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Optical 5G Transport: Challenges and Opportunities

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Kista 5G Transport Lab

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Outline

- Transport service evolution from 4G to 5G
- Transport challenges in the new 5G services paradigm
- Programmable and flexible transport infrastructure
- Use case: C-RAN architecture
  - Impact of different resource abstraction policies
  - Benefits of dynamic resource sharing
- Data plane options for NFV
- Conclusions

Mobile networks evolution

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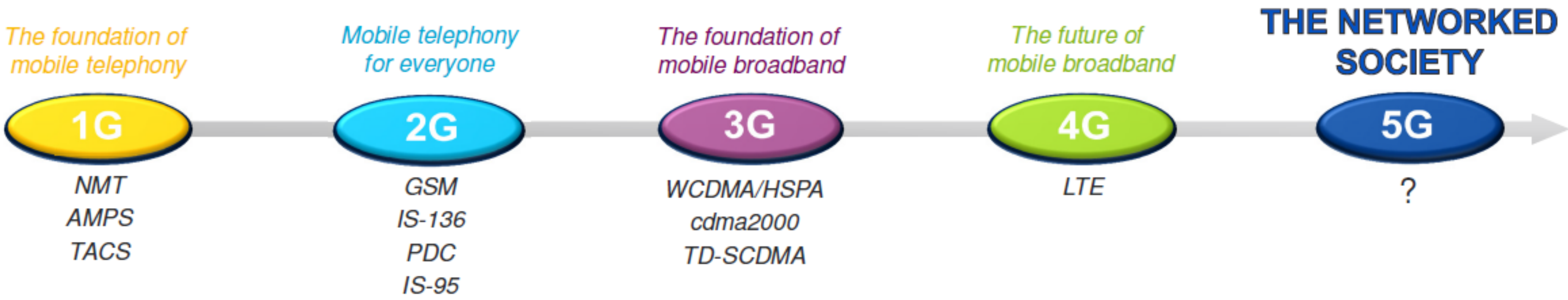
- What can we expect from next generation of mobile networks?

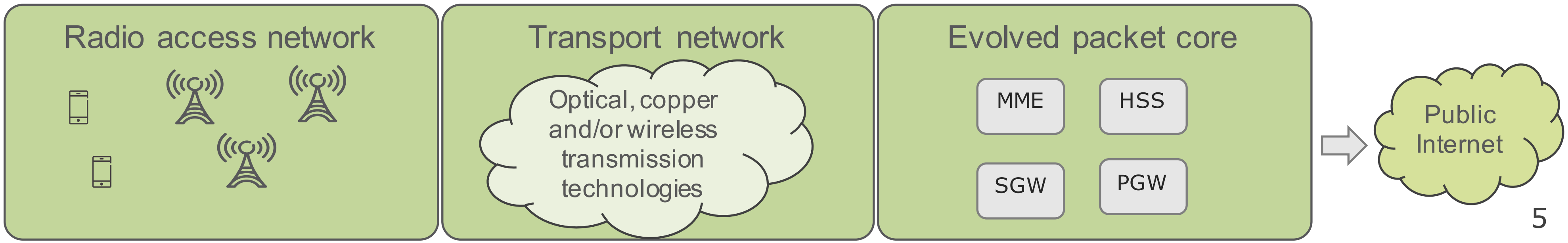


- 5G vision:
  - *user- and machine-centric communications* where access to information is available *anywhere* and *anytime* to *anyone* and *anything*, the so called ***Networked Society****

*http://www.ericsson.com/thinkingahead/networked_society

What is a transport networks?

- Transport network is the segment connecting the base stations (eNodeB) with their peering point in the Evolved Packet Core (EPC)
  - mobility management (MME), service gateway (SGW), packet data network gateway (PGW), home subscriber services (HSS)
- Transport technologies: copper, optical, and/or wireless technologies
- Research on 5G focused on new radio access networks (RAN): *high peak-rates* per subscriber; handle *very large number of simultaneously connected devices*; *better coverage, outage probability, and latency*
- So far less attention is put on defining the 5G transport network



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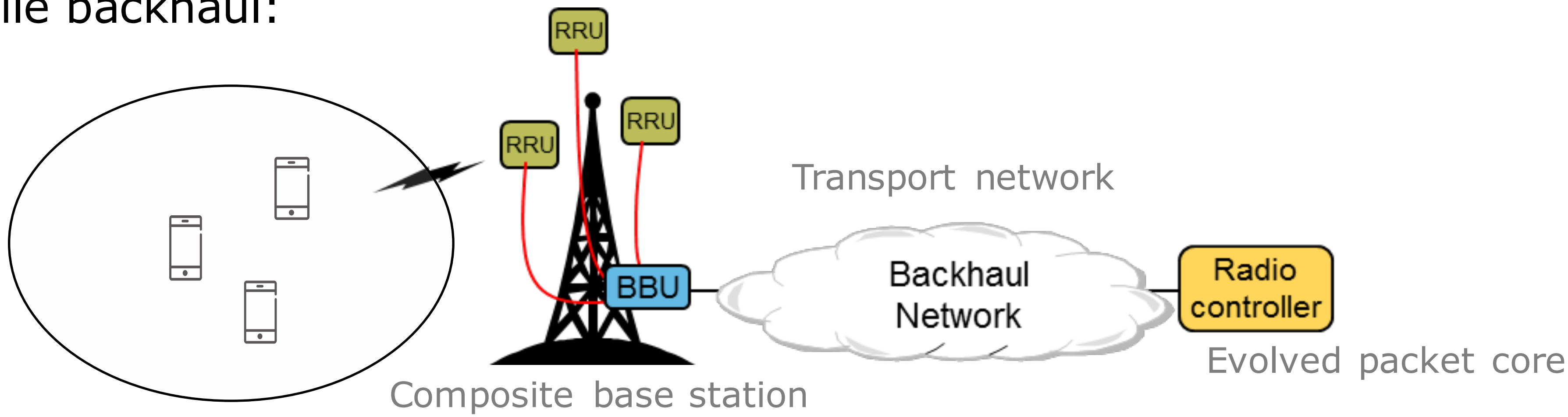
Transport services in 4G

- Before getting into the specifics of what should be the requirements of a 5G transport network it might be useful to understand how transport services look like in 4G networks
- With *current mobile networks* the transport should be able to accommodate
  - Backhaul services (distributed RAN)
  - Fronthaul services (centralized RAN)
- and support
  - Advanced radio coordination features
  - (Massive) multi-input multiple-output (MIMO) antennas architectures
- Idea: look at the current requirements and try to identify possible critical aspects when having to serve new 5G services

M. Fiorani, et al.,"On the Design of 5G Transport Networks," *Springer Photonic Network Communications (PNET) Journal*, 2015

Backhaul services

➤ Mobile backhaul:



EU FP7 Project COMBO. http://www.ict-combo.eu/

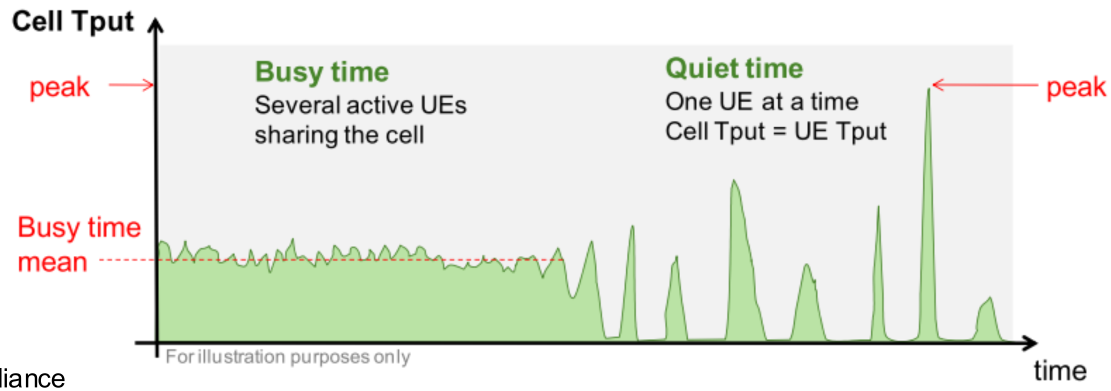
➤ Macro base station composed of: (1) Antennas, (2) Remote Radio Units (RRUs), (3) Baseband Unit (BBU)

➤ BBU performs baseband signal processing and generates packet-based backhaul traffic. The backhaul traffic is composed of: data traffic (S1) + control traffic (X2)

➤ Backhaul *data traffic is proportional to the data generated by the users*

Backhaul: dimensioning

- Transport dimensioning for backhaul*:
  - During "quite times", peak bitrate corresponds to one user equipment (UE) with a good link served by one sector
  - During "busy time", many UEs are served by each sector and the average bitrate is related to the average spectral efficiency over the coverage area
- Provisioned capacity for a base station with N sectors typically obtained as maximum of:
  - peak bitrate for single sector
  - N x (busy hour average bitrate)



*"Guidelines for LTE Backhaul Traffic Estimation", White Paper by NGMN Alliance

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Peak rate and busy hour requirements

- The peak bitrate of a sector depends on*:
  - Radio access network (RAN) configuration
    - ✓ Channel bandwidth, MIMO (# of antennas/sector), peak spectral efficiency
  - UE category (as specified by 3GPP) served by the sector
- Average busy hour bitrate*: simulation for an urban macro cell environment

All values in Mbps								Total U-plane + Transport overhead			
Scenario		Single Cell		Single base station		X2 Overhead		No IPsec		IPsec	
		Mean	Peak	Tri-cell Tput		overhead	4%	overhead	10%	overhead	25%
		(as load-> infinity)	(95%ile @ low load)	busy time mean	peak (95%ile)	busy time mean	peak	busy time mean	peak (95%ile)	busy time mean	peak (95%ile)
DL	1: 2x2, 10 MHz, cat2 (50 Mbps)	10.5	37.8	31.5	37.8	1.3	0	36.0	41.6	41.0	47.3
DL	2: 2x2, 10 MHz, cat3 (100 Mbps)	11.0	58.5	33.0	58.5	1.3	0	37.8	64.4	42.9	73.2
DL	3: 2x2, 20 MHz, cat3 (100 Mbps)	20.5	95.7	61.5	95.7	2.5	0	70.4	105.3	80.0	119.6
DL	4: 2x2, 20 MHz, cat4 (150 Mbps)	21.0	117.7	63.0	117.7	2.5	0	72.1	129.5	81.9	147.1
DL	5: 4x2, 20 MHz, cat4 (150 Mbps)	25.0	123.1	75.0	123.1	3.0	0	85.8	135.4	97.5	153.9
UL	1: 1x2, 10 MHz, cat3 (50 Mbps)	8.0	20.8	24.0	20.8	1.0	0	27.5	22.8	31.2	26.0
UL	2: 1x2, 20 MHz, cat3 (50 Mbps)	15.0	38.2	45.0	38.2	1.8	0	51.5	42.0	58.5	47.7
UL	3: 1x2, 20 MHz, cat5 (75 Mbps)	16.0	47.8	48.0	47.8	1.9	0	54.9	52.5	62.4	59.7
UL	4: 1x2, 20 MHz, cat3 (50 Mbps)*	14.0	46.9	42.0	46.9	1.7	0	48.0	51.6	54.6	58.6
UL	5: 1x4, 20 MHz, cat3 (50 Mbps)	26.0	46.2	78.0	46.2	3.1	0	89.2	50.8	101.4	57.8

*"Guidelines for LTE Backhaul Traffic Estimation", White Paper by NGMN Alliance

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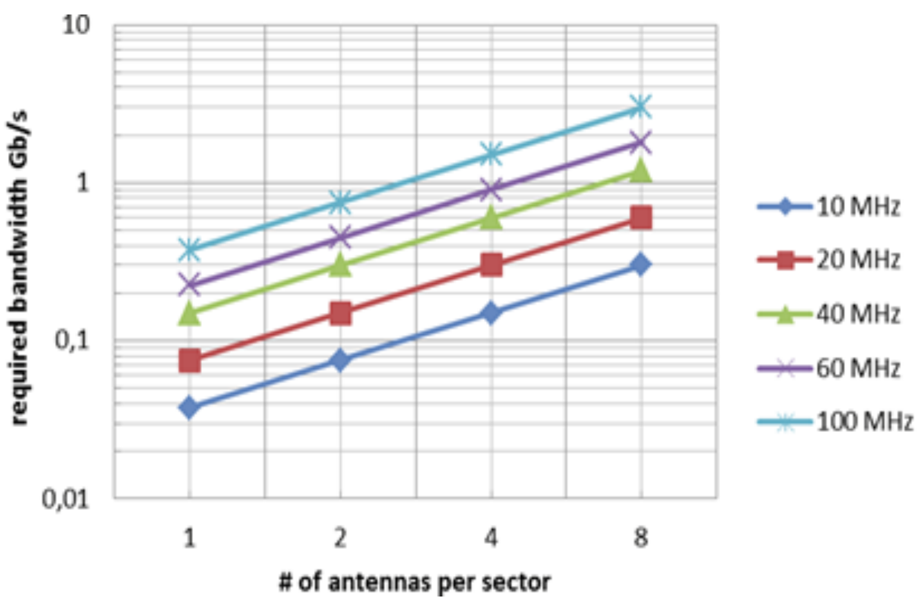
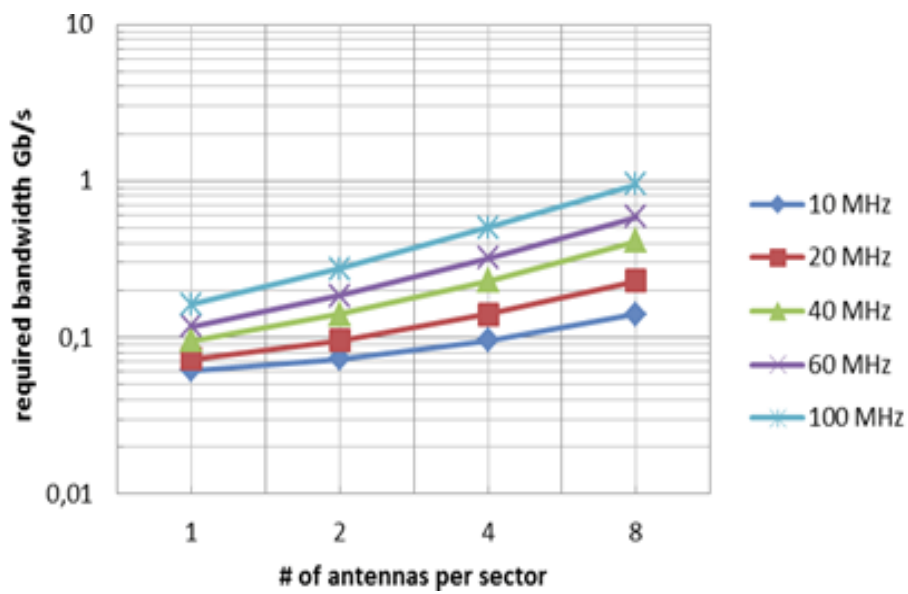
Backhaul: required bandwidth

Data traffic S1 per macro site*



Coordination traffic X2 between sites*



Assumption on X2 traffic:
50 Mb/s base rate + 0.3 x S1 traffic

Typical values for LTE-A base station (BS):

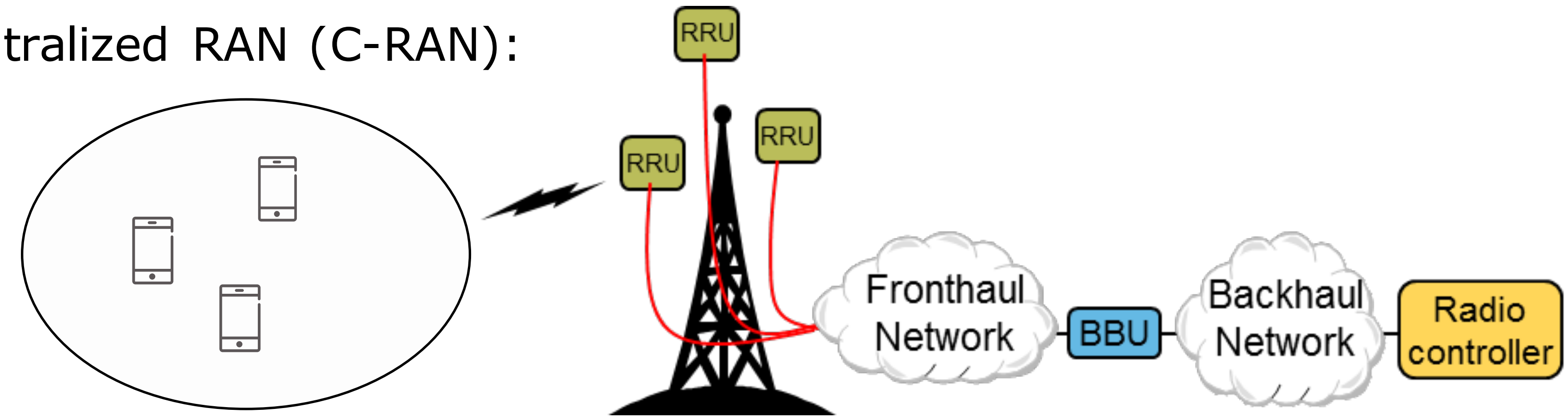
- Macro BS: 40 MHz with 4x4 MIMO = 830 Mbps per macro base station
- Small cell Var.1: 20 MHz with 2x2 MIMO = 245 Mbps per small cell
- Small cell Var.2: 40 MHz with 4x4 MIMO = 830 Mbps per small cell

MIMO and larger spectrum as well as additional X2 traffic drive the need for >1G backhaul links

*EU FP7 Project COMBO. http://www.ict-combo.eu/

Fronthaul services

- Centralized RAN (C-RAN):



EU FP7 Project COMBO. http://www.ict-combo.eu/

- The BBUs are decoupled from the base station and centralized in one or more *pools* (alternatively also BBU *hotels* or even BBU *clouds*)
- The transport network is divided in two parts:
  - Fronthaul: traffic between RRUs and BBU pool
    - ✓ Carries the sampled I/Q data generated at the RRU (C1 traffic)
    - ✓ Popular radio interface for D-RoF is Common Public Radio Interface (CPRI)
  - Backhaul: traffic between BBU pool and EPC (S1 + X2)

Motivation and challenges

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- Motivations for C-RAN:
  - More efficient radio coordination
  - Energy and cost savings (sharing infrastructure, BBU functionalities, reduced footprint outdoor equipment)
  - Easy hardware/software upgrades, maintenance, and reparation
- Challenges for C-RAN:
  - Fronthaul latency requirements
    - ✓ LTE physical layer hybrid automated repeat request process (HARQ) requires maximum round-trip delay of 3ms, including both transport and BBU processing time
  - Fronthaul traffic capacity requirements
    - ✓ *Constant bit-rate → independent from traffic generated by the users equipment*
    - ✓ Using CPRI*:

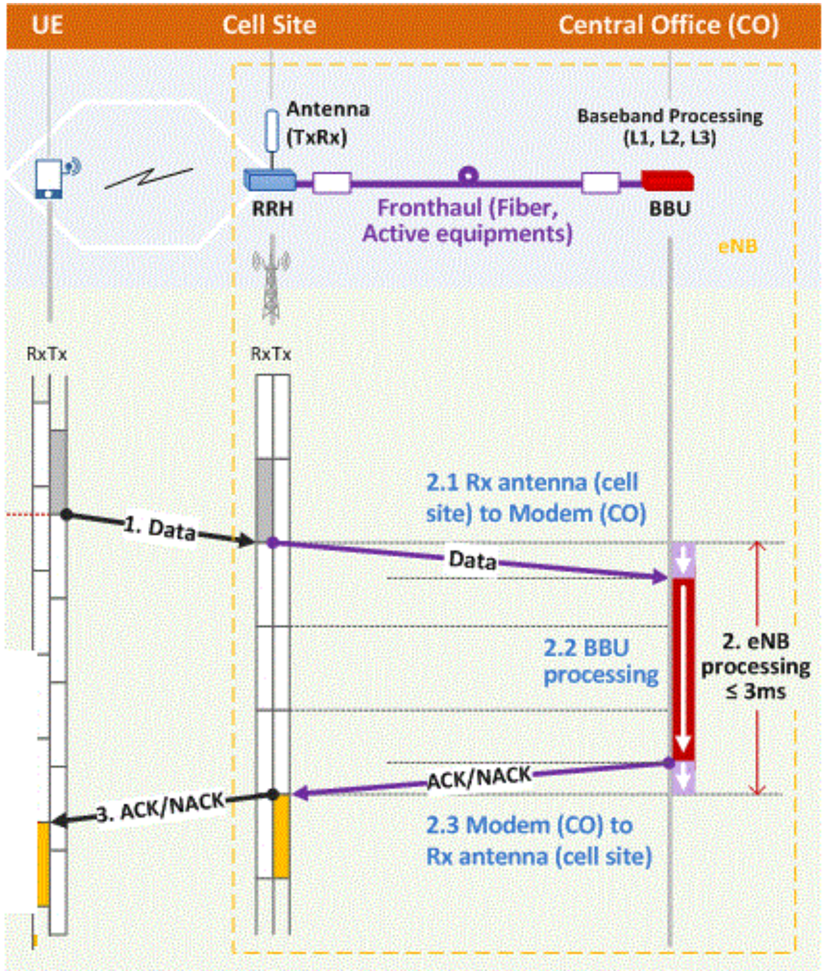
$$B_{CPRI} = \underbrace{N_S \cdot N_{Ant}}_{\text{Radio configuration}} \cdot \underbrace{R_S \cdot 2N_{Res}}_{\text{Analog to digital conversion}} \cdot \underbrace{O_{CW} \cdot O_{LC}}_{\text{Control overhead}}$$

N_s: # sector
N_{ant}: # ant. elements
R_s: sampling rate
N_{res}: bit/sample
O_{CW}: overhead
O_{LC}: line coding

*http://www.cpri.info

Fronthaul: latency requirements

- LTE physical layer HARQ requires that eNodeB indicates within 4 ms to the user equipment (UE) to retransmit an erroneous packet
- Gives a 3ms budget including both transport and BBU processing time
- Maximum theoretical RTT delay limit for the transport: 400 μs
- A good practice is to limit the RoF transmission delay to around 100 μs
- Maximum distance between a RRU and a BBU not to exceed 20 km*



*C-RAN - The Road Towards Green RAN; China Mobile White Paper, Version 3.0 (Dec 2013)

Fronthaul: capacity requirements

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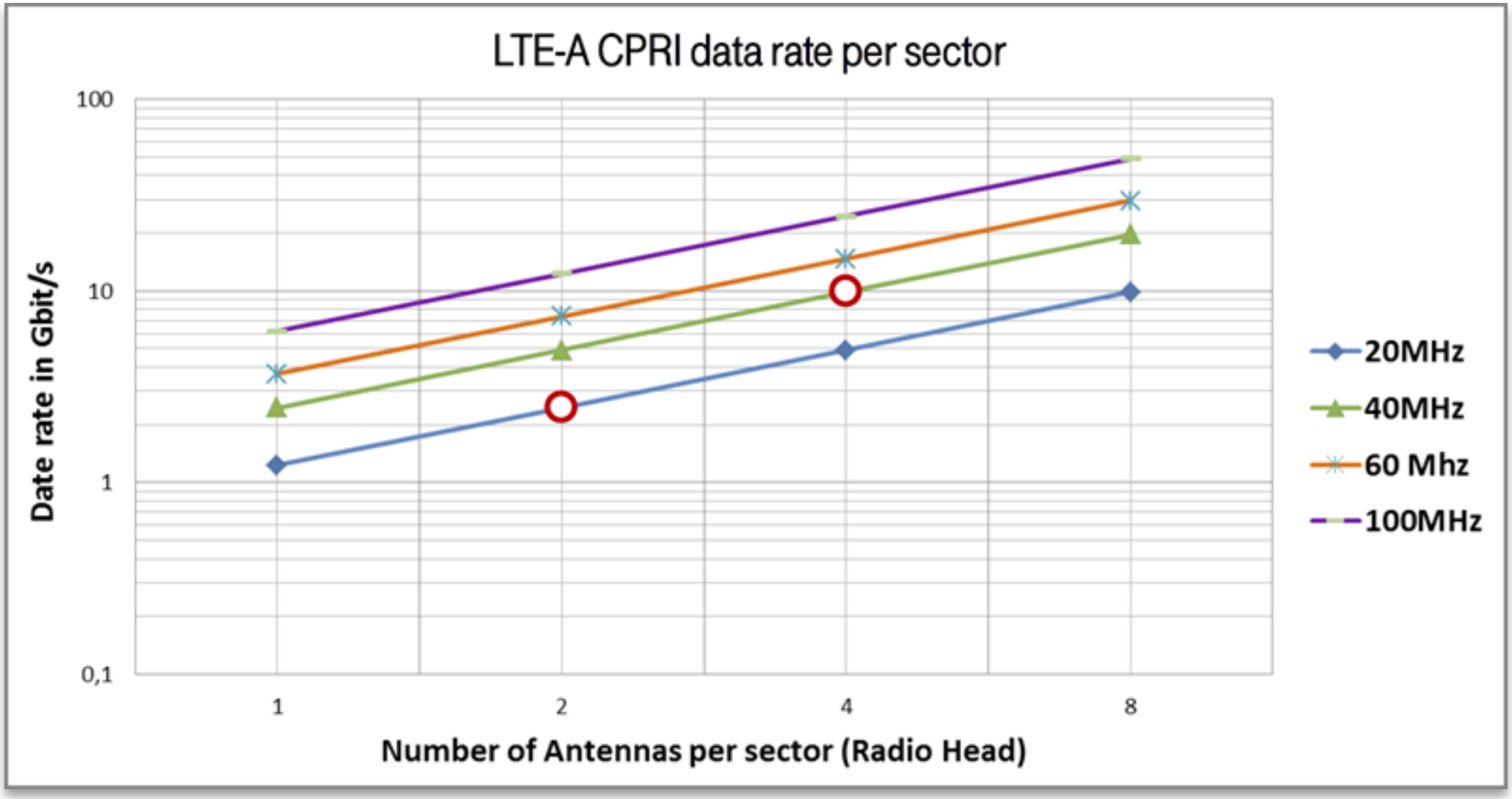

- Typical values for LTE-A base station (BS):
  - Macro BS: 40 MHz with 4x4 MIMO = 10 Gbps per sector, 3 CPRI links per macro BS, total of 30 Gbps per macro BS
  - Small cell Var.1: 20 MHz with 2x2 MIMO = 2.5 Gbps per sector
  - Small cell Var.2: 40 MHz with 4x4 MIMO = 10 Gbps per sector

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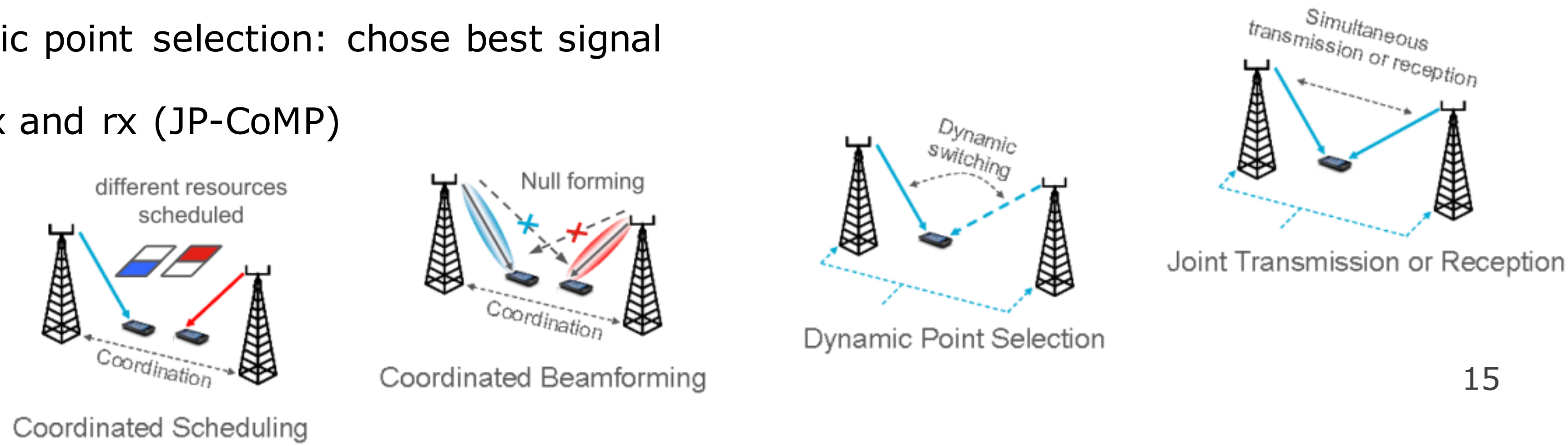
Advanced radio coordination

- Radio coordination improves transmission spectral efficiency, in particular at cell edges. Also used to mitigate interference in HetNet
- Different radio coordination schemes and algorithms:
  - Enhanced inter-cell interference coordination (eICIC)
  - Coordinated multi-point (CoMP)
    - ✓ Coordinated scheduling: interference management
    - ✓ Coordinated beamforming: interference management
    - ✓ Dynamic point selection: chose best signal
    - ✓ Joint tx and rx (JP-CoMP)



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Radio coordination benefits and requirements

Coordination Classification	Coordination Feature	Max Throughput Gain	Max Capacity Gain	Delay Class
Very Tight Coordination	Fast uplink CoMP (uplink joint reception/selection)	High	High	0.1-0.5 ms
	Fast downlink CoMP (coordinated link adaptation, coordinated scheduling, coordinated beamforming, dynamic point selection)	Medium	Medium	
	Combined Cell	Medium		
Tight Coordination	Slow uplink CoMP	Medium	Small	1-20 ms
	Slow downlink CoMP (e.g., Postponed Dynamic Point Blanking)	Small		
Moderate Coordination	eICIC	Medium	Small	20-50 ms

Small gain: <20% - Medium gain: 20-50% - High gain: >50%

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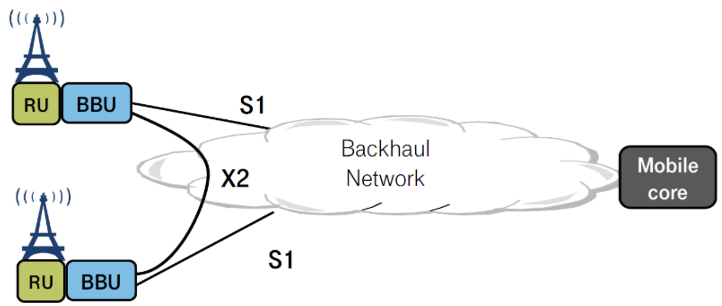
Radio coordination with BH and FH

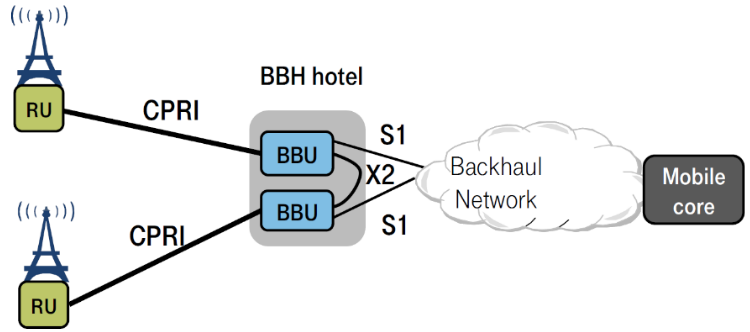
Backhaul

- An interconnection of X2 interface required, link distances between sites will cause delay
- To support JP-CoMP delay < 0.5 ms interconnection required



Fronthaul

- X2 interfaces are collocated, X2 delay close to zero
- Fulfils inherently X2 delay requirements for CoMP < 0.5 ms



- Backhaul: X2 connection needs to support delay < 0.5 ms for JP-CoMP (difficult)
- Fronthaul: fulfils inherently X2 delay requirements for JP-CoMP < 0.5 ms

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Impact of MIMO

- Regular (i.e., a few elements) MIMO configurations already used in current LTE deployments
- m-MIMO: provide BS with *large spatial multiplexing gains* and *beamforming capabilities* thanks to hundreds of antenna elements
- It is expected new 5G radio access interfaces will include*: technology backward compatible with LTE and LTE-A, new technology (NX) based on m-MIMO
- Transport capacity requirement with m-MIMO:
  - Backhaul → rise to up to 10 Gbps (in LTE-A was ≈ 1 Gbps)
  - Fronthaul: may reach the Tbps per base station

$$B_{\mathrm{CPRI}} = \underbrace{N_S \cdot N_{\mathrm{Ant}}}_{\text{Radio configuration}} \cdot \underbrace{R_S \cdot 2N_{\mathrm{Res}}}_{\text{Analog to digital conversion}} \cdot \underbrace{O_{\mathrm{CW}} \cdot O_{\mathrm{LC}}}_{\text{Control overhead}}$$

*S. Tombaz, et al., "Energy Performance of 5G-NX Wireless Access Utilizing Massive Beamforming and an Ultra-lean System Design", in IEEE GLOBECOM, 2015

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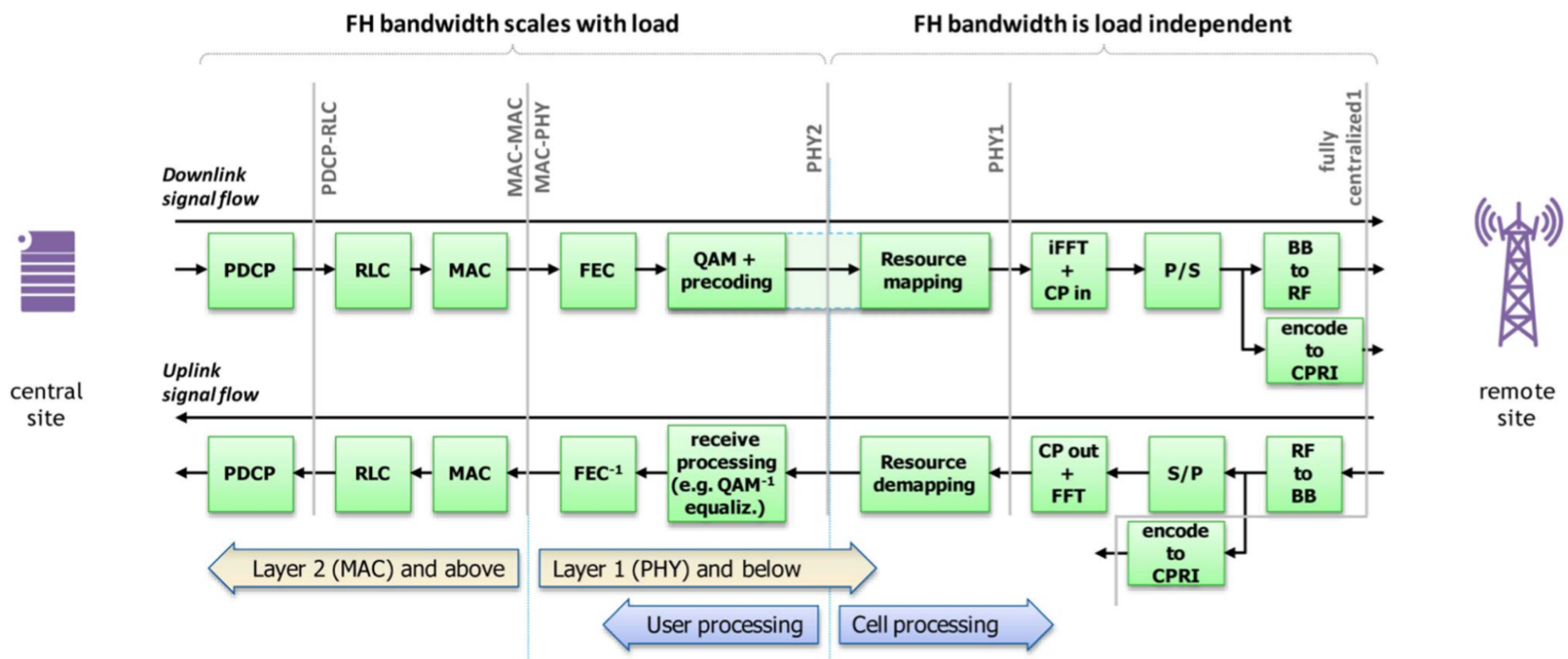
Midhaul with split processing

- Splitting the wireless processing chain so that the capacity on interface is dependent on the amount of data to be transmitted over the air
- “PHY2” separates processing of user data from processing of cell signals with a bit rate in the range 0% - 20% of the CPRI bit rate
- Split points has impact on Radio coordination (PHY1 and PHY2 still OK) and energy savings (Layer 1 functions are the most consuming)



Further study on critical C-RAN technologies”, White Paper by NGMN Alliance

T. Pfeiffer, “Next Generation Mobile Fronthaul and Midhaul Architectures”, IEEE/OSA (JONC), 2015

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Evolution from 4G to 5G transport

- Backhaul services (user rate dependent) with increased capacity requirements (i.e., tens of Gbps or more)
- Centralized architectures will have to be revisited to consider the new requirements:
  - m-MIMO might create bottlenecks in the transport if not carefully addressed
  - Midhaul solutions can help but there is a tradeoff with
    - Achievable level of radio coordination
    - Benefits of C-RAN from the mobile network side are drastically reduced (some of the more energy consuming functionality are again distributed)
- No “one solution fits all” approach, but rather a solution with/without centralized processing depending on the requirements of on the specific 5G service(s)
- Need to map 5G service requirements into transport requirements

5G requirements

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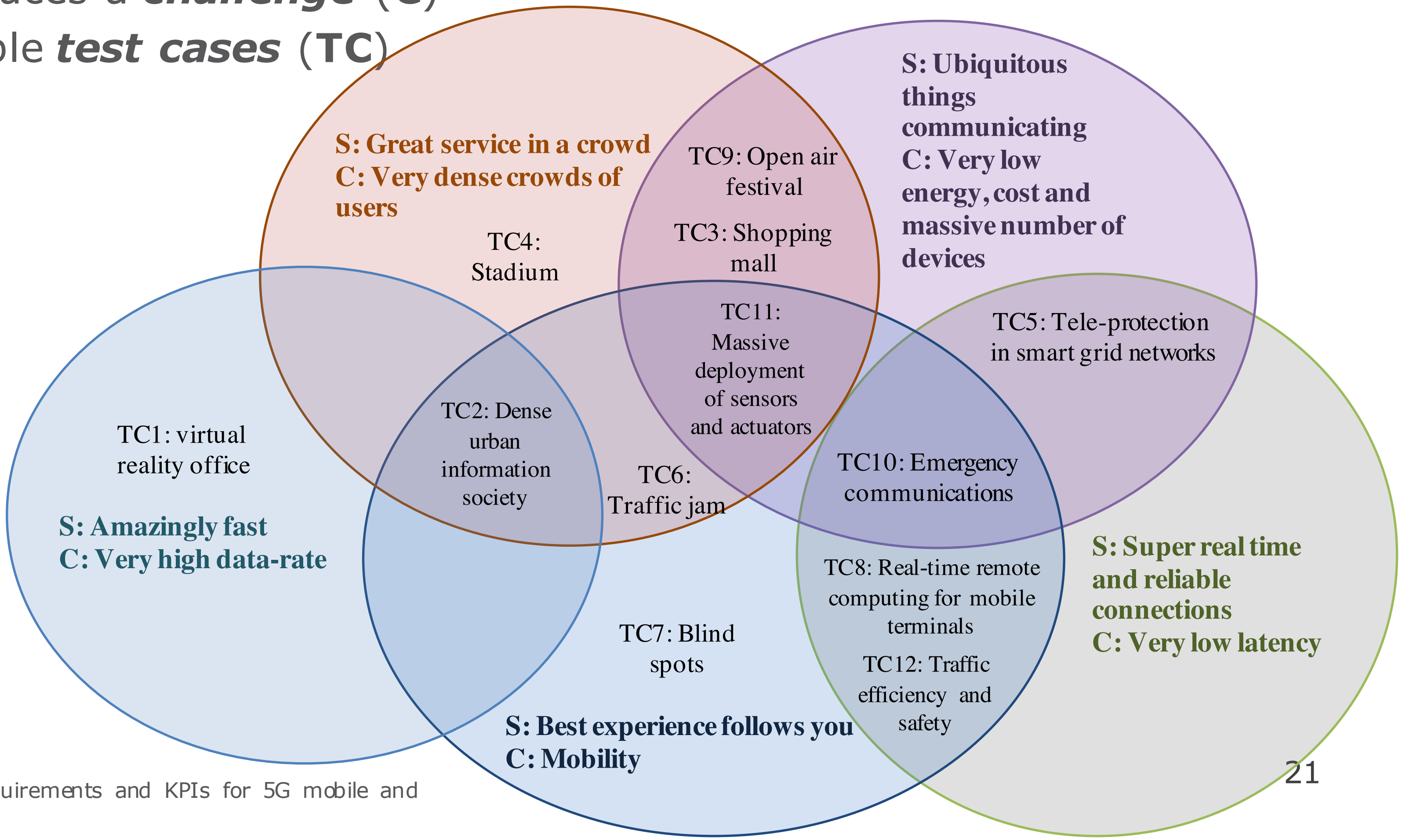
- EU FP7 METIS 2020 project: laying the foundation of 5G[1]
- 5G defined in terms of ***scenarios*** (**S**) supported
- Each scenario introduces a ***challenge*** (**C**)
- Each scenario multiple ***test cases*** (**TC**)



[1]METIS deliverable D1.1, "Scenarios, requirements and KPIs for 5G mobile and wireless system", April, 2013.

5G transport requirements

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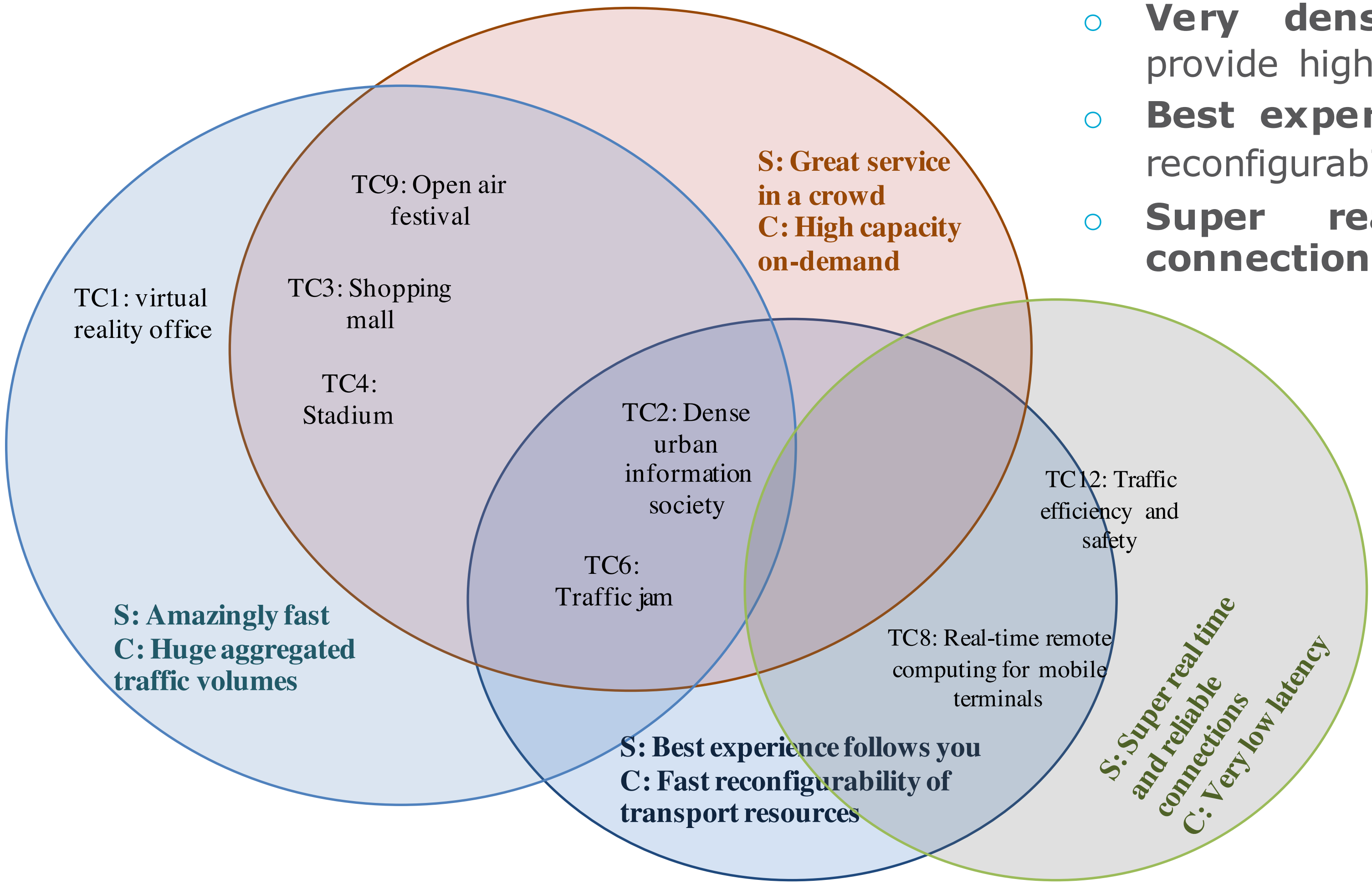
- The 5G challenges → transport challenges:



- **Very high data rate** → huge aggregated traffic volumes
- **Very dense crowds of users** → provide high capacity on-demand
- **Best experience follows you** → fast reconfigurability of transport resources
- **Super real time and reliable connections** → very low latency

- The **massive number of connected devices** not a major issue: the traffic from a large number of machines over a geographical area will be aggregated in the transport

M. Fiorani, et al., "Challenges for 5G Transport Networks", *in Proc. of IEEE ANTS*, 2014.

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How to enable these functionalities?

- Two main directions for provisioning high capacity on-demand and in a flexible way
- **Overprovisioning**: high capacity on-demand with (possibly) fast resource reconfiguration is satisfied thanks to the ubiquitous availability of ultra-high capacity transport
  - Pros: relatively low complexity at the control plane
  - Cons: potentially high cost because of inefficient use of network resources
- **"Intelligence"** in the transport infrastructure
  - **Dynamic resource sharing:** re-configurable systems for dynamically sharing limited transport resources
  - **Network functions virtualization (NFV)**: dynamically push network functions to different locations, e.g., closer to the users so that a portion of the traffic requests can be served locally

M. Fiorani, et al., "On the Design of 5G Transport Networks," *Springer Photonic Network Communications (PNET) Journal*, 2015

How to add intelligence to transport?

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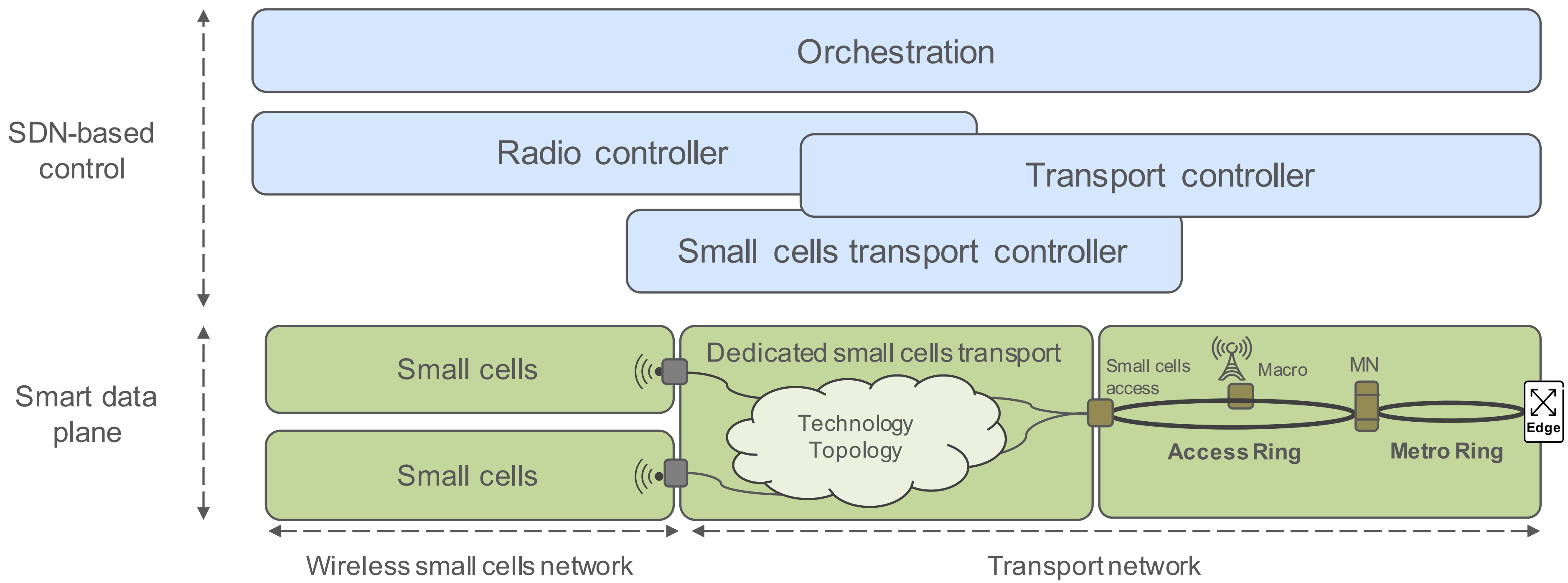
- Programmability/flexibility (resource sharing and/or NFV) puts requirements on the control plane
- A SDN-based control plane with end-to-end orchestration could provide a framework for such a scenario
- One possible control plane architecture might be:



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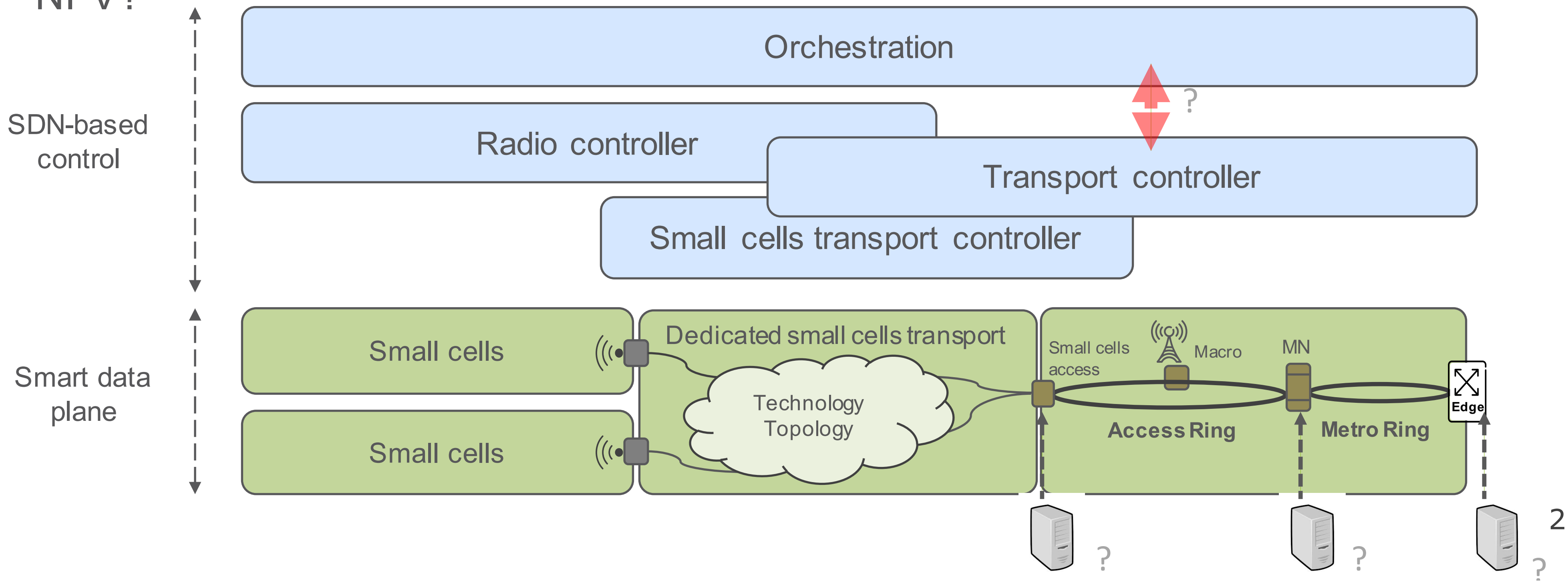
Some interesting open questions

- If orchestration helps in using resources efficiently → what's the best level of details to be used to advertise the availability of transport resources?
- With orchestration what are the advantages brought by dynamic resource sharing?
- What are good (i.e., power/cost) architectural options that allow the placement of NFV?



Transport resources abstraction: the C-RAN use case

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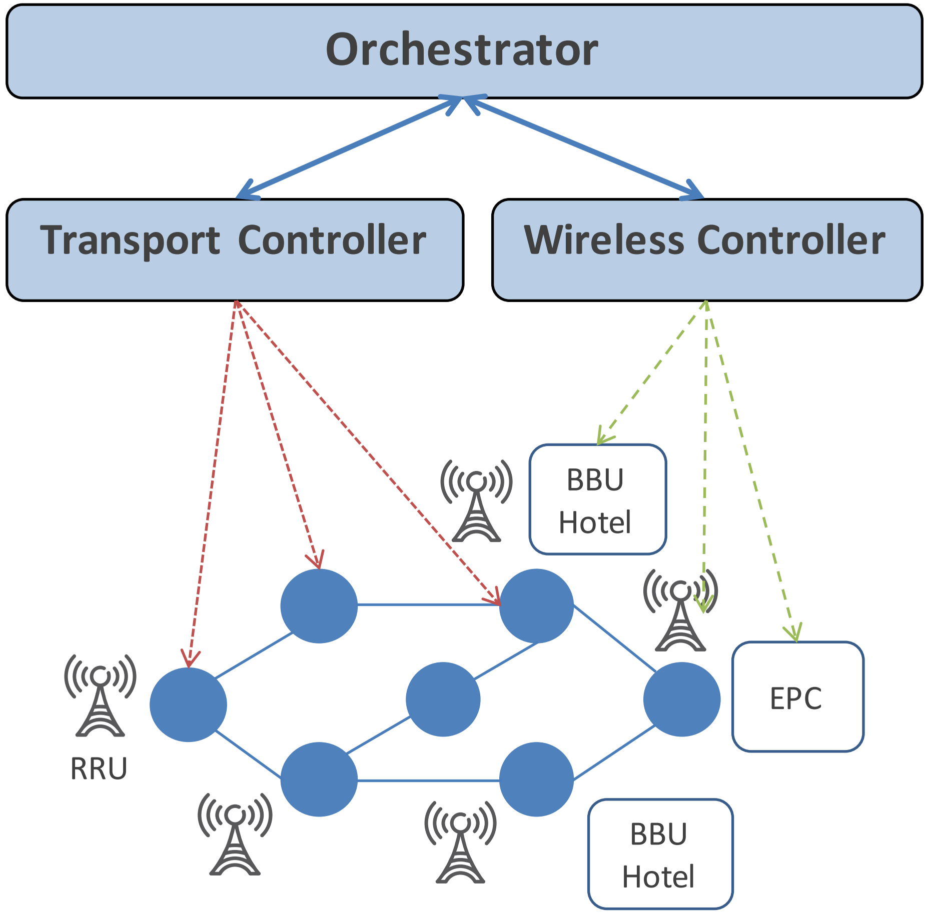
- Orchestration implies knowledge of condition of the wireless and the transport network
- Every time a new RRU needs to be turned on, lightpath needs to be established between RRU and BBU hotel, as well as one between BBU and EPC
- Tradeoff between abstraction level (i.e., performance) and complexity (i.e., scalability, messaging overhead)



M. Fiorani, et al., "Transport Abstraction Models for a SDN-Controlled Centralized RAN", *IEEE Communication Letters*, August 2015.

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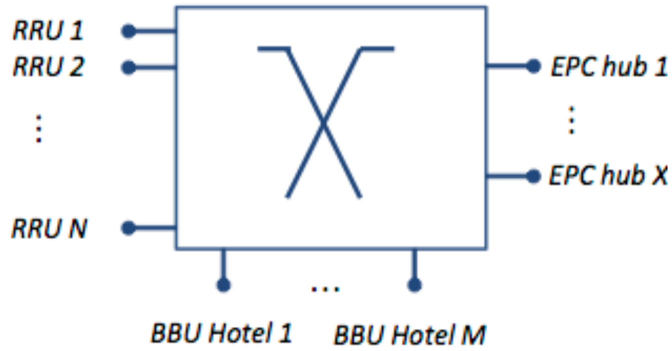
Abstraction policies

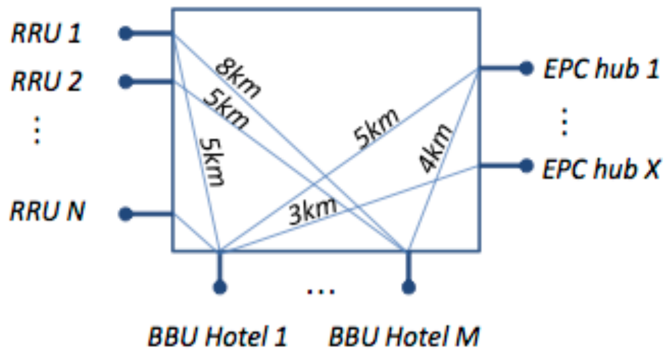
Big Switch Basic

- Transport network presented to the orchestrator as a single node (switch)
- No updates between transport controllers and orchestrator required



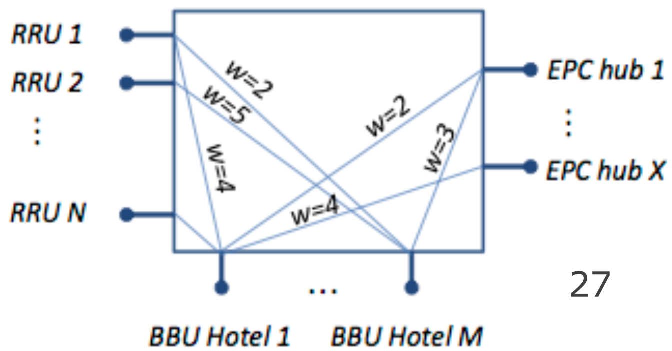
Virtual Link with Constant Weights

- Transport network presented to the orchestrator as a number of potential connections (virtual links) among switch ports
- Each virtual link is assigned a constant weight
- Whenever *connectivity is lost* between 2 switch ports corresponding *virtual link* is *deleted*
- Updates between controller and orchestrator are required



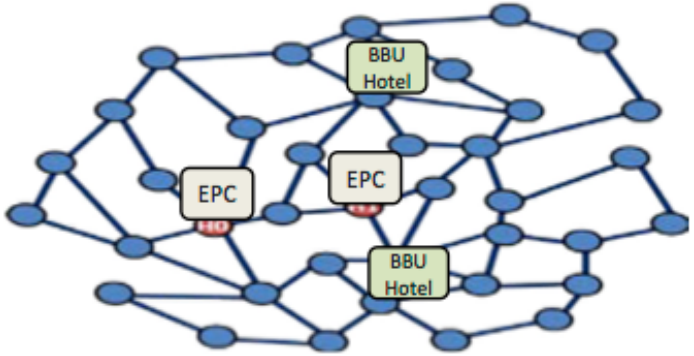
Virtual Link with Variable Weights

- Transport network presented to the orchestrator as a number of potential connections (virtual links) switch ports
- Each virtual link is assigned a variable weight, i.e., # of wavelength between 2 switch ports
- Updates between controller and orchestrator are required

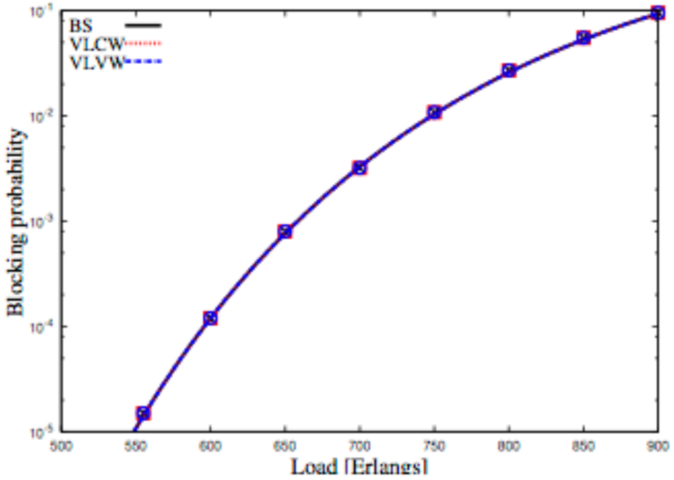


Resources abstraction: results

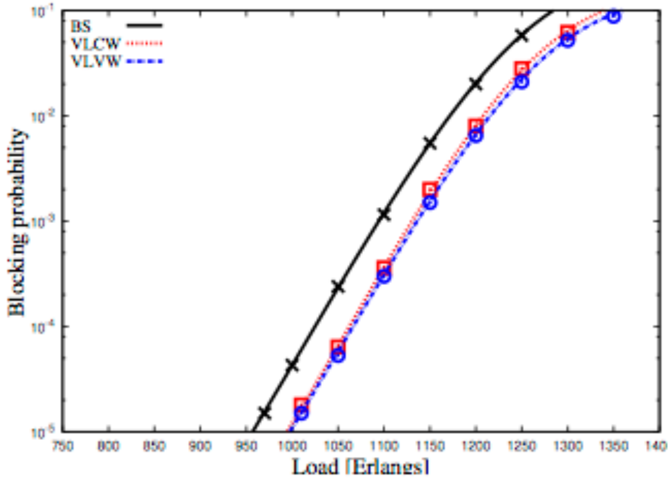
- 38 nodes, 2 BBU Hotels, EPC accessible via two node



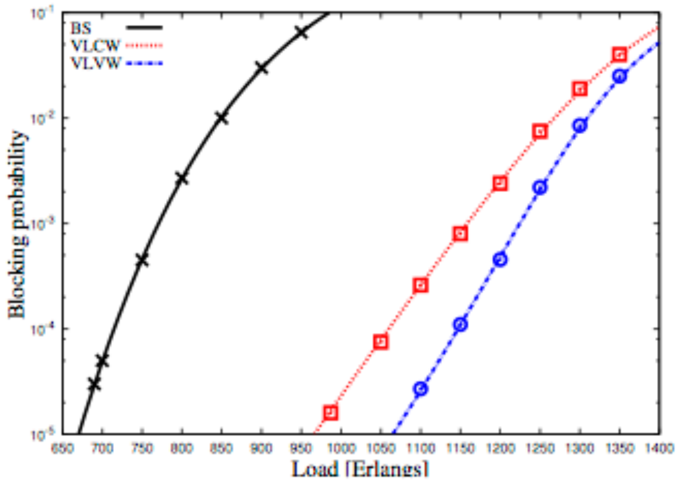
(a) Metro topology.



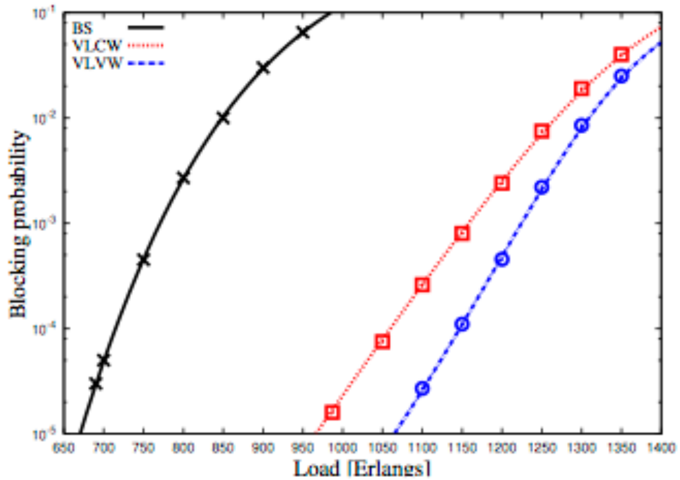
(b) $\eta = 0.5$.



(c) $\eta = 0.9$.



(d) $\eta = 1.0$.



(e) $\eta = 1.1$.

Blocking probability values for η=1.

Parameter	Load	BS	VLCW	VLVW
W=256	1160	0.1440	0.0010	0.0002
W=128	570	0.1433	0.0010	0.0002
W=64	280	0.1431	0.0010	0.0002
h=100	1150	0.1440	0.0010	0.0002
h=50	1160	0.1440	0.0010	0.0002
h=25	1170	0.1440	0.0010	0.0002
$\sum_{i=1}^{N_H} D^i_{BBU}$=11	1160	0.1440	0.0010	0.0002
$\sum_{i=1}^{N_H} D^i_{BBU}$=9	940	0.1418	0.0010	0.0002
$\sum_{i=1}^{N_H} D^i_{BBU}$=7	730	0.1408	0.0010	0.0002

(f) Sensitivity analysis.

- η = ration of amount of radio resources vs. transport resources

$$\eta = \frac{\lceil (1+b) \cdot \sum_{i=1}^{N_H} N^i_{BBU} \rceil}{W \cdot \sum_{i=1}^{N_H} D^i_{BBU}}$$

Advantages of dynamic resource sharing

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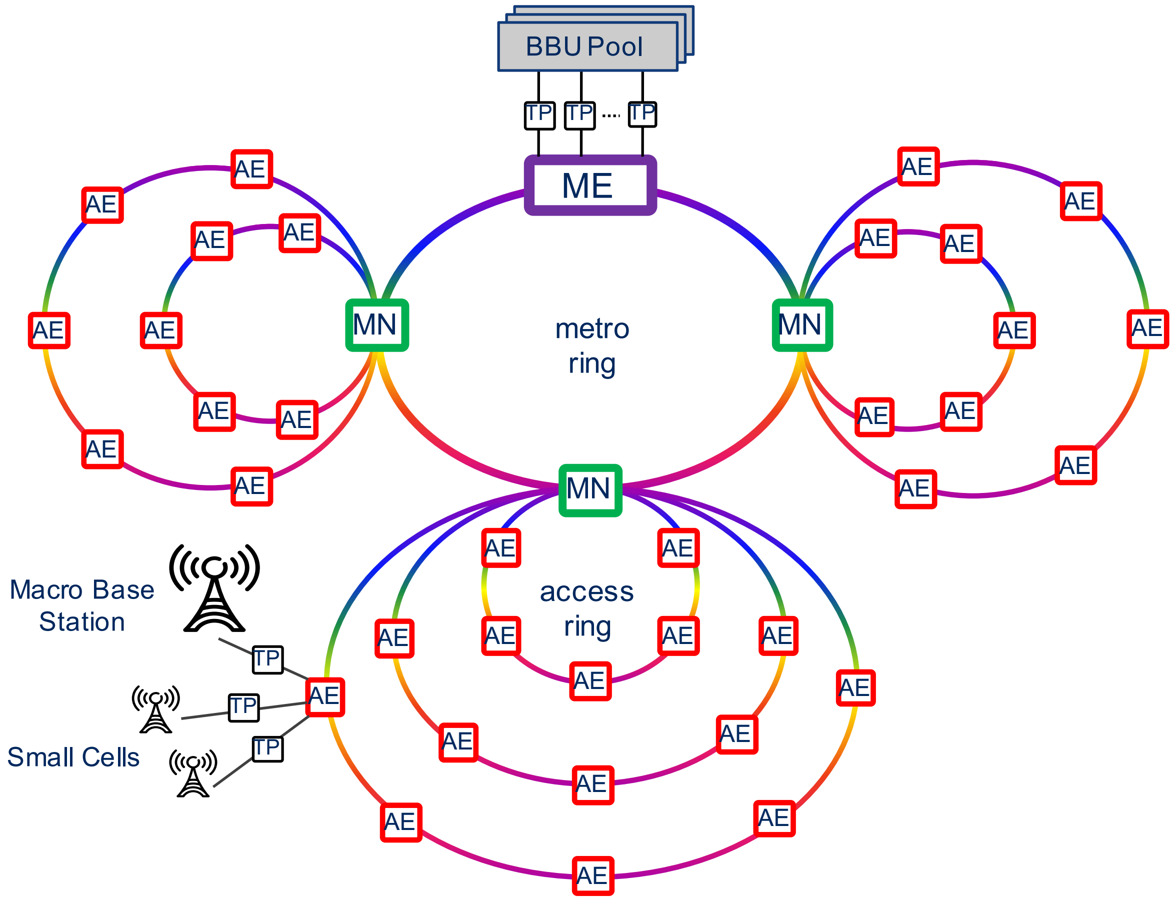
- 7 access rings with 5 access edge (AE) nodes per ring
- 1 metro ring with 3 metro nodes (MNs) and 1 ME connected with BBU pools
- 1 macro base station (MBS) and N small cells (SCs) per AE
- Daily traffic variations over the ARs (residential vs. office areas vs. city center)



Daily traffic variations over the ARs

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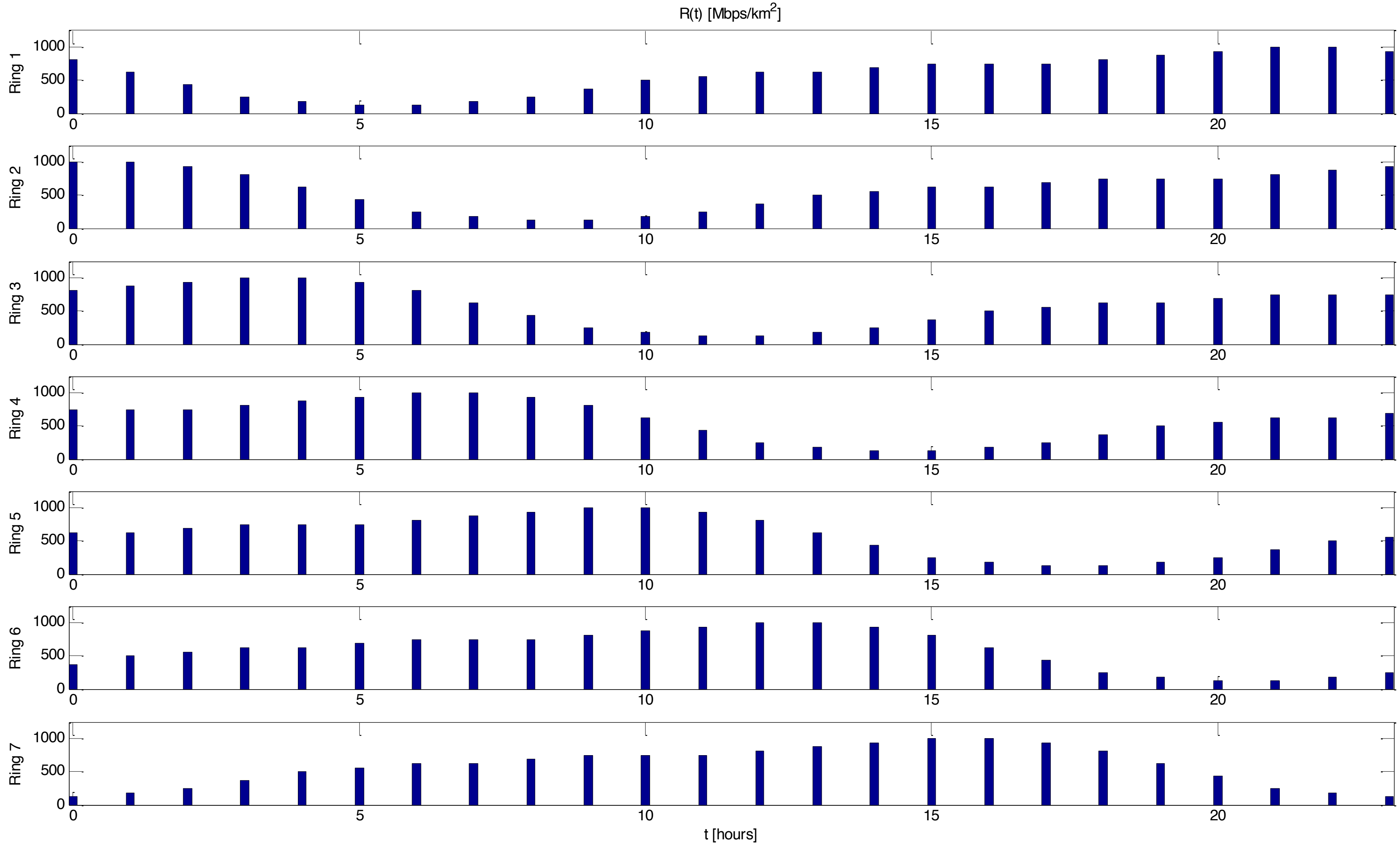
- Traffic profile over 24h for each ring, shifted by 3 hours



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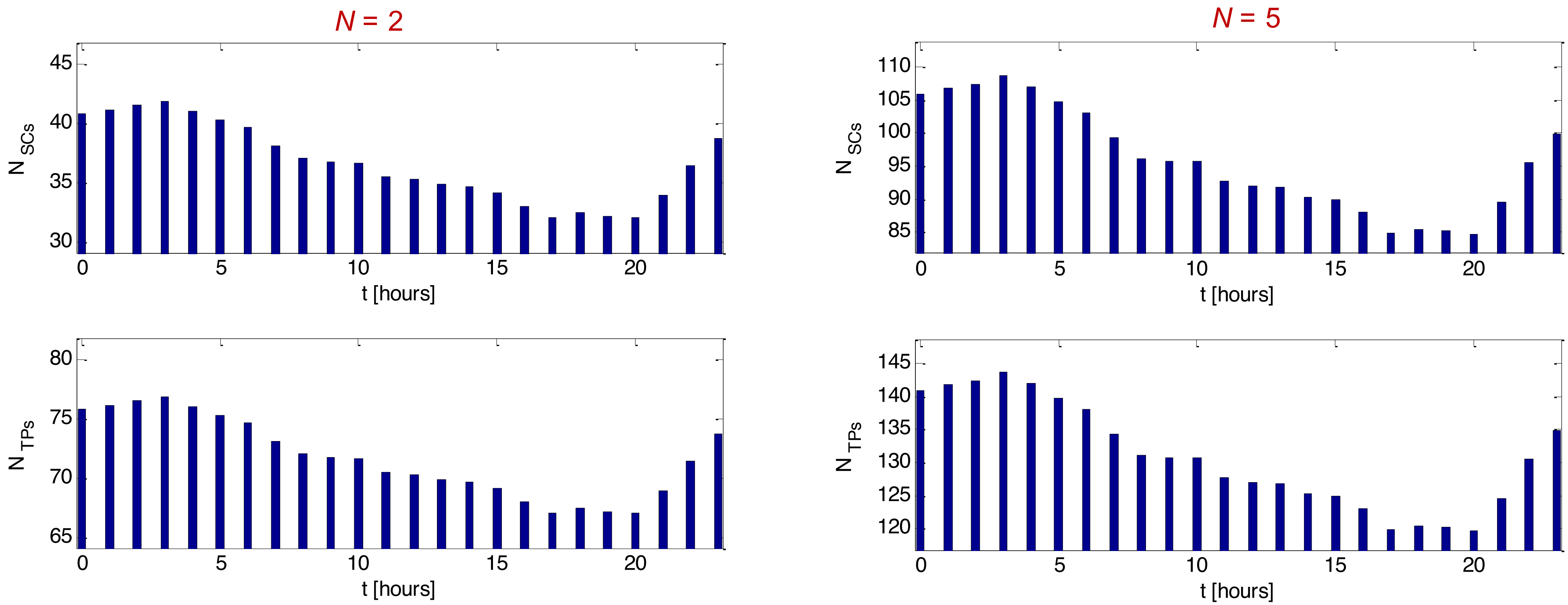
Simulation results

- No. of experiments = 100, Available lambdas per pool = 96; N=2



	No. of transponders for *N* = 2	No. of transponders for *N* = 5
Peak Dimensioning	35 (for MBS) + 70 (for SCs) = 105	35 (for MBS) + 175 (for SCs) = 210
Dynamic Resource Sharing	77	144

⇩ Saving = 26.7%

⇩ Saving = 31.4%

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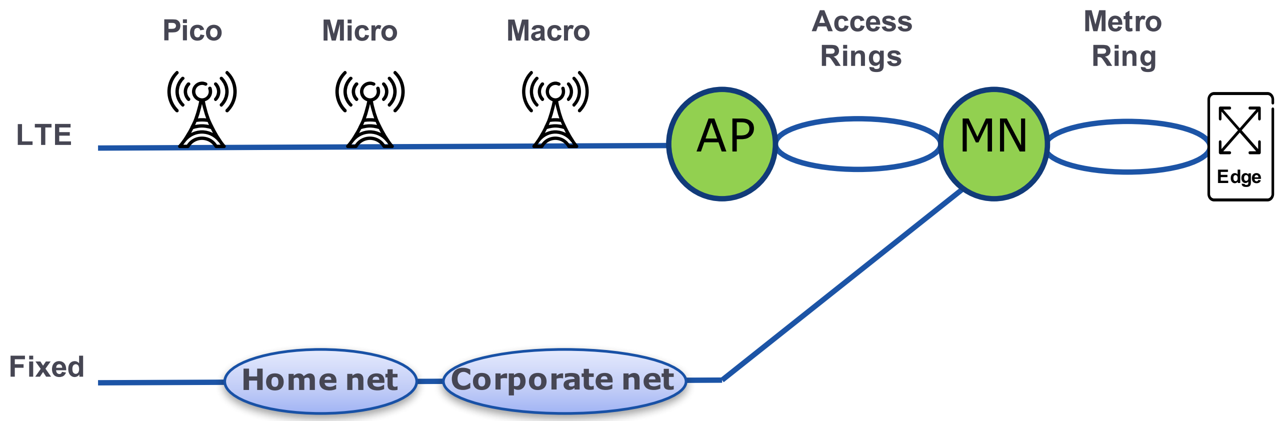
Data plane options for NFV

- "Metro simplification" is a power/cost efficient architecture allowing for the reduction of the number of local exchanges (i.e., simplification)*
- Two types of rings
  - Optical access ring: collects the traffic from mobile network
  - Optical metro ring: aggregates and transmits toward the service edge



* Skubic B., Pappa I., "Energy consumption analysis of converged networks: Node consolidation vs metro simplification", *OFC/NFOEC*, 2013

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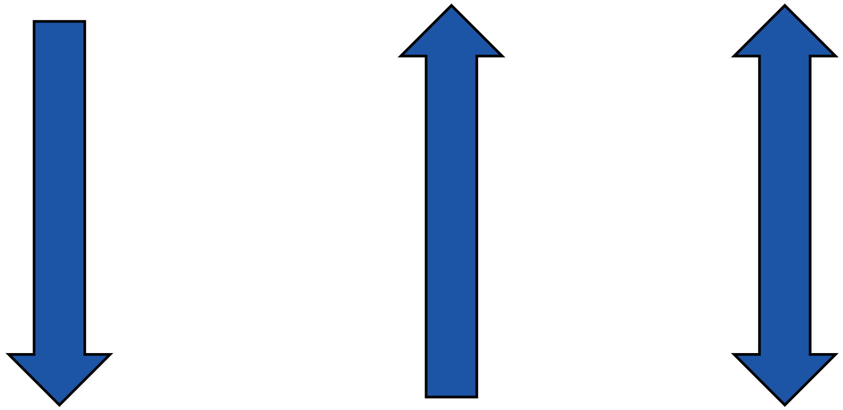
KPIs and objective

- Architectures for metro simplification:
  - Optical DWDM switching
  - Electronic packet switching
  - Electronic packet switching + caching



Complexity
required number of complex network components

Capacity
required number of optical channels

Power/Cost?

- Objective:
  - Assess power consumption/cost of different architectures for metro simplification
  - Identify the most promising solution(s)

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Scenario: very dense urban area

Scenario:

1. CO service area: 2 km^2
2. Macro: 60 (30 per km^2)
3. Micro: 600
4. Pico (indoor):6000
5. Buildings (in 2 km^2 area): 400
6. Businesses: 10 per building
7. Homes: 50 per building
8. People: 200k
9. People (office): 160k
10. People (res): 40k
11. Devices: 200k-2M

Service Requirements :

1. Macro: 228 Mb/s
2. Micro: 90 Mb/s
3. Pico (indoor): 132 Mb/s
4. Residential user: 16 Mb/s
5. Business user: 202 Mb/s

	Number per AP	Rate [Gbps]	Traffic [Gbps] per AP	Total Traffic [Gbps] for 60 APs
LTE				
Macro	1	0.228	0.228	13.7
Micro	10	0.090	0.9	54
Pico	100	0.132	13.2	792
Fixed				
Residential	333	0.016	5.33	320
Business	67	0.202	13.47	808

** Note that only LTE backhaul (no CPRI) is assumed.

M. R. Raza, M. Fiorani, B. Skubic, J. Mårtensson, L. Wosinska, P. Monti, "Power and Cost Modeling for 5G Transport Networks," *in Proc. of IEEE ICTON,* 2015

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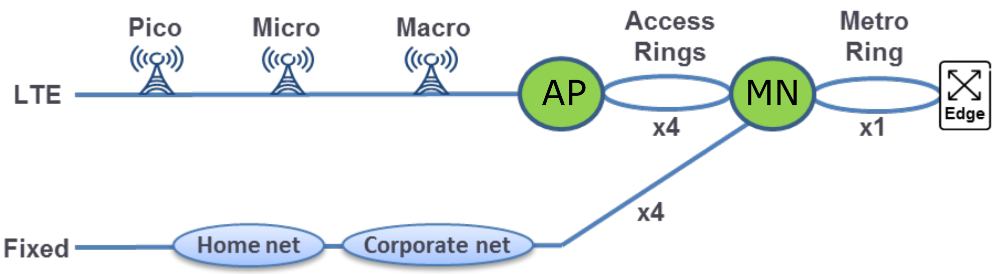
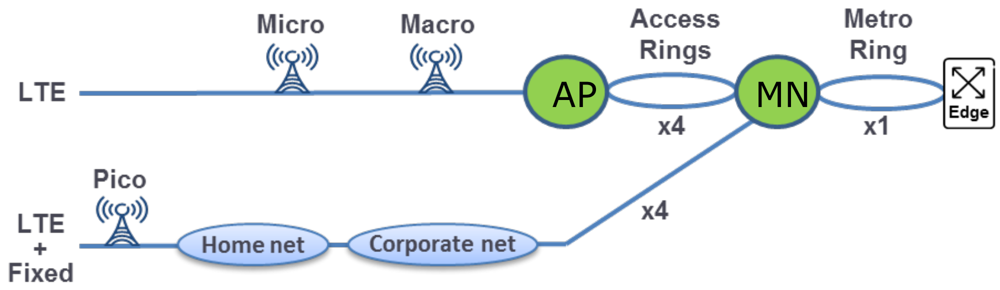
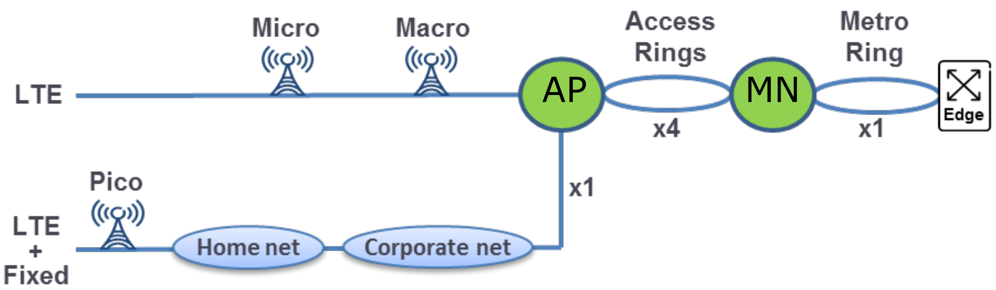
Data plane architecture options



Deployment A



Deployment B



Deployment C

Case I = optical switching at MN / no caching
Case II = optical switching at MN / caching at AP
Case III = electronic switching at MN / no caching
Case IV = electronic switching at MN / caching at MN
Case V = electronic switching at MN (hybrid 10G/100G) / no caching
Case VI = electronic switching at MN (hybrid 10G/100G) / caching at MN

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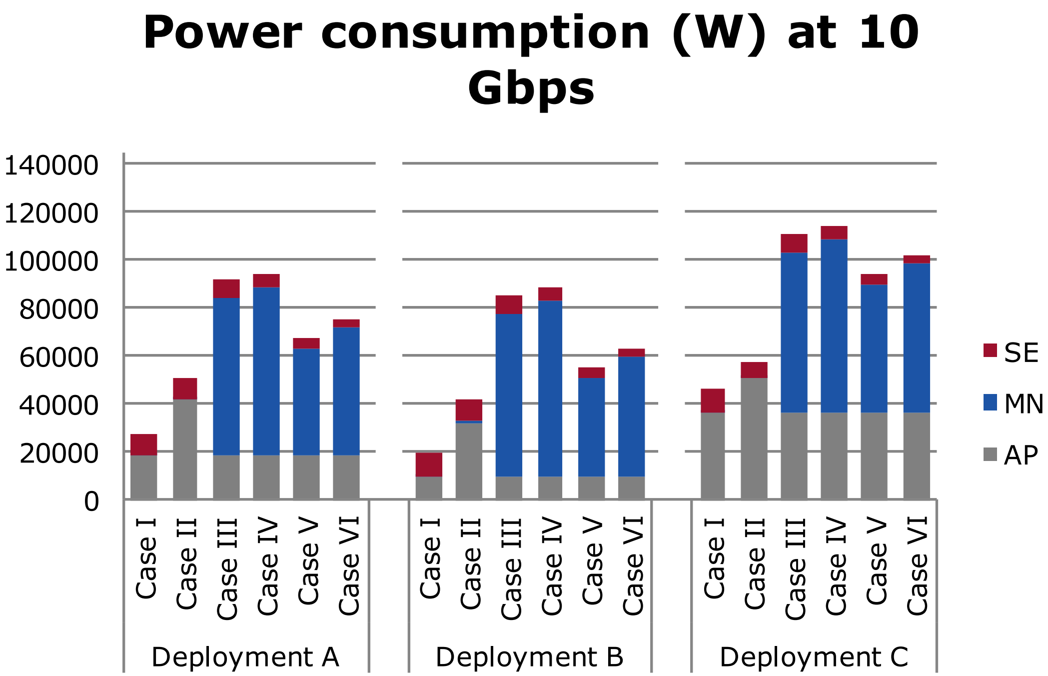
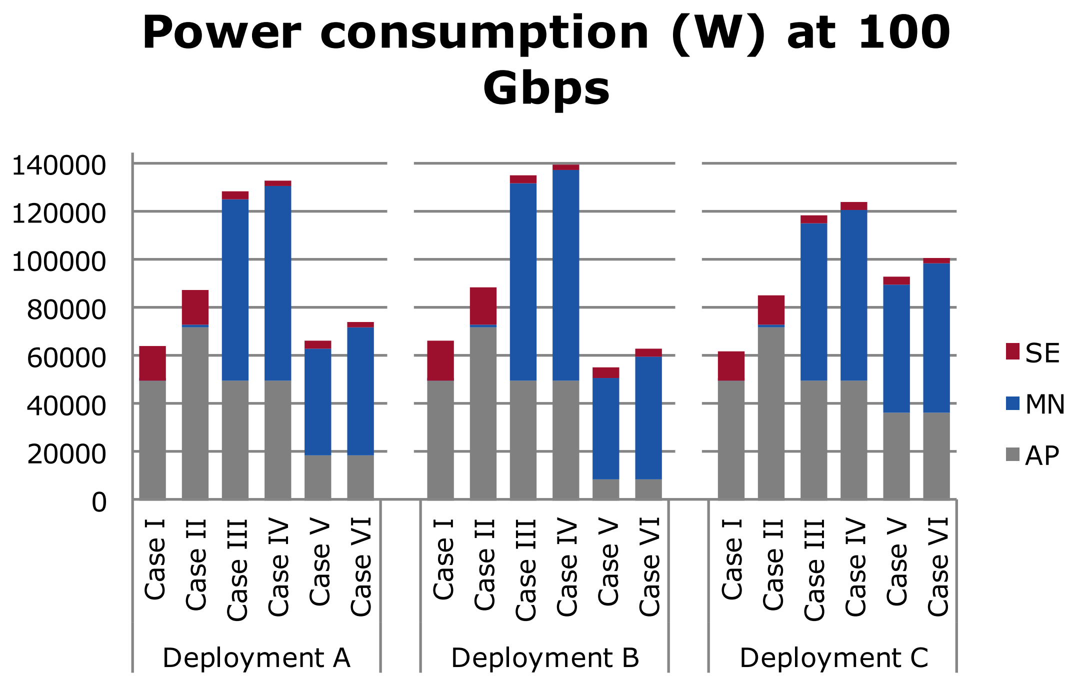
Power consumption evaluation





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	Power Consumption [Watt]	Cost [CU] in Year 2014	Cost [CU] in Year 2018
Ethernet 10 Gbps port	38	1.56	0.89
Ethernet 100 Gbps port	205	28.89	10
WSS 10 Gbps / 100 Gbps	20	5.56	3.89

M. R. Raza, M. Fiorani, B. Skubic, J. Mårtensson, L. Wosinska, P. Monti, "Power and Cost Modeling for 5G Transport Networks," *in Proc. of IEEE ICTON,* 2015

Cost evaluation: the 2014 case

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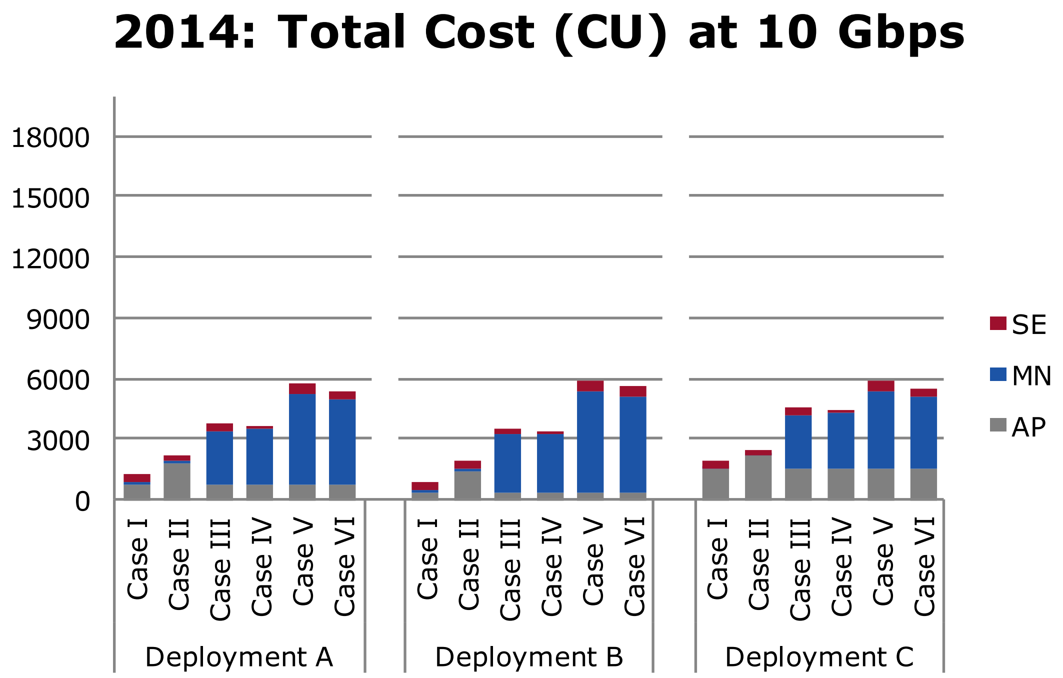

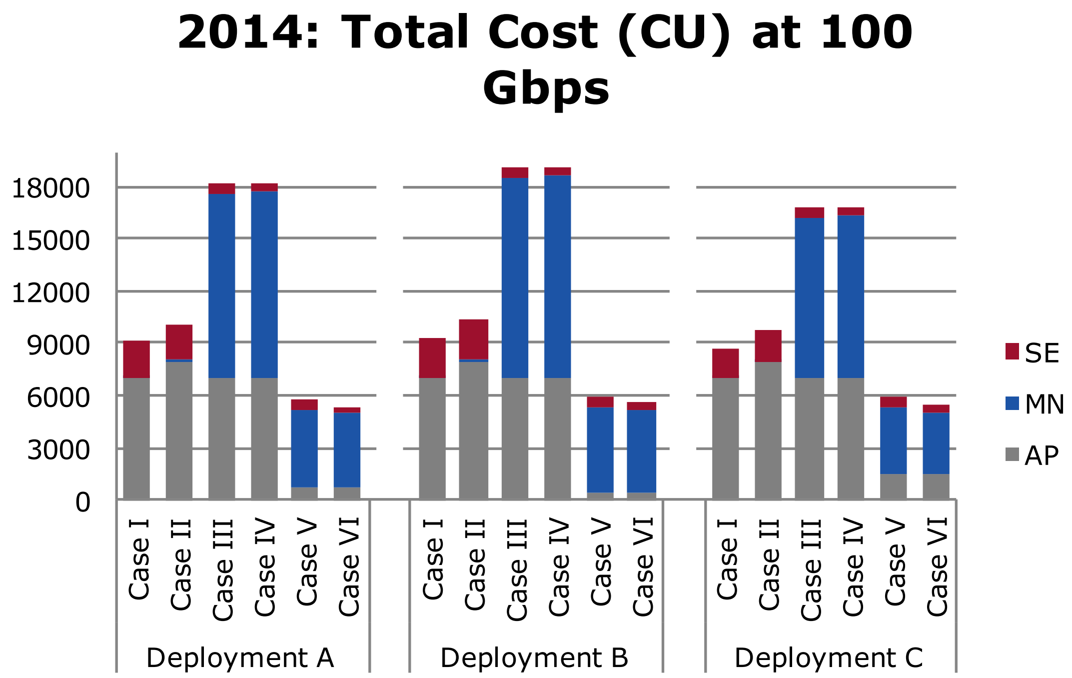

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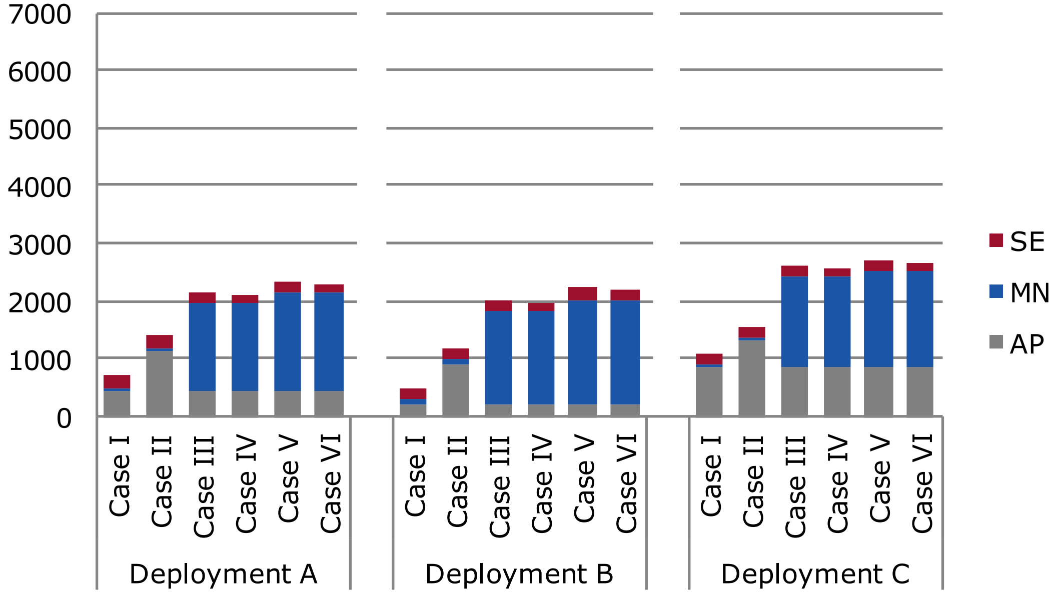
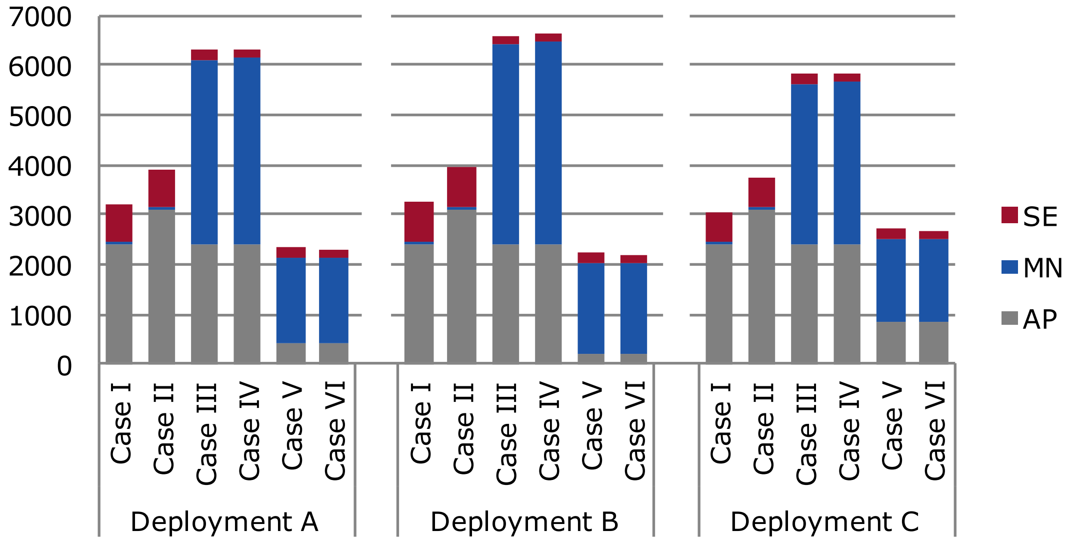
Cost evaluation: the 2018 case

2018: Total Cost (CU) at 10 Gbps



2018: Total Cost (CU) at 100 Gbps



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Concluding remarks

- Focus of new 5G radio technologies: high peak-rates per subscriber; handle large number of simultaneously connected devices; better coverage, outage probability, and latency

- Will not have a “one solution fits all” approach, but a solution with/without centralized processing depending on the requirements of on the specific 5G service(s)

- Transport will evolve towards a *programmable* infrastructure able to *flexibly* adapt to the various 5G service needs

- Highlighted a few directions on how programmability and flexibility can be achieved (*joint orchestration with dynamic resources sharing*) and demonstrated some of benefits that can be obtained

- Development and deployment of new radio and transport networks need to go hand in hand in order to be able to get the best of out the new 5G communication paradigm

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Optical 5G Transport: Challenges and Opportunities

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How to enable these functionalities?

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- The type of resources that can be dynamically virtualized depends on:
  - User traffic type
  - Business model (agreement between wireless and transport providers)
- Example of resources that can be virtualized:
  - Wireless network functions: BB processing, evolved packet core (EPC)
  - Transport network functions: packet aggregation
  - Cloud resources: cache/storage
- Servers needs to be available in different network locations: