GTTI Annual Meeting 2019
June 27th 2019, Pavia

POLITECNICO DI MILANO





Interference Mitigation Techniques in Hybrid Wired-Wireless Communications Systems for Cloud Radio Access Networks with Analog Fronthauling

Andrea Matera

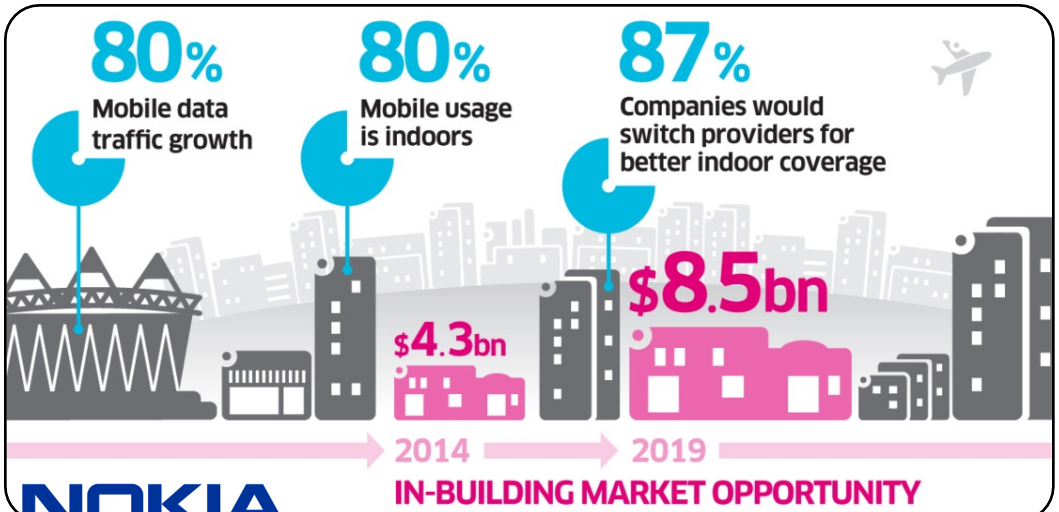
Advisor: Prof. Umberto Spagnolini

Ph.D. in Information Technology
Politecnico di Milano, Dipartimento di Elettronica Informazione e Bioingegneria (DEIB)

Indoor Coverage : a Major Challenge for 5G New Radio

2020 forecast CISCO

On the Go	Hotspot	Work	Home
4%	11%	35%	50%



5G calls for **low-latency**, **bandwidth-efficient** and **cost-effective** transport solutions to cope with:

- **massive number of users**/antennas/cells
- **challenging interference scenarios**

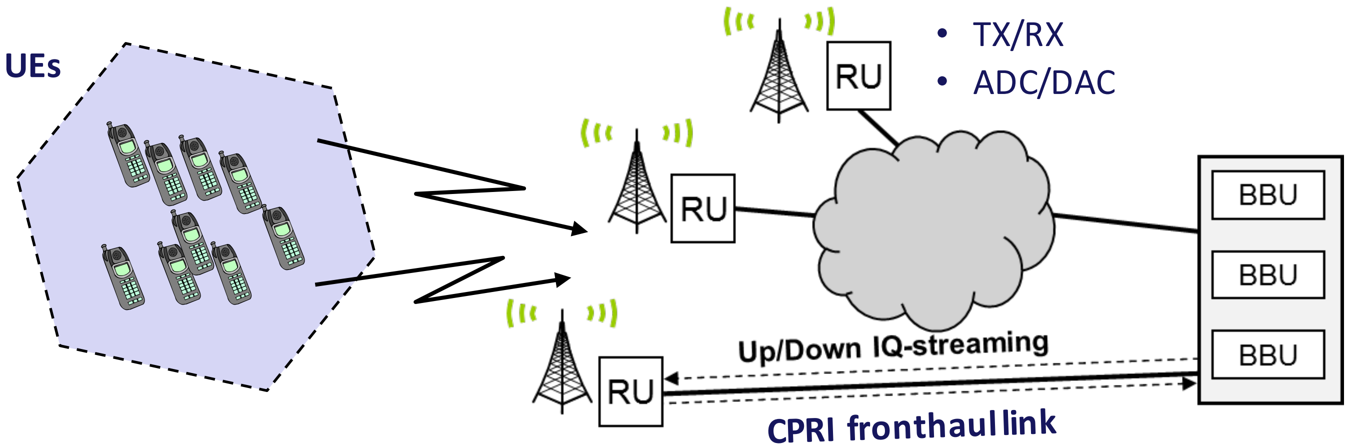
Huawei LampSite 3.0

Nokia Flexi-Zone

Ericsson Radio Dot

ERICSSON

Cloud Radio Access Networks: the *4G*-to-*5G* Transition



Remote Antenna Unit:
- TX/RX
- ADC/DAC

BaseBand Unit Pool:
- Centralized baseband signal processing
- *Cooperative MultiPoint (CoMP)* techniques (interference mitigation)

Digital IQ-streaming (CPRI), bandwidth requirements:

$$R_{CPRI} = \underbrace{B_w}_{\text{Channel bandwidth}} \times \underbrace{2 \cdot 16}_{\text{Bits resolution per IQ sample}} \times \underbrace{N_{RAU}}_{\text{Number of RAU antennas}}$$

✓ 4G Settings

$B_w = 20\ MHz$, 64-QAM, 4×2 MIMO, 1 UE:
- Air-link data-rate: $\mathbf{240\ Mbps}$
- Digital IQ-streaming (CPRI): $\mathbf{6.4\ Gbps}$

✗ 5G Settings

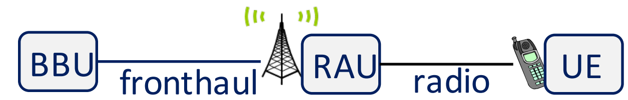
$B_w = 100\ MHz$, 256-QAM, 64×2 MIMO, 9 UE:
- Air-link data-rate: $\mathbf{15\ Gbps}$
- Digital IQ-streaming (CPRI): $\mathbf{256\ Gbps}$!!!

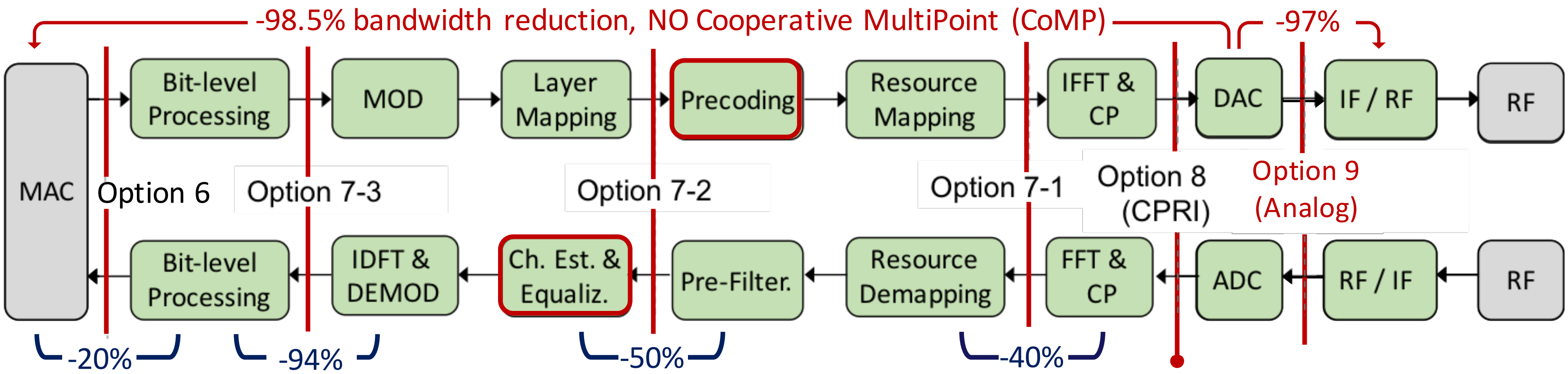
5G RAN Functional Split Options & Analog Fronthauling

Centralized BBU processing | *Local* RAU processing

✓ relaxed bandwidth requirements | X tight bandwidth requirements

X poor Cooperative MultiPoint (CoMP) | ✓ good Cooperative MultiPoint (CoMP)





-20%
✓ MAC payload (e.g., no channel coding)
X no full CoMP

-94%
✓ rate scales with N_{UE} and *not* with $N_{RAU} \gg N_{UE}$
X no full CoMP

-50%
✓ unused RBs removal
X no full CoMP

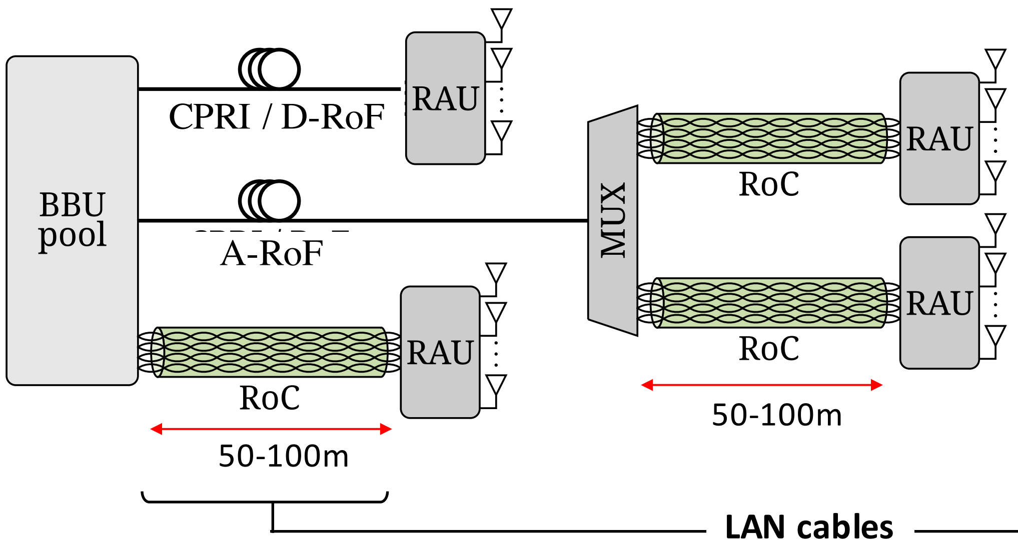
-40%
✓ CP and guard subcarrier removal
✓ full CoMP

✓ full CoMP
X prohibitive rate requir.

Option 9 - Analog Fronthauling

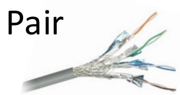
- ✓ allow for **full Cooperative MultiPoint (CoMP)** techniques;
- ✓ **relaxed bandwidth constraints** (i.e., no digitalization at RAU, no ×32 bandwidth expansion)
- ✓ **ultra low-latency** (i.e., up to signal propagation only, no DSP at the RAU)
- ✓ **RAUs are all-analog, cheap and simple** (only up/down conversion and amplification)

The Analog MIMO Radio-over-Copper (RoC) Paradigm



- **Cat-5e:** Unshielded Twisted Pair (UTP)

- **Cat-6/6a:** Shielded Twisted Pair (STP)



- **Cat-7/7a:** STP with foiling over each individual twisted pair

	Digital RoF (CPRI)	Analog RoF	RoC
Bandwidth	$\times 18 - 30$	$\times 1$	$\times 1$
Latency (5G: $<$ 1ms)	Low-medium ($\sim 100\mu s$)	Very Low (propagation only)	Very Low (propagation only)
Complexity of Components	High-speed electronics and optics	Low-speed electronics and optics	Low-speed electronics
Power Supply	External	External	Power Over Ethernet (PoE)
Infrastructural Cost	Very High (optic infrastructure)	Very High (optic infrastructure)	Very Low (pre-existing cables)

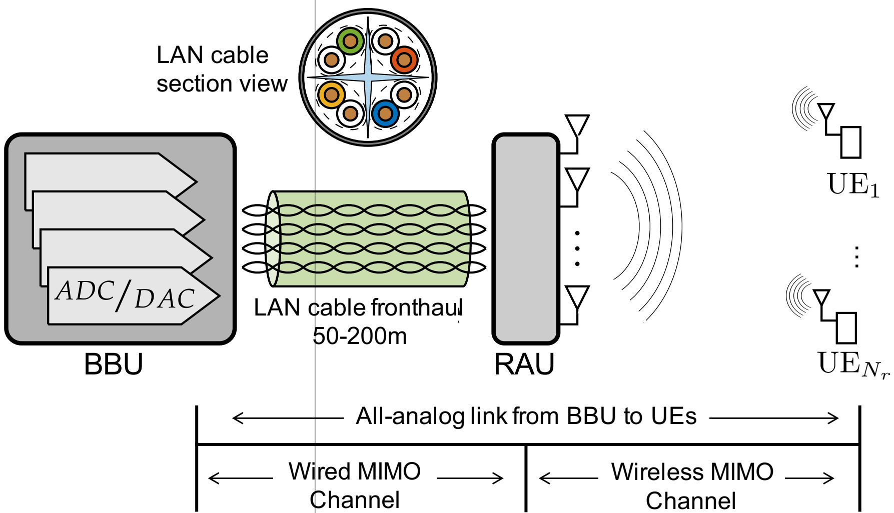
Analog MIMO-RoC for In-Building Solutions

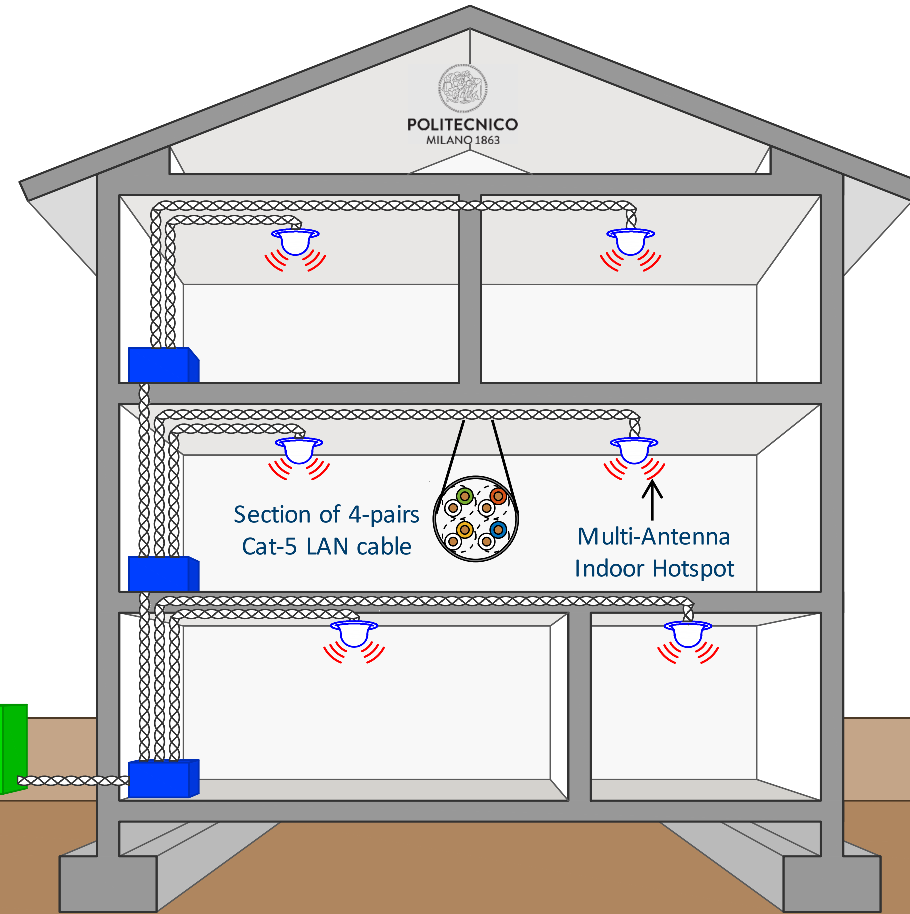
All-analog copper link (50-200m) from BBU to the antennas:

- ✓ no bandwidth expansion
- ✓ low latency

Multi-Pair Cat 5/6/7 cables (already deployed in buildings):

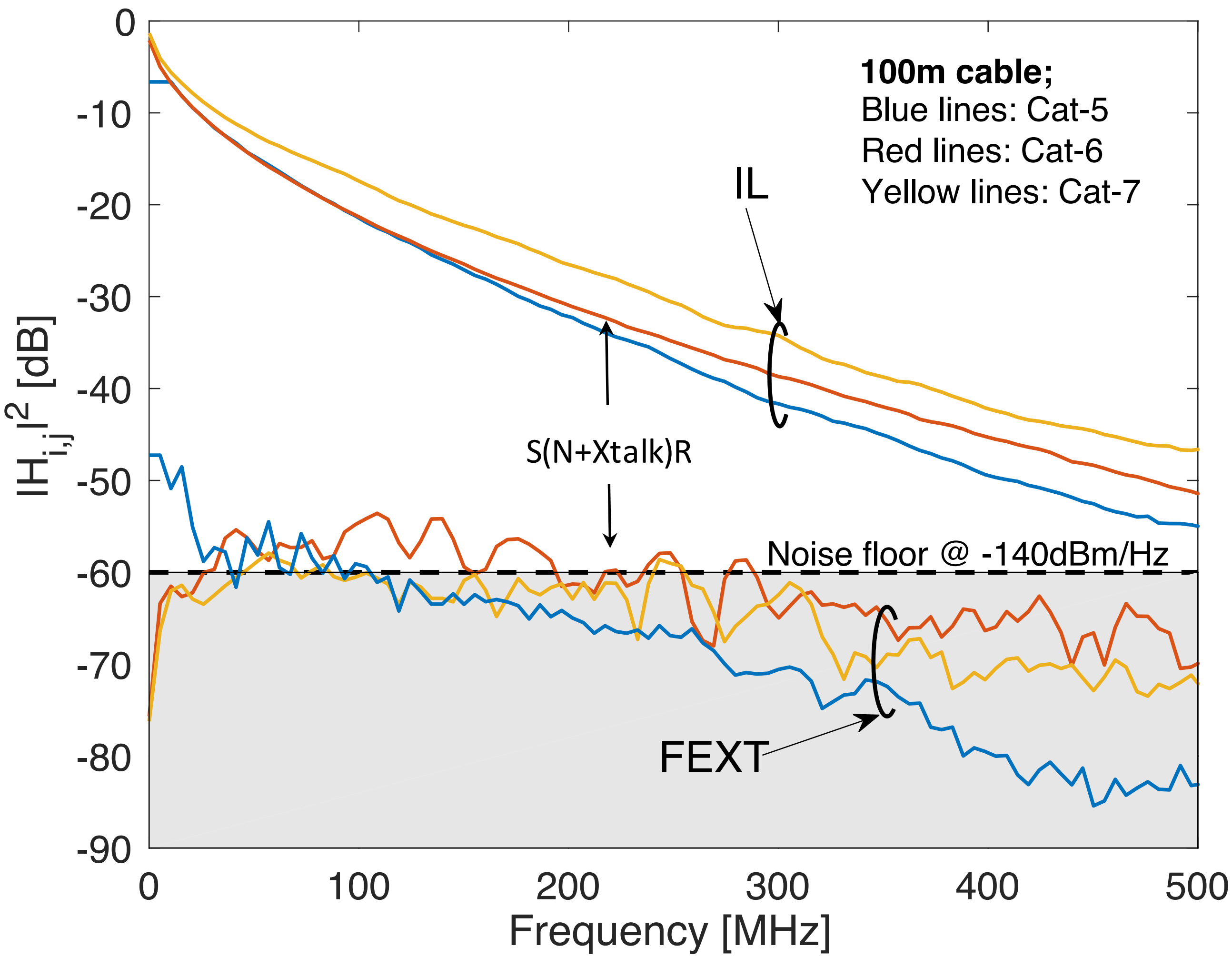
- ✓ No extra infrastructure cost
- ✓ 4 twisted pair channels with up to 1GHz bandwidth/ea.
- ✓ Power Over Ethernet (PoE)





Base Band Processing: enhanced interference managment

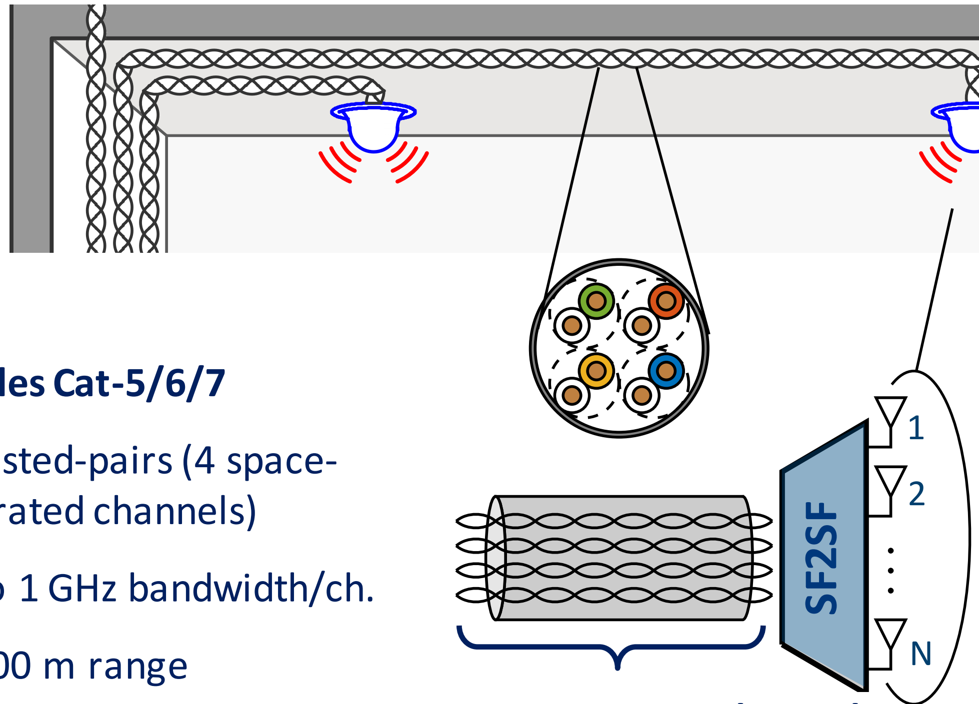
LAN Cables Transport Capability for Analog MIMO-RoC



- ✓ Up to **10 Gbps** air-link data-rate
- ✓ Capable to serve up to **60 RAU antennas** (20-MHz LTE signal per antenna)

S. H. R. Naqvi, **A. Matera**, L. Combi and U. Spagnolini, *"On the Transport Capability of LAN Cables in All-Analog MIMO RoC Fronthaul"*, IEEE WCNC 2017, San Francisco

Space-Frequency to Space-Frequency Multiplexing



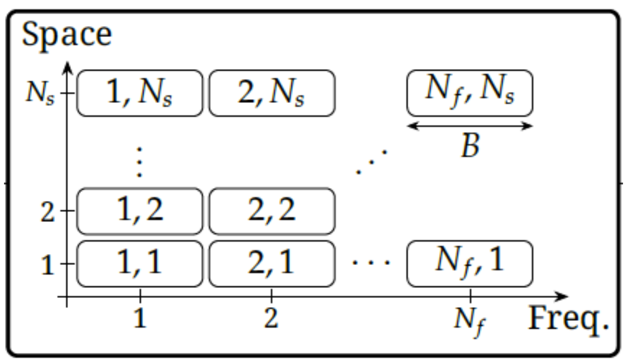
LAN cables Cat-5/6/7

- 4 Twisted-pairs (4 space-separated channels)
- Up to 1 GHz bandwidth/ch.
- 50-200 m range

Multi-Antenna RAU:

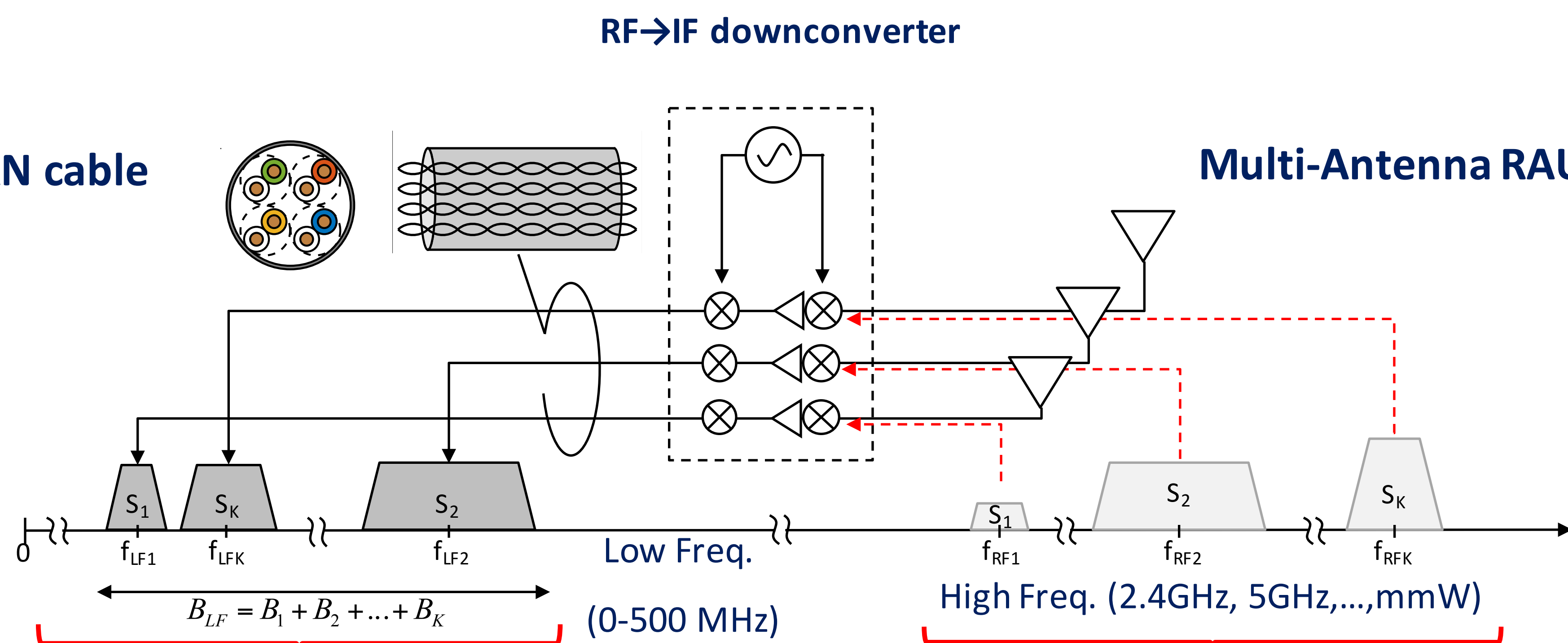
- # Antennas >> 10
- Multi-RAT (LTE+WiFi+5G)
- Cheap/simple/self-powered

Space-Frequency Channel



SF2SF: Mapping between the **Space/Frequency** dimensions of the air channel (**antennas/spectrum**) and the **Space/Frequency** dimensions of the copper cable (**pair/frequency**)

Space-Frequency to Space-Frequency: Principle

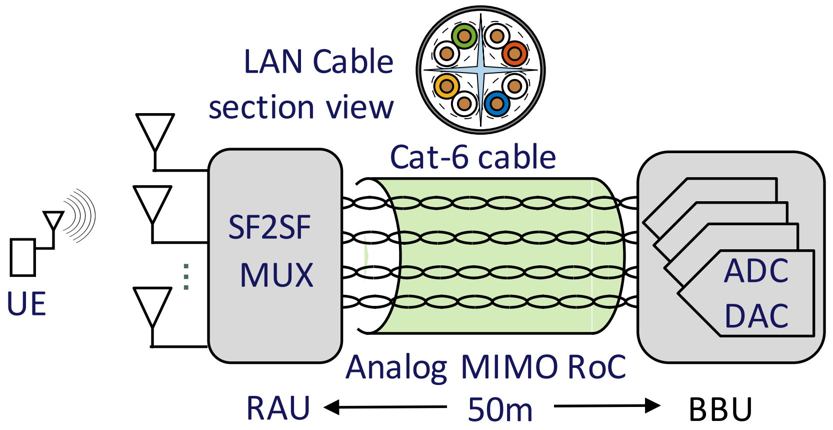


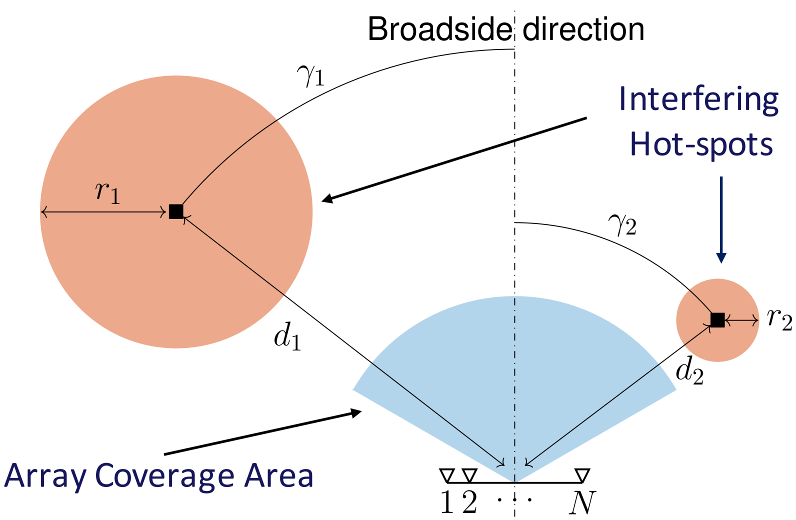
Air-link services mapped onto IF bands chosen to comply with cable attenuation & crosstalk

Air-link services

(RF bands)

A-MIMO-RoC Uplink: Outdoor Single-User Channel





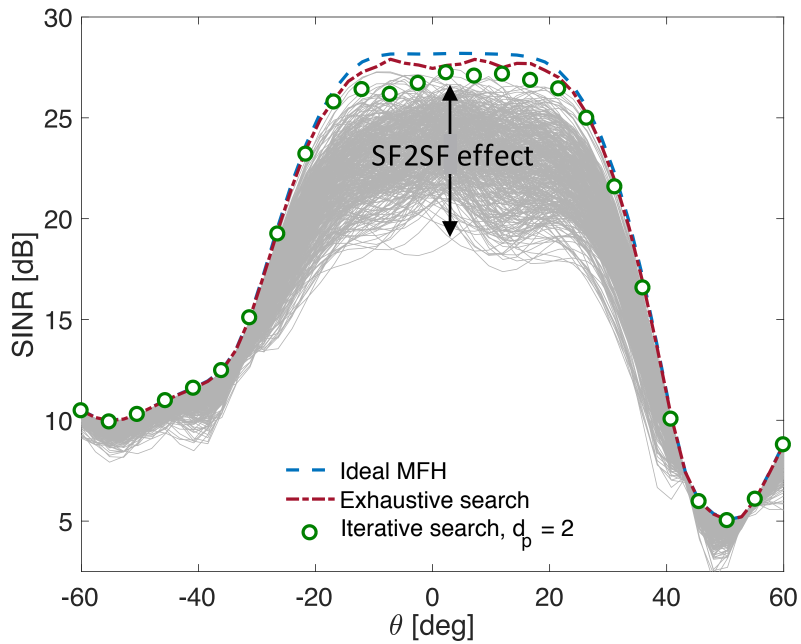
Simulation Parameters

Interferers: $r_1 = 100\text{m},\ d_1 = 250\text{m},\ \gamma_1 = -50^\circ$

$r_2 = 30\text{m},\ d_2 = 150\text{m},\ \gamma_2 = +50^\circ$

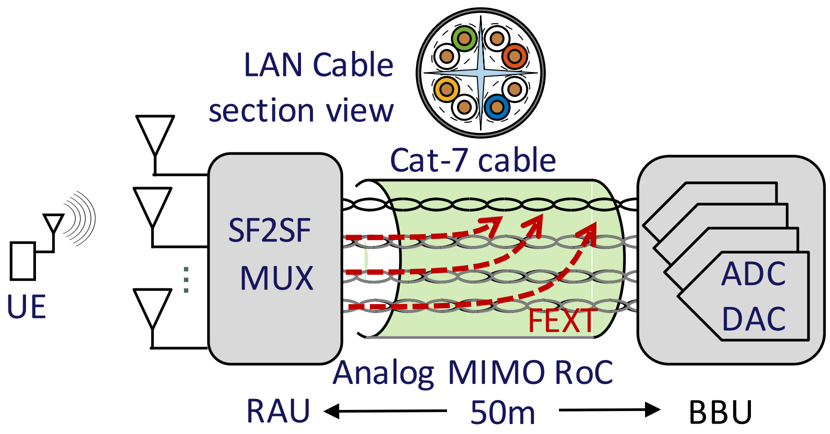
Radio Link SNR: $20\,\text{dB}$

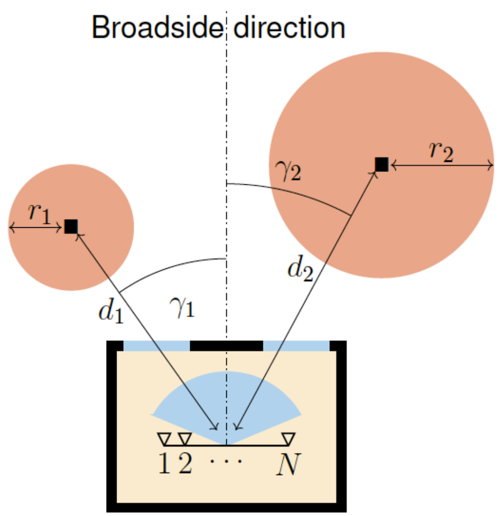
LAN Cable: 50m Cat-6, 1 GHz bandwidth



A. Matera, L. Combi, S. H. R. Naqvi, and U. Spagnolini, *“Space-Frequency to Space-Frequency for MIMO Radio over Copper”*, IEEE ICC 2017, Paris

A-MIMO-RoC Uplink: Indoor Single-Pair Single-User Channel



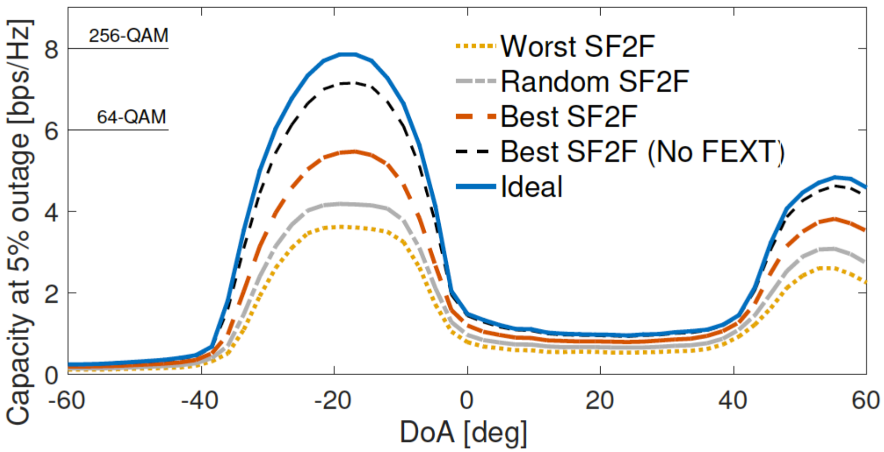


Simulation Parameters

Interferers: $r_1 = 50\text{m},\ d_1 = 125\text{m},\ \gamma_1 = -60\text{deg}$
$r_2 = 100\text{m},\ d_2 = 250\text{m},\ \gamma_2 = 20\text{deg}$

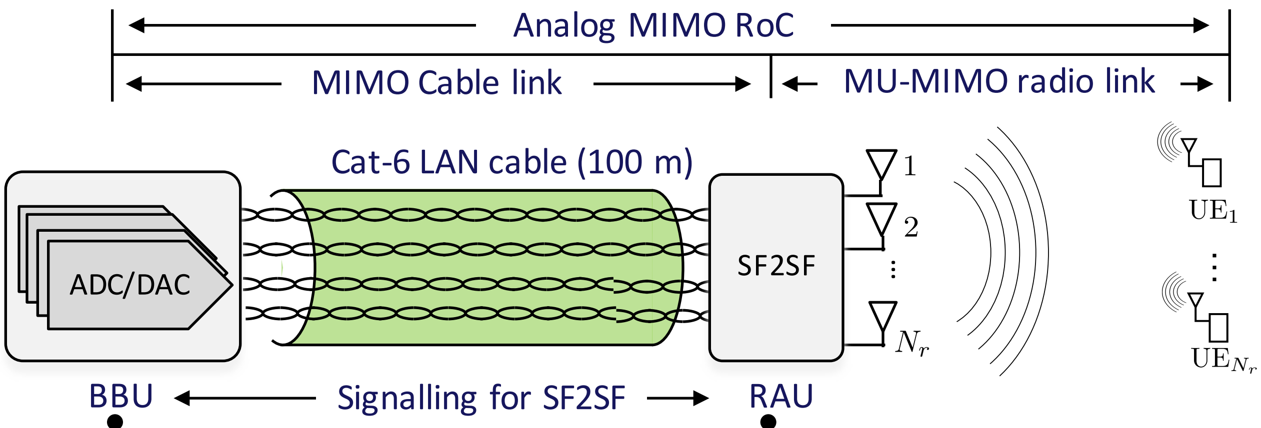
Radio Link SNR: $15\,\text{dB}$

LAN Cable: 50m Cat-7, 500 MHz bandwidth



A. Matera and U. Spagnolini, *"On the Optimal Space-Frequency to Frequency Mapping in Indoor Single-Pair RoC Fronthaul",* IEEE EuCNC 2017, Oulu, Finland

A-MIMO-RoC Downlink: Multi-User Case (1)



BBU Processing (Digital processing):

- ✓ Non-linear precoding optimization of the overall cascade wired-wireless channel;
- ✓ Per-line per-carrier and aggregated per-line power constraints at the cable input;
- ✓ *maximum min-rate* SF2SF optimization and signalling to RAU

RAU Processing (all-analog processing, low-latency, low-complexity):

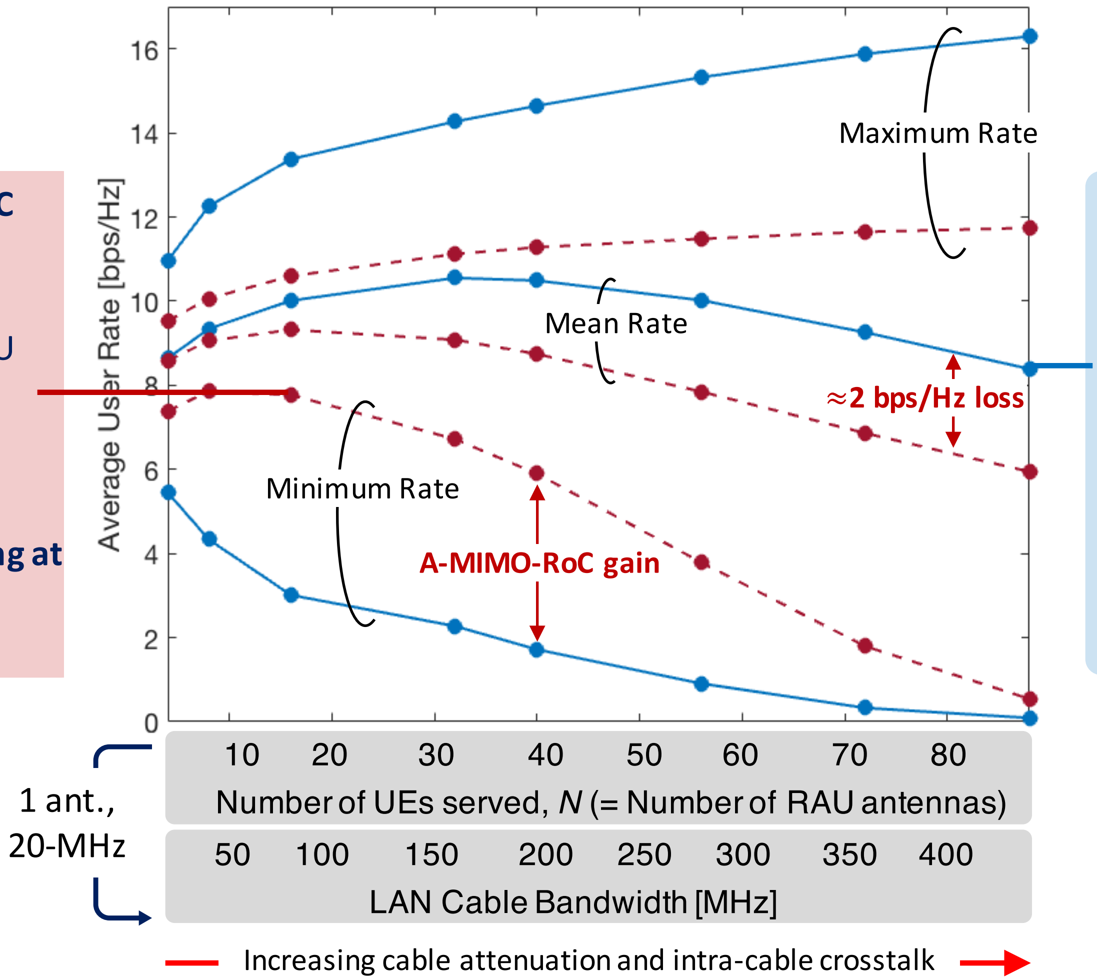
- ✓ SF2SF implementation
- ✓ Power amplification/scaling for the fulfillment of RAU power constraints
- ✓ Up/down-conversion, TX/RX
- ✓ User ordering optimization

A. Matera and U. Spagnolini, *"Analog MIMO Radio-over-Copper Downlink with Space-Frequency to Space-Frequency Multiplexing for Multi-User 5G Indoor Systems"*, in IEEE Transactions on Wireless Communications, 18 (5), 2813-2827

A-MIMO-RoC Downlink: Multi-User Case (2)

Proposed A-MIMO-RoC design:

- ✓ Digital non-linear precoding at the BBU (THP);
- ✓ User ordering optimization;
- ✓ **All-analog processing at the RAU (SF2SF and power scaling)**



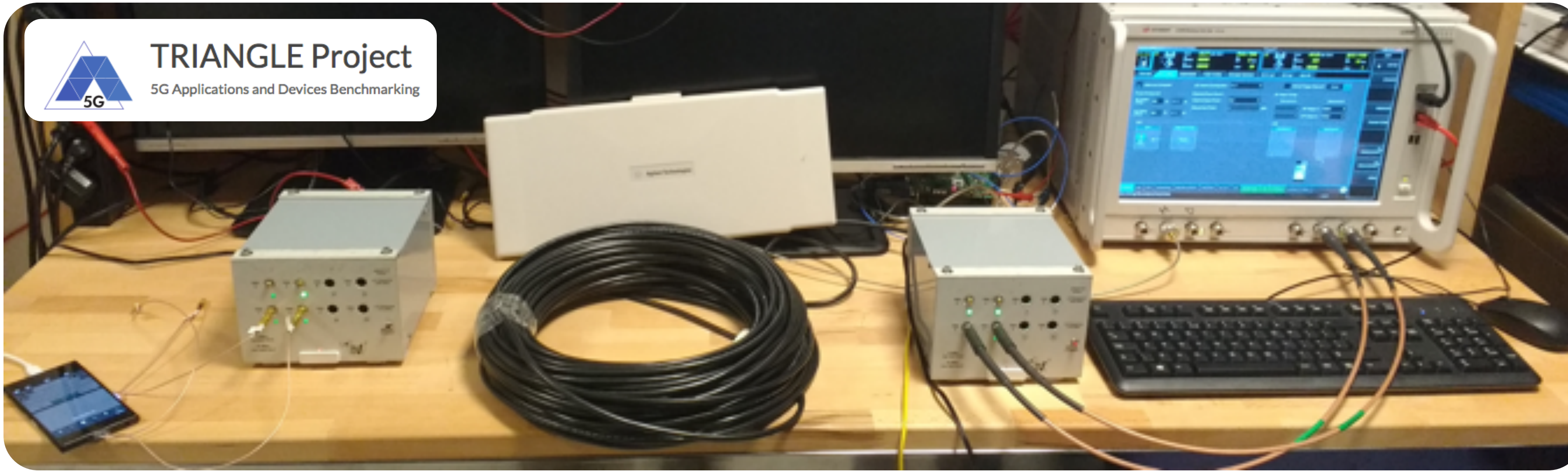
Optimal MU-MIMO A&F [Chae-etal_2008]:

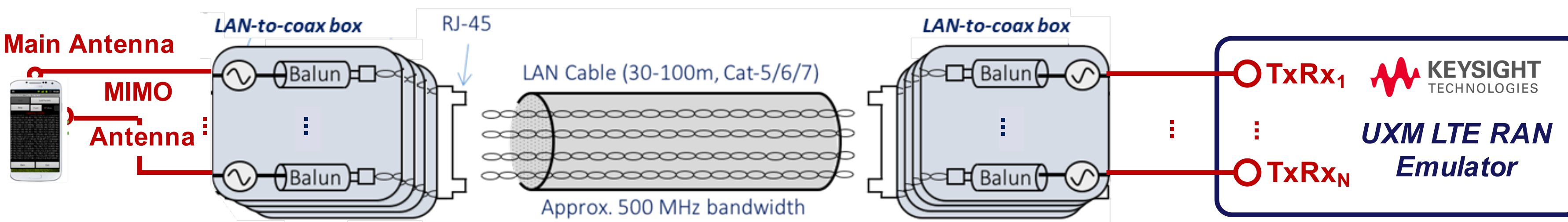
- ✓ Digital non-linear precoding at the BBU (THP);
- ✓ User ordering optimization;
- X **Digital processing at the RAU (Optimal SVD processing)**

A-MIMO-RoC: comparable performance w/o digital RAU processing -> Low-complexity/Low-latency!

A. Matera and U. Spagnolini, *“Analog MIMO Radio-over-Copper Downlink with Space-Frequency to Space-Frequency Multiplexing for Multi-User 5G Indoor Systems”*, in IEEE Transactions on Wireless Communications, 18 (5), 2813-2827

A-MIMO-RoC: Experimental Setup for LTE testing





LTE User Terminal
- Commercial device
- RF cables connections
- Throughput, BLER

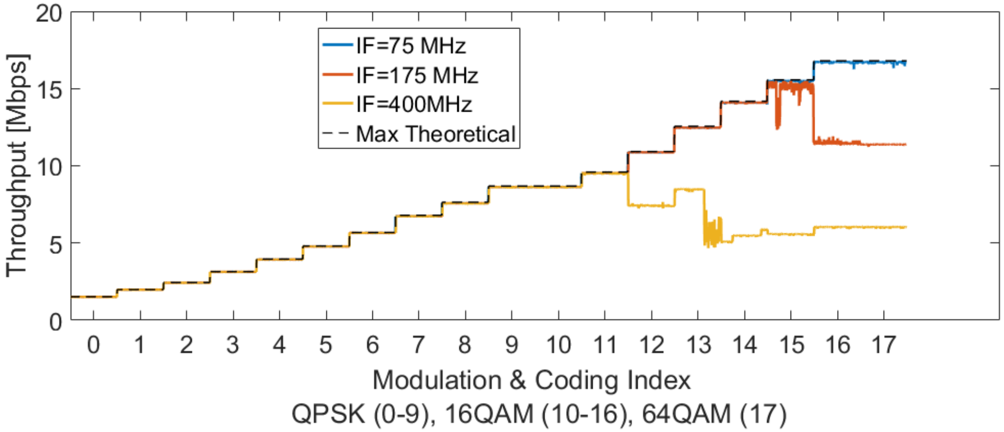
LTE signal de-multiplexing from cable:
- Adaptation from twisted-pair to coax
- IF -> RF up-conversion
- Reverse mapping from select pair-frequency to antenna

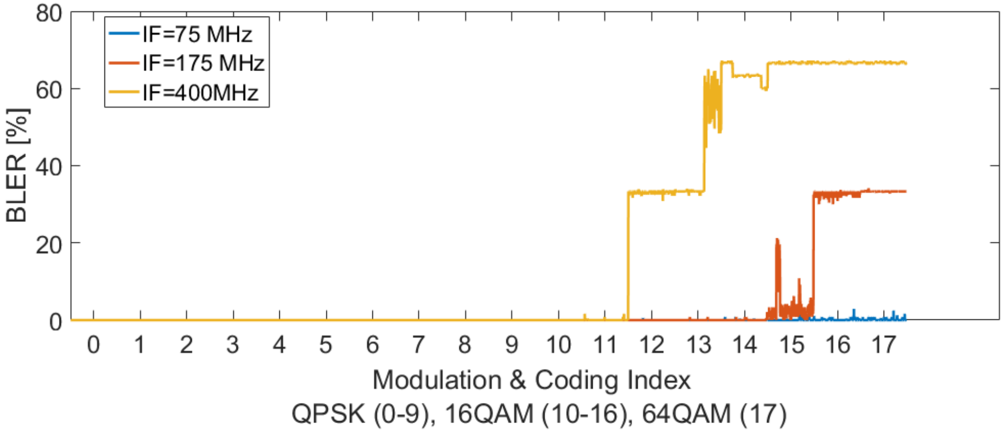
LAN Cable:
- Cat5e
- 4 twisted-pairs
- 50m
- 0-400 MHz bandwidth/pair

LTE signal multiplexing over cable:
- Adaptation from coax to twisted-pair
- RF -> IF down-conversion
- Choice of cable-pair and cable IF (0-400 MHz)

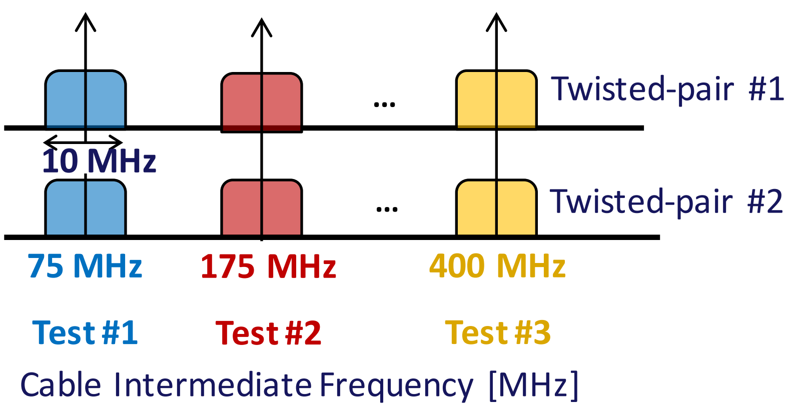
LTE signal generation:
- Channel bandwidth 5, 10 and 20 MHz;
- LTE B38 (TDD), 2570-2620 GHz
- 2x2 MIMO (Static MIMO channel)

LTE DL Performance vs Cable IF: 10 MHz BW





- **Channel bandwidth:** 10 MHz
- **LTE band:** 38 TDD, 2570-2620 GHz
- **Antenna configuration:** 2x2MIMO (Static MIMO channel)
- **Transmission Mode:** TM3 spatial multiplexing
- **TX Power:** -20 dBm/10 MHz, -50.8 dBm/15 kHz
- **RF signal mapping over cable:** 2 LTE bands mapped over two different cable-pairs at the same cable-IF



A. Matera, V. Rampa, M. Donati, A. Colamonico, A. F. Cattoni and U. Spagnolini, *"A First Experimental Evlauation of Analog MIMO Radio-over-Copper"*, available on arXiv, https://arxiv.org/abs/1809.05363

Summary

1. Investigation of interference mitigation techniques for wired and wireless communication systems, *separately*;
2. Proposal of Analog MIMO Radio-over-Copper (RoC) for indoor deployments: feasibility of employing LAN cables;
3. A-MIMO-RoC theory and extensive numerical evaluations:
    i. Analog MIMO-RoC in uplink direction with Space-frequency to Space-Frequency (SF2SF) multiplexing;
    ii. Analog MIMO-RoC in multi-user downlink with SF2SF multiplexing;
    iii. Analog MIMO-RoC for Heterogeneous 5G Networks;
4. Prototyping A-MIMO-RoC and experimental evaluation.

Conclusions

- ✓ a single 100-m long LAN cable is capable to transport up to 60 RAU antennas each carrying a 20-MHz LTE signal;
- ✓ Analog MIMO-RoC performance are greatly improved by the proposed Space-Frequency to Space-Frequency (SF2SF) multiplexing in both uplink and downlink directions;
- ✓ In Analog MIMO-RoC multi-user settings, the joint optimization of SF2SF, transmit precoding, and user ordering attains the performance of state-of-the-art techniques, and improves the minimum user rate;
- ✓ Analog MIMO-RoC prototype confirmed experimentally that a single LAN cable can exploited up to several hundreds of MHz for relaying multi-antenna RF signals indoors (even multi-RAT, e.g., LTE + WiFi).

THANKS FOR THE ATTENTION

Do you have any question?

andrea.matera@polimi.it