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

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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

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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**

- Traditional mobile networks implement most of the “wireless-related” protocol in the base stations, that are located at the antenna sites.
- **Backhaul**: 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

Baseband units (BBU) pools at Central Office

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

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

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

Base Station

- RF TX
- RF RX
- Antenna
- Radio-frequency analog electronics

Central office

- Optical fiber link
- Transport of information as IP packets

Physical Layer protocol
(intensive DSP in LTE-Advanced, 5G)

Network layer interface

Gigabit Ethernet optical cards

This layer 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.
«Zooming in» at the physical layer

Physical Layer DSP

Network layer interface

Very high speed bit rate transfer at this interface

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

- $30.72 \text{ Msamples/s} \times 2 \times 15 = \textbf{921.6 Mbit/s}$
The new vision: Digitized Radio over Fiber (DRoF)

- **I/Q modulator**
- **RF local oscillators**
- **I/Q demod**
- **I/Q modulator**
- **RF local oscillators**
- **I/Q demod**
- **Optical fiber link** (usually P2P but it can also be PON)

Remote Radio Head (RRH)

Baseband Unit (BBU)
- **CPRI transceiver**
- **Physical Layer DSP**
- **Network layer interface**

Central office

Bit rates in the Gbps range at this interface

Very thin framing protocol (such as CPRI)

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
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

- 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
**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
Towards a Flexible Functional Split for Cloud-RAN Networks

Resulting bit rates

Bandwidth and latency demands

Split A
- A/D conversion / pre-processing
- Lower PHY (incl. DET)
- Upper PHY (incl. FEC)
- MAC (incl. MUX, HARQ)
- RLC (RB buffers, ARQ)
- PDCP (ciphering)
- RRC/C-Plane
- EPC

Split D
- Radio Access Point

Downlink
20MHz; 2x2 MIMO

1.8Gbps; 5μs

470Mbps; ~1 ms

100Mbps; ~3 ms

70Mbps; ~100 ms

70Mbps; ~3 ms

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AN ALTERNATIVE APPROACH:

DSP-AGGREGATED FDMA-BASED FRONTHAULING
Aggregation by FDM - functional schematic

Spectrum for LTE signal (complex envelope)

\[ G_1(f) \]

Frequency up-conversion around \( f_1 \)

Spectrum for LTE signal (complex envelope)

\[ G_2(f) \]

Frequency up-conversion around \( f_2 \)

Spectrum for LTE signal (complex envelope)

\[ G_N(f) \]

Frequency up-conversion around \( f_N \)

\[ \sum \]

Electrical FDM aggregated signal

\[ f_1 \quad f_2 \quad \cdots \quad f_N \]
Aggregation by FDM - functional schematic

Electrical FDM aggregated signal

$G_{FDM}(f)$

Directly Modulated Laser

$I_{in}(t)$

Optical Fiber

PIN photodiode

$I_{out}(t)$

Radio over Fiber link

Electrical domain

FDM De-aggregation

Electrical domain

Spectrum for LTE signal
(complex envelope)

$G_1(f)$

#1

$G_N(f)$

#N
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.

Equivalent implementation by Digital Signal Processing (DSP)
Each of these “slices” is a LTE 20 MHz OFDM signal.
The DSP-aggregation principle

Digitized Time-Domain complex envelopes for $K$ LTE signals

Time domain $\tilde{x}_1[i]$, $\tilde{x}_2[i]$, $\ldots$, $\tilde{x}_K[i]$

\[ N=16 \text{ points FFT} \]

Frequency domain $\tilde{X}_1[i]$, $\tilde{X}_2[i]$, $\tilde{X}_K[i]$

\[ M = 2 \cdot K \cdot N \]

Vector

Complex conjugates $\tilde{X}_1[i]$, $\tilde{X}_2[i]$, $\tilde{X}_K[i]$

\[ f_1, f_2 \to f_k \]

IFFT

\[ M = 2 \cdot K \cdot N \]

Time domain $x_{FDM}[i]$
Variants of this architecture are under consideration in ITU-T FSAN

- Recommendation ITU-T G.RoF

**Series G**

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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.
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 $48 \times 1.23\,\text{Gbit/s} \approx 60\,\text{Gbit/s}$.

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
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

96 LTE-like channels

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

Our presentation at ECOC 2016 - Dusseldorf

ODN loss range compliant with ITU-T PON specs
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
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

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Legend:
- BBU: Base-Band Units
- RRH: Remote Radio Head
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- DSP-A: DSP Aggregator
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- ODN: Optical Distribution Network
Multi-lambda CWDM version

- $M$ wavelengths
- $K$ radio waveform per wavelength
- $N$ MO-EDFA outputs

In our experiments:
- $M=4$ wavelengths
- $K=192$ radio waveforms per wavelength
- $N=24$ RRHs
Using a tunable optical filter and proper DSP-de-aggregation, each of the $N$ RRH can select an arbitrary subset of the $M \times K$ 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

EVM = 8%

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

- Equally spaced, 4 lambdas
- Un-equally spaced, 4 lambdas, up to 0.5 nm detuning
WDM spectrum at MC-EDFA output

$\Delta f = 400\text{GHz}$

Measured wavelength at 1550.92 nm
Using up to four wavelengths

- Single-output EDFA, 1 λ
- Multi-output EDFA, 1 λ
- Multi-output EDFA, 2 λs
- Multi-output EDFA, 4 λs unequal

EVM [%] vs. Optical path loss [dB]
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
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BACK-UP SLIDES
The example given in the previous slide may be relevant in a few years...

... 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

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

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

\[
I_{out}(t) = k \cdot I_{in}(t) + I_{offset}
\]
Multi-output EDFA, WDM 400GHz, ODN = 21dB
WDM spectrum at MC-EDFA output
\[ \Delta f = 400\text{GHz} \]

Measured wavelength at 1550.92 nm
WDM spectrum at MC-EDFA output
\( \Delta f = 400\text{GHz} \)
WDM spectrum at MC-EDFA output
\[ \Delta f = 400\text{GHz} \]
This work was a joint effort between POLITO and ISMB

As mentioned in the introduction, the first part of this research was sponsored by CISCO Photonics in 2015

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