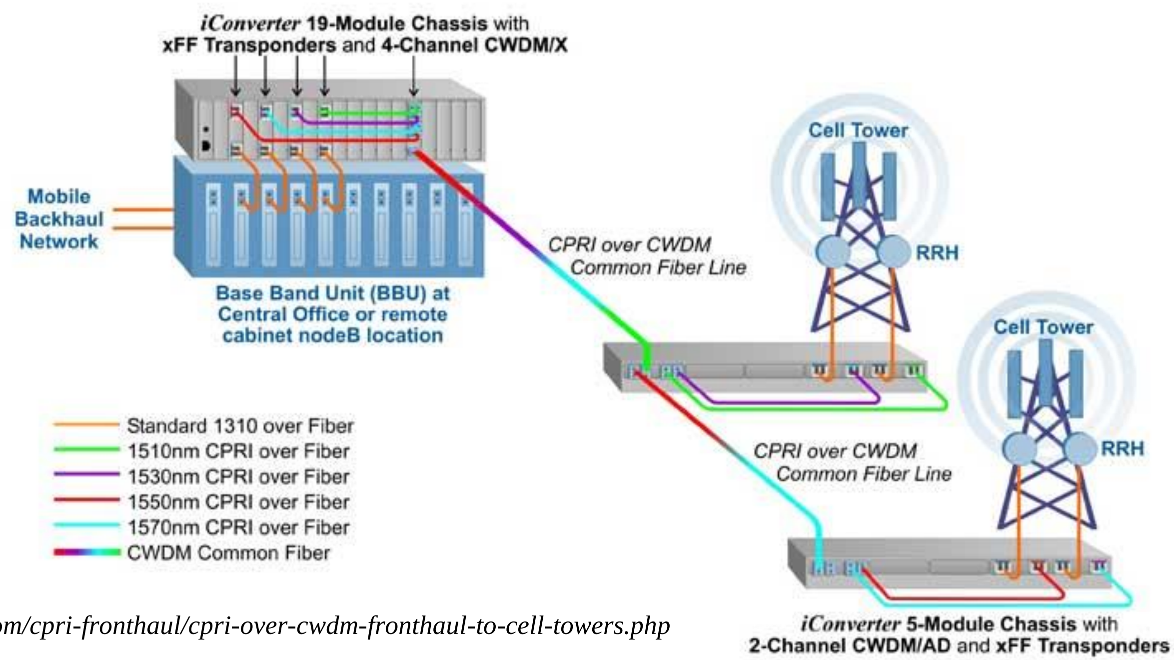
BACK-UP SLIDES

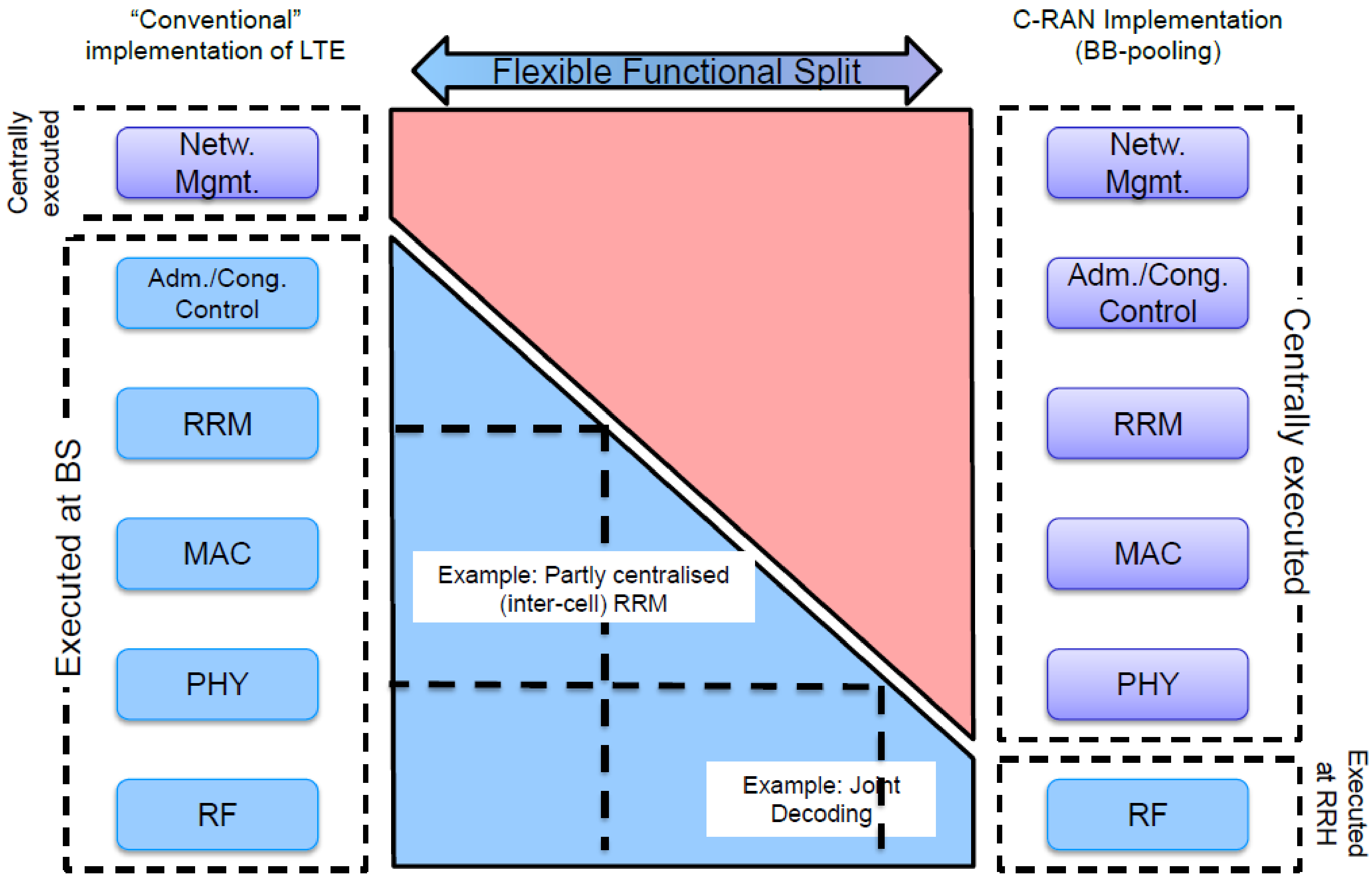
Fronthauling evolution

- The example given in the previous slide may be relevant in a few year…
- … but even today (December 2016) there are already installations using CPRI-based fronthauling which requires several links in parallel at 10 Gbps
  - There are commercial products available today using CPRI on Coarse-WDM



http://www.omnitron-systems.com/cpri-fronthaul/cpri-over-cwdm-fronthaul-to-cell-towers.php

Functional-split architecture



Picture taken from:

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Structure of the LTE radio signal

- LTE is a very complex standard, but in a nutshell each radio signal is as follows:
  - 20 MHz used band “per channel” (for the highest rates)
    - Currently (2016) it is more common to have 5 MHz per channel
  - DAC and ADC running at 30.72 Msamples/s
  - OFDM using 2048 points, up to 64-QAM for higher rates
    - Some carriers are not used for better spectral shaping

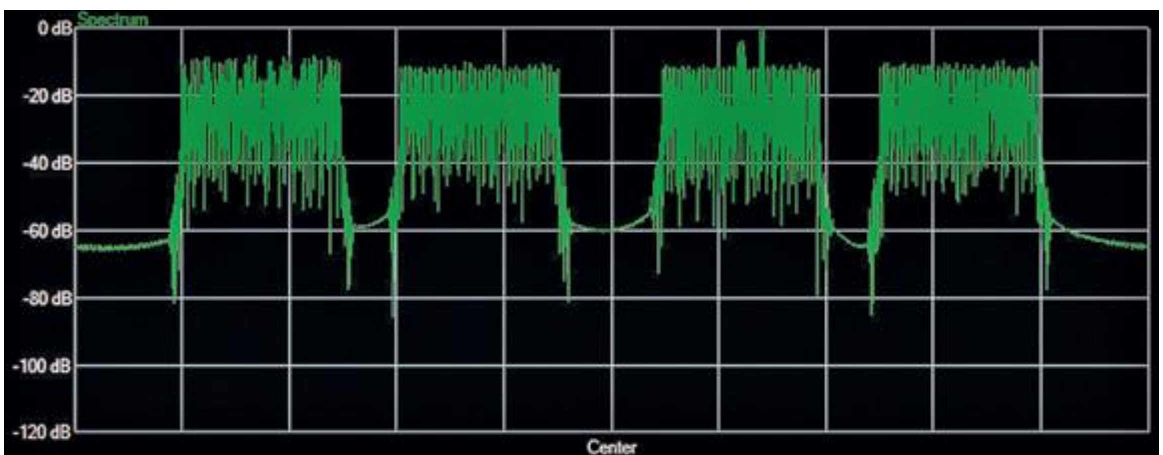


Fig 3. The spectrum of the LTE-Advanced configuration includes four non-contiguous 20-MHz carriers http://electronicdesign.com/4g/wireless-companies-follow-roadmap-past-4g-and-5g

Structure of the LTE radio signal

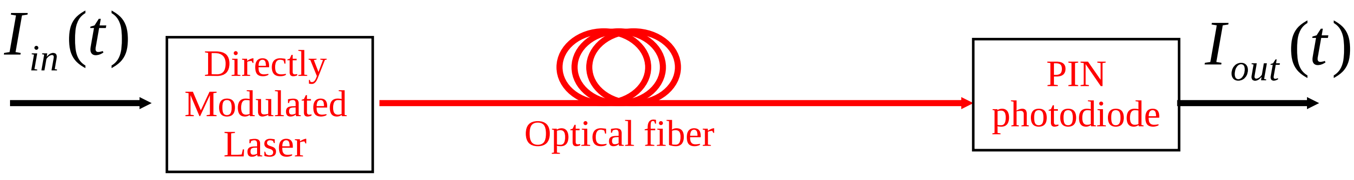
- The OFDM subcarrier are thus spaced 15KHz
  - (=30.72 MHZ/2014 FFT points)

- The peak radio bit rate (using 64-QAM) is of the order of:
  - 20 MHz x 6 Bit/s/Hz = 120 Mbit/s gross (about 100 Mbit/s net)

- Typically, MIMO will be used at the antenna site
  - Up to 4x4 MIMO expected for LTE-advanced
  - May grows to even higher NxM MIMO in 5G

Two key observations

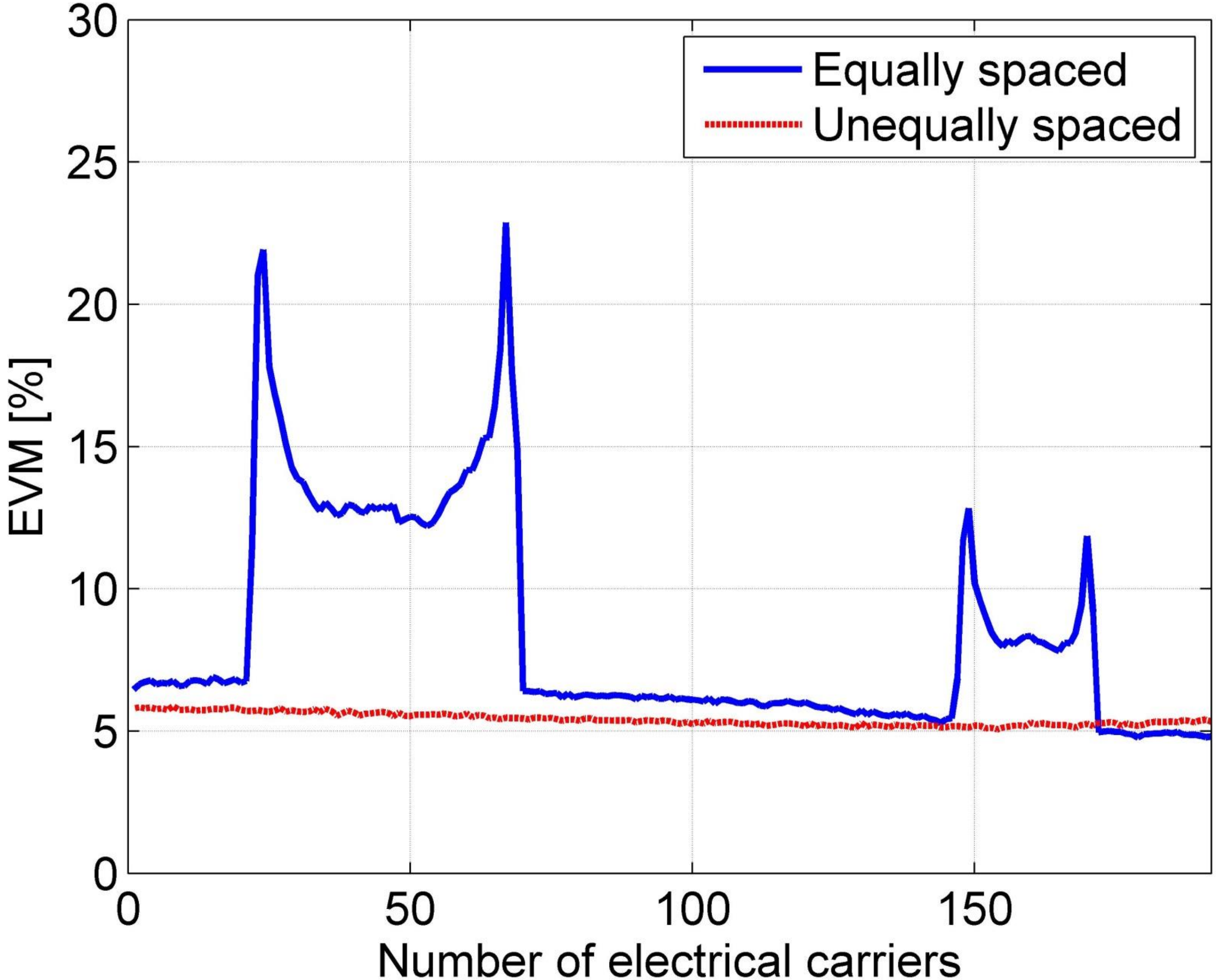
- We briefly mentioned when talking about CATV that a direct-detection optical link can in principle carry any analog electrical signal



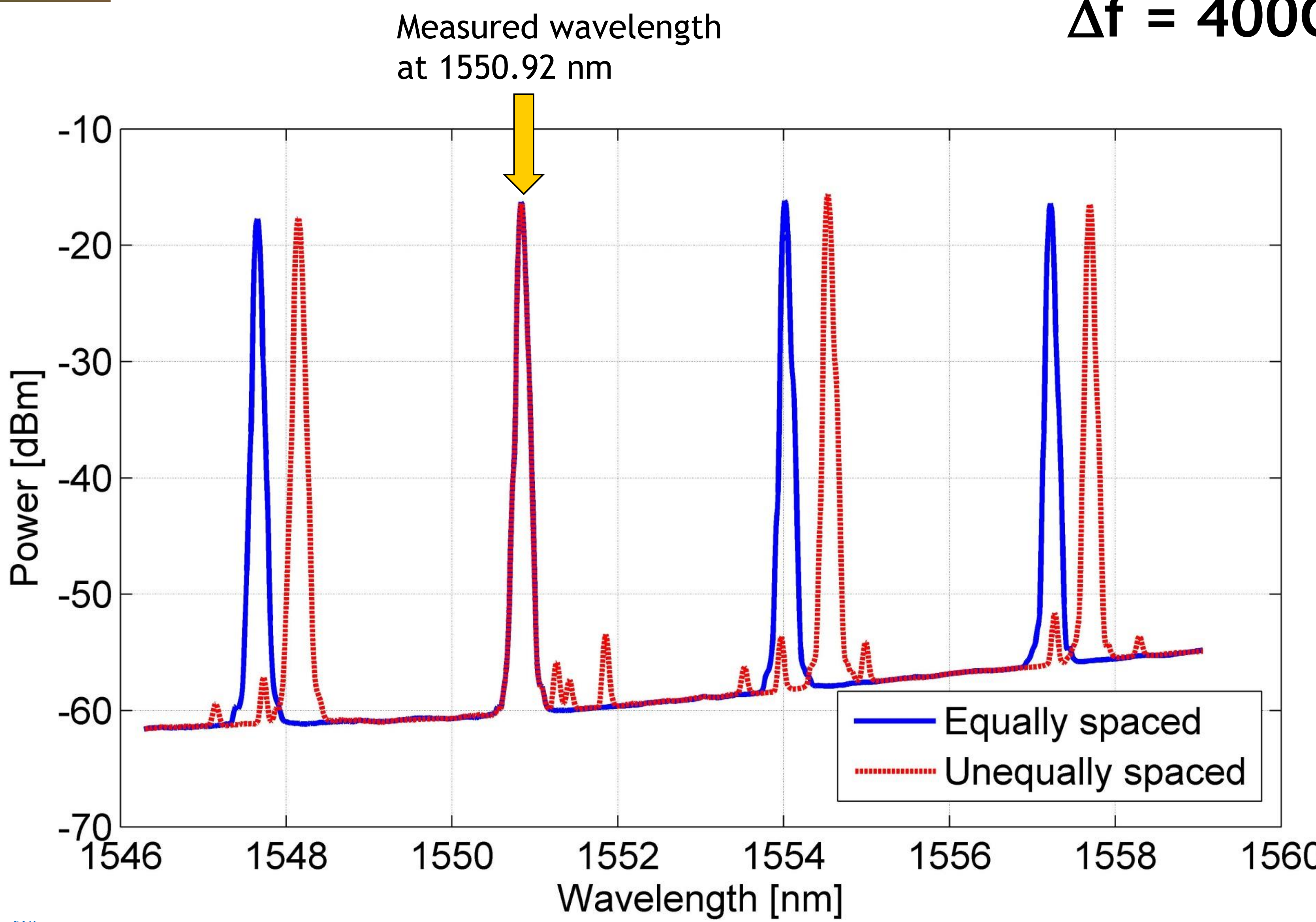
$$I_{out}(t) = k \cdot I_{in}(t) + I_{offset}$$

- In DSP-aggregated fronthauling, many LTE radio waveforms are <u>frequency-division multiplexed</u> in the electrical domain, and then sent on an “analog optical link”

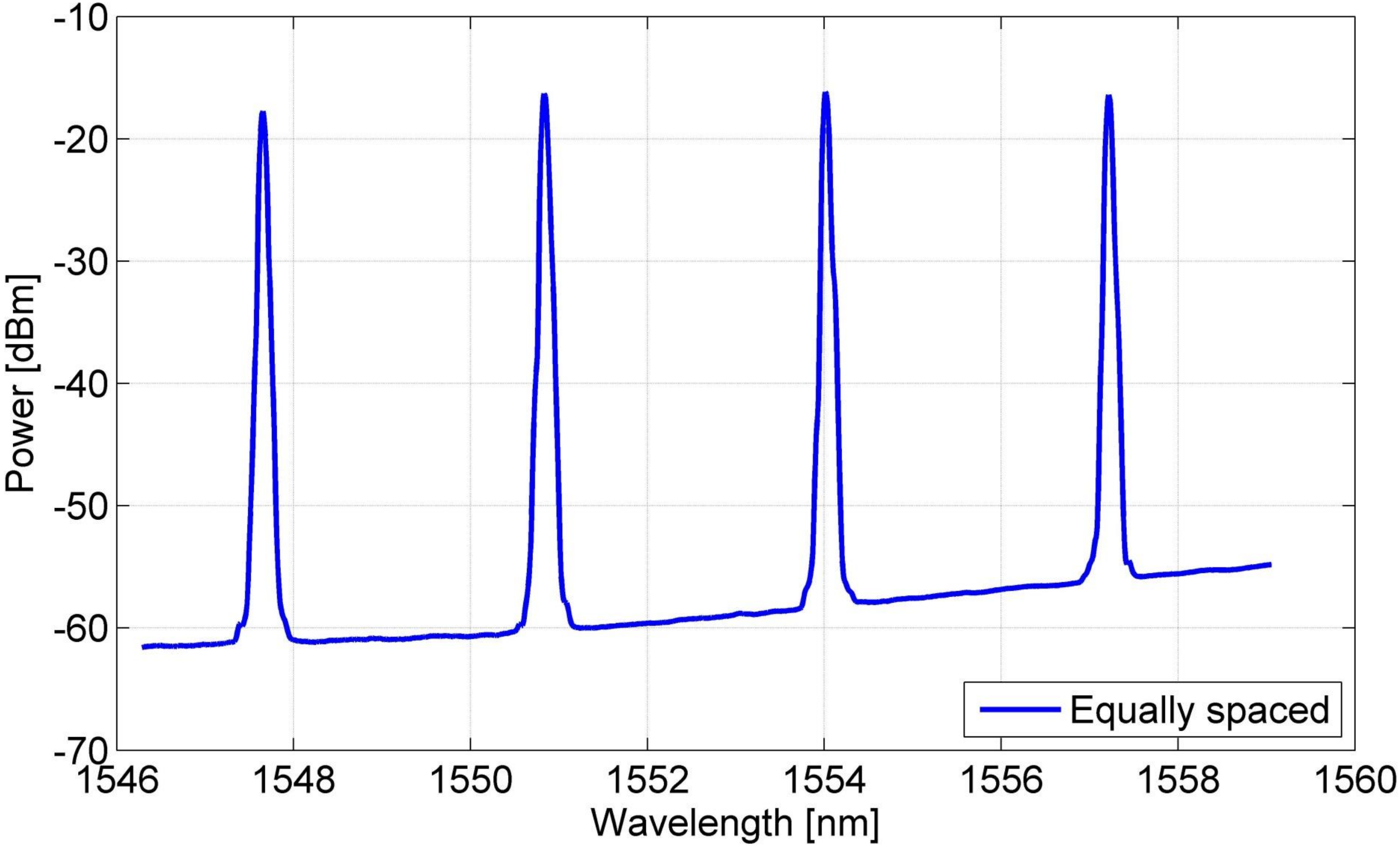
Multi-output EDFA, WDM 100GHz, OSNR 21dB



WDM spectrum at MC-EDFA output
Δf = 400GHz



WDM spectrum at MC-EDFA output
Δf = 400GHz



WDM spectrum at MC-EDFA output
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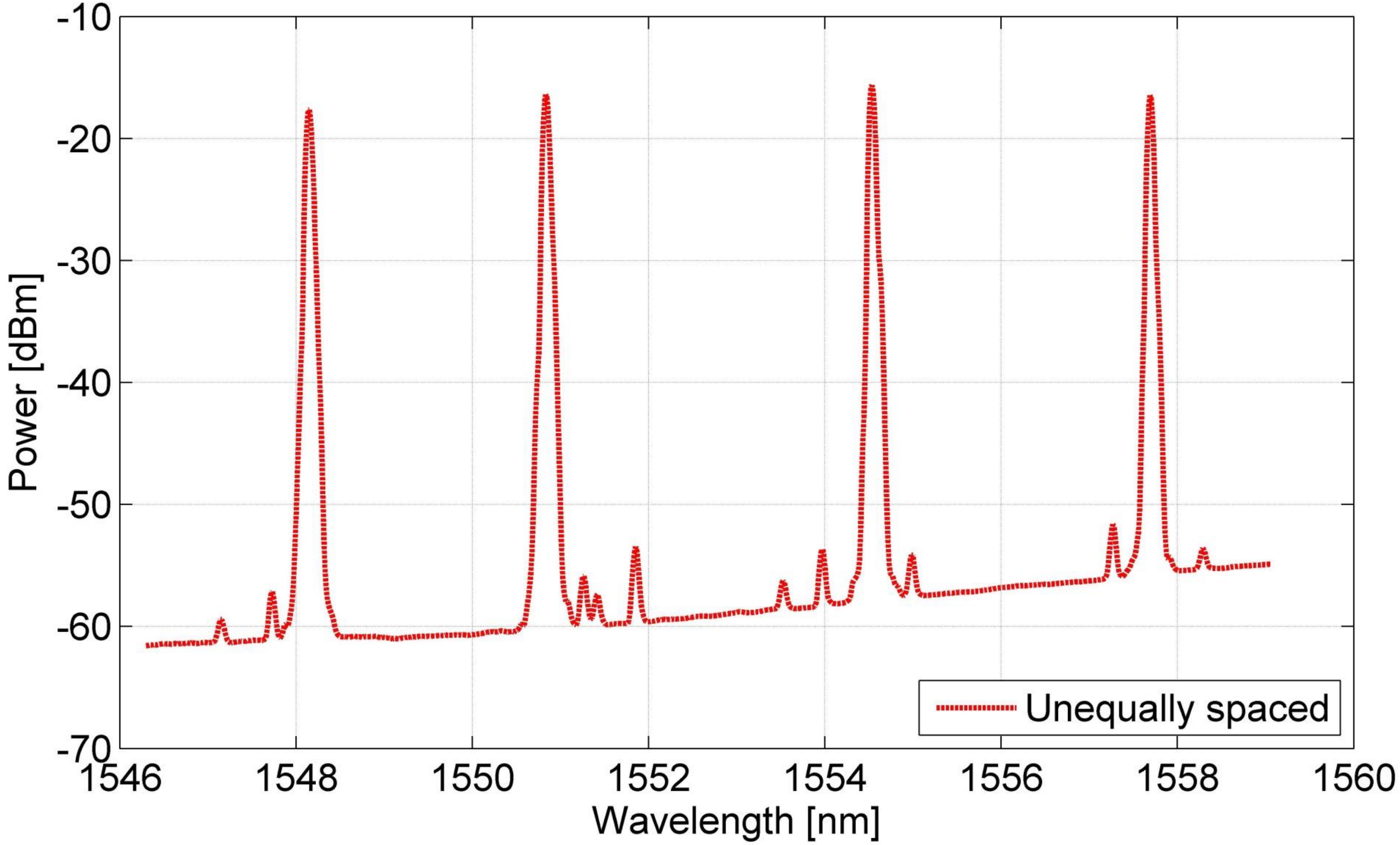

Acnowledgments

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- We also would like to thank Tektronix for lending us the instruments