Fixed mobile convergence

Fixed-mobile convergence

Question: how to increase mobile capacity by 1000 times (by 2033??)

Some popular estimates of factors for capacity increase:

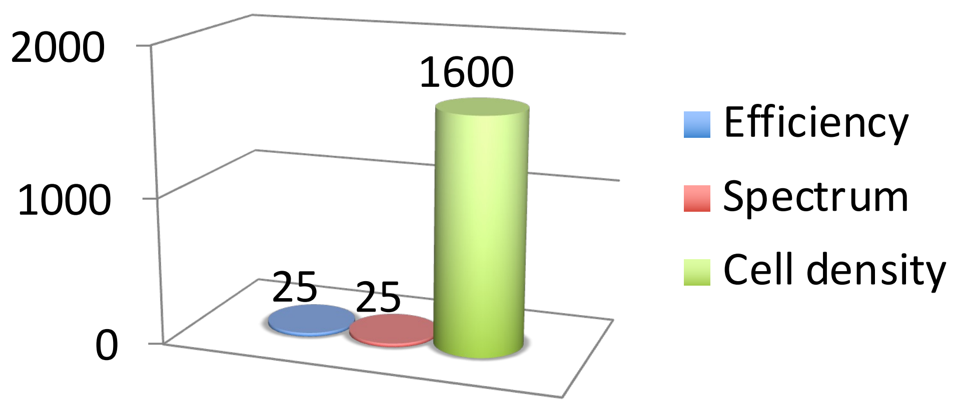
- Efficiency (MIMO, Smart scheduling, enhanced-CoMP) -> x3
- Spectrum (Carrier Aggregation, New Bands, Authorized Shared Access) -> x2
- **Density (Advanced Macros, HetNet management, Flexible small cells)**

➔ $$\frac{1000}{2\cdot 3} = 167$$

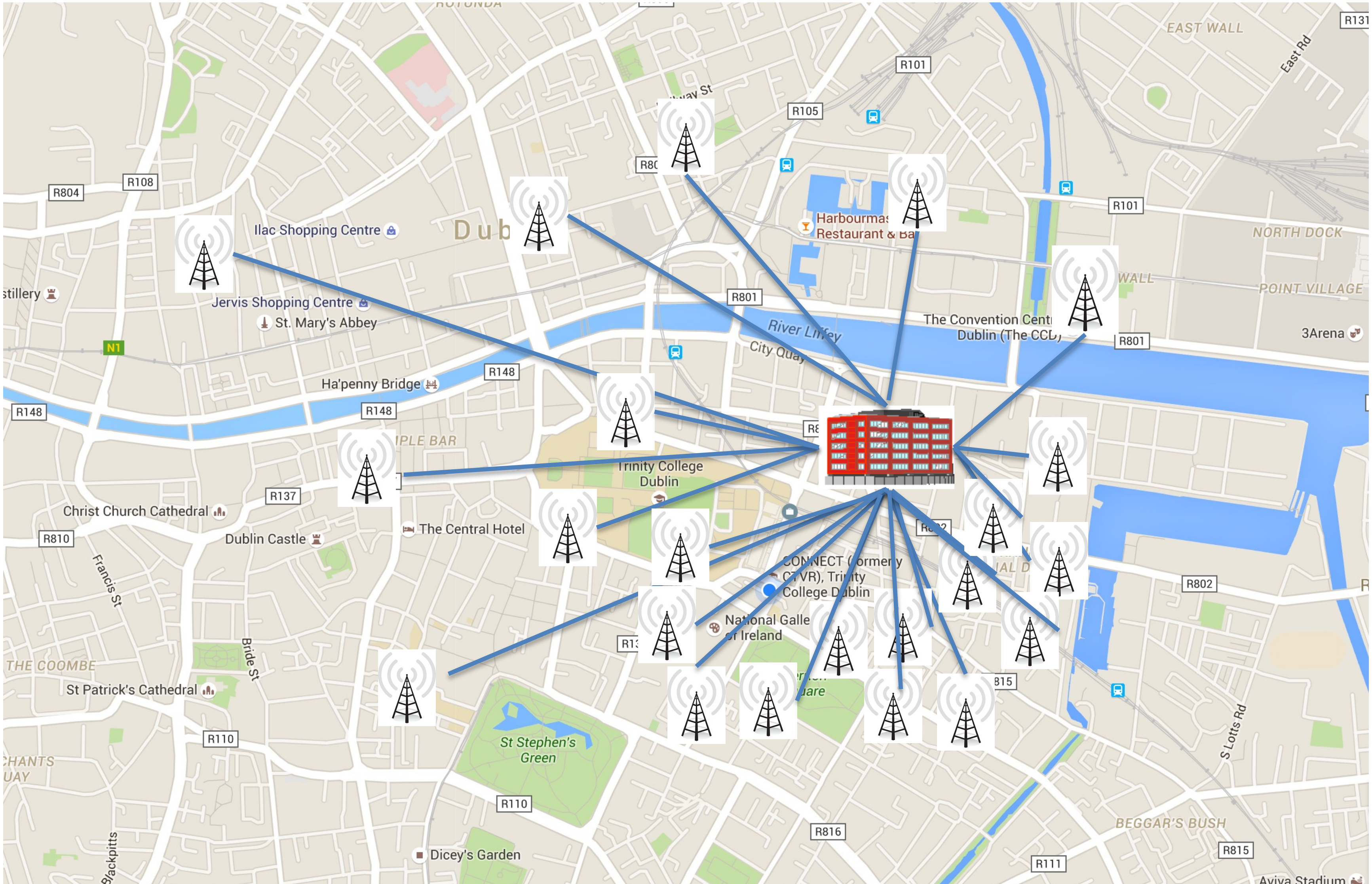
Source: Nokia, enhance mobile networks to deliver 1000 times more capacity by 2020

This is in line with what happened in the past:

Cooper's law (of spectral efficiency): 1 million times improvement in the past 45 years



Higher Cell Density



Why is high cell density a well known 5G challenge?

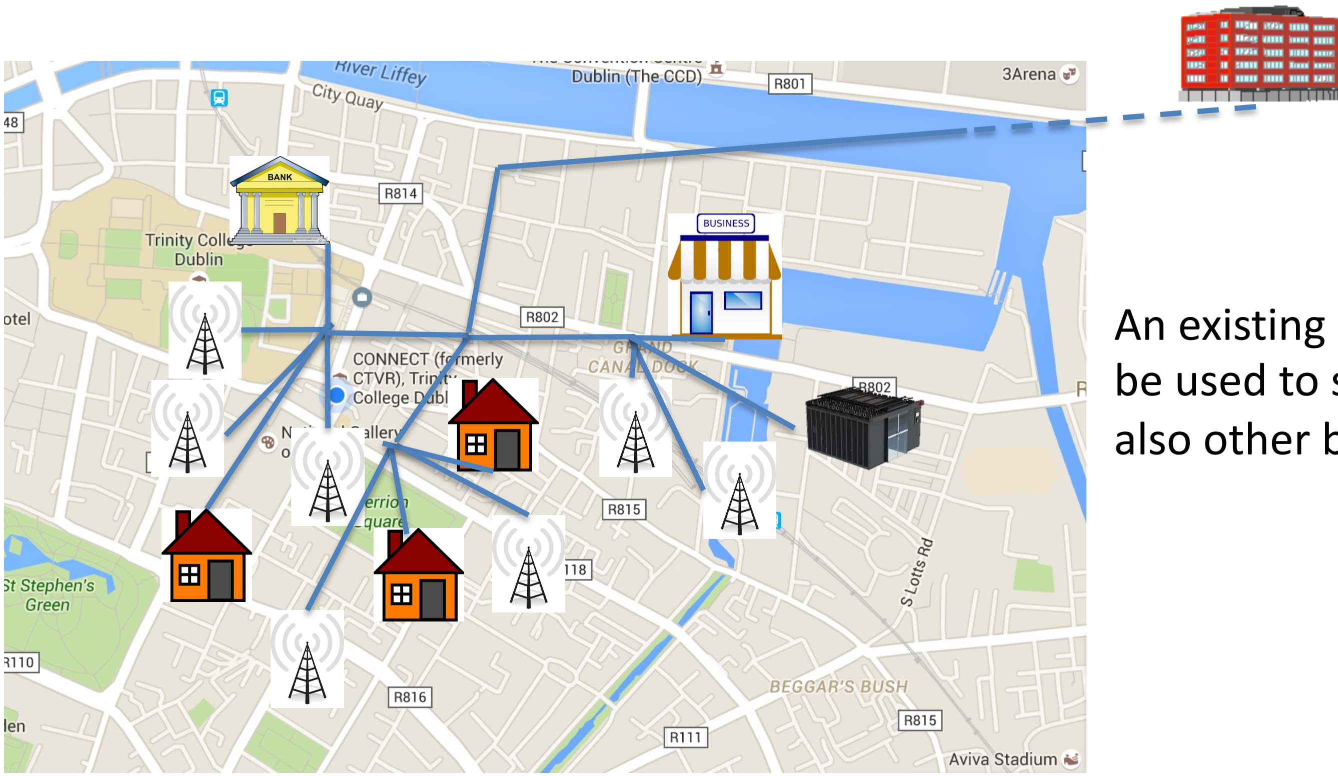
A. There will be too many radio emissions that could damage our health
B. The dense copper network interconnecting the base stations will create too much interference
C. There will be too much concentration of energy to feed the base stations
D. The fibre backhaul network for the cells will be more expensive than the radio network itself

Cell density issue

- Backhauling a macro BS with fibre, is feasible from a cost perspective, because the BS aggregates many users, thus it generates considerable revenue

- With higher cell density, each (small) cell only serves a few users at a time (this is the way it can provide higher rates)
  - This means the revenue of that small cell is much less than that of a macro cell
  - Thus it probably cannot justify the cost of an individual fibre connection
    - …unless the use is willing to pay much more for the data plan (which is typically not the case)

Shared PON for mobile backhauling



An existing FTTH infrastructure can be used to serve mobile cells, but also other businesses

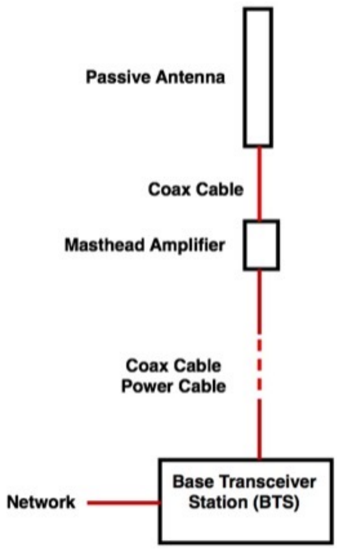
- An optical access network, if well architected can allow service multiplexing: any access point (a home, a macro cell, a small cell, a business, a micro cache or small data center) can request assured capacity from the low Mb/s to multiple 100s Gb/s.

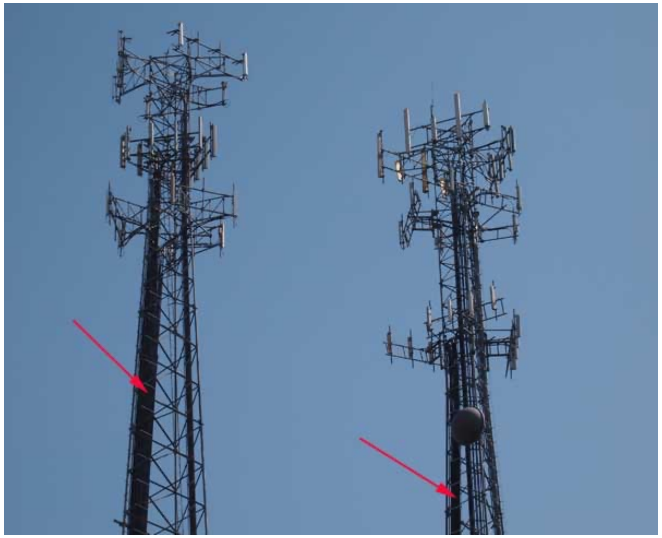
Coax in distributed RAN

- Up to 4G, base stations used to be distributed, meaning that each cell has a mast, antenna as well as all the radio and digital processing units up to layer 3.

- Recently this is changing, and the digital processing part starts becoming centralized

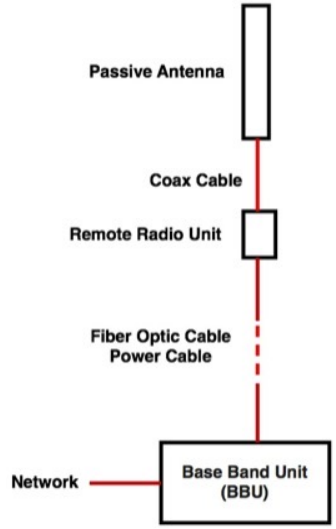
- The idea comes from a technique that was developed for a different reason.
  - In the past the antenna at the top of the mast was connected to the BaseBand Unit (BBU) at the bottom through a coaxial cable
  - This had issues as a large coax (5cm – to decrease transmission loss) was needed to connect the bottom of the mast to the top: generating problems of bulkiness, wind resistance and ultimately cost.

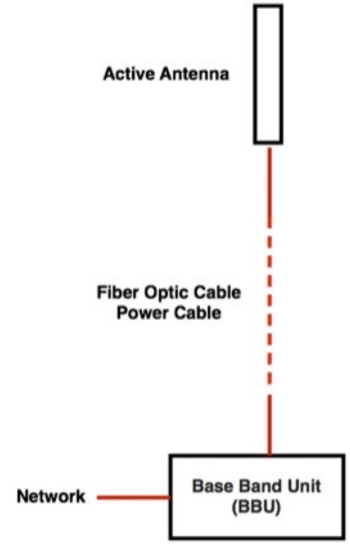




Fibre optics in distributed RAN

- In order to reduce this issue, vendors have come up with a solution to replace the coax with fibre
  - One single fibre has enough capacity to replace all copper wires and takes up a very small space.



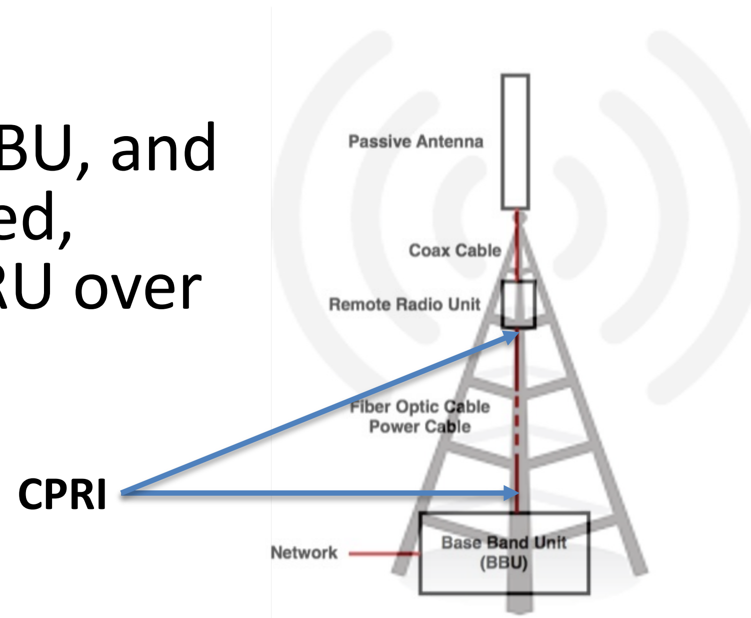


Newer integrated solution

CPRI

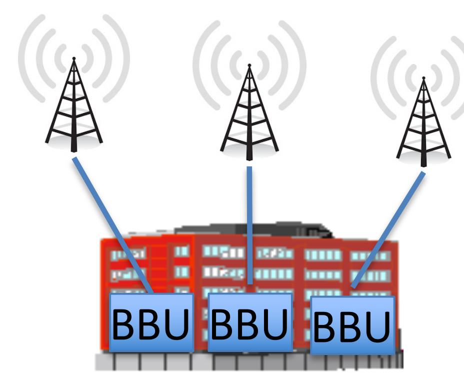
- The connection between the BBU and RRU over fibre is through a protocol called Common Public Radio Interface (CPRI).
  - Cooperation between Ericsson, Huawei, NEC, Nokia.
  - There is also another one called Open Base Station Architecture Initiative (OBSAI), by Hyundai, LG, Nokia, Samsung and ZTE.

- The idea is that all digital processing is done at the BBU, and then the RF signal is sampled, digitized and sent to the RRU over fibre.



BBU Hoteling

- This concept then generated new ideas.
- Once you define a fibre interface between BBU and RRU, you get in principle the advantages of fibre transmission (longer transmission distance and large capacity)
- So if a fibre link can easily cover distances of many km, why not placing the BBU in a completely different location:
  - For example I can place the BBU inside a building, where it's more secure, less prone to weather condition, and I can use a place that is more suitable rather than being constrained by the location of the mast
  - In addition I can use the same building to place more than one BBU, each connected through fibre to its own antenna mast.

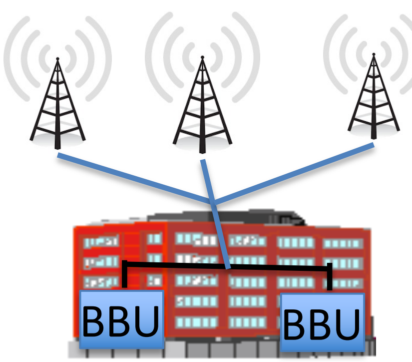


BBU hoteling

BBU pooling

- Then the ideas kept coming, so once you have multiple antenna masts connected to the same building, why not trying some statistical multiplexing of the data and use a smaller number of BBUs (not all cells will be working at peak rate all the time)
  - This was the concept of BBU pooling
  - However it needs a new type of BBU, capable of using multiple masts at the same time and of multiplexing traffic from them

- The idea is now implemented through a concept called Network Function Virtualization (NFV).
- What used to be proprietary hardware boxes, such as firewalls, routers, but also BBUs get implemented through software running on top of off-the-shelf servers
  - So a BBU becomes a software instance running on top of a server and I can create as many of them as I need (provided I have enough processing power)



BBU pooling

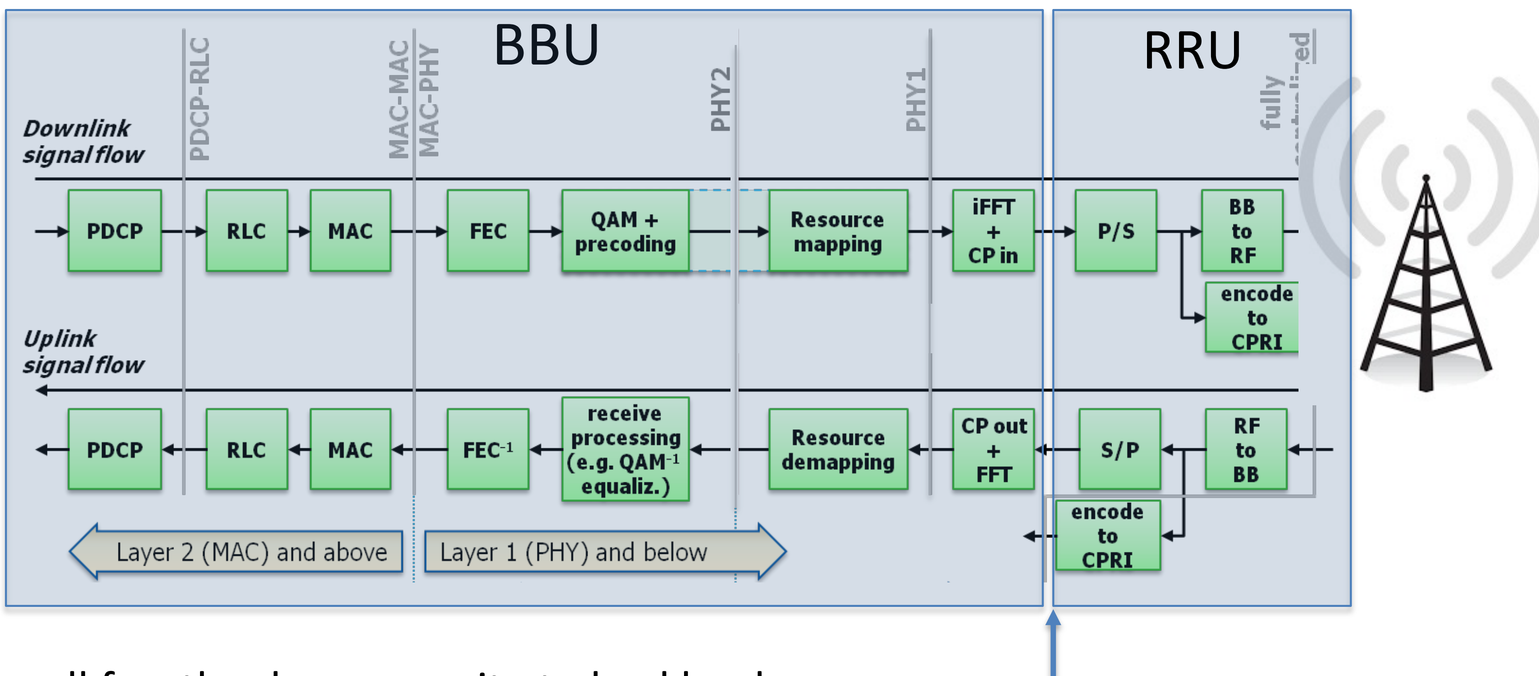
Cloud-RAN

- Finally, once the BBU is software running on a server, you can evolve the concept to cloud computing.
  - You don’t need to place your servers in a number of locations, but you can build a large data centre and do everything in there
  - … or you can even use servers provided by a third party… the real cloud computing

- This is the concept of Cloud-RAN

Fronthaul

- How does CPRI work?
- This is the LTE stack:
  - CPRI puts the division line close to the Antenna



This is call fronthaul, as opposite to backhaul, because the CPRI signal transmitted is part of the front end of the base station

CPRI over fibre

Fronthaul transmission rate

- The fronthaul interface samples the wireless signal and then transmits the I/Q samples over fibre
- It practically transmits a digitized version of the radio wave

- Let's calculate the data rate that it requires:

$$R = R_s \times N_q \times N_a \times N_b \times R_c \times R_l$$

  - R_s is the sampling rate, and is 30.37MHz for a 10MHz wireless bandwidth (notice that there is oversampling)
  - N_q is the number of bits used to digitize each samples and it's typically 15 bits
  - N_a is the number of antennas used
  - N_b is the number of 10MHz frequency bands used
  - R_c is the overhead given by word control ratio (16/15)
  - R_l is the overhead given by he line coding (10/8 or 66/64)

- Also notice that this rate is independent of the actual rate offered to the users. CPRI always transmits the maximum rate independently of actual usage.

RAT vs Fronthaul rates

Examples:

1. Macro cell: 8x8 MIMO, 3 sectors, 5 x 20MHz channels, 64 QAM
   a. RAT rate (ideal case calculations):
      i. 10MHz capacity with 64QAM (i.e., 6 bits per symbol) gives 60 Mb/s, but in practice ~ 40 Mb/s
      ii. For 100 MHZ, x10 = 400 Mb/s
      iii. With 8 MIMO antennas = 400 x 8 = 3.2Gb/s
      iv. With 3 sectors, x3 = **9.4 Gb/s**
   b. Fronthaul rate
      i. R_s=30.37 MHz, N_q= 16, N_a=8 MIMO x 3 sectors = 24, N_b=10, R_c=16/15, R_l=10/8
      ii. R=30.37x16x24x10x16/15x10/8= **155.494 Gb/s**

   ➔ **Fronthaul/RAT = 155.494/9.4, which is about 16 times higher**

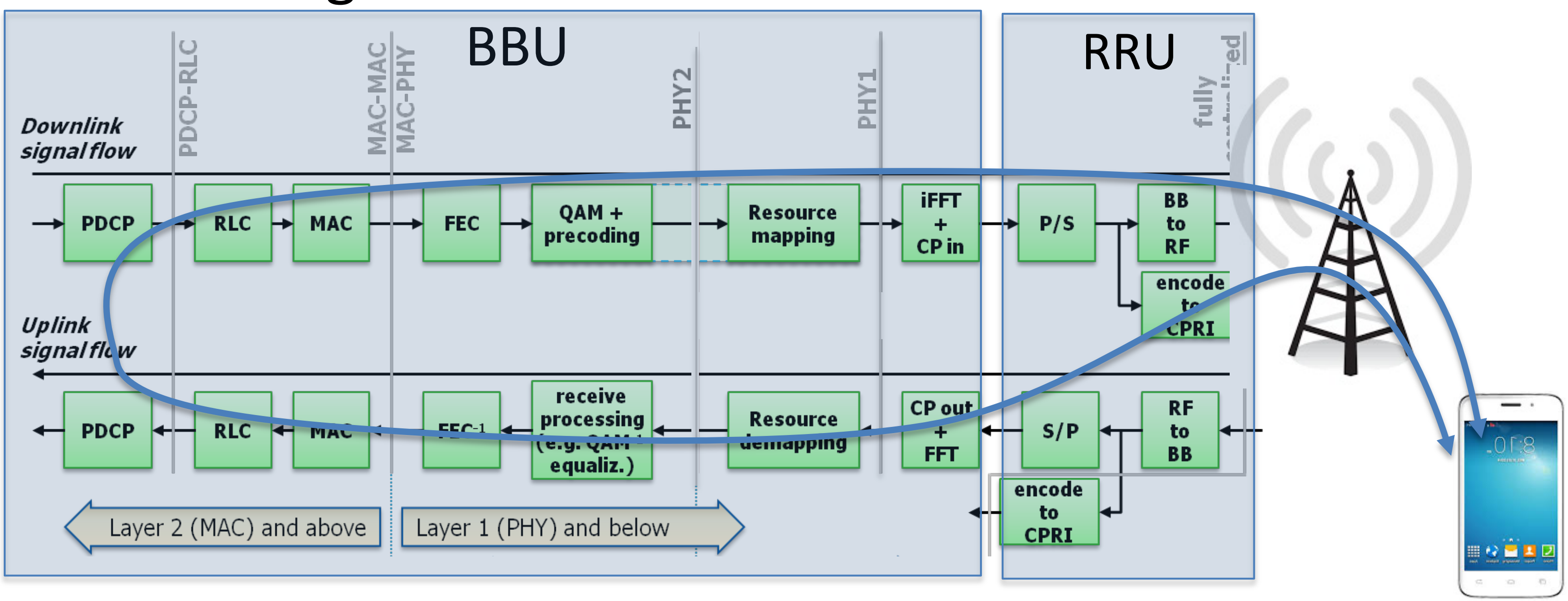
2. Small cell: 2x2 MIMO, 1 sector, 20 MHz channel, 64 QAM
   a. RAT rate = 40Mb/s x 2 x 2 = 160 Mb/s
   b. Fronthaul rate = 30.37 MHz x 16 x 2 x 2 x 16/15 x 10/8 = 2.59 Gb/s

Fronthaul requires a transmission capacity 16 times higher than the equivalent backhaul rate!

This is independent of usage… it's a sustained rate!

Fronthaul latency issue

- Fronthaul also presents an issue with latency:
  - The Hybrid Automatic Repeat reQuest (HARQ) system requires that messages between UI and BBU are acknowledged within 3 ms.



- There are several processing units that take up time: typically the fronthaul transmission part over firbe is given a constraint of **<u>200-400 us</u>** ➔ 20-40km RTT in fibre (only transmission)

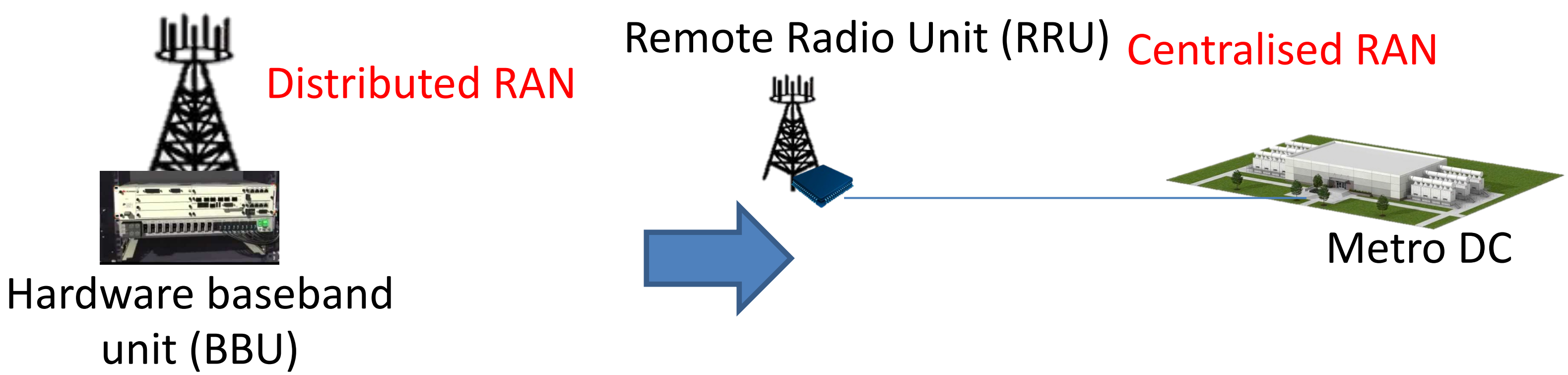
Fronthaul over fibre solutions

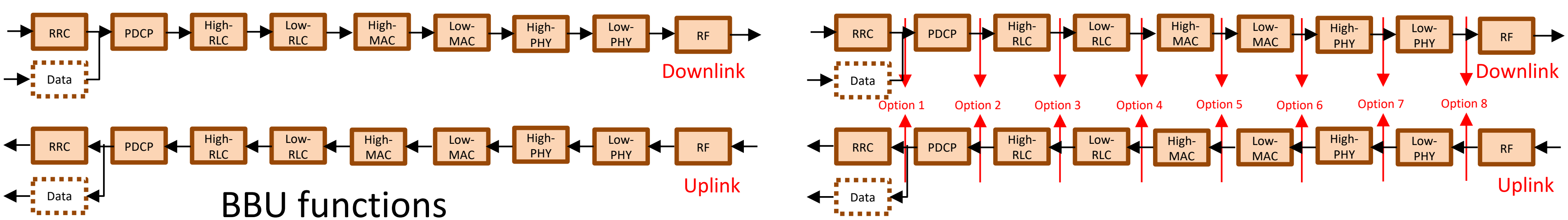
- Fronthaul over individual fibre (each RRU has an independent fibre):
  - Simple ptp link, the only constraint is to use a standard technology (e.g., 10GE, 40GE, 100GE or coherent…)
  - Fibre length limited to 20-40 km for latency issue
  - However for high density cell deployment the fibre network cost becomes unsustainable

- Fronthaul over PON:
  - Virtual ptp (assign an independent wavelength to a RRU) works similarly to ptp fibre
    - It use less fibre than ptp but more expensive transceivers (they have to work as WDM)
  - Ptmp, i.e. TDM multiplexing between different base stations (or even with residential users)
    - If rate of each RRU is relatively low (<<10G) then it makes sense to multiplex some of them
    - However currently it would only work with fixed bandwidth allocation (i.e. no DBA), since the DBA mechanism introduces few ms additional latency.

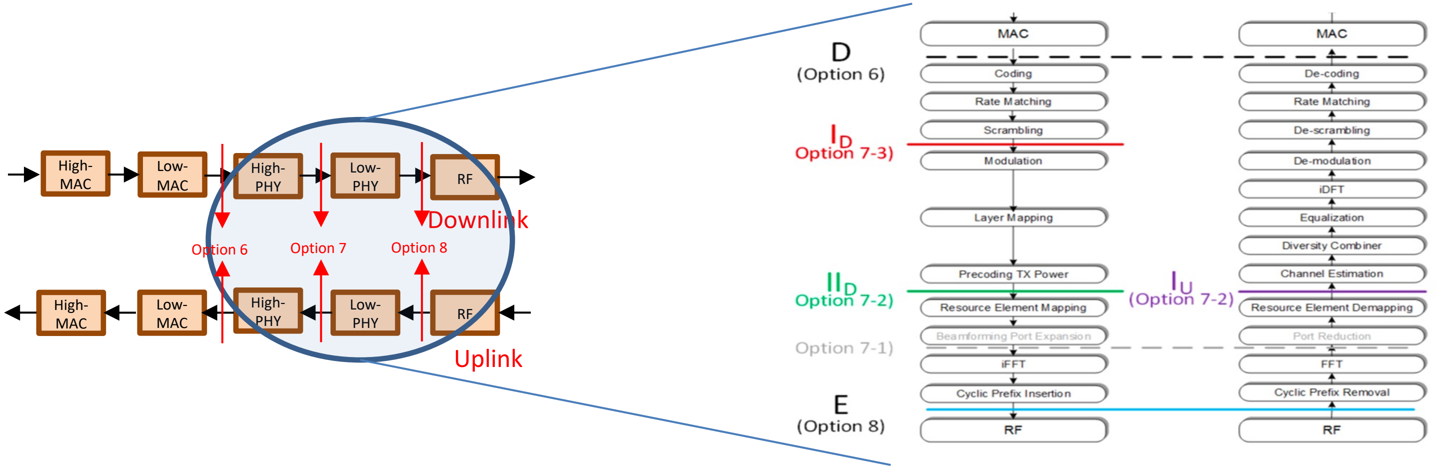
Solution for Fronthaul capacity issue

- Split PHY processing or midhauling:
  - Doing a bit more processing at the RRU can reduce the optical transmission rate considerably
  - In addition it restores the proportionality with the user traffic, thus reintroducing the possibility of carrying out statistical multiplexing





Even more splits…



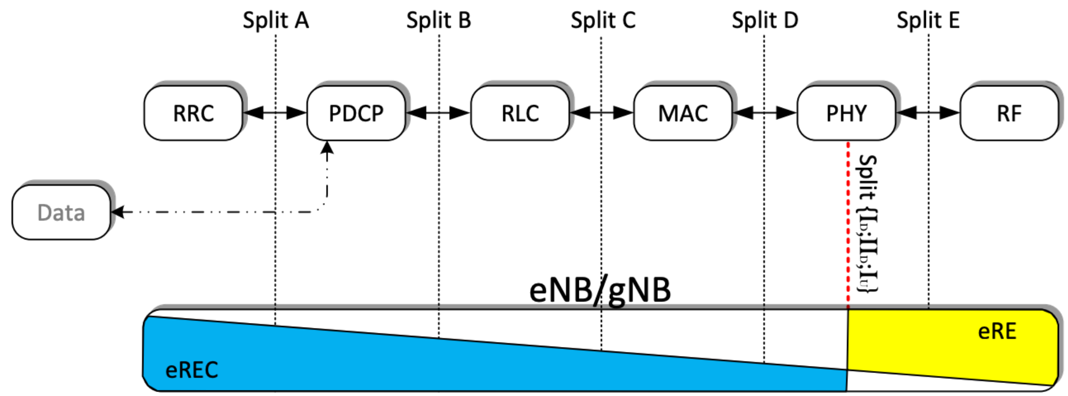
Source: Next Generation Mobile Network (NGMN) alliance. NGMN Overview on 5G RAN Functional Decomposition. Feb., 2018

- Notice that the limit on latency remains unless a split option of 3 or lower is used (need to have the HARQ at the RRU)
- Due to the lower capacity and the fact it allows for statistical multiplexing, it now makes it even more interesting to transmit it over PON (ptmp)
  - Using fix bandwidth allocation however is now inefficient because we want to implement statistical multiplexing
  - While the DBA can do that, current implementations introduce a few ms latency (DBA first needs to get the report from the ONU and then assign capacity)

Capacity and latency requirements for functional splits

- evolved CPRI (eCPRI) is the new standard that has identified these functional splits

Split	Fronthaul capacity needs	Fronthaul latency requirement
A	Low, Scales with # MIMO layers	Relaxed
B	Low, Scales with # MIMO layers	Relaxed
C	Low, Scales with # MIMO layers	Relaxed
D	Low, Scales with # MIMO layers	Very Strict
E	Very High, Scales with # antenna ports	Very Strict
$\{I_D;II_D;I_U\}$	See section 6.1.1	Very Strict



eCPRI Specification V1.1 (2018-01-10):

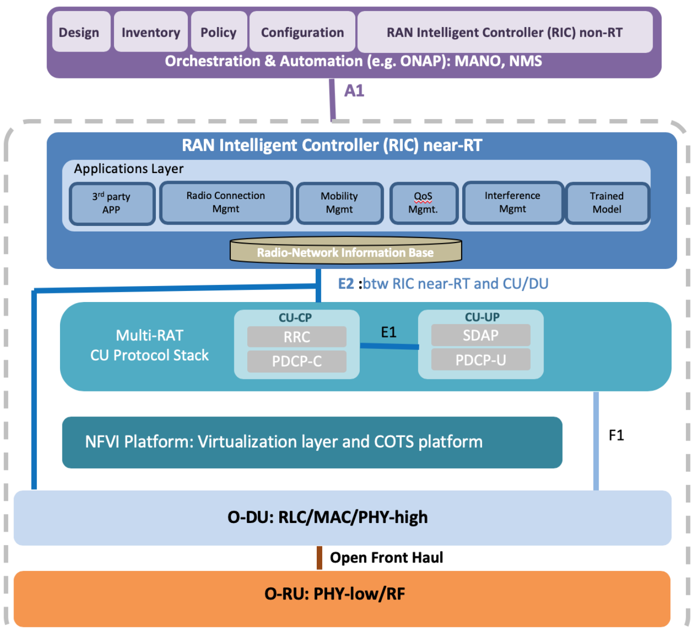
http://www.cpri.info/downloads/eCPRI_v_1_1_2018_01_10.pdf

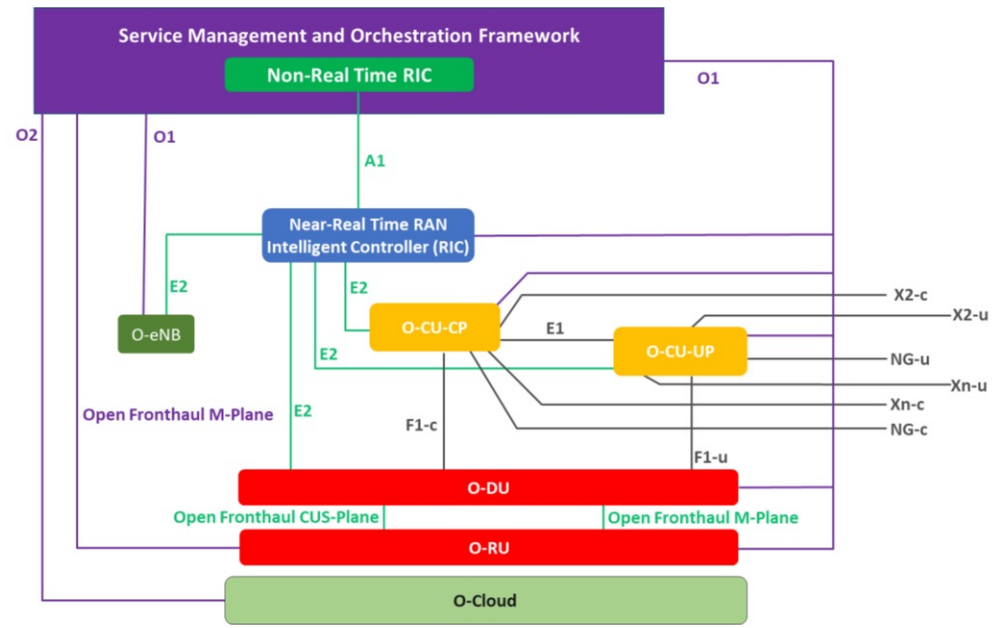
	Split D		Split I_D		Split II_D		Split E
	User Data [Gbps]	Control [Gbps]	User Data [Gbps]	Control [Gbps]	User Data [Gbps]	Control [Gbps]	User Data [Gbps]
eREC→ eRE	3 (assumption)	<< 1	< 4	< 10	~ 20	< 10	236
			Split I_U				
eRE → eREC	1.5 (assumption)	<< 1	~ 20	< 10	~ 20	< 10	236

- It also enables data to be packetized and transmitted over Ethernet
  - a new version of Ethernt is being developed for that can keep very low latency and jitter: IEEE 802.1CM (Time sensitive networking)

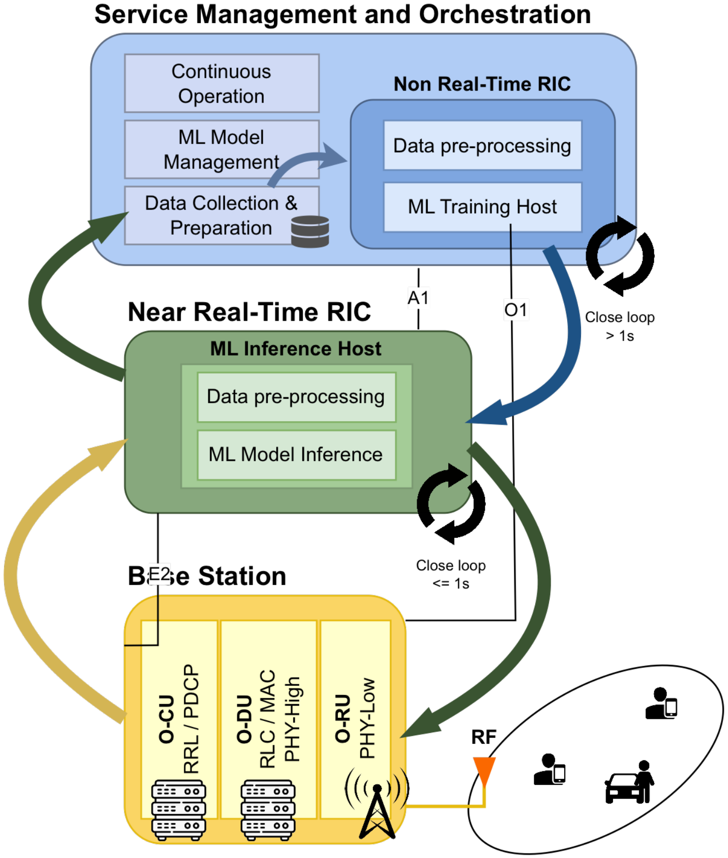
Opening the Radio Access Network OpenRAN

- Next step is to bring this concept to proper commercialization (actually replacing current large vendor base stations)
- Define one one specific split (called 7.2) and start defining interfaces so that vendors can start producing the different parts

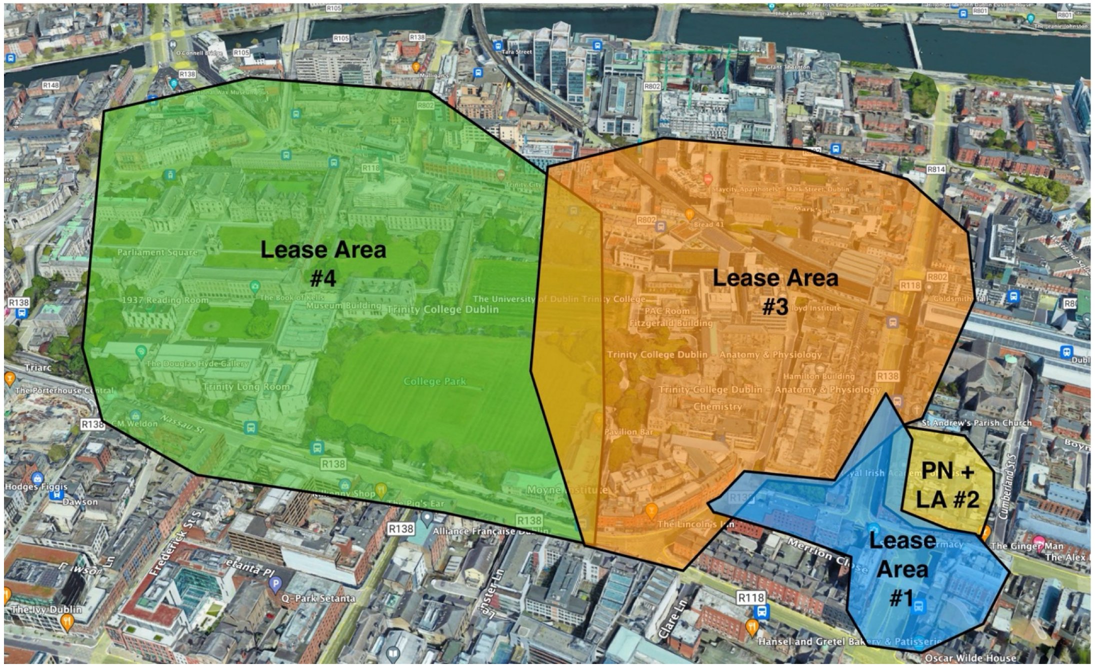




1) ML-based handover prediction

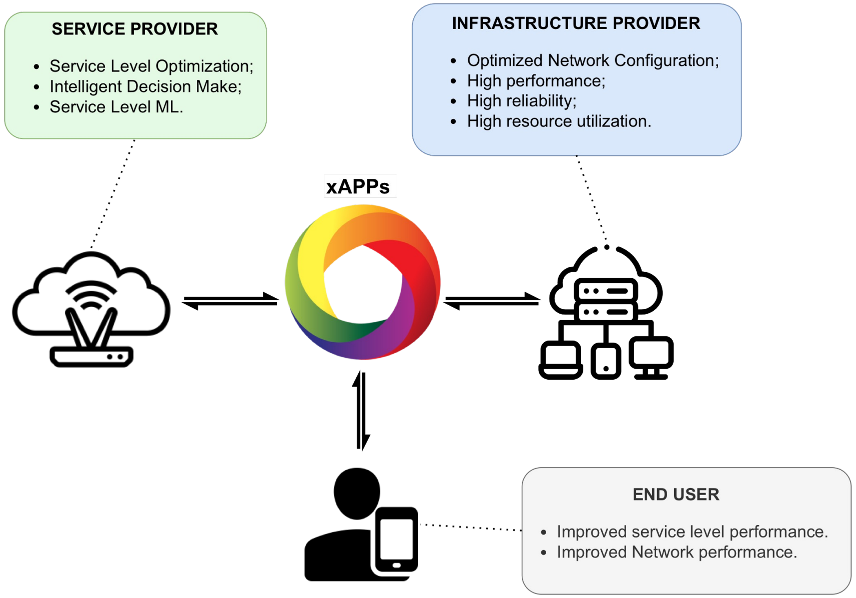


O-RAN architecture
with ML training and interference nodes

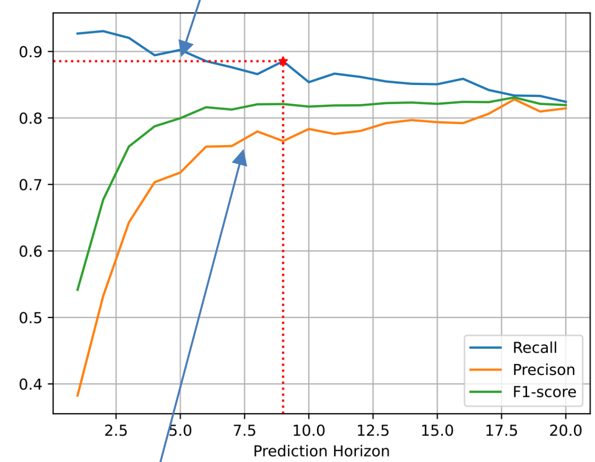


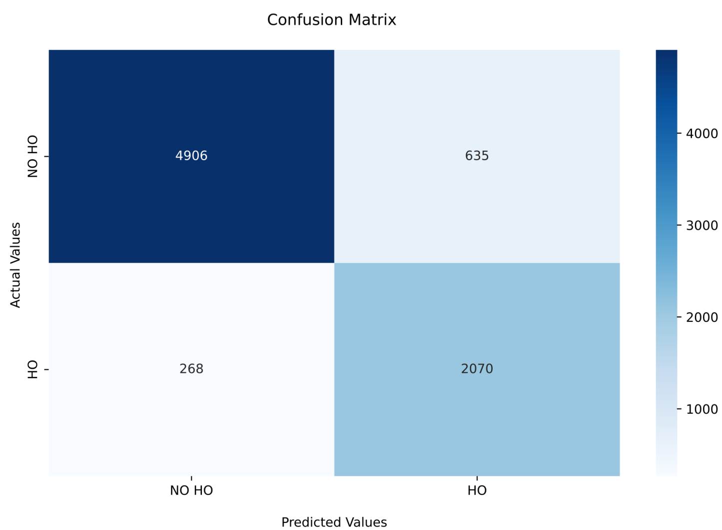
Resource allocation areas, located around
the Trinity College Dublin campus.

ML-based handover prediction



Higher recall means making more resources available than necessary

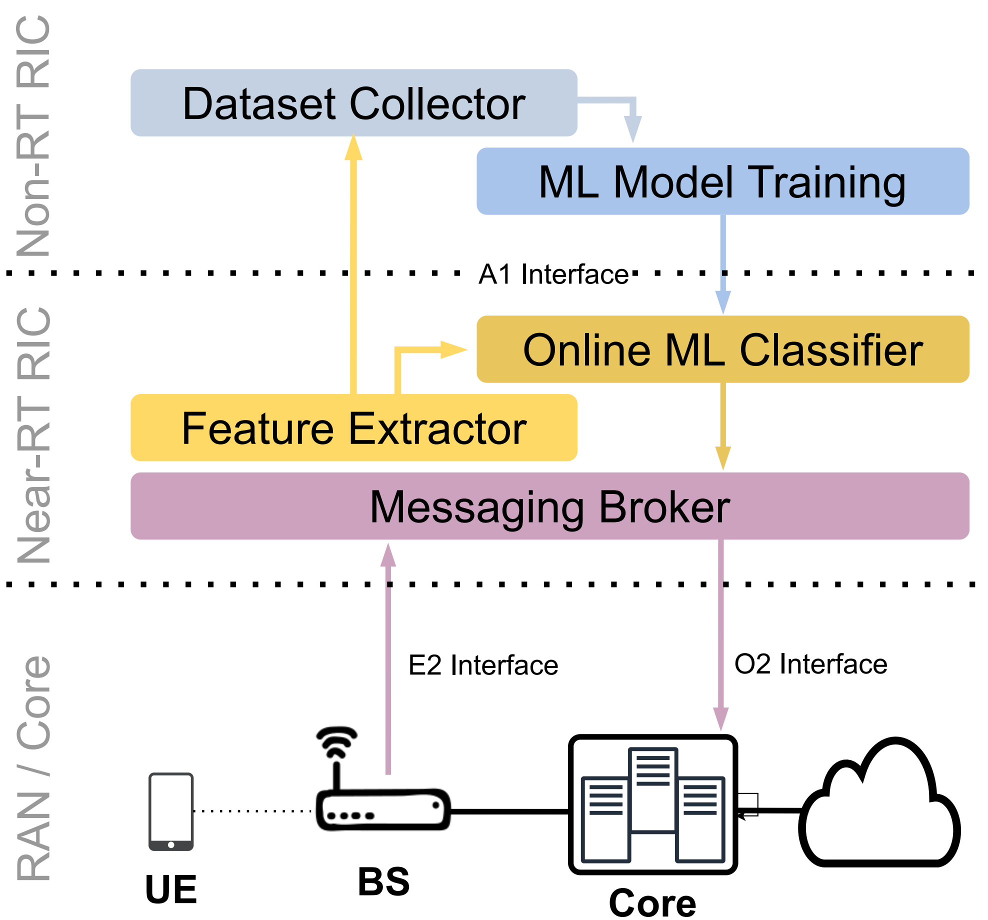




Higher when there is handover following my handover prediction

➔ Minimise resource wastage

2) ML-based Early attack detection

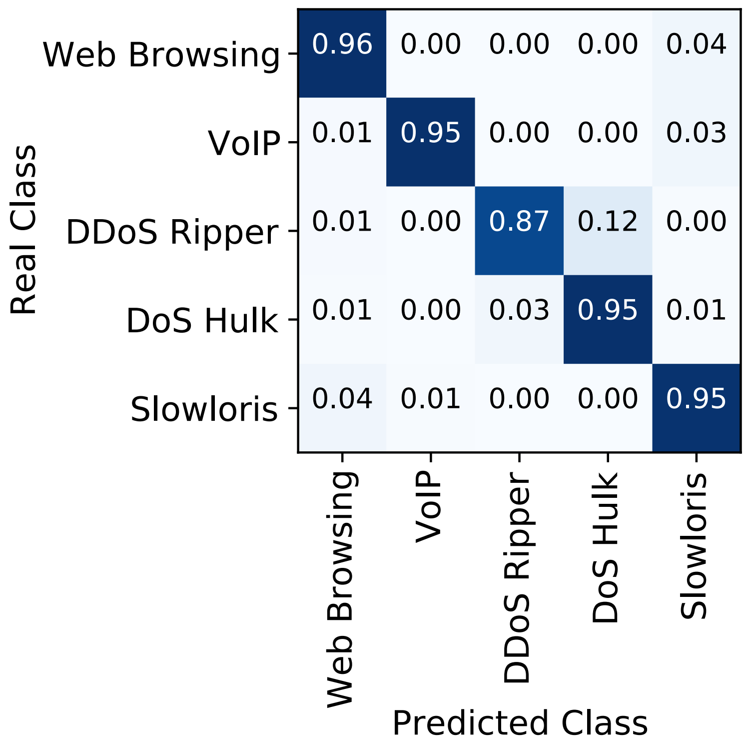


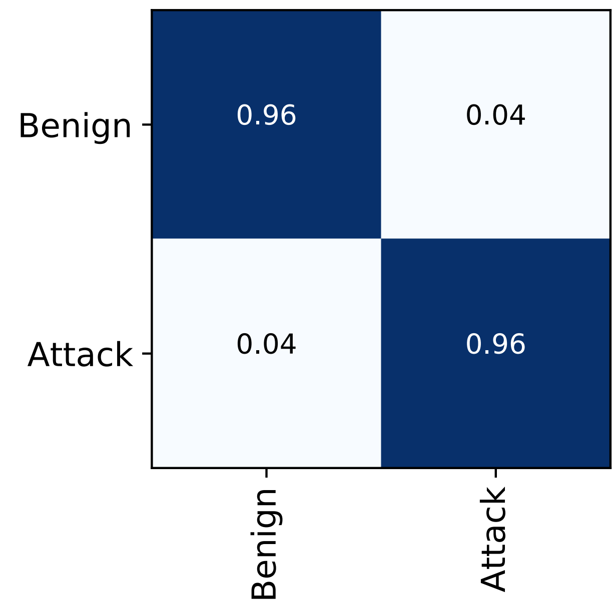
Machine learning has been used to detect attacks at the packet level, using features such as IP address TCP ports, packet size, etc.

- Could we detect attacks before they enter the packet network?

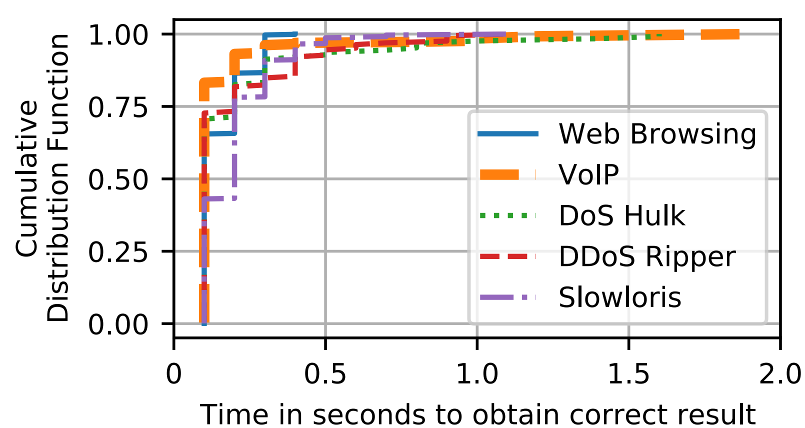
==> Detect attacks at the PHY layer of a base station using information such as transmission time, time interval between transmission

ML-based Early attack detection





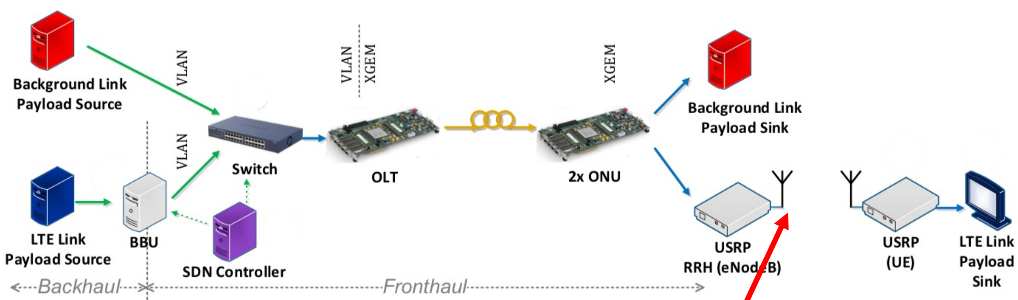
This can also be integrated with other detections at the packet level: improve accuracy and reduce risk of attack



3) Example of fixed/mobile convergence: variable rate fronthaul

Adapt wireless bandwidth to required cell capacity
➔ Fronthaul rate is reduced proportionally

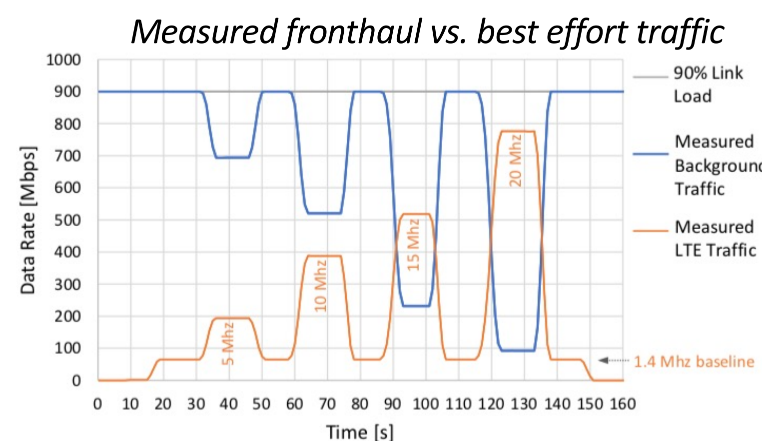
1. BBU → SDN: Assess capacity used by the cell
2. SDN → BBU: Adaptation of wireless bandwidth
   SDN → PON: Adaptation of reserved PON capacity to new fronthaul rate



ossible use cases:
Mix fronthaul with other low priority traffic
Statistical multiplex across adjacent small cells

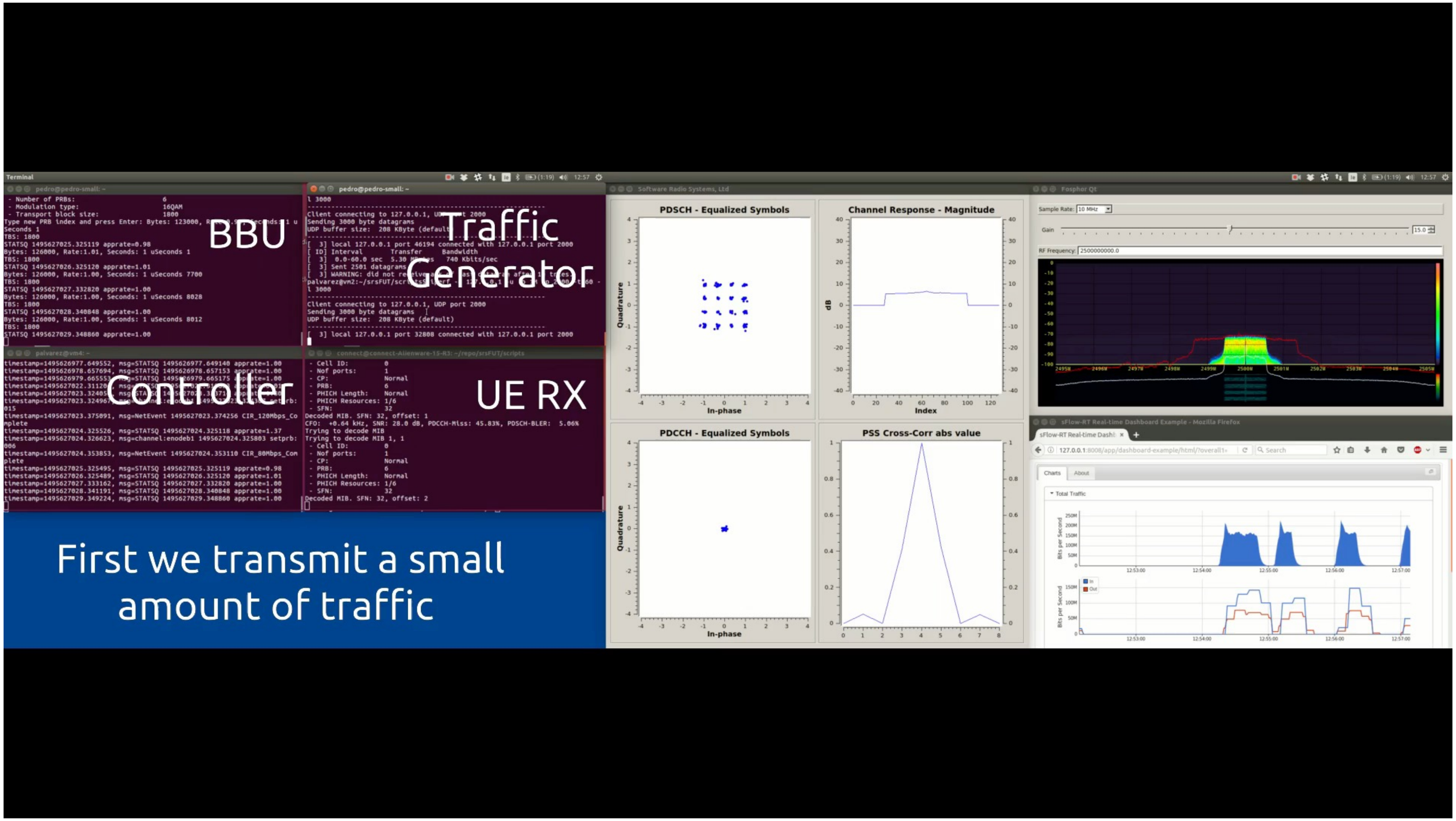
Adaptive cell bandwidth

Wireless Bandwidth	PRB Number	Fronthaul Rate	Max Cell Capacity
1.4 MHz	6	61 Mbps	1.8 Mbps
3 MHz	15	121 Mbps	4.584 Mbps
5 MHz	25	182 Mbps	7.736 Mbps
10 MHz	50	364 Mbps	15.264 Mbps
15 MHz	75	485 Mbps	22.92 Mbps
20 MHz	100	730 Mbps	30.576 Mbps

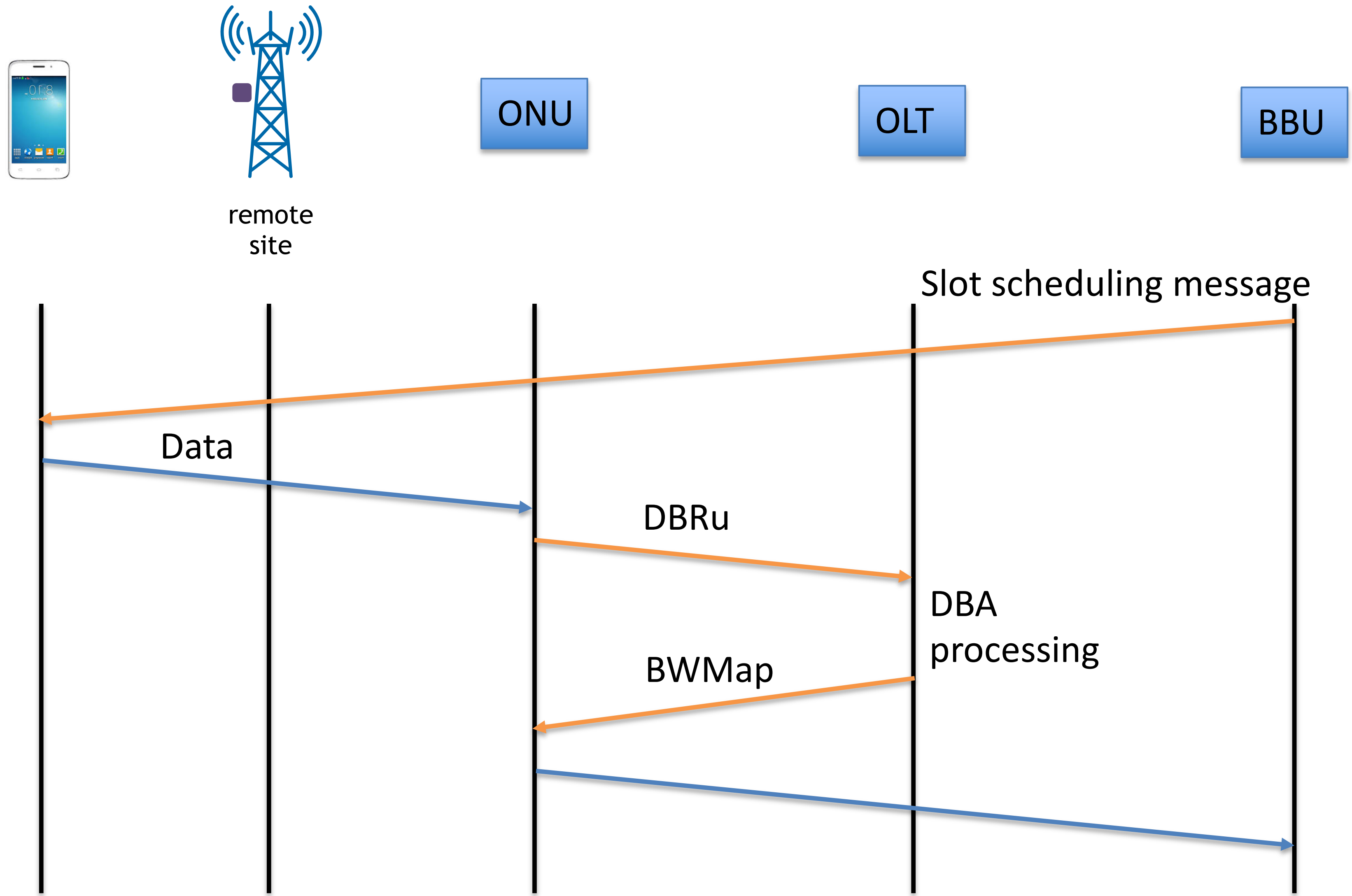


P. Alvarez, et al. Experimental Demonstration of SDN-controlled Variable-rate Fronthaul for Converged LTE-over-PON. OFC 2018

Fixed-mobile convergence with variable rate fronthaul over PON



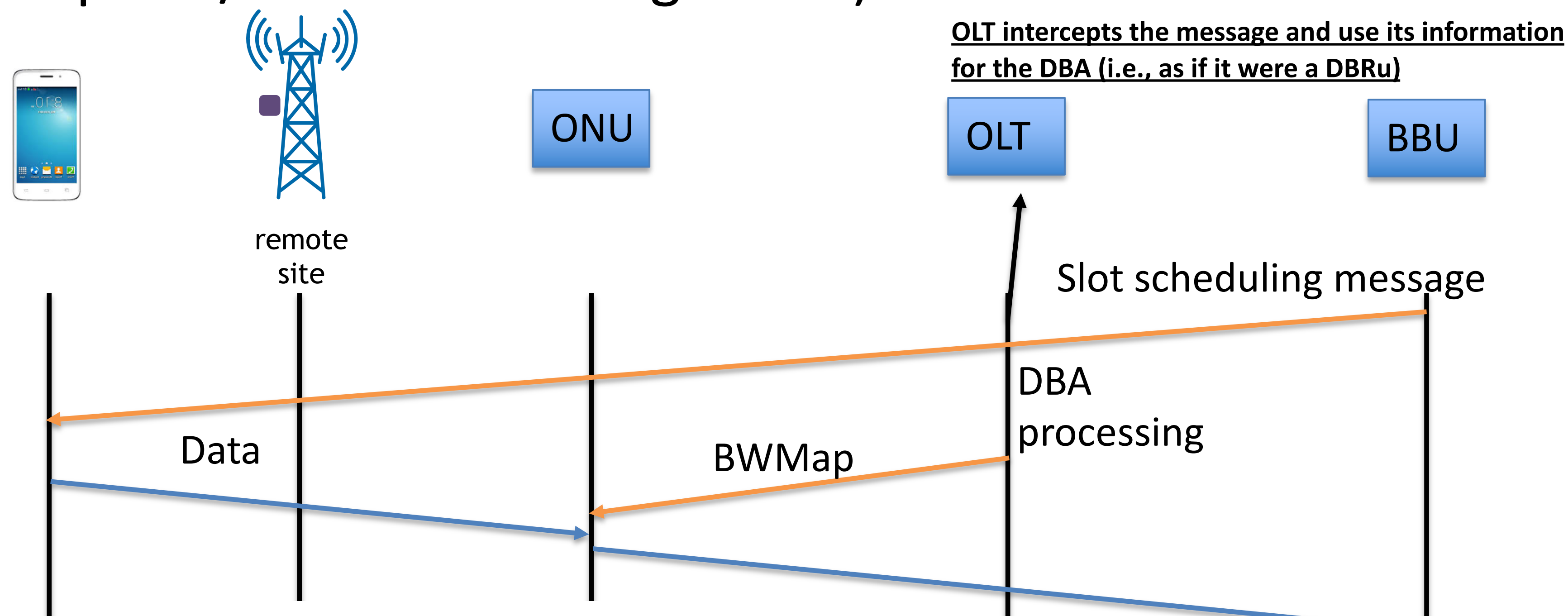
DBA latency issue (only in upstream)

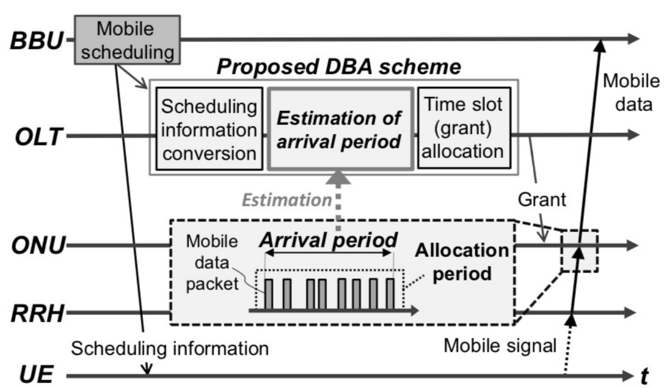


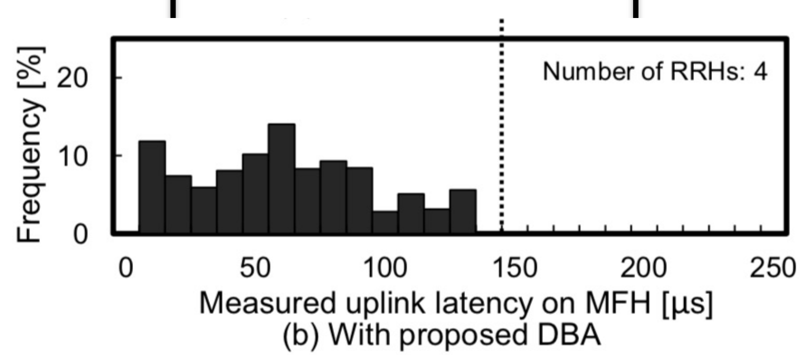
Cooperative DBA Solution

- Synchronise BBU scheduling and OLT DBA (this is optical/wireless convergence…)

Standardised in ITU-T G.989.3Am1







Source: H. Uzawa, et al. Practical Mobile-DBA Scheme Considering Data Arrival Period for 5G Mobile Fronthaul with TDM-PON. ECOC 2017.

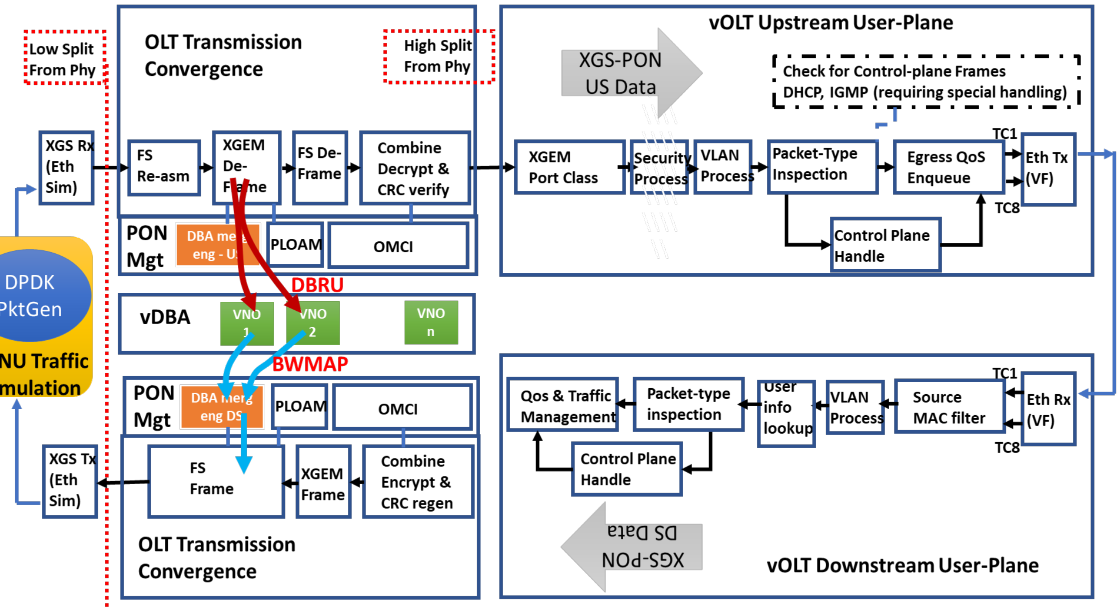
The virtual PON implementation

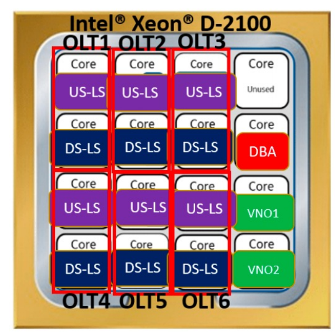
XGS-PON compliant protocol implemented in software

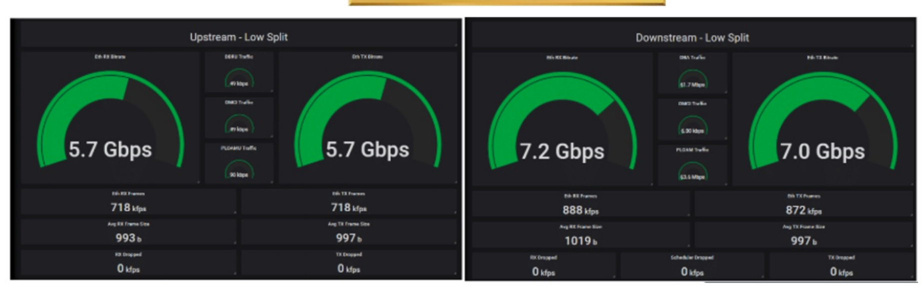
Two implementations:

- High split: part of the protocol in GPP (i.e., Intel Xeon) software, part in dedicated programmable hardware (FPGA)
- Low-split: all is done in the GPP

<u>The DBA is in GPP software in both cases</u>

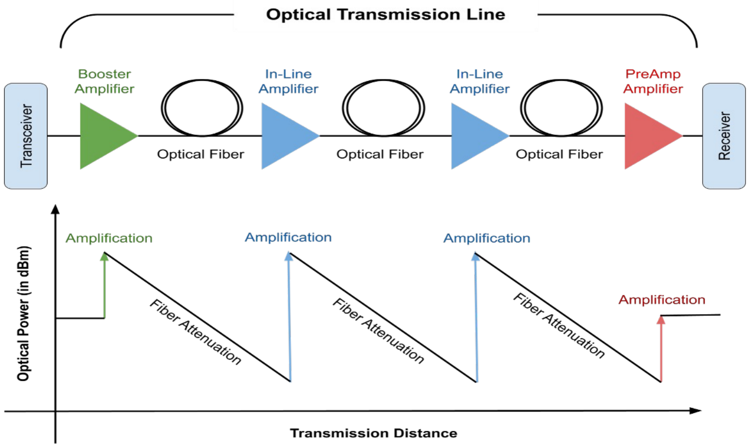


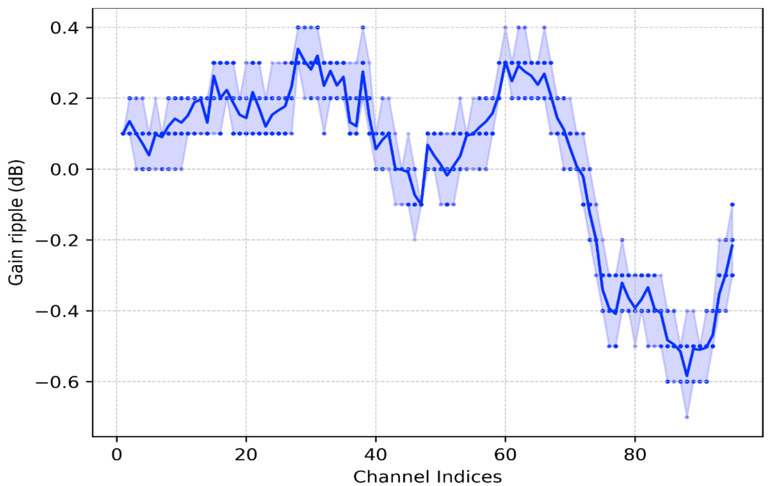




- M. Ruffini, D. Coyle, J. Singh, R. Sexton, B. Ryan, R. Giller, M. O'Hanlon and F. Slyne. Evolution of access network sharing towards software based passive optical network: can virtual OLTs run at full line rate?. IEEE ONDM, May 2020
- F, Slyne, D. Coyle, J. Singh, R. Sexton, B. Ryan, R. Giller, M. O'Hanlon and
- M. Ruffini. Experimental Demonstration of multiple Disaggregated OLTs with Virtualised Multi Tenant DBA, over General Purpose Processor. OSA Optical Fiber Communications Conference (OFC), March 2020
- F. Slyne, J. Singh, R. Giller and M. Ruffini. Experimental Demonstration of DPDK Optimised VNF Implementation of Virtual DBA in a Multi-Tenant PON. Proc. of ECOC 2018
- F. Slyne, A. Elrasad, C. Blumm and M. Ruffini. Demonstration of Real Time VNF Implementation of OLT with Virtual DBA for Sliceable Multi-Tenant PONs. Proc. of Optical Fibre Communications conference (OFC), paper Tu3D.4, March 2018

Example of application of Machine Learning to optical networks: Transfer learning of EDFA modeling for Digital Twin

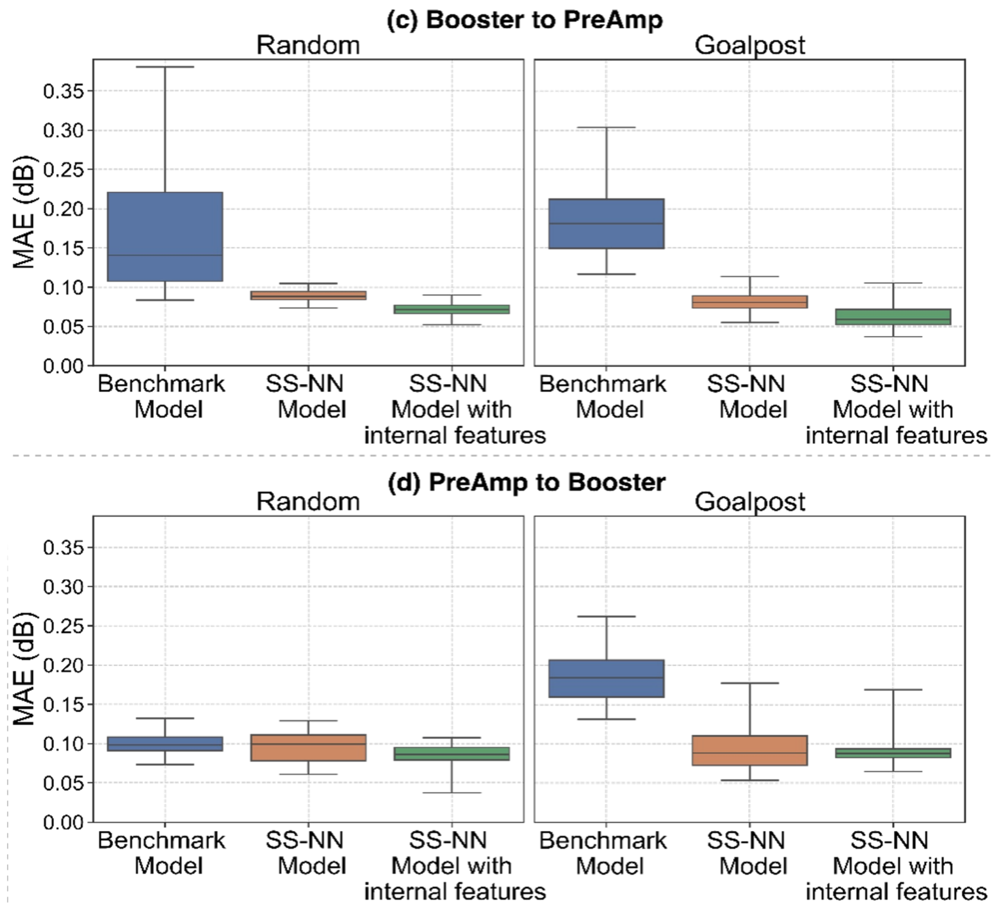




- Different WDM channels undergo different amplification and noise figure, causing:
  - Different power levels
  - Different noise levels
  - QoT Degradation when adding and dropping signals dynamically

- Spectral shape dependency, Vendor Inconsistencies and Fabrication errors make modeling the gain-function a highly non-convex problem.

Results - TL to Cross EDFA Type

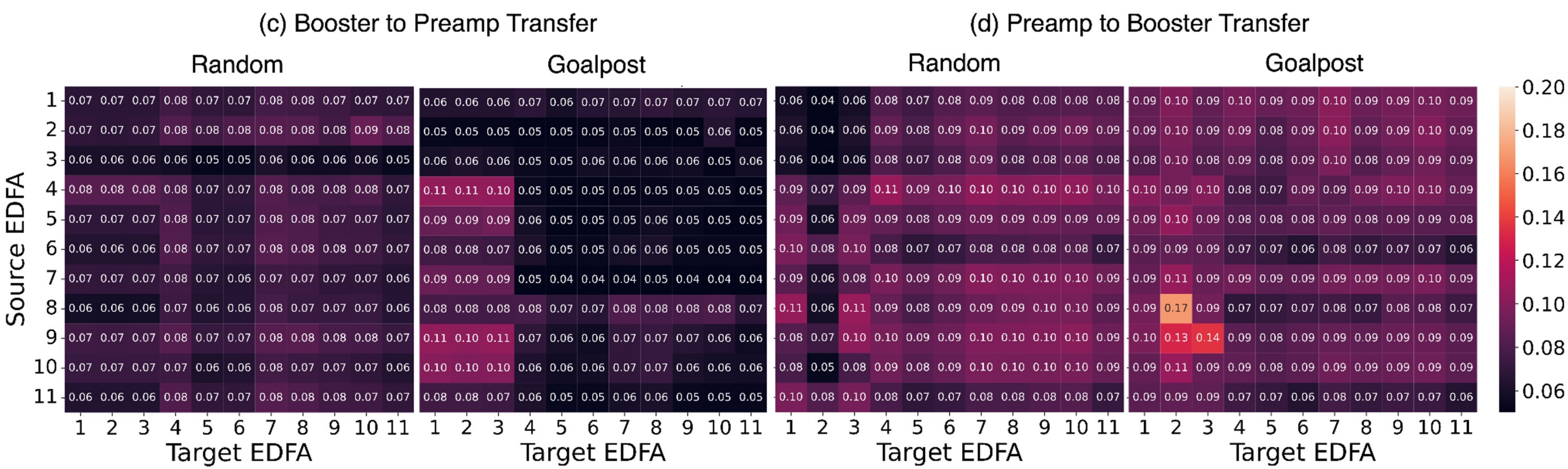


- MAE within 0.11 dB for B→P transfer
- MAE within 0.17 dB for P→B transfers

[1] Z. Wang, et al. Transfer Learning-based ROADM EDFA Wavelength Dependent Gain Prediction Using Minimized Data Collection. OFC 23, paper Th2A.1.

** Boxplot distribution of MAE across 22 EDFAs of (a) Booster to PreAmp TL and (b) PreAmp to Booster TL. The boxes denote the interquartile range, and the whiskers denote the min/max.*

Results - TL to Cross EDFA Type: Confusion Matrix



** Heatmap distribution of MAE across 22 EDFAs of (a) Booster to PreAmp TL and (b) PreAmp to Booster TL*