A World Leading SFI Research Centre

Trinity College Dubli
Coláiste na Tríonóide, Baile Átha Clia
The University of Dublin

CONNECT
Centre for Future Networks

Passive Optical Networks: architectures, technology and evolution towards virtualised systems

Prof. Marco Ruffini
Dept. Computer Science and Statistics, Trinity College Dublin
CONNECT and IPIC research centres

Trinity College Dublin
The University of Dublin

5G STEP 4WD school
17-21 February 2020,
Chalmers University, Gothenburg, Sweden.

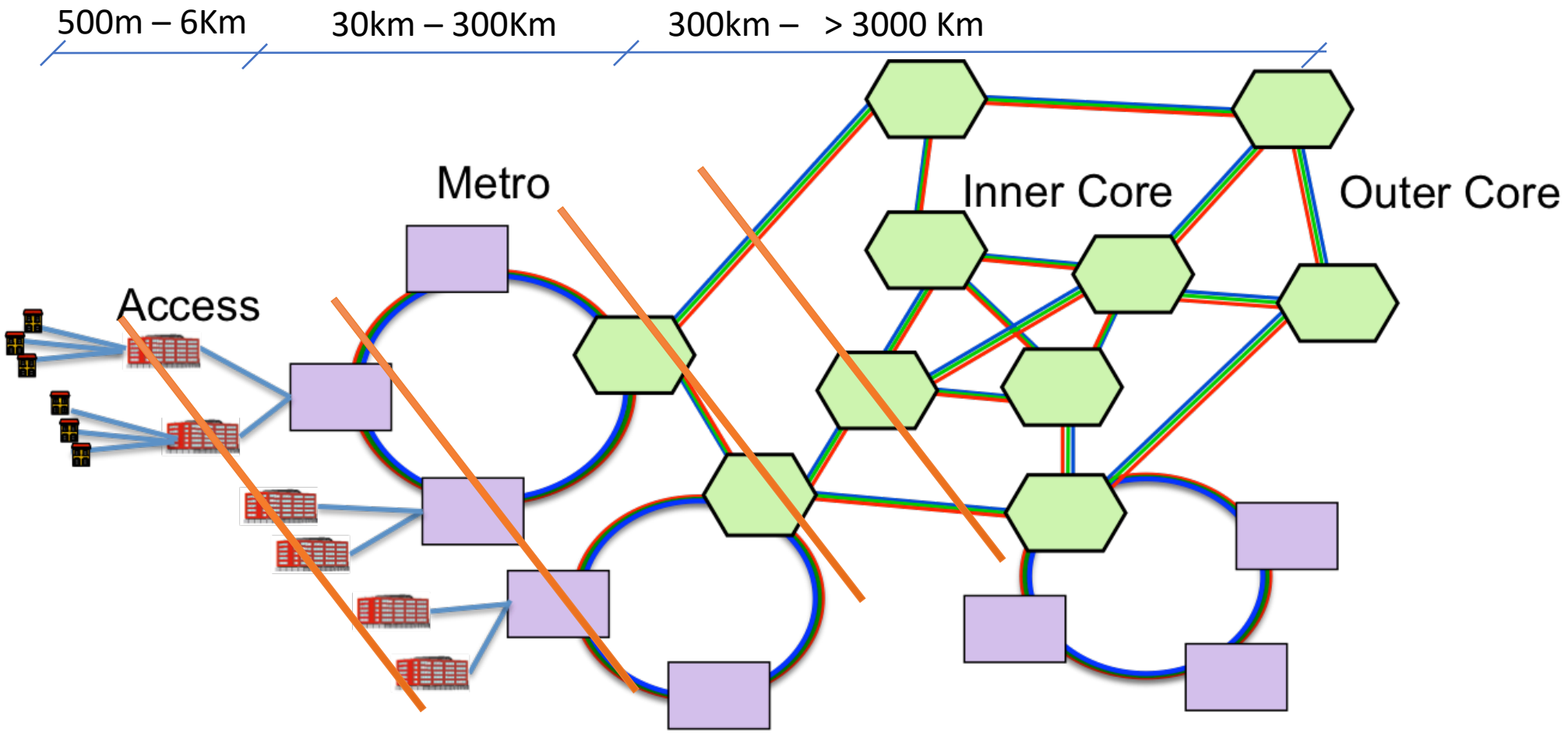
Science Foundation Ireland sfi For what's next

IPIC
BRINGING PHOTONICS TO LIFE

Content of the talk

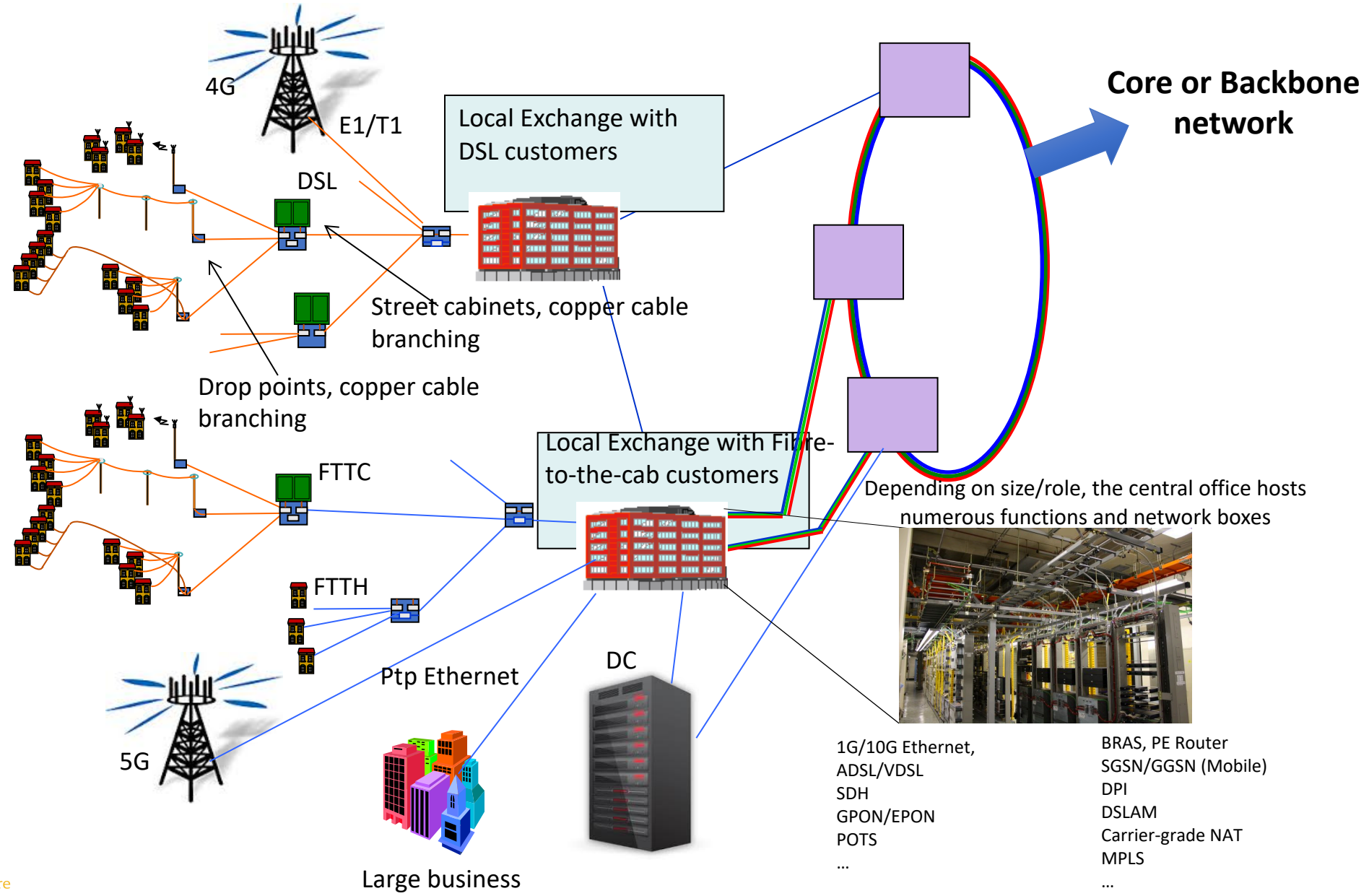
- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don’t forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON

Network architecture (access/metro/core view)



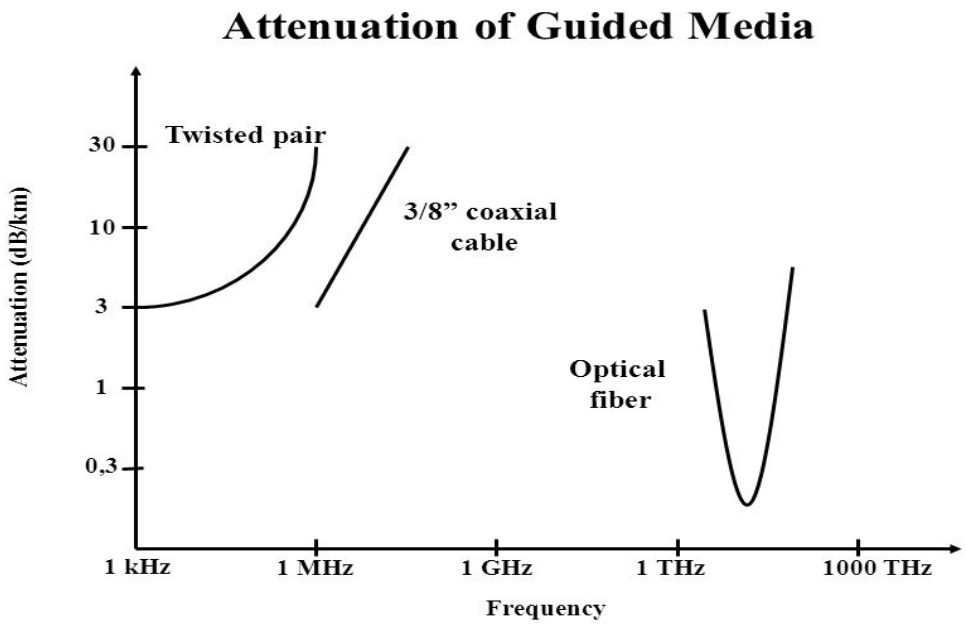
Based on progressive customer traffic aggregation through Optical-Electronic-Optical (OEO) conversion

Access and metro network view



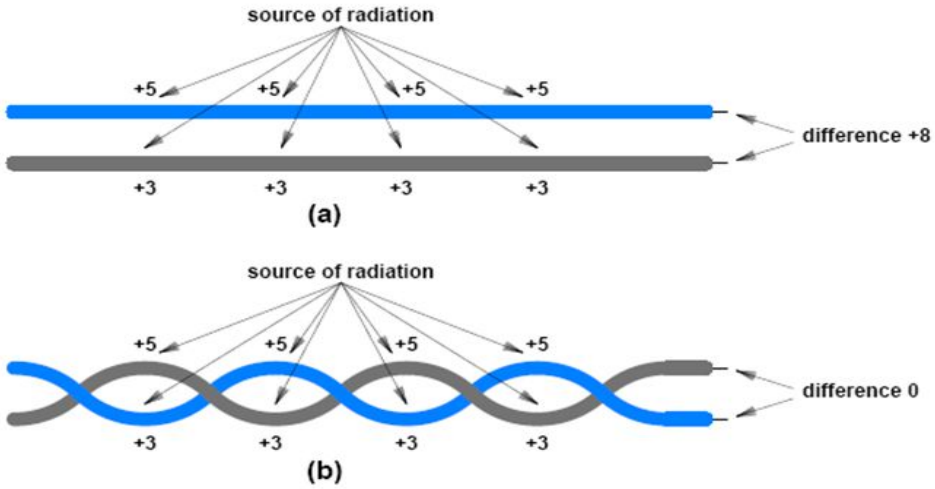
Issues with access networks

- The aim is to provide higher capacity, followed by lower latency and higher availability of the service
- The issue is the cost per connection upgrade, which is on a per-user basis.
- This explain why many connections, especially in the rural areas are still based on copper.
- The problem with copper is that the bandwidth (and thus capacity) is highly attenuated with distance

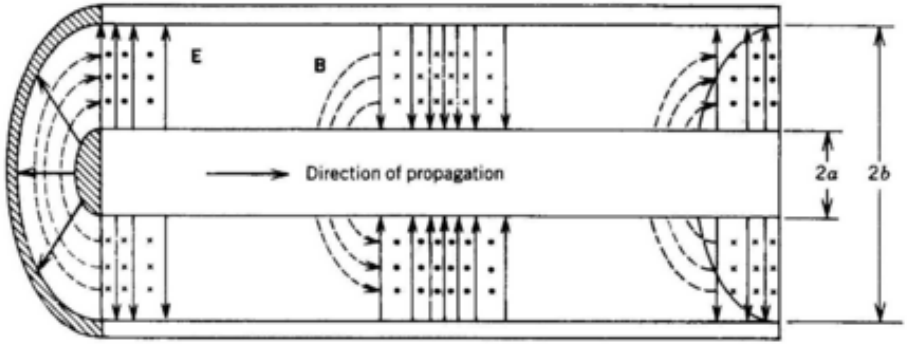


Twisted pair and coaxial

- Twisting the copper helps reducing interference from external sources, but still severely limited in capacity

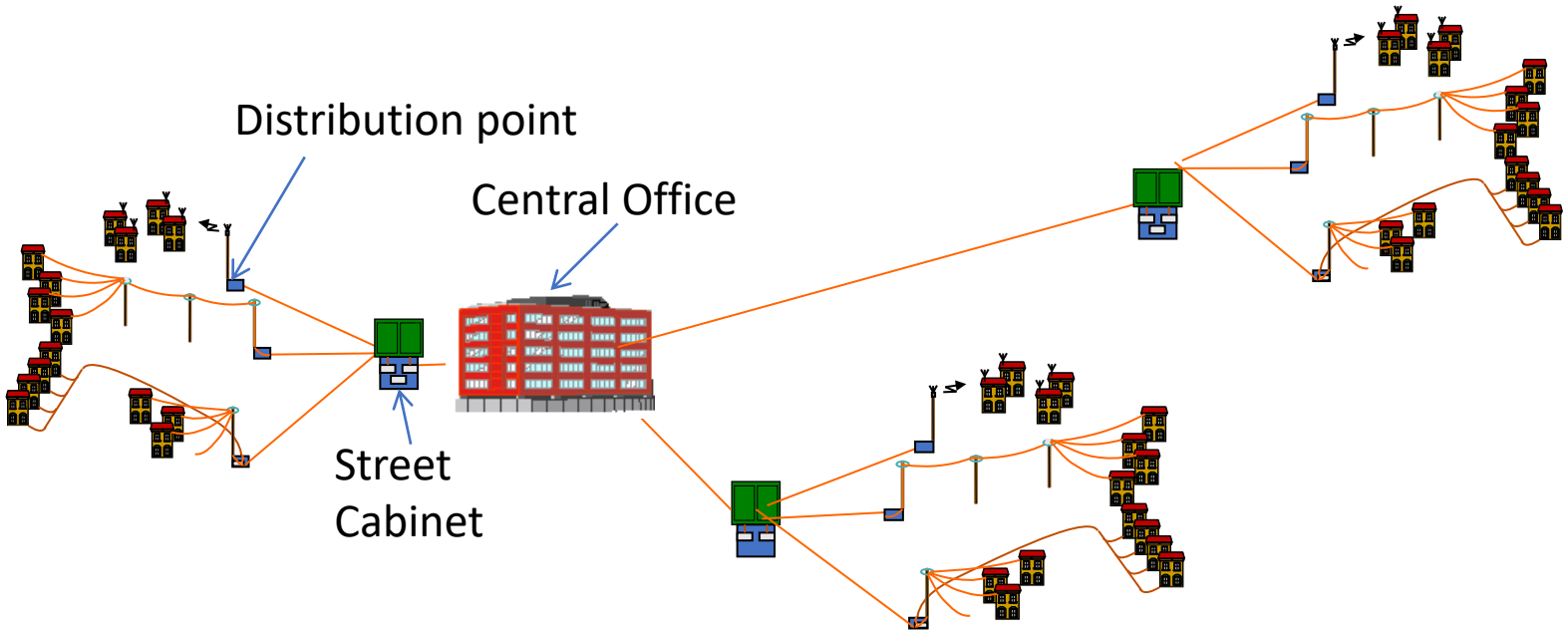


- However the coaxial uses the Faraday principle by using an external sheet to confine the radiation within the cable



How do we solve this?

- You have a long copper line (between 500m and 6 km, 2 km in average)
- You don’t have the money to replace all copper with fibre
- Users want more capacity but only willing to pay 50-100 € per month

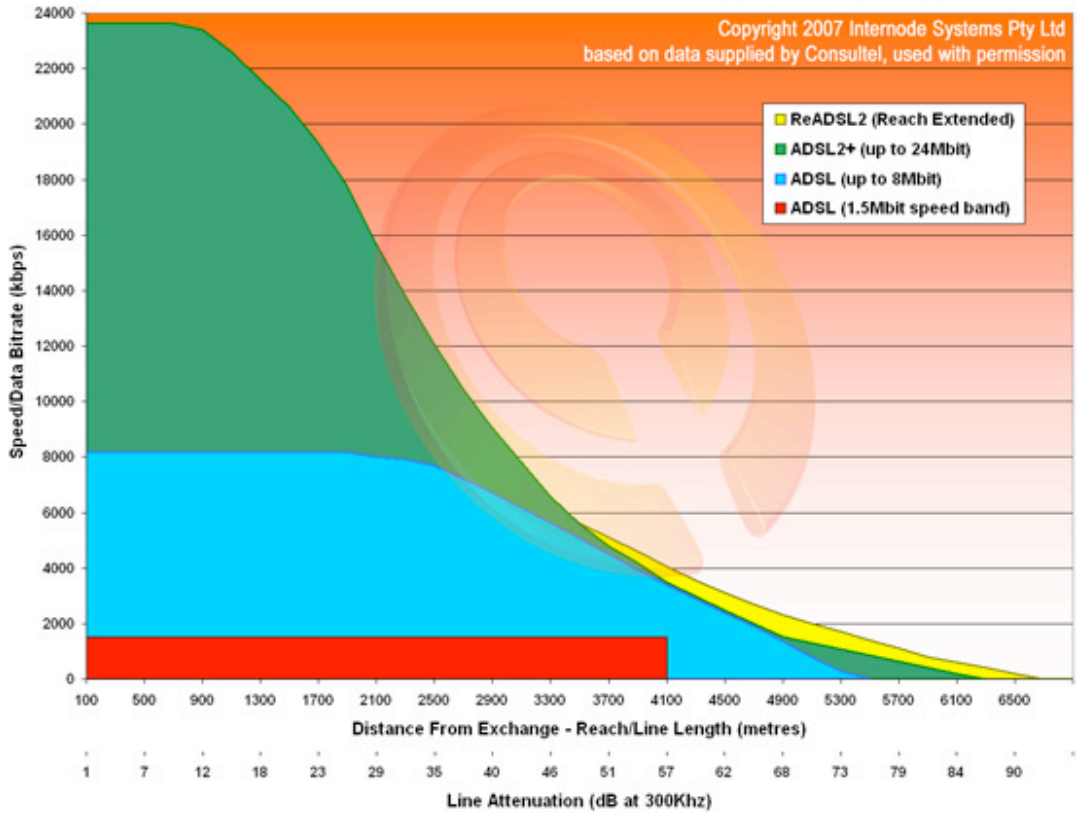


Capacity vs. distance of DSL

Shannon–Hartley theorem

$$C = B \cdot log_2\left(1 + \frac{S}{N}\right)$$

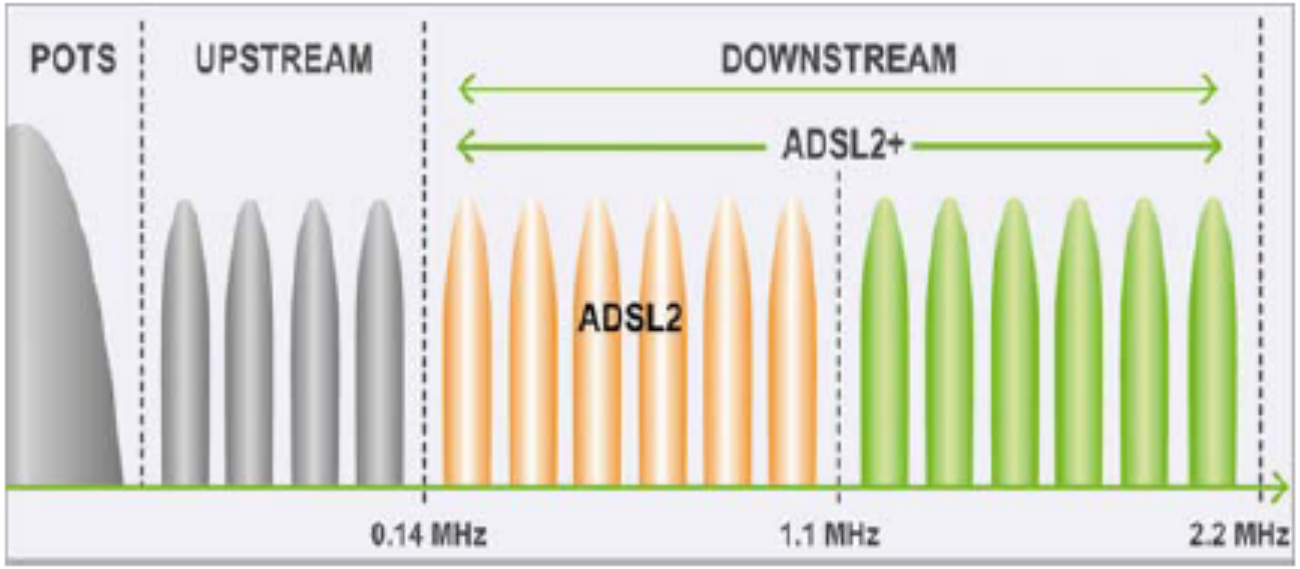
C = capacity [b/s]
B = bandwidth [Hz]
S/N = Signal to noise ratio [linear]



DSL capacity reduction with distance

- The solution is obviously to reduce the distance of the copper link

DSL details

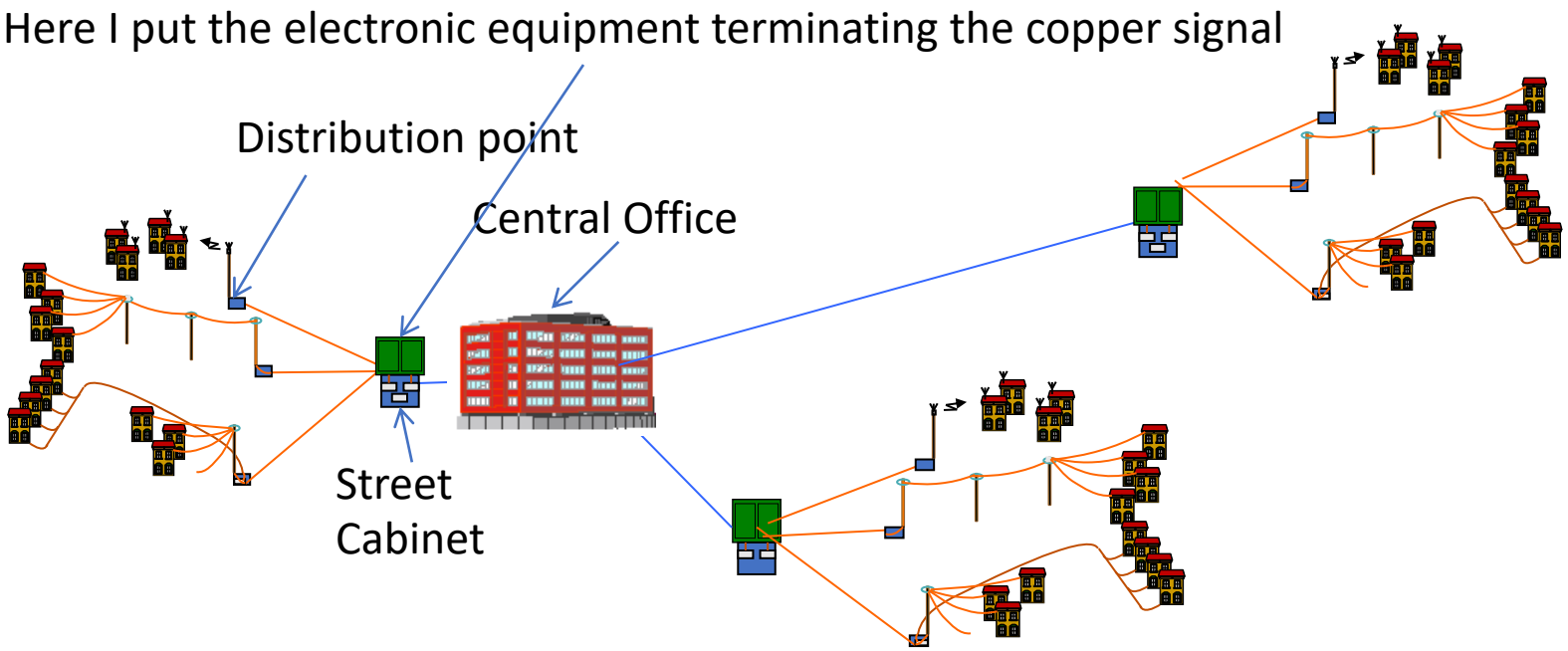


- ADSL occupies up to 1.1 MHz bandwidth, using Discrete Multi-Tone Modulation (DMT - similar to OFDM) with 256 channels
  - Achieves up to 8 Mb/s DS, 1.3 Mb/s US
- ADSL-2 also occupies up to 1.1 MHz bandwidth, using DMT but improving modulation efficiency, reducing framing overhead, ...
  - Achieves up to 12 Mb/s DS, 3.5 Mb/s US
- ADSL-2+ occupies up to 2.2 MHz bandwidth, using DMT
  - Achieves up to 24 Mb/s DS, 3.3 Mb/s US

Fibre-to-the-cabinet (FTTC)

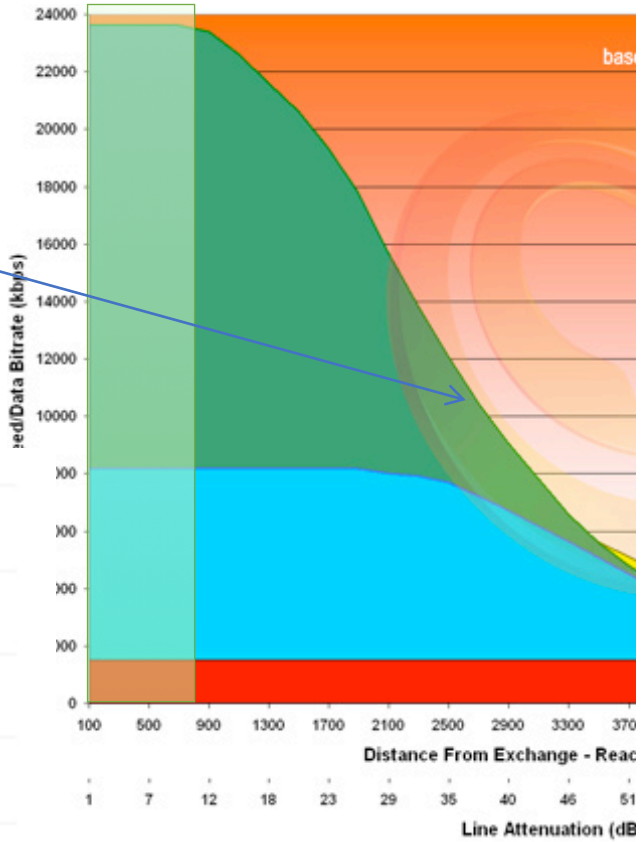
- Replace the first part of the copper (that shared by most users) with fibre

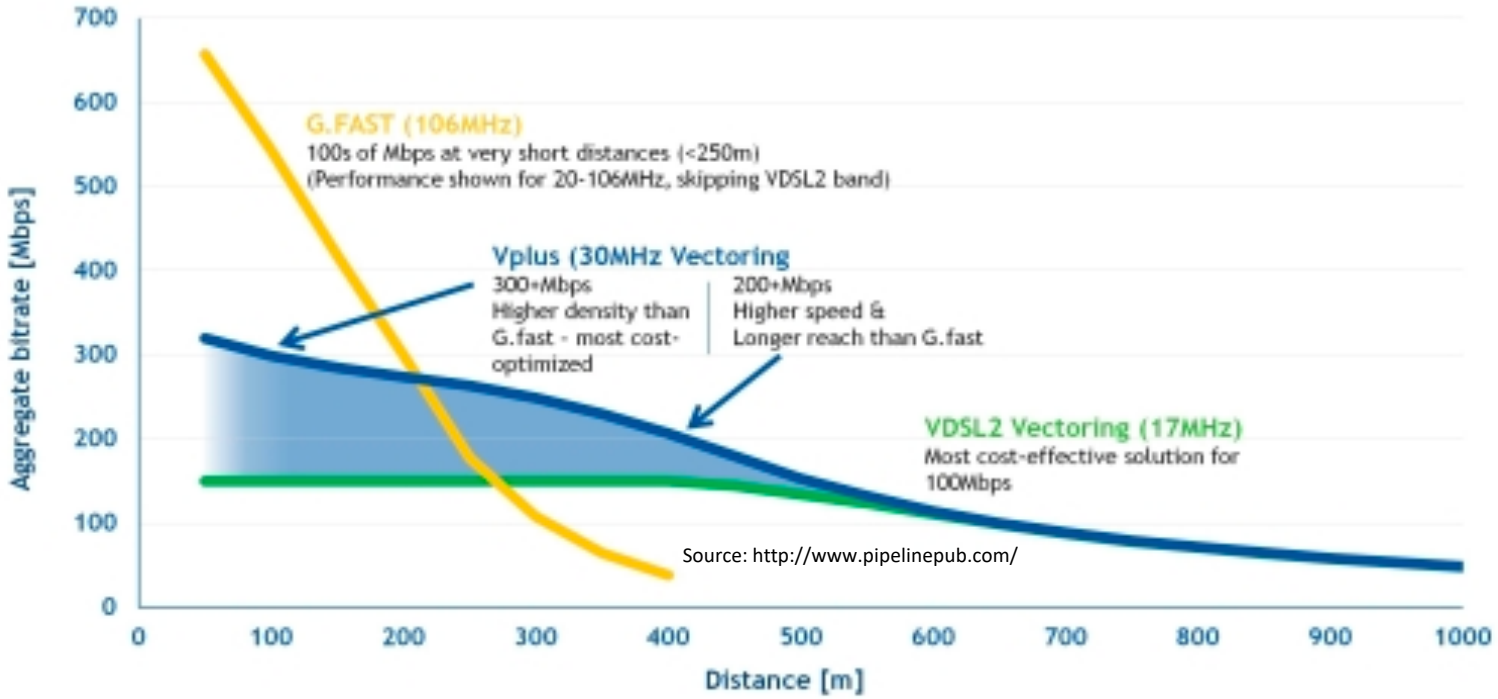
➔ The overall distance now decreases to about 100-700m, average 500m)



FTTC

- So DSL works on the far side
- But the higher SNR allows to develop also better technology

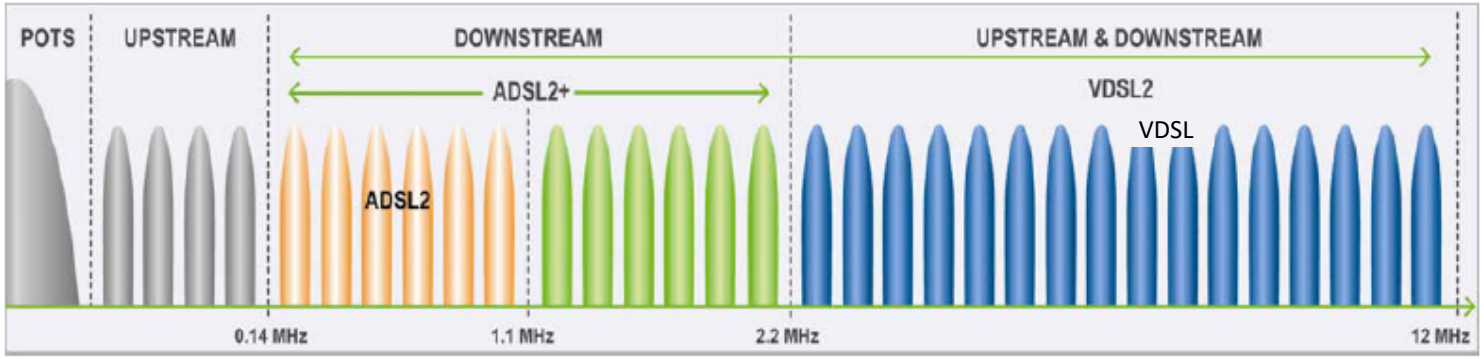




Source: http://www.pipelinepub.com/

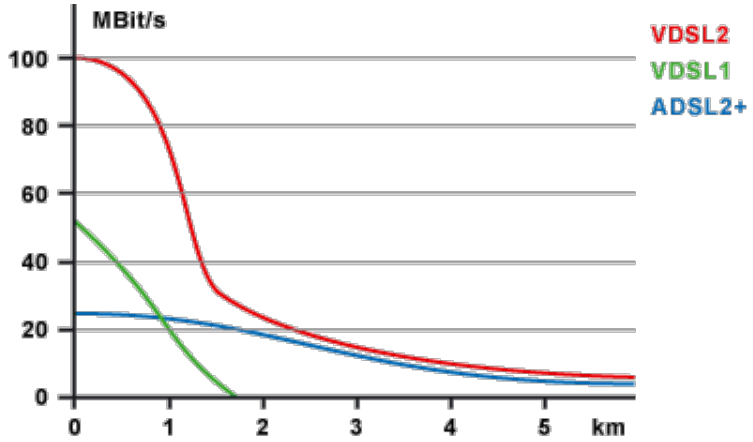
VDSL / VDSL2

- VDSL and VDSL 2 have many different profiles that were developed over the years
- A typical VDSL maximum rate is of 52 and 16 Mbps, respectively in DS/US (ITU-G.993.1 year 2001), using frequencies up to 12 MHz



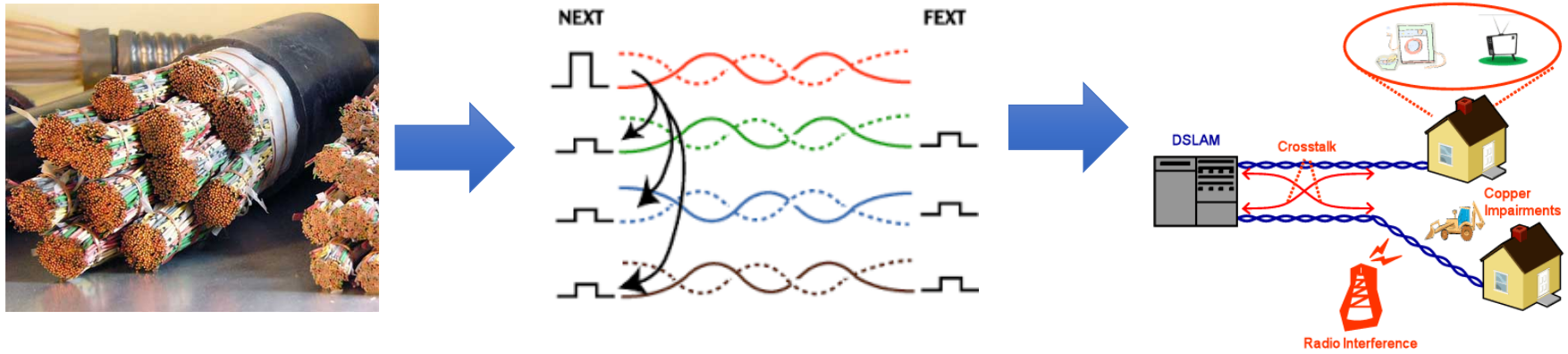
- VDSL2 (ITU-G.993.2 year 2006), uses frequencies up to 30 MHz to achieve symmetric 100MB/s capacity.

The higher the frequency used, the shorter the reach, although VDSL2 adapts to the ADSL2+ performance over longer loops

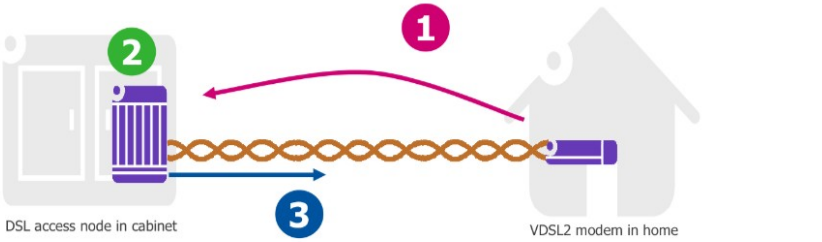


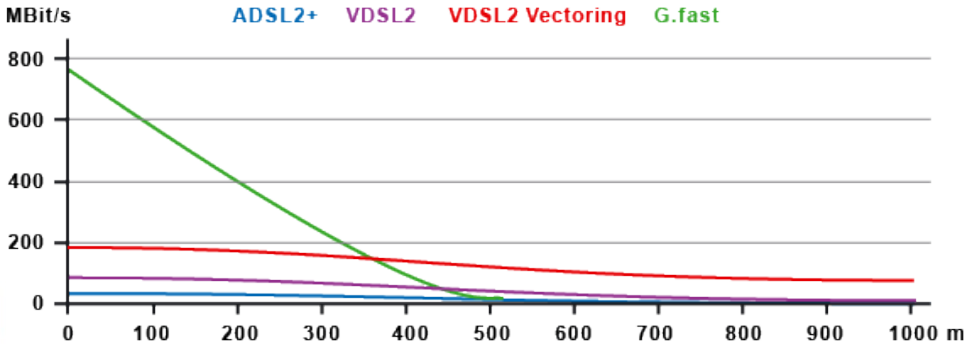
Vectoring

- It turns out that a significant portion of the noise in the line is due to cross-talk between adjacent copper pairs



- Vectoring (ITU-T-G.993.5) applies noise cancellation to the line, but it needs to have access to all interferes lines





G.fast

- G.fast increases the rate by using much larger bandwidth, up to 212 MHz
  - Notice that it overlaps with FM radio!
  - Also, due to overlap with ADSL and VDSL, the starting frequency can be set between 2 and 30 MHz.
- Initially targeting distances up to 250m, was then extended to up to 500m.
- Duplex is in the time domain (TDD) so the DS/US ratio can change (e.g., 90/10 or 50/50)

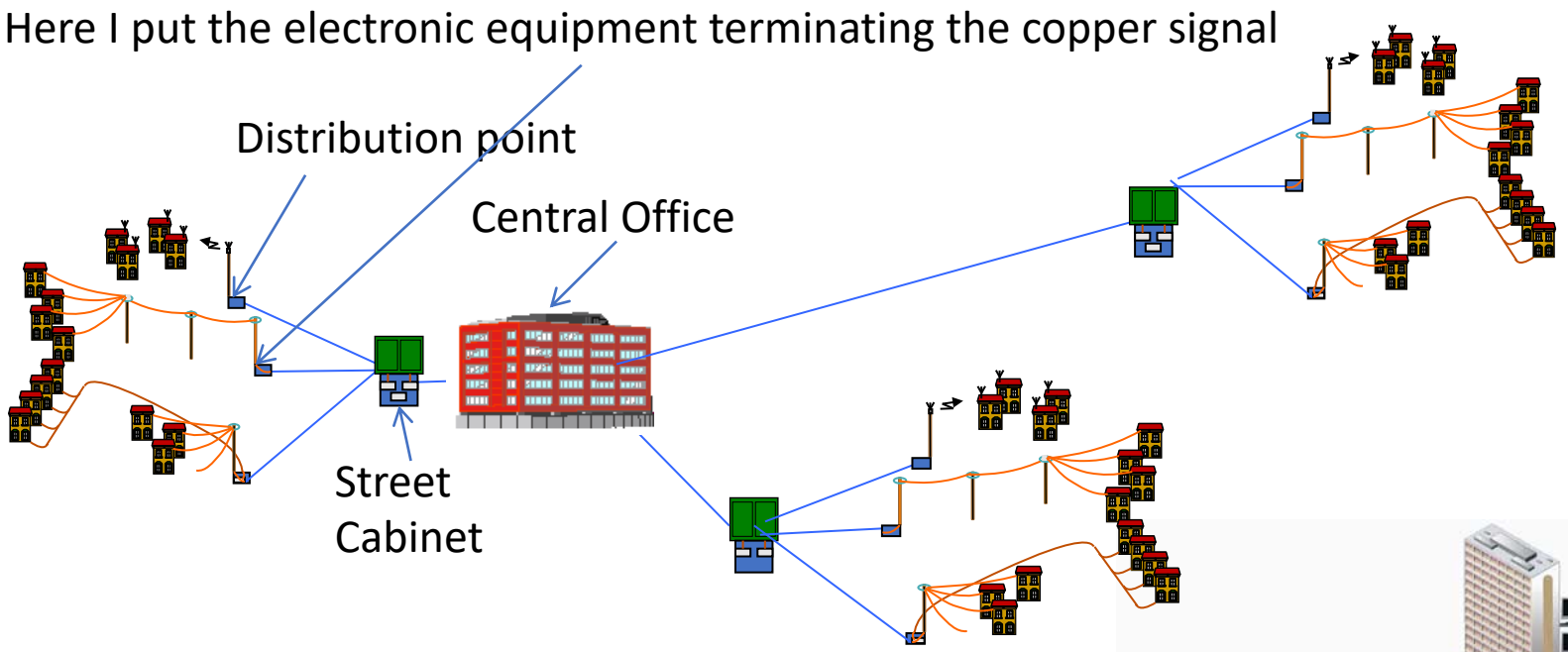
  - **<u>This technology can work both for FTTC and FTTDp</u>**

Distance	Performance target
<100 m, FTTB	500–1000 Mbit/s
100 m	500 Mbit/s
200 m	200 Mbit/s
250 m	150 Mbit/s
500 m	100 Mbit/s

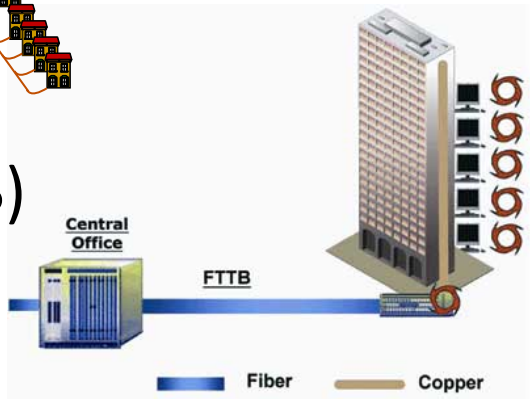
Fibre-to-the-distribution-point (FTTDp)

- Replace the copper all the way to the DP (that shared by most users) with fibre

➔ The overall distance now decreases to about 50 -100m

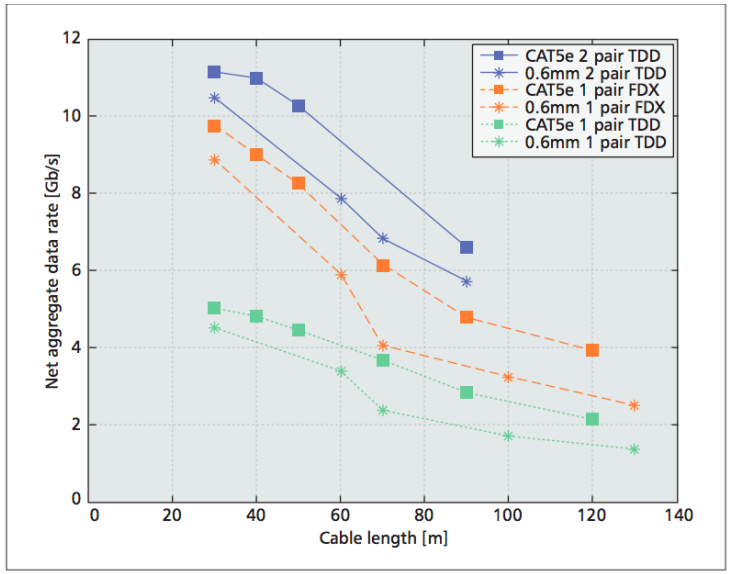


- This is also referred to Fibre-to-the-building (FTTB)



FTTDp technology

- G.FAST (as mentioned before)
- XG.FAST (now known as G.mgfast)
  - Under standardisation, aiming at 10Gb/s symmetric over very short copper distance
  - Technology:
    - It uses bandwidth up to 848MHz
    - Bonding: use of two copper pairs per users (where available), or coaxial
    - Phantom mode: create a third virtual pair of two physical copper pairs
    - Adanced cross-talk cancellation
    - Full-Duplex transmission (FDX): use same bandwidth both DS and US with echo cancellation



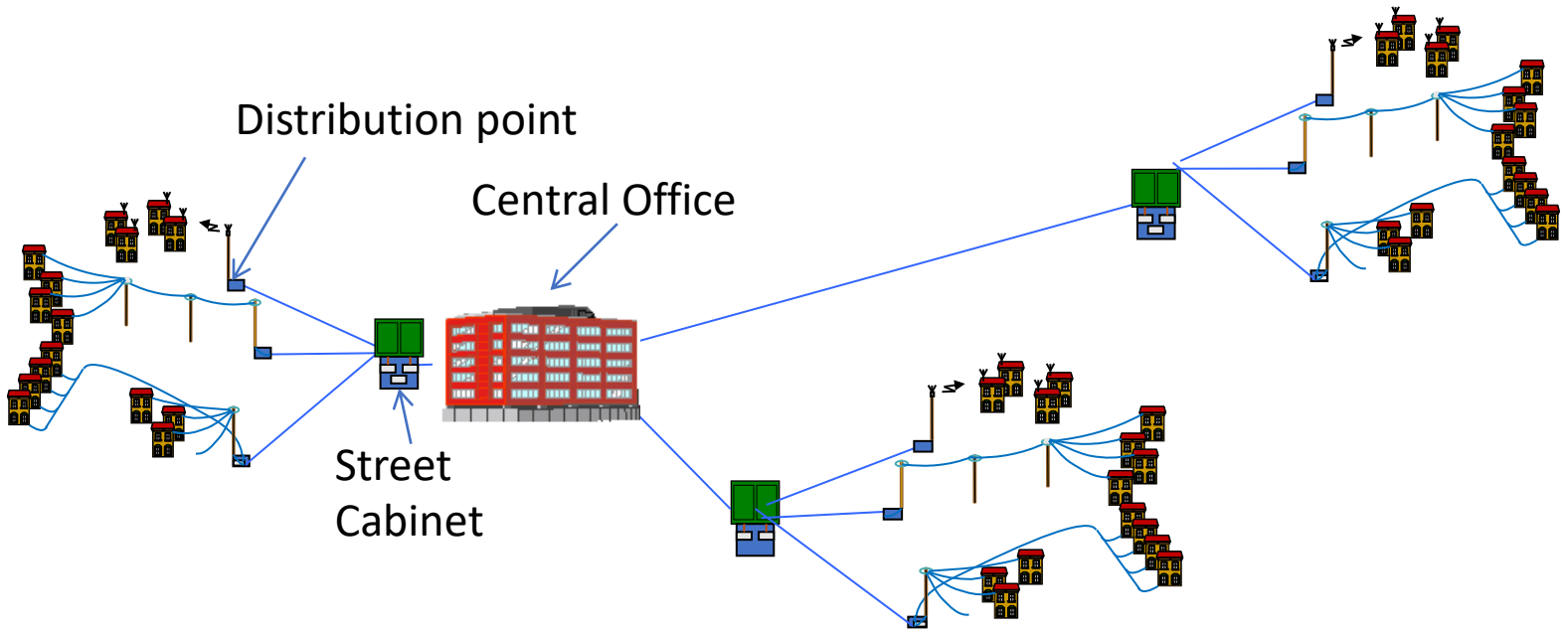
Notice that in a building you could use Gigabit Ethernet or 10GE, but **this means installing new Cat-5 or Cat-6 cables**

V. Oksman et al., MGFAST: A New Generation of Copper Broadband Access. IEEE Comm Mag, Aug. 2019

IEEE Communications Magazine — Communications Standards Supplement • December 2015

Fibre-to-the-home (FTTH)

- Replace the copper <u>all the way</u> to the house (or premises – FTTP)
- **<u>No copper remains</u>**, and the user can avail of the full speed of optical technology



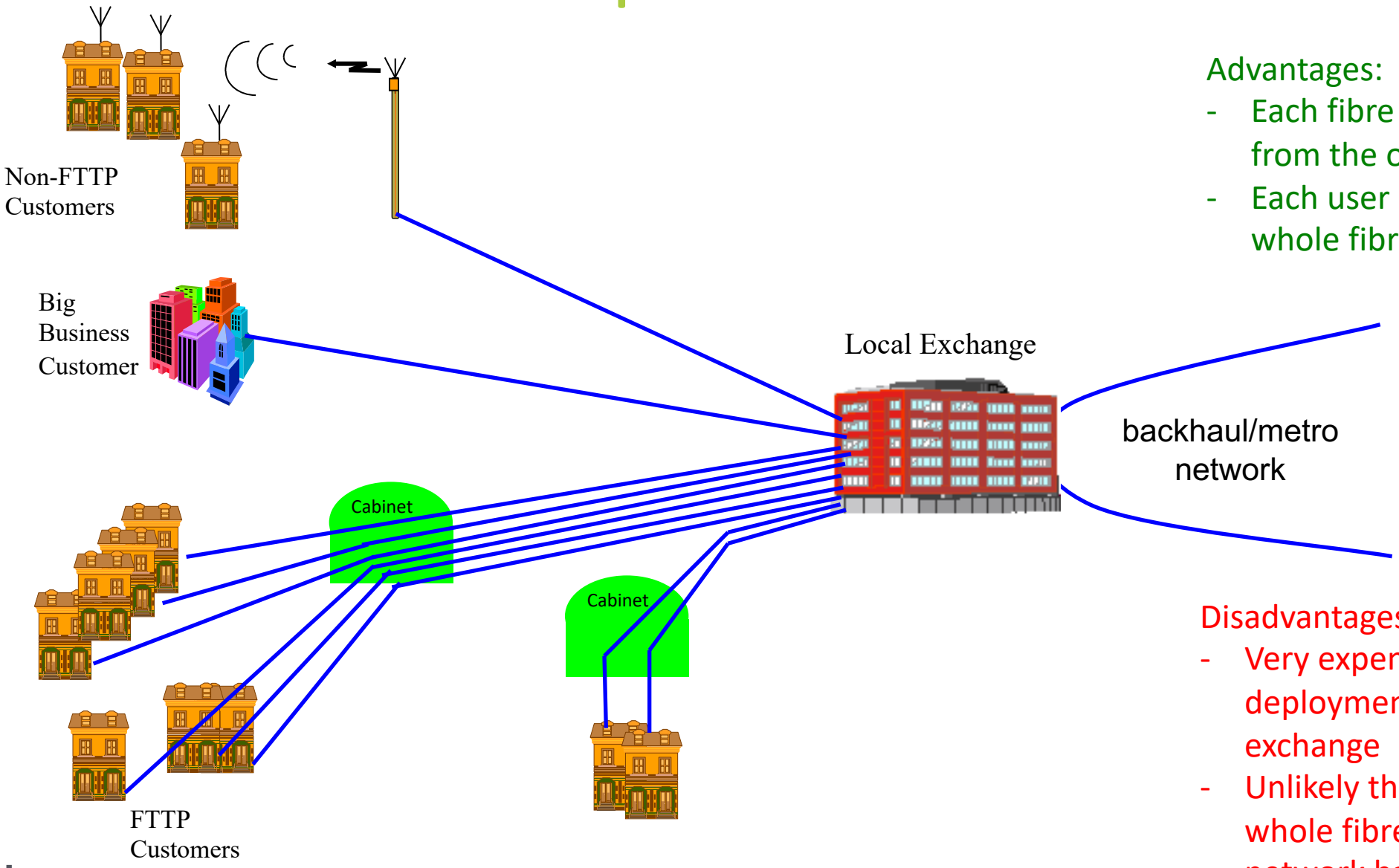
FTTH technology

- Point-to-point fibre

- Passive Optical Networks (PON)
  - Time division multiplexing PONs
  - Wavelength Division Multiplexing PONs
  - Time/Wavelength Division Multiplexing PON

  - Implemented in several standards:
    - IEEE (EPON, 10G-EPON)
    - ITU-T standards (GPON, XG-PON, XGS-PON, NG-PON2)

Point-to-point fibre



Advantages:

- Each fibre is totally independent from the others
- Each user can potentially have a whole fibre bandwidth

Disadvantages:

- Very expensive both in the fibre deployment and at the local exchange
- Unlikely that user will benefit of whole fibre bandwidth, because of network bandwidth aggregation

Point-to-point fibre

- In a point to point fibre development each user is served by an individual fibre connection
- The idea is simple: replace the copper with fibre and leave everything else as it is
- Each fibre has a termination at the user end and a termination at the network end (central office)
- The typical technology of use is Gigabit Ethernet (GE) over fibre or in some cases 10GE.
- This can easily be upgraded to 25G, 100G, etc., even on an individual customer basis as technology becomes available

- The Ethernet MAC remains the same as previous 10 and 100 Megabit standards, while the PHY layer changes. GE technology is very cost effective and works both on copper (any laptop today) and fibre.

Passive optical network (PON)

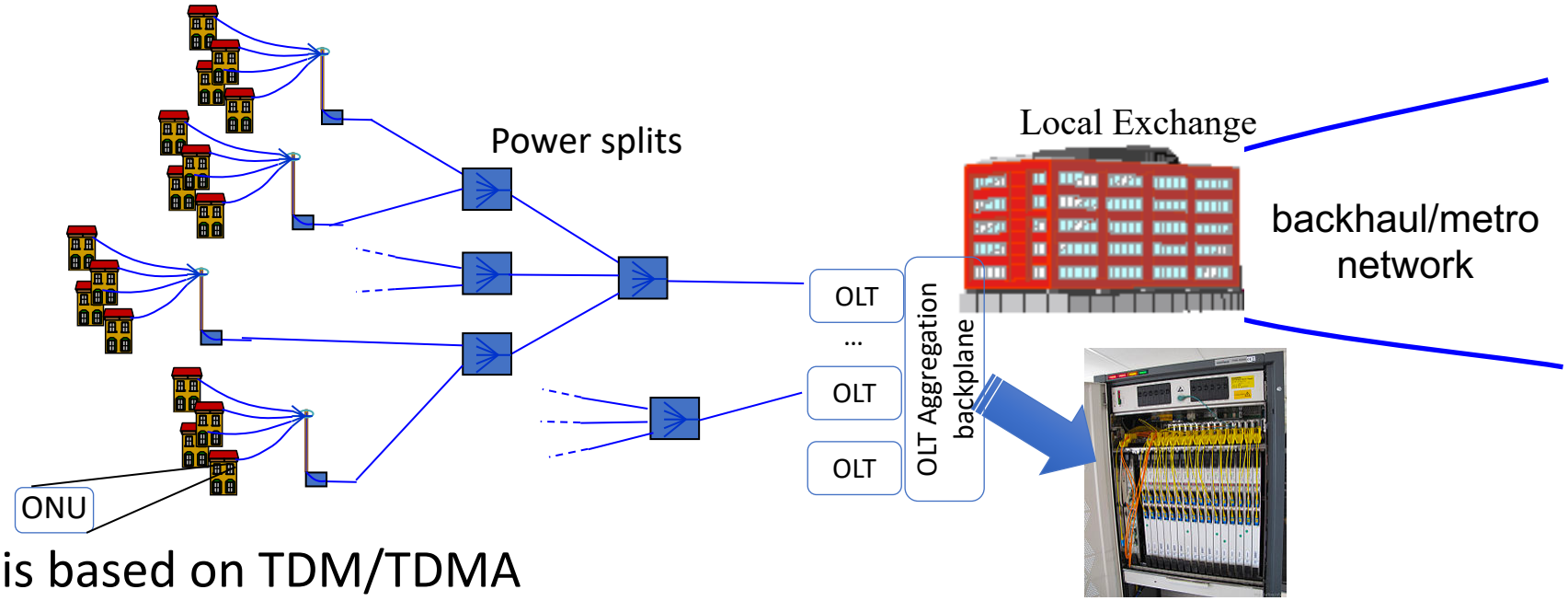
- It is expensive to deploy fibre solutions to the access as the cost of each connection is not shared among users

- PtP fibre doesn’t help much as:
  - it requires one individual fibre per user
  - at the network end it requires one termination port per user

- PONs were invented to reduce the cost for Capital (CAPEX) and Operarional (OPEX) expenditures:
  - The idea is to share the optical fibre into a tree structure using passive optical splitters
  - It allows one network termination or Optical Line Terminal (OLT) to serve many Optical Network Units (ONUs) at the user side
  - It also reduces power consumption and footprint substantially

Time Division Multiplexing PON (TDM-PON)

- There are both IEEE (EPON and 10GEPON) and ITU-T (GPON, XG-PON, XGS-PON) for FTTH
- IEEE PON standards are typically used in Asia, while ITU-T is used in Europe and US.

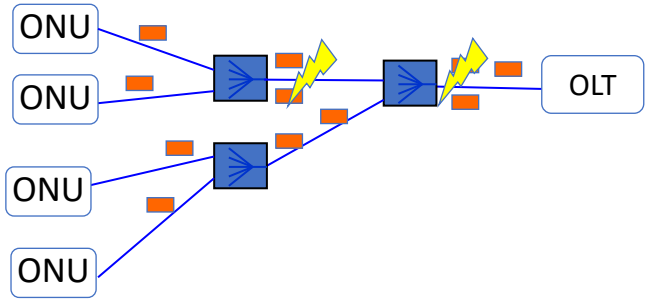


- The protocol is based on TDM/TDMA
- Downstream the OLT broadcasts data to every ONU, and each ONU filters out the data destined to it.
- Upstream is different as all data will converge into the same link to the OLT

➔ A MAC needs to be implemented for the upstream transmission

Downstream and upstream channels

- Downstream transmission (OLT => ONU) is achieved through broadcast, the ONUs filter out the packets destined for them
- The downstream signal is continuous, and such receivers are not expensive.
- In the upstream direction a MAC is implemented to avoid collision of signals from different ONUs.



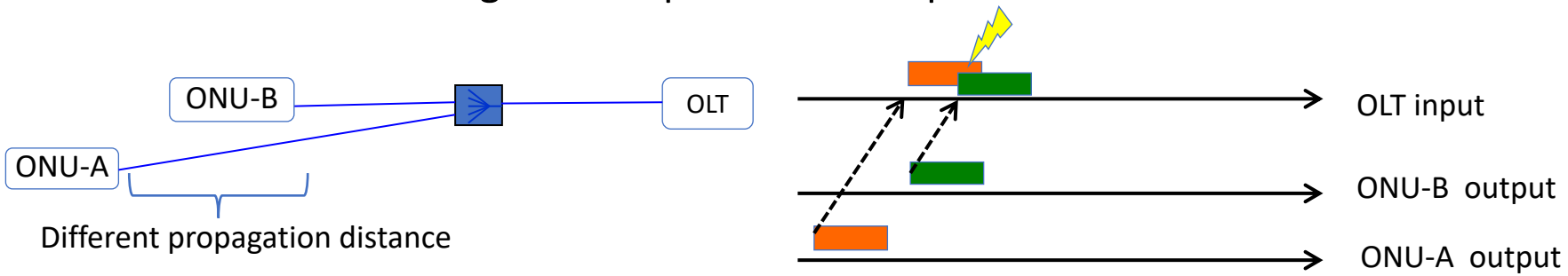
- The access to the upstream channel is TDMA.
- The OLT receiver operates in “burst-mode”, i.e. it receives short burst of data. A burst-mode receiver is more complex and expensive than a continuous-mode one

Ranging operations

- The OLT has the task of synchronizing all ONUs for upstream transmission.
- However the ONUs have all different distance from the OLT

  => Their different propagation time needs to be considered

  Otherwise two burst might overlap at the OLT input



- The OLT operates “Ranging” operations to figure out the relative time shift of the ONUs
- This is operated whenever a new ONU joins the PON

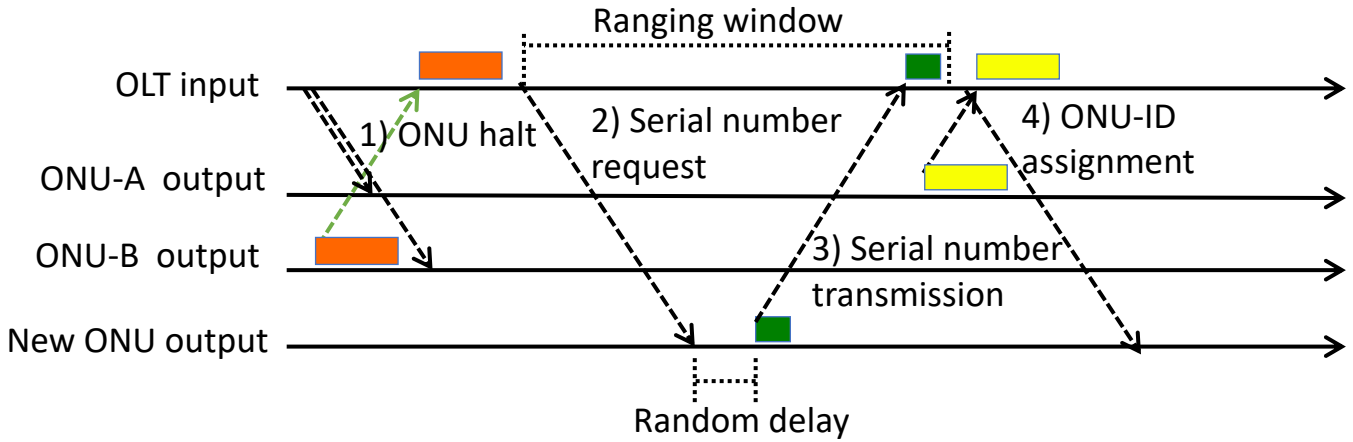
Light in fibre travels at about $2*10^8$ m/s ➔ it takes 5 ns to travel 1 m

- 100m difference translates into 500 ns
- At 10Gb/s one bit lasts 0.1 ns

➔ 100 m equals to 1000 bits difference

Ranging phase 1

- Phase 1 is used to register a new ONU

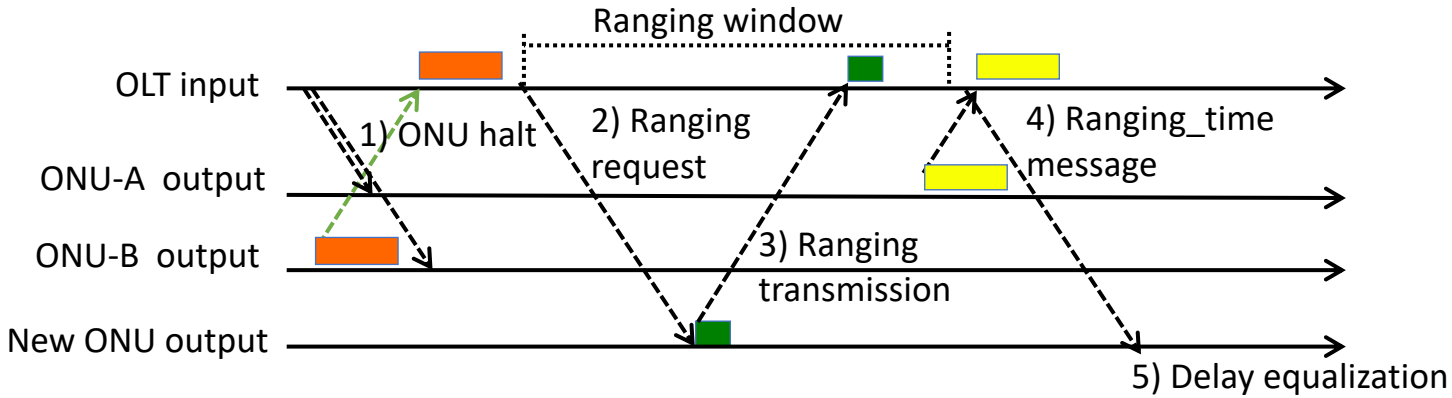


1. The OLT sends a halt msg to all ONUs to stop upstream transmission
2. OLT request serial number to unregistered ONU(s)
3. After receiving the request, an unregistered ONU transmits the serial number after waiting for a random time (up to 48 µs)
4. The OLT registers the ONU assigning it an ONU-ID value

The ranging window limits the distance between the OLT and furthest ONU. In GPON this is 20km => 200 µs (delay of 5µs for each Km, calculated for the round trip)

Ranging phase 2

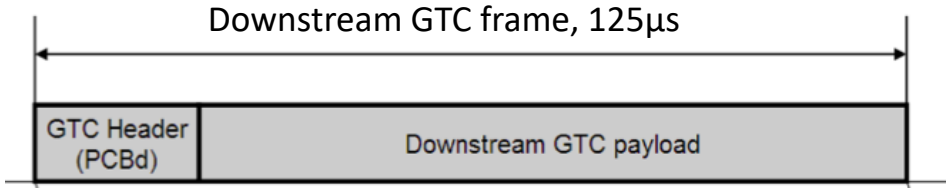
- Phase 2 is used to measure the Round-Trip-Delay (RTD) to the ONU



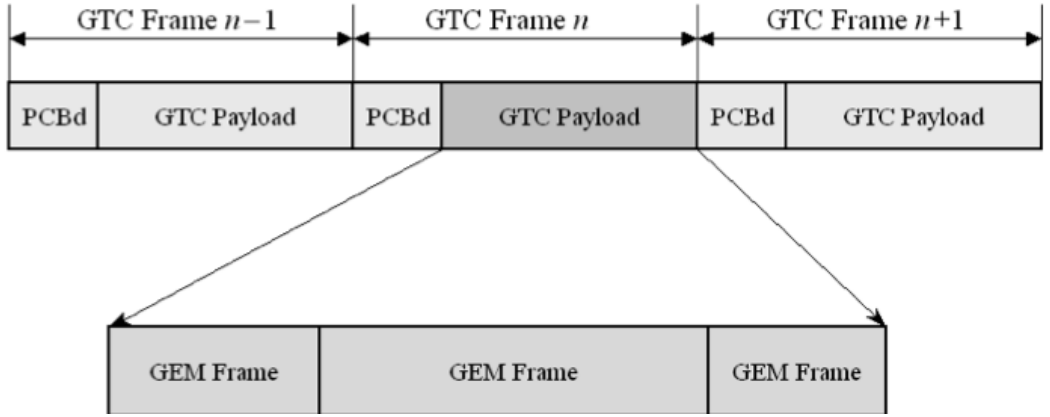
1. OLT sends a halt msg to all ONUs to stop upstream transmission
2. OLT sends a Ranging request to a specific ONU (using ONU-ID)
3. The ONU with that ONU-ID sends back a Ranging message to OLT
4. OLT calculates the RTD for that ONU and notifies the ONU of its Equalization Delay(=Teqd-RTD), where Teqd is max RTD (e.g., 200µs)
5. The ONU stores the Equalization delay and uses it for all upstream transmissions

Downstream frame

- Each frame is 125µs long (inherited from Sonet/SDH standards)
- The frame is scrambled, i.e., passed through a function that transforms it in a different sequence of bits.
  - The opposite function (de-scrambling) is applied at the receiver
  - Used to avoid too many 1s or 0s in sequence (can loose synchronization)

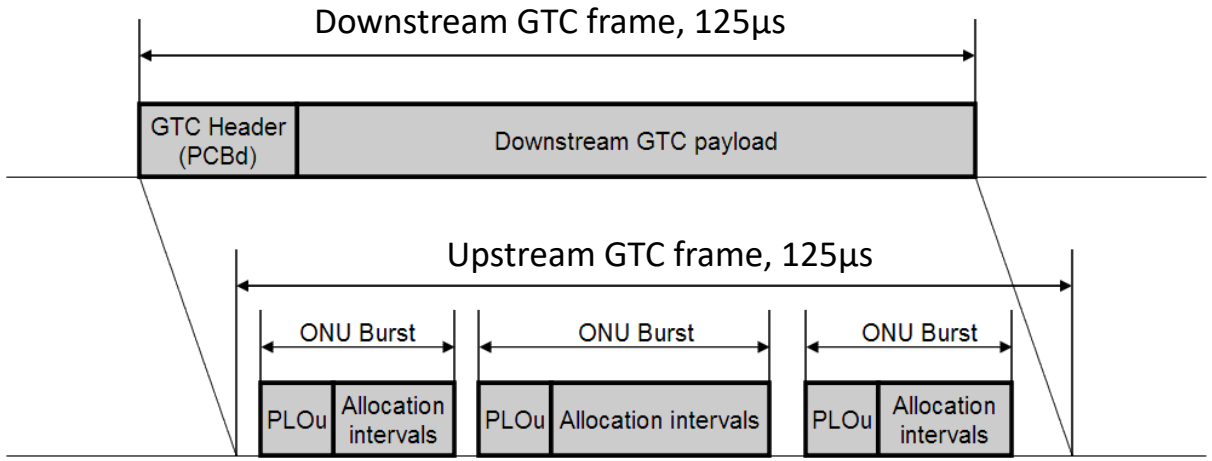


- Each GTC payload carries multiple GEM frames, each directed to a different GEM port



Upstream burst structure

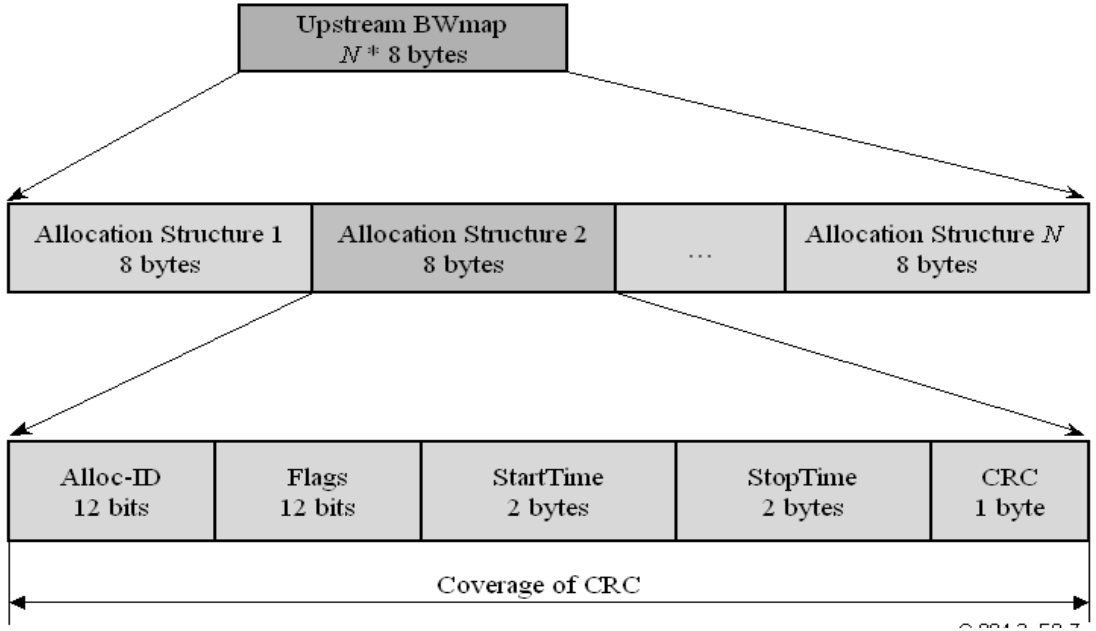
- Upstream transmission is arranged in bursts rather than continuous frames.
- However a sequence of burst is delimited within a frame of 125µs, for symmetry with the downstream frame
- The bandwidth allocation map sent in the downstream frame allocates all traffic for the corresponding upstream frame



- The upstream bursts are also scrambled

Bandwidth map for upstream traffic scheduling

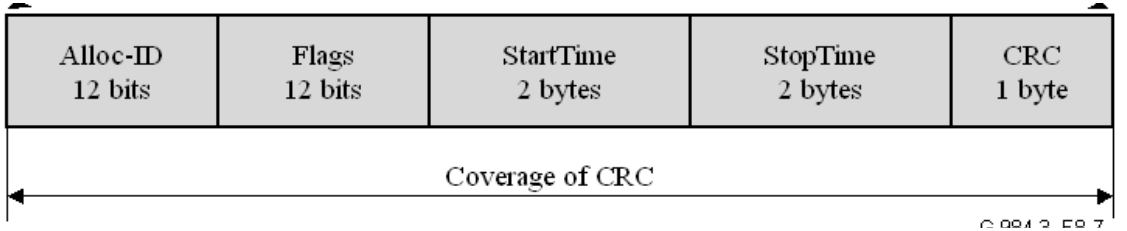
- It's used to tell the ONUs when to transmit their payload upstream
- It's at the base of the upstream MAC and is organized by the OLT



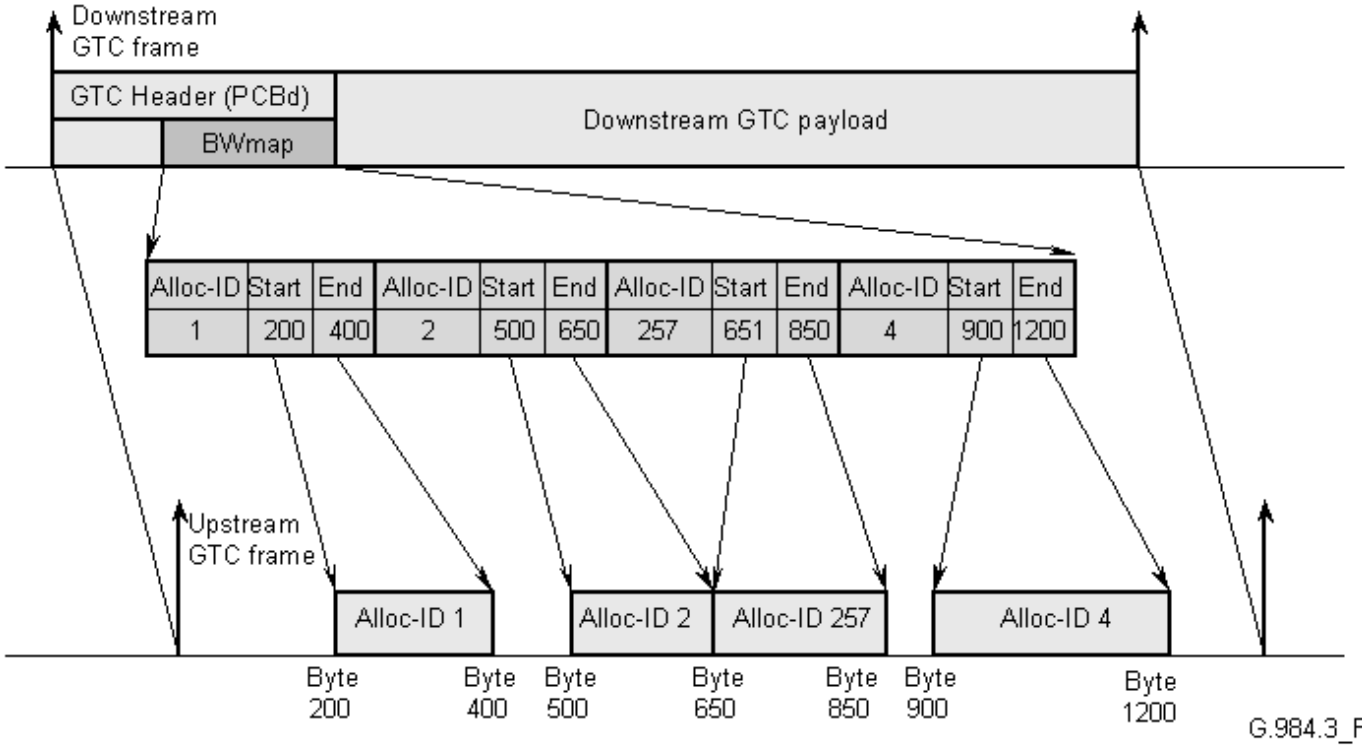
- Alloc-ID: indicates the recipient of the bandwidth allocation (the T-CONT)
- Flags: indicates whether the ONU should send a management packet, should use FEC, send a Dynamic Bandwidth Request

- StartTime: indicates the starting point of the frame allocation. It's in bytes and the reference point is the beginning of the upstream GTC frame

Bandwidth map

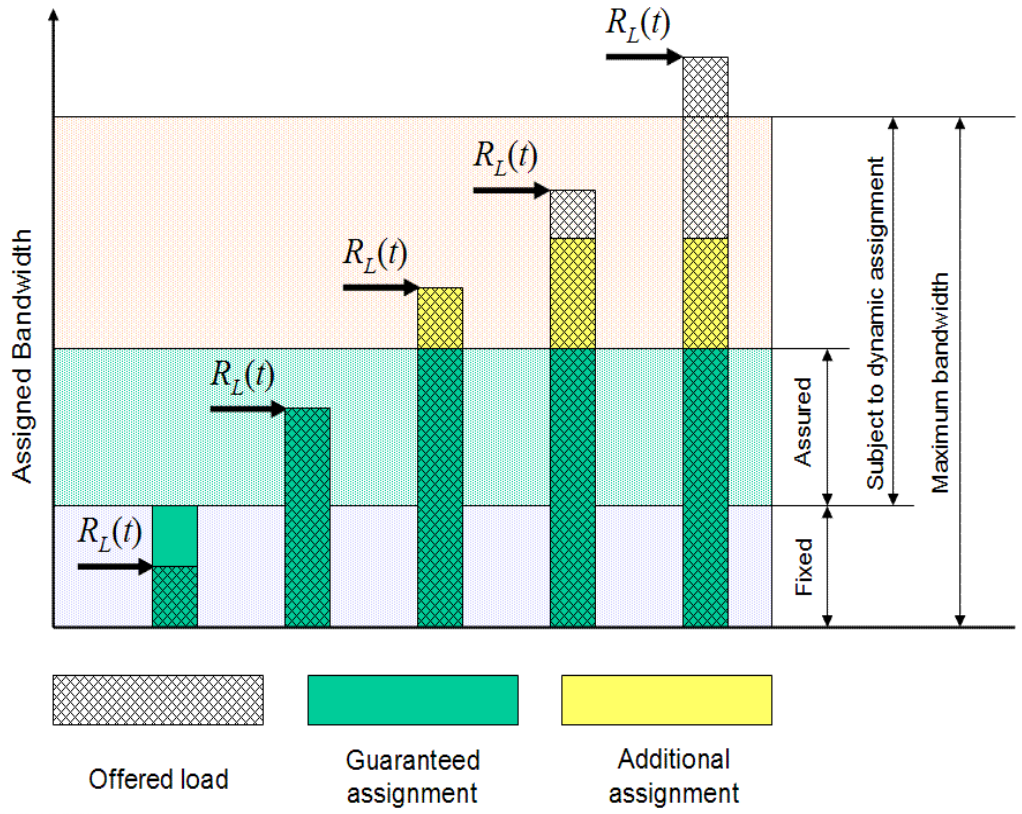


- StopTime: indicates the stop point of the frame allocation
- CRC: Cyclic redundancy code protecting the bandwidth allocation
- Example:



Dynamic Bandwidth Assignment (DBA)

- DBA is the process by which the OLT decides how to assign upstream transmission opportunities (e.g., bandwidth) to the ONUs
- The mechanism works either by:
  1. Status reporting: the ONU informs the OLT on how much bandwidth it needs
  2. Traffic monitoring: OLT decides based on the observed traffic pattern



- A small fixed bandwidth is typically assigned to each ONU
- A variable bandwidth is assigned depending on demand
- The variable part is divided in:
  - Guaranteed: this is always available for the ONU when needed (e.g., by contract)
  - Additional: it can be assigned if there is enough spare bandwidth available

Difference between GPON and EPON upstream

GPON

Stricter specifications, rigid frame structure and strong QoS focus:

- uses traffic containers (T-CONT) as uplink traffic scheduling units to enable QoS service prioritization: Fixed, Assured, Non-Assured, Best-Effort.
- Each ONU can have multiple T-CONTs with different classes

Mechanism:

- ONUs send traffic report indicating their buffer occupancy whenever they have a transmission opportunity (typically every N frames)
- The OLT collects all such reports from a frame, then calculate a grant allocation for the next downstream frame.
- The allocation is sent at the beginning of the frame for all ONUs that will transmit in that frame, called Bandwidth Map

EPON

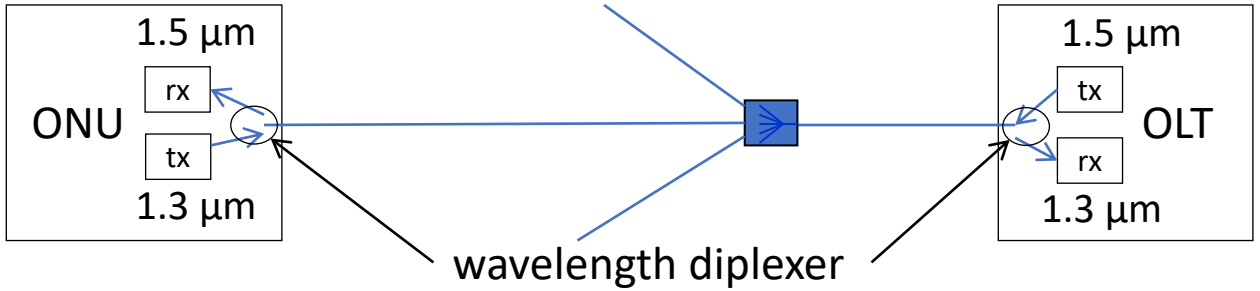
Looser standard definition, use of “packetized” Ethernet packets frame structure

Mechanism for IPACT algorithm (Interleaved Polling with Adaptive Cycle Time):

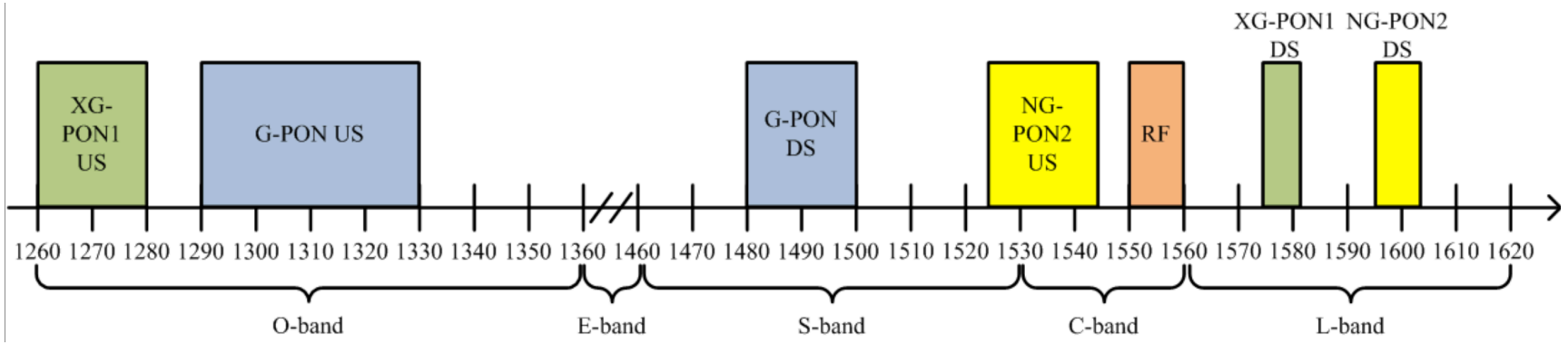
- The OLT sends a grant to a given ONU specifying the amount of data it can transmit
- Upon receiving it the ONU transmits immediately that amount of data and then indicates how much more data it needs to transmit.
- The OLT will iterate the process across all ONUs

Duplex scheme

- The most (economically) convenient duplex scheme is wavelength division duplex over single fibre, although two-fibre systems are allowed by the standard

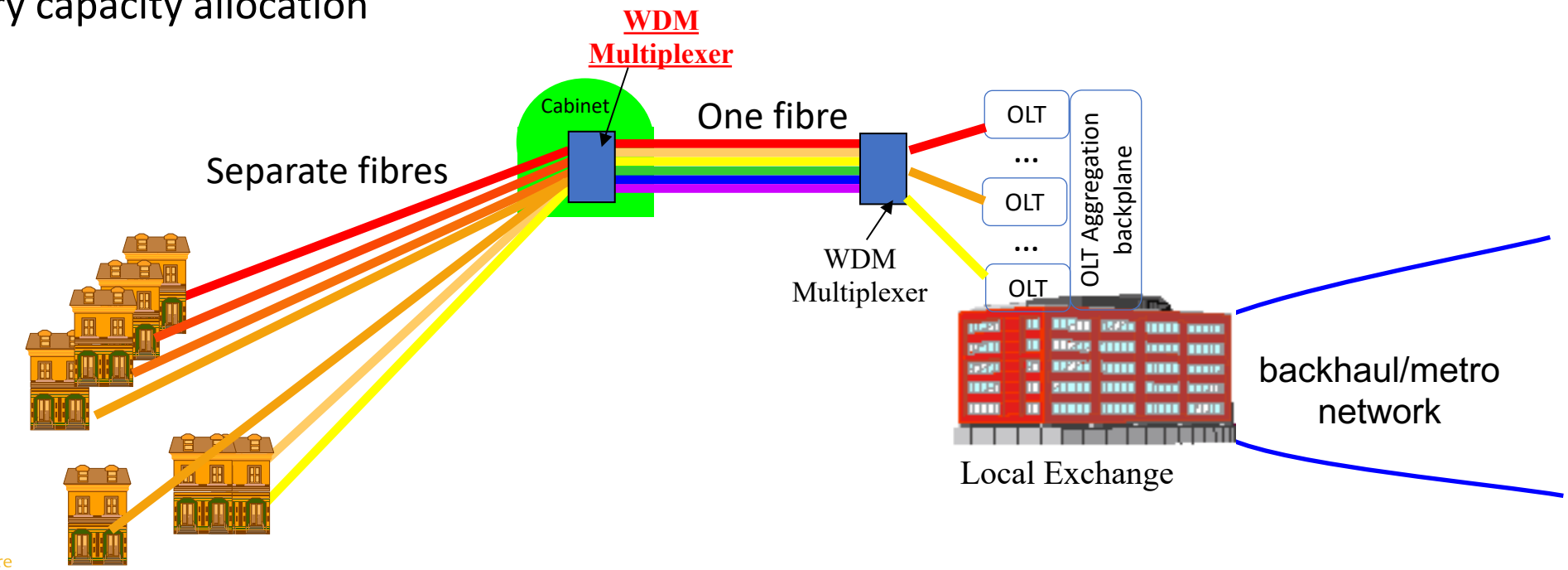


- Different wavelengths are required to avoid that reflections from the transmitted signal adds to the received signals
- Since single-mode fibre has low dispersion at 1.3 µm, cheaper wider-linewidth lasers (FP) can be used at the ONU (customer side)
- More expensive DFB lasers need to be used at the OLT to limit dispersion at the 1.5 µm wavelength.



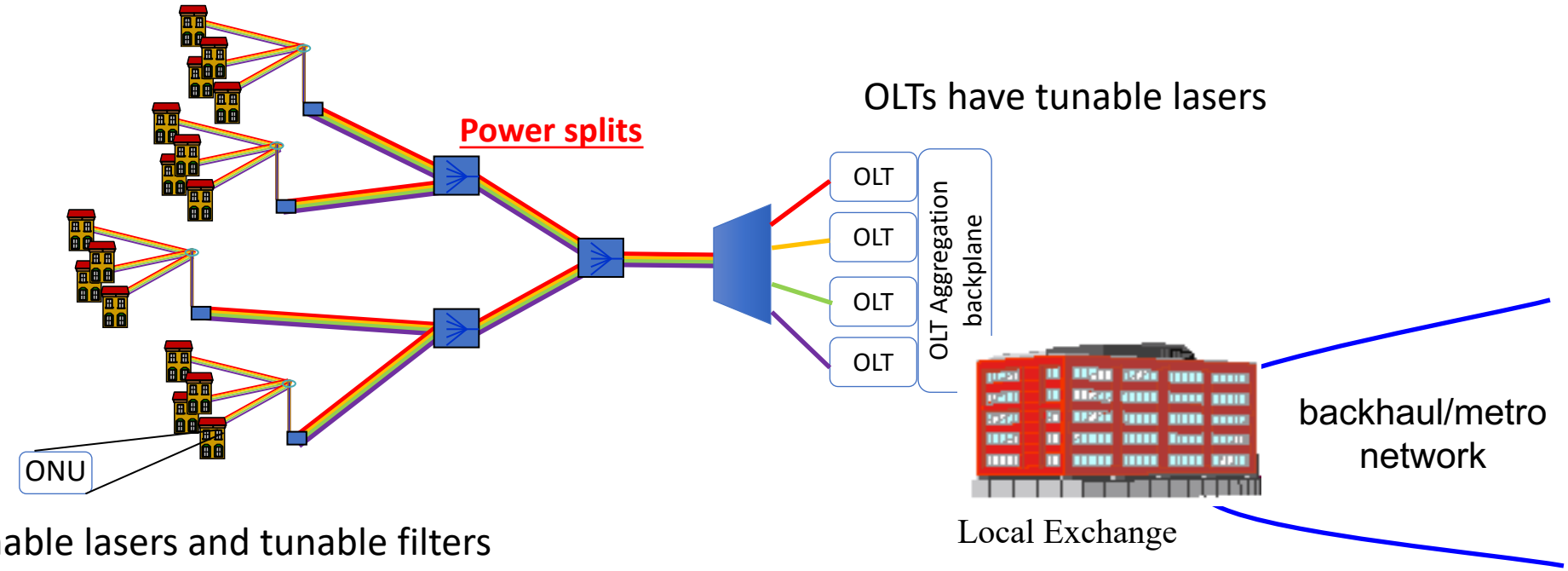
Wavelength Division Multiplexing PON (WDM-PON)

- In WDM-PON each user is served by a separate wavelength channel and a WDM splitter is placed in the cabinet to separate the wavelengths into different fibres
- Logically it is a point-to-point connection as each user is served by a different wavelength channel
- The channel would normally use 1GE or 10GE, although no WDM-PON standard exists
- The issue is that a wavelength is fixed to a destination, so there is little room for more arbitrary capacity allocation



Time/Wavelength Division Multiplexing PON (TWDM-PON)

- The concept is the same as the TDM-PON, but now multiple wavelengths are used over the fibre



ONUs have tunable lasers and tunable filters

- ONUs can tune laser and receiving filter to select a different OLT
  - For example if one OLT is congested, ONUs can be moved to a different OLT
  - Or one ONU can be linked to a dedicated OLT (logical PtP) for the time required to complete a service (e.g., 10G bandwidth-on-demand - BoD)
  - **Passive splitters and tunable end point is the most flexible solution as it can offer very different capacity, on demand, to different type of users**

Wavelength tuning issues

- NG-PON2 products started to appear in 2014, but ONUs were too expensive
  - The XGS-PON was developed: single wavelength 10G symmetric.

- Wavelength tuning is expensive, because tunable lasers require individual characterization
  - Tuning is achieved by injecting a number of currents, whose behavior depends on the individual physical component.

- Also, burst transmission can cause transient change in wavelength (need gating)

- Some proposals involved a coarsely characterized device, whose tuning would be adjusted during operation:
  - When the ONU comes up it can appear at any wavelength
    → Need to synchronize quite windows across all wavelength channels

PON Standards

	Standard	Year	Typical Rate DS/US [Gb/s]	Power budget [dB]	Split ratio	Logical/ Differential/ Fibre reach	DS Wavelength	US Wavelength
ITU-T	GPON G.984	2008	2.5/1.25	21-31	Max 64, typical 32	60/20/10-20 km	1480-1500	1260-1360
ITU-T	XG-PON G.987	2012	10/2.5	29-31	Max 256, Typical 64	60/40/10-40 km	1575-1580	1260-1280
ITU-T	XGS-PON G.9807	2016	10/10	--	128	--/--/--	--	--
ITU-T	NG-PON2 G.989	2015	10/10 x 4 PON + 10/10 x 4 PtP	29-35	Max 256, Typical 64	60/40/20-40	1596-1603	1524-1544
IEEE	EPON 802.3ah	2004	1.25/1.25	20-33	Typical 32	--/10/10-20	1480-1500	1260-1360
IEEE	10G-EPON 802.3av	2009	10/1.25-10	20-33	Typical 32	--/10/10-20	1575-1580	1260-1280

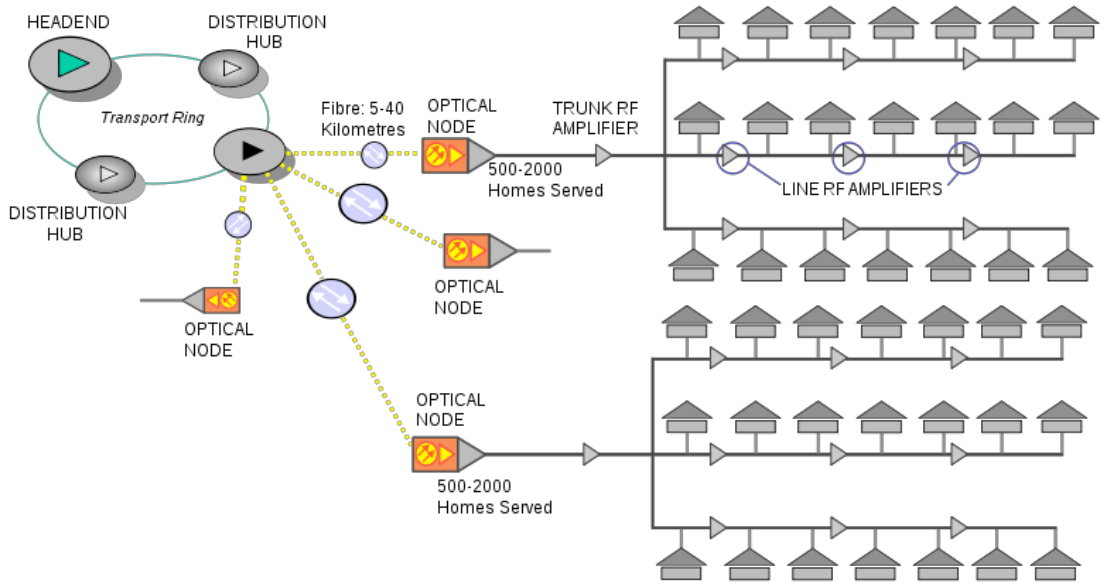
- IEEE P802.3ca task force and ITU-T working on >10G speed. This is strongly driven by low-cost optical Ethernet components.

- IEEE 25G-EPON expected in 2020 (two wavelengths for 50G, 1342 and 1358 nm)
- ITU-T 50G-PON expected also in 2020

- Research is ongoing for higher rates (how to tackle dispersion, the lower power budget, etc.)
- At what point does the PON become coherent?

Don’t forget DOCSIS!

- **<u>This is a copper technology. But it utilizes a coaxial cable instead of a twisted copper pair!</u>**
- The cable network is different from the telephone network, as cable in not point-to-point, but is shared among a number of houses.
- The standard for cable broadband is called DOCSIS (Data Over Cable Service Interface Specification).
- Different version of DOCSIS have been released over time, providing higher speed, but also requiring a shorter cable loop (i.e., the fibre termination was progressively brought closer to the homes)



DOCSIS PHY

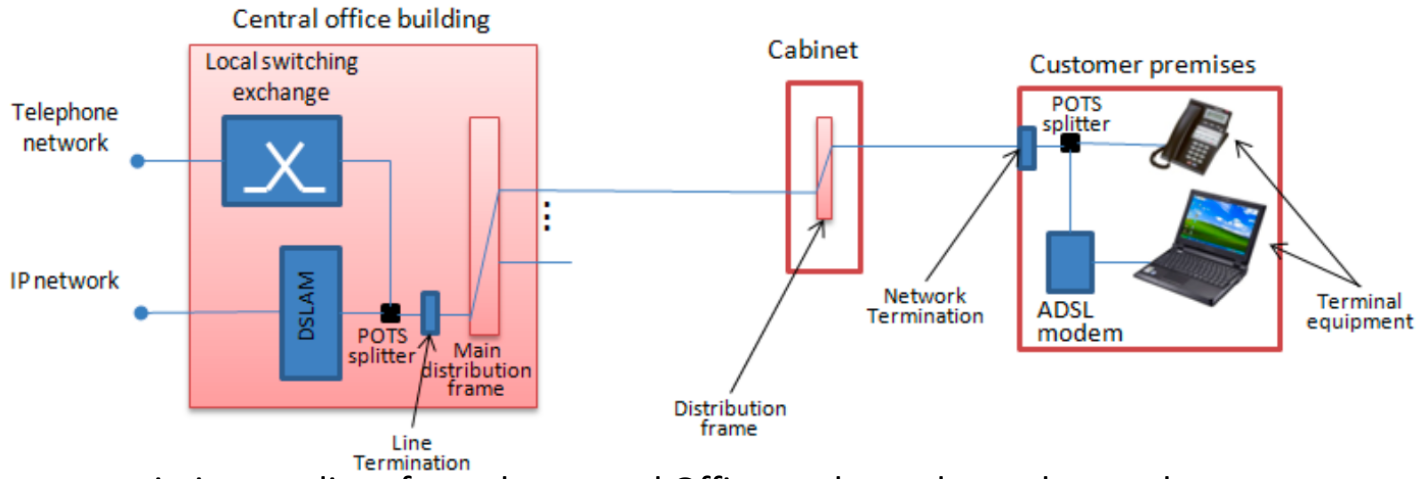
Version	Year	Max DS channels	DS ch width [MHz]	DS Modulation	DS rate [Mb/s]	Max US channels	US ch width [MHz]	US Modulation	US rates [Mb/s]
1.0	1997	1	6	64/256 QAM	42.88	1	0.2-3.2	QPSK/ 16QAM	10.24
2.0	2001	1	6	64/256 QAM	42.88	1	6.4	QPSK/ 8-128QAM	30.72
3.0	2006	32	6	64/256 QAM	1372.16	8	6.4	QPSK/ 8-128QAM	245.76
3.1	2013	2-5	25/50KHz OFDM 192MHz block	64-4096QAM	10 Gb/s	2	25/50KHz OFDMA 96MHz block	QPSK/ 8-4096QAM	1,000

- The European version EuroDOCSIS has different channel bandwidth (8MHz instead of 6 for the 1.0 to 3.0 versions)
- The full-duplex DOCSIS 3.1 (renamed DOCSIS 4.0 provides symmetric 10Gb/s and uses up to 1.8GHz of bandwidth in the cable)

Content of the talk

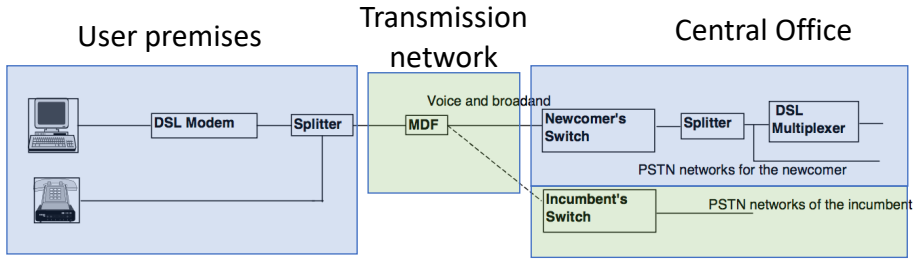
- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don't forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON
- Conclusions

Local Loop Unbundling

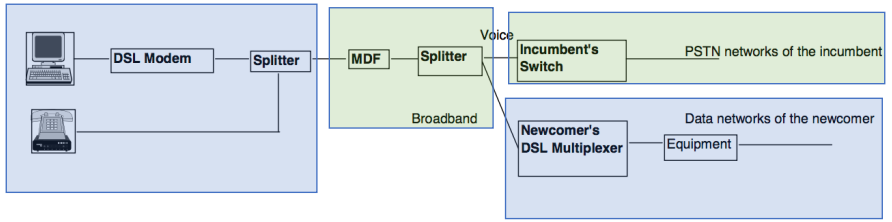


- The local loop is the transmission medium from the central Office to the end user, hence the name
- Local Loop Unbundling gives new operators (Other Licensed Operators –OLO) access to the network of the ex national operator (incumbent operator)
- This is a physical connection as the OLO physically connects the end user to its own equipment in the central office

Full unbundling



Line sharing

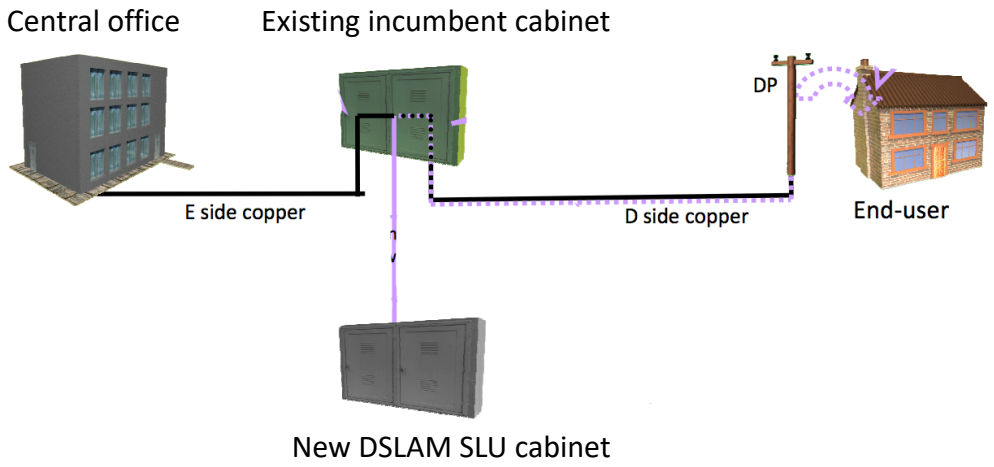


= incumbent responsibility

= OLO responsibility

Sub Loop Unbundling (SLU)

- LLU is useful for DSL, but technology like VDSL2 that use FTTCabinet need to share copper from the cabinet to the end user (i.e., the sub-loop)
- SLU then deals with sharing of the copper from the cabinet to the user

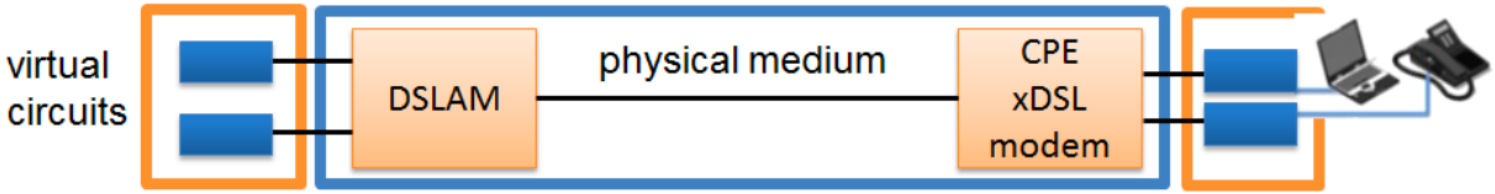


- With SLU an OLO terminates the copper pair of an end user to its cabinet. This creates problems with vectoring:
  - Vectoring works by carrying out signal processing across all the copper lines sharing a common cable
  - If different OLOs terminate the line this cross-processing is not possible anymore, thus the higher rates of vectoring cannot be achieved.

Bitstream access

- Bitstream access involves the creation of virtual circuits so that an OLO can offer broadband to an end user through a virtual circuit
  - The virtual circuit is created through VLANs
  - The OLO does not need to physically terminate the user at the MDF

- The interconnection point can be at the local exchange although often is only at the regional Point of Presence (PoP) of the incumbent



  - The advantage is that the OLO does not need to provide physical infrastructure to terminate the copper lines
    - The capital cost for providing the service is lower
    - It increases competition

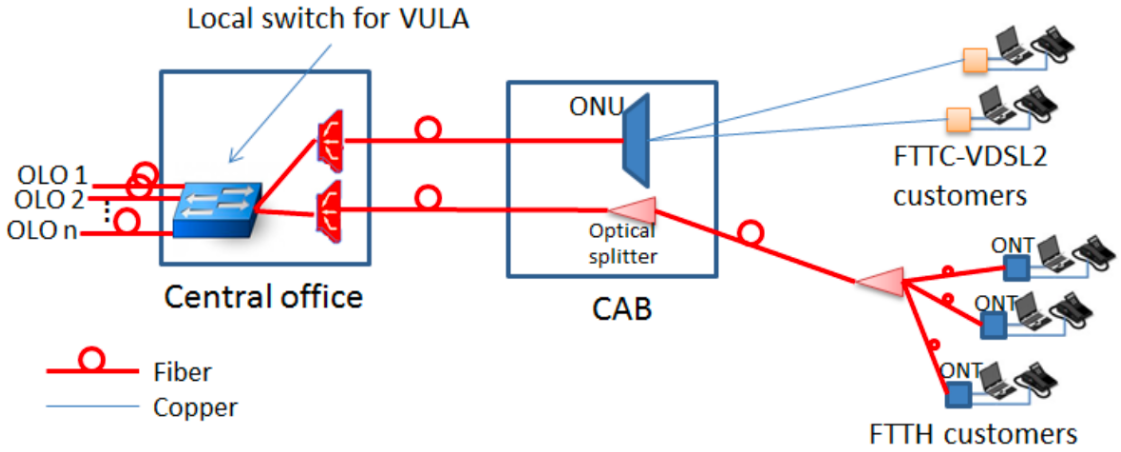
Is more needed?

- So with bitstream access an OLO can provide services to an end user without owning access infrastructure..
  - Why considering other options?
  - Is this not the best option?
  - What else could an OLO possibly want?

- The problem with bitstream is that it offers a standard rate connection to the OLOs without service differentiation:
  - All OLOs can only offer to the end user the same type of service
  - An OLO cannot differentiate their product from other OLOs or the incumbent
  - The only competition can be on price or on leveraging their brand, but the service provided is exactly the same as other OLOs

Virtual Unbundling Line Access (VULA)

- VULA was born to allow OLOs to differentiate their product by:
  - Putting the interconnection at the first aggregation point
  - Having uncontended access between user and interconnection point
  - Being able to decide quality of service parameters
  - Being in control of the Customer Premises Equipment (CPE)



- In VULA, the OLO can put the interconnection in the central office, similarly to LLU.
  - This allows better control over the service offered
  - But it requires more investment by the OLO

Next Generation Access (NGA) Bitstream

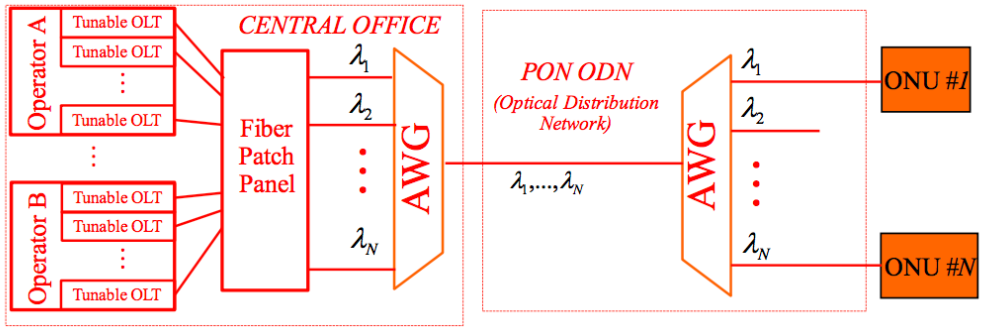
- It provides a way for OLOs to avoid the need to interconnect at every Local Exchange, while offering better service than legacy bitstream
- Interconnection points can be Metro, Regional or National PoPs
- Improved service compared to legacy bitstream include:
  - Higher bit rates and FTTH technology
  - IPTV
  - Multicast
  - Layer2 access
  - Traffic QoS classification
  - Ability for the user to subscribe to multiple OLOs

PON unbundling

- As access network progress towards fibre access, the question raises on how to unbundle them
  - Point-to-point fibre is easy as it allows for LLU
    - For this reason a number of countries have adopted this strategy (e.g., Sweden), but the cost is high. In Switzerland they have deployed 4 fibres per home…
  - PONs are more difficult, but it depends on the technology
    - For WDM-PON in principle wavelength unbundling could be done so the OLOs could access different wavelengths…
    - For TDM-PON, the issue is that the signal from multiple ONUs goes to the same OLT, so it cannot be physically split, but needs to be accessed after the OLT
    - TWDM-PON offers the best options, on an infrastructure with power splitters

Wavelength-routed vs. power-split PON

Wavelength-routed

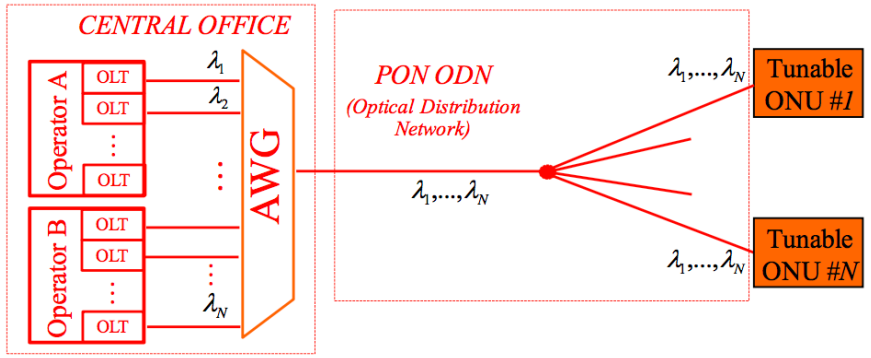


Clear separation, like LLU, as each user is set on a different wavelength and operators can access them at the central office by using specific wavelengths

Higher cost as each user is terminated on an individual port

Low flexibility has each user can only receive a wavelength

Power-split



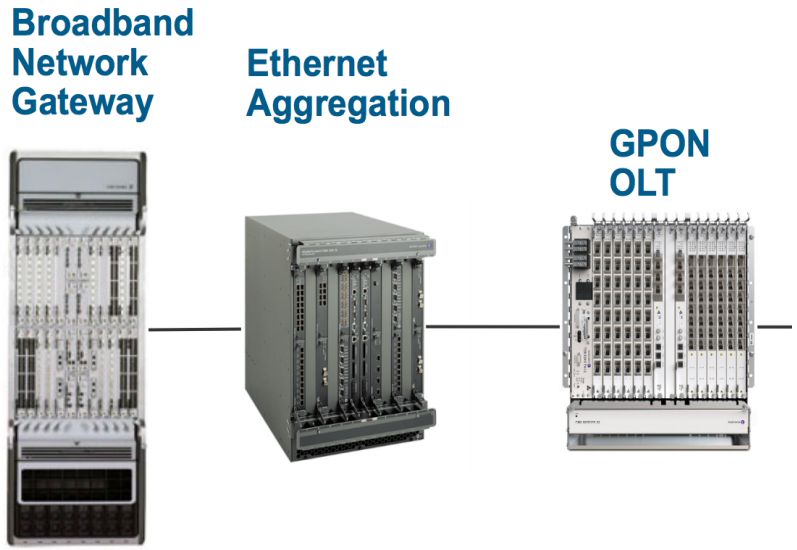
It gives maximum flexibility:

- OLOs can operate at specific wavelengths were end users can subscribe by tuning
- Capacity assignment is quite arbitrary, as OLOs can decrease the number of users per PON dynamically to give more capacity
- OLOs can assign more than one wavelength to a user, if the user has ONUs with more transceivers
- …

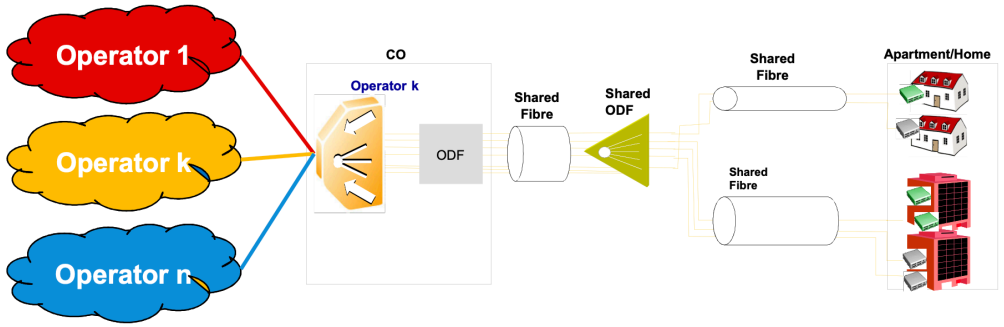
Lower cost as it allows multiplexing between users

Is this enough for 5G?

- Remember that 5G is not only a Radio Access Technology (RAN) but is meant to support services that require end-to-end, QoS-oriented, high performance.
- It also spans highly heterogeneous technology across optics, wireless and cloud.
- Take a closed system from any vendor like this:
  - How do you make it operate with other devices that only other vendors might produce (e.g., macro cell, small cell, etc?)
  - How do you make it operate on multi-tenancy scenarios?
- And more generally how do you unify your fixed, mobile and cloud environment, keeping multi-tenancy and end-to-end slicing availability?

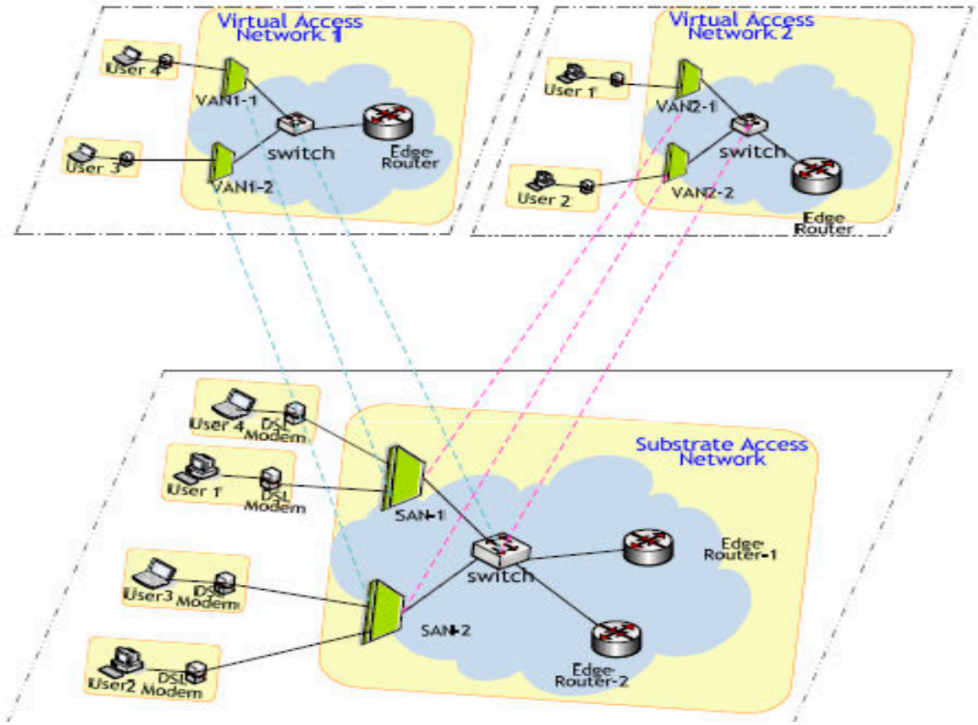


The BBF approach: Fixed Access Network Sharing (FANS)

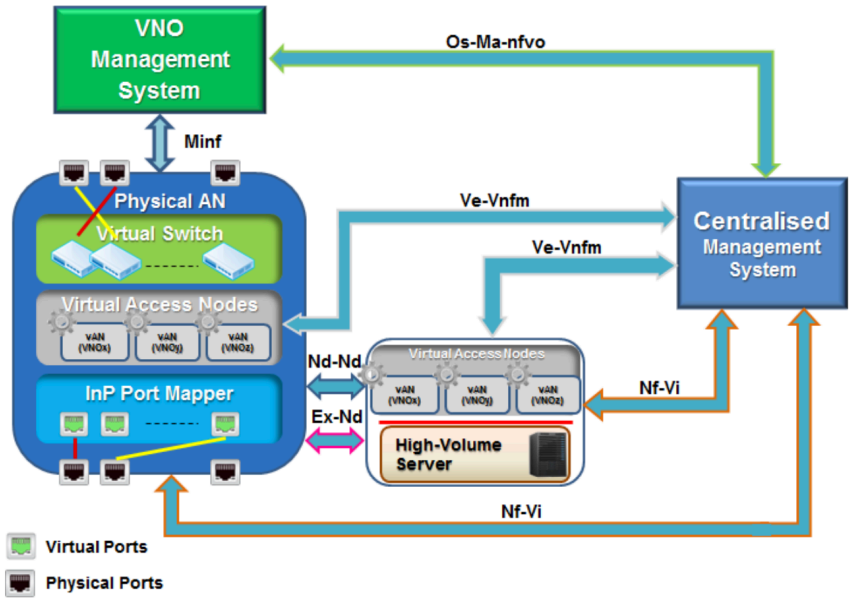


Bitstream: an operator makes use of the active equipment of another operator. Typically deliver basic services

FANS: VNOs can create and manage a virtual network on top of the Infrastructure from the InP. Can run complex and customised protocols/services, etc.



Bruno Cornaglia, "Fixed Access Network Sharing". Workshop presentation, 41st ECOC, 27th September, 2015, Valencia (Spain).



BBF TR-370
Fixed Access Network Sharing - Architecture and Nodal Requirements. Nov. 2017.

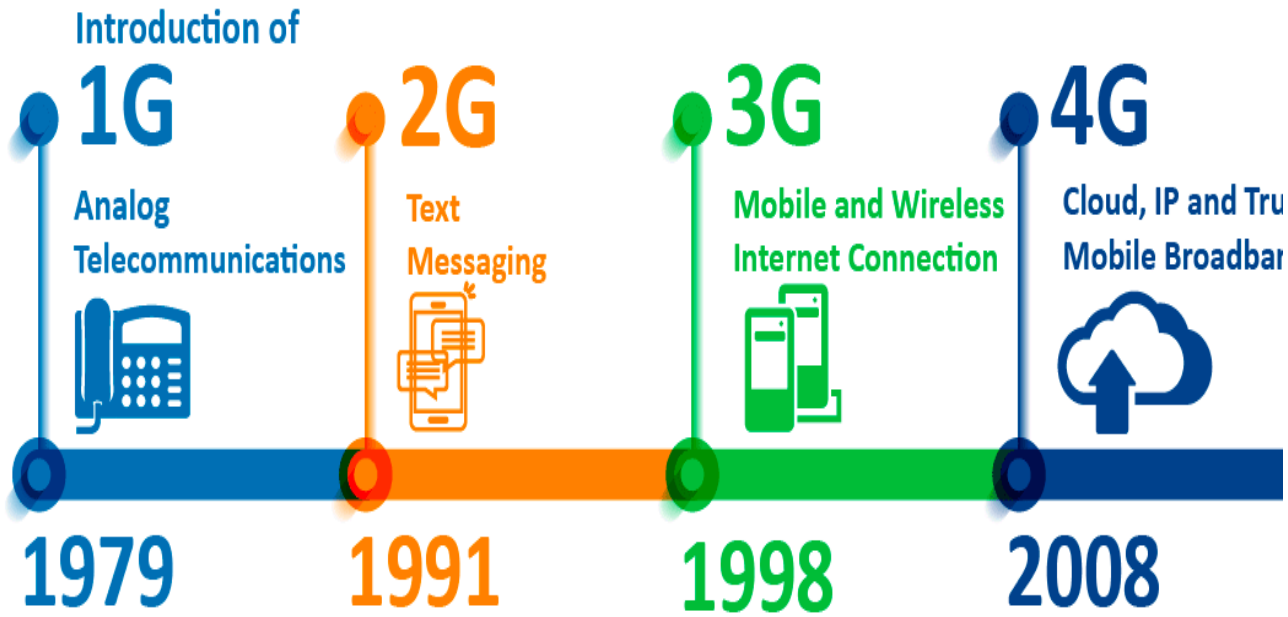
FANS introduce the concept of virtual access node:

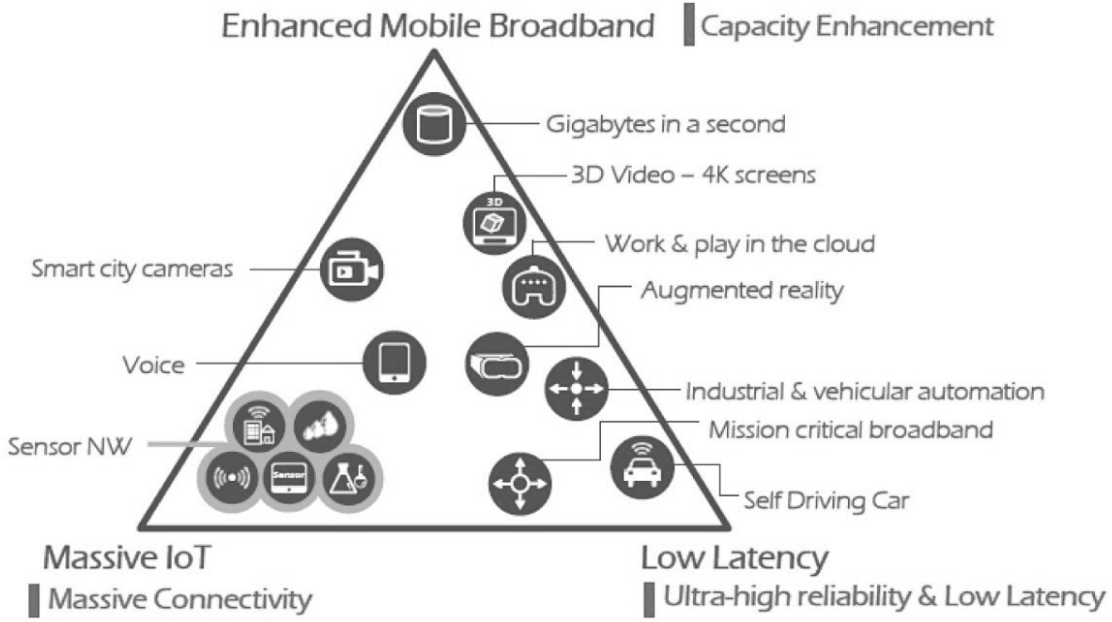
- Can be located in access node or cloud
- Enables disaggregation between physical and virtual ports

Content of the talk

- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don’t forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON
- Conclusions

5G: what is it and how did we get here?





(Source: ETRI graphic, from ITU-R IMT 2020 requirements)

Radio technology	Peak rate	Average rate	e2e delay (service level)
Enhanced mobile broadband (eMBB)	5-10 / 20 Gb/s (UL/DL)	100 Mb/s per user in urban/suburban areas 1-4 Gb/s (hot spot areas)	10 ms
Ultra-reliable low latency communication (URLLC) / Critical machine type communication (incl. D2D)	much lower than in eMBB: N × Mb/s	much lower than in eMBB: n × Mb/s	1-2.5 ms
Massive machine type communication (mMTC)	much lower than in eMBB: N × Mb/s	much lower than in eMBB: n × kb/s - n × Mb/s	1-50 ms

5G wireless fronthaul requirements in a passive optical network contextITU-T, Series G, Supplement 66 (07/2019)

Who's 5G for?

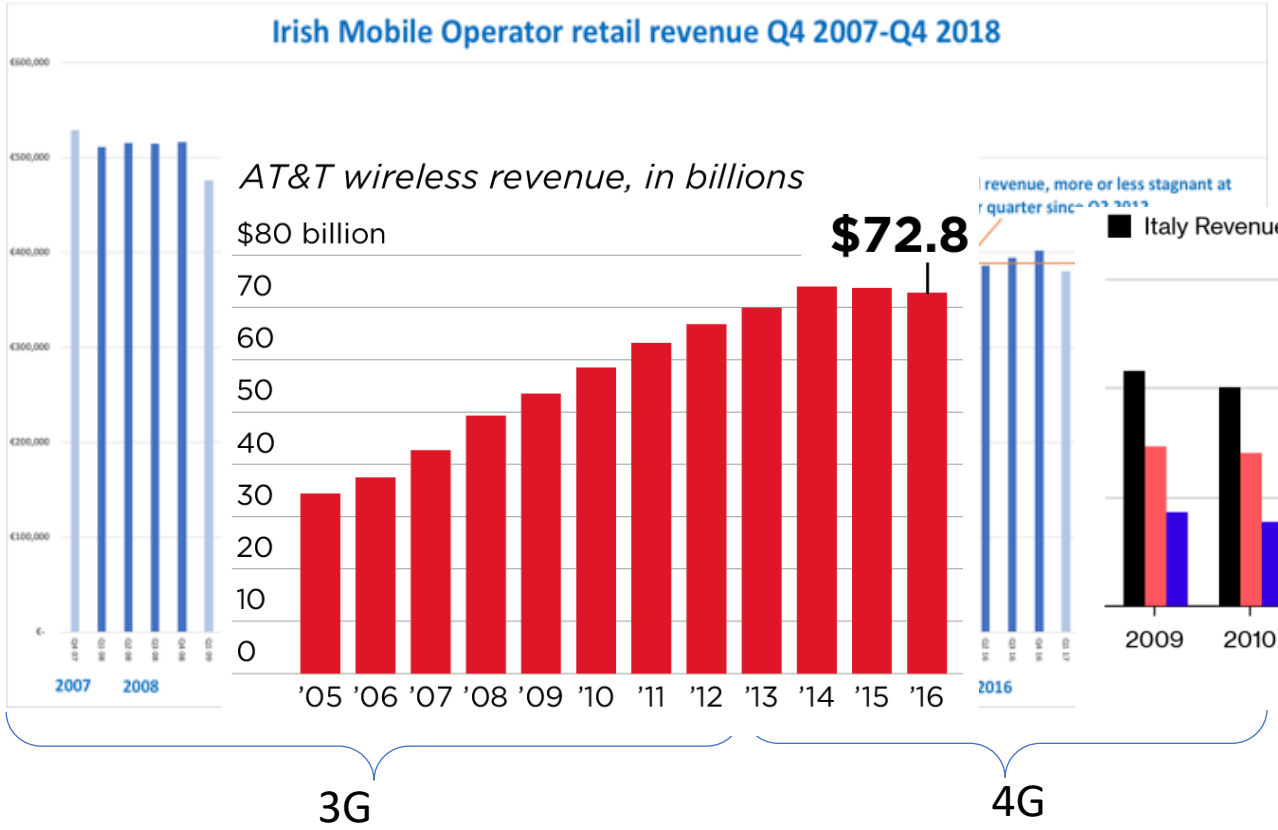
- Us all!

This we can already do:

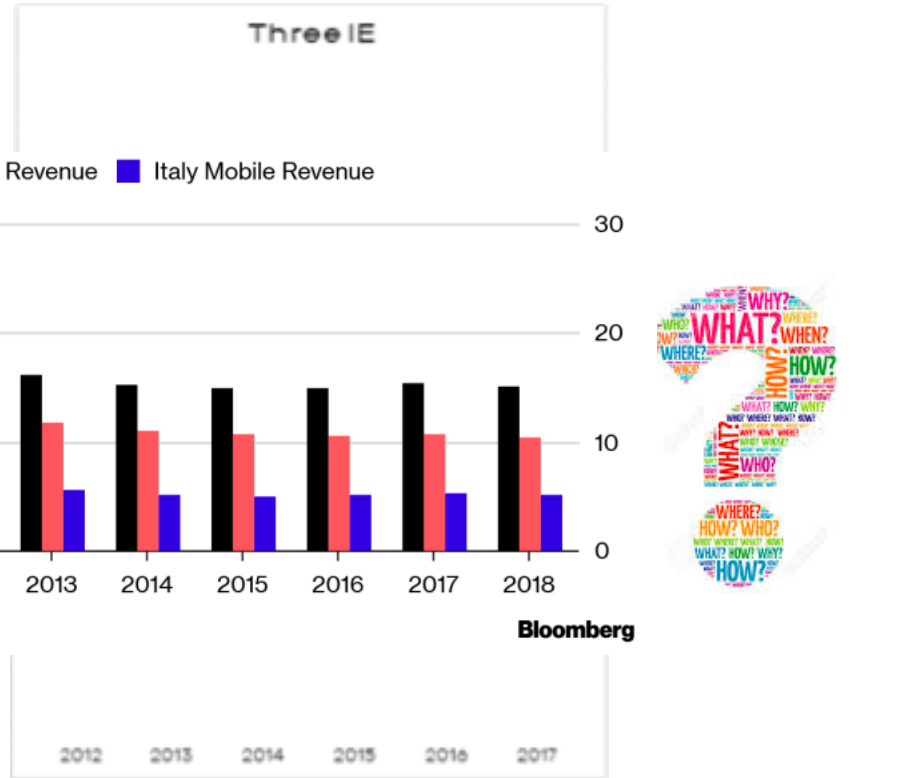
This we will be able to:

One small issue about 5G...

- Broadband revenue generated by retail users is very static (often negative)



Profitability



Notice that many operators didn't manage to charge 4G more than 3G

Will 5G change this? How??

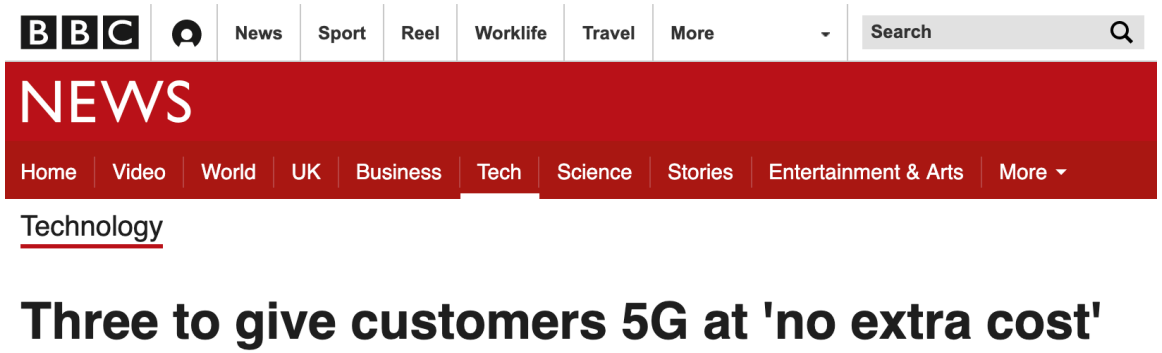
Surely it should do something different than 3G-to-4G transition:

e.g., not just offering higher bandwidth, at same price

BUT… this is what we see today:

Verizon's 5G network is live in Chicago and Minneapolis.

"…could see speeds between 450 Mbps to 1Gbps and latency connecting to the network less than 30 milliseconds"

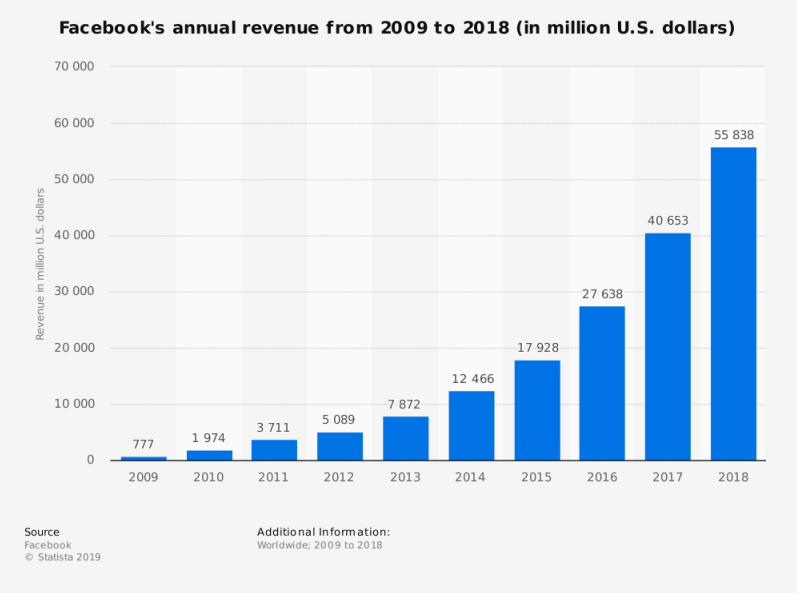


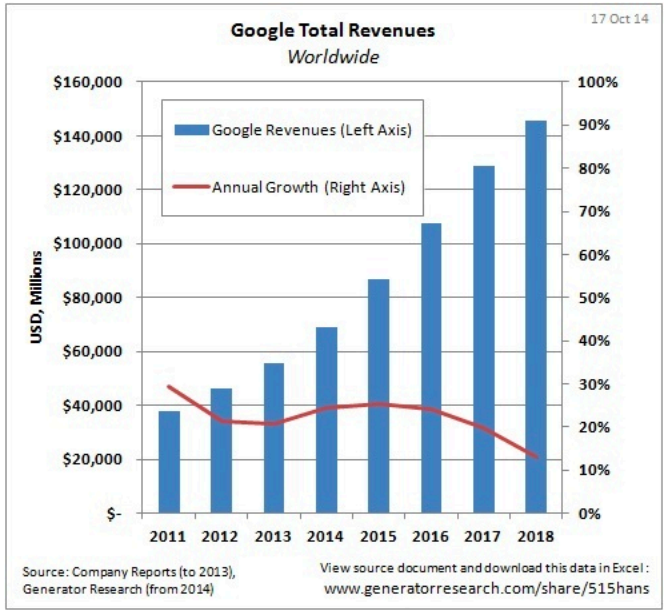
Current 5G = 4G + 1G

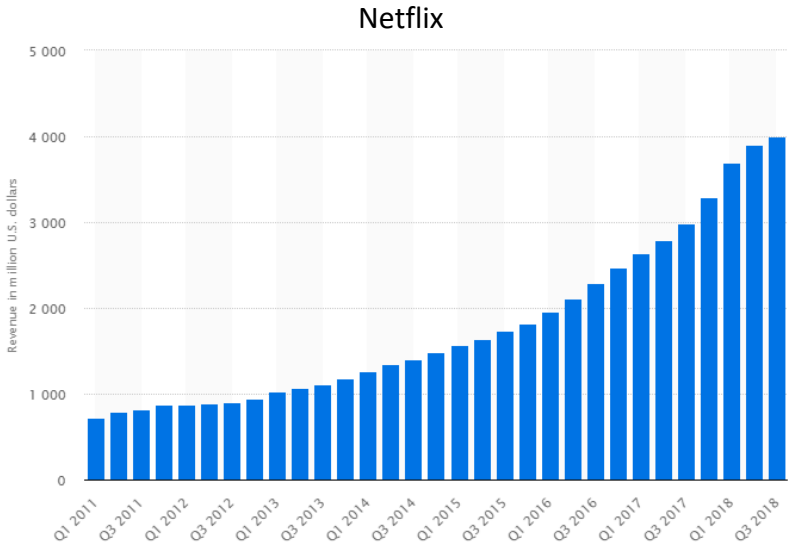
But the 5G community promises that this will change in the next few years..

How to fix it?

- For many years we have seen that revenue is in the higher layers, where most of the value is.

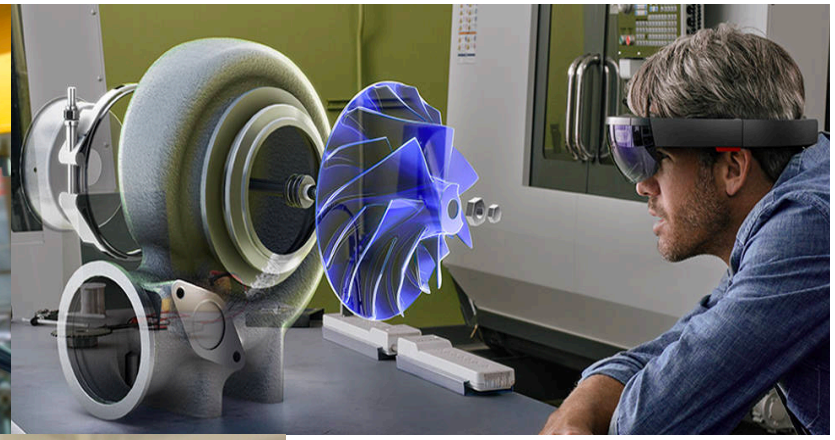


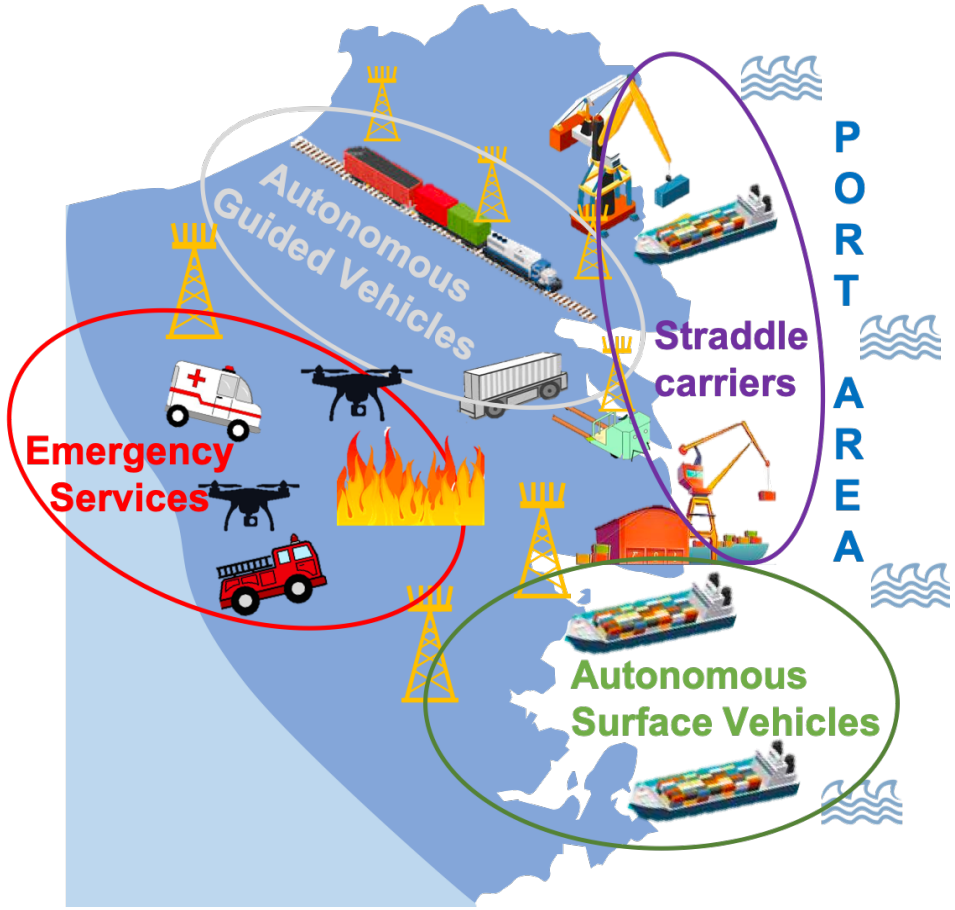




New value in new applications: how to attract them?

- Attract *new* users/businesses by providing new *unprecedented* features:





- Likely to be driven by Industry 4.0
- Innovation is required also in user devices (e.g., AR/VR goggles, etc.)

From Industry 4.0 to every day's life

- Till the day we'll be fully immersed in the digital world…

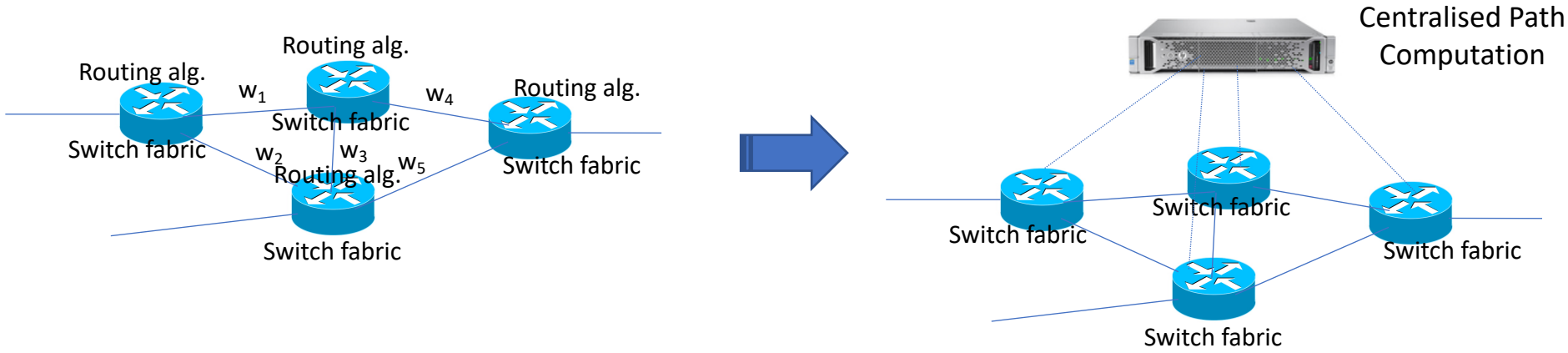
https://www.youtube.com/watch?v=t5ixBsHPMxk

Content of the talk

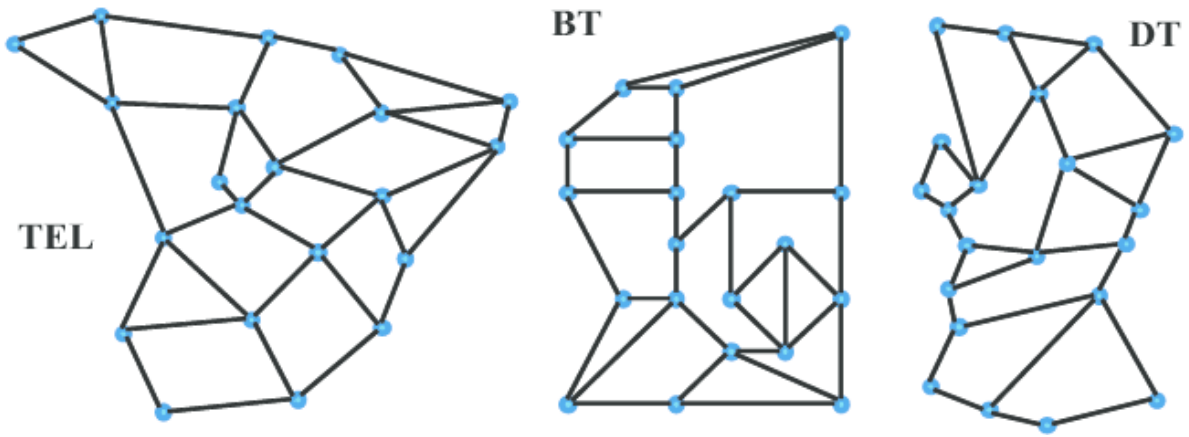
- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don't forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON
- Conclusions

Software Defined Networks

- Move from a system where routers run independent (but converging algorithms) to a system where all routes are decided by a central entity



- Advantages:
  - More flexibility in deciding routes
  - The system opens up and facilitate development of integrated software



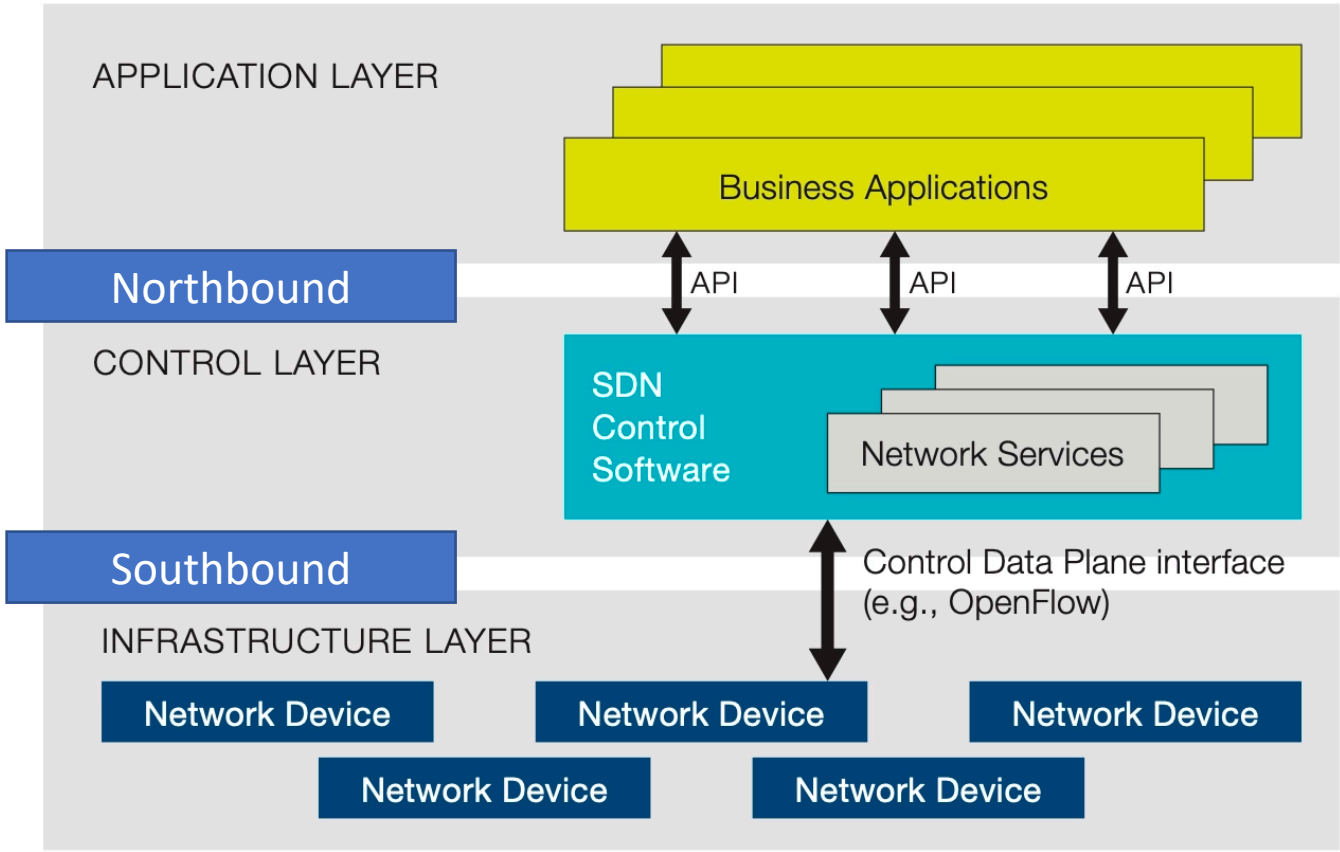
An SDN architecture

The control plane (controller) becomes the Operating System for the network.

Programmability requires well defined and standardized interfaces:

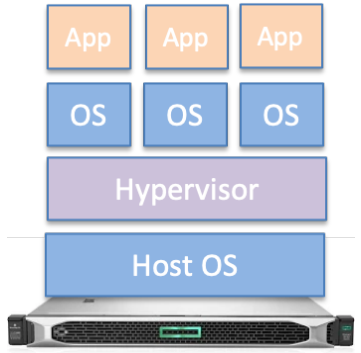
- Southbound interface to send instructions to network devices (think of hardware drivers)
- Northbound APIs are used by applications (e.g., the entity setting up a service) to express their intent

The controller transforms abstract, high-level intents into physical layer commands



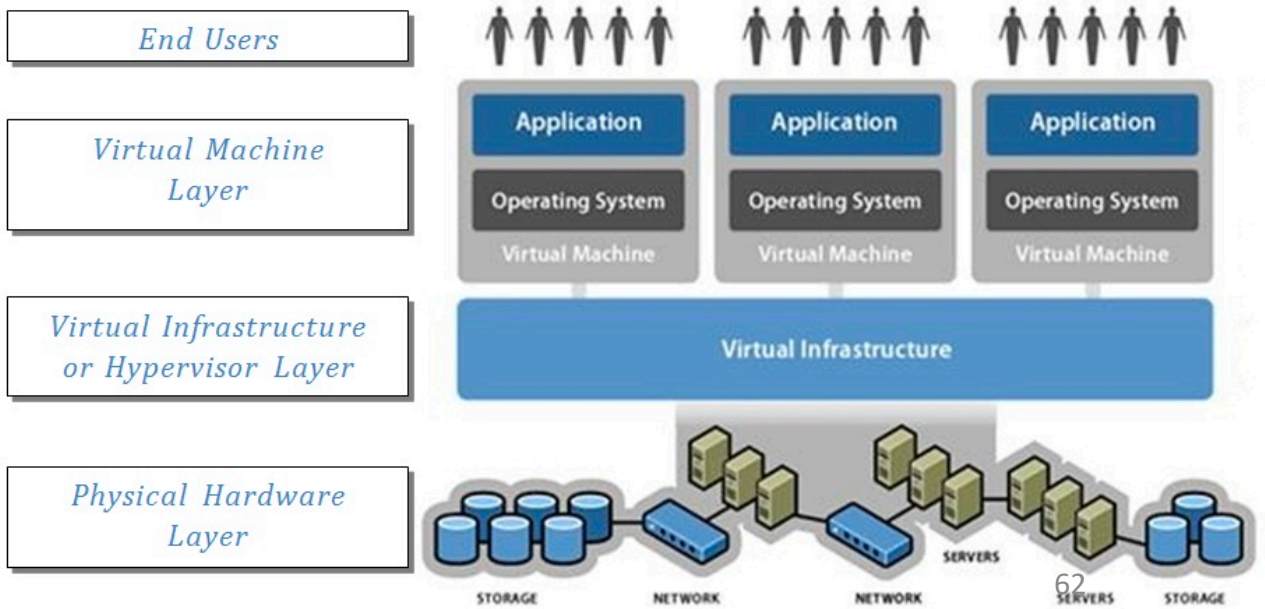
Virtualisation

Virtualisation gives the illusion of obtaining control of a physical entity or resource.



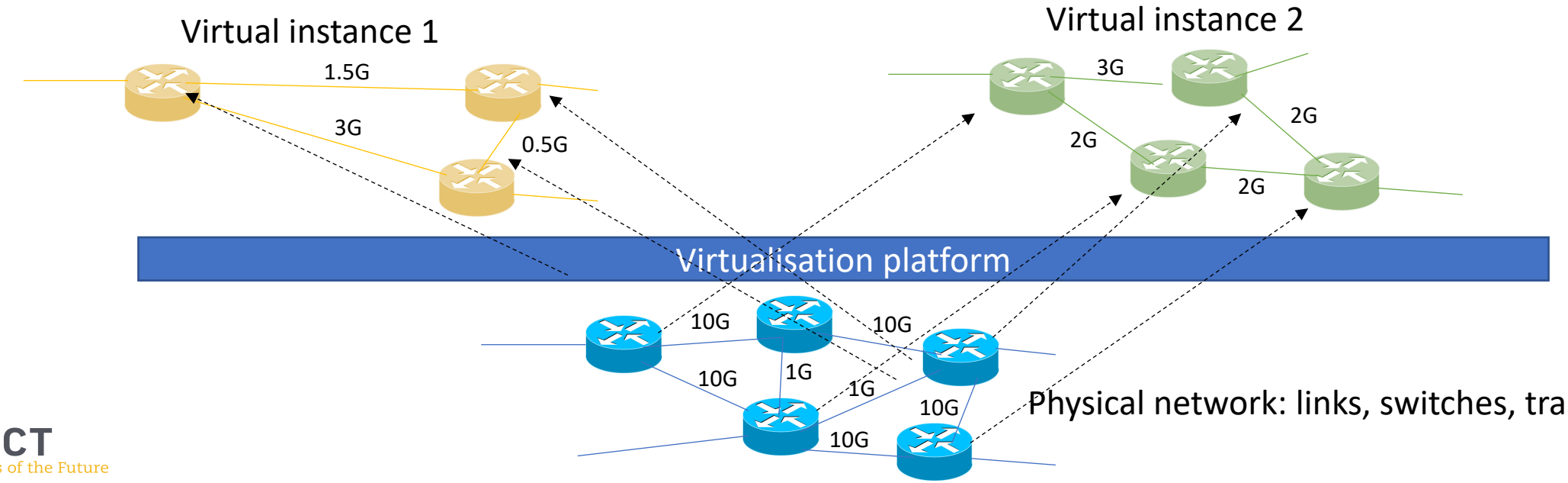
In Data centres the principle extends to the whole infrastructure

Completely decouple end user resources from physical hardware resources:
Increase in efficiency, lower energy usage, lower capital costs,…



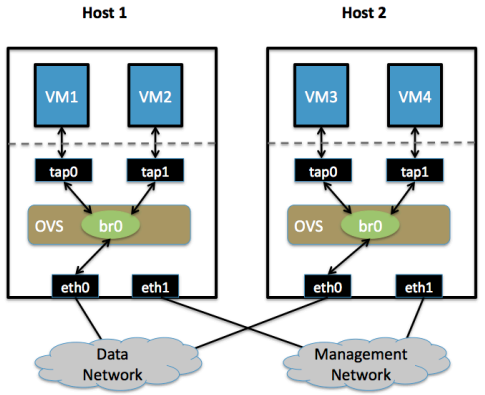
Network Virtualisation

- In networks, virtualisation could be seen as abstracting the functionality of a piece of hardware infrastructure into software.
  - relies on a virtualisation platform to associate the virtual network with real hardware links
  - can provide the ability to instantiate an entire network overlay in software

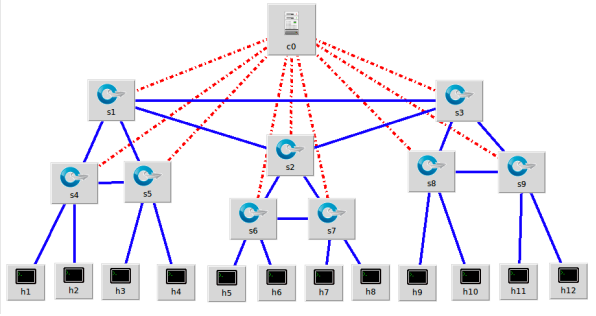


Some examples of network virtualisation testbeds

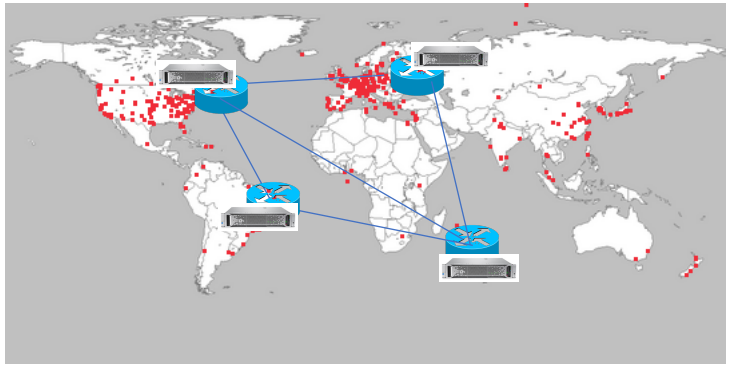
- From local scale:
  - OpenvSwitch (OvS): a virtual packet switch operating in Linux environment



  - Mininet: emulation platform comprising of virtual switches, hosts, and links
    - Can be used to test SDN controllers behaviour



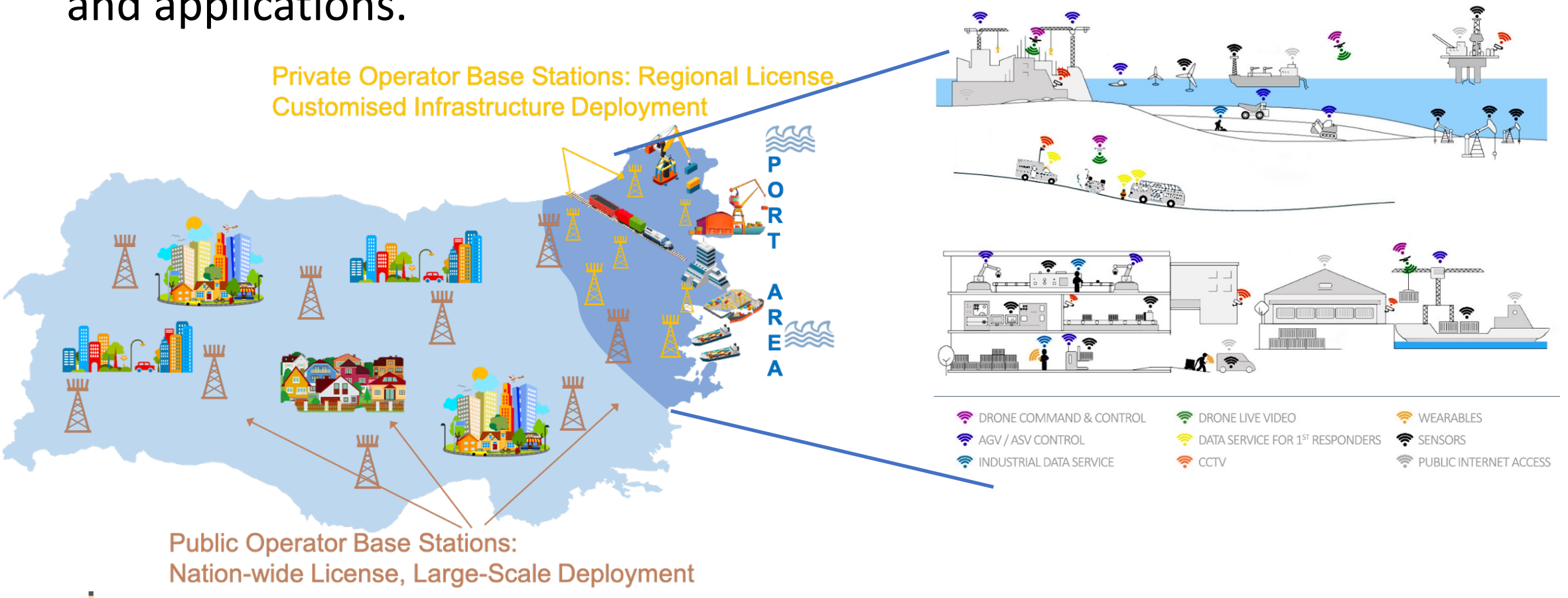
- To global scale:
  - Planetlab applies the idea of virtualisation using nodes and links spread out across the globe



- Today many others exist, including wireless and optical domains

Network slicing

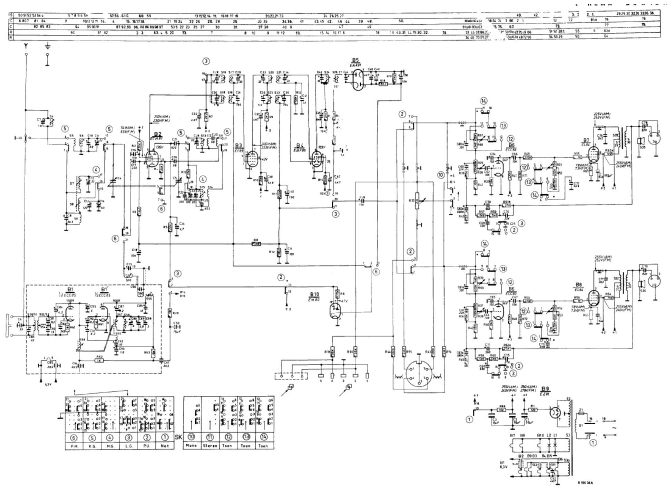
Virtualisation enables slicing, meaning that you can take a network infrastructure and partition it dynamically to serve different use cases and applications.

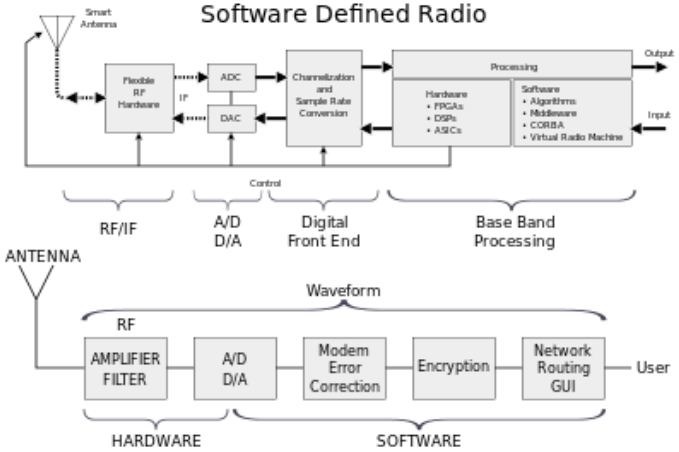


From virtualisation to network function virtualization (NFV)

- NFV moves functions from dedicated hardware to software running on commodity servers

Software Defined Radio is an early example: GNU radio

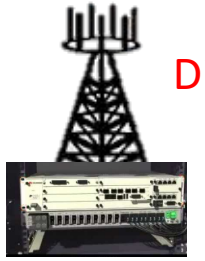




- Advantages:
  - flexibility of adapting transmission format to environment and application
  - coordination with other radios (either distributed or centralized)
  - Integration with other software components…

SDR in today's telcos

- SDR today stronger than ever:
  - C-RAN based on SDR ➔ srsLTE, Amarisoft, Flexran, OpenAirInterface, OpenLTE, or the implementations based on GNU radio,…
  - Enabling flexibility in resource allocation, statistical multiplexing,…
  - Also, integration with other elements for convergence with other technologies, joint orchestration,…

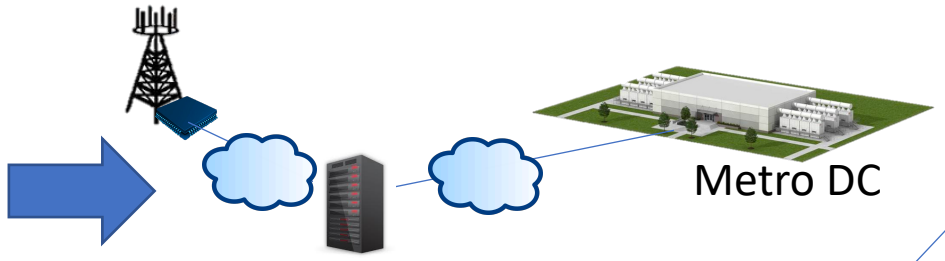


Distributed RAN

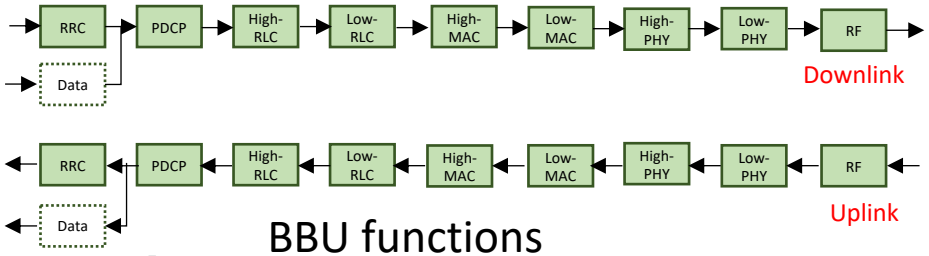
Hardware baseband unit (BBU)

Remote Radio Unit (RRU)

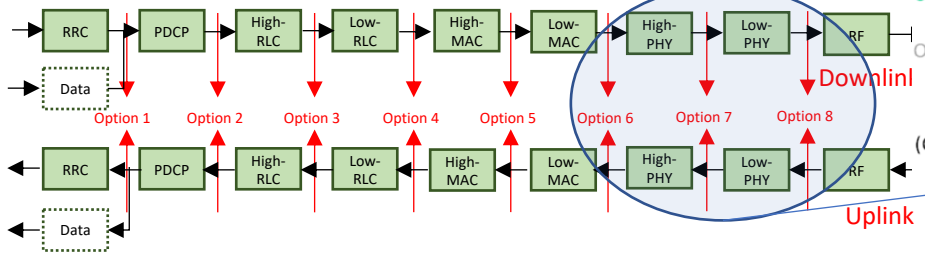
Centralised RAN

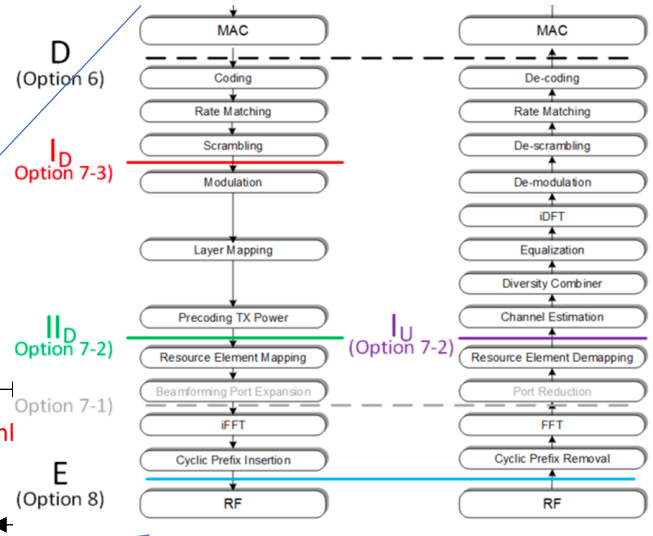


Edge cloud node



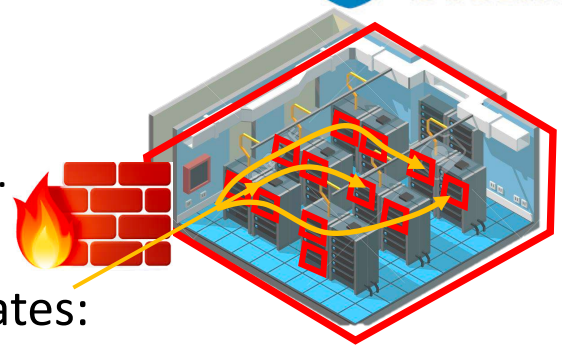
BBU functions





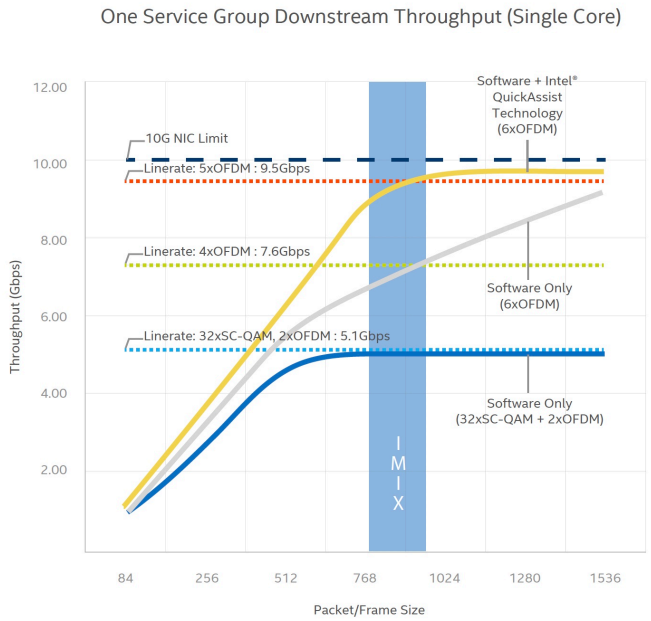
Source: Next Generation Mobile Network (NGMN) alliance. NGMN Overview on 5G RAN Functional Decomposition. Feb., 2018

Network functions

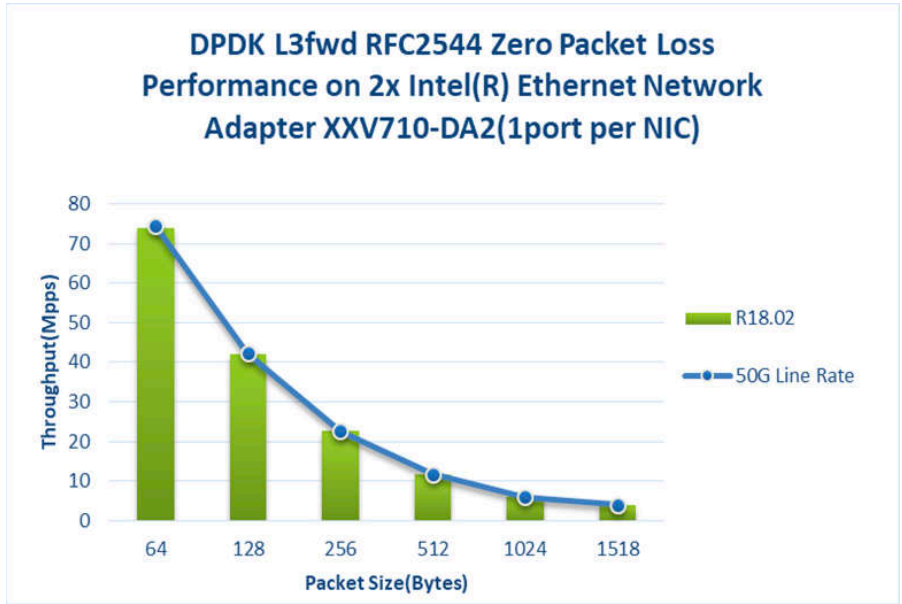


- The NFV concept applies to several other telco functions:
  - Firewall: in VMware NSX it's integrated in each VM, for better customization, flexibility, security.
- In general all functions that require packet processing and switching are good candidates:
  - Service Gateway (vSG): e.g., route the request to the specific service provider
  - Broadband Network Gateway (vBNG o vBRAS): aggregates incoming access connections, enforces QoS, provides layer 3 (IP) connectivity
  - Customer Premises Equipment (vCPE): operates routers, firewalls, VPNs, NAT
- Highly improved packet processing/switching performance (e.g., Data Plane Development Kit – DPDK)

Full MAC of DOCSIS3.1 in single core of Xeon processor.



Source: M. O'Hanlon, B. Ryan. Mazimising the performance of DOCSIS 3.0/3.1 processing on Intel Xeon processors, 2017.

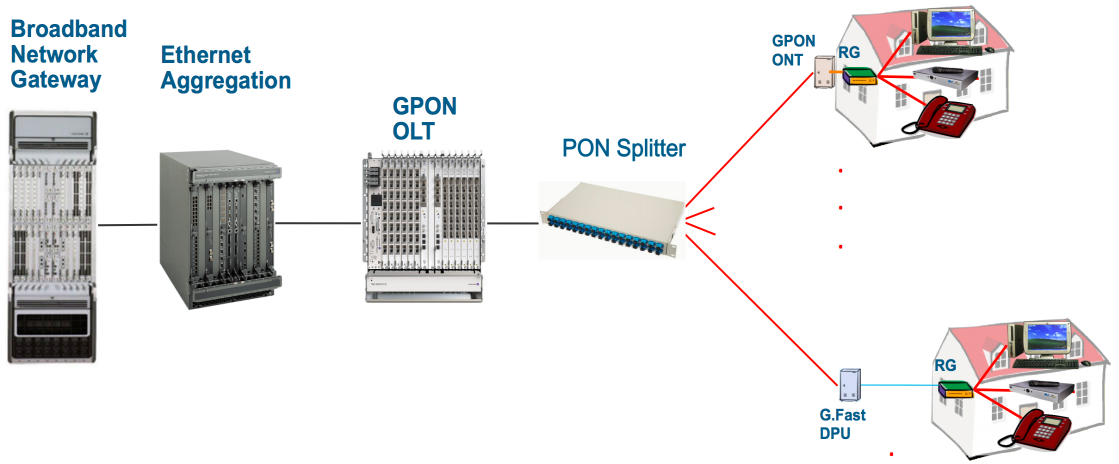


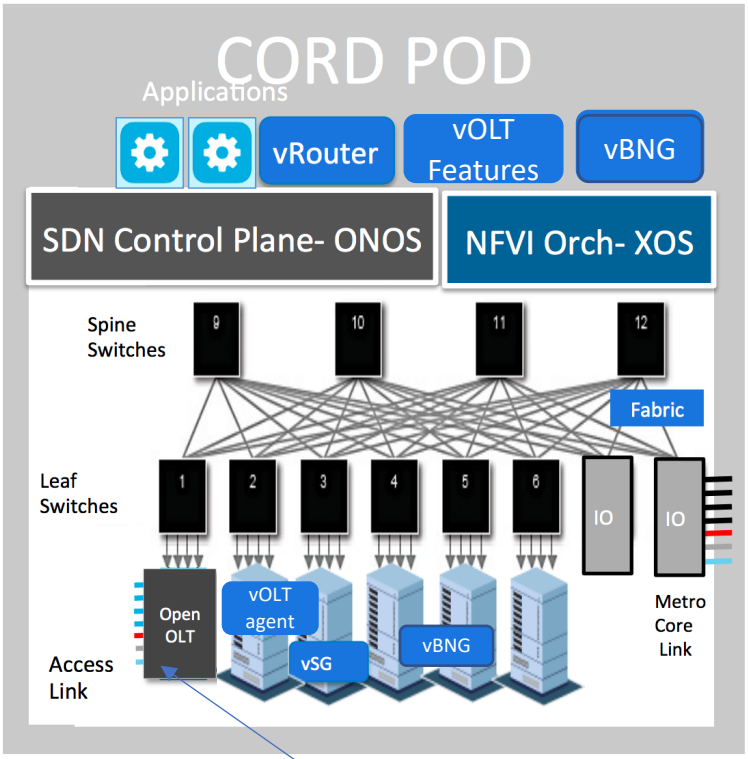
Packet switching performance on Xeon processor

Source: DPDK Intel NIC Performance Report Release 18.02, May 2018

Central Office Virtualisation

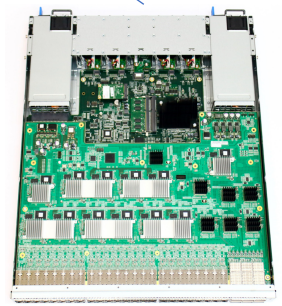
- Getting SDN and NFV into the central office:



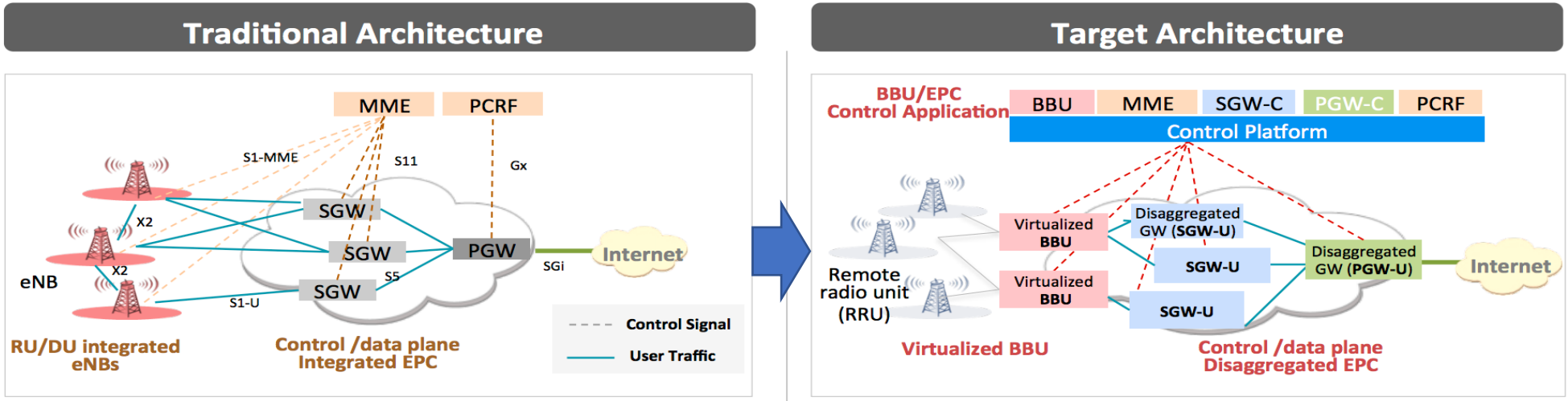


- Driven by development, not by standard
- Being trialed by several operators world-wide
  - E.g., AT&T recently carried out trials on XGS-PON using OLT white boxes

Commodity Hardware
Source: http://opencord.org/



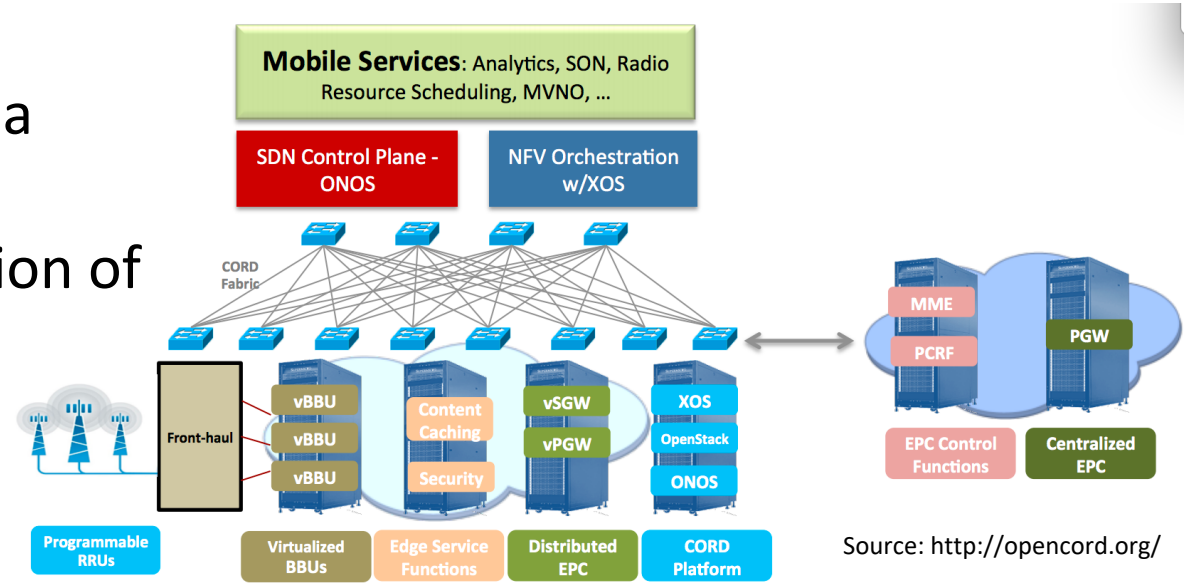
Multi-service example: Mobile-CORD



with proprietary boxes & solutions

with commodity H/W & open source/open API

- Software and programmability a main enabler of convergence
- E.g., enables tighter orchestration of resources (see fixed/mobile)



Source: http://opencord.org/

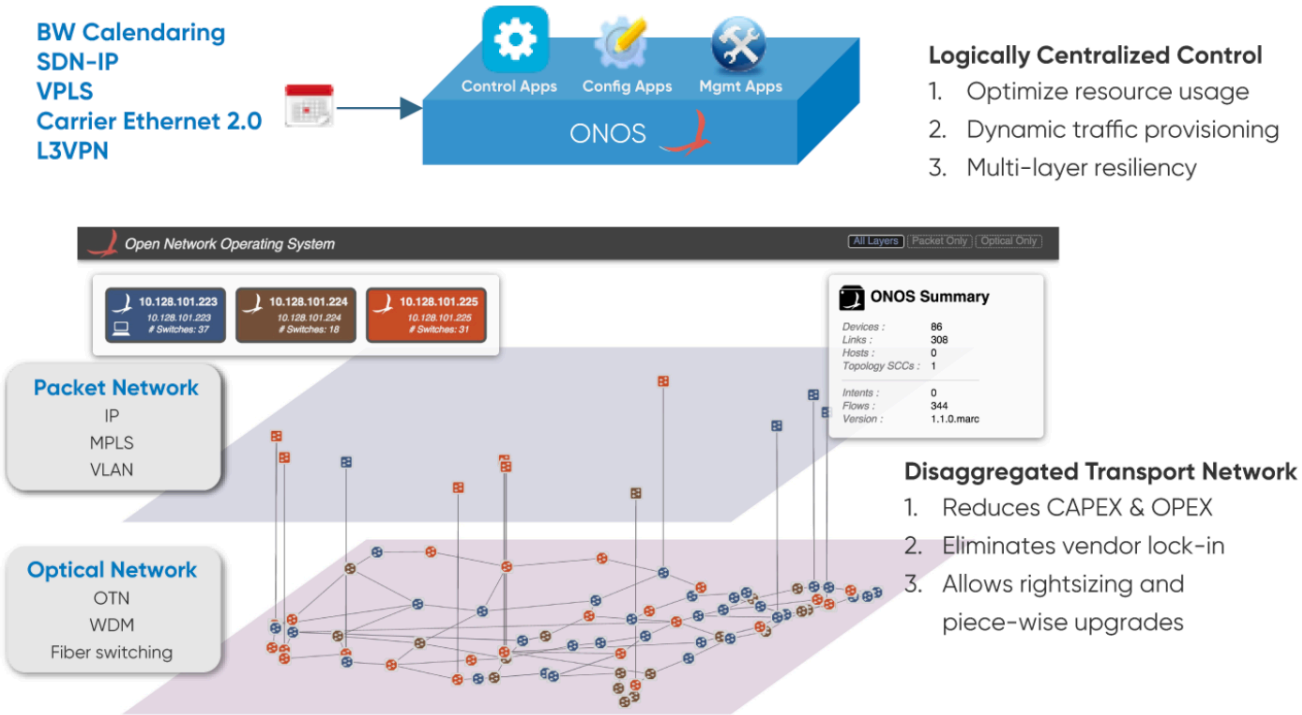
Open Disaggregated Transport Network (ODTN)

Pros:

- Open market of component from multiple vendors brings cost down
- No vendor lock-down, faster network upgrades
- Possibility of full integration with other control layers to achieve dynamic, fast, end-to-end optical re-configurability.

Challenges:

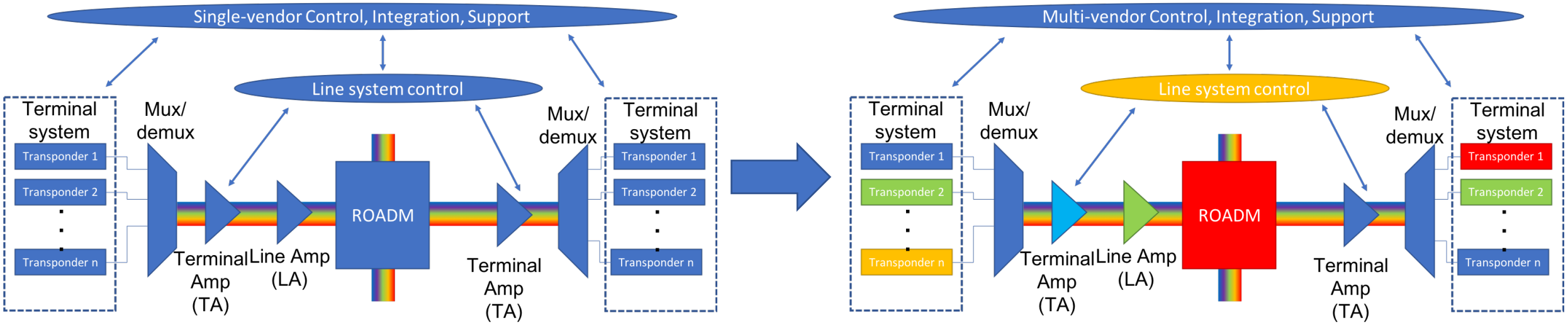
- Building an end-to-end analog system
  - How to do end-to-end system optimization with components whose behavior is not well known?
  - Avoid use of large margins
- Could this hinder research investment from transponder manufacturers?



Source: https://www.opennetworking.org

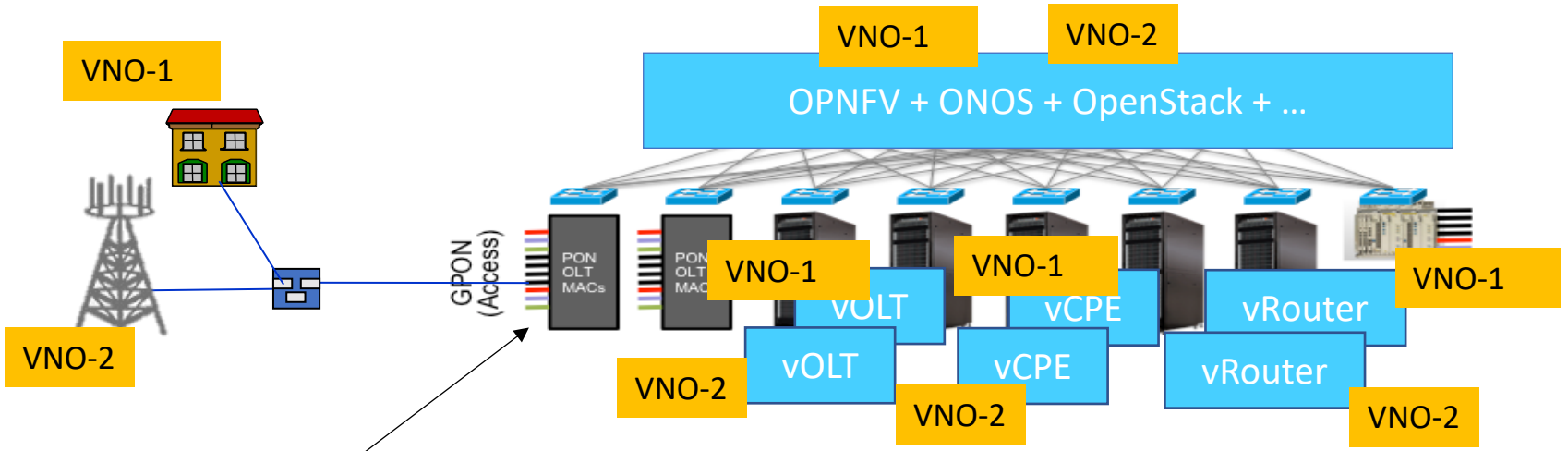
Optical layer disaggregation

- With CORD, etc. the NFV paradigm was pushed down to the MAC layer of optical technologies (e.g., in PON with the VOLTHA)..
- ..and for wireless technologies down to the physical layer (software radio implementation of LTE)
- So, what about the optical transmission layer?



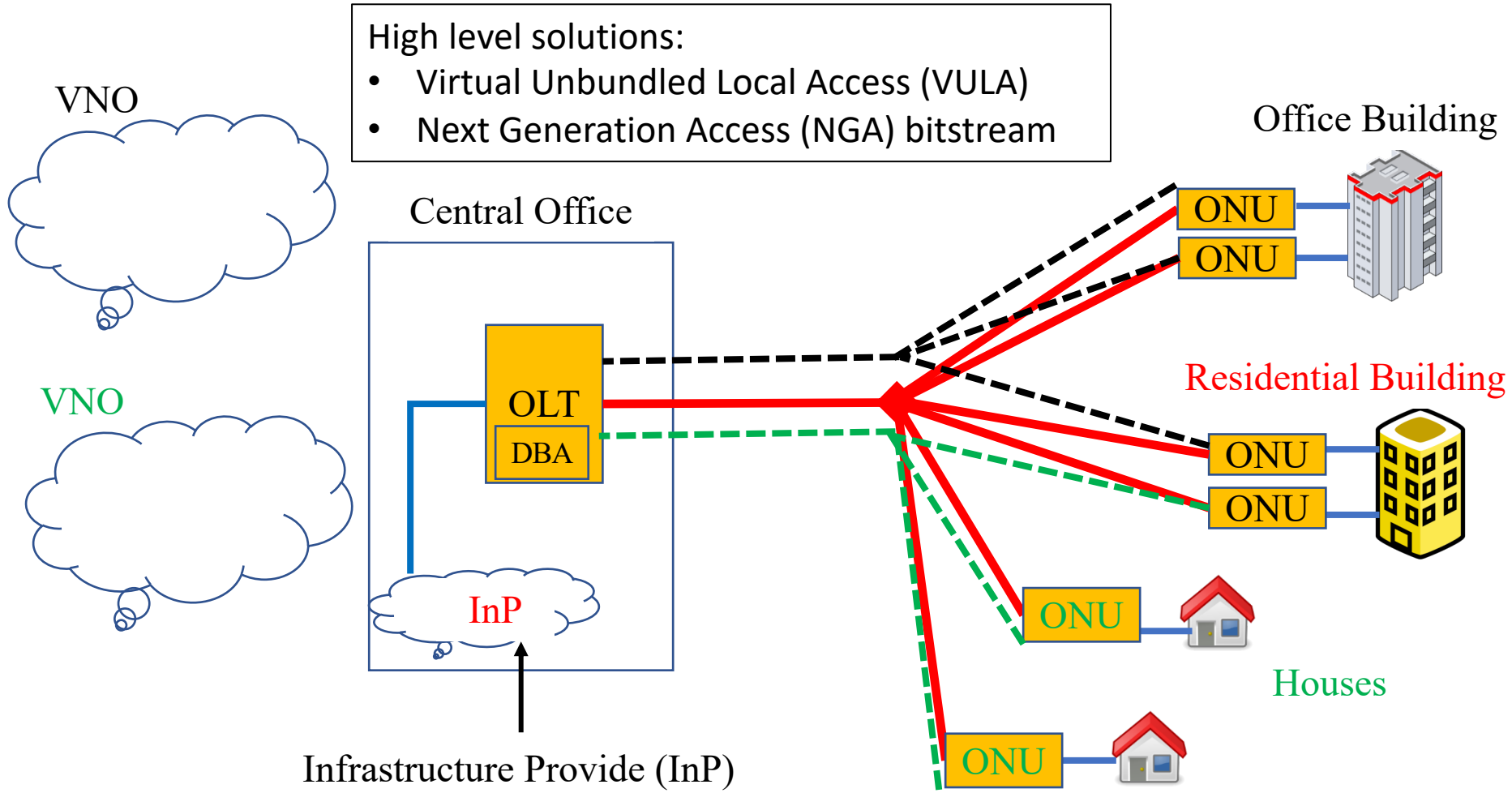
- What it means:
  - Mix and match transponders, amplifiers, ROADMs, control loops, optical control plane …

Is CORD virtualization enough for PONs?



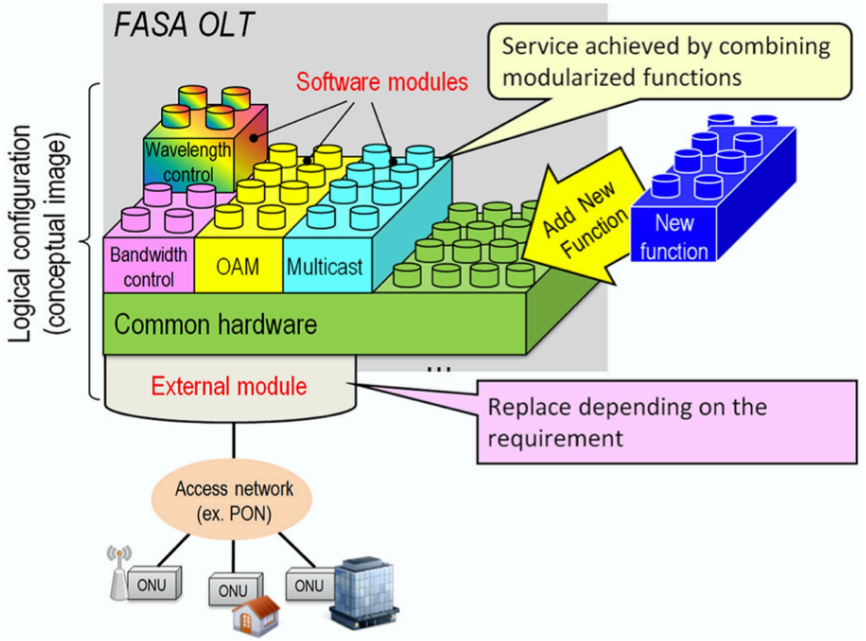
- Functions are virtualized and multiple instances can be assigned to different Virtual Network Operators (VNOs)
- … but for example Dynamic Bandwidth Allocation (DBA) is carried out in hardware

This is the current PON Multi-Tenancy

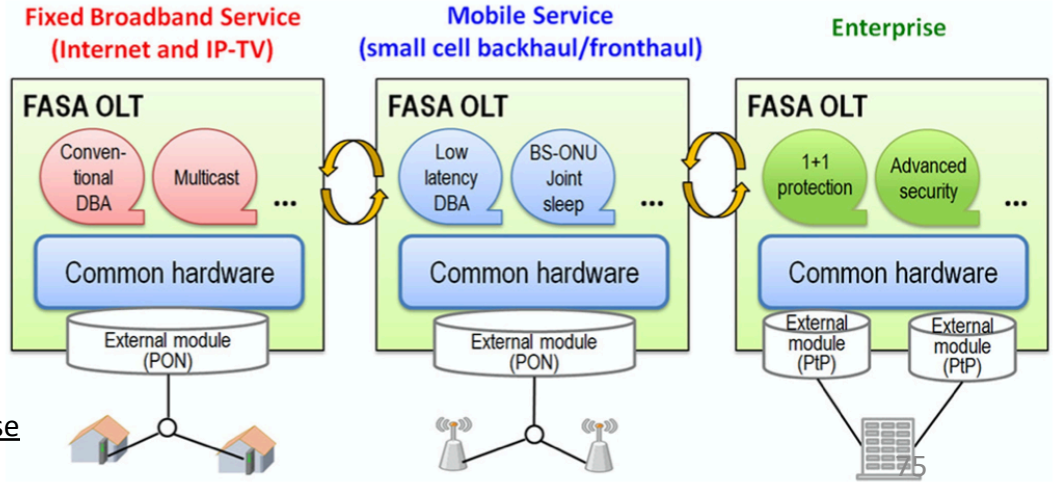


NTT's Flexible Access System Architecture (FASA)

- Disaggregate the OLT, using software functions



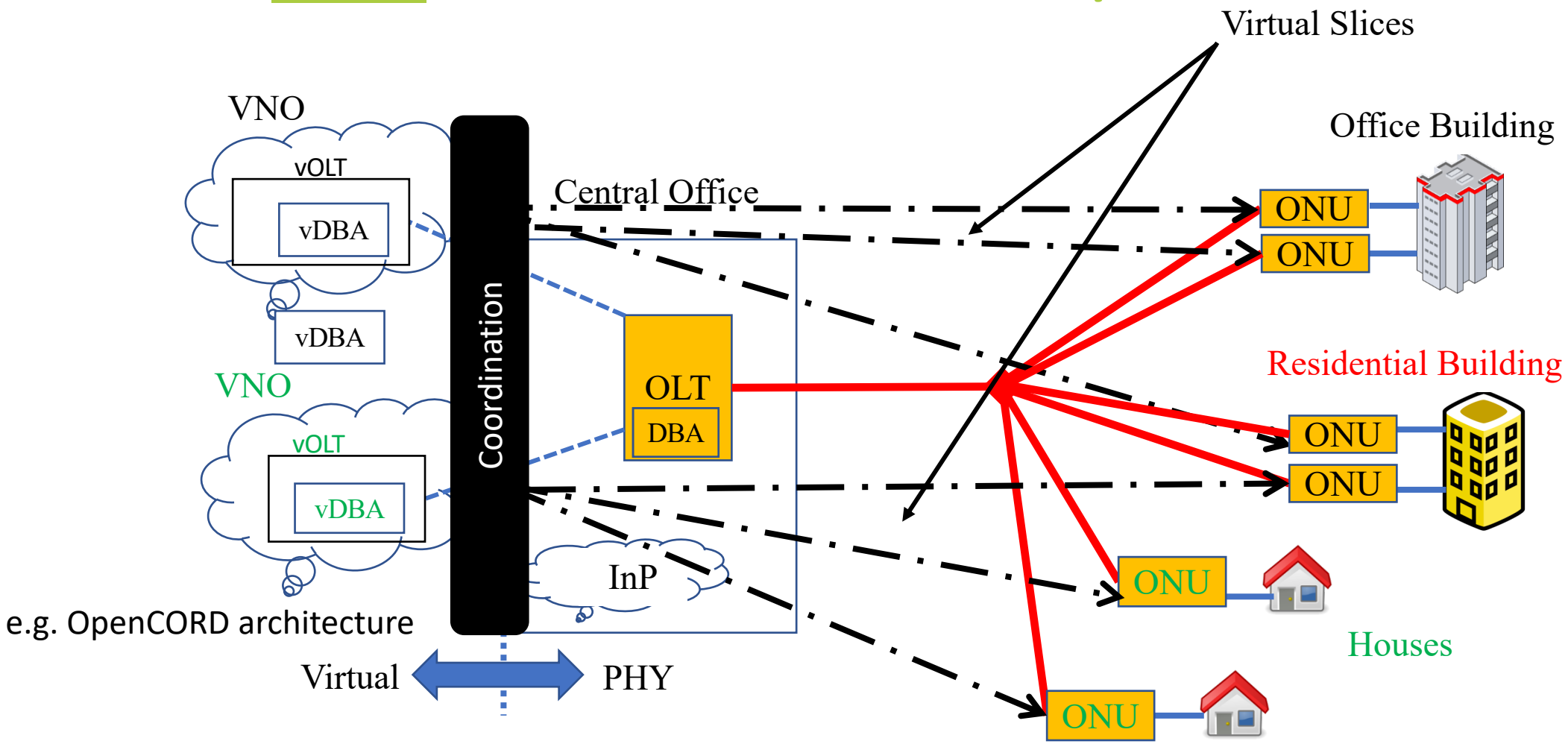
- The DBA is also software, so it can be modified, depending on the application



Included in BBF TR-402 standard "PON Abstraction Interface for Time-critical Applications"

June-Ichi Kani et al., Flexible Access System Architecture (FASA) to Support Diverse Requirements and Agile Service Creation. JLT, April 2018.

This is True PON Multi-Tenancy



Option 1: assign entire frames to different VNOs - The Slice Scheduler (SS)

- Slice Scheduler proposed in **
- The idea to assign entire upstream frames to different VNOs in order to keep physical frame **isolation**.
- It intuitively looses efficiency, as unused capacity is wasted

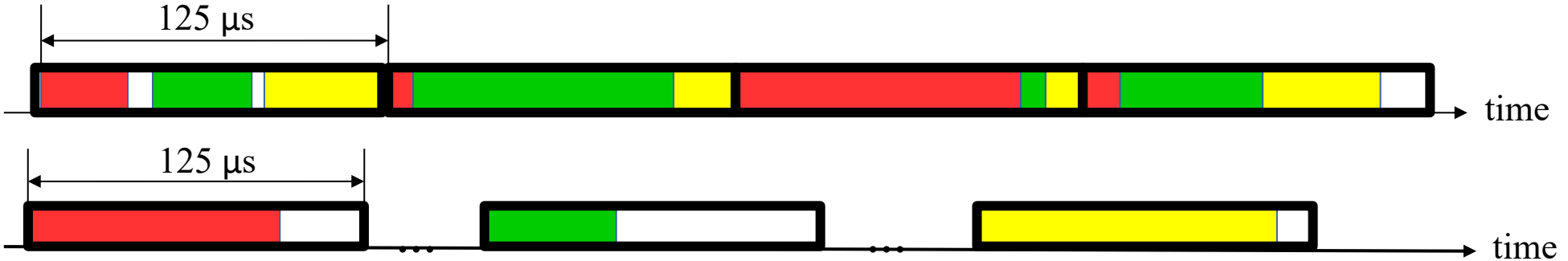
Slice Scheduler

** C. Li, W. Guo, W. Wang, W. Hu, and M. Xia, "Bandwidth resource sharing on the xg-pon transmission convergence layer in a multi-operator scenario," Journal of Optical Communications and Networking, vol. 8, no. 11, pp. 835–843, 2016.

Option 2: Frame Level Sharing

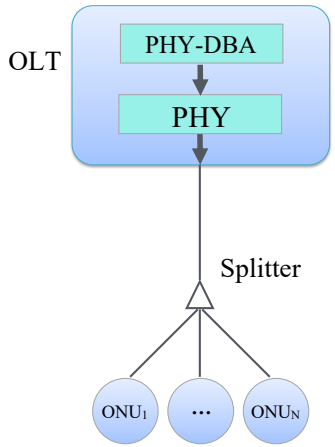
- Our work proposed in **
- Allows sharing every frame across all VNOs

Frame Level Sharing
vs.
Slice Scheduler

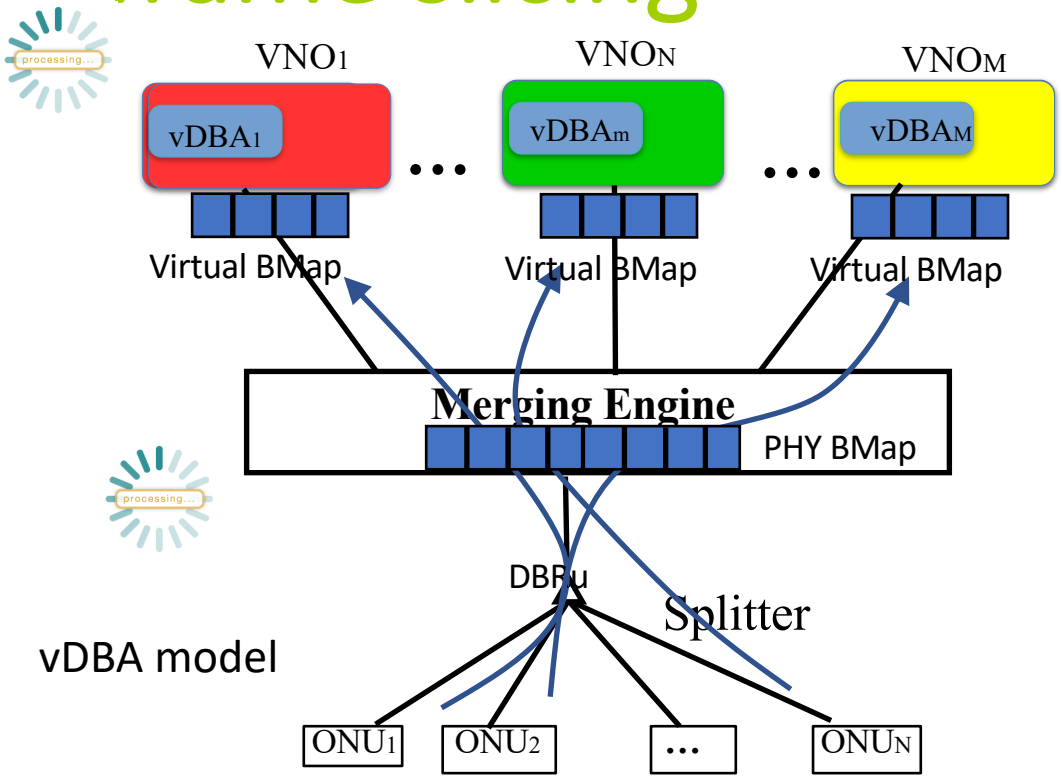


** Amr Elrasad, Nima Afraz, and Marco Ruffini, Virtual Dynamic Bandwidth Allocation Enabling True PON Multi-Tenancy. Proc. of Optical Fibre Communications conference (OFC), paper M3I.3, March 2017

Full disaggregation of the OLT with upstream frame slicing



Current physical DBA model



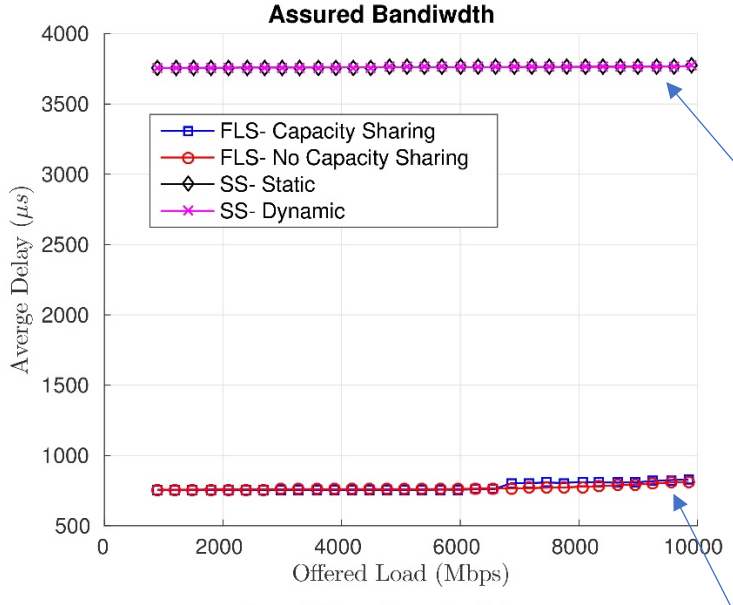
vDBA model

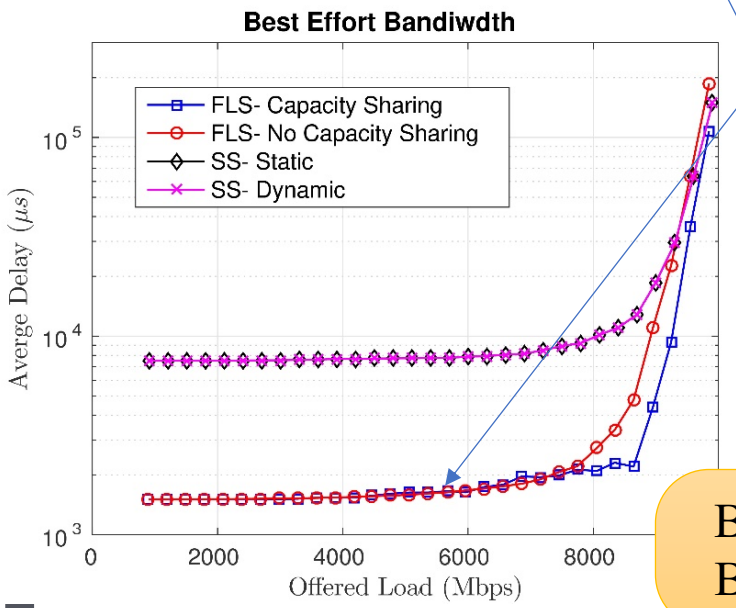
- Work on DBA virtualization to enable fine-grained control to different tenants.
- Also other use cases: e.g., for service differentiation, for mobile front haul (more on this later)
- Also included in BBF TR-402 “PON Abstraction Interface for Time-critical Applications” and recently in TR-370i2 “Fixed Access Network Sharing (FANS)

Virtual DBA – Slice isolation performance

TRINITY COLLEGE DUBLIN

5 VNOs, Balanced





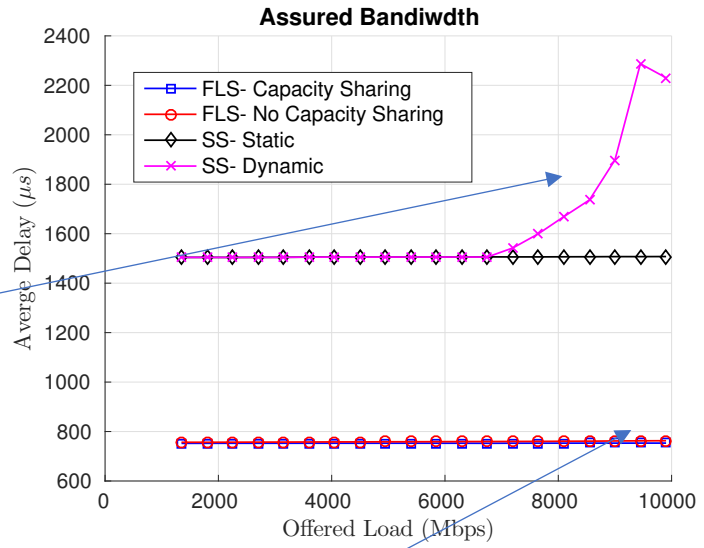
Assured Bandwidth

Previous work:
Assign different frames to different VNOs:

With our vDBA:

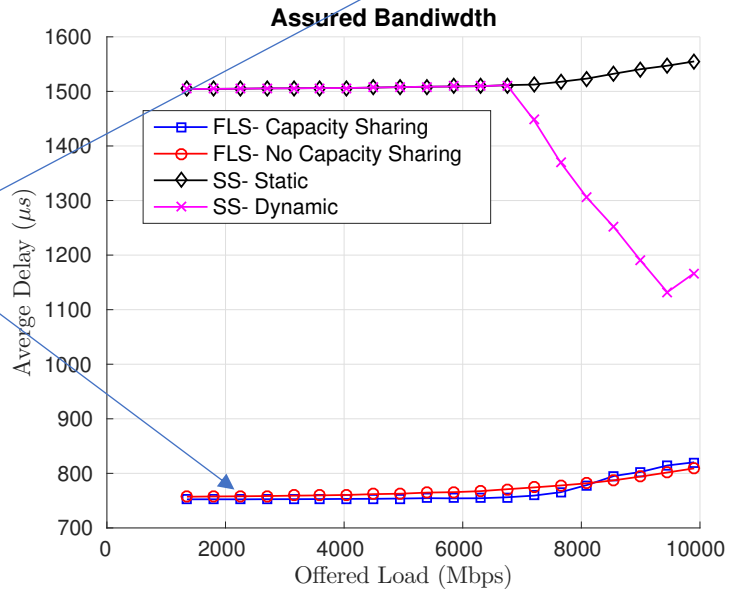
- delay is independent of number of VNOs
- Achieve isolation between VNOs with different load

Best Effort Bandwidth



Low load VNO

2 VNOs, high loaded ratio 1:2



Hi load VNO

CONNECT Networks of the Future

IPIC BRINGING PHOTONICS TO LIFE

Virtual DBA Excess Sharing - Challenge

Non-Sharing Policy - Complete Isolation

- The VNOs can only ask for up to their pre-dedicated capacity (Negotiated)
- Drawback: Wasting excess BW - Reversing the Benefit of Sharing

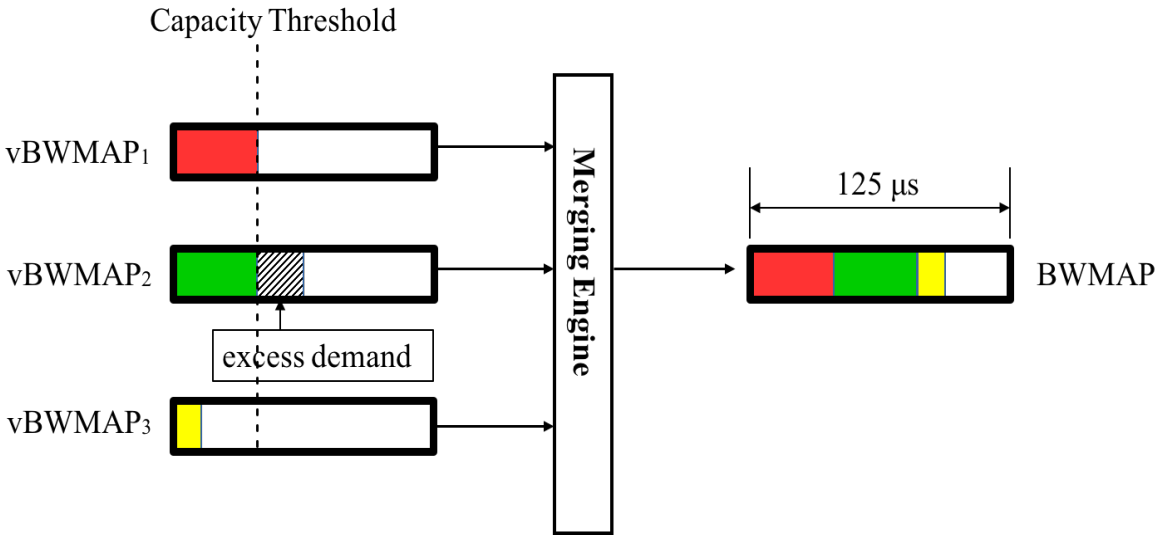
Sharing the Excess Capacity Policy

- The VNOs can ask for up to the entire PON capacity
- Advantage: Reuses the excess BW

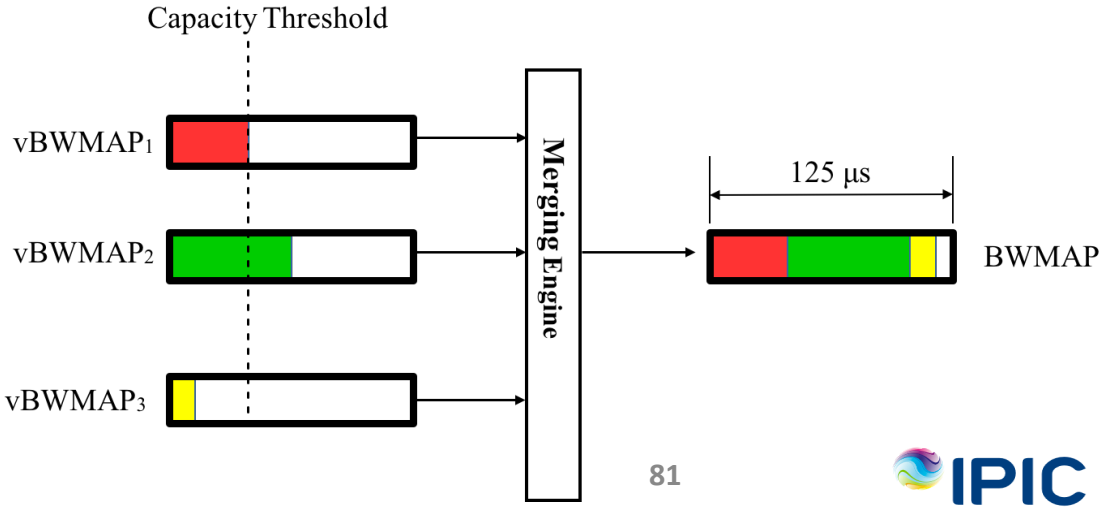
Sharing Incentive

- Why would a VNO share excess bandwidth with other VNOs instead of blindly assigning it to its own users?
- **Solution: A Monetisation Mechanism** to enable trading between the VNOs.

No Capacity Sharing



Capacity Sharing



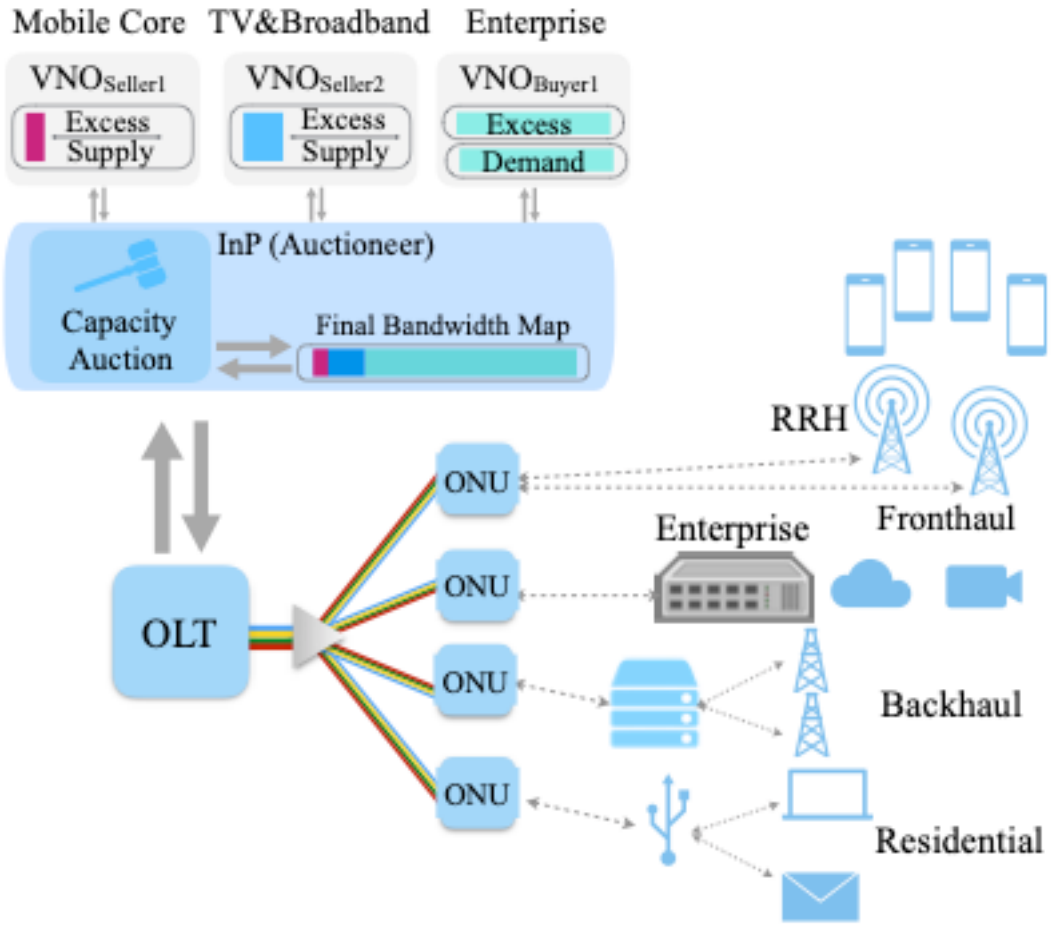
Solution: Multi-Tenant PON Market

Incentive Solution:

- Monetary Compensation for Excess Bandwidth

Market features:

- Multiple traders (sellers, buyers) on both sides
- Multiple Identical frame units to trade
- Roles change in each frame



Improved McAfee Double Auction

A Multi-Item Double Auction Mechanism:

- Meets desirable economic properties:
  - Truthfulness
  - Individual Rationality
  - Budget Balance

Algorithm 1: Multi-Item Double Auction

1 Sort sellers ascending so $v_1^B > v_2^B > ... > v_m^B$

2 Sort buyers descending so $v_1^S < v_2^S < ... < v_n^S$

3 Find $max(S_L, B_K)\ \forall\ v_L < v_K$ **and** $\sum_1^K q_j^B \leq \sum_1^L q_i^S$

4 $\gamma = \frac{1}{2} \times (v_{L+1} + v_{K+1})$

5 **if** $\gamma \in [v_L, v_K]$ **then**

6 $\quad \Theta_{Pr} = \min(\sum_1^{i=L} q_i, \sum_1^{j=K} q_j)$ — Quantity

$\quad p^B = p^S = \gamma$ — Pricing

8 **else if** $\gamma \notin [v_L, v_K]$ **then**

9 $\quad \Theta_{Pr} = \min(\sum_1^{i=L-1} q_i, \sum_1^{j=K-1} q_j)$ — Quantity

10 $\quad p^B = v_K$

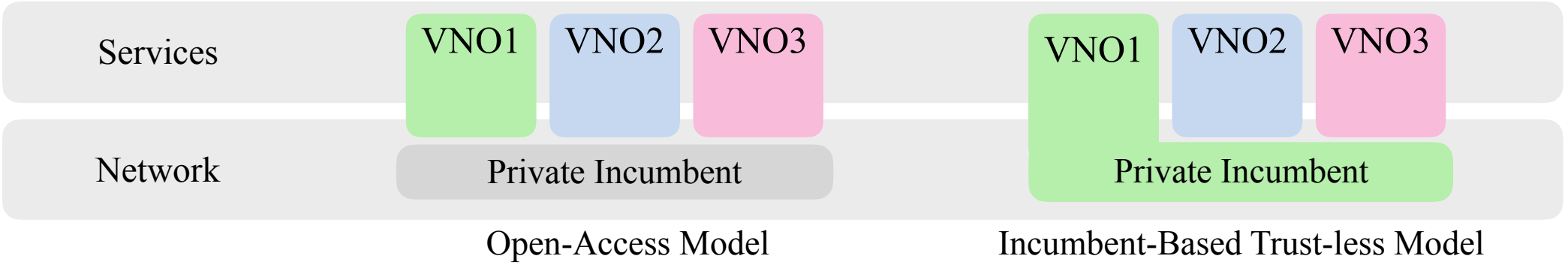
11 $\quad p^S = v_L$ — Pricing

N. Afraz and M. Ruffini, "A Sharing Platform for Multi-Tenant PONs," in Journal of Lightwave Technology, vol. 36, no. 23, pp. 5413-5423, 1 Dec.1, 2018.

The problem with Incumbent access networks

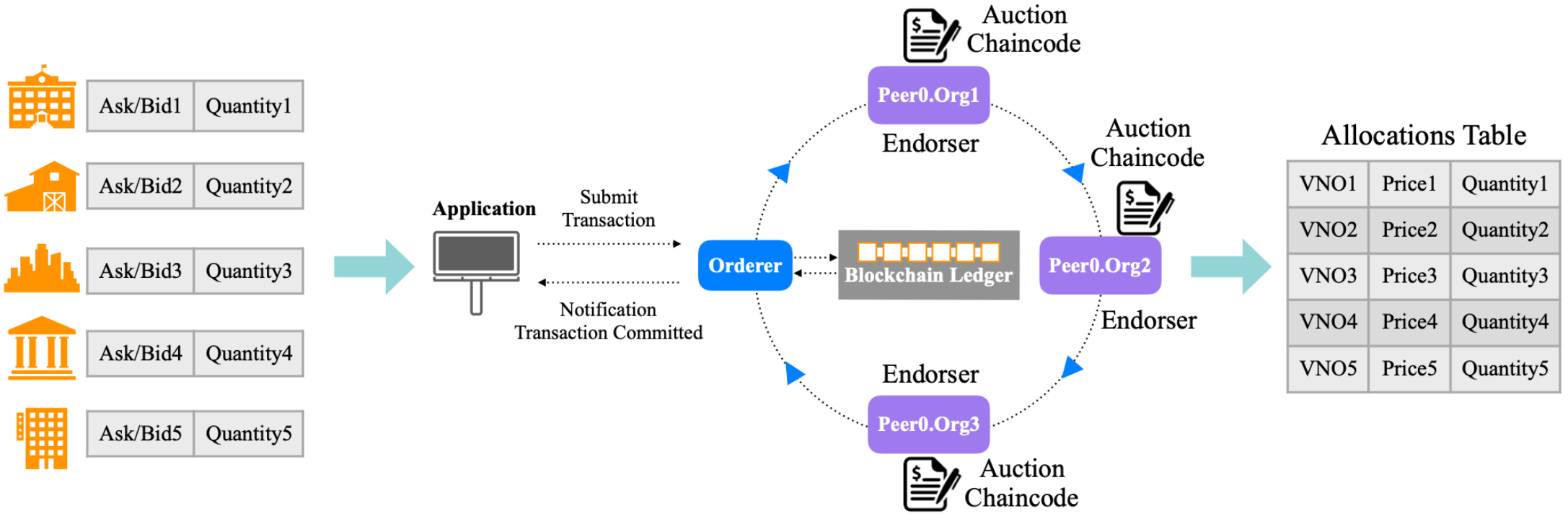
- The previous work however requires that all VNOs trust the infrastructure provider (OK in open access model)

- However today the incumbent-based model is widespread

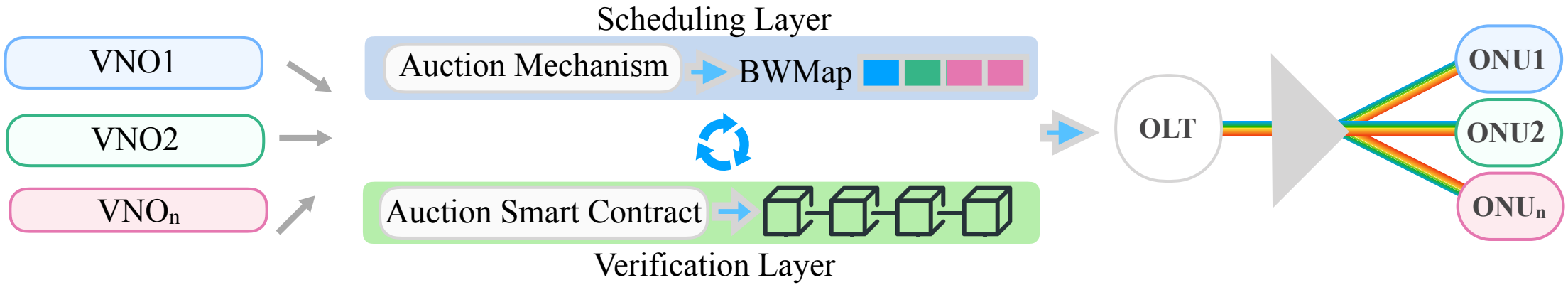


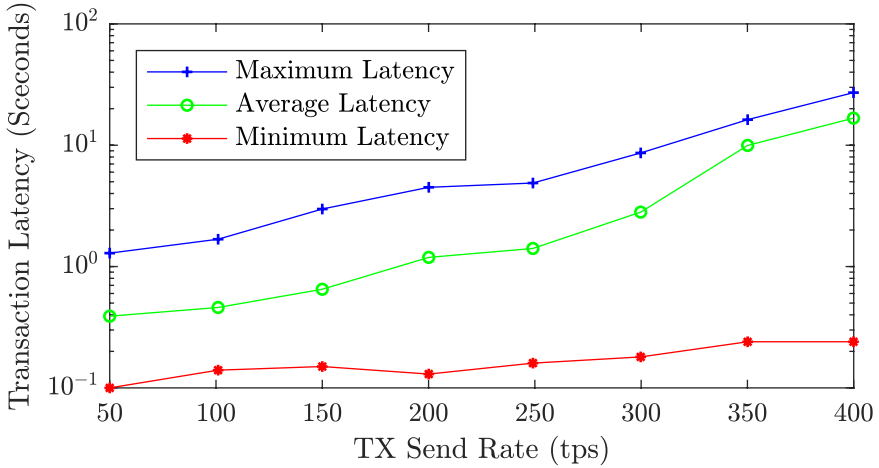
Distributed Market on Blockchain

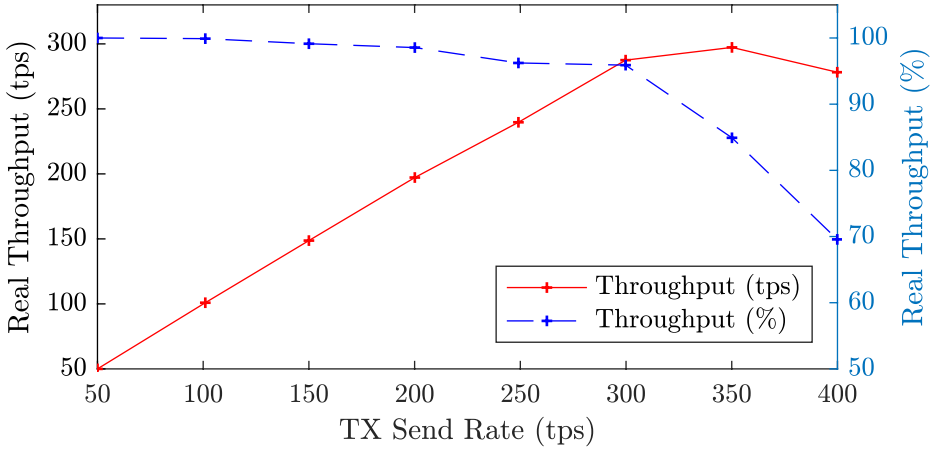
Fault Tolerant distributed record-keeping
- Distributed ledger technology
Manipulation-proof distributed Auction
- Smart Contract technology



Blockchain as verification mechanism

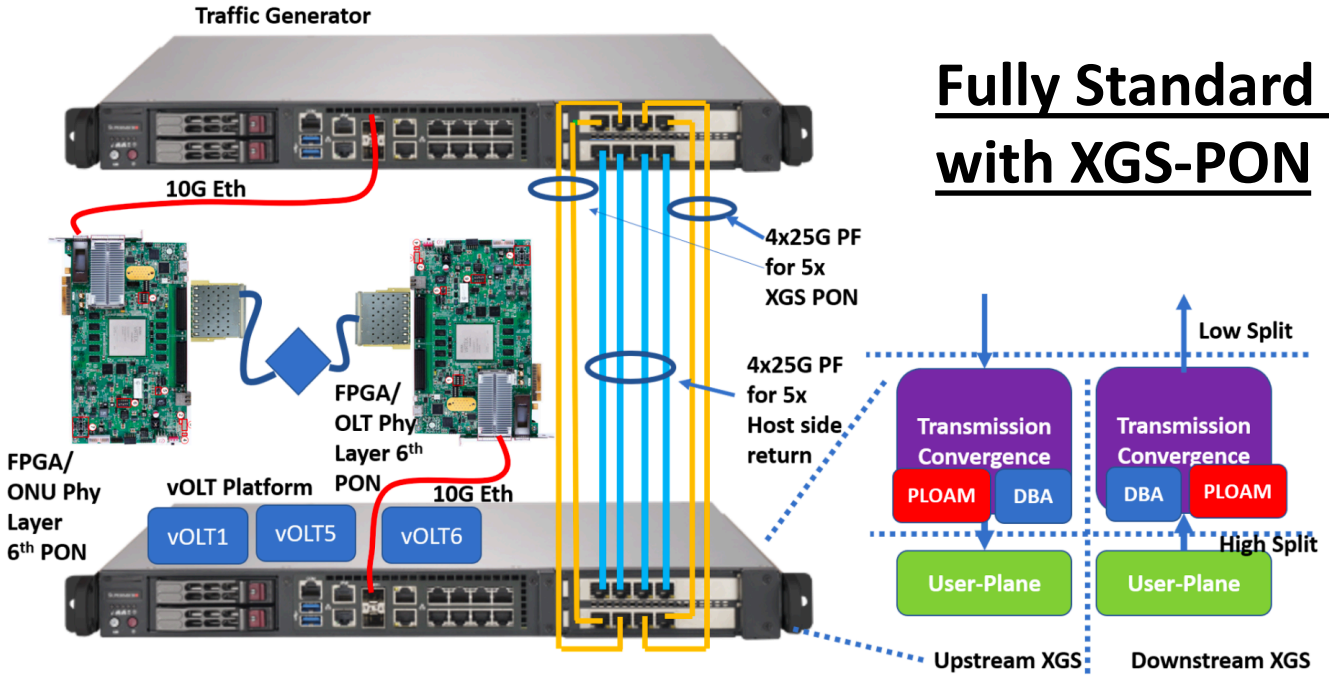




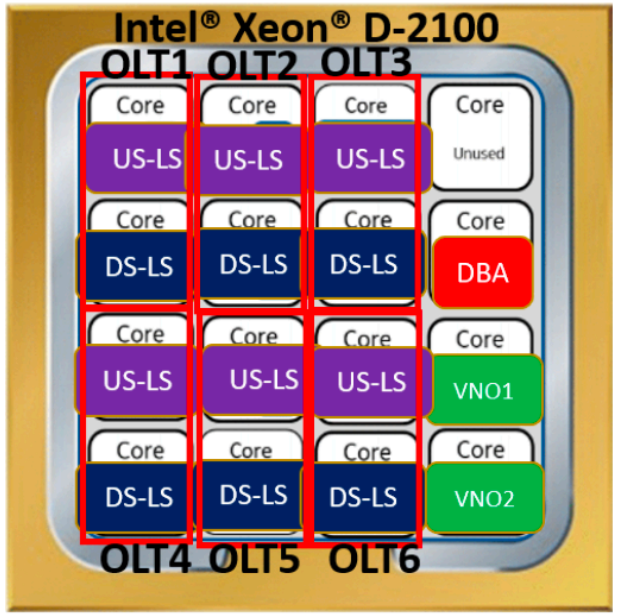


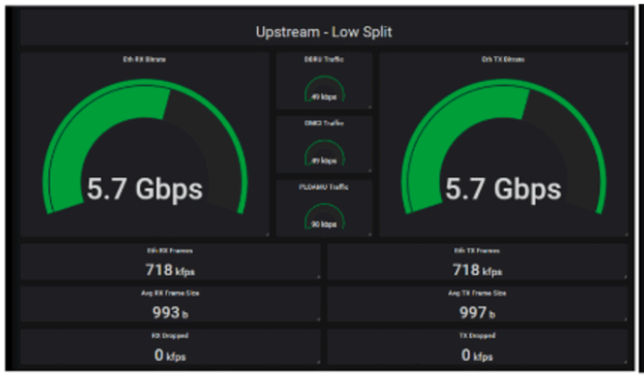
N. Afraz and M. Ruffini. A Distributed Bilateral Resource Market Mechanism for Future Telecommunications Networks. Proc. of IEEE Globecom 2019.

The virtual PON in practice



Fully Standard compliant with XGS-PON

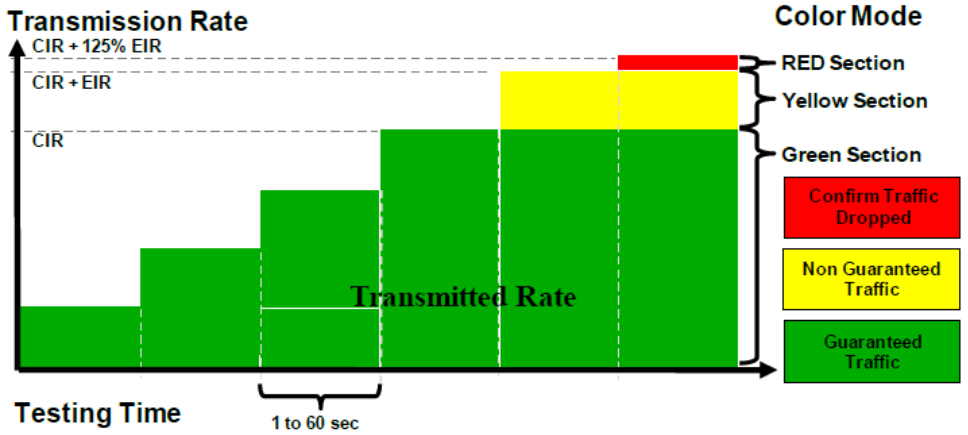


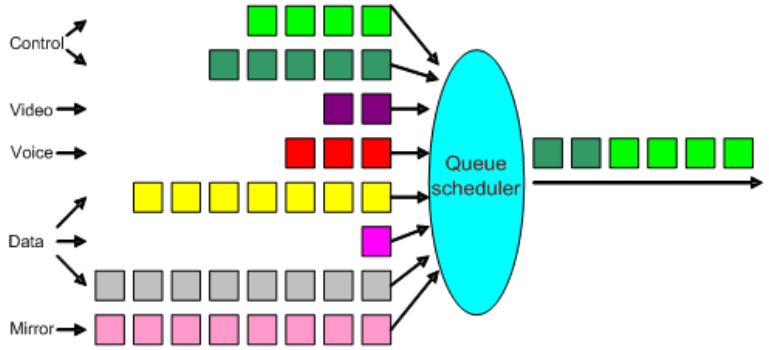


F. Slyne et al., Experimental Demonstration of multiple Disaggregated OLTs with Virtualised Multi Tenant DBA, over General Purpose Processor. OFC 2020.

What about Downstream QoS?

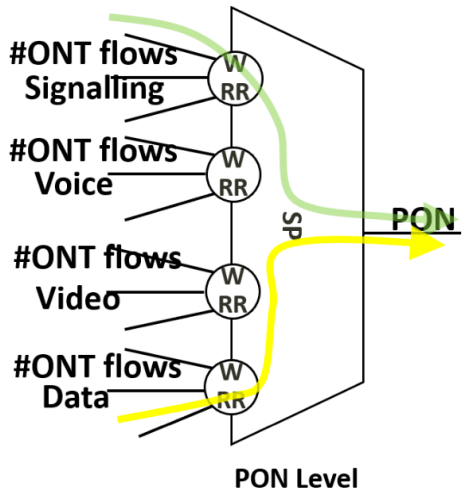
- Typically the backend operates this, through the usual Ethernet queue management mechanisms:
  - Packet coloring (green/yellow/red), with policers and limiters
  - Use queues with different priorities
  - Use of different schedulers to pick the next packets from all the available queues:
    - Strict Priority, Weighed Round Robin, etc.



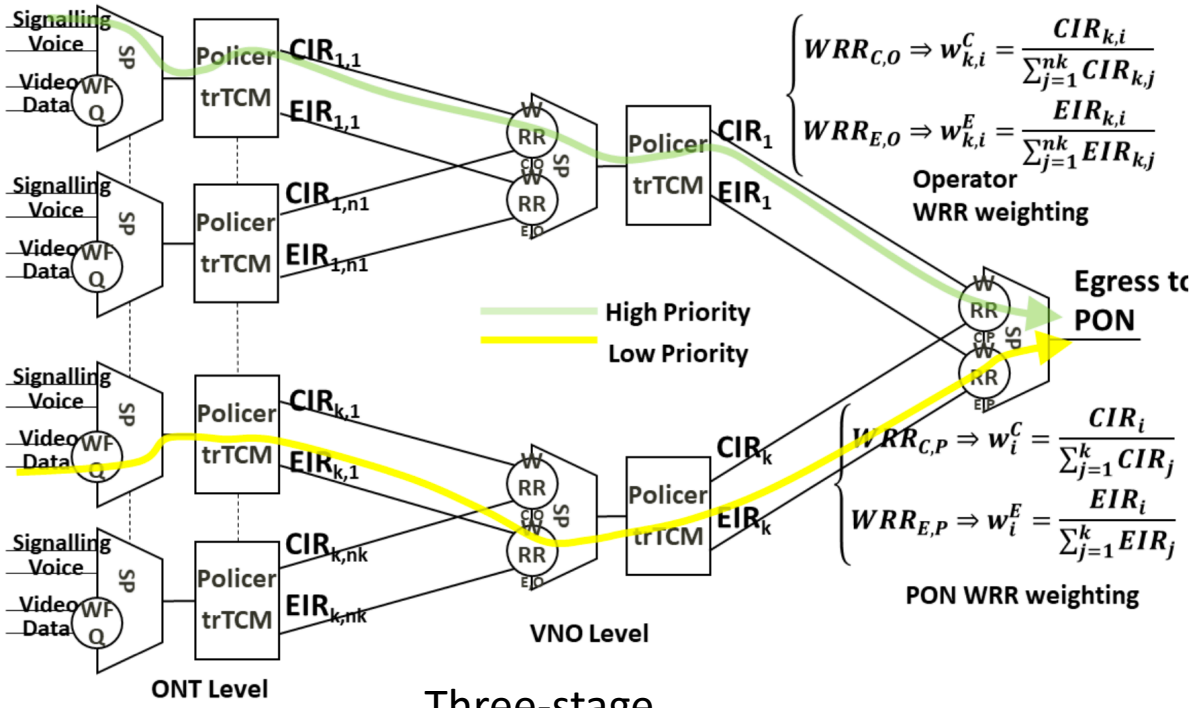


The Hierarchical QoS (H-QoS)

- However, in a shared PON there are multipole levels of QoS:
  - Differentiate per: ONU and Application (end user); PON system; VNO
- The H-QoS puts together multiple queue levels to achieve this multi-stage approach:



Single-stage



Three-stage

Standardised in BBF TR-370i2

F. Slyne, et al., 3-stage Hierarchical Quality of Service for Multi-tenant Passive Optical Network. ONDM 2019.

Content of the talk

- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don't forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON
- Conclusions

The problem with cell densification

Question: how to increase mobile capacity by 1000 times (by 2025?? – used to be 2020…)

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)**

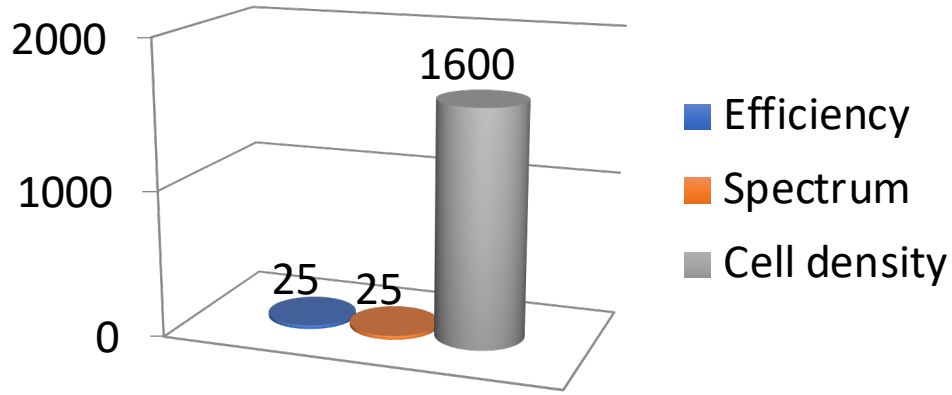
➔

$$\frac{1000}{2 \cdot 3} = 167$$

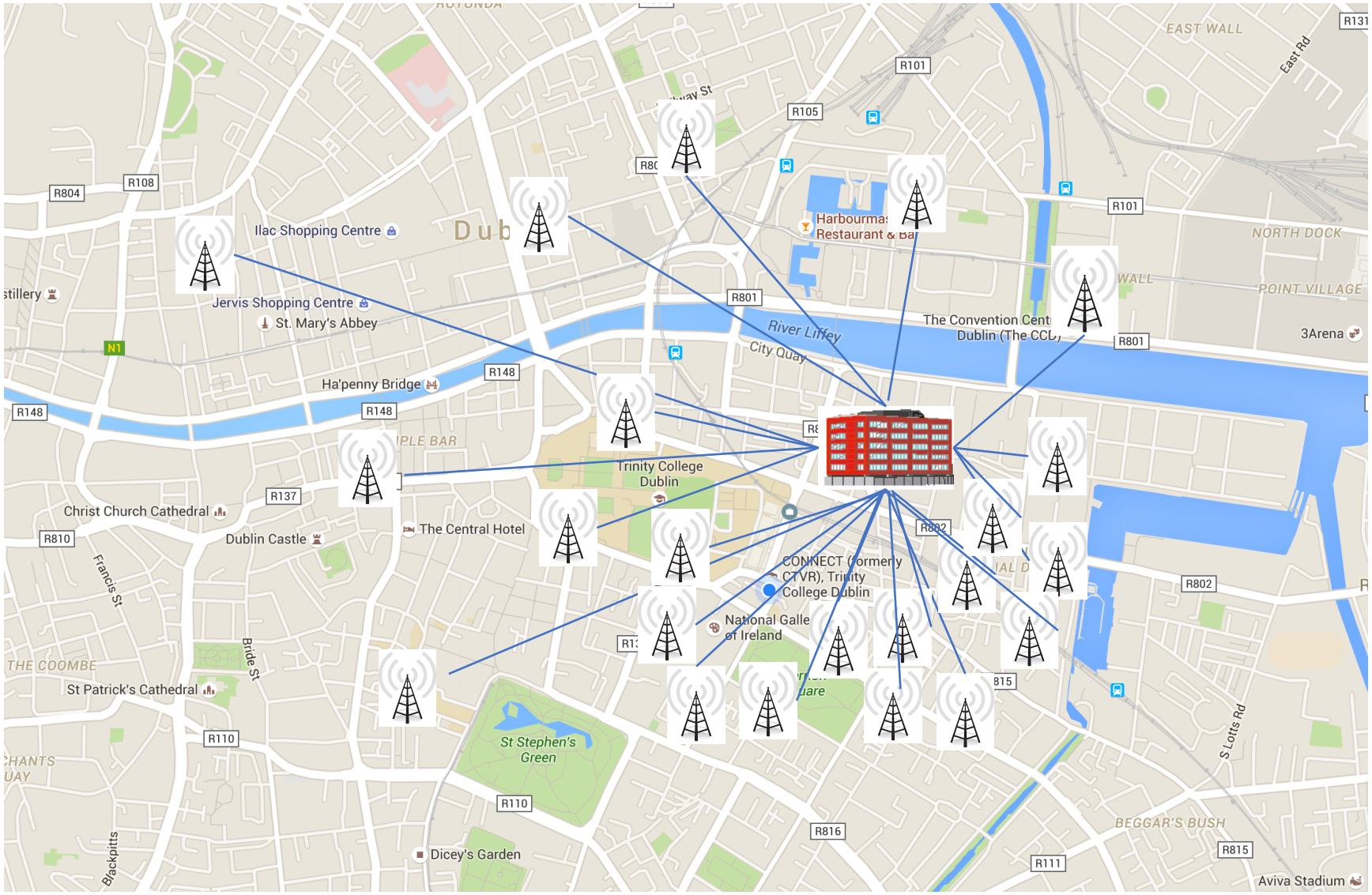
Source: Nokia, enhance mobile networks to deliver 1000 times more capacity by 2020

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

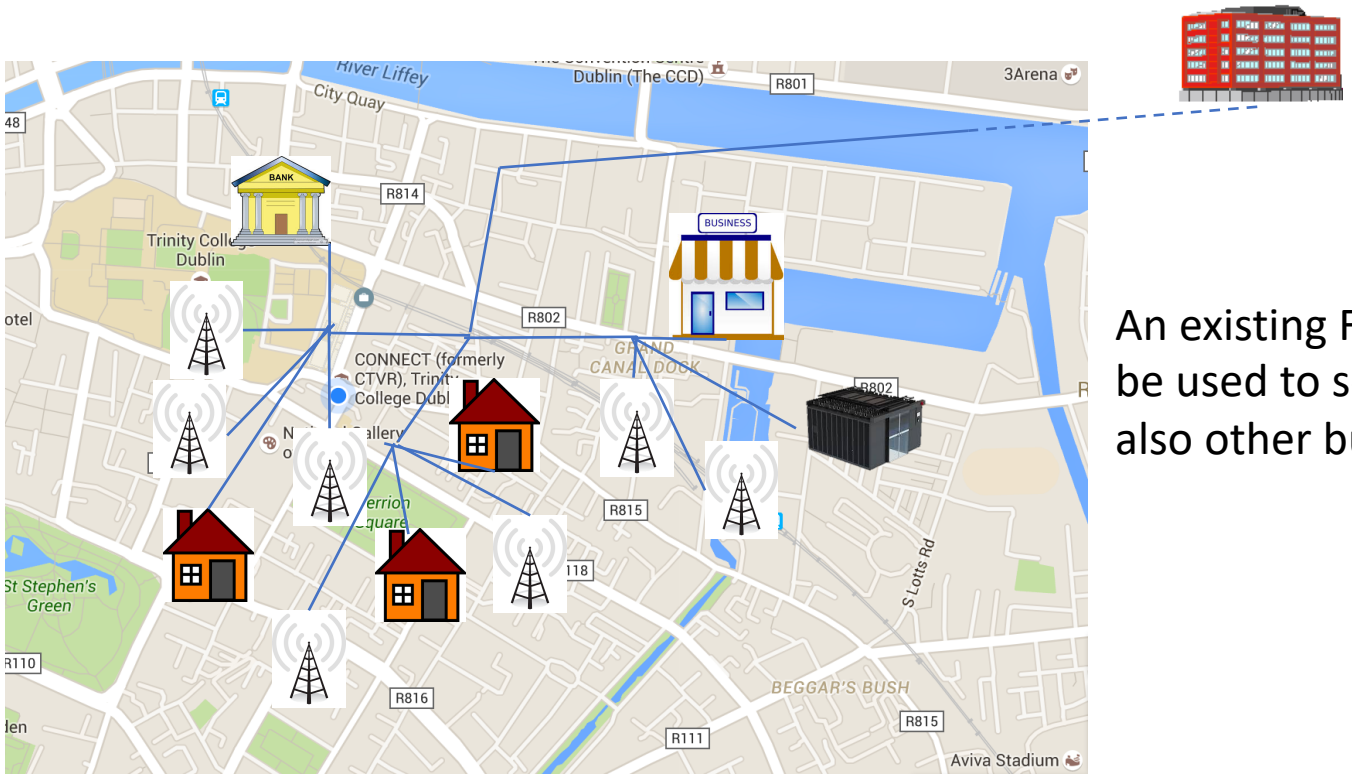


The problem with cell densification



Shared PON for mobile backhauling

- PONs were developed exactly to provide optical access at the lowest cost point



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

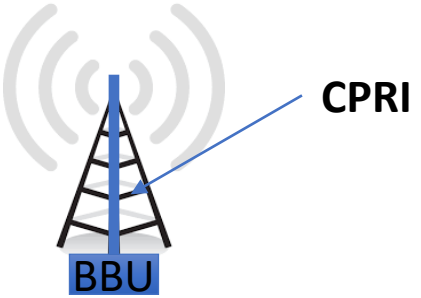
- An optical access network, if well architected can allow service multiplexing: any access point (a home, a macro cell, a small cell, a business, a micro cache or small data center) can request assured capacity from the low Mb/s to multiple 100s Gb/s.

Cloud RAN

Great example of changing requirements and need for flexible network architecture

Placing Base Band Unit (BBU) at different location than the Remote Radio Unit (RRU).

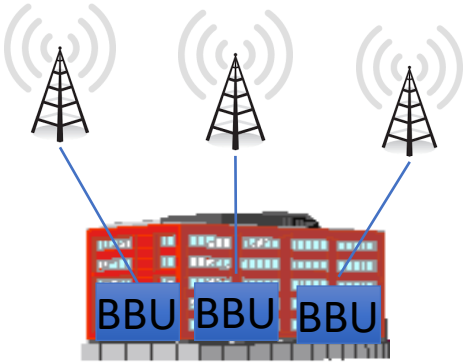
A well-known interface for this “Fronthaul”
transmission is the Commmon Public Radio Interface (CPRI)



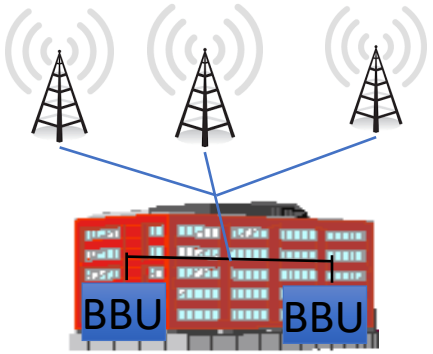
This gave the idea to move the BBU further out giving raise to the Cloud RAN concept

Examples of Fronthaul architectures

One virtual BBU to many RRU



BBU hoteling



BBU pooling

BBU cloud

Split 8 capacity issue

- Split 8 samples the wireless signal and then transmits the I/Q samples over fibre
- It practically transmits a digitized version of the radio wave

Capacity required : $B = R_s \times N_q \times N_a \times N_b \times R_c \times R_l$

- R_s: Sampling rate
- N_q: Quantization bits
- N_a: Antennas
- N_b: Frequency bands
- R_c: Word control ratio
- R_l: Line coding ratio

J-I Kani et al., Options for future mobile backhaul and fronthaul, Elsevier OFT issue on access networks, November 2015

Examples:

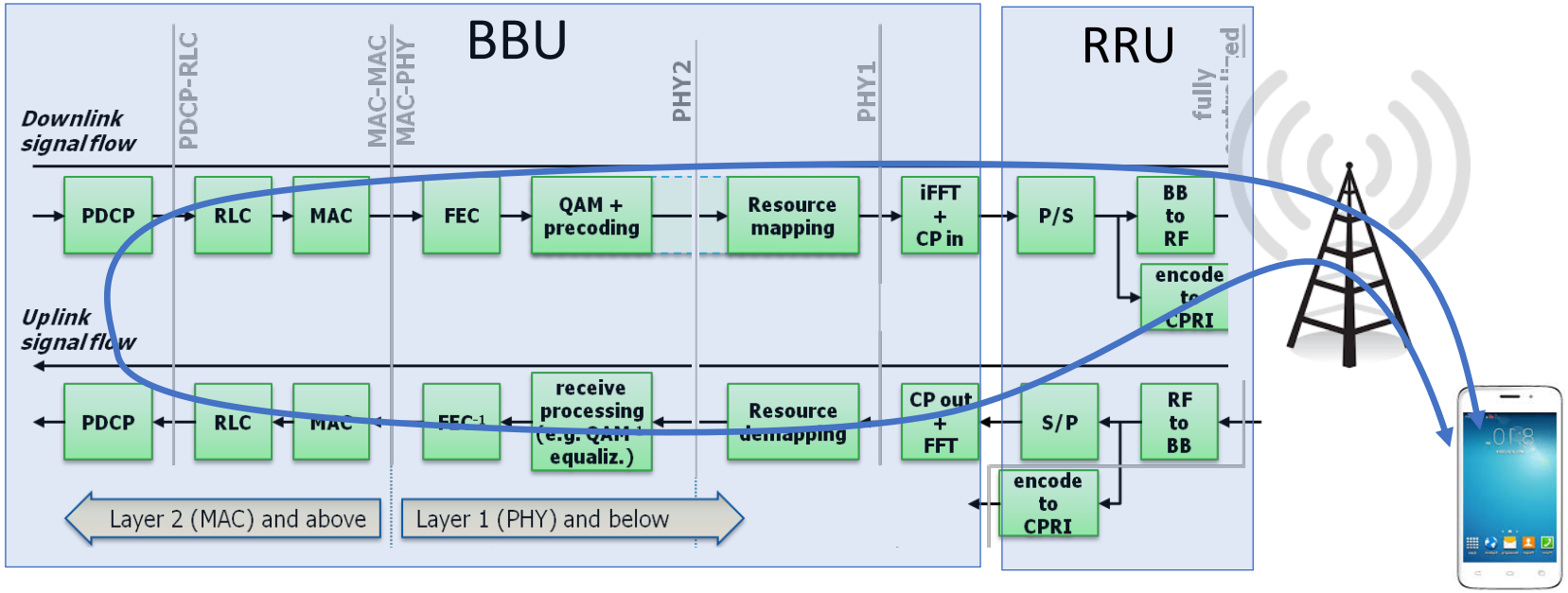
- Take a macro cell: 8x8 MIMO, 3 sectors, 5 x 20MHz channels
  ➔ backhaul rate (64-QAM): 9 Gb/s ➔ fronthaul rate 148 Gb/s

- Take a small cell: 2x2 MIMO, 1 sector, 20 MHz channel
  ➔ backhaul rate (64-QAM) 150 Mb/s ➔ fronthaul rate 2.5 Gb/s

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

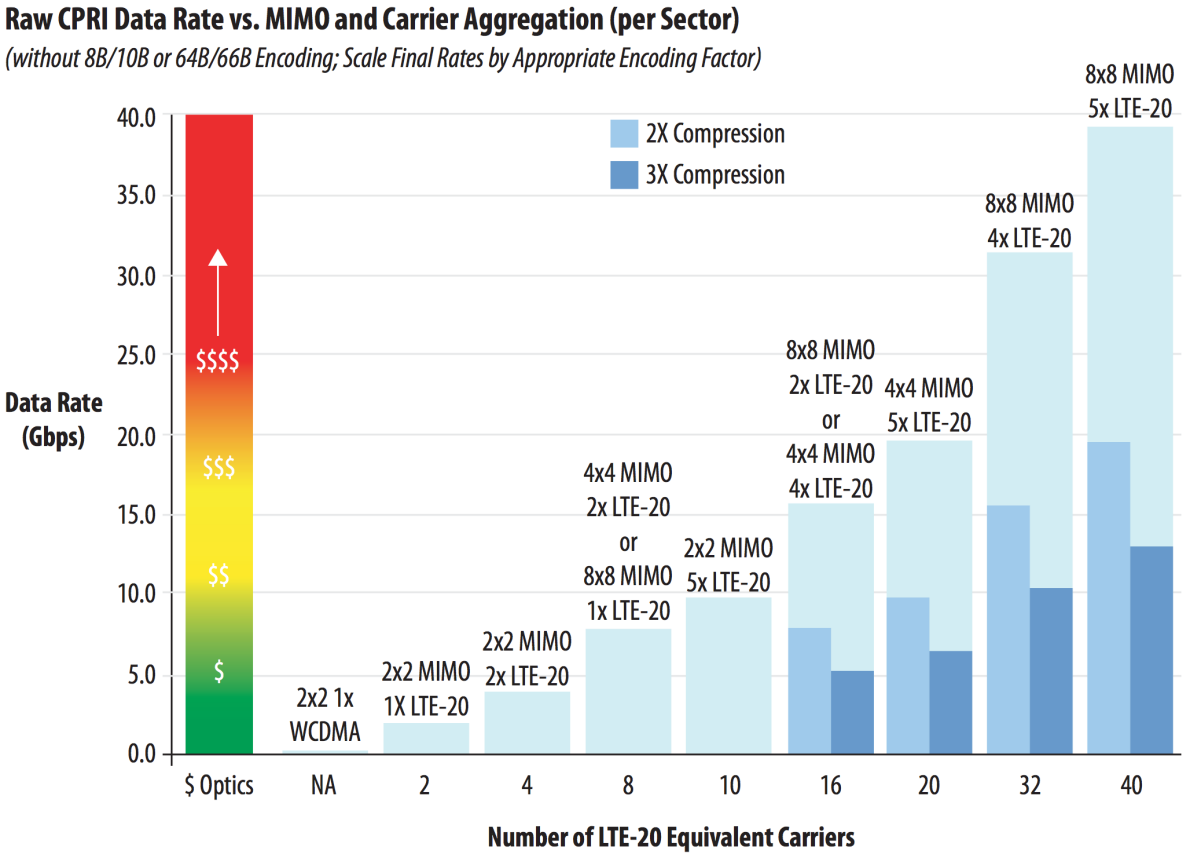
The latency issue

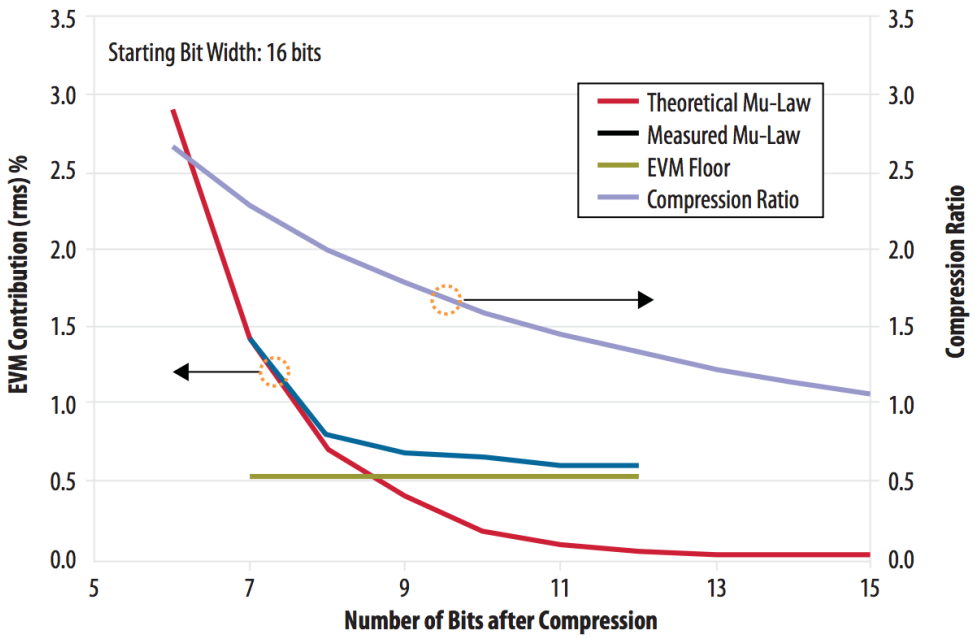
- The Low Layer Splits also presents an issue with latency:
  - The Hybrid Automatic Repeat reQuest (HARQ) system requires that messages between UI and BBU are acknowledged within 3 ms.



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

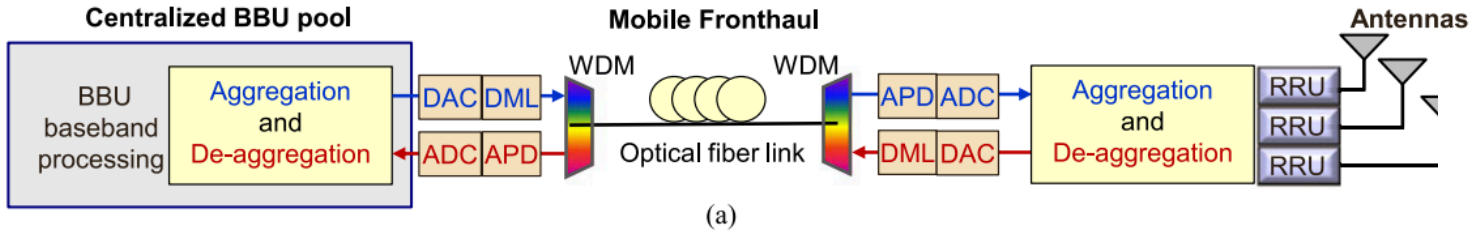
Solution: split-8 compression



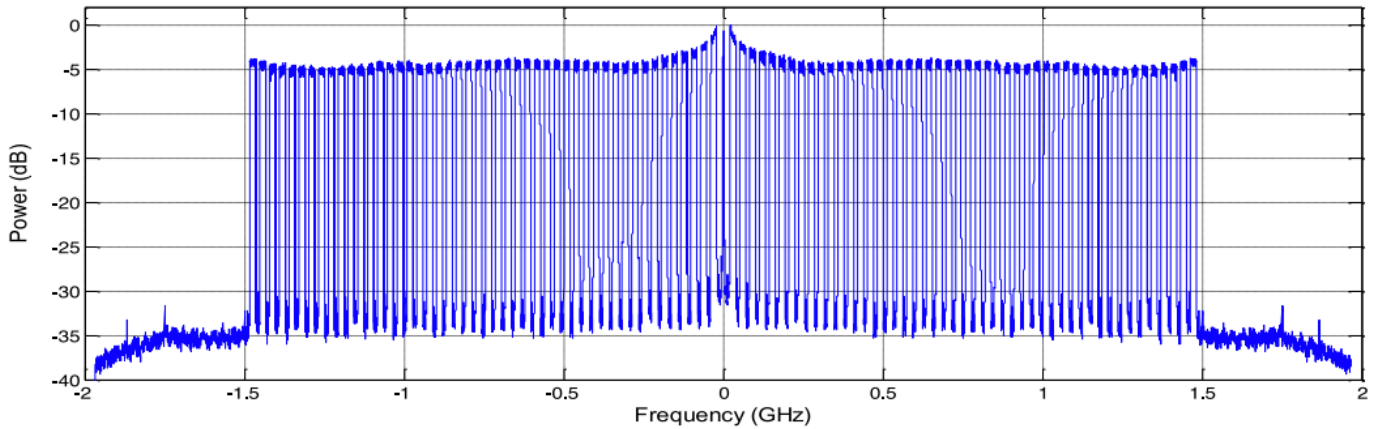


- Short–term solution and does not address latency

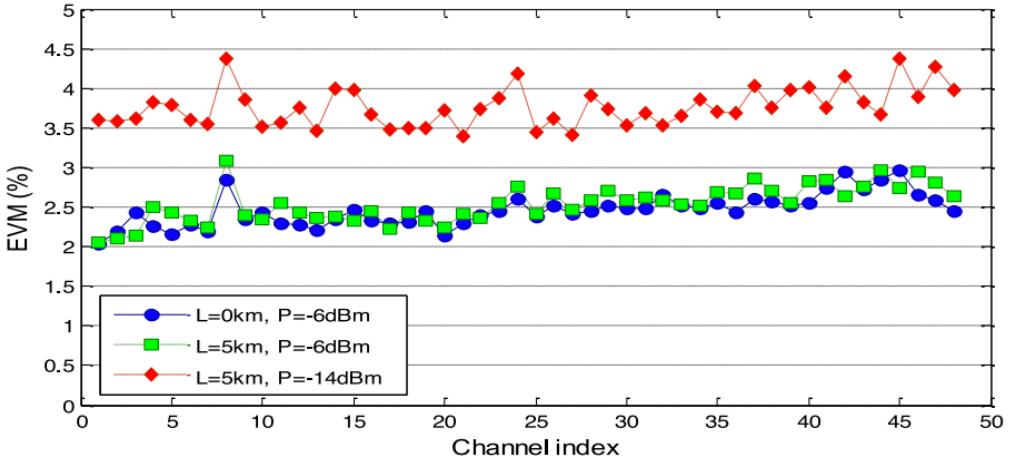
Analogue Radio over Fibre



(a)



(b)

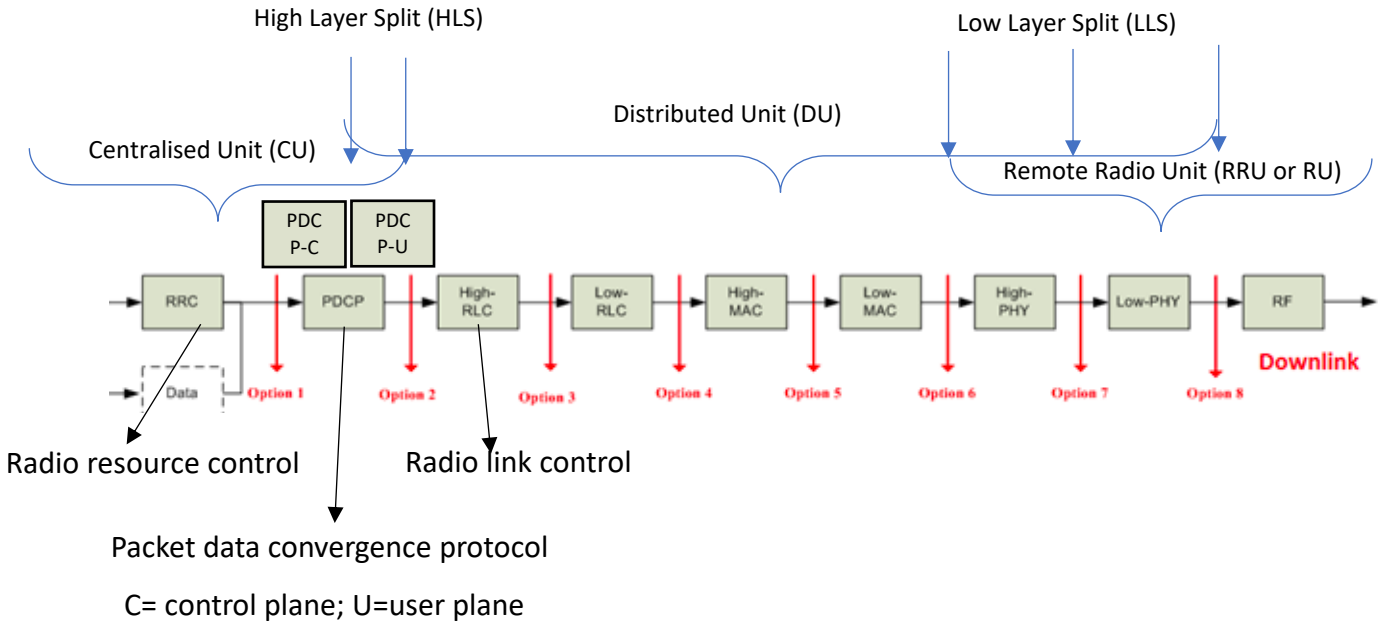


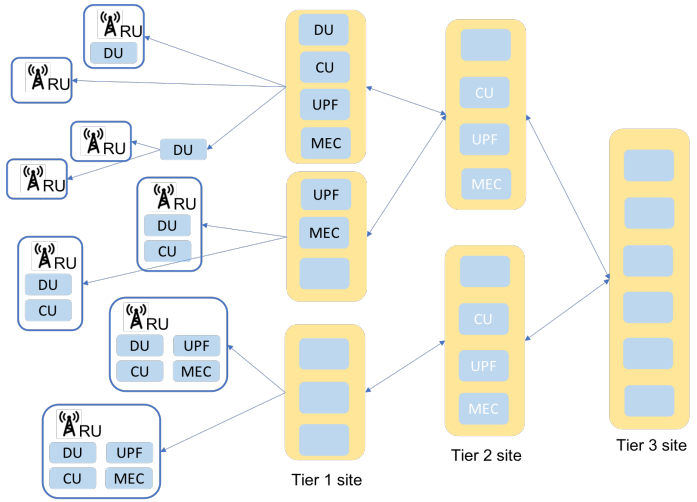
Xiang Liu et al., Efficient Mobile Fronthaul via DSP-Based Channel Aggregation. JLT, March 2016

- ITU-T Radio over fibre systems G.9803 (Nov. 2018)considering coexistence of PON with RoF (on dedicated wavelength channel)

Functional split

LLS is the low latency interface, between RRU and DU





Protocol split option	Required downlink bandwidth	Required uplink bandwidth	One way latency (order of magnitude)
Option 1	4 Gb/s	3 Gb/s	1-10 ms
Option 2	**4016 Mb/s**	**3024 Mb/s**	
Option 3	[lower than Option 2 for UL/DL]		
Option 4	4000 Mb/s	3000 Mb/s	100 to few 100 µsec
Option 5	4000 Mb/s	3000 Mb/s	
Option 6	**4133 Mb/s**	**5640 Mb/s**	
Option 7a	**10.1-22.2 Gb/s**	**16.6-21.6 Gb/s**	
Option 7b	**37.8-86.1 Gb/s**	**53.8-86.1 Gb/s**	
Option 7c	**10.1-22.2 Gb/s**	**53.8-86.1 Gb/s**	
Option 8	157.3 Gb/s	157.3 Gb/s	

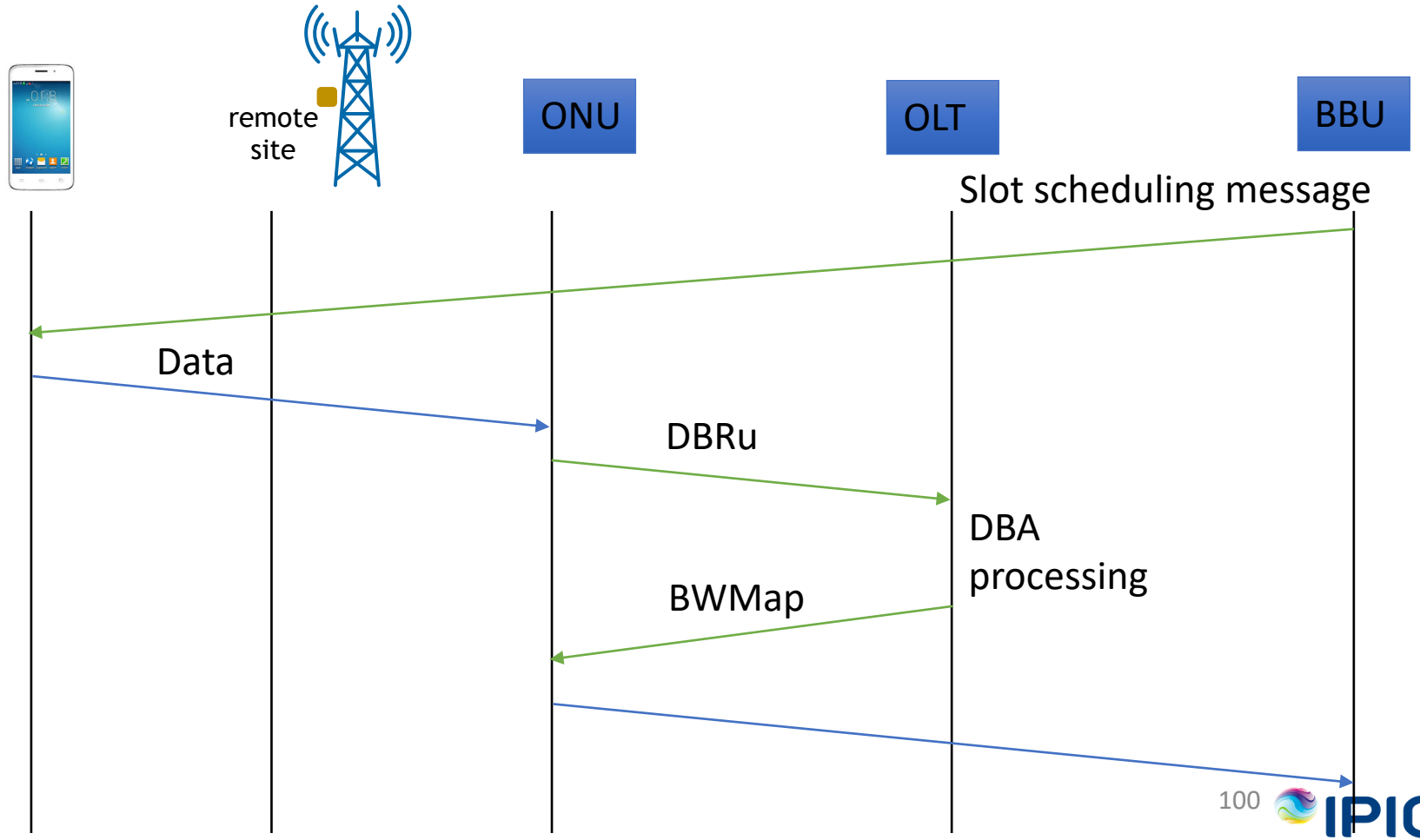
Simplification:

- Low Layer Split (LLS): DU-RRU → Fx interface: low latency, high to medium capacity
- High Layer Split (HLS): CU-DU → F1 interface: medium-high latency, low capacity

5G wireless fronthaul requirements in a passive optical network contextITU-T, Series G, Supplement 66 (07/2019)

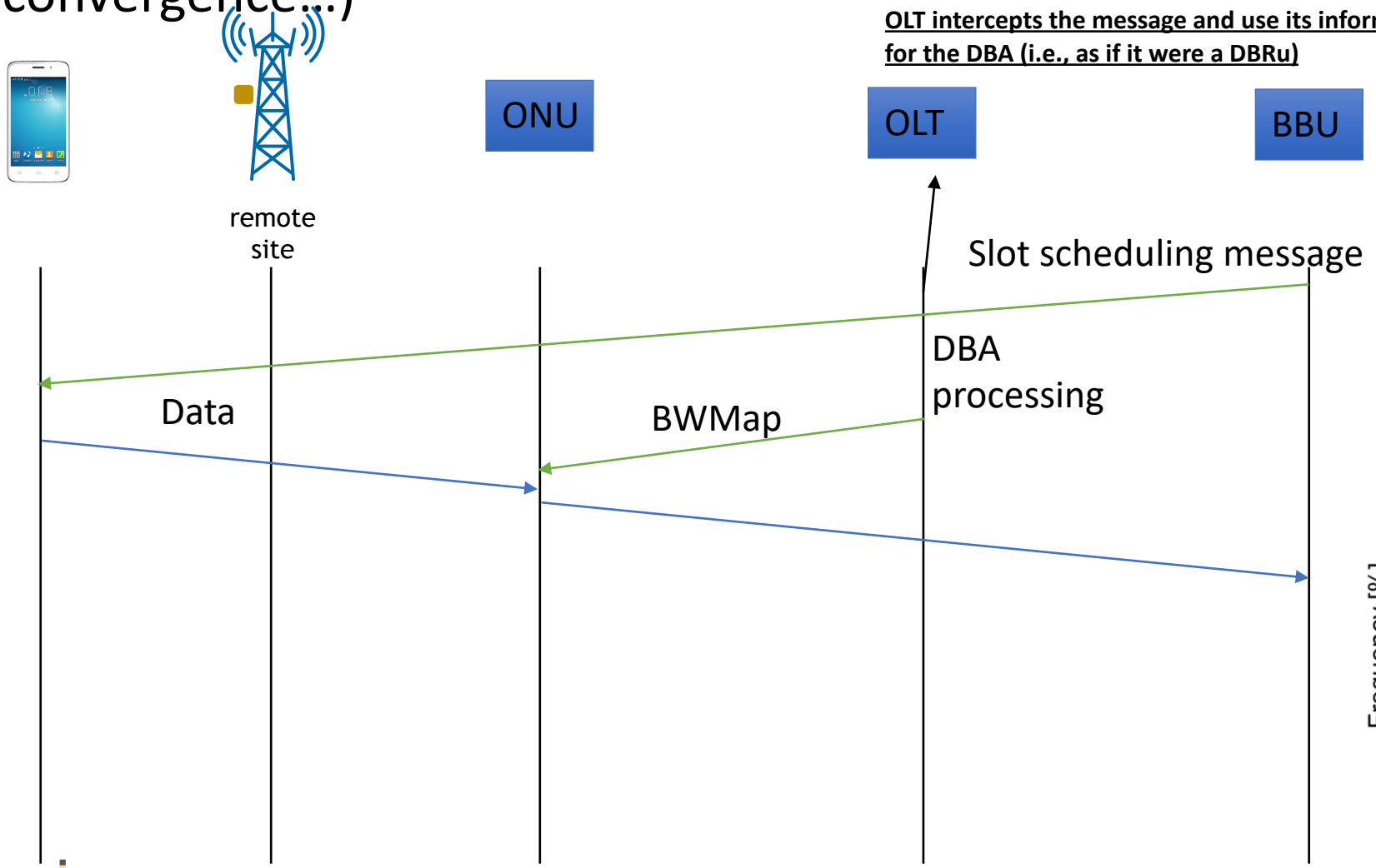
So, can we use a PON for C-RAN?

- Split 8 doesn't make sense as it does not allow statistical multiplexing
- Other splits make sense
- However the DBA introduces latency in the PON upstream scheduling

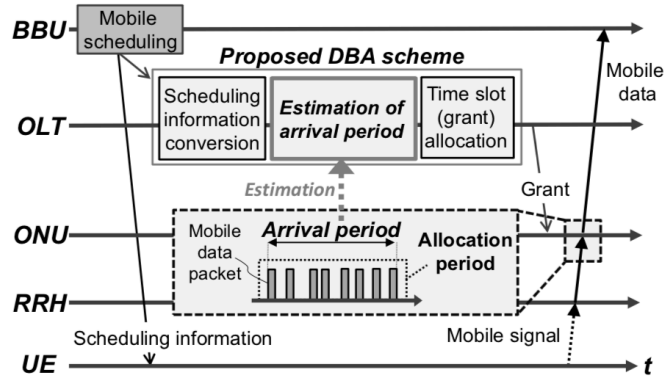


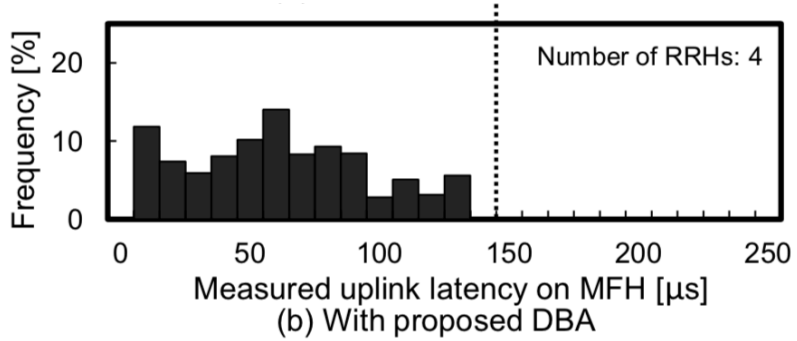
Cooperative DBA Solution

- 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

Does Co-DBA solve the PON latency issue for all URLLC use cases?

- Cooperative DBA is an efficient coordination between wireless and PON schedulers
  - Based on the fact that that the BBU provides the OLT with upstream scheduling information a few ms in advance.

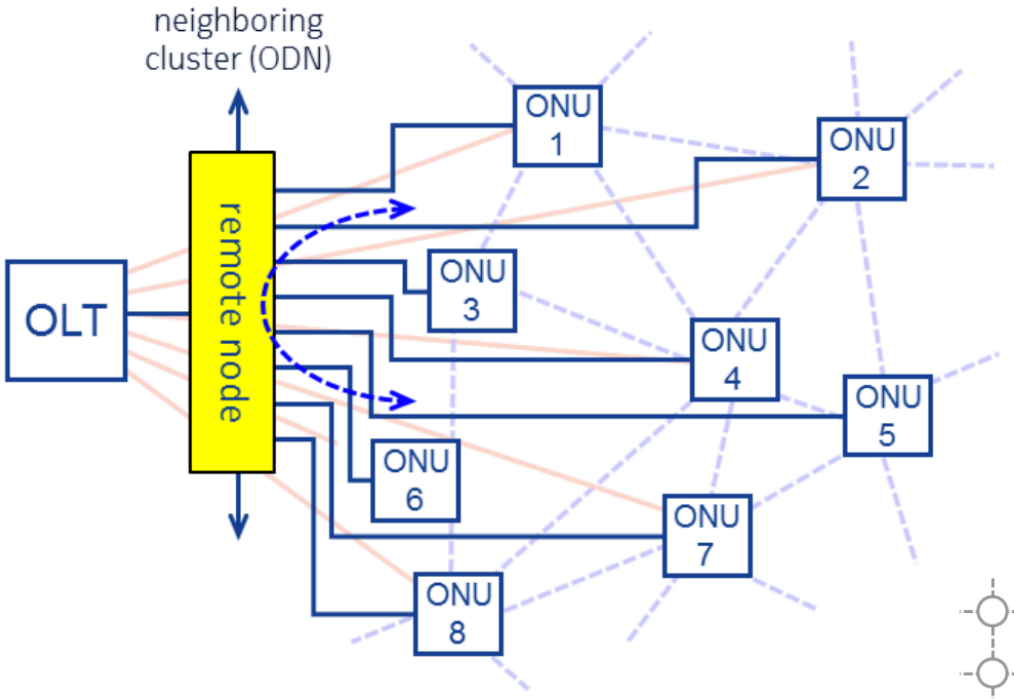
- What if the latency is at the application level?

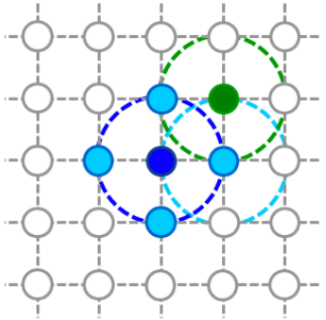
- Still an open issues, with some solutions to mitigate the problem:
  - Use fixed bandwidth allocation; cons very inefficient
  - Reduce DBA cycle (more for each frame); cons: inefficient

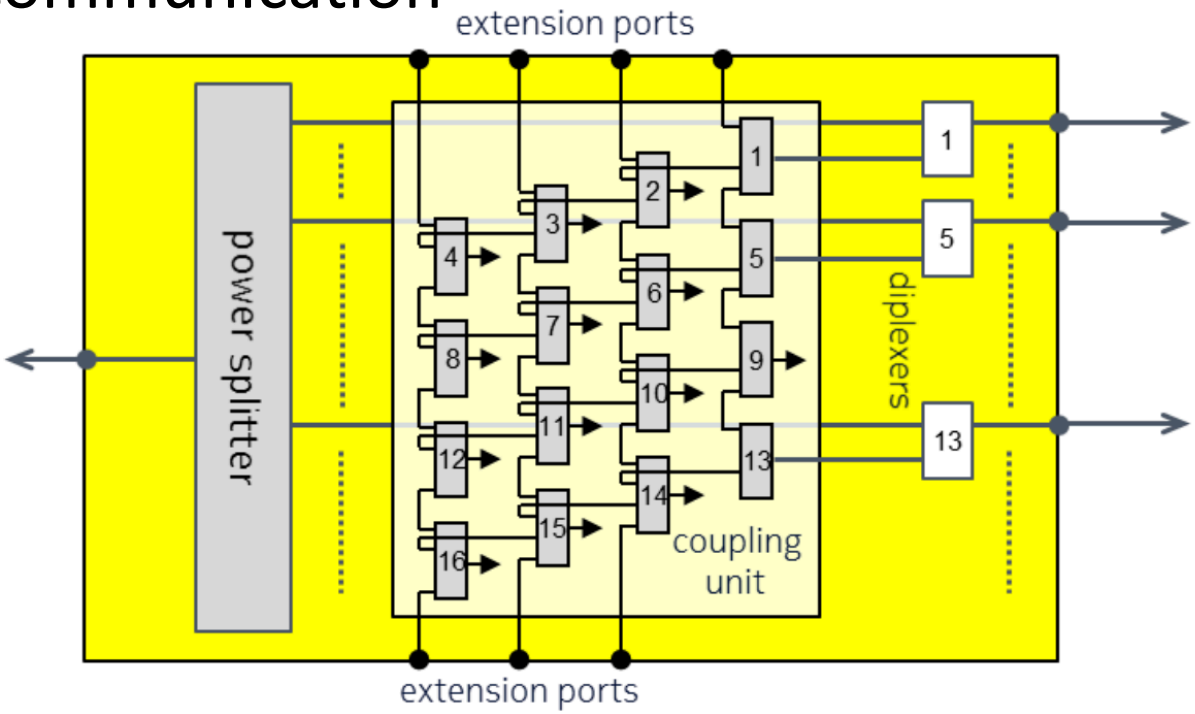
  - Predict packet arrival (e.g., using ML):
    - good, but can it be generalized to multiple applications?
    - Can it predict the arrival time with microsecond precision (e.g., at the same order of the DBA scheduling?)

Augmented PON architectures

Provide both North-South and East-West communication

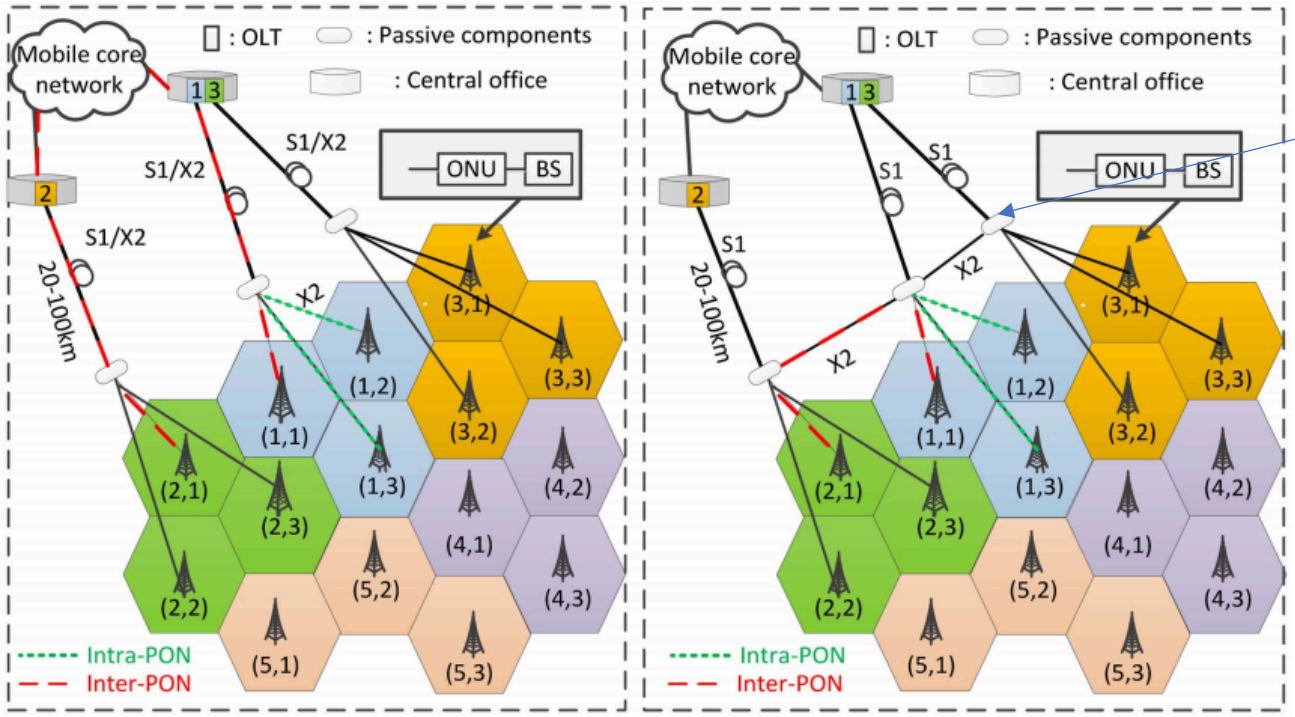




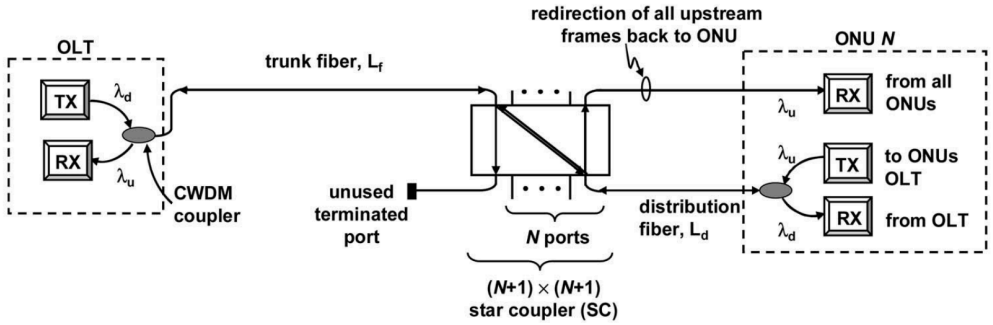


T. Pfeiffer, Can PON technologies accelerate 5G deployments. ONDM 2018

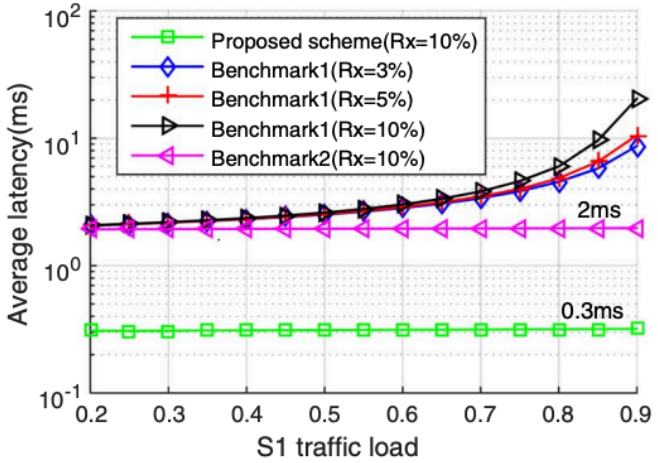
Augmented PON architectures



Loop back signals using a star coupler architecture



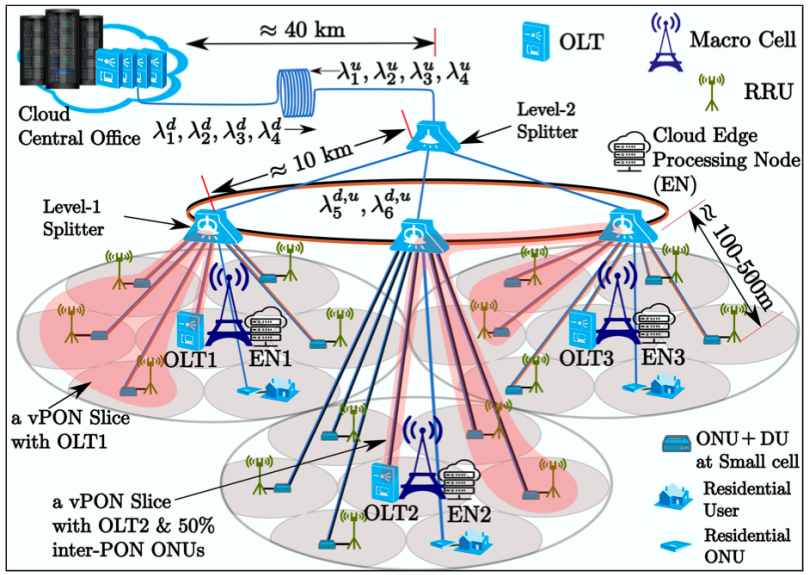
E. Wong et al., Customer-controlled dynamic bandwidth allocation scheme for differentiated services in passive optical networks. JON July 2006

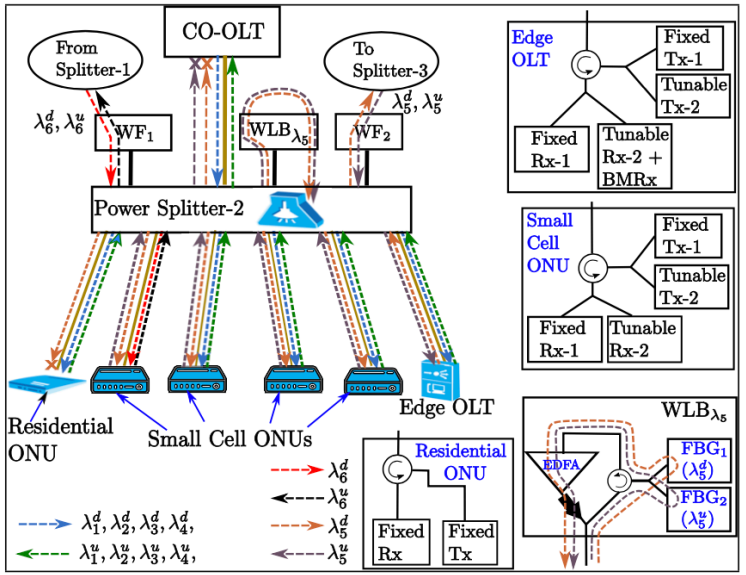


Enabling low-latency (e.g, 0.3 ms) communication across BS (enabling joint transmission, scheduling, etc)

Jun Li and Jiajia Chen, Passive Optical Network Based Mobile Backhaul Enabling Ultra-Low Latency for Communications Among Base Stations. JOCN Oct. 2017

Generalisation: PON architectures for MEC

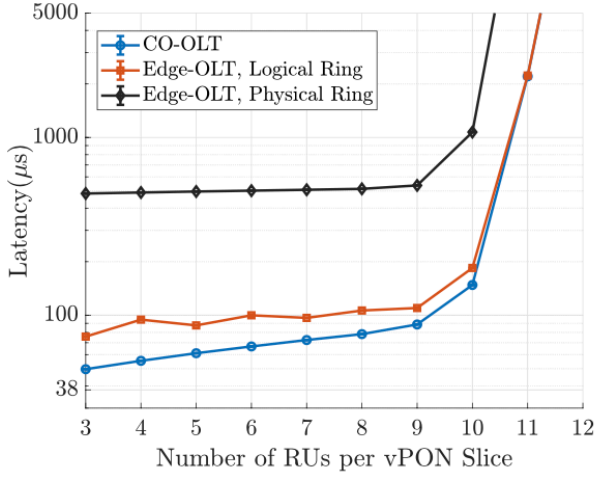




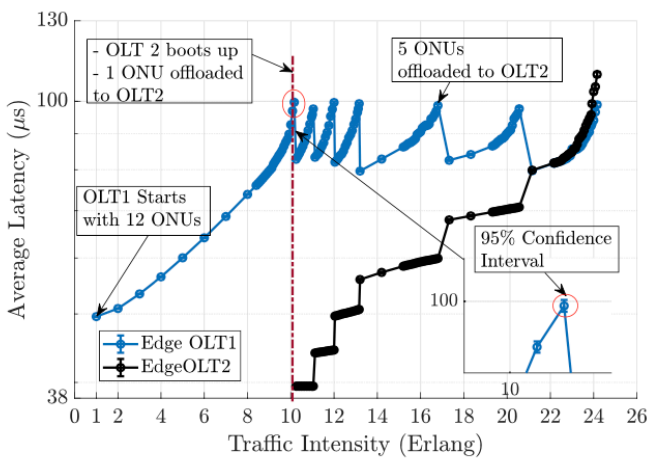
- Virtualization across all ONUs and OLTs to create arbitrary slices (use both time and wavelength domains)

S. Das, M. Ruffini. PON Virtualisation with EAST-WEST Communications for Low-Latency Converged Multi-Access Edge Computing (MEC). OFC 2020.

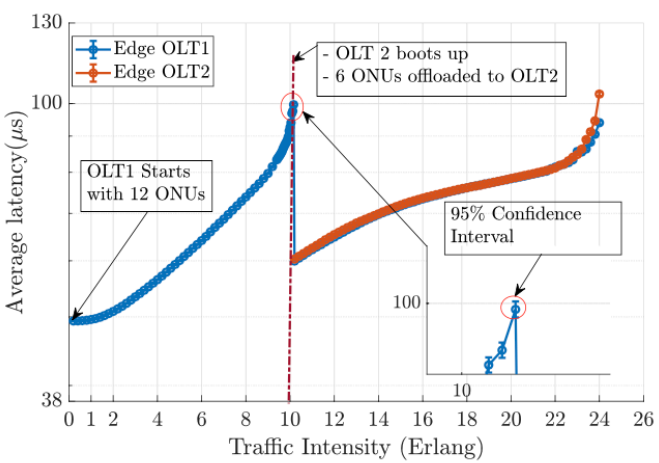
Latency gain at 12.5 Erlang



Migrating OLT to keep latency below given threshold (e.g., 100 us)



One ONU at a time

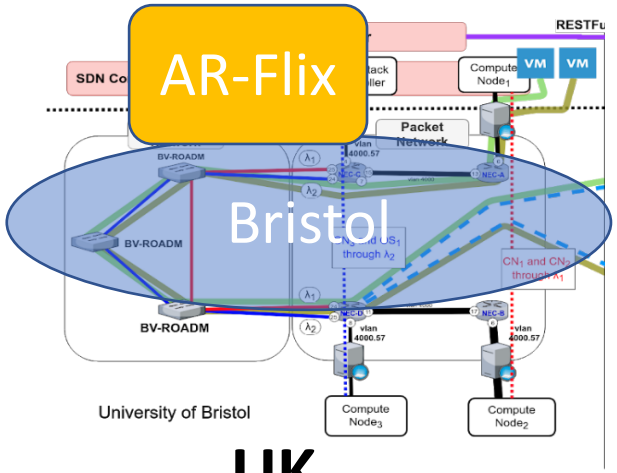


Half ONUs migrated to second OLT

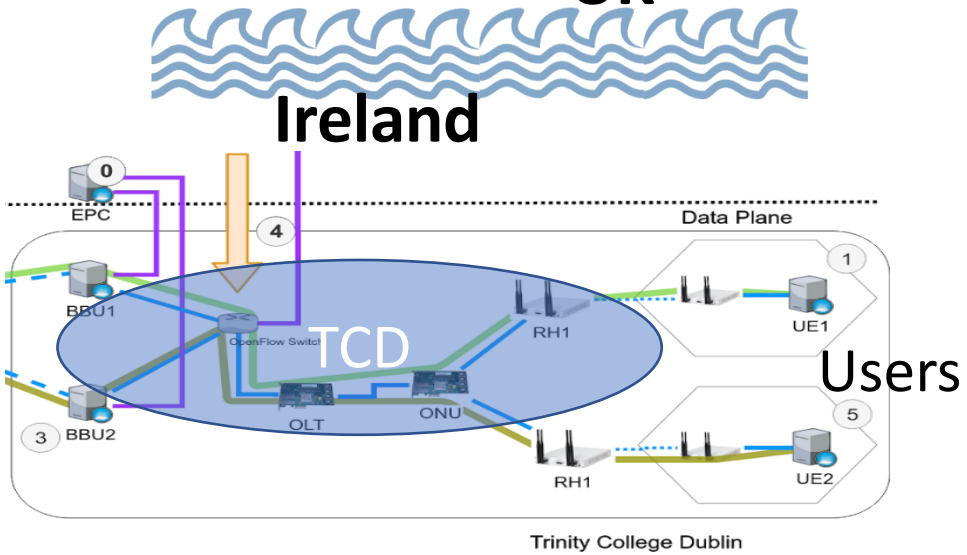
Example of fixed/mobile convergence: Practical use case demonstration

TRINITY COLLEGE DUBLIN

- A large UK Operator (Bristol) provides network connectivity to a large content providers (AR-Flix) in the UK. The content provider decides it also wants to access the Irish market and asks Bristol to provide high-QoS connectivity to wireless users in Ireland. Its service require "guaranteed performance" to work seamlessly.



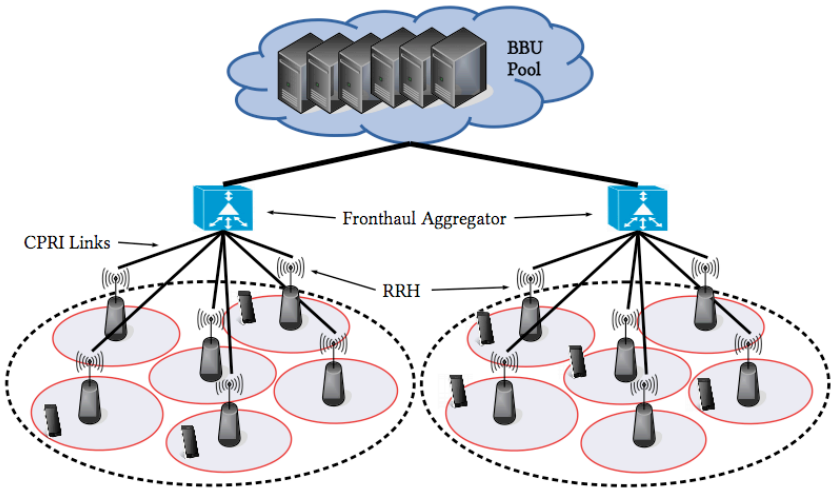
- Bristol thus leases wireless capacity from TCD (which owns the wireless license in Ireland), but it wants to minimise its leasing cost, thus dynamically request only the capacity (wireless spectrum and optical bandwidth) that is actually required by the users, while the remaining is allocated to users of local content.



Variable rate fronthaul

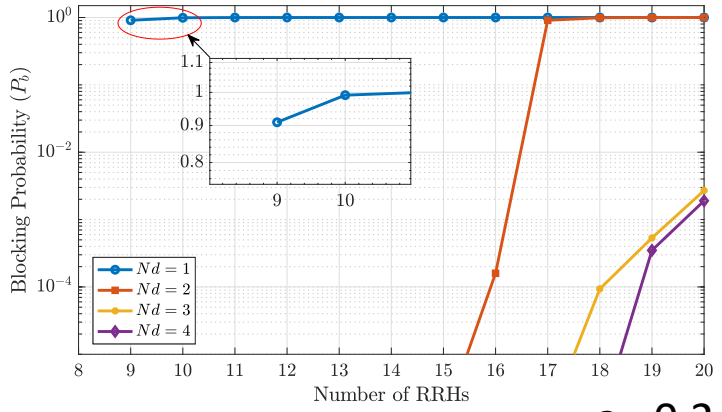
- Key goal is to re-instate the statistical multiplexing of base stations

➔ cells linked to a fronthaul aggregator (Ethernet switch or PON network)

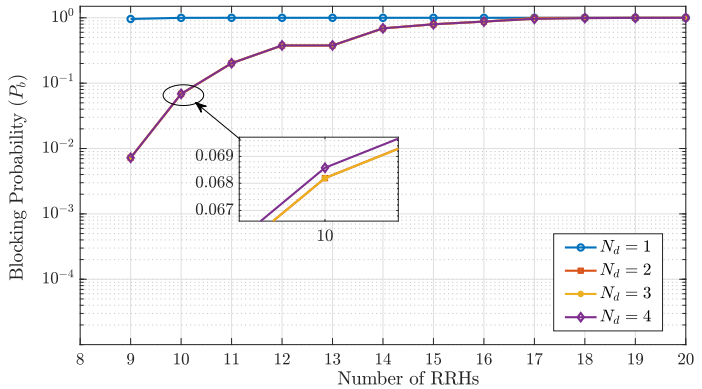


Parameters	values	
Service Rate per server (each RRH)	0.5	
Number of servers (each RRH)	50	
Number of data rates available for fronthaul	1	1228.8 Mbps
	2	{614.4, 1228.8} Mbps
	3	{307.2, 614.4, 1228.8} Mbps
	4	{153.6, 307.2, 614.4, 1228.8} Mbps
Capacity of FHA link	10 Gbps	
Max number of RRH per Aggregator	20	
Number of servers in Aggregator	20	

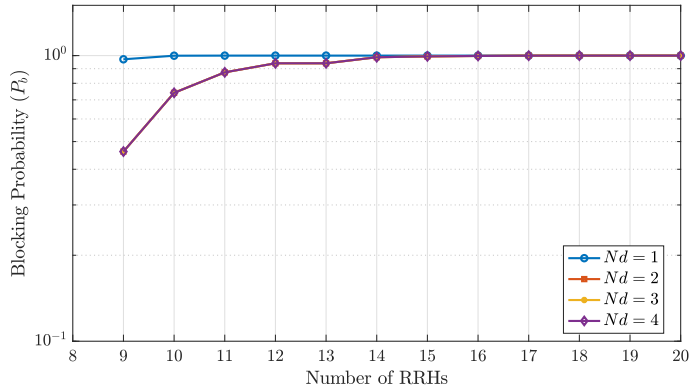
LTE bandwidth configuration (in MHz)	FFT size	Number of PRBs	CPRI data rate (in Mbps)	Max supported users
1.25	128	6	76.8	3
2.5	256	12	153.6	6
5	512	25	307.2	12
10	1024	50	614.4	25
15	1536	75	921.6	37
20	2048	100	1228.8	50



a= 0.2



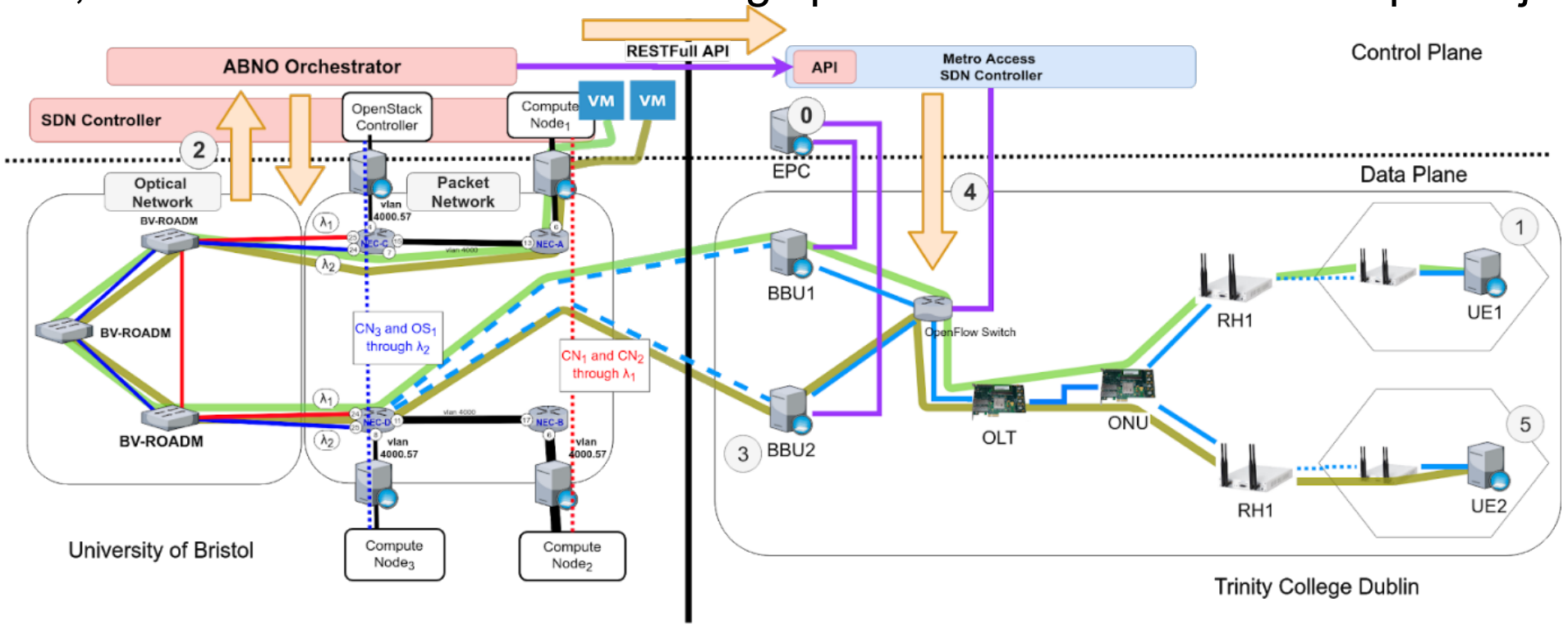
a= incoming/served requests a= 0.5



a= 0.7

DEMO Setup

- Optical core network connected to servers representing content providers (UnivBris)
- Wireless edge network with fronthaul operating over fibre access PON (TCD)
- SDN system controlling:
  - optical core path and computing resources (UnivBris);
  - liaise with TCD controller for configuring TCD access network: adaptation between the BBU, the RRH and the PON enabling spectrum reuse across multiple adjacent cells.



F. Slyne, et al. Coordinated fibre and wireless spectrum allocation in SDN-controlled wireless-optical-cloud converged architecture. ECOC 2019.

Content of the talk

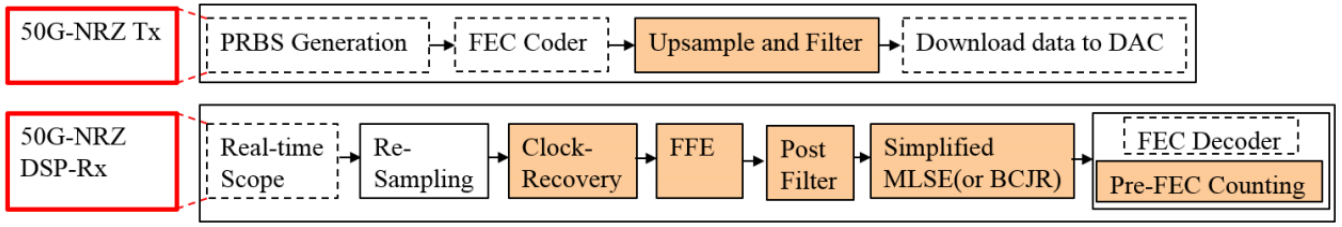
- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don’t forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for beyond 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON
- Conclusions

Higher rates

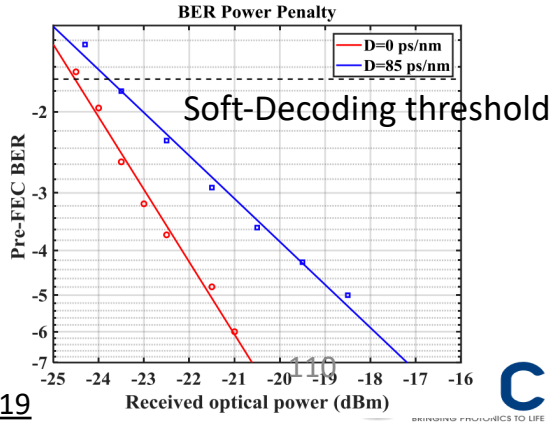
- Evolution from Data centre standards (e.g., the 25Gx4 of the 100GE)
- PAM-4 would enable 50G on 25GBaud, but receiver penalty of 8-9dB too high for PONs
  - ➔ NRZ is preferred choice
- 50G APD difficult to produce at low cost point
  - Use of 25G APD receivers with Electrical Duo Binary (reduces the bandwidth of an NRZ signal)
- DSP for equalization required to counteract low bandwidth of receiver
- Chromatic dispersion is also a problem (the requirement is of 1dB penalty over 20km distance) ➔ 74 ps/nm
  - EBD can just meet this requirement

D. van Veen, V. Houtsma, Strategies for economical next-generation 50G and 100G passive optical networks. JOCN, Jan. 2020

- Example work using DSP for Clock recovery, equalization, LDPC (soft or hard decoding)



Enables 20 km transmission distance

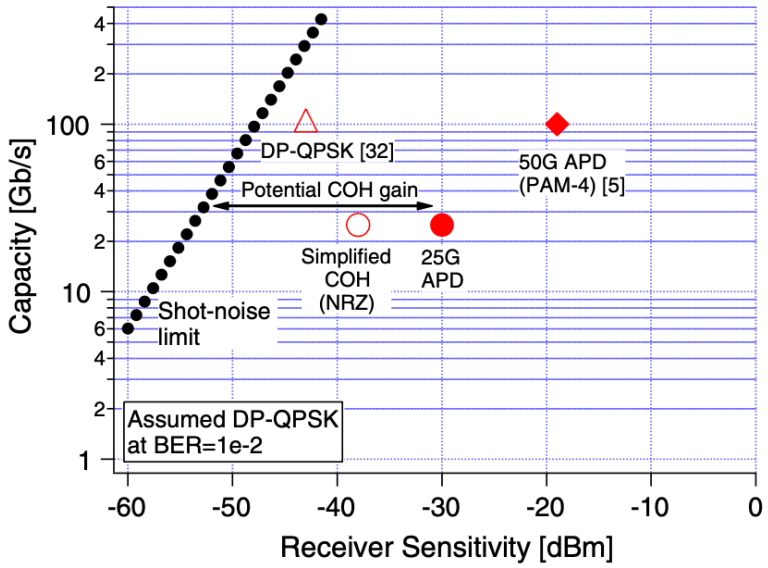


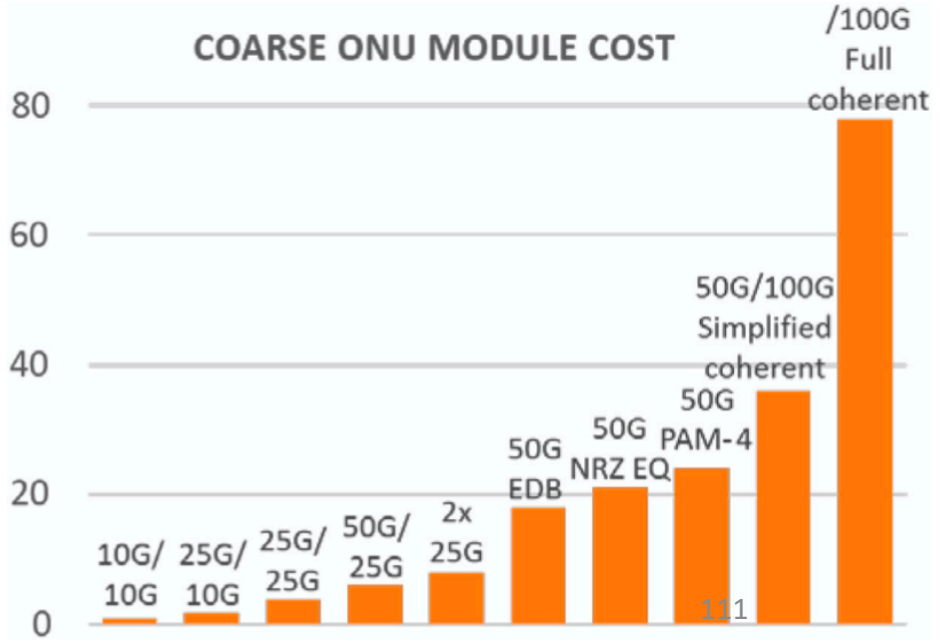
M. Tao et al., Improved Dispersion Tolerance for 50G-PON Downstream Transmission via Receiver-Side Equalization. OFC 2019

What about 100G?

- Single channel on direct detection not really an option due to severe chromatic dispersion and power budget
- Use of multiple wavelengths is an option (e.g., as with 50G EPON).
- However one big question is whether coherent technology could be used.
  - Cost has gone down and now we see coherent in the metro (about 10k for a 200G Tx/Rx)
- Advantages:
  - Use of 25Gbaud technology, with higher modulation formats
  - Compensate dispersion (and overall equalization) through DSP
  - Improve in power budget due to increase in sensitivity
  - Faster receiver tuning

D. van Veen, V. Houtsma, Strategies for economical next-generation 50G and 100G passive optical networks. JOCN, Jan. 2020

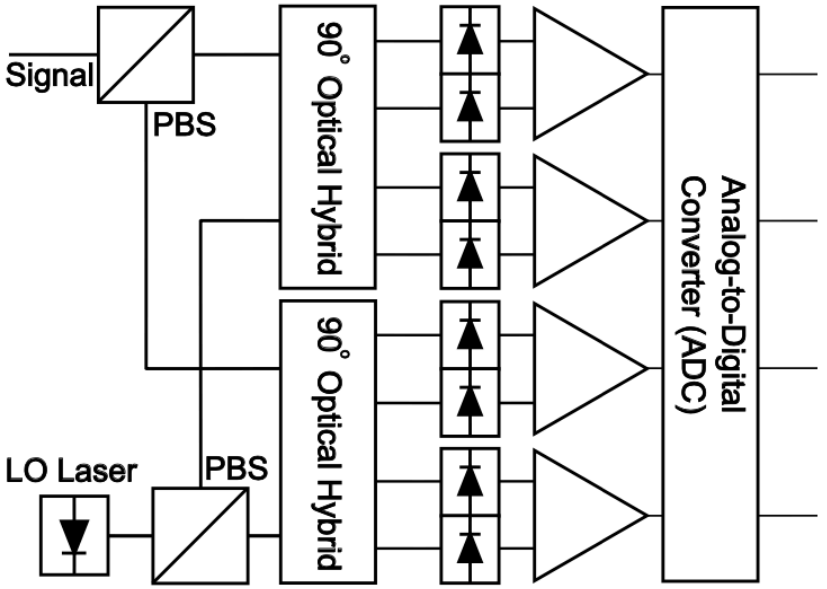




Coherent PON technology

Cost driven by the coherent receiver:

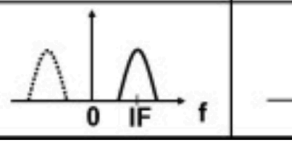
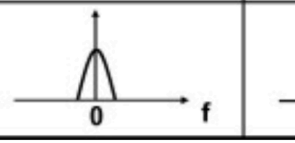
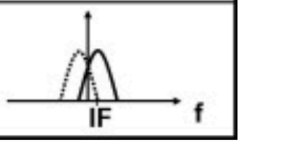
- 2 x polarization beam splitters (for polarization diversity)
- 2 x 90^{o} optical hybrids (for phase diversity)
- 4 x balanced photodetectors
- 4 x analog-to-digital converters (ADC)
- 1 x local oscillator laser (LO).



Full coherent receiver

Concept of coherent reception: local oscillator beats coherently with signal to extract phase information

- Homodyne: LO same frequency as signal and LO is frequency stabilized
- Heterodyne: LO at different frequency of LO signal and LO is frequency stabilized
- Intradyne: LO same frequency as signal but LO is free running. Phase error is compensated for digitally

Heterodyne	Homodyne	Intradyne
Analog optical PLL + DSP (frequency - stabilized LO)	Analog optical PLL + DSP (frequency - stabilized LO)	Digital phase compensation + DSP (free -running LO)
High multiplicity	High multiplicity	Low multiplicity
		

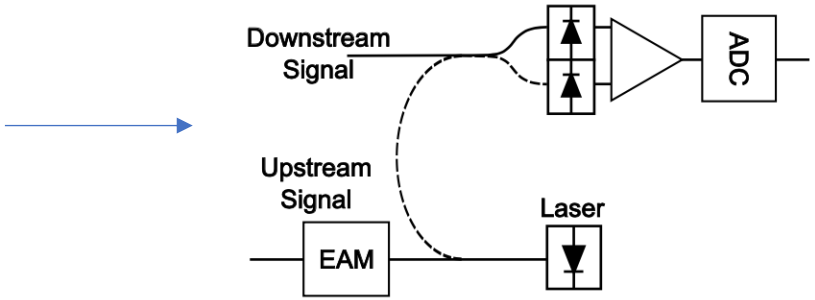
D Lavery et al., Opportunities for Optical Access Network Transceivers Beyond OOK, JOCN, Feb. 2019.

Optical Fiber Telecommunications Systems and Networks A. 6th Edition, 2013

Reduce cost of coherent receivers

For access networks, the idea is to reduce cost by simplifying the receiver:

- Use polarization insensitive architectures to remove the 90° optical hybrid
- Quasi- coherent detection: use LO to improve sensitivity, but only detect envelope (not suitable for higher-order modulation formats)
- Use the same laser for LO and for upstream transmission
- Reduce complexity of the ADC (lower resolution)

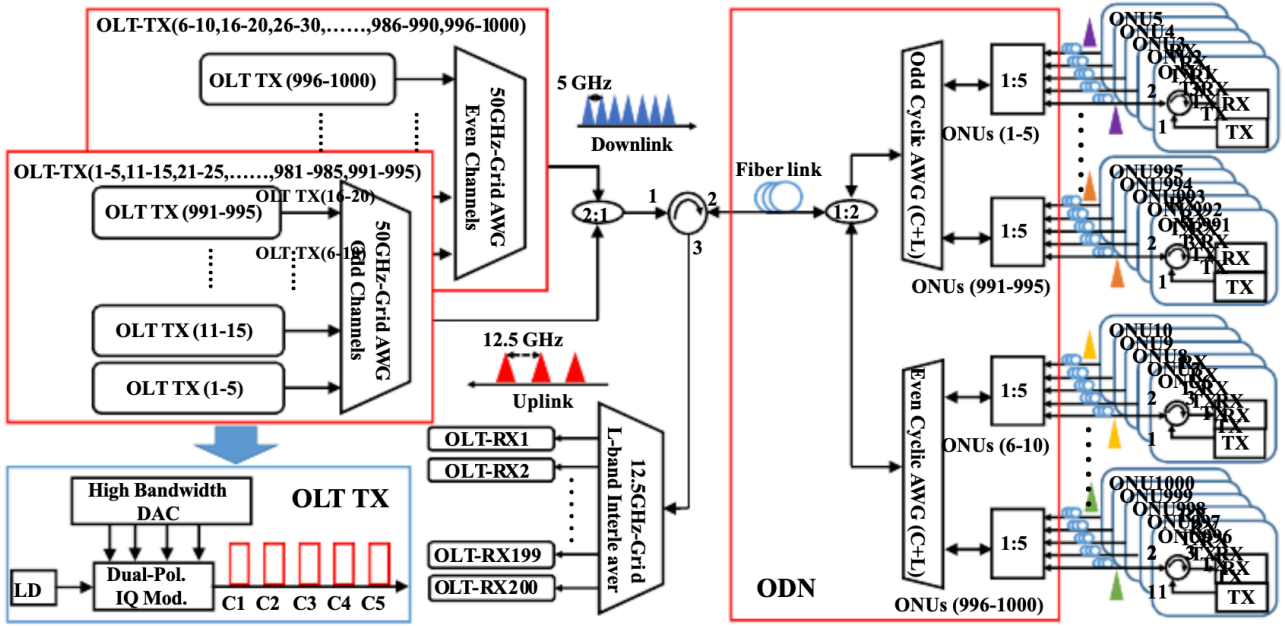


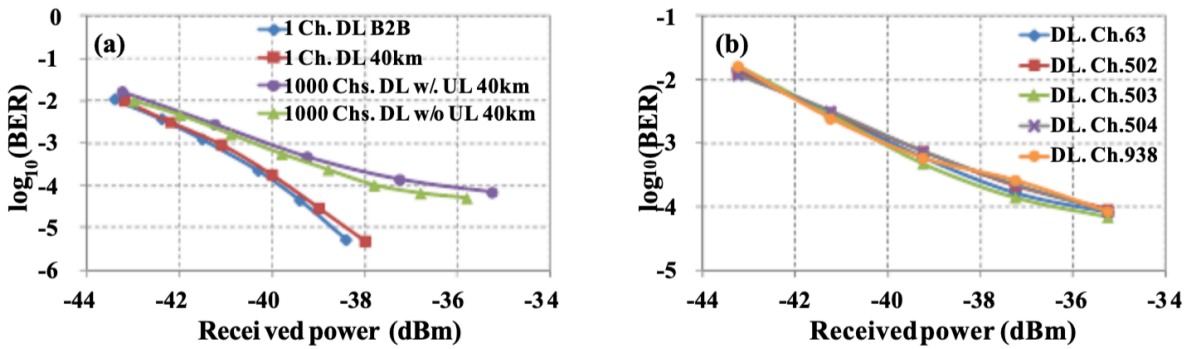
However they suffer from reduced sensitivity, higher bandwidth and still require expensive LO.

A different approach is to maintain the complexity of the receiver (with all its benefits), but reduce the number of electronic/digital components.
Take advantage of photonic circuit integration (exploit integration of silicon and III-V), such as micro-transfer printing.

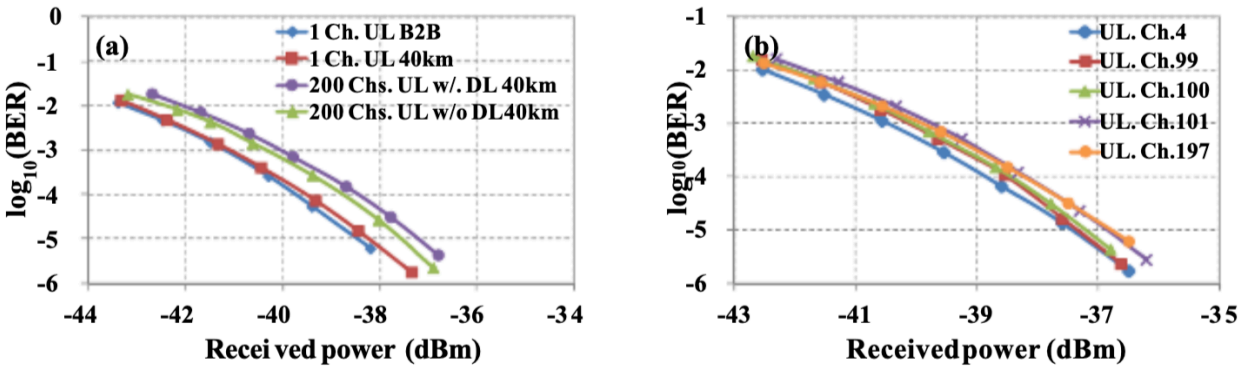
D Lavery et al., Opportunities for Optical Access Network Transceivers Beyond OOK, JOCN, Feb. 2019.

UDWDM-PON





Downstream performance



Upstream performance

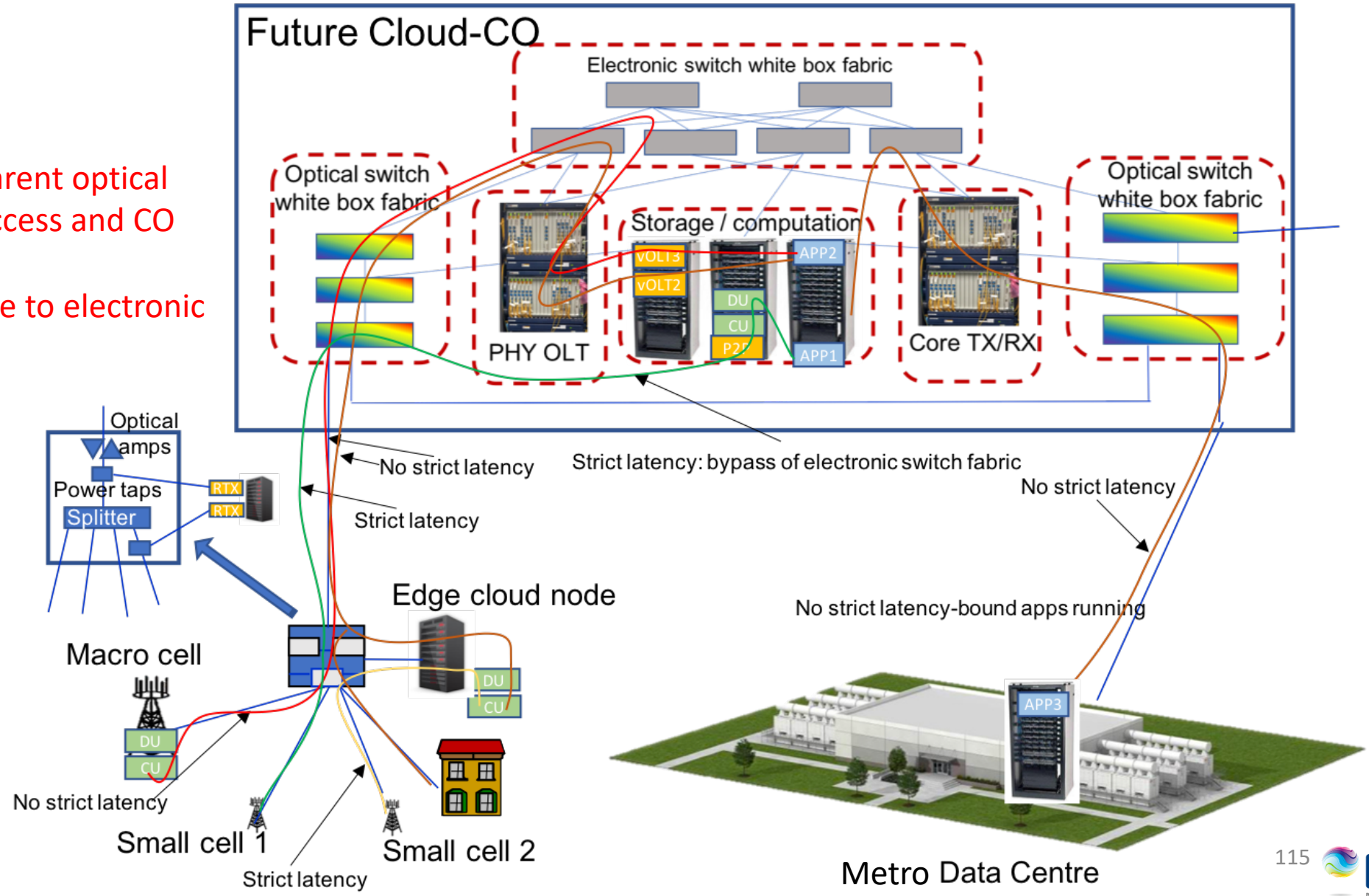
- 1000 individual wavelength channels downstream
  - DP-QPSK, 5GHz spacing 10Gb/s, C band, 28dB
  - PS-QPSK, 7.5Gb/s, 30 dB
- 200 channels upstream with TDM
  - 12.5GHz spacing, DP-QPSK, 10 Gb/s, L band

Real-time bidirectional coherent ultra-dense TWDM-PON for 1000 ONUs. J. LI et al., Optics Express, Sept. 2018.

Sample use case: convergence of mobile, optical and cloud

Orchestration of transparent optical connections between access and CO

Reduce latency/jitter due to electronic switching, etc.



Sample use case… cont'd

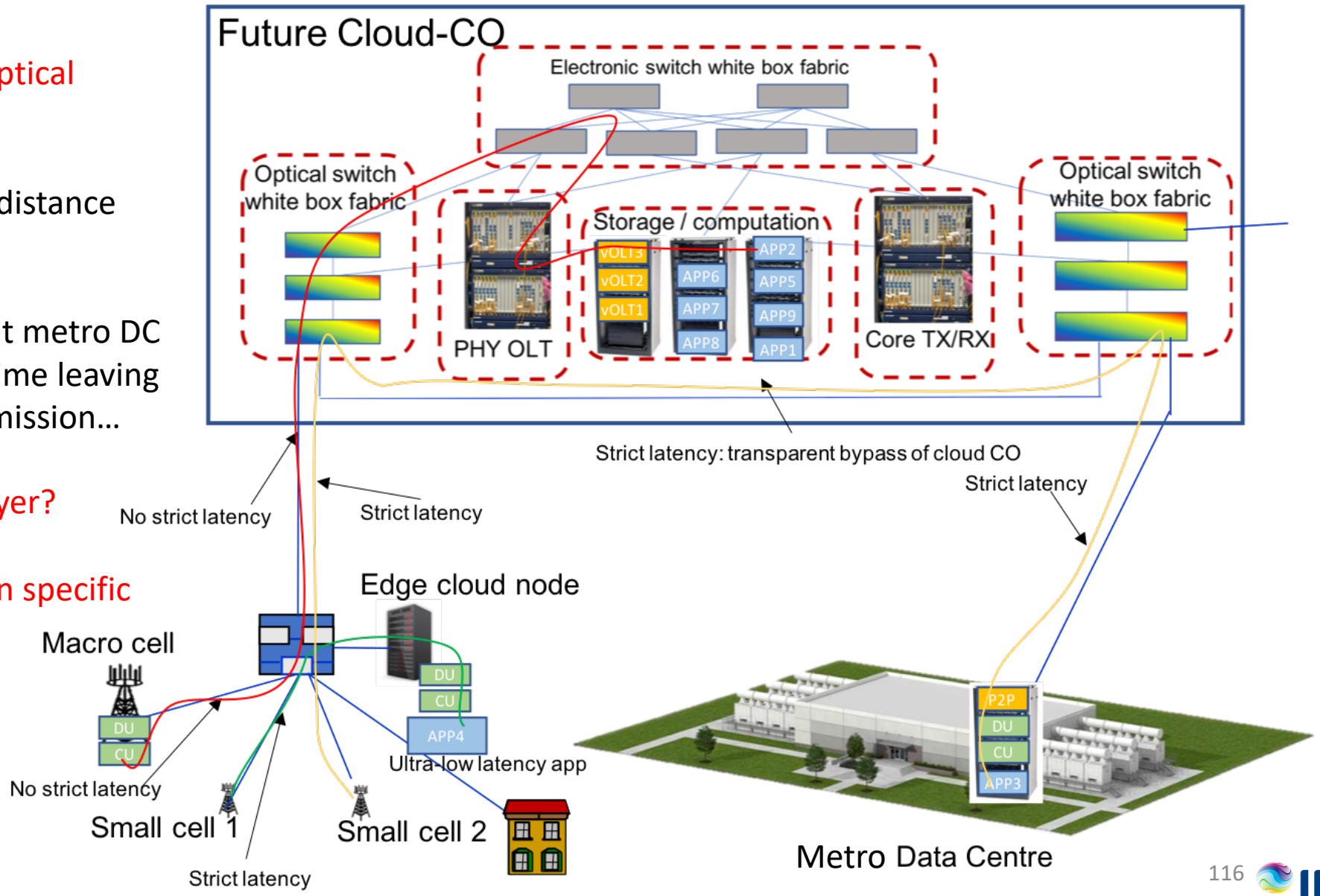
Orchestration of transparent optical connections across the metro

In principle metro data centre distance limited to 40 km by latency…

…but more processing power at metro DC can decrease VNF processing time leaving more latency budget for transmission…

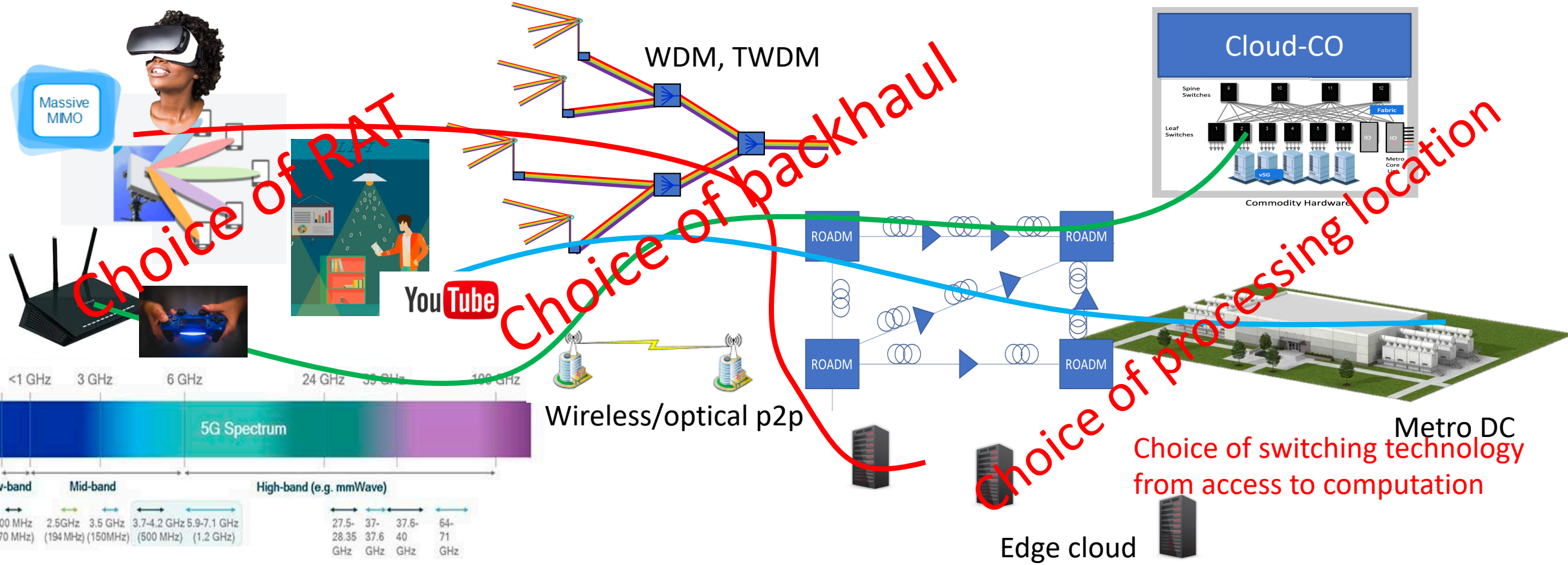
Need to open up the optical layer?

Surely need to be able to assign specific (e.g., powerful) resources as needed



We are considering the horizontal orchestration

- Interconnect multiple domains, each with multiple technologies



Choice of switching technology from access to computation

Technologies are so different and variable that end-to-end statistical characterisation might be the only option

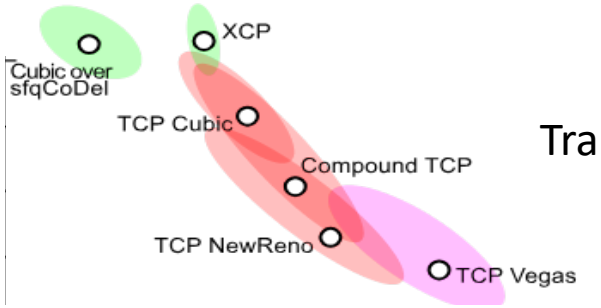
What about the vertical orchestration?

In addition to orchestrating physical domains.. orchestrate the protocol stack…

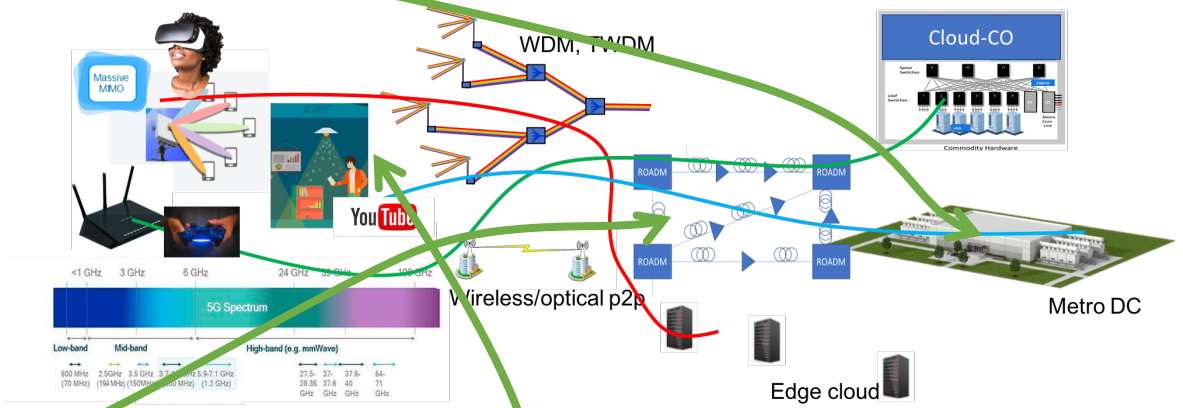
Link with function placement

Cooperate with Horizontal Orchestration

Application coding

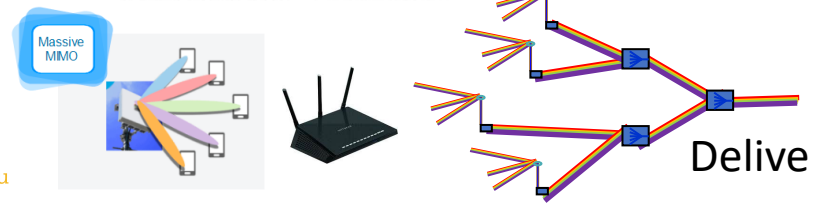


Transport protocol



Link with the network path selection

Route selection



Delivery technology

Link with access technology

Content of the talk

- Evolution of access networks from DSL to full optical
  - DSL, FTTCab, FTTDp
  - Fibre: point-to-point, TDM-PON, WDM-PON, TWDM-PON
  - (Don't forget DOCSIS)
- Access network sharing
  - LLU, SLU, bitstream
  - VULA, NGA bitstream
  - PON unbundling?
- What are the new requirements for 5G?
- The network virtualisation
  - SDN, VNF, slicing
  - CORD, SEBA,
  - Full PON virtualisation
- Enabling convergence of fixed and mobile (and now edge cloud)
  - Densification, functional split,
  - A converged demo
- Physical layer innovations
  - Higher rate
  - Coherent PON, UD-WDM-PON

Questions?

CONNECT
Centre for Future Networks

Thank you for your attention!

Marco Ruffini
CONNECT / The centre for future networks and communications
The University of Dublin, Trinity College, Ireland
marco.ruffini@tcd.ie, www.marcoruffini.com
skype: ruffinim