New Broadband Normal

NBN

Melbourne IEEE Communications Society, RMIT
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With special thanks to **Dr. Ioannis Kanellakopoulos**

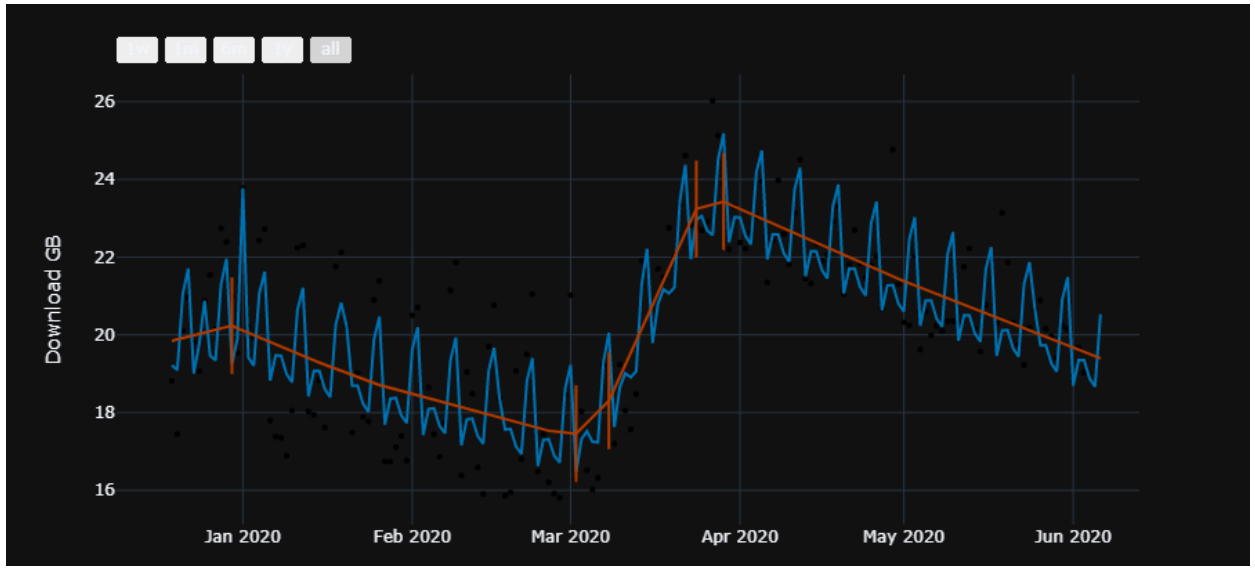
Reliably Fast Broadband & Wi-Fi for the Home

Agenda/Outline

- The Pandemic-induced “new normal”
  - National Broadband Network ≙ *nbn* existing
  - → New Broadband Normal ≙ **NBN** future
- Spectrum and Space (Wireless Dimensionality) and “CSL”
- Convergence and channelization
- Ergodic Spectrum Management (AI-based QoE management)

NBN Data Traffic

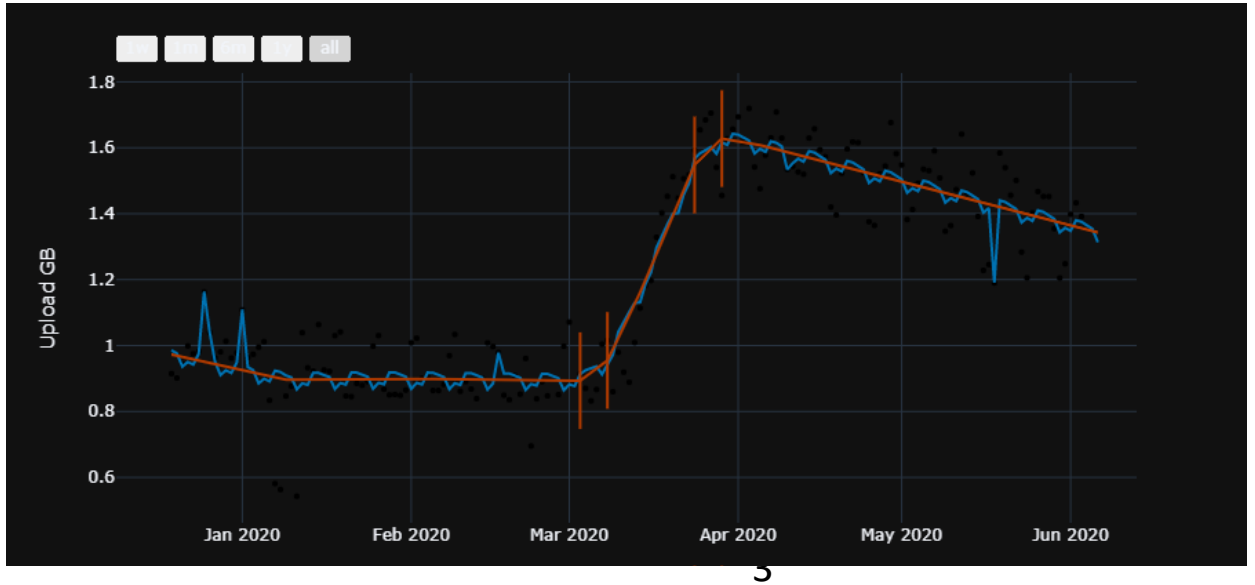
Downlink
daily
averaged



Minimum increase (NA Operator)

Range: 30-50% increase

Uplink
daily
averaged



Maximum increase (EU Operator)

Range: 50-100% increase

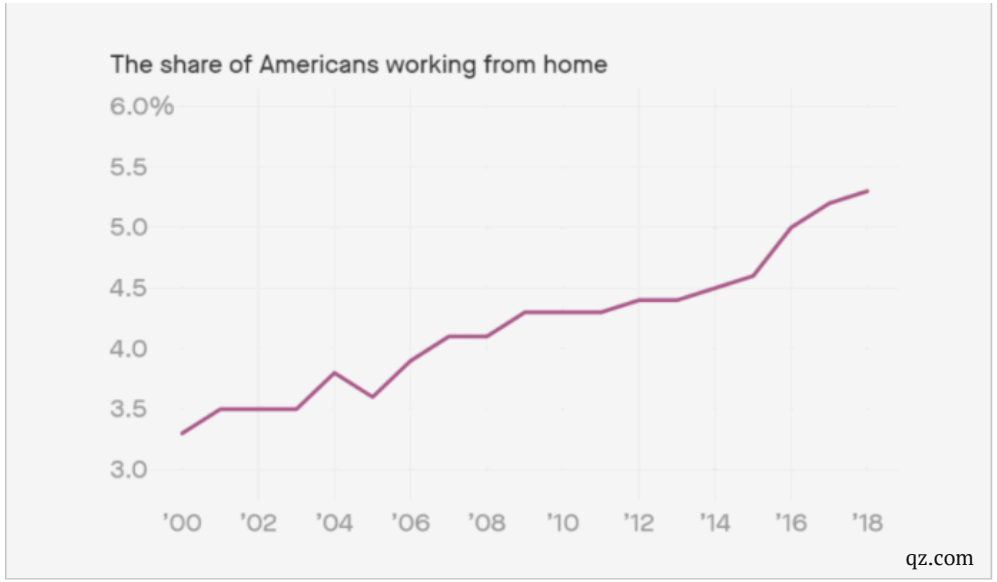
Drivers to New (broadband) Normal of increased use?

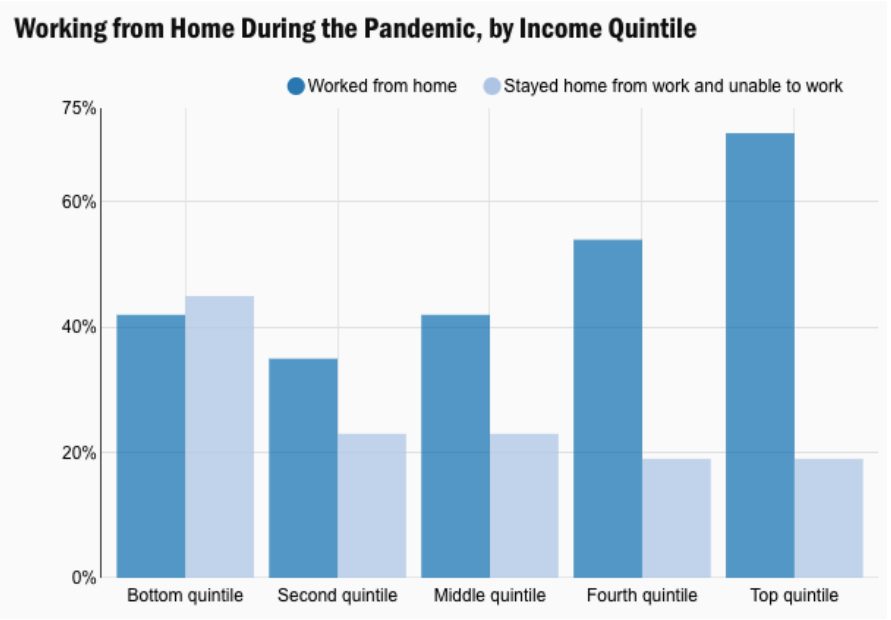
- Large number of employees working from home
  - Trend is highest among professionals
  - More uplink traffic (speakers and video)
- Employees downloading/uploading more work files
- Students viewing on-line lessons
  - Stanford Spring Quarter 2020, 6,000 student survey
    - 4/5 said productivity reduced by online somewhat
    - 1/6 said the issue was poor broadband connection
- Entertainment (those with more time suddenly and no where to go)
- Telemedicine
- Tele court system …

NBN Telework Acceleration

more teleworkers in residential access

will pay more for higher-grade solution





Telework 6 % → 50+ % in pandemic

NBN: Remain 30+ % after pandemic

Reeves and Rothwell (2020)

Telework & ability-to-pay strongly correlated

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Some Australian data rates

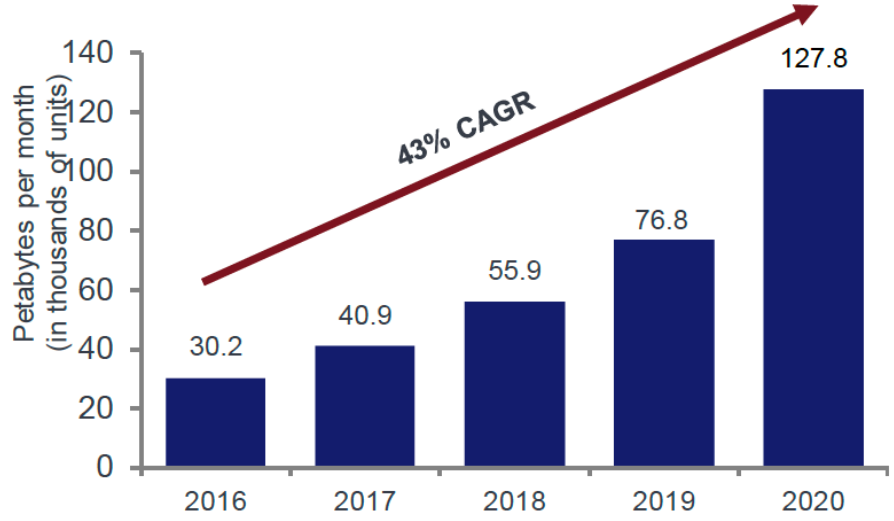
Table 2. [Telstra] Estimation of bandwidth requirements by application (Mbps)

Application category	Downstream bandwidth in 2015	Assumed CAGR (%)	Downstream bandwidth in 2020*	Downstream bandwidth in 2025
Basic Internet	2	25	~6	~20
Home Office/VPN	16	30	~60	~250
Cloud computing	16	30	~60	~250
State-of-the-art media and entertainment (4k, 3D, UHD)	14	20	~40	~90
Progressive media (8k, VR)	25	30	~100	~300
Communication	1.5	20	~5	~8
Video communication (HD)	8	15	~10	~25
Gaming	25	30	~100	~300
E-Health	2.5	30	~10	~50
E-Home/E-Facility	2.5	30	~10	~50
Mobile Offloading	2	30	~10	~15

Source: WIK. *Calculated by Telstra from WIK data

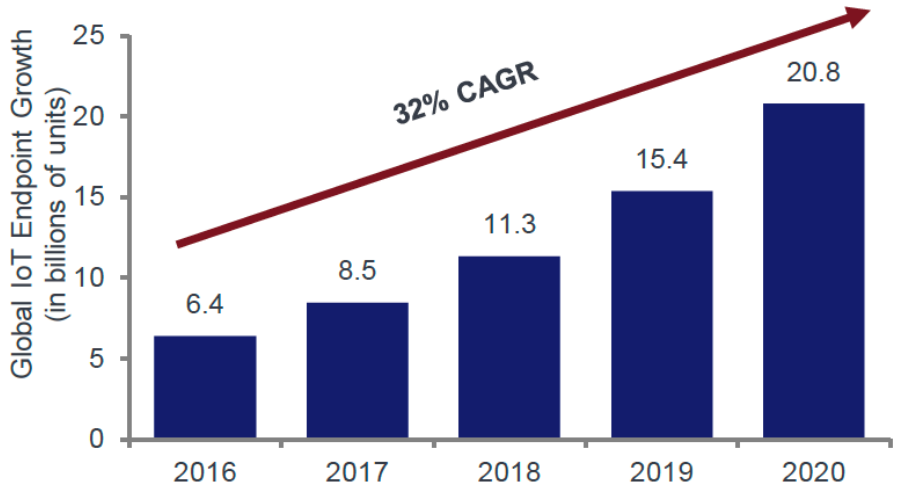
Not to mention the usual internet-traffic drivers

Global Consumer Video-related Internet Traffic Growth(1)



As video-related internet traffic grows, so does the need for increased internet bandwidth and speed

Global IoT Endpoint Growth(2)

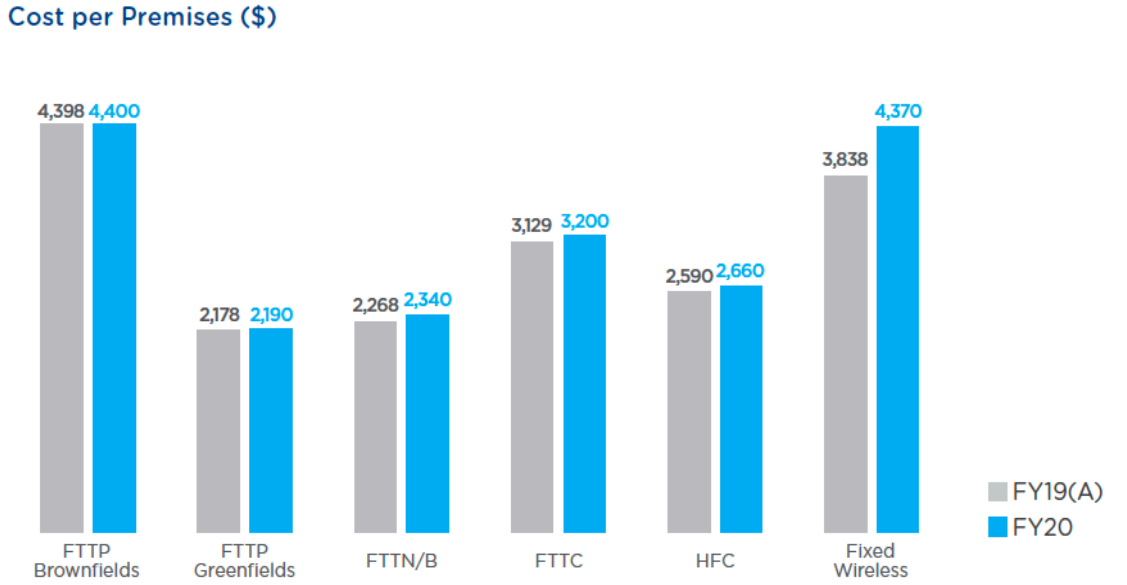


The number of devices connected to the Internet, including machines, sensors, and cameras that make up the Internet of Things (IoT), continues to grow at a steady pace. The growth of IoT has resulted in a complex system that has placed increased strain on broadband connections

Source: 1) Cisco, 2) Gartner,

More applications, more traffic, more devices

nbn – 2019 Annual Report



2018 – DT CEO T. Hoettges estimates 300-500B Euros to deploy 5G within EU

Table *nbn* technology mix at end of initial rollout

Access Technology	Premises Passed ("Ready to Connect")		Capable at 100 Mbps or above
	Number (million)	Proportion of total premises (%)	Proportion (%)
FTTP (brownfields)	1.1	9.5%	100%
FTTP (greenfields)	0.9	7.8%	100%
HFC	2.5	21.6%	100%
FTTN/FTTB	4.7	40.5%	FTTN 24% FTTB 100%
FTTK	1.4	12.1%	100%
Fixed Wireless	0.6	5.2%	0%
Satellite	0.4	3.4%	0%
Total	11.7	100%	

Broadbar
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ber 2020
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Report of Australia's Broadband Futures Project 2020

- FTTP and 5G fixed are most expensive
  - Others all use copper
- Existing nodes/cabinets already have fiber
  - cost is much less (obviously)

Spectrum and Space (wireless dimensionality)

CSL = Cellular Subscriber Lines*

Reliably Fast Broadband & Wi-Fi for the Home

*__Cellular Subscriber Lines__, J.M. Cioffi, C.S. Hwang, I. Kanellakopoulos, J. Oh, K. Kerpez, ***Invited Paper*** to appear in IEEE Transactions on Communication, 2020.

Dimensionality in Wireless

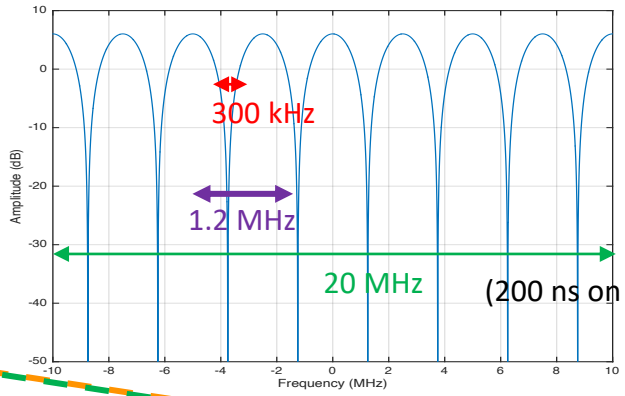
- Time-Frequency
  - 2 x time x bandwidth = # of dimensions

2G

3G

4G / Wi-Fi

5G



(200 ns on 2nd path)

LTE – "Resource Blocks"

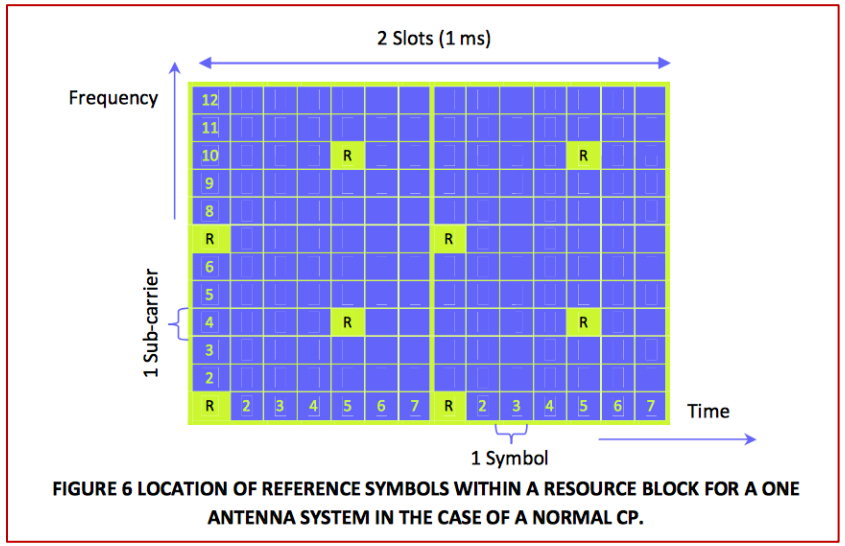
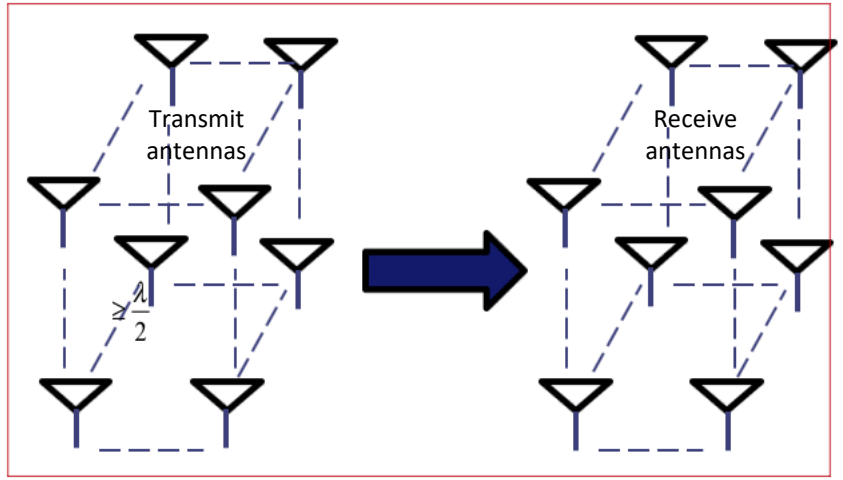


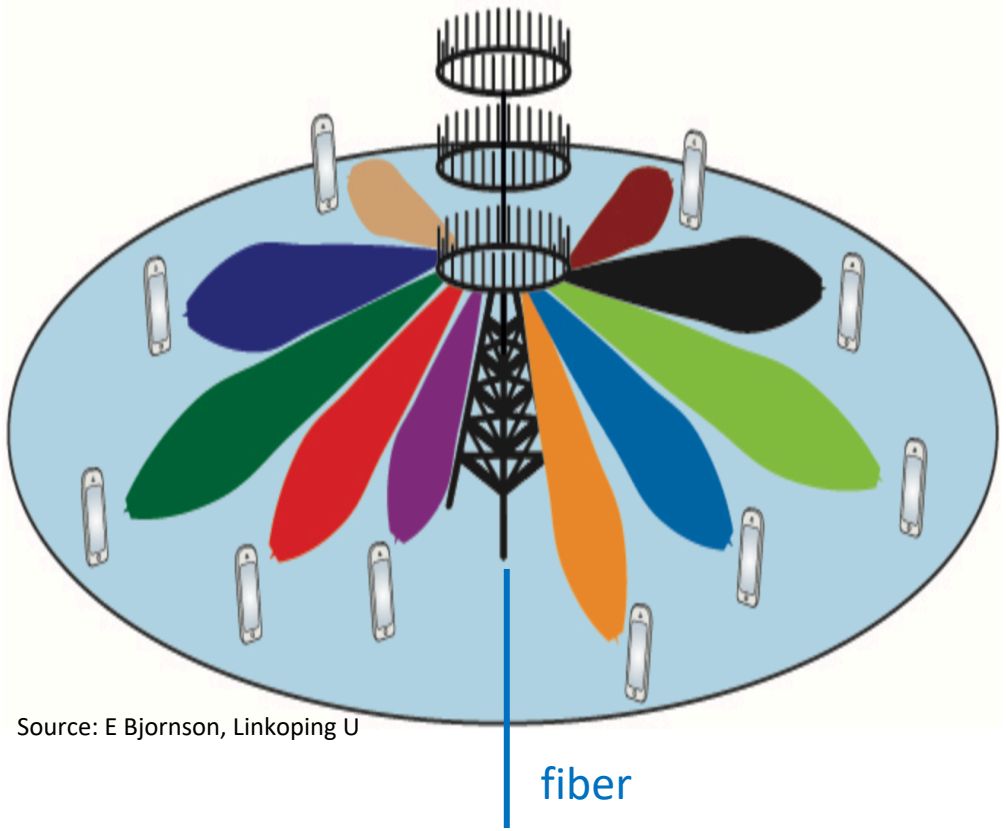
FIGURE 6 LOCATION OF REFERENCE SYMBOLS WITHIN A RESOURCE BLOCK FOR A ONE ANTENNA SYSTEM IN THE CASE OF A NORMAL CP.

- Time-Space
  - 3D (at least …..)
  - Spacing of half wavelength or more
  - Wavelengths are getting small (cm to mm
  - Can time-schedule spatial-dimension use
  - Number of channels can be up to # of antennas "streams"



5G MU-MIMO migration (cost paths)

5G Massive MIMO ; radius r_{5G} → small (more fiber)



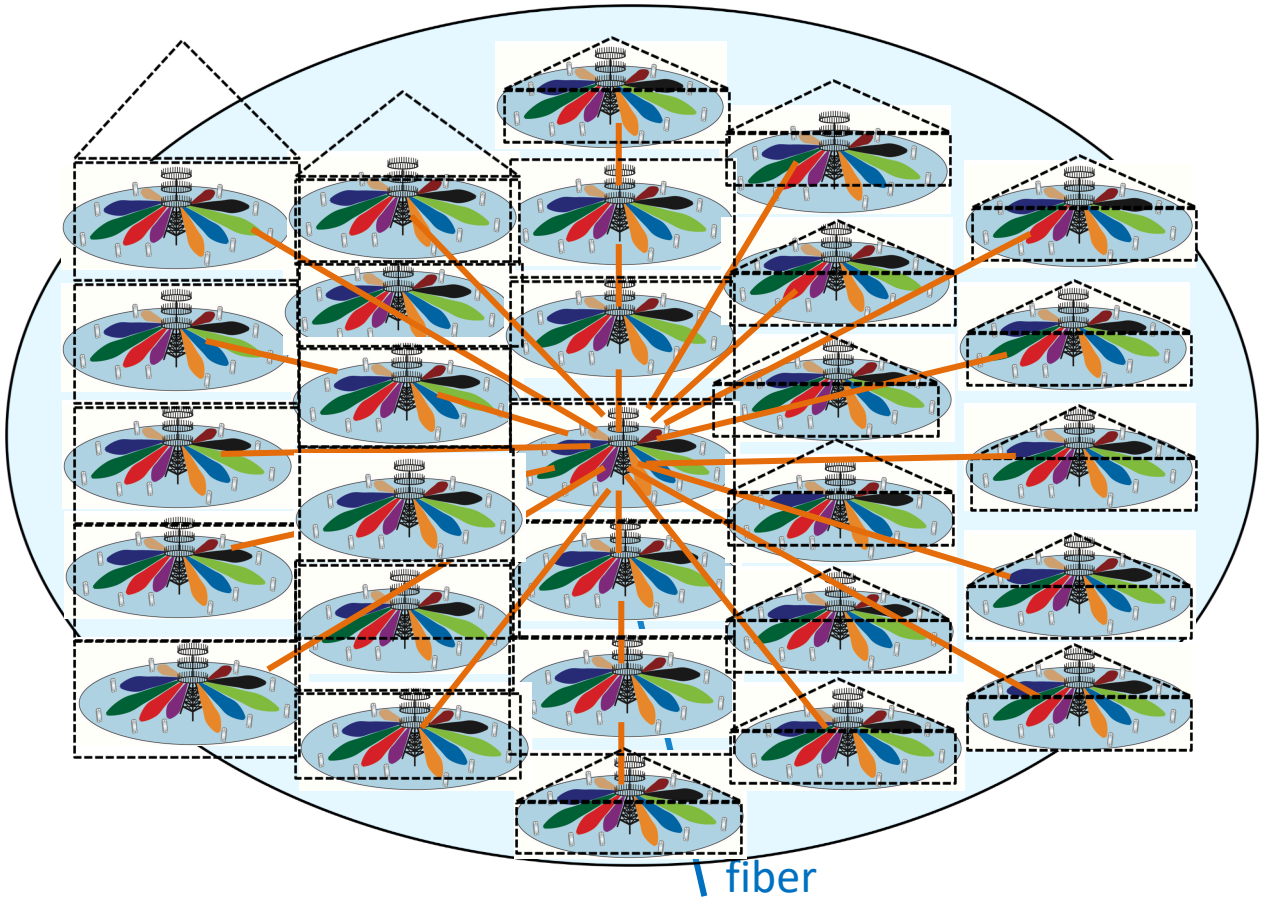
Source: E Bjornson, Linkoping U

fiber

Center is connected to Mobile Edge Computing (MEC)

- higher-power antenna arrays
- difficult arc/beam carving (co-linear interference issues)
- needs fiber to each antenna array (expensive for smaller cells / mmW)

Cellular Subscriber Lines (CSL) r_{CSL} very small (copper)



fiber

Each of these smaller "cells" is at end of copper in a building

- lower power, smaller antennas
- inside home or business
- copper link IF is part of the small-cell link
- Massive MEC (& cloud) → more efficient space & spectrum

CSL: 10x more data for 10% of the cost and 1% of the power

- User advantage is $N_{user} \propto \left(\frac{r_{CSL}}{r_{5G}}\right)^2$
  - If $r_{5G} = 200m$ and $r_{CSL} = 20m$, Then $N_{user} \rightarrow 100\times$
    - Requires good cloud/edge management
  - Path loss is less: loss $\propto \left(\frac{r_{CSL}}{r_{5G}}\right)^{\alpha}$ where $\alpha = 4$ (maybe even 5), considering in-home.
  - Despite 100x as many antennas, total driver power is significantly less
    - Cheaper antennas
    - Better spatial resolution
- Much higher use of available resources
- It costs significantly less and provides a higher performance level
  - And NBN can use the *nbn* node architecture already built
- CSL = "Massive Distributed Antenna System" – many more cheap antennas
- Mobile spectrum outdoors, with longer distances, still also also available
  - With appropriate adaptive spectrum management

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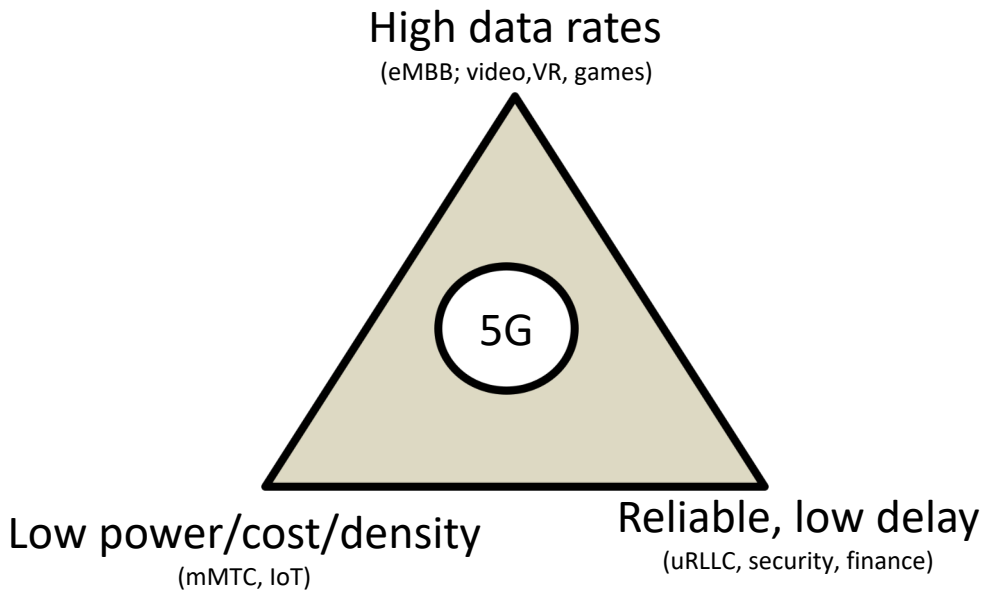
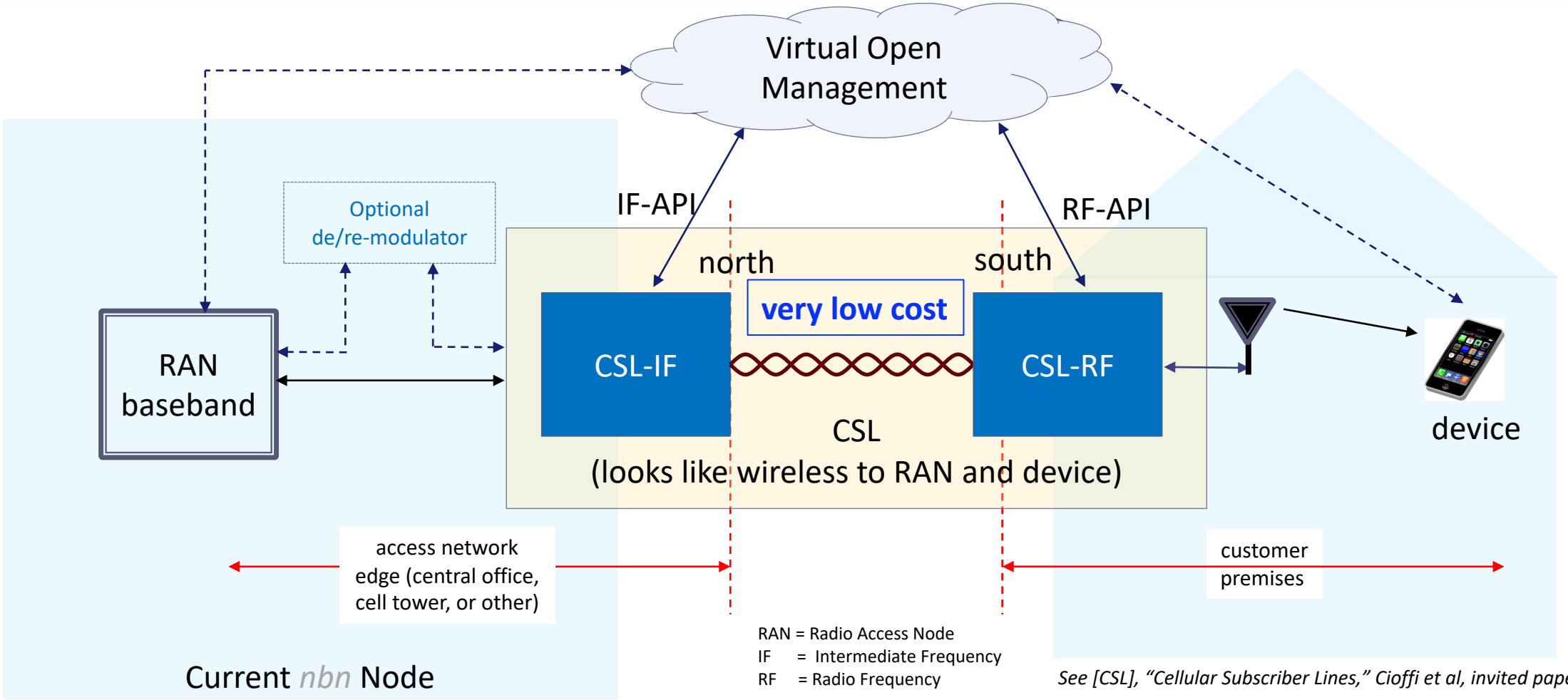
5G Challenges Table (vs CSL)

- Well-known 5G triangle
- Compare with CSL



5G	CSL
mMTC (**m**assive **M**achine-**T**ype **C**om)	Creates 100x more base stations at lower cost Reduces power by 100x Increases density by 10x to 100x
eMBB (**e**nhanced **M**obile **B**road**B**and)	Supports 100 Mbps range to more places inside (and outside) home
uRLLC **u**ltra **R**eliable **L**ow-**L**atency **C**om	< 1ms latency ; requires good cloud and edge mgmt
Long deployment cycle	Sooner

CSL keeps all the nice 5G system! - just adds a simple IF

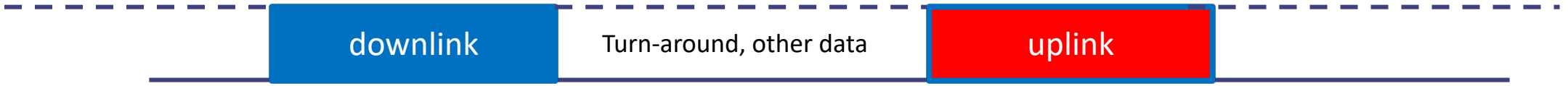


See [CSL], "Cellular Subscriber Lines," Cioffi et al, invited paper IEEE Com Trans, soon

- The baseband wireless link now includes the copper baseband
  - Which (usually) has less attenuation than same-length wireless link
  - Analog amplification possible CSL-RF
  - Multiplex several cellular spatial streams on single wire

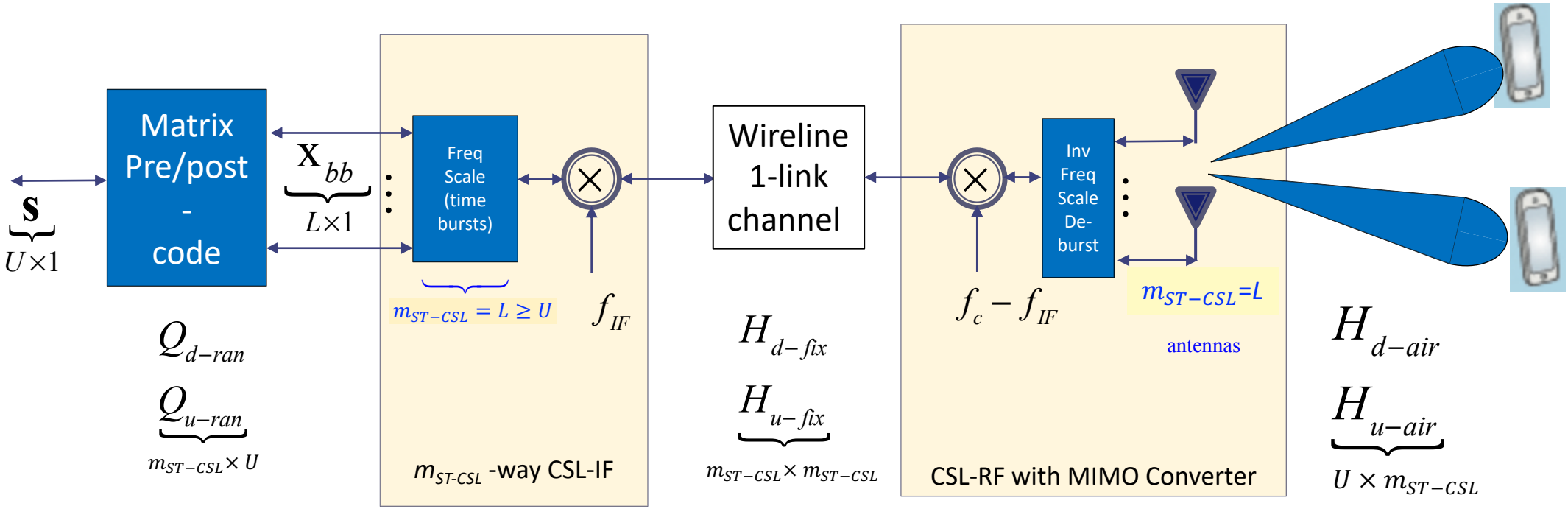
Time-Domain Burst Format (frequency-scaled in baseband)

- Runs at 8/3 3GPP bandwidth



- Low latency option << 1ms
- Turn-around time has “much extra” for other service
- Performance pretty close to best xDSLs (G.fast, etc) anyway [CSL]

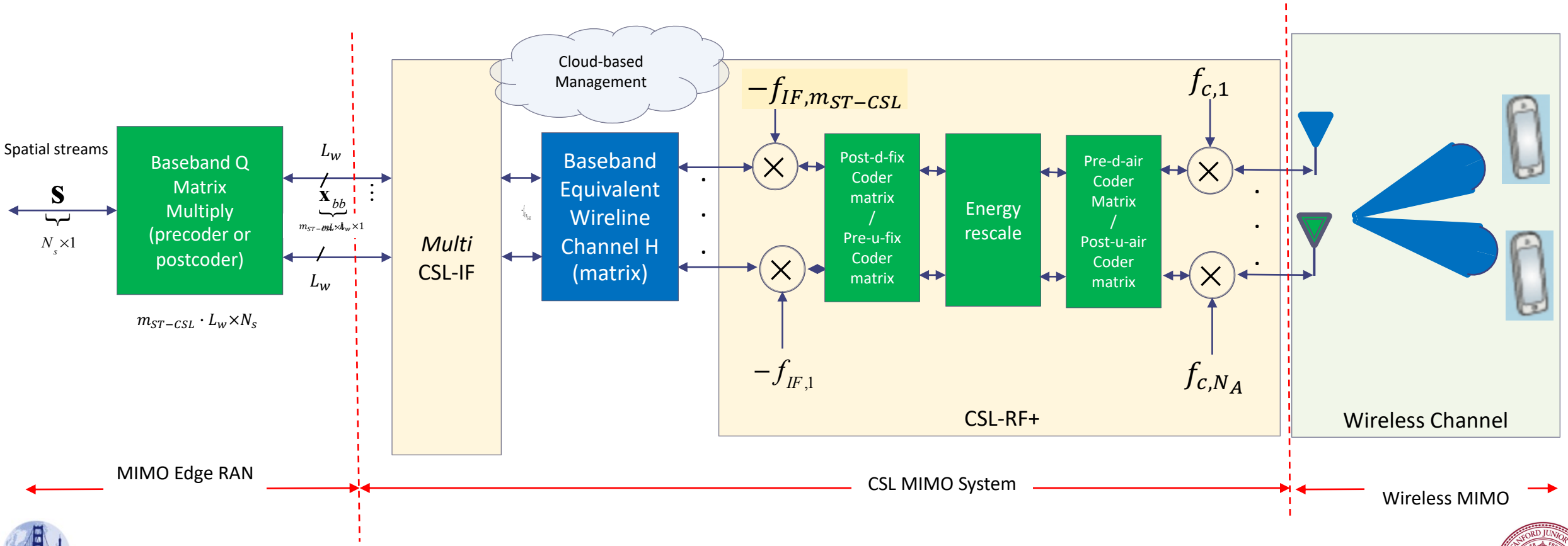
Multiple spatial streams can share one line



- MIMO processing full power on only the final wireless link
  - Better performance because there is no crosstalk from other spatial streams on the single line
- There can be crosstalk from other CSLs on other single lines in same binder

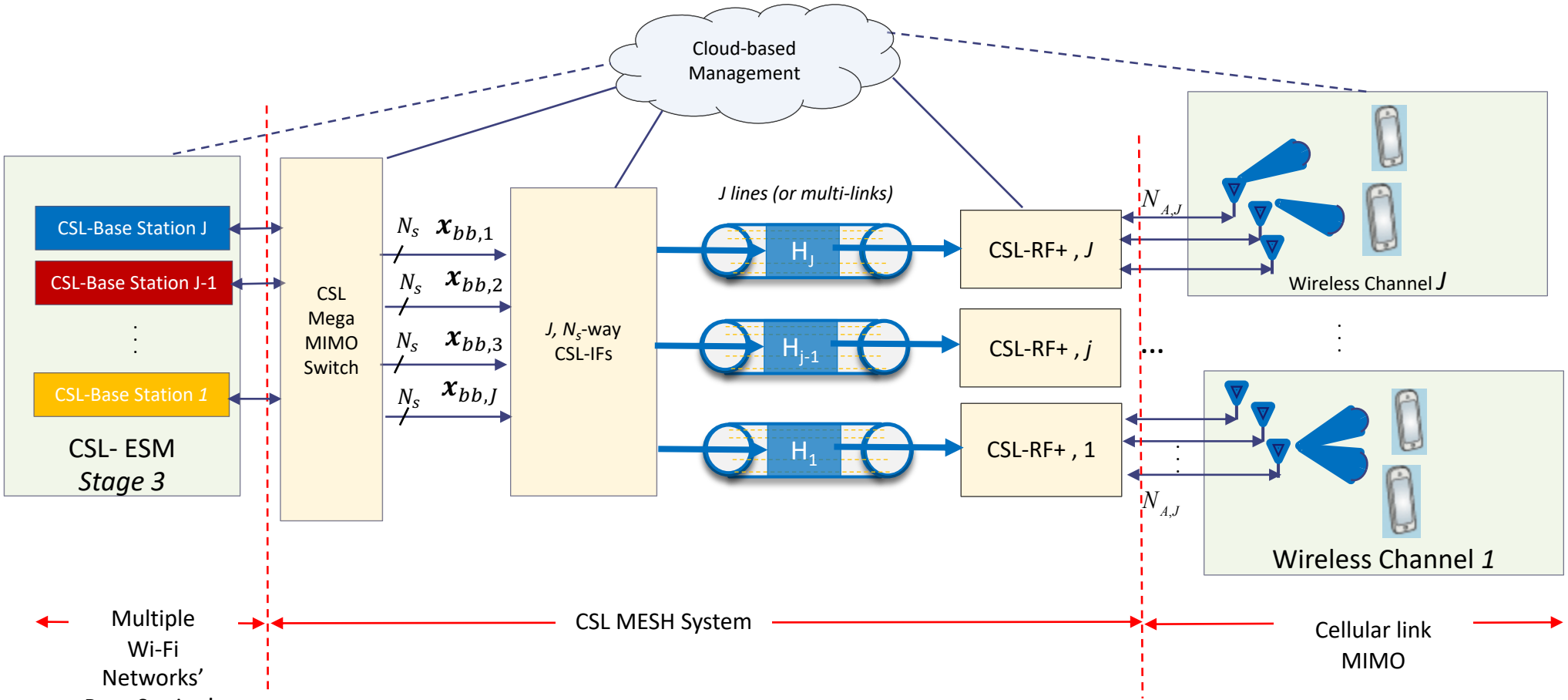
Multi-Link CSL?

- There can be crosstalk between CSL lines
- Unused copper lines to one place? - Bond them together
- Multiple antennas still low power, but their effect can be magnified



Mega-MIMO (puts it all together)

- Many Massive MIMOs
- CSL Switch allows very flexible spatial use
  - Overlapping homes can assist each others



Convergence and Channelization

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But *nbn* has no spectrum?

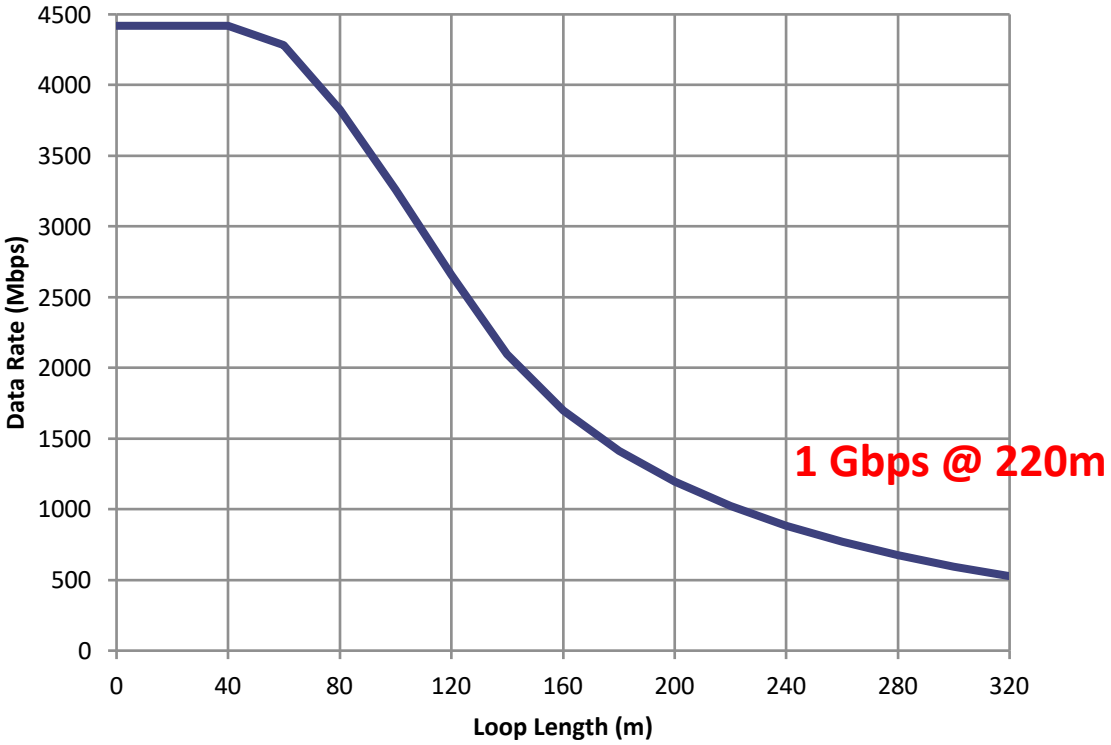
- **NBN** probably will!
  - 5G-NRU allows (cognitive) use of unlicensed bands
  - 6 GHz (Wi-Fi6e) band increasingly unlicensed (all, or in part)
- 5G-NRU
  - Allows use of 3GPP channelization in unlicensed bands
  - TDD will allow flexibility in deciding use of spatial streams

Table 3 – 3GPP channel bandwidth's corresponding wireline lengths		
3GPP Channelization	CSL Baseband Spectrum	Max twisted-pair length
1 MHz[1]	500 kHz – 5 MHz	2 km
3 MHz	500 kHz – 12 MHz	1.5 km
5 MHz	500 kHz – 25 MHz	1 km
10 MHz	500 kHz – 50 MHz	500 meters
20 MHz	500 kHz – 125 MHz	200 meters
100 MHz	50 - m0 kHz – 625 MHz	100 meters
200 MHz	500 kHz – 1250 MHz	50 meters
400 MHz	500 kHz – 2500 MHz	20 meters

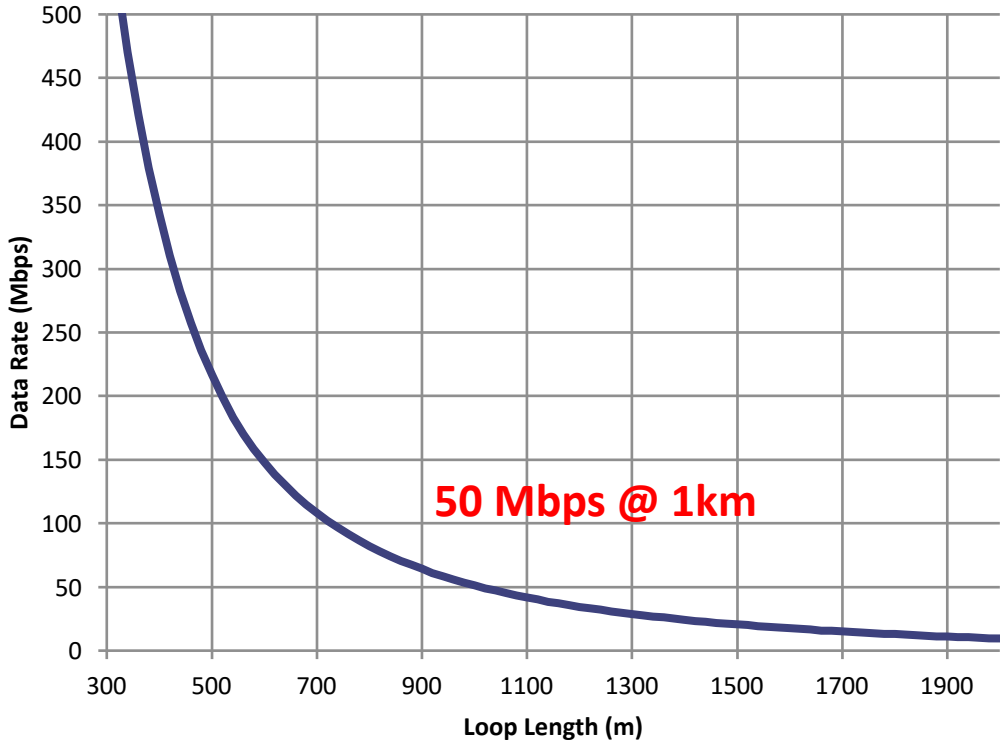
[1]or 1.4 MHz exactly

Data Rates (down plus up)

Shorter-line **NBN** nodes



Longer-line **NBN** nodes



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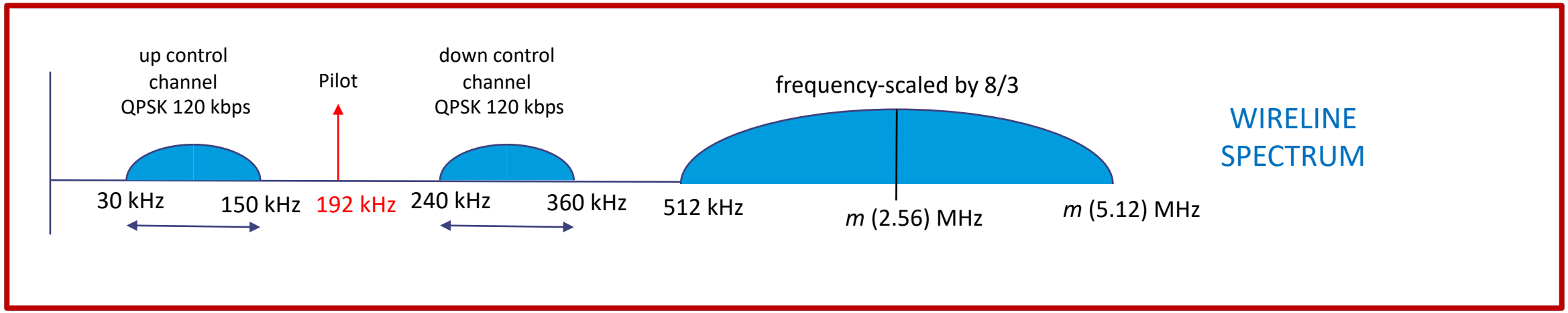
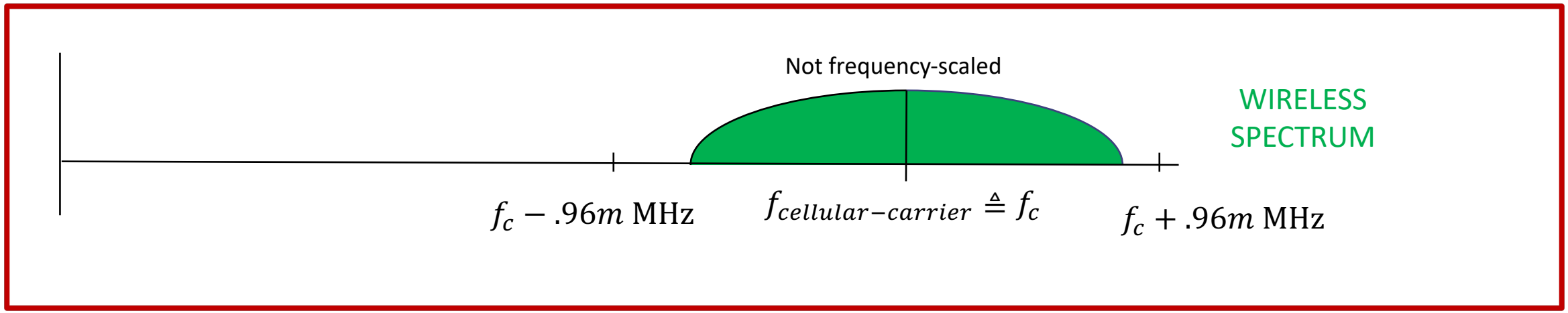
IF and RF passband spectra





Some Practical Issues (see [CSL])

- Timing alignment of distributed antennas/cells
  - IEEE 1588 system, CSL system measures its own delay and adjusts to 1 symbol
- Knowing widest usable band
  - Loop-back sounding used with baseband chirp in off-line maintenance/training mode
- Non-5G/cellular compatible devices (namely Wi-Fi, IoT)
  - Reserves ~20% of digital bandwidth (in TDD) for non-cellular data signals continued use while cellular in use
  - All available while not in use

Ergodic Spectrum Management[2] (ESM)

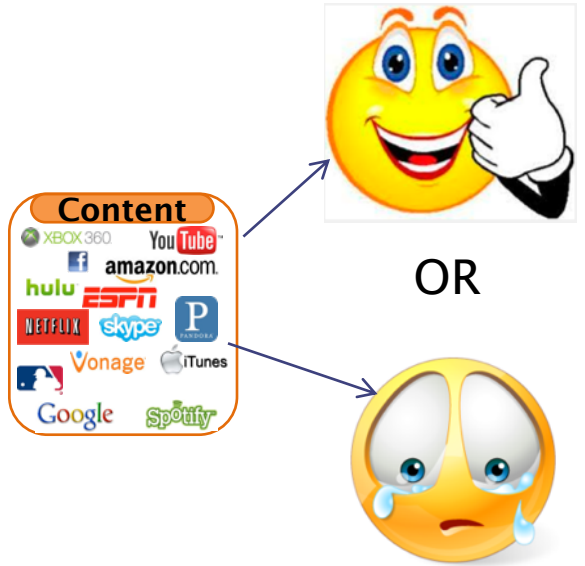
managing resources and QoE

Reliably Fast Broadband & Wi-Fi for the Home

[2]J. M. Cioffi, C.-S. Hwang and K. J. Kerpez, "**Ergodic Spectrum Management (ESM), *invited paper,"*** *IEEE Transactions on Communications,* vol. 68, no. 3, pp. 1794-1821, March 2020.

QoE or QoS?

- **Quality of Experience = QoE**
  - Customer complaints
    - Calls
    - Chatbots, Chat rooms, …
  - Mean Opinion Scores
  - Like or (“not like”) buttons
  - Churn (drop or switch service)
    - Including abandon page/app



- **Quality of Service = QoS**
  - Packet Error Rates
    - Bit error rates
  - Outages (or retrains)
  - Data rates
  - SNRs (signal to noise ratios)
  - RSSI (received signal strength indication)
  - Efficiency in bits/Hz or bits/area

Today's Example

- Workers/collaboration on a videoconference call
- The connection is bad so one person's voice becomes unintelligible (or dropped)
  - All workers productivity/value consequently reduces
- CSL system would allow failover to another wireless path
  - If either path (full wireless or cascade of wires/wireless) is not functioning well
  - If each has 10% probability of independent outage, then overall is 1%
- An issue in building next-generation broadband is "who pays"
  - Employers will value better work-from-home productivity of their employees
  - This is QoE value (learned function of QoS)

BUFFER RAGE: An another QoE Metric

50% of Internet Users Experience ***Buffer Rage*** Daily

(December 2018 FWA Survey)

Buffer Rage = "a state of uncontrollable fury or violent anger induced by the delayed or interrupted enjoyment of streaming"

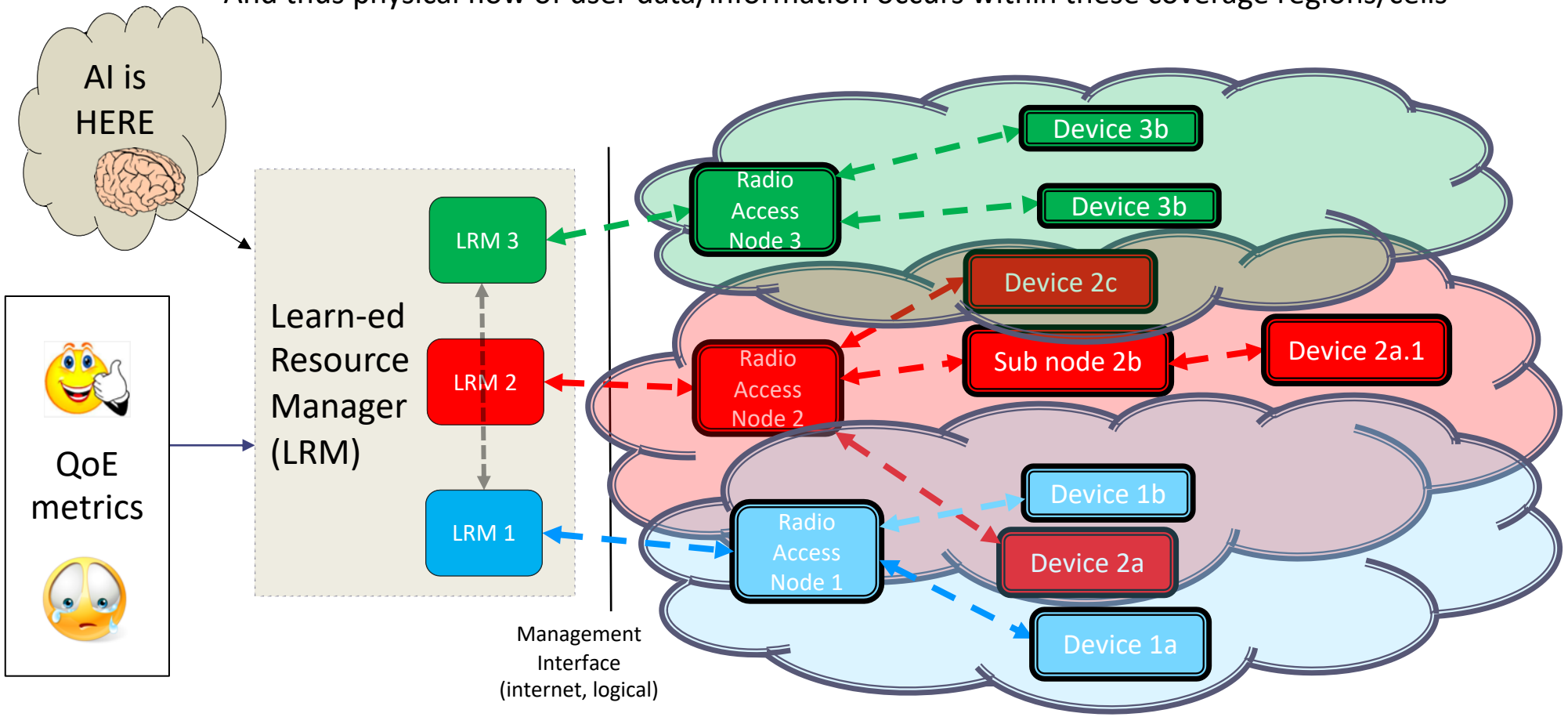
https://thefwa.com/cases/buffer-rage

- Despite LTE rev16 4G, 5G-NR, Wi-Fi 6 (11ax), fiber proclamations, etc
- Despite convergence (Wi5G, LAA, etc) and SDNFV
- Often the QoS metrics may meet targets, but still low QoE

LTE= Long Term Evolution (wireless standard from 3GPP group)
NR = New Radio ; LAA = Licensed Access Assist
SDNFV = Software Defined Network Function Virtualization

Overlapping Wireless Coverage Challenge

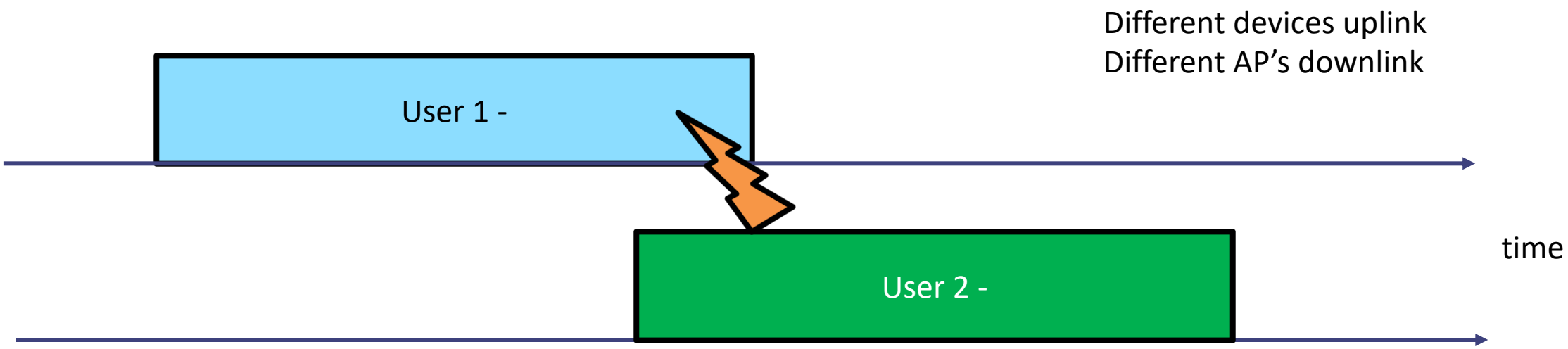
Shaded clouds represent radio coverage for the radio nodes (blue 1, red 2, green 3),
And thus physical flow of user data/information occurs within these coverage regions/cells



Dashed line indicates management information flow

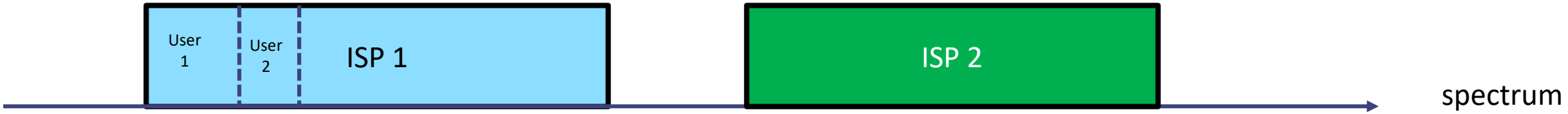
Does all resource management have to be very high speed and at the edge? (No)

Wi-Fi is a Collision-based protocol



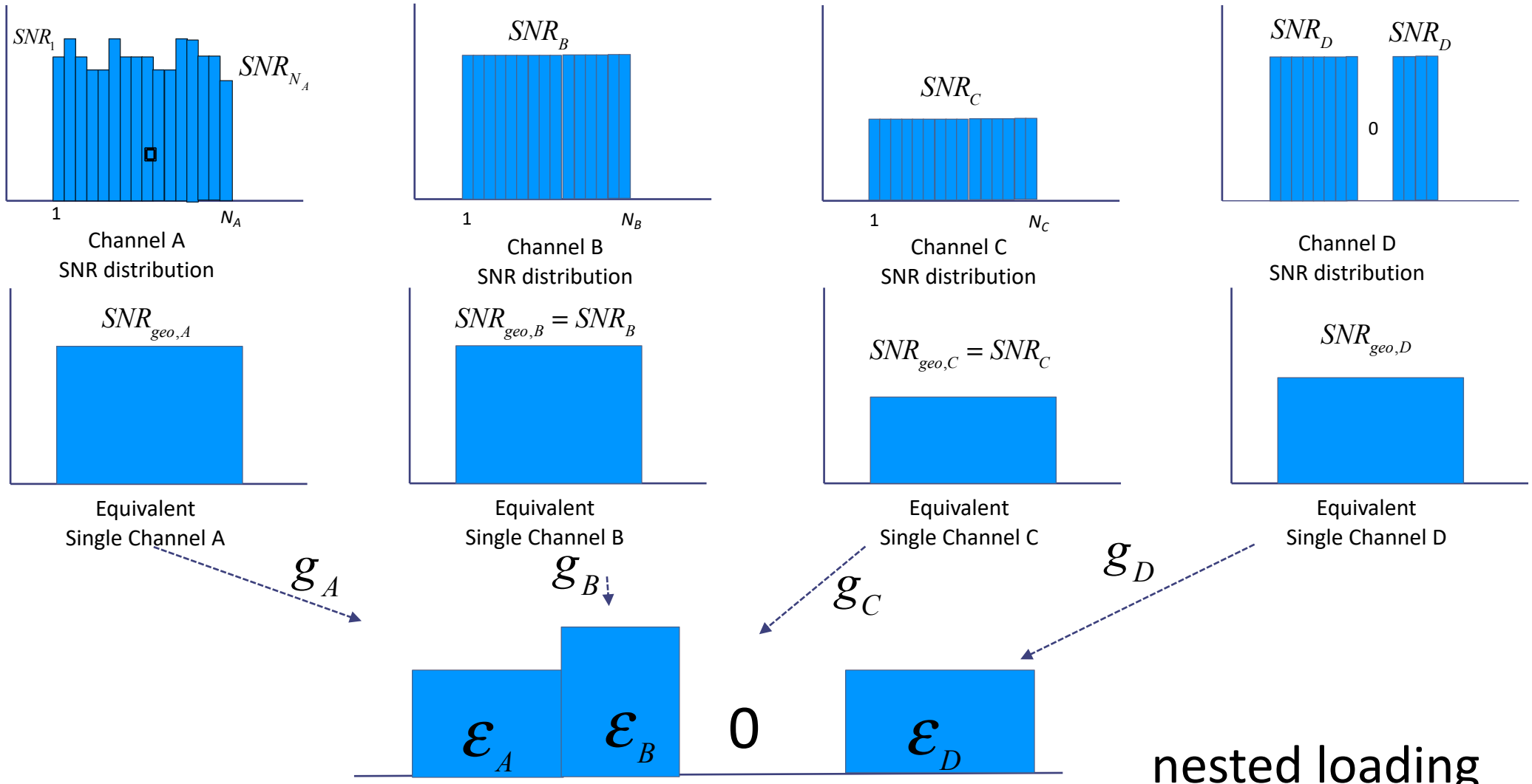
- Both will wait random period and try again
- Cellular avoids collisions through central control
- Can use different dimensions (requires resource management – central or distributed)
- 802.11ax allows some cellular-control elements – resource blocks (2 MHz, compared to 180 kHz in cellular)
  - Also space division allowed (spatial streams)

Cellular is centrally controlled



- Sharing is largely through Mobile Virtual Network Operation (MVNO)
- Some “borrowing” from adjacent cells (same ISP) – “CoMP”
- The two are mixed in unlicensed bands

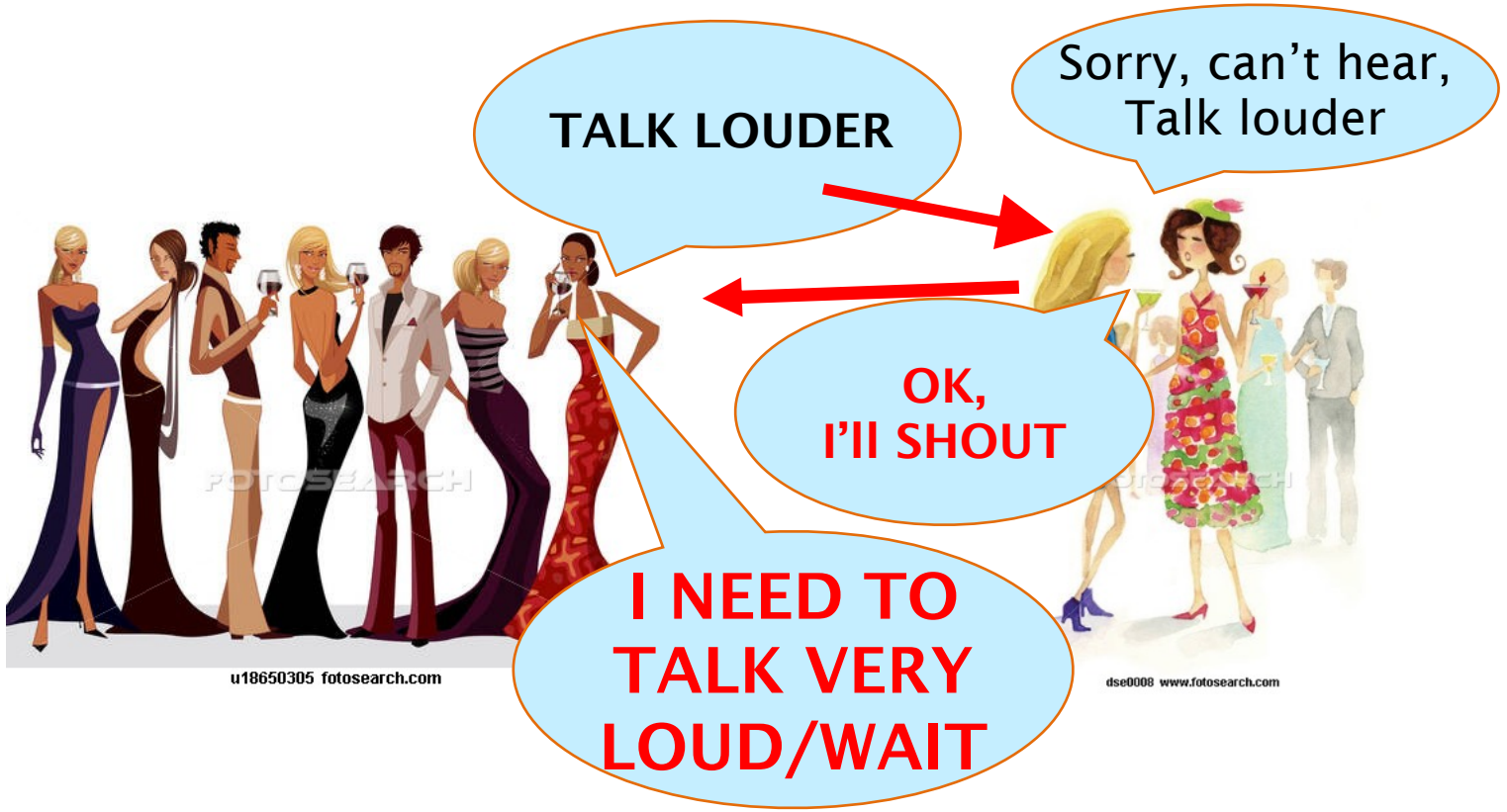
Adaptive Dimensions with Channel Aggregation



nested loading

$$\varepsilon_X = N_X \cdot \bar{\varepsilon}_X \quad \text{for } X = A, B, C, D$$

Cocktail Party Effect (crosstalk) – Wi-Fi collision protocol



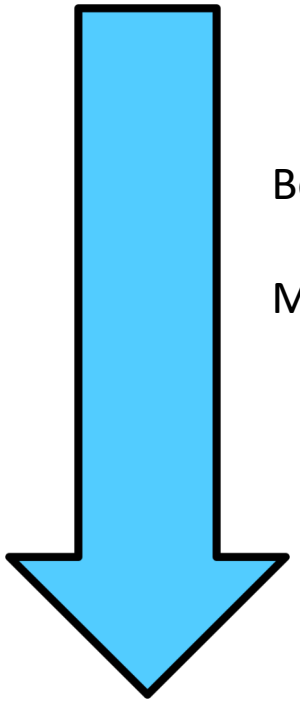
- Solution: All speak politely at low volume (lower power)
  - All send more information (more power and/or higher data rate)
- This is how dynamic spectrum access best works

ESM Stages

ESM Stage 1
Each node knows & reports its channel cascades
LRM distributes energy, code policy as function thereof

ESM Stage 2
LRM provides higher coordination for wider network coordination

ESM Stage 3
Coordinated Massive DAS
(distributed antenna system)

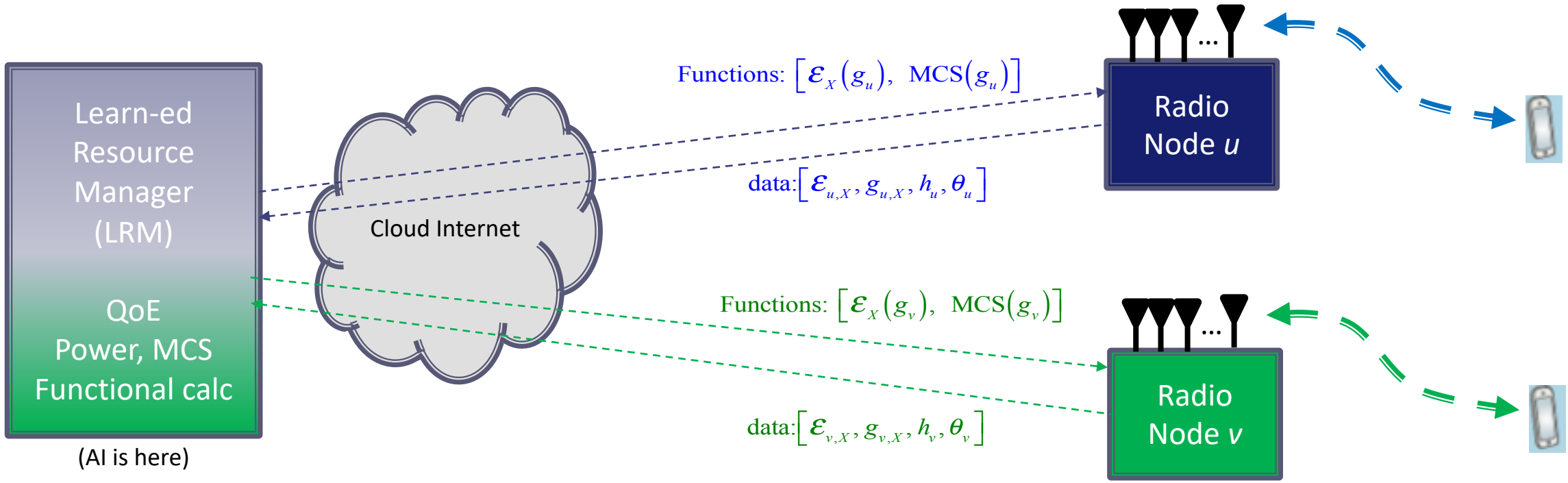


Better performance

More coordination

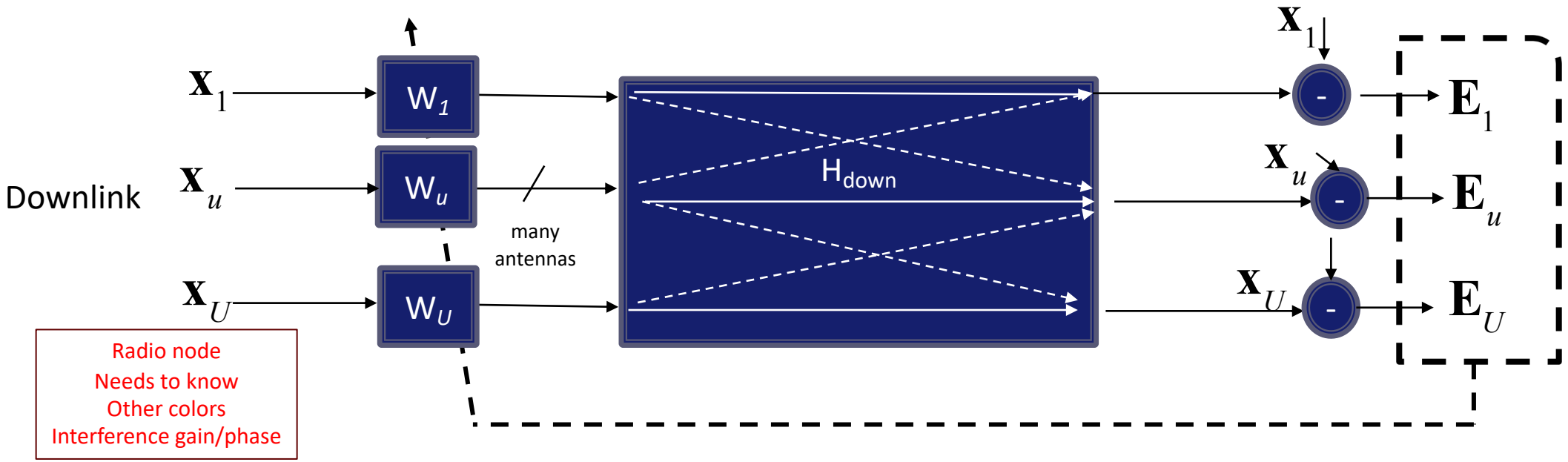
- ODD = Orthogonal Dimension Division

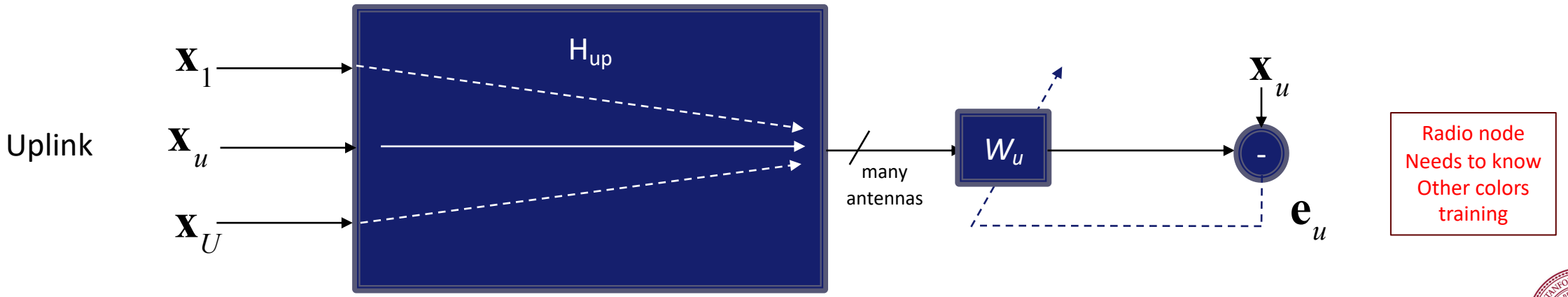
Simple ESM ecosystem



- LRM provides policy (functional descriptions, not specific params)
  - LRM collects data
- All through the conventional management interfaces

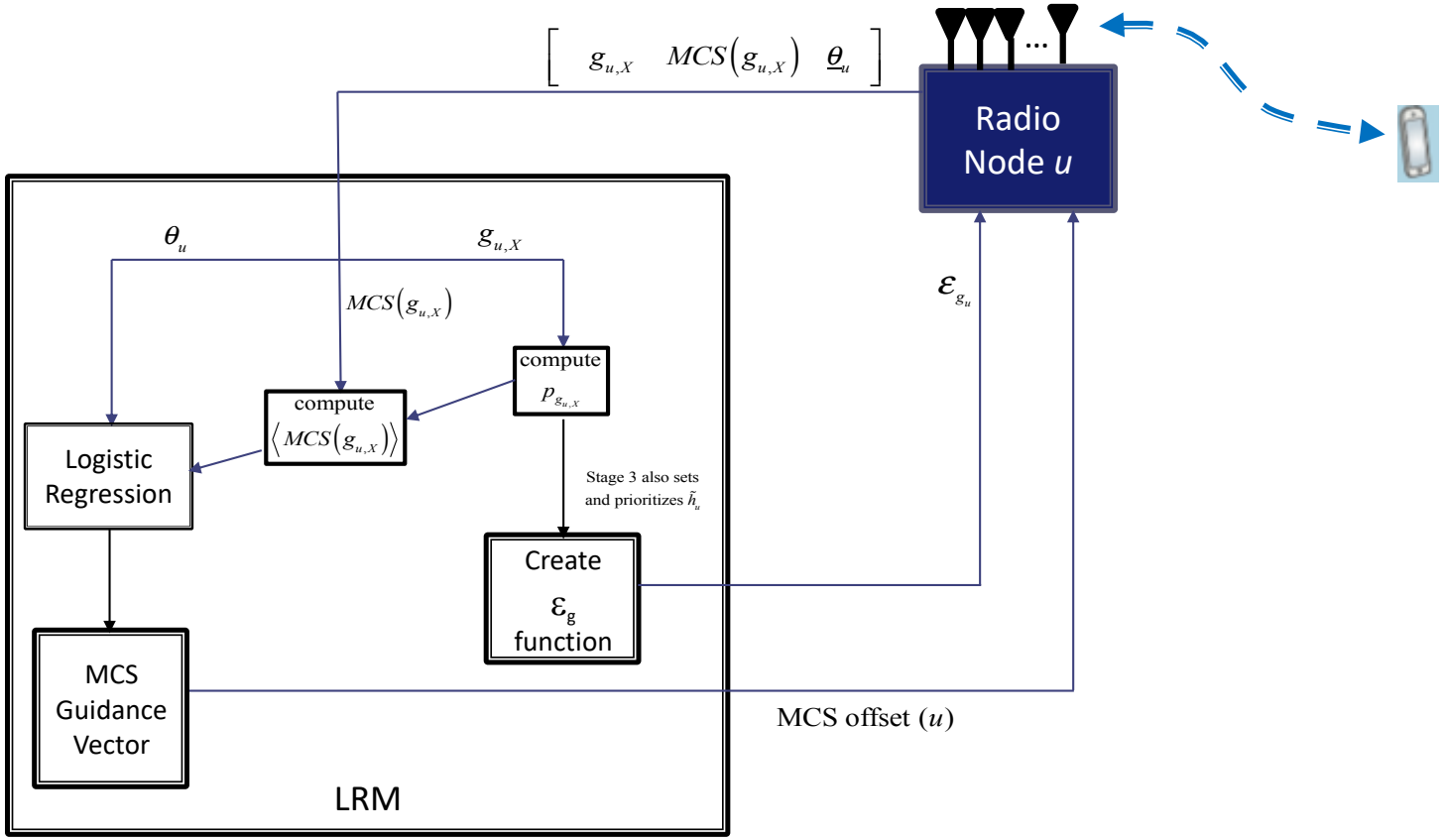
Stage 3 Concept – Vector Interference Channel





New Criterion then relates directly predicted QoE to QoS

- Select constellation and code (MCS)
  - Through reinforced learning



$$\max_{r,C} \bar{b} = r \cdot \log_2 |C|$$

$$\text{subject to: } \Pr\left\{ LLR_{QoE} < threshold \right\} \le 1 - r$$

Quality of Experience Measure

- p_{QoE} is the probability of good experience
  - Can vary with application, customer, *and of course connection*

- Turn into pos/neg quantity as log likelihood ratio

$$LLR_{QoE} = \log_{10}\left(\frac{p_{QoE}}{1-p_{QoE}}\right)$$

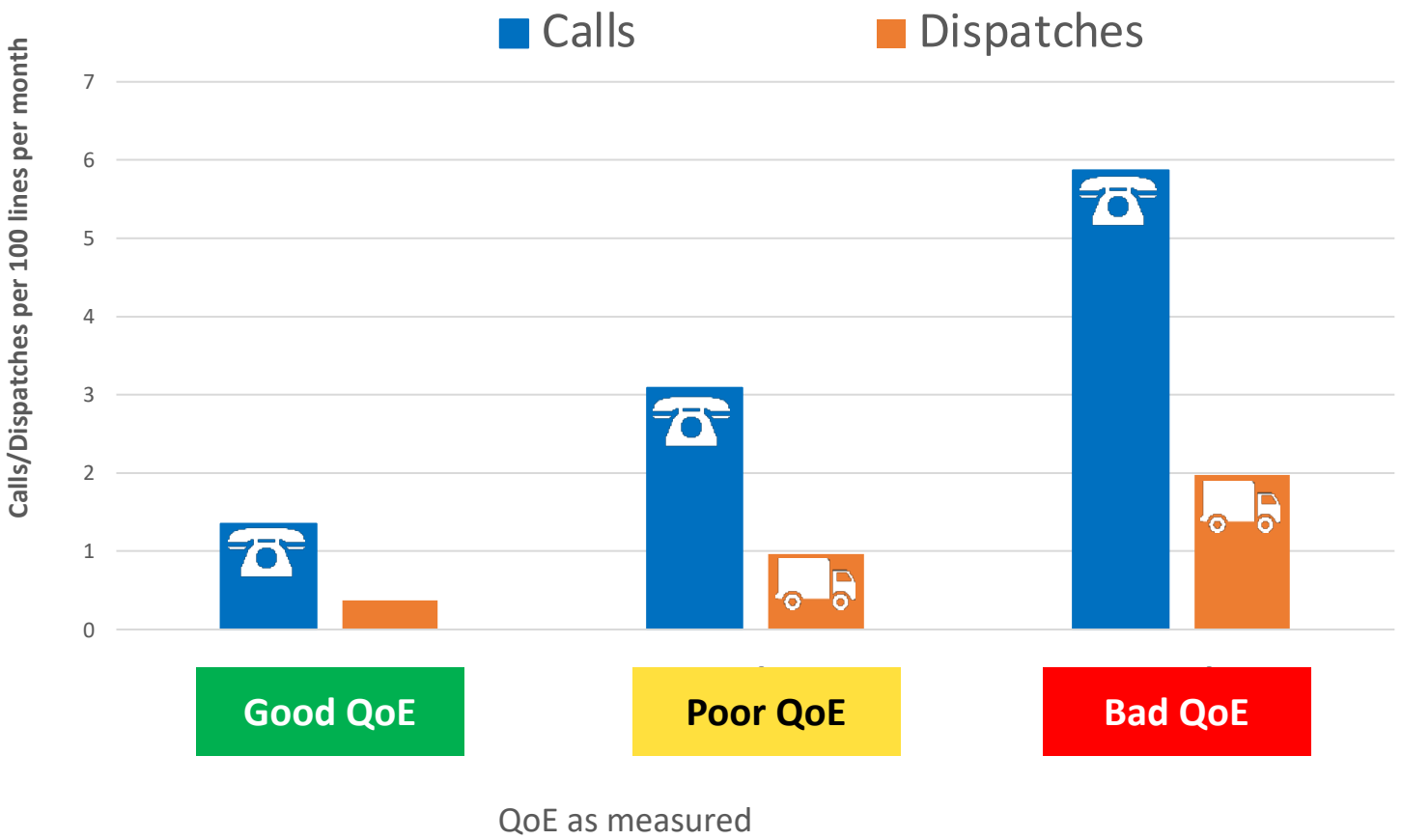
+2 = 99% happy
+5 = five-nines happy

- Training data for estimating p_{QoE}
  - Complaint calls, likes/(unlikes), dispatches, mean-opinion scores, customer service drop

- LRM relates QoE to QoS parameters
  - Determine weights β
  - Using training data
  - Estimates QoE on live data

$$LLR_{QoE} = \underbrace{\beta_1}_{\substack{\text{regression}\\\text{weight}}} \cdot \underbrace{\theta_1}_{\substack{\text{packet}\\\text{error}}} + \underbrace{\beta_2}_{\substack{\text{regression}\\\text{weight}}} \cdot \underbrace{\theta_2}_{\substack{\text{retrains}}} + \underbrace{\beta_3}_{\substack{\text{regression}\\\text{weight}}} \cdot \underbrace{\theta_3}_{\substack{\text{data-rate}\\\text{changes}}} + \ldots$$

Effectiveness of QoE estimation (field results)



Use State-Transition Machine (Markov Model) for the MCS adaptation

- Communicate simpler "aggressive, same, passive" on local MCS algorithm

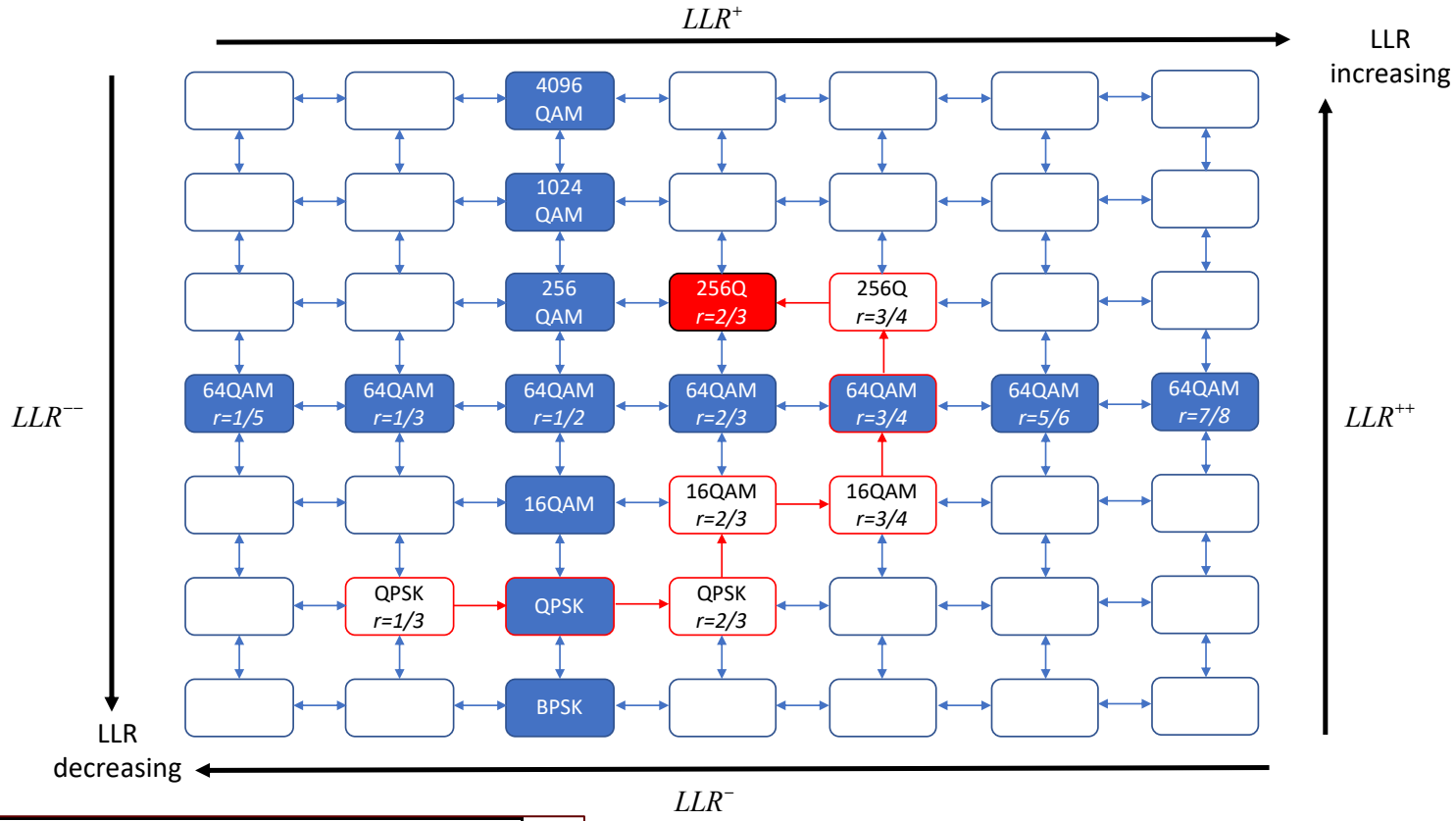
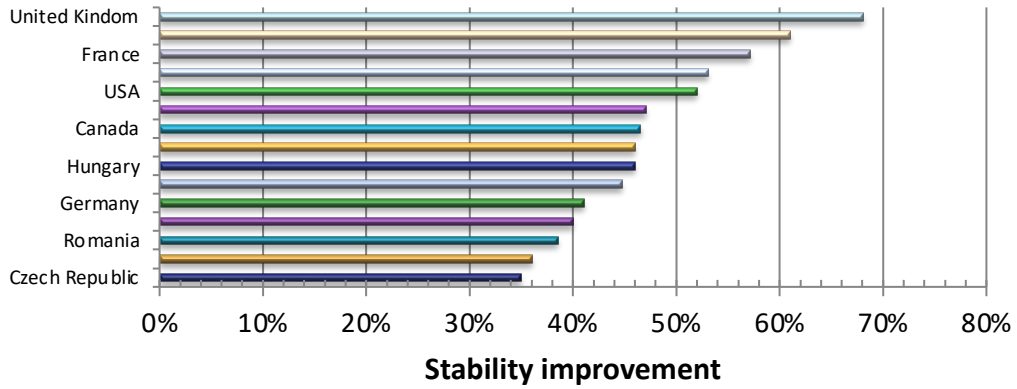


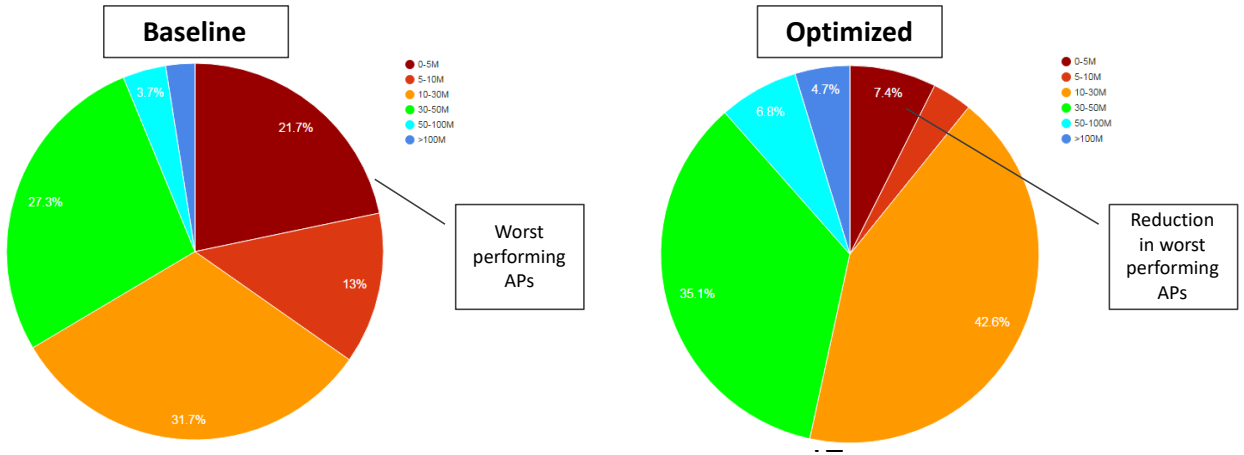
Table 4 – Example table of QoE state transitions for 1% discontent probability		
Increase constellation size $\|C\|$	$LLR > LLR^{++} \geq 3.0$	Move up (+2)
Increase code rate r	$LLR^{+} = 2.5 \leq LLR < 3.0 = LLR^{++}$	Move right (+1)
No change	$2.0 \leq LLR < 2.5 = LLR^{+}$	Stay (0)
Decrease code rate r	$LLR^{--} = 1.9 \leq LLR < 2.0 = LLR^{-}$	Move left (-1)
Decrease constellation size $\|C\|$	$LLR < 1.9 = LLR^{--}$	Move down (-2)

Some Results of this reinforced learning method

- Different countries
  - Call data and dispatch data used for training



- WiFi Data rates before and after (large network)
  - Data rate changes used for training



Conclusions

- Advance Australian network in throughput and QoE
  - 1 Gbps doable
- ***Cost and Power effective***
  - Can't run a fiber to everyone's wristwatch anyway
  - Leverages well all the expense already made
- Use all the resources (dimensions) available well and efficiently
  - Perhaps this is the true "mixed" advance
- *nbn* might transcend to **NBN**

Thank You

End of Presentation

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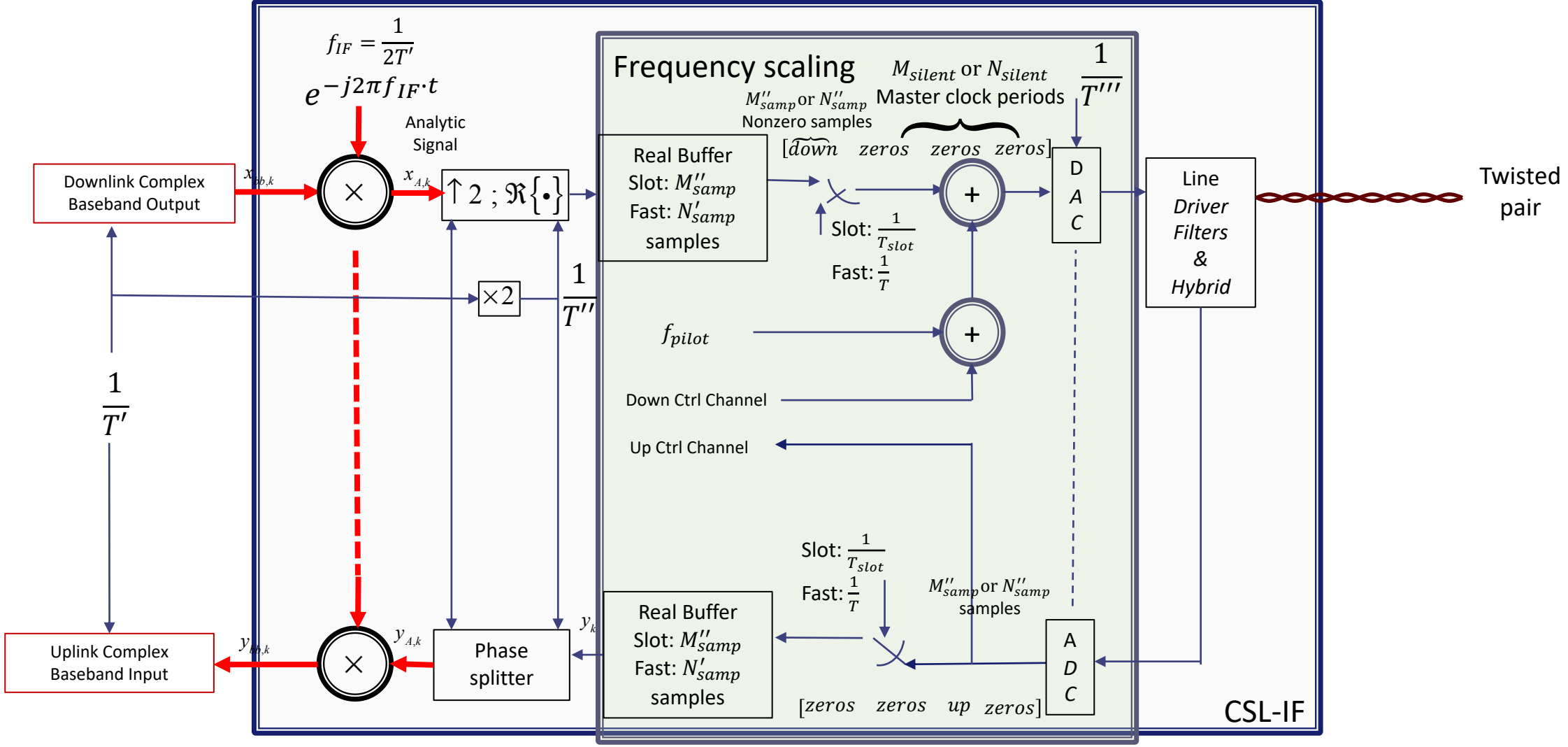
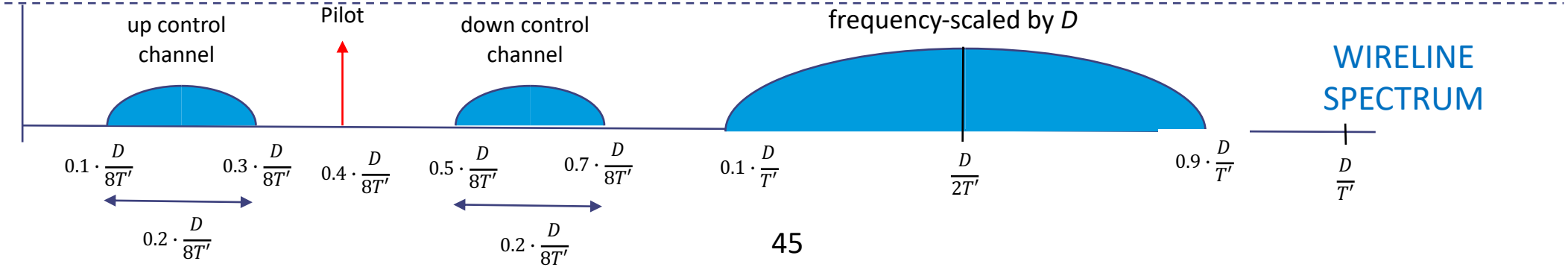
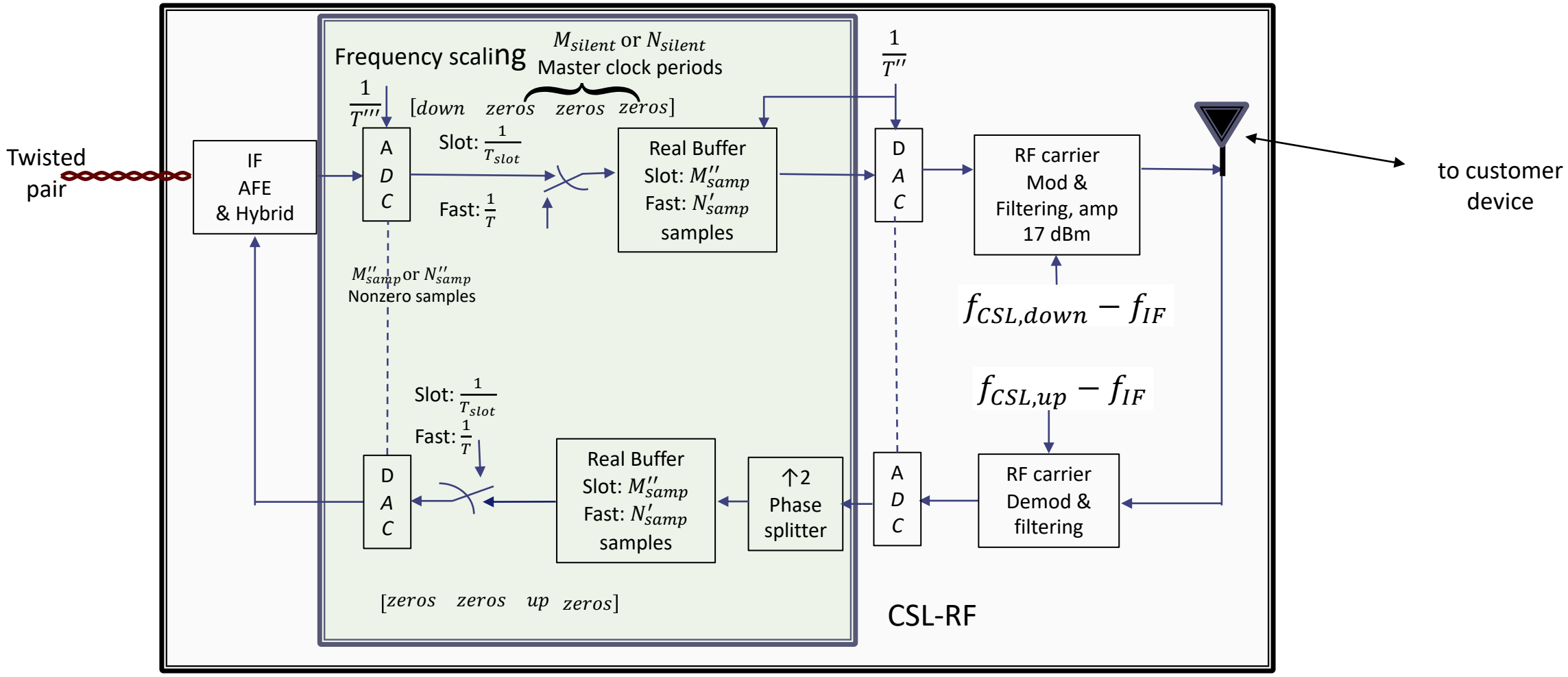
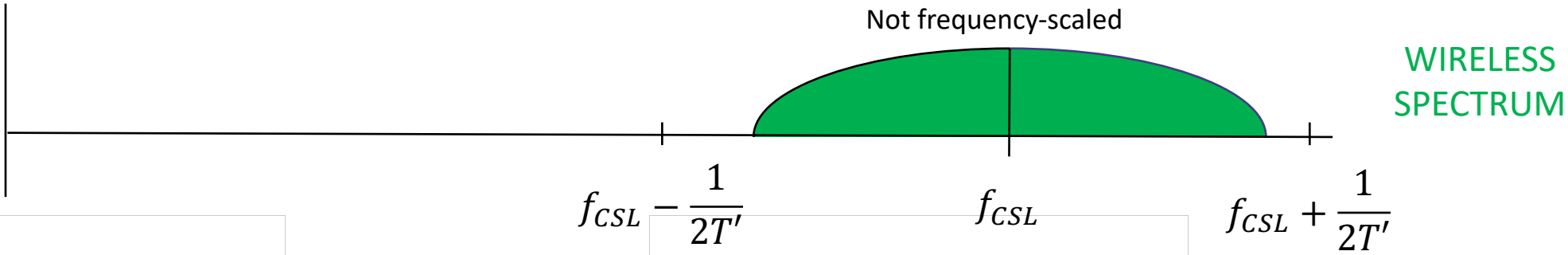

$f_{IF} = \frac{1}{2T'}$
$e^{-j2\pi f_{IF} \cdot t}$
Analytic Signal
Downlink Complex Baseband Output
$x_{bb,k}$
$x_{A,k}$
$\uparrow 2\ ;\ \Re\{\bullet\}$
$\times 2$
$\frac{1}{T''}$
$\frac{1}{T'}$
Uplink Complex Baseband Input
$y_{bb,k}$
$y_{A,k}$
y_k
Phase splitter
Frequency scaling
Real Buffer
Slot: M''_{samp}
Fast: N'_{samp}
samples
M''_{samp} or N''_{samp}
Nonzero samples
M_{silent} or N_{silent}
Master clock periods
$\frac{1}{T'''}$
$[\widetilde{down}\ \ zeros\ \ zeros\ \ zeros]$
Slot: $\frac{1}{T_{slot}}$
Fast: $\frac{1}{T}$
f_{pilot}
Down Ctrl Channel
Up Ctrl Channel
D A C
Line Driver Filters & Hybrid
Twisted pair
Slot: $\frac{1}{T_{slot}}$
Fast: $\frac{1}{T}$
M''_{samp} or N''_{samp} samples
Real Buffer
Slot: M''_{samp}
Fast: N'_{samp}
samples
$[zeros\ \ zeros\ \ up\ \ zeros]$
A D C
CSL-IF

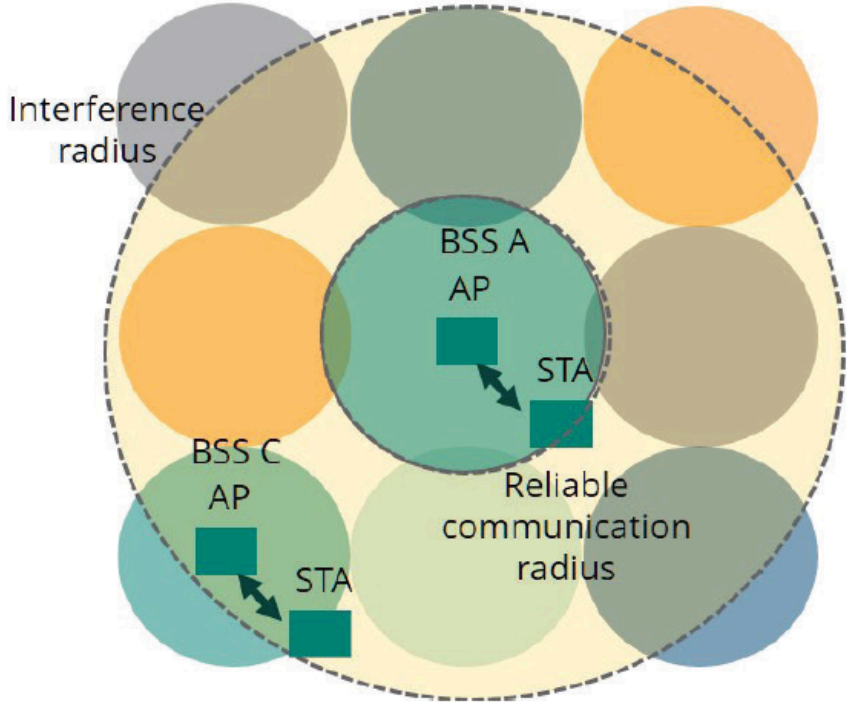

up control channel
Pilot
down control channel
frequency-scaled by D
WIRELINE SPECTRUM
$0.1 \cdot \frac{D}{8T'}$
$0.3 \cdot \frac{D}{8T'}$
$0.4 \cdot \frac{D}{8T'}$
$0.5 \cdot \frac{D}{8T'}$
$0.7 \cdot \frac{D}{8T'}$
$0.1 \cdot \frac{D}{T'}$
$\frac{D}{2T'}$
$0.9 \cdot \frac{D}{T'}$
$\frac{D}{T'}$
$0.2 \cdot \frac{D}{8T'}$
$0.2 \cdot \frac{D}{8T'}$


Twisted pair
IF AFE & Hybrid
Frequency scaling
M_{silent} or N_{silent} Master clock periods
$\frac{1}{T'''}$
$[down \quad zeros \quad zeros \quad zeros]$
A D C
Slot: $\frac{1}{T_{slot}}$
Fast: $\frac{1}{T}$
Real Buffer Slot: M''_{samp} Fast: N'_{samp} samples
$\frac{1}{T''}$
D A C
RF carrier Mod & Filtering, amp 17 dBm
to customer device
M''_{samp} or N''_{samp} Nonzero samples
$f_{CSL,down} - f_{IF}$
$f_{CSL,up} - f_{IF}$
Slot: $\frac{1}{T_{slot}}$
Fast: $\frac{1}{T}$
D A C
Real Buffer Slot: M''_{samp} Fast: N'_{samp} samples
↑2 Phase splitter
A D C
RF carrier Demod & filtering
$[zeros \quad zeros \quad up \quad zeros]$
CSL-RF


Not frequency-scaled
WIRELESS SPECTRUM
$f_{CSL} - \frac{1}{2T'}$
f_{CSL}
$f_{CSL} + \frac{1}{2T'}$

Wi-Fi Coloring – 802.11ax

- Different AP's can use different "colors" (frequency plans)
- Determined in largely distributed manner
- The "colors" are somewhat analogous to the routing tables in internet
  - Provide guidance on how (where) to send signals
- Can be signaled from AP to AP
- Distributed algorithms can be used
  - No single entity may control all the AP's
  - Especially in residential use



Aruba White Paper – 802.11ax – 5-30-18