DEPARTMENT OF ELECTRONIC & ELECTRICAL ENGINEERING

Towards Mobile Fronthaul for 6G Networks

Tutorial

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OFC 2023 Radio-Over-Fiber for 5G and Beyond Systems, Tutorial, Tue 7th Mar 2023

Abstract

In less than a decade, rapid developments have taken place in mobile fronthaul technology. As research and development for 6G commences, the future possible directions for fronthaul technology will be outlined in this tutorial.

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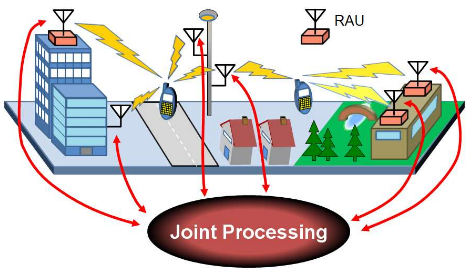
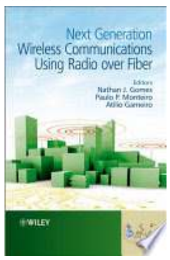
Fiber-radio and me…

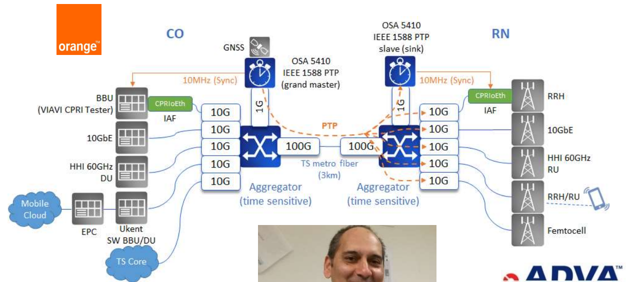


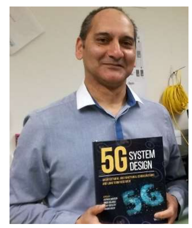
Futon



iCirrus

NIRVANA





ADVA Optical Networking
IRT Future Radio Technology
VIAVI
Fraunhofer Heinrich-Hertz-Institut
University of Kent
TelekomSlovenije

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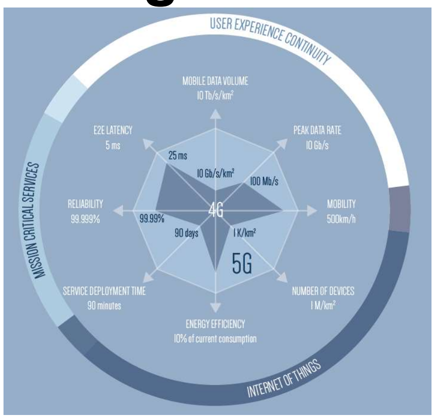
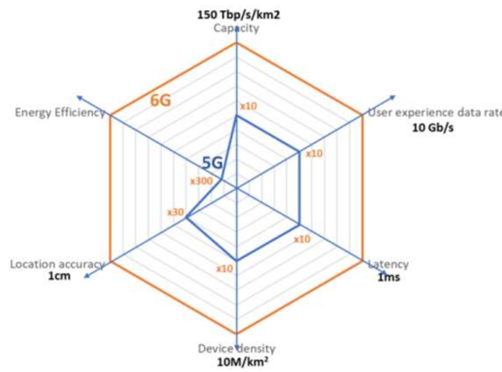
Overview

- 5G and 6G: vision and supporting wireless technologies
- Mobile fronthaul for 5G and beyond: considerations and requirements
- Mobile fronthaul examples:
    - Analog
    - Digital/digitized
    - DSP-based aggregation
- Efficient mobile fronthaul
- Summary

Moving from 5G to 6G



[Source: 5G PPP Vision Paper, 2015]

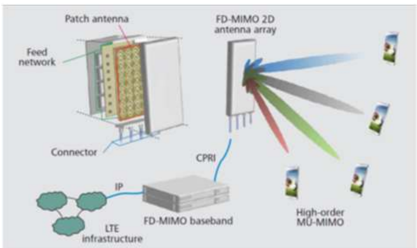


[Source: 5GIA, European Vision for the 6G Network Ecosystem, 2021]

Key wireless technologies (1): smaller cells

- Cell sizes typically reduced due to
  1. Greater numbers of users and user densities
  2. Need for enhanced data rates (high SNR)
- Leads to reduced transmit powers
- Heterogeneous networks: macro-, micro-, pico-, femto-, atto-cells …. Overlays
- Centralization of baseband functions?

Key wireless technologies (2): beamforming

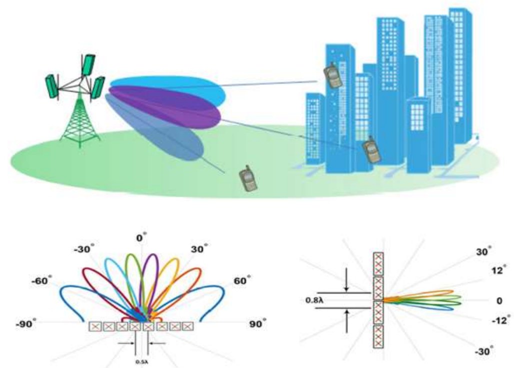


From **Kim et al**., "Full dimension MIMO (FD-MIMO): the next evolution of MIMO in LTE systems", *IEEE Wireless Communications Magazine*, April 2014

Current mMIMO Active Antenna Systems may have 64, 128 or 256 antenna elements to form beams

Can be used to form single beam or multiple beams, by grouping elements into subarrays

Other antenna systems possible: e.g. lens antennas using elements for different feed points to lens (number of beams limited by feed points and RF chains)



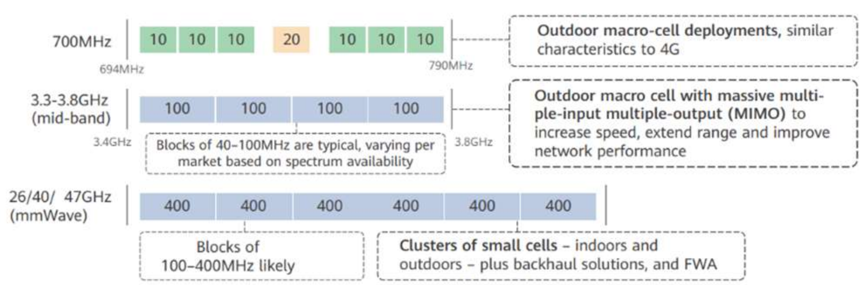
From **Wang et al**., "3D Beamforming Technologies and Field Trials in 5G Massive MIMO Systems". IEEE Open Journal of Vehicular Technology, 2020

Highly directive beams can help meet energy efficiency targets

Key wireless technologies (3): new spectrum

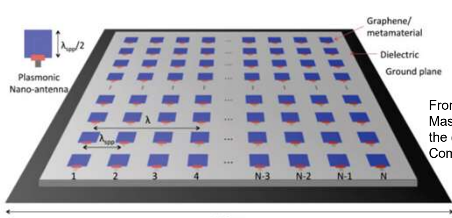
Spectrum available for 5G

Credit: Moniem-Tech Communication Engineering Frontier Knowledge Base (2021)



- Millimetre-wave: blocks of GHz or more
- THz: blocks of tens of GHz or more?
- Optical (IR, VLC): ???

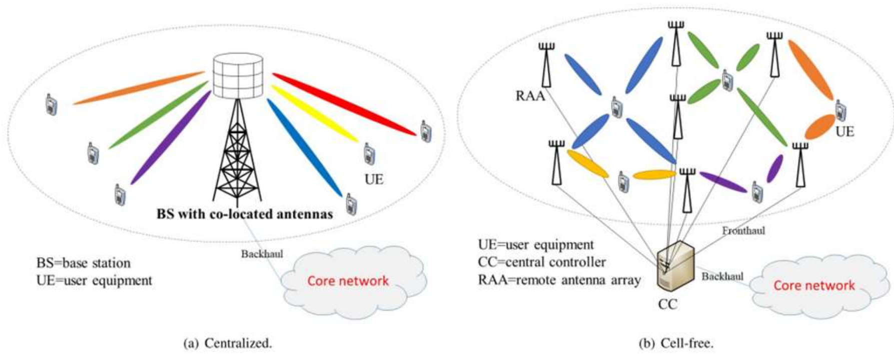
From: Teixeira et al. "On Energy Efficiency of Visible Light Communication Systems", IEEE J. Emerging Selected Topics Power Electronics, vol. 9, no. 5, Oct 2021



From: **Akyildiz, Jornet**: "Realizing Ultra-Massive MIMO (1024×1024) communication in the (0.06–10) Terahertz band", Nano Communication Networks, 2016

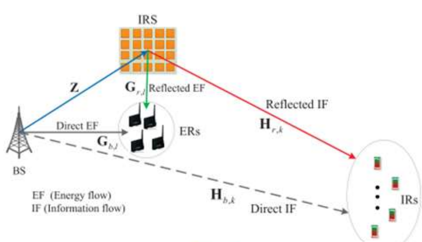
Key wireless technologies (4): distributed MIMO

- Distributed MIMO, CoMP (Coordinated MultiPoint) with joint transmission/reception
- Cell-free MIMO/user-centric networks
- Cell-free massive MIMO



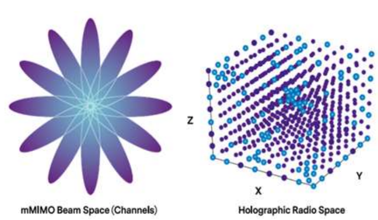
Zhao et al., "Power Allocation in Cell-Free Massive MIMO: A Deep Learning Method", IEEE Access, May 2020

Key wireless technologies (5): others



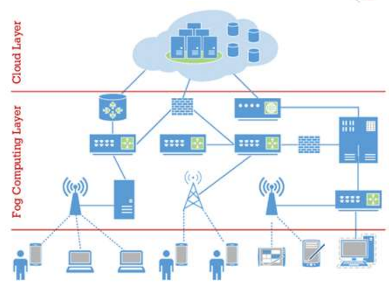
Intelligent reflecting surfaces

Pan et al., "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer", IEEE JSAC, 2021



Holographic radio

6G Flagship, White paper on Broadband Connectivity in 6G, June 2020



Fog computing, Fog RAN, Edge computing, Wireless edge caching…

Gedeon et al, Fog Computing: Current Research and Future Challenges, 2018

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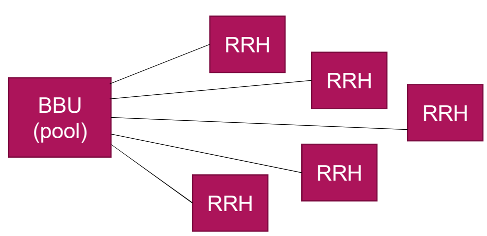
C-RAN and mobile fronthaul



- Centralized-RAN brings energy, space, shared equipment savings
- Was seen as distinct from small cell architecture
- Less backhauling, more scope for cooperation…
- Cooperative-RAN – centralised base stations enhance cooperation, joint processing of signals
- Cloud-RAN – pooling of functions in generalised, shared hardware
- Evolution towards virtualised RAN

Mobile fronthaul

Currently used fronthaul technology overwhelmingly based on Common Public Radio Interface (CPRI)

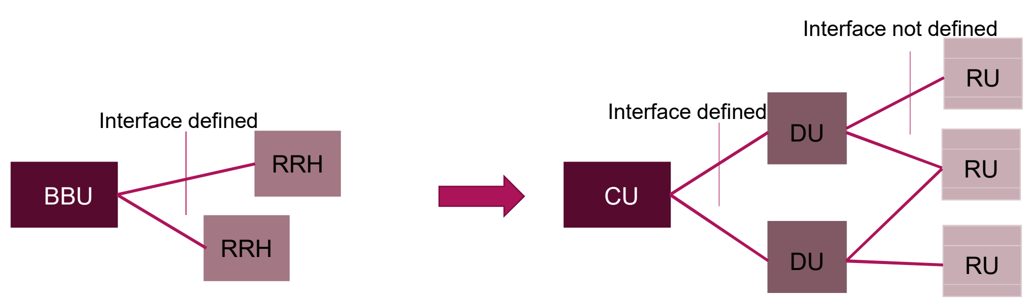
Advantages:
Fully centralised -> maximises virtualisation benefits
Synchronous, TDM-based -> inherently robust to timing

Disadvantages:
Sampled waveforms -> high bit-rates!
Multiple antenna streams -> high-bit rates!!
Little or no statistical multiplexing gains in aggregation -> high bit-rates!!!

Current CPRI interfaces		Projected requirements	
Line rate	Example use	Possible use	Approx. line rate*
614.4 Mb/s	10 MHz LTE channel with 8B10B coding	1 GHz bandwidth, 1 antenna	50 Gb/s
4.9152 Gb/s	8 x 10 MHz with 8B10B	8 x 100 MHz	40 Gb/s
10.1376 Gb/s	10 x 20 MHz with 64B66B	10 x 400 MHz	200 Gb/s
24.33024 Gb/s	24 x 20 MHz with 64B66B	128 x 500 MHz	3.2 Tb/s

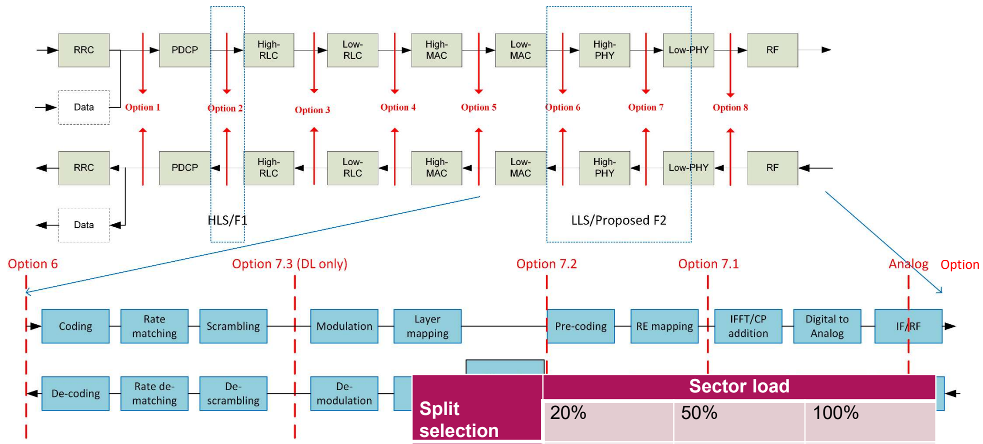
Fronthaul redefinition for 5G

- Bit-rates for digitized time domain waveforms are too high (increased bandwidths, multiple antenna streams)
- Major redefinition in 5G



See Gomes, et al. (2015) *Fronthaul evolution: From CPRI to Ethernet.* Optical Fiber Technology

RAN functional splits:



Split selection	Sector load		
	20%	50%	100%
Split 7.1	12.2	12.2	12.2
Split 7.2	2.5	6.1	12.2
MAC-PHY (6)	0.2-1.0	0.5-2.5	1.0-5.0

Calculated bit-rates (Gb/s) for selected split-points; comparable to 40 Gb/s I/Q rate on previous slide

Important: Need to conform to architectures

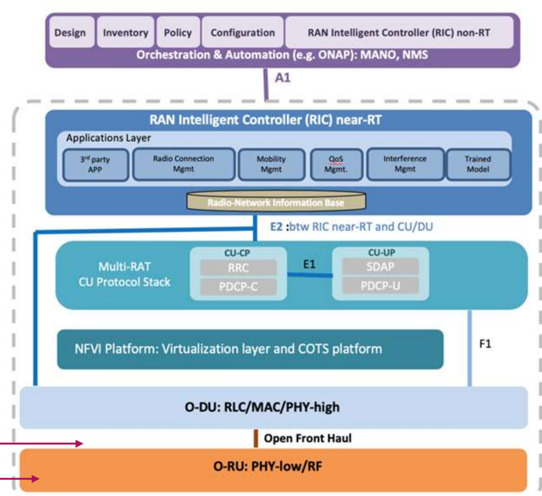
Open RAN: O-RAN architecture

E2 interface for a near-RT RAN intelligent controller (RIC)

A1 interface for orchestration, management and non-RT RIC

F1 is standard higher-layer split interface

Note: Open Front Haul



6G RoF needs to be here

Summary of fronthaul requirements

- Support large/massive MIMO arrays, beamforming, varying numbers of beams
- Support distributed (massive) MIMO, holographic radio: RU synchronization
- Support heterogeneous networks: 4G, 5G, 6G, bandwidth parts, WiFi, WiGig
- Fiber distribution, at low-cost (bandwidth efficient, passive?)
- Energy-efficient fronthaul transport and distribution/aggregation

$$EE = \frac{B\ \log_2(1 + \frac{P_{Tx}/L}{N_0 B})}{P_c + P_{Tx}}$$

Mobile fronthaul key considerations

Mobile fronthaul involves the insertion of an additional component into the radio access network. This component will cause additional:

	Signal impairment	Delay
	Noise and distortion	Application dependent (order ms?) MAC dependent (10km – 20km fiber limit) Synchronization dependent
Analog RoF	Additive noise, nonlinearity	Minimal additional processing delay
Digital RoF	Quantization noise Under-/over-sampling	Higher additional processing delay Packetization, queuing delays?

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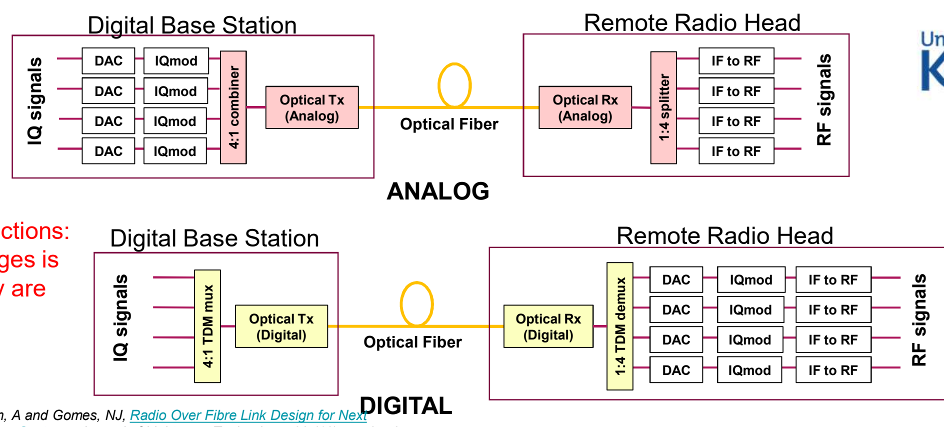
Transmission Link Designs

Requirements
- 4 x 100MHz radio channels per link direction (downlink only shown here)
- Single wavelength to allow low cost CWDM to be used to support multiple remote heads



Similar functions: what changes is where they are placed

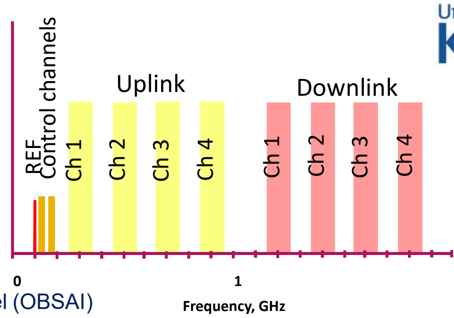
Wake, D, Nkansah, A and Gomes, NJ, Radio Over Fibre Link Design for Next Generation Wireless Systems. Journal of Lightwave Technology, 28 (16). pp. 2456-2464, 2010

Optical Transceiver Requirements

Our Conclusions circa 2010…

ANALOGUE

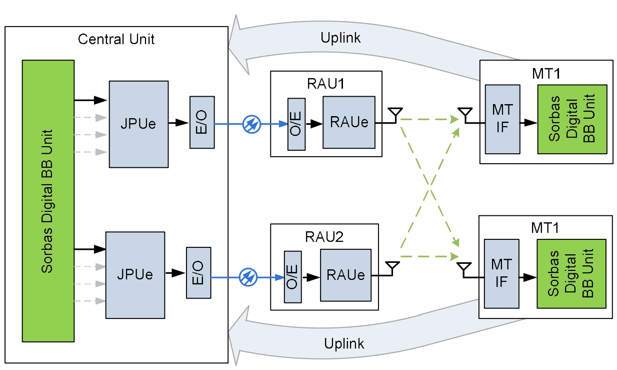
- Subcarrier multiplexing (transmission at IF) so that all radio channels can be carried on a single link
- Frequency plan requires a total bandwidth of less than 2GHz for all radio channels (both uplink and downlink directions) with wide guard bands



DIGITAL

- Sampling rate of 153.6MHz extrapolated for 100MHz channel (OBSAI)
- 4915Mb/s required for 100MHz LTE channel assuming I and Q sample width of 16 bits
- One CPRI/OBSAI 6144Mb/s channel can only support a single 100MHz radio channel
- Four radio channels require a bit rate of more than 24Gb/s
- Serial link necessary to conserve optical wavelengths (for support of multiple remote radio heads)
- Cost comparison: several times (perhaps order of magnitude) more expensive than analog approach

CoMP demonstrator



JPU = joint processing unit
JPUe = JPU electrical
O/E = optical to electrical
RAUe = RAU electrical

Block diagram of the distributed antenna precoding demonstrator.

- Separated Uplink on 2.5 GHz
- JPUe, RAUe, MT RF, antennas and optical links were custom designed and manufactured for the prototype

Throughput increase with CoMP

Measurements at 240 different MT positions in lab environment

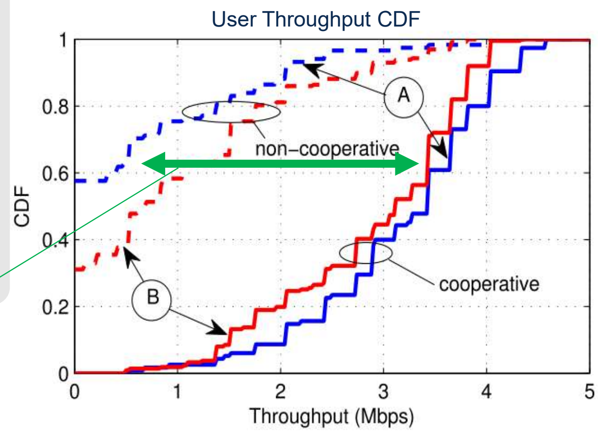
Cooperative Mode: Full precoding

Non-Cooperative Mode:
User streams are transmitted separately (conventional systems)

A: Symmetric channels
B: Asymmetric channels

Compared to conventional systems the throughput can be significantly increased

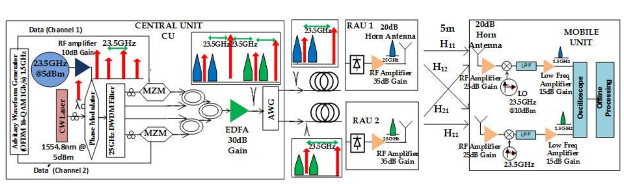
Users share allocation of 1.8 MHz

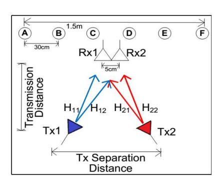


mmW-MIMO with analog fiber transport

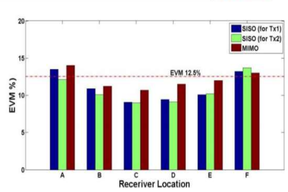
Radio over Fiber Transport of mm-Wave 2×2 MIMO for Spatial Diversity and Multiplexing

- Modulation of Single Laser Source
- Generation of independent set of data for MIMO operation: Two 1Gb/s (OFDM 16-QAM) data streams at 1.5GHz IF
- DWDM-RoF Transport and Direct Photonic Upconversion
- 2x2 MIMO transmission over 2km RoF link and 6m wireless distance to achieve Spatial Diversity and Spatial Multiplexing

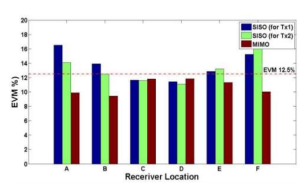




U. Habib et al, "Analog Radio-over-Fiber Supported Increased RAU Spacing for 60GHz Distributed MIMO employing Spatial Diversity and Multiplexing," in J. Lightwave tech., doi: JLT.2018.2832028

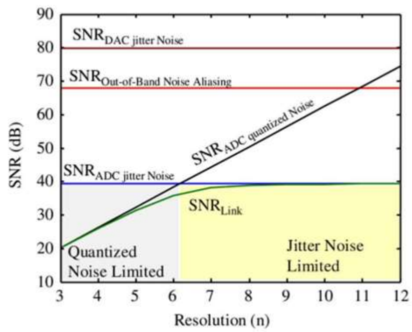


SISO (0.5Gb/s) Versus Zero Forcing MIMO Receiver (2x2MIMO)

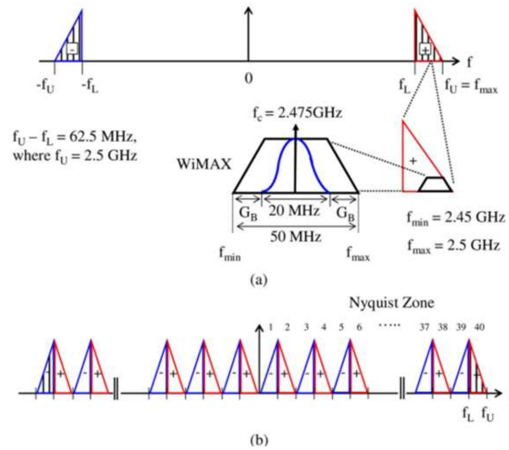


Performance of 2x2 STBC operation at different User Locations

Digitized RoF



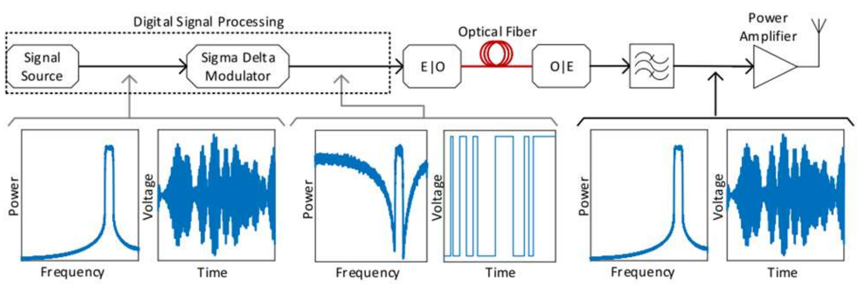
Gamage et al.,"Design and Analysis of Digitized RF-Over-Fiber Links", J. Lightwave Technol., 2009



Multichannel SNR and dynamic range degradation not as great as with A-RoF

Yang et al., "Multichannel Digitized RF-Over-Fiber Transmission Based on Bandpass Sampling and FPGA", IEEE Trans. MTT, 2010

Digitized RoF: 1-bit DRoF/Σ-Δ Modulation



Sezgin et al., "A Low-Complexity Distributed-MIMO Testbed Based on High-Speed Sigma–Delta-Over-Fiber", IEEE Trans. MTT, 2019

Oversampling: single-bit digitization, but bandwidth expansion is through oversampling
Approx. 50% improvement of BW efficiency compared to CPRI

Wang et al., "Delta-Sigma Modulation for Next Generation Fronthaul Interface", J. Lightwave Technol., 2019

Possible advantage is simplification of receiver – filter/integrator will restore original signal, no need for high-speed DAC

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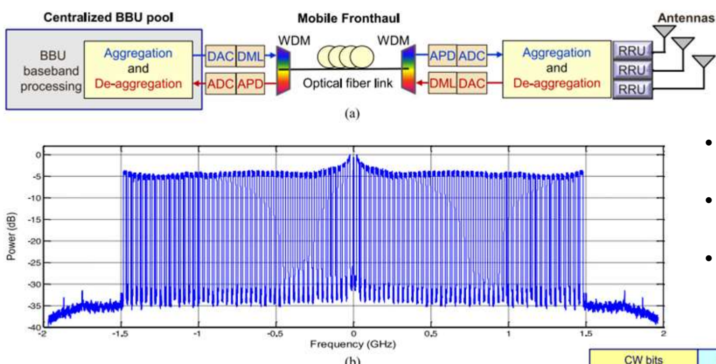
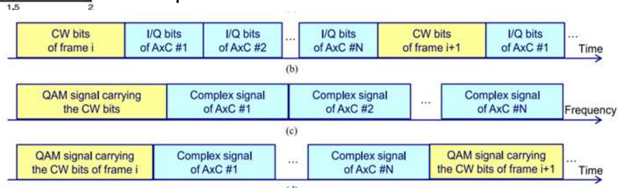
DSP-based aggregation for analog RoF



Liu et al., "Efficient Mobile Fronthaul via DSP-Based Channel Aggregation", J. Lightwave Technol., 2016

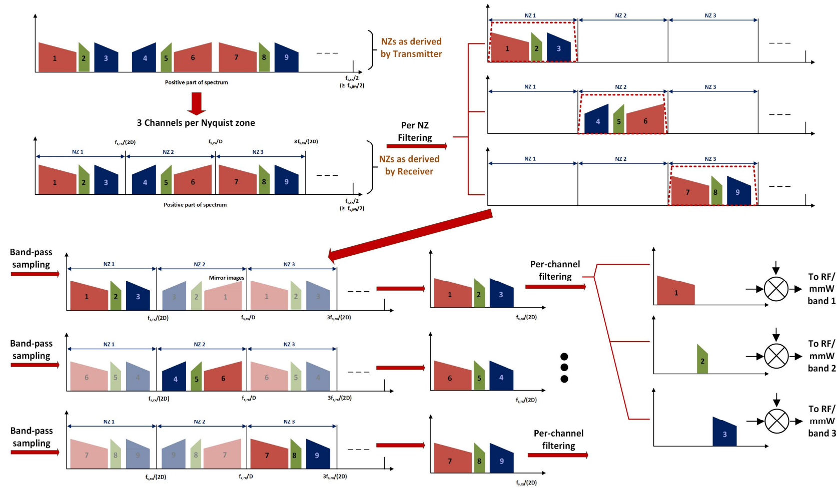
- OFDM signals resampled to minimize processing latency
- 1.6 GHz RF bandwidth for what would have been near 40Gb/s CPRI rate
- Prediction: 400 Gb/s CPRI rate with 40GSa/s ADC/DAC and 15 GHz optical link



Also possible to aggregate in time-domain for CPRI-compatibility

Zeng et al., "Real-time demonstration of CPRI-Compatible Efficient Mobile Fronthaul using FPGAs", J. Lightwave Technol., 2017

Nyquist Zone mapping (of frequency domain symbols)



Multiplexing can be more efficient. Simplification through placement of signals.

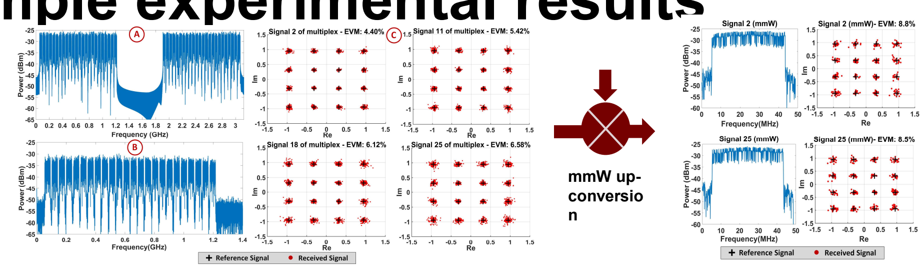
See Noor et al., (2020) *Comparison of Digital Signal Processing Approaches for Subcarrier Multiplexed 5G and Beyond Analog Fronthaul.* Journal of Optical Communications and Networking, 2 (3). pp. 62-71

Example experimental results

IF BW:
3 GHz

Data rate:
3.66 Gb/s
Or
7.12 Gb/s

CPRI equiv:
>45 Gb/s
Or
>90 Gb/s



A. Transmit spectrum of 64 SSB/ 32 DMT signal multiplex; B. Received spectrum; C. EVM/ constellation diagrams of Signals 2, 11, 18 and 25 of multiplex.

Signals 2 and 25 of multiplex after mmW up-conversion.

Experimental results with signals generated in MATLAB, downloaded into Arbitrary Waveform Generator
Received signals captured in high-speed oscilloscope and demodulated offline in MATLAB.

Noor et al., A Flexible Subcarrier Multiplexing System with Analog Transport and Digital Processing for 5G (and beyond) Fronthaul. Journal of Lightwave Technology, 37 (14). pp. 3689-3700, 2019

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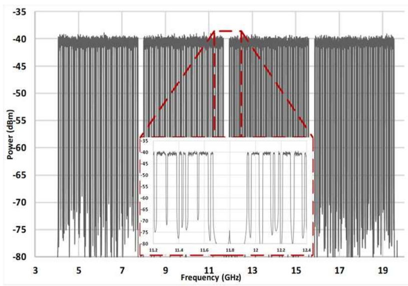
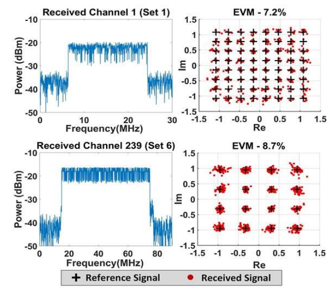
Benchmarked simulation results



Spectrum of 240-channel multiplex with mixed 5G numerologies, channel bandwidths and modulation levels (**MATLAB-VPI cosimulation**).



Channel 1 (18 MHz) Channel 239 (60 MHz) of multiplex.

Simulation results with optical link model (in VPI TransmissionMaker) benchmarked against experimental measurements

Noor et al., A Flexible Subcarrier Multiplexing System with Analog Transport and Digital Processing for 5G (and beyond) Fronthaul. Journal of Lightwave Technology, 37 (14). pp. 3689-3700, 2019

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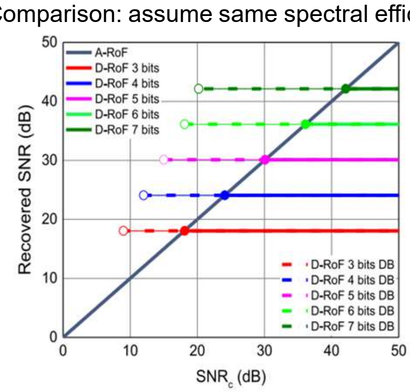
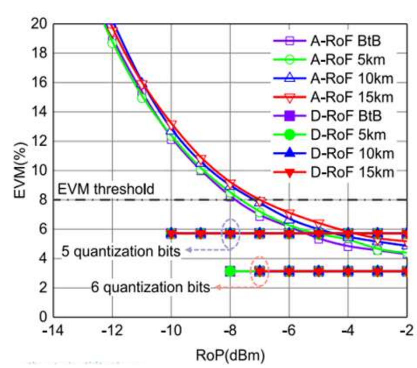
Digital or Analog?

Bandwidth efficiency for digital transmission can be improved by multi-level modulation (could even be OFDM or DMT, with QAM)
Comparison: assume same spectral efficiency.



Ji et al., "Spectral Efficiency Comparison Between Analog and Digital RoF for Mobile Fronthaul Transmission Link", J. Lightwave Technol., 2020



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Efficient Fronthaul Transport

Packetized transport of digital signals can lead to statistical multiplexing gains:
- OK for CU-DU, HLS (midhaul)
- depends on DU-RU fronthaul split point, and must meet MAC latency constraints

Packet-based Ethernet transport requires:
- Frequency synchronization, SyncE or other PHY layer framing structure
- Phase/time synchronization, PTP …
- TSN mechanisms required

Time-aware shaping (gating), gap-filling look promising

Assimakopoulos et al., "A Converged Evolved Ethernet Fronthaul for the 5G Era", IEEE J. Selected Areas in Communications, 2019

PON transport requires above, too.

Co-operative Dynamic Bandwidth Allocation algorithm uses BS's knowledge of downlink and uplink allocations to inform PON's OLT in granting bandwidth

Pfeiffer et al., PON going beyond FTTH, J. Optical Communications and Networking, 2021

Efficient Fronthaul Transport (2)

PHY layer symbol rate is constant, and continually on for SyncE

An adjustable PHY layer rate may save energy

In order of increasingly fine granularity:

1. Turn wavelengths on/off
2. Use bandwidth variable transponders – change modulation level (link changes from 50 to 100 to 150 to 200 Gb/s in same bandwidth)
3. Use bandwidth variable transponders (2) – change modulation level for groups of subcarriers within DMT scheme
   - Match to 5 Gb/s granularity of FlexE

Liao et al., "Calendar Allocation Based on Client Traffic in the Flexible Ethernet Standard," IEEE Int. Conf. Communications (ICC), 2020
Chughtai et al., "User and resource allocation in latency constrained Xhaul via reinforcement learning", J. Optical Communications and Networking, to appear

Summary

- 5G will continue to place increasing demands on fronthaul: increased use of mm-waves, beamforming
- 6G will increase these demands further, through (e.g.): increased bandwidths (mm-wave and THz), more antenna access points, Fog RAN, cell-free mMIMO, holographic radio
- Fronthaul needs to support the above, with bandwidth efficiency (economically realizable fibre-optic links), low-latency links, energy efficiency
- Digital and analog transport offer differing advantages in terms of performance, bandwidth efficiency, energy efficiency, simplicity/complexity (e.g. of RUs)
- Trade-offs can be balanced using multi-level and adjustable bit-rate transmission systems