5G

Mobile Communications for 2020

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Presentation Outline

4G (3GPP-LTE)

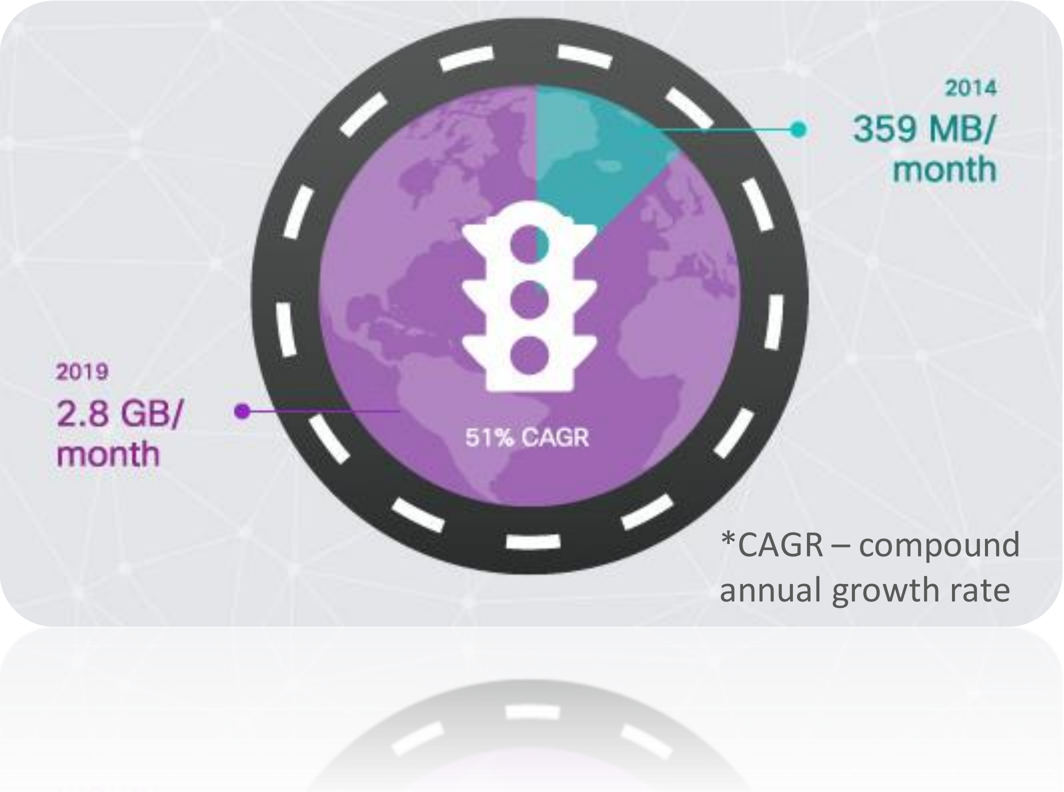
- 4G LTE networks are still expanding across global markets
  - In June 2015, 418 commercial LTE networks in 142 countries
    - 67 LTE-A in 39 countries
  - LTE subscriptions reached 635 million at 1Q2015 and will reach 2 billion by the end of 2018
    - Eastern Asia leads the market with 49% LTE subscriptions
  - In March 2105, LTE had 9% market share
    - GSM still has 56% of the world market
    - North America leads in terms of Market Share (44% are LTE users), only 2,6% in Latin America
  - Brazil LTE subscriptions reached 3,7 million at the end of July 2014
- 4G 3GPP activities still ongoing
  - Rel-12 (Mar2015) recently frozen
  - Rel-13 (Mar 2016) ongoing
    - Several research topics: Enhanced Small Cell for LTE, LTE Multi-Antenna/site technologies like 3D-beamforming, Interworking with WiFi, SON, Advanced receivers, MTC, D2D, etc

So why do we need 5G????

Drivers and Vision

- Why 5G?
  - **Mobile IP traffic** is expected to overtake fixed traffic in 2019, when it will correspond to 66% of the total IP traffic: up to 500 Exabytes by 2020. (1 Exabyte = 1 million terabytes).

Average throughput per month per connected device (mobile networks)



http://www.cisco.com/c/dam/en/us/solutions/service-provider/vni-service-adoption-forecast/index.html

Drivers and Vision

- Why 5G?
  - Number of **mobile users** will increase 4.3% annually, from 2014 to 2019. In 2019, this number is expected to reach 5.2 billion, in contrast to 4.3 billion in 2014.

Number of mobile users: 2014 and 2019

http://www.cisco.com/c/dam/en/us/solutions/service-provider/vni-service-adoption-forecast/index.html

Drivers and Vision

- Why 5G?
  - Number of **connected devices** will surpass the world's population, going up to 11 billion in 2019.
    - North America: 3.1 per capita
    - Latin America: 1.5 per capita
    - Western Europe: 2.8 per capita
    - Central and Eastern Europe: 2.1 per capita
    - Middle East and Africa: 1.1 per capita
    - Asia Pacific: 1.3 per capita

Average throughput per connected device (mobile networks)

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http://www.cisco.com/c/dam/en/us/solutions/service-provider/vni-service-adoption-forecast/index.html

Drivers and Visions

- What is 5G
  - Nobody really knows....
- Different scenarios and visions
  - Industry
  - Research Forums
  - Regulators
  - International Organizations
- But a few common issues
  - Not only an evolved/faster 4G, but
  - Internet of Things
    - ✓ Many more terminals
    - ✓ Higher reliability
    - ✓ Lower latency
    - ✓ .....

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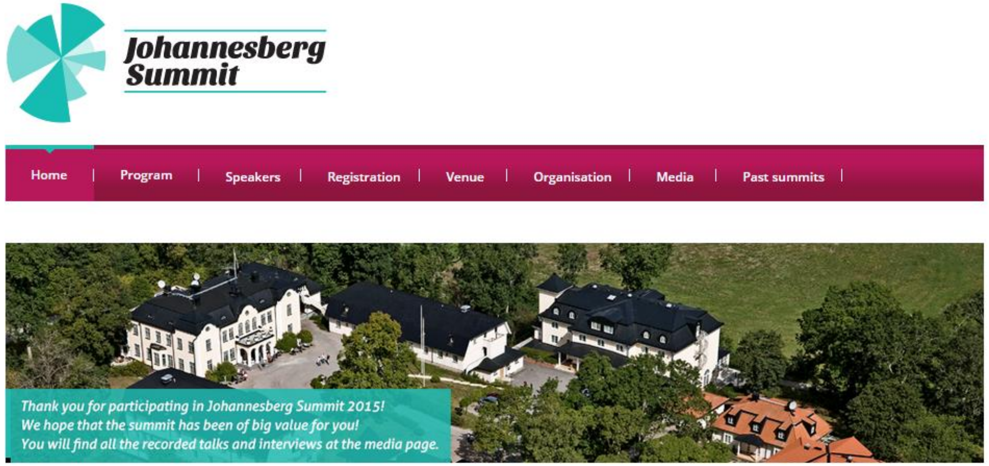
KEY FORUMS & CONFERENCES



KEY CONSORTIUMS

Research Centres

AALBORG UNIVERSITY DENMARK

Aalto University

Fraunhofer Heinrich Hertz Institute

KTH VETENSKAP OCH KONST

UNIVERSITY of OULU

RWTH AACHEN UNIVERSITY

TECHNISCHE UNIVERSITÄT DRESDEN

it instituto de telecomunicações

INDT

INDUSTRY

NOKIA
Connecting People

QUALCOMM

Microsoft

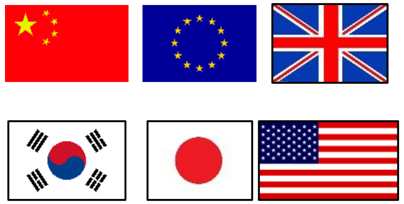
ERICSSON

Alcatel-Lucent

NTT docomo

HUAWEI

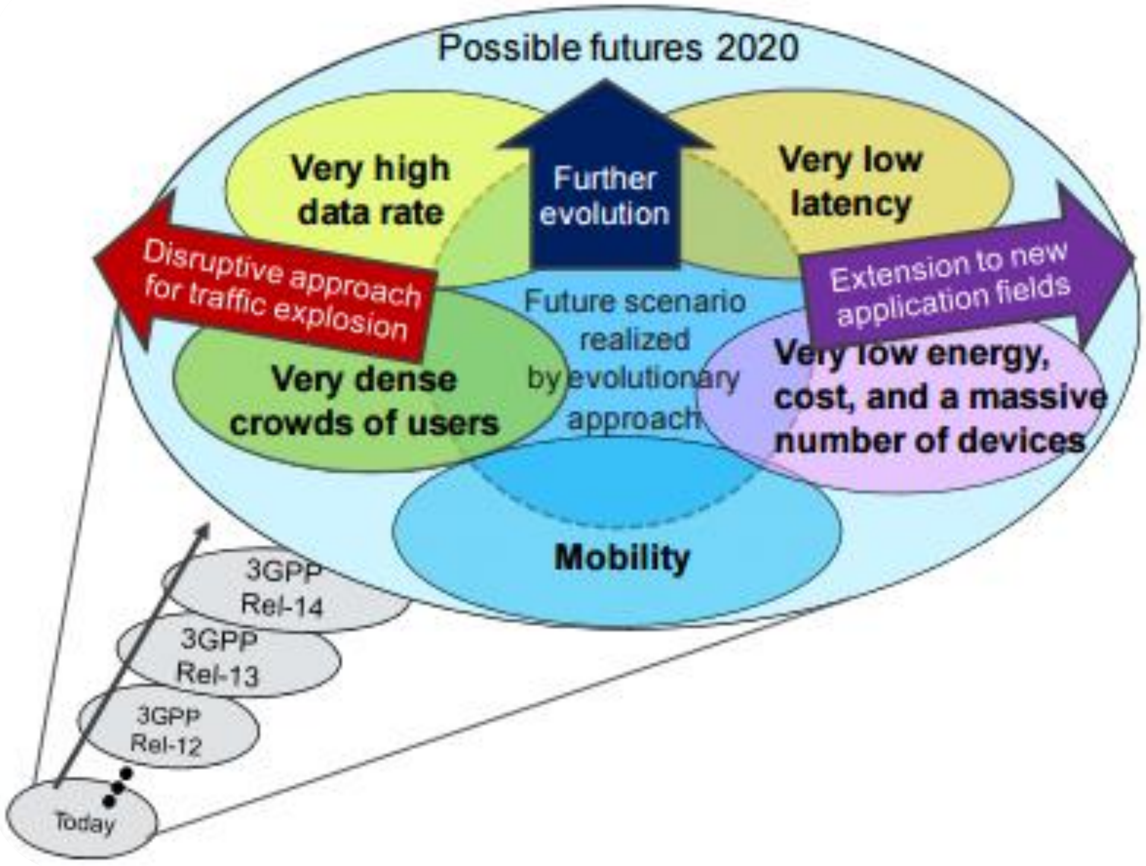
SAMSUNG



Scenarios and Challenges

- Why 5G?
  - New **communication challenges** and requirements that are not achieved by current technologies:
    - Amazingly fast
    - Great service in a crowd
    - Ubiquitous things communicating
    - Best experience follows you
    - Super real-time and reliable connections

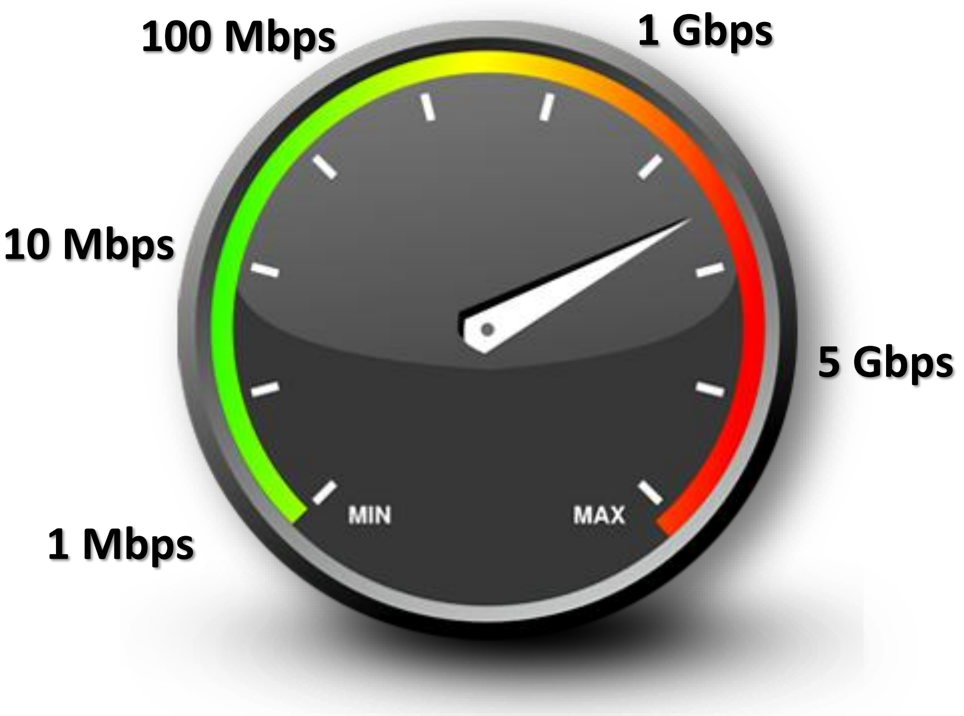
Possible Futures in 2020



https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

Scenarios and Challenges

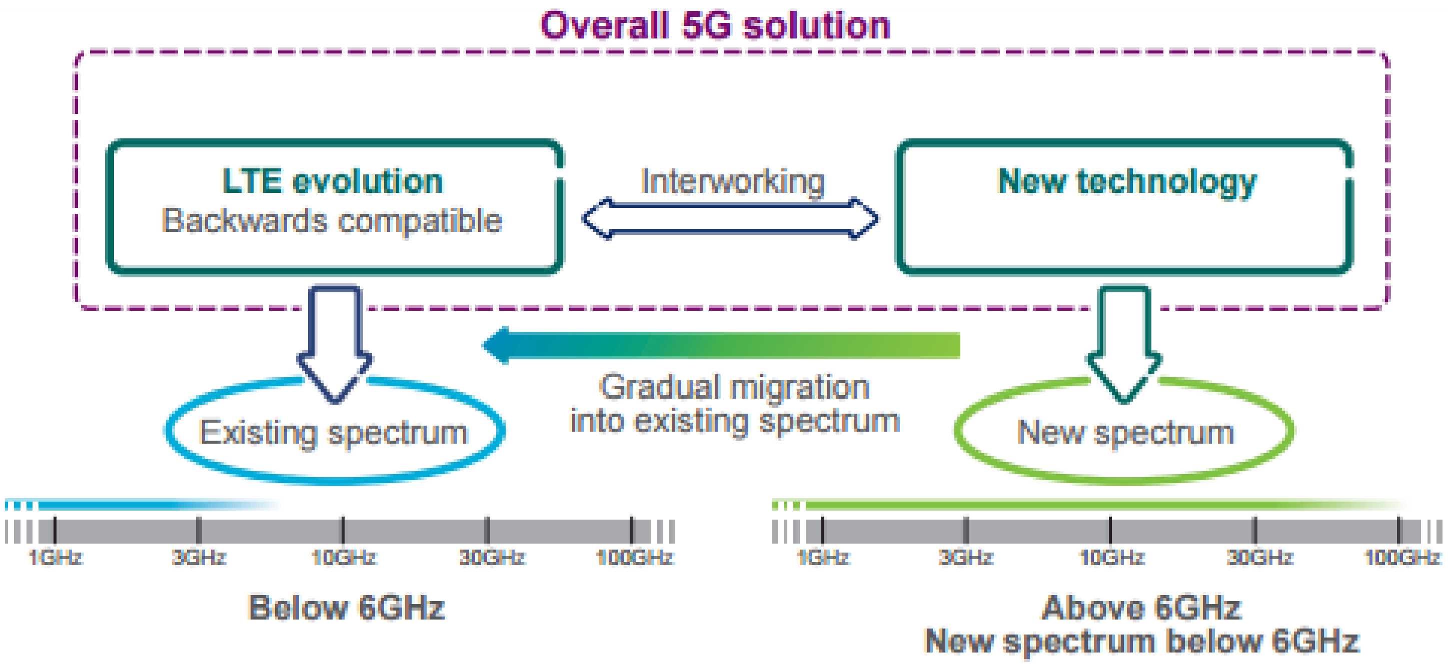
- Amazingly fast
  - 5G technology should support **1000 times higher mobile traffic** data volume per area.
  - Provide high data-rates at the application layer. In this scenario, users can enjoy the great experience of instantaneous connection.



https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

Scenarios and Challenges

- Amazingly fast
  - In order to realize this, **wider carriers in new spectrum bands** might be needed.
  - Many companies foresee the interworking of LTE evolution and new 5G technology, occupying a new spectrum band in the millimeter and centimeter wave bands.



http://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf

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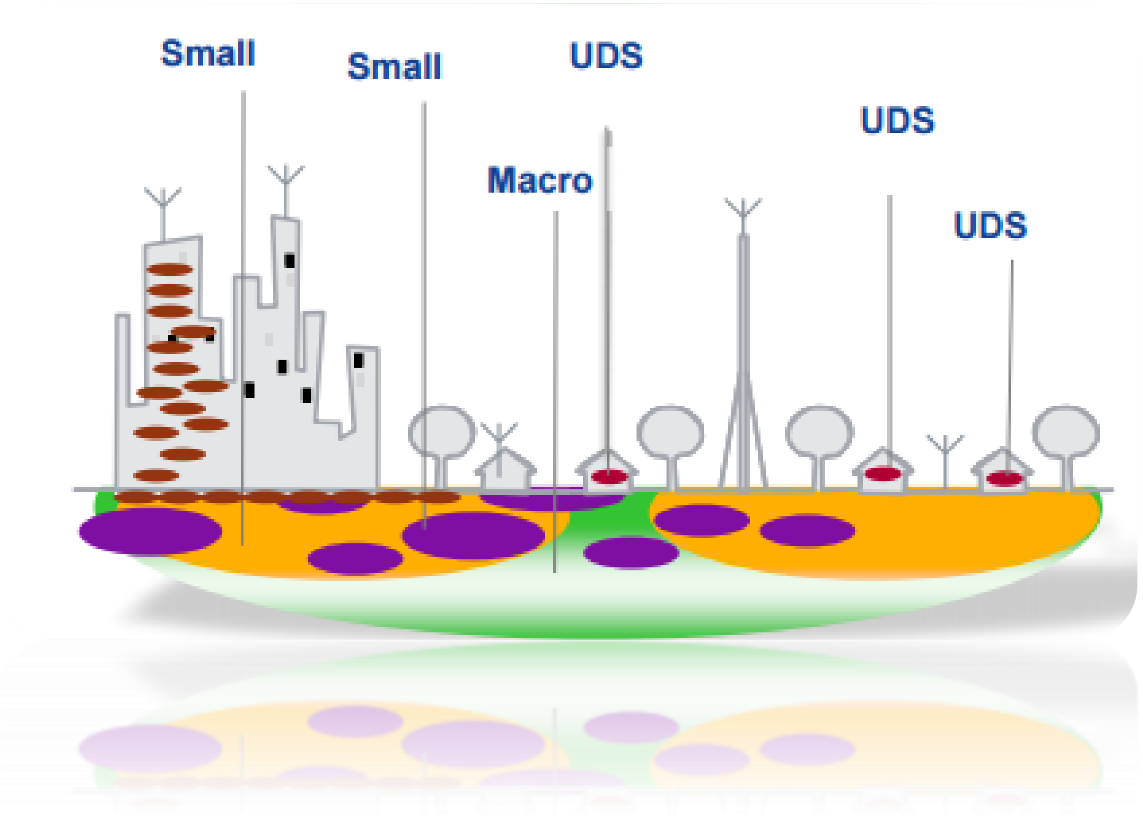
Scenarios and Challenges

- Amazingly fast
  - 5G will be a heterogeneous deployment, where the total capacity will be the sum of capacity of macro cells, small cells and ultra-dense small cells.



http://www.ieee-ctw.org/2014/slides/session1/Preben_Mogensen_230514_v3.pdf

Scenarios and Challenges

- Great Service in a Crowd
  - End-user demands for future communication solutions to work well in a crowd.
  - The technical challenge is **to provide such service at high traffic density per area despite a large number of UEs**, such as handsets and machines/devices per area in combination with deployment cost constraints.

https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

Scenarios and Challenges

- Ubiquitous things communicating
  - This scenario addresses the **communication needs of a massive deployment of ubiquitous machine-type devices**, ranging from low complexity devices to more advanced devices.
  - Future networks expect **10 times to 100 times higher number of connected devices,** and **10 times longer battery life.**
  - The challenge is to meet the requirements of cost, energy consumption, transmission power, latency, that are not met by current technologies.

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https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

Scenarios and Challenges

- Best experience follows you
  - This scenario strives at bringing a similar user experience for users on the move, or for static users.
  - Challenges:
    - ✓ Robust and reliable connectivity solutions
    - ✓ Ability to efficiently manage mobility in the network

https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

Scenarios and Challenges

- Super real-time and reliable connections
  - Machine-to-machine latency requirements are much more stringent than human communication requirements.
  - Applications: smart grids, e-health, efficient industrial communications, real-time tactile control, gaming!
  - Challenges:
    - ✓ Decrease 5 times the end-to-end latency
    - ✓ Latency reliability up to 99.999%

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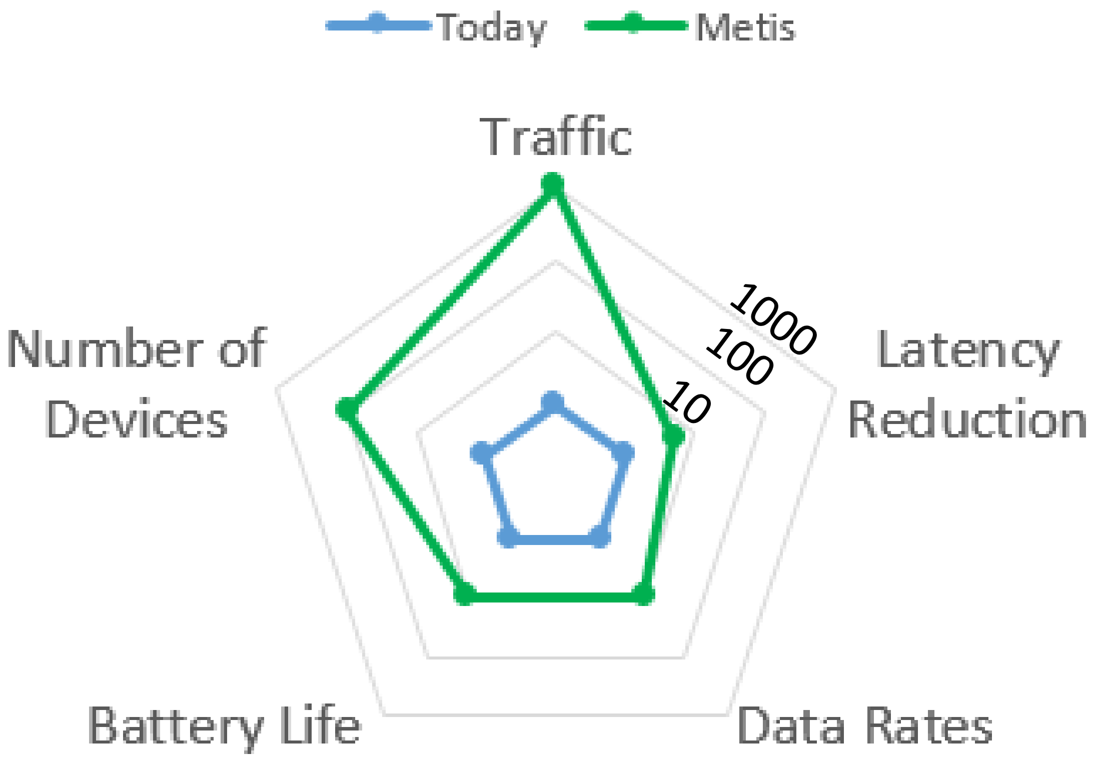
https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf

What are 5G requirements?



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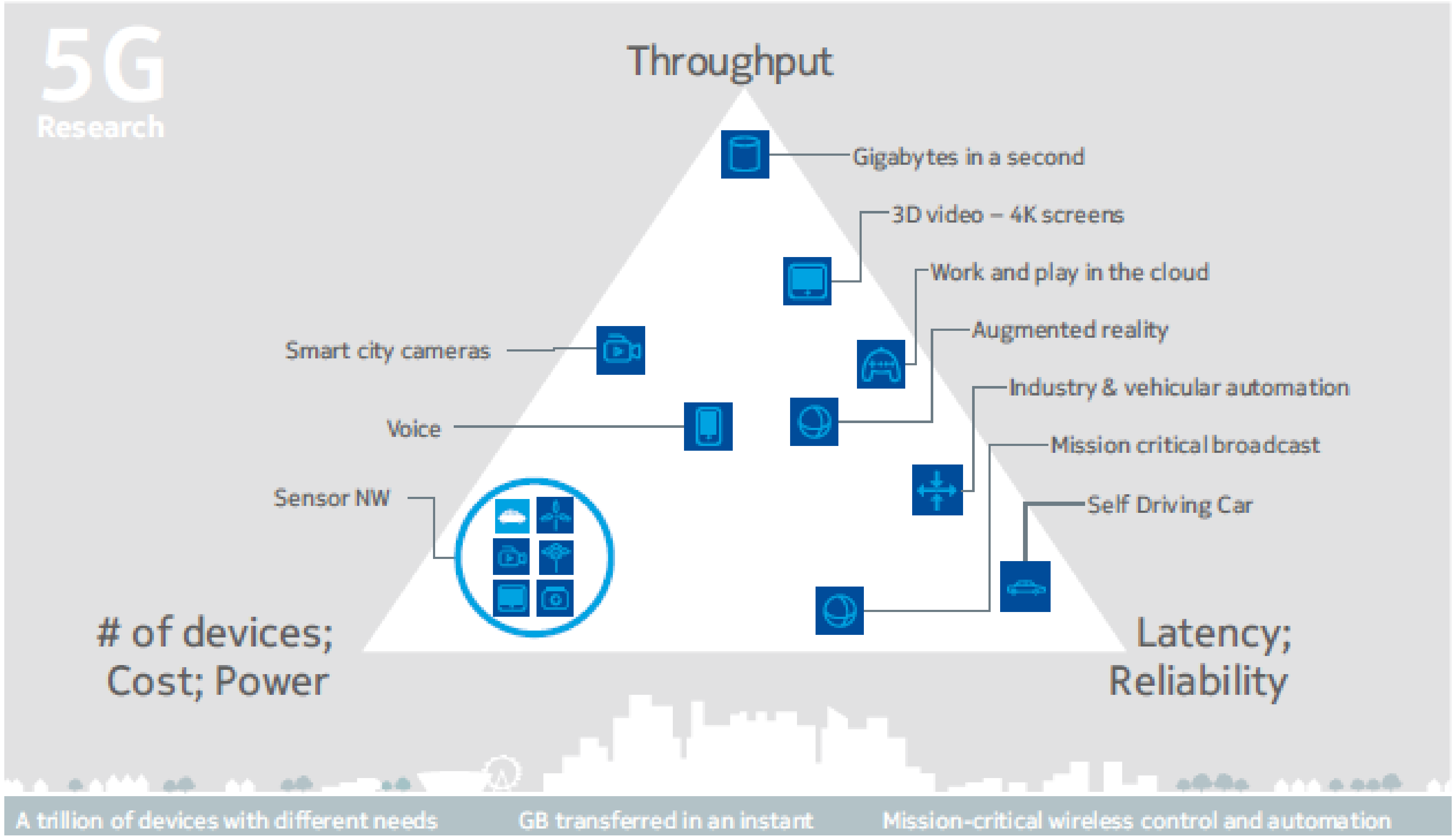
What are 5G requirements?

NOKIA



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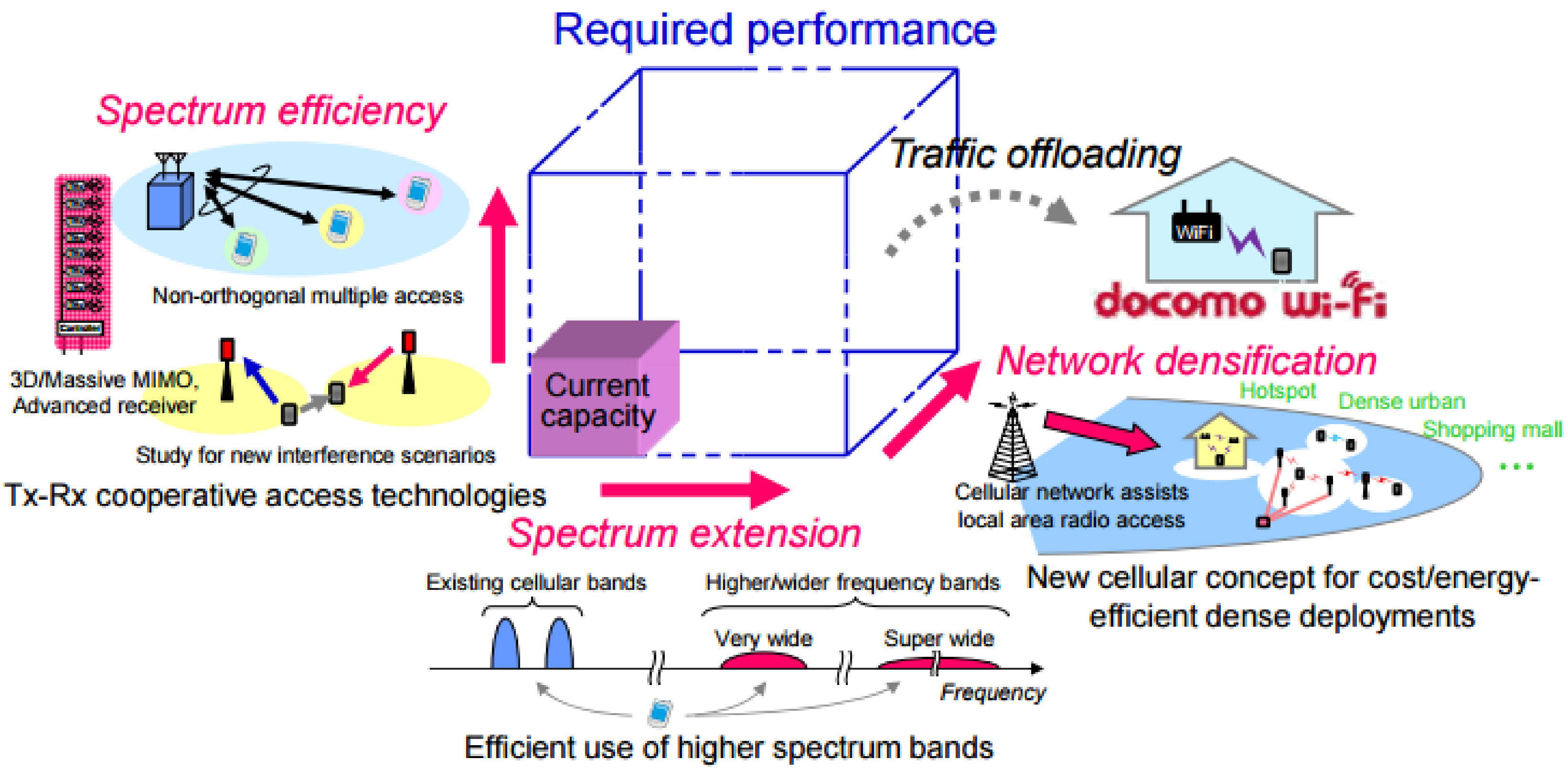
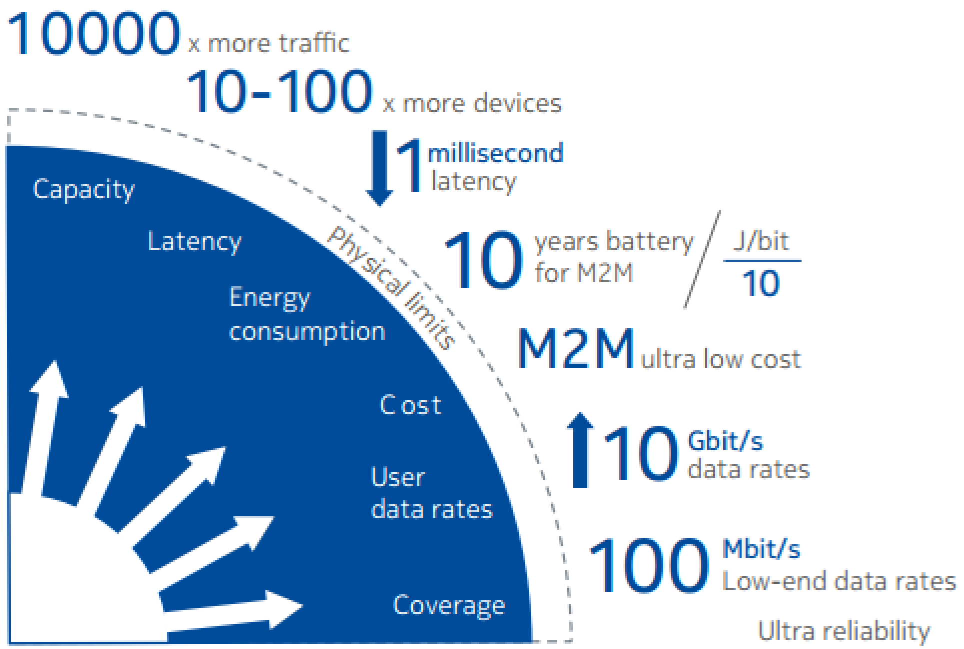


https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_5g/DOCOMO_5G_White_Paper.pdf

WHAT IS 5G?



- Nokia believes that communications beyond 2020 will involve a combination of existing and evolving systems, like LTE-Advanced and Wi-Fi, coupled with new, revolutionary technologies designed to meet new requirements, such as virtually zero latency to support tactile Internet, machine control or augmented reality.

- 5G will be the set of technical components and systems needed to handle these requirements and overcome the limits of current systems

WHAT IS 5G?

ERICSSON

- 5G is the next step in the evolution of mobile communication. It will be a key component of the Networked Society and will help realize the vision of essentially unlimited access to information and sharing of data anywhere and anytime for anyone and anything.

- 5G will therefore not only be about mobile connectivity for people. Rather, the aim of 5G is to provide ubiquitous connectivity for any kind of device and any kind of application that may benefit from being connected.

WHAT IS 5G?

- 5G wireless networks will support 1,000-fold gains in capacity, connections for at least 100 billion devices, and a 10 Gb/s individual user experience capable of extremely low latency and response times.
- Deployment of these networks will emerge between 2020 and 2030. 5G radio access will be built upon both new radio access technologies (RAT) and evolved existing wireless technologies (LTE, HSPA, GSM and WiFi). Breakthroughs in wireless network innovation will also drive economic and societal growth in entirely new ways.
- 5G will realize networks capable of providing zero-distance connectivity between people and connected machines.

HUAWEI

WHAT IS 5G?

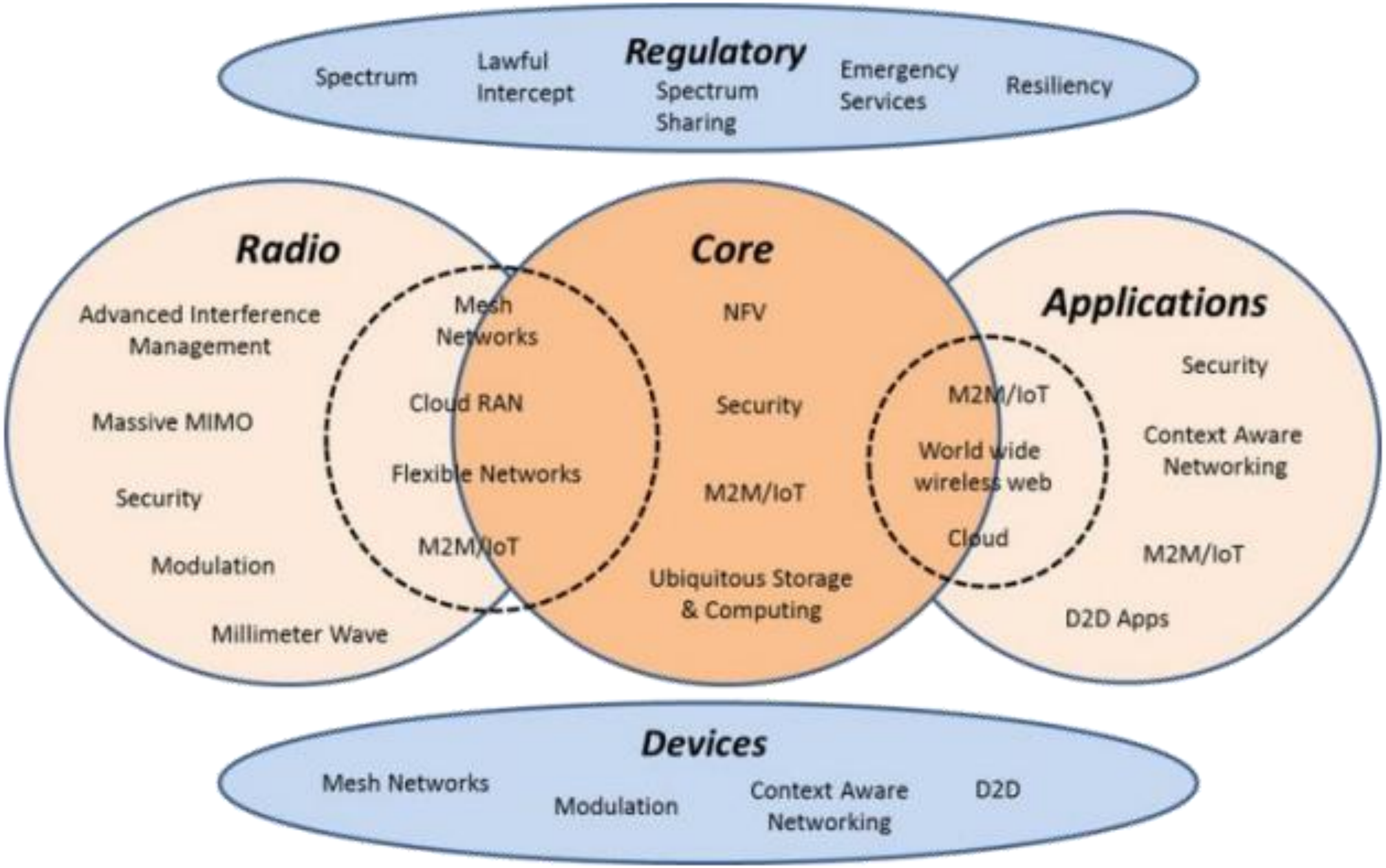
- **Understanding 5G**
  The new GSMA report examines the two main views on 5G that exist today, which are frequently mixed together to form the basis of the 5G definition:

- ***View 1 – The hyper-connected vision:*** In this view, 5G is seen as a blend of existing technologies (2G, 3G, 4G, Wi-Fi and others) that can deliver greater coverage and availability, higher network density in terms of cells and devices, and the ability to provide the connectivity that enables machine-to-machine (M2M) services and the Internet of Things.

- ***View 2 – Next-generation radio access technology:*** This perspective outlines 5G in 'generational' terms, setting specific targets that new radio interfaces must meet in terms of data rates (faster than 1Gbps downlink) and latency (less than 1ms delay).

HOW WILL WE GET THERE?

How will we get there?



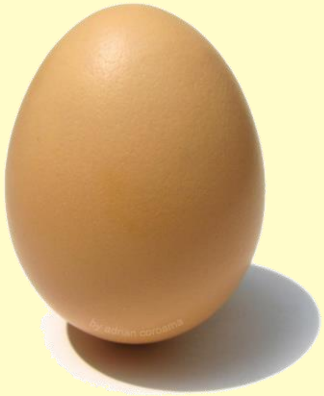
Keathley (AT&T), *The Road to 5G - Requirements Capabilities and_Expectations*, 5G Summit 2015

ARCHITECTURE

4G Evolution

- Evolution usually does not happen out of the blue

It takes some time to go from here… … to here.



LTE architecture has been evolved in most recent releases

4G Evolution

LTE ADVANCED

	3GPP Release 8 - 9	3GPP Releases 10	3GPP Releases 11-12	Beyond Release 12
Network Architecture	• SON: Automatic Neigh. , Handover Opt • Home eNodeB	• SON: Drive Testing Minimization • Carrier Aggregation	• SON: Network Energy Saving for E-UTRAN • D2D Communications • Small Cells	• Small Cell Enhancements • D2D Communications Enhancements • Relay nodes

4G Evolution

LTE ADVANCED (Releases 10 to 12)

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MIMO	• 4x4 DL MIMO	• 8X8 DL MIMO • 4x4 UL MIMO		• 8x8 UL MIMO

4G Evolution

		LTE ADVANCED		
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MIMO	• 4x4 DL MIMO	• 8X8 DL MIMO • 4x4 UL MIMO		• 8x8 UL MIMO
Waveforms	• OFDMA			• New Carrier Type

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4G Evolution

LTE ADVANCED (3GPP Releases 10 and 3GPP Releases 11-12)

	3GPP Release 8 - 9	3GPP Releases 10	3GPP Releases 11-12	Beyond Release 12
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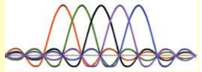
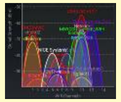
Waveforms 	• OFDMA			• New Carrier Type
Interference Management 	• ICIC		• COMP • HetNet • e-ICIC	

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4G Evolution

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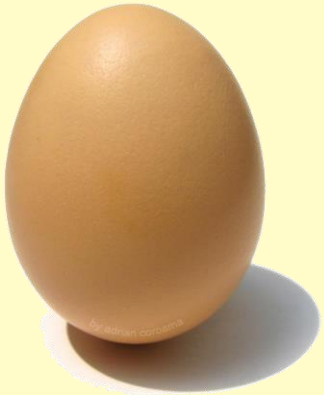

… to here.

LTE architecture has been evolved in most recent releases

inthehallofmirrors.typepad.co.uk/.a/6a00d8341c345453ef019b0255f7a1970c-popup

But sometimes we need a ***disruptive*** technology

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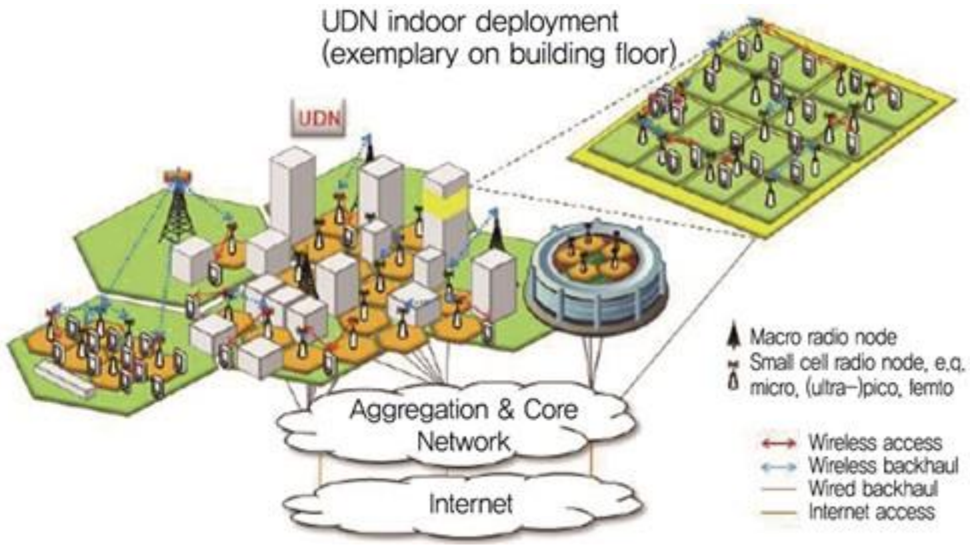
So what’s disruptive about 5G??

Ultra Dense Networks

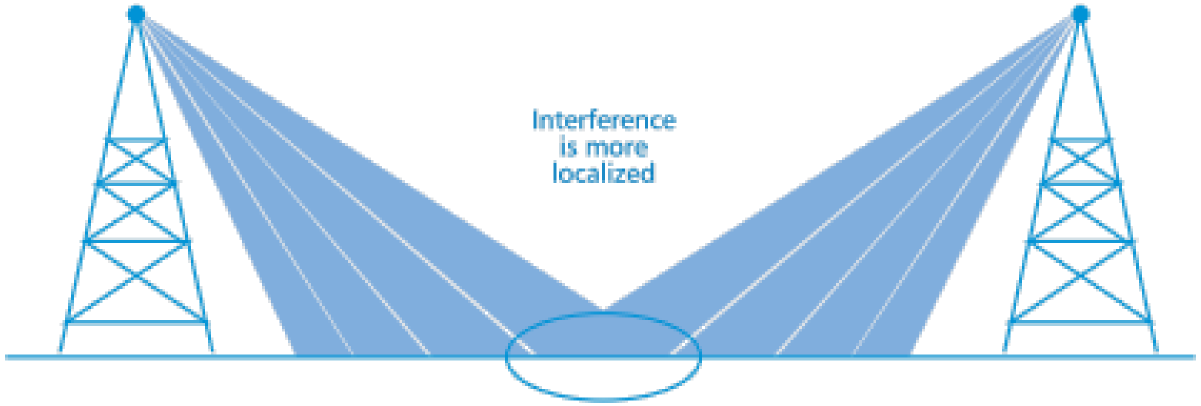
- Cooper's law
  - Capacity of wireless systems double every 18 months
    - ✓Most of it obtained by tighter spectrum reuse and smaller cells
      - Macro → Micro → Pico → Femto → ….
      - Ultra-dense Networks



https://ettrends.etri.re.kr

CoMP (Cooperative MultiPoint)

- Extension of CoMP may be employed to make use of all its potential
  - using UE capabilities for interference cancellation
    - ✓Reduces coordination at network
  - with massive MIMO



Jungnickel et al., IEEE Comm Mag., May 2014

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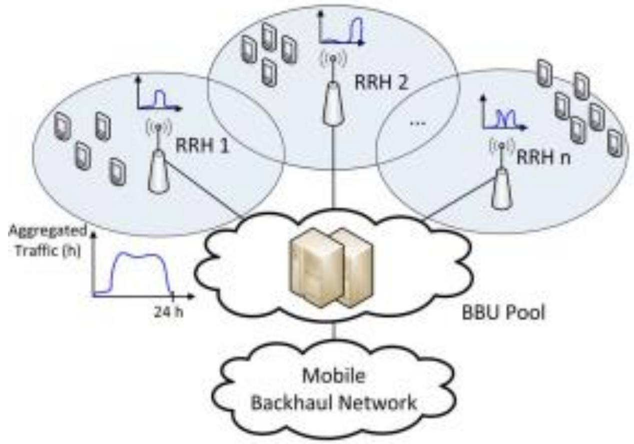
Cloud RAN

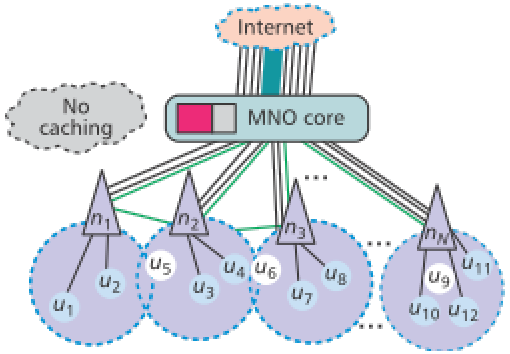
- Networks are moving from a BS-centered to a cloud-based architecture
- Modem Signal processing moves to servers connected to the cloud
    - Distributed antennas with a centralized server

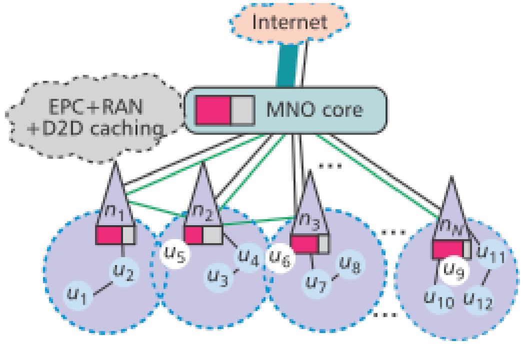


Checko et al., *Cloud RAN for Mobile Networks—A Technology Overview*, IEEE Comm. Surveys and Tutorials, 2015

Caching at RAN

- Popular content cache can be moved from network servers to packet core network and to radio network
  - NodeBs and even mobile terminals
    - ✓Minimize backhaul traffic!
  - Distributed cache is an option
    - ✓Using multicast coding, e.g. fountain codes
  - Where to cache?
  - What to cache?





Wang et al., *Cache in the Air: Exploiting Content Caching and Delivery Techniques for 5G Systems*, IEEE Comm. Magazine, 2014

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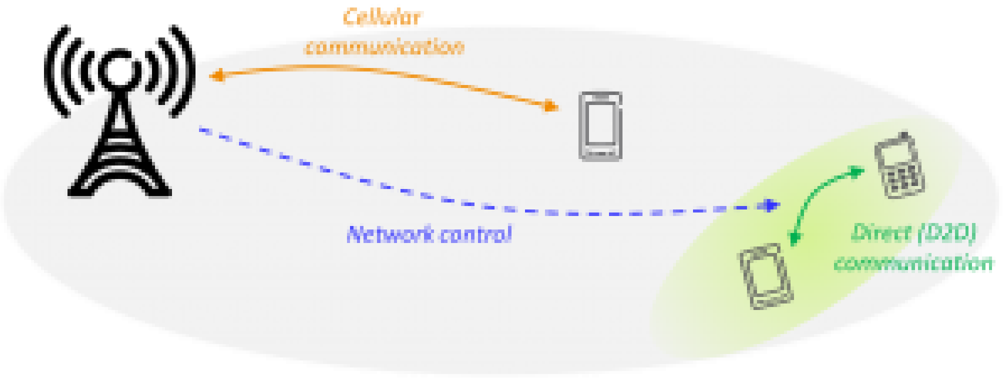
Device-to-Device (D2D)

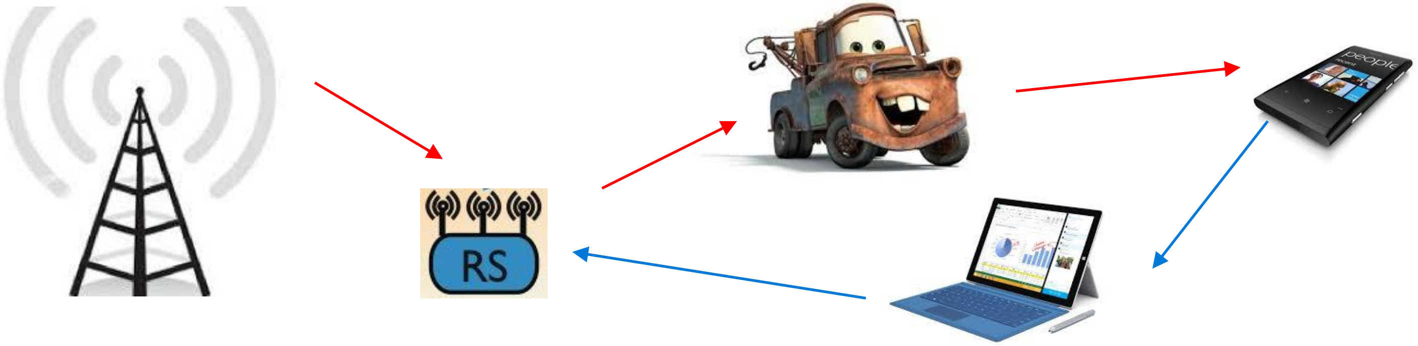
- D2D is an essential technology for 5G (not an add-on, as in 4G)
  - Shorter links, hence lower transmit power, higher data rates
  - But more complex interference scenario
  - Needed for critical communications / emergency services
- Network-controlled D2D likely
- Challenges
  - Device Discovery
  - Beamforming
  - Interference management
  - …



http://www.ericsson.com/research-blog/5g/device-device-communications/

MultiHop

- Multihop relays
  - Improve coverage and capacity
  - Reduce power consumption
  - May be essential for critical communications / emergency services
- Possibly with moving/temporary relays
  - Including device-to-device
- Dynamic routing algorithms are needed



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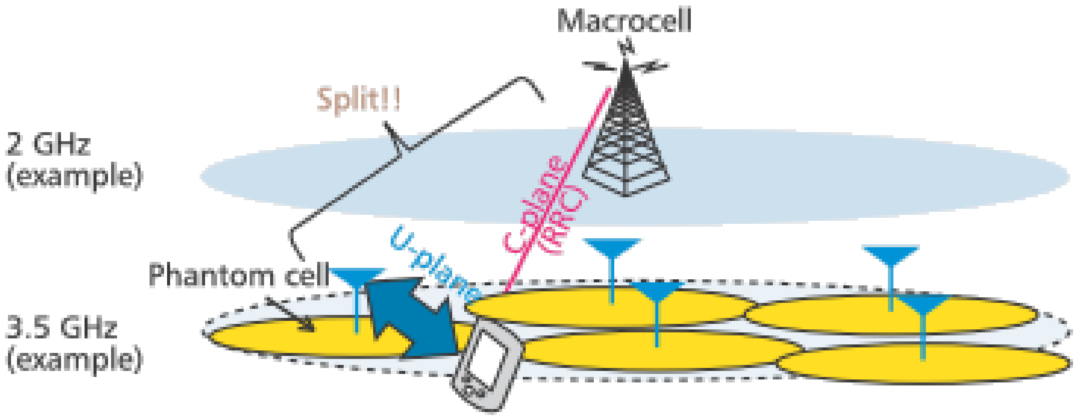
Phantom Cells

- User Plane and Control Plane will be separated
  - Signalling and resource management is done at macrocells
    - ✓facilitates mobility management
  - Data transmission can be done at small cells at higher frequencies
    - ✓Higher capacity
    - ✓Lower energy consumption



Nakamura et al., *Trends in Small Cell Enhancements in LTE Advanced*, IEEE Comm. Magazine, 2013

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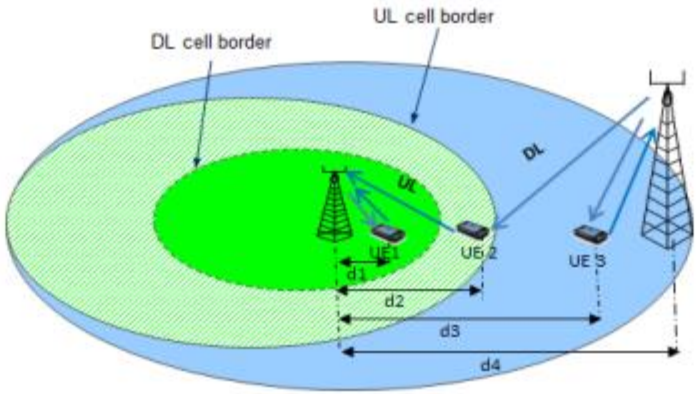
UL/DL decoupling

- Ideal serving cell can be different in Uplink and Downlink
  - In Uplink low-power transmission from UE favours nearby small cells
  - In Downlink, high-power transmission and multiple antenas configuration may favour larger cells
  - Depends also on traffic load in each cell
  - Results in higher throughput/ lower energy consumption



Elshaer et al., *Downlink and Uplink Decoupling: a Disruptive Architectural Design for 5G Networks*, Globecom 2014

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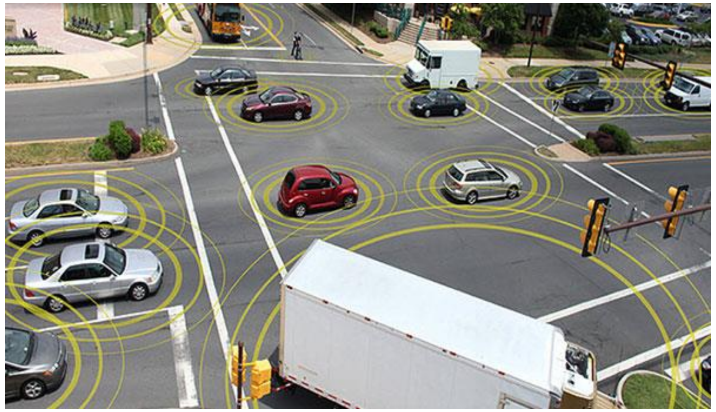
V2X

- Enabler technology for Intelligent Transportation Systems
  - Vehicle-to-vehicle (v2v)
  - Vehicle-to-Roadside infrastructure (v2i)
  - and beyond (v2x), e.g., vehicle-to-pedestrians
- D2D is enabler
- Latency and reliability are critical!
- But high mobility is a complicator
  - For PHY (Doppler spread)
  - For MAC (resource assignment)
  - For Routing / mobility management



https://autoskills.aaa.com/web/aaa/blog/-/blogs/v2x-challenges-to-deployment

Moving Networks

- Mobile Femtocells may be installed in vehicles
  - E.g, Trains, Trams and Buses
  - Can be seen as moving relay stations
- Lower energy consumption
- Higher spectral efficiency
- Reduced handover signalling
- But dynamic backhaul is a challenge

Haider et al., *A Simulation Based Study of Mobile Femtocell Assisted LTE Networks*, IWCMC 2011

Cell Sleep Mode

- Cells may be switched off when low/no traffic demand
  - High potential energy savings!
  - Reduced backhaul
  - Traffic load may vary a lot, particularly for small cells
    - ✓Fast and reliable algorithms must be devised

Turn off selected cell sites at light traffic hours

Intel, *Towards Future 5G Mobile Networks, Intel,* Globecom 2014

Self-Organizing Networks (SON)

- 5G is characterized by:
  - heterogeneous networks
  - different backhaul technologies
  - ultra-dense scenarios,
  - flexible requirements,
  - changing environment (relays, nomadic nodes, energy saving mode)

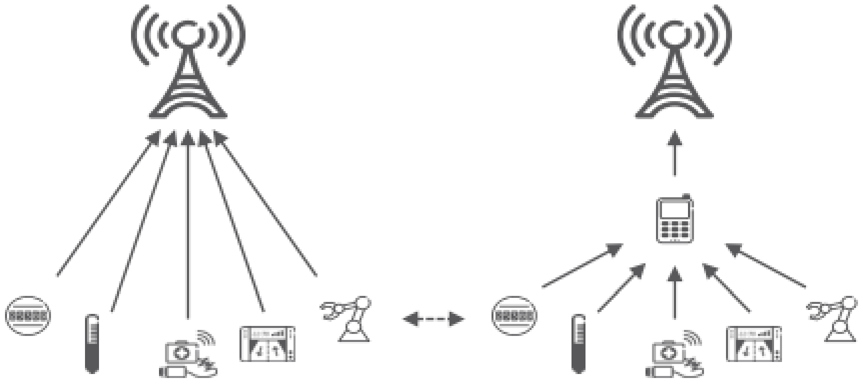
- Too complex for manually operation, SON must be taken to a new level
  - Differently from 3G/4G networks, SON is not an option for 5G, but mandatory

SON

- Challenges for SON
  - End-to-end network visibility
  - Small and large time scales
  - Focus on energy efficiency
  - Definition of the right KPIs
  - Faster action – from reactive to proactive

Massive Machine-Type Communications

- Radio Access for Internet-of-Things
- Support for tenths of billions of devices
- Each BS should keep registration of hundreds/thousands of devices
  - Many low-power devices (are off most of the time)
  - Signalling load must be kept to the bare minimum
  - Support for both connection-oriented/connectionless approach
  - Possibly unsynchronised devices
  - Contention/reservation based?



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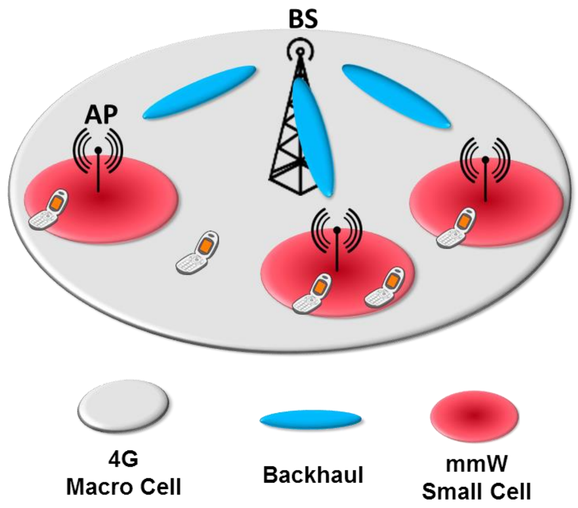
Wireless Backhaul

- 5G will rely on UDN with very large number of network nodes
  - It is not feasible to install fiber links to all of them
  - Some nodes may be moving
- Wireless backhaul is essential!
- Using Massive MIMO / millimeter waves
  - Very directive links
  - Very large bandwidths (several GHz)



http://www.miwaves.eu/

Mobility Management

- Use of small cells pose a challenge for handover
  - Control/user plane Split (phantom cells) help reduce handover overhead
  - UE-autonomous handover
    - ✓decision can be made by EU instead of network
    - ✓But with network assistance / prediction
- Moving networks is also a challenge
  - But helps reduce HO signalling
- Directive links in mmWave are also a complicator

Context Awareness

- Context Awareness may help resorce allocation
- Context includes:
  - Location Information
  - Predictive approaches
    - ✓traffic
    - ✓coverage
    - ✓channel state information
    - ✓trajectory
  - QoS requirements

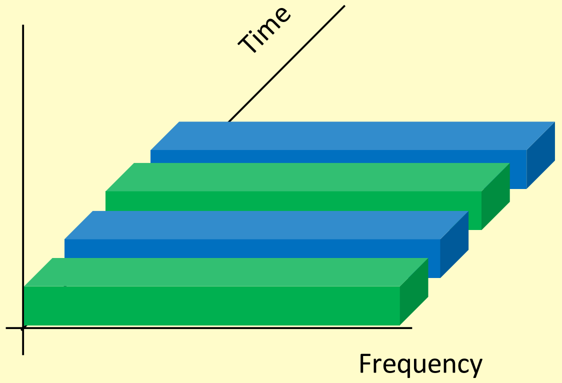
Other Issues

- Some very important issues are not covered here
  - Security
    - ✓ for cheap low-complexity machine-type devices
    - ✓For safety-critical communications (e.g., V2X)
  - AAA (Authentication, authorization and accounting)
    - ✓different technologies, possibly diferente network operators
  - OAM (Operations, Administration and Maintainance)
  - SDN (Software-Defined Networks)
    - ✓Essential for core network

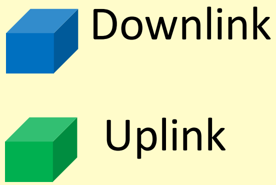
FRAME STRUCTURE

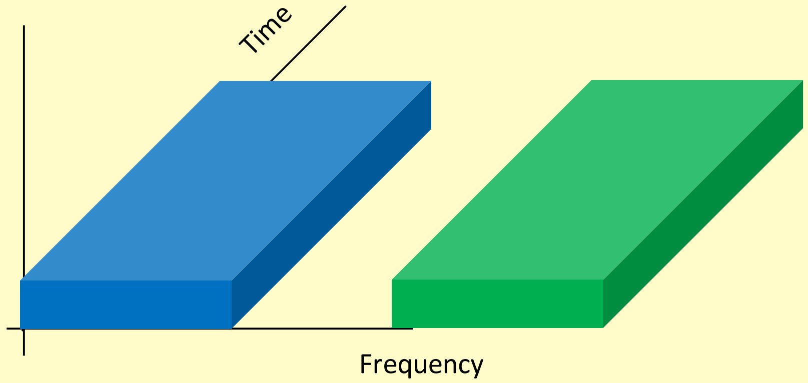
Duplexing

- So far, communication systems duplex signals either in time or in frequency, due to technical difficulties in implementing full-duplex integrated circuits.
- Consider LTE, for example, where two frame types are defined:
  - Frame Format 1: FDD
  - Frame Format 2: TDD



TDD



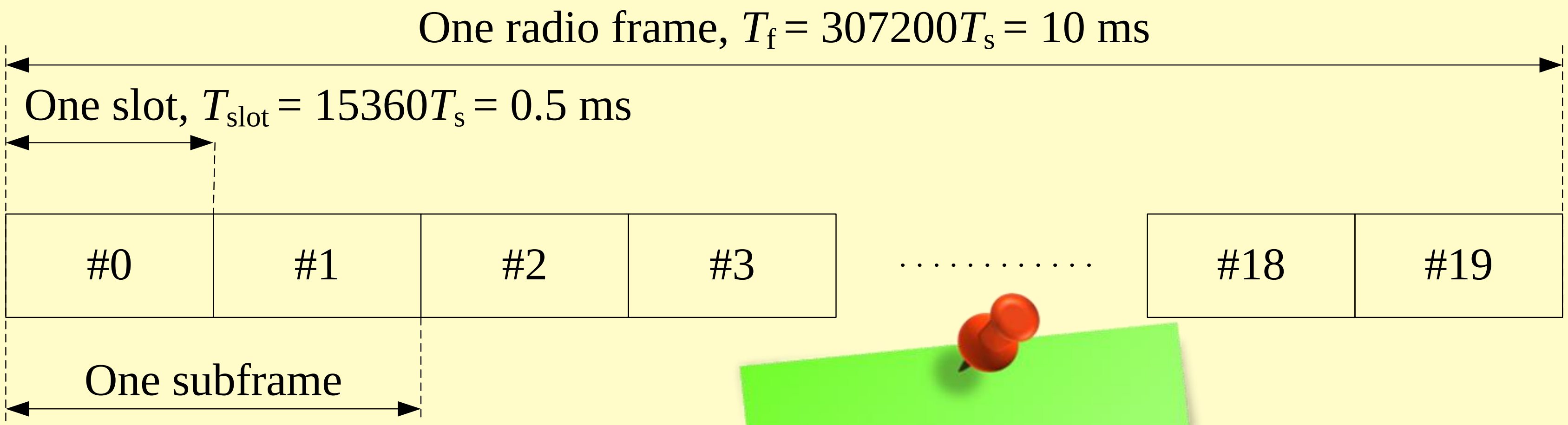


FDD

3GPP TS 36.211 V12.3.0

LTE Frame Type 1

- LTE Frame Type 1
  - FDD frame: two frequency bands are needed...

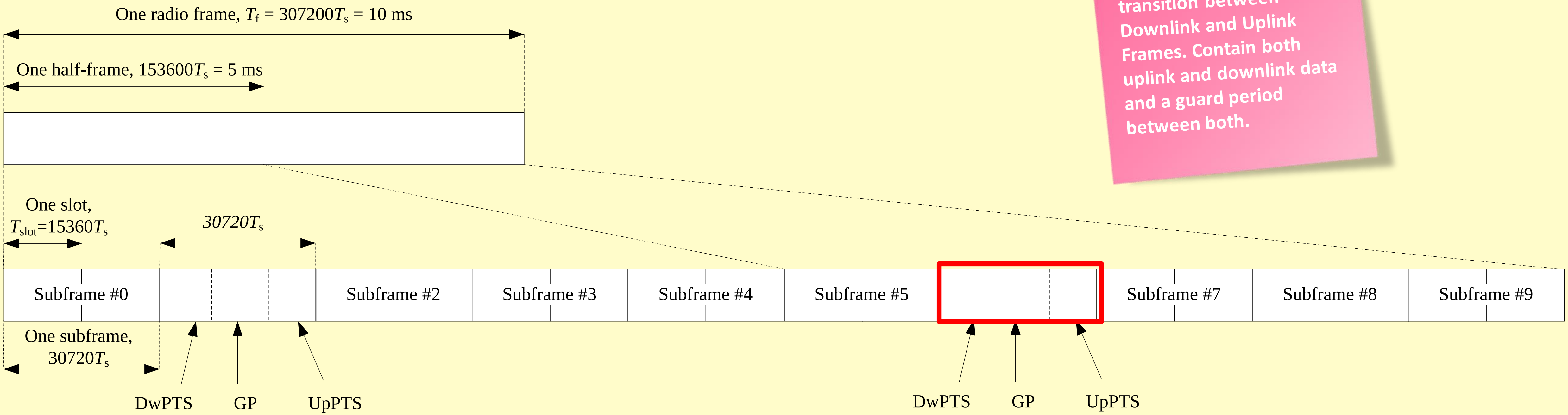


1. TTI = 1 ms
2. HARQ retransmissions: 8 ms
3. 4 ms delay considered in UE processing

3GPP TS 36.211 V12.3.0

LTE Frame Type 2

- LTE Frame Type 2 (TDD) :



Special Subframes: transition between Downlink and Uplink Frames. Contain both uplink and downlink data and a guard period between both.

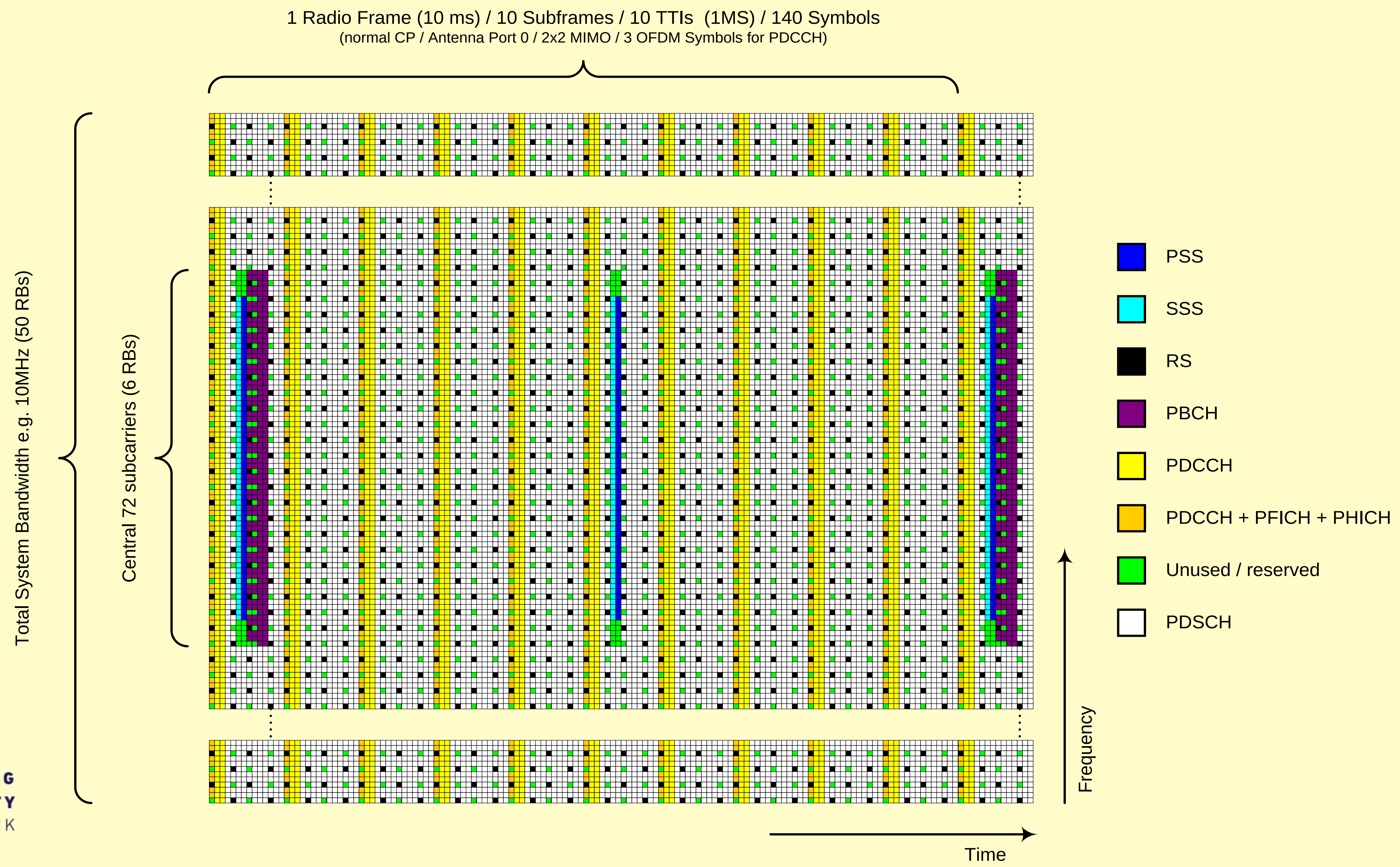
3GPP TS 36.211 V12.3.0

LTE Frame Type 2

- TDD frames also contain a certain proportion of subframes used for DL and UL, as given tin the table below.
- Change in pattern may occur periodically e.g. 640 ms
- Only 7 combinations are available...

Uplink-downlink configuration	Downlink-to-Uplink Switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

LTE Frame: DL Physical data & Control Channels



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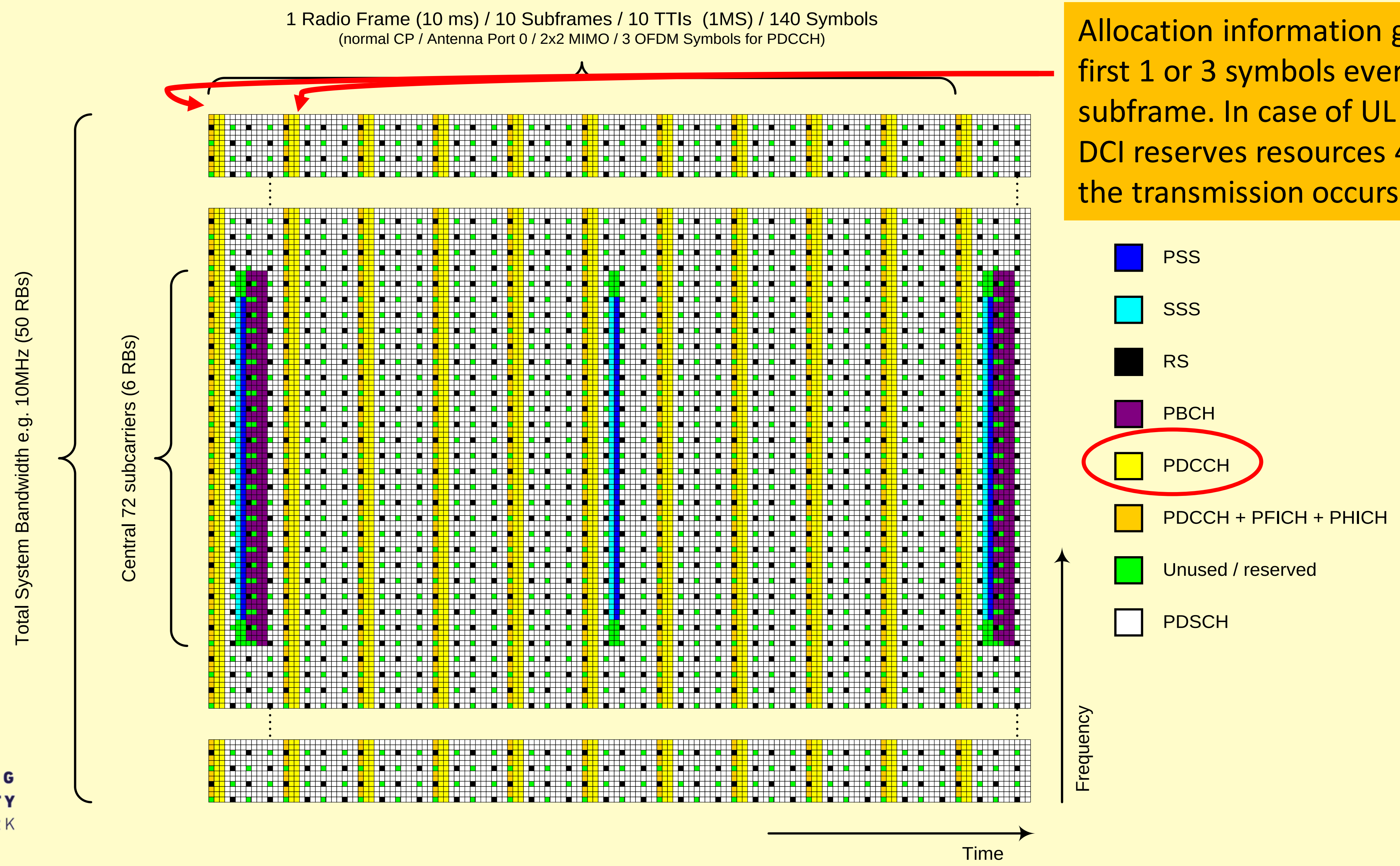
LTE Frame: DL Physical data & Control Channels



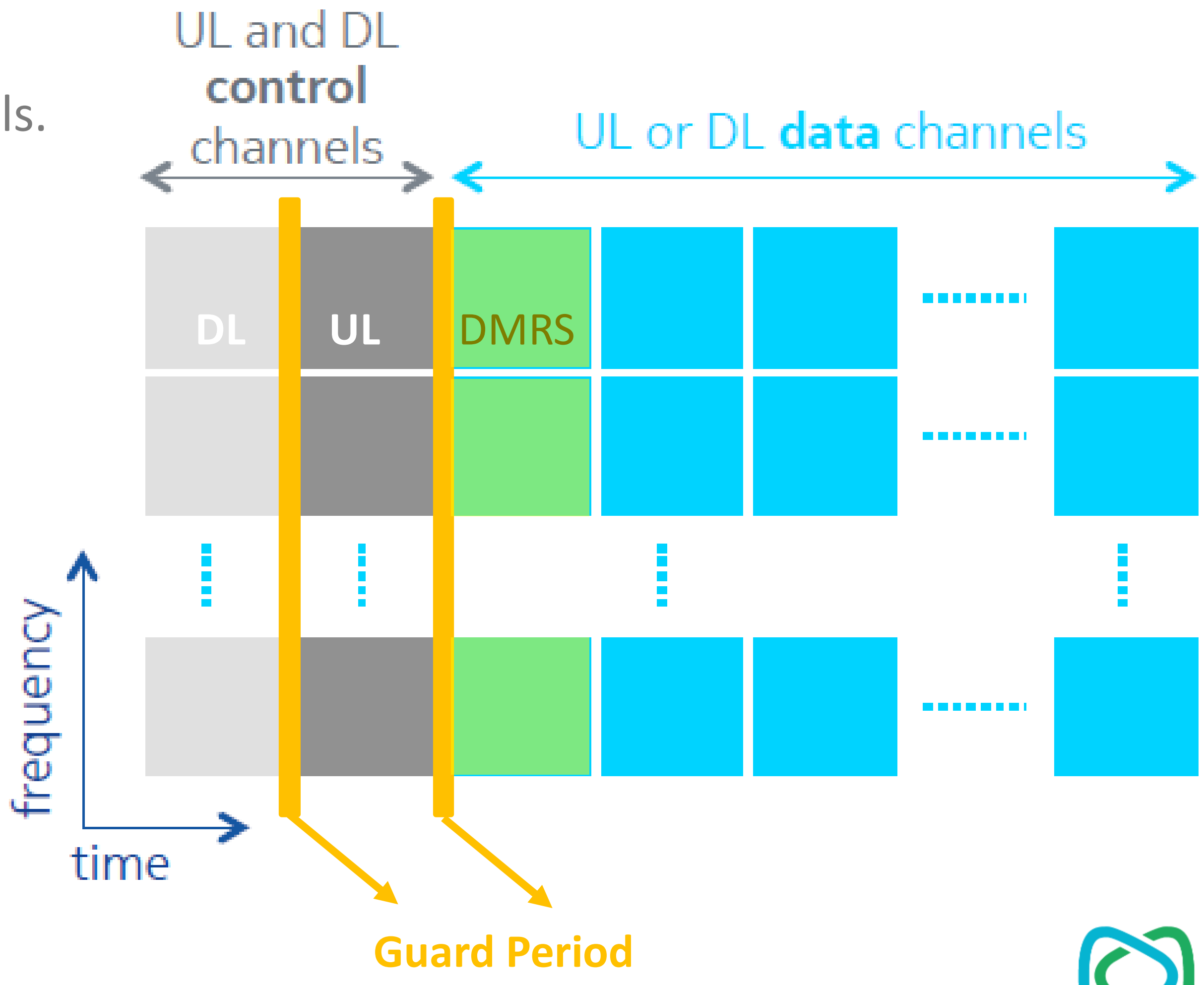
Allocation information goes in the first 1 or 3 symbols every subframe. In case of UL scheduling, DCI reserves resources 4ms before the transmission occurs (FDD)

What about 5G frame format?

- It is not defined yet, but we know that:
  - Latency should be reduced
  - A lot of different applications must be supported, take for example:
    - ✓ Broadband connections with large packets and high data rate.
    - ✓ Sensors with small packets and low energy consumption.
- Some proposals were already made:
  - Dynamic TDD
  - Full Duplex frame

Dynamic TDD

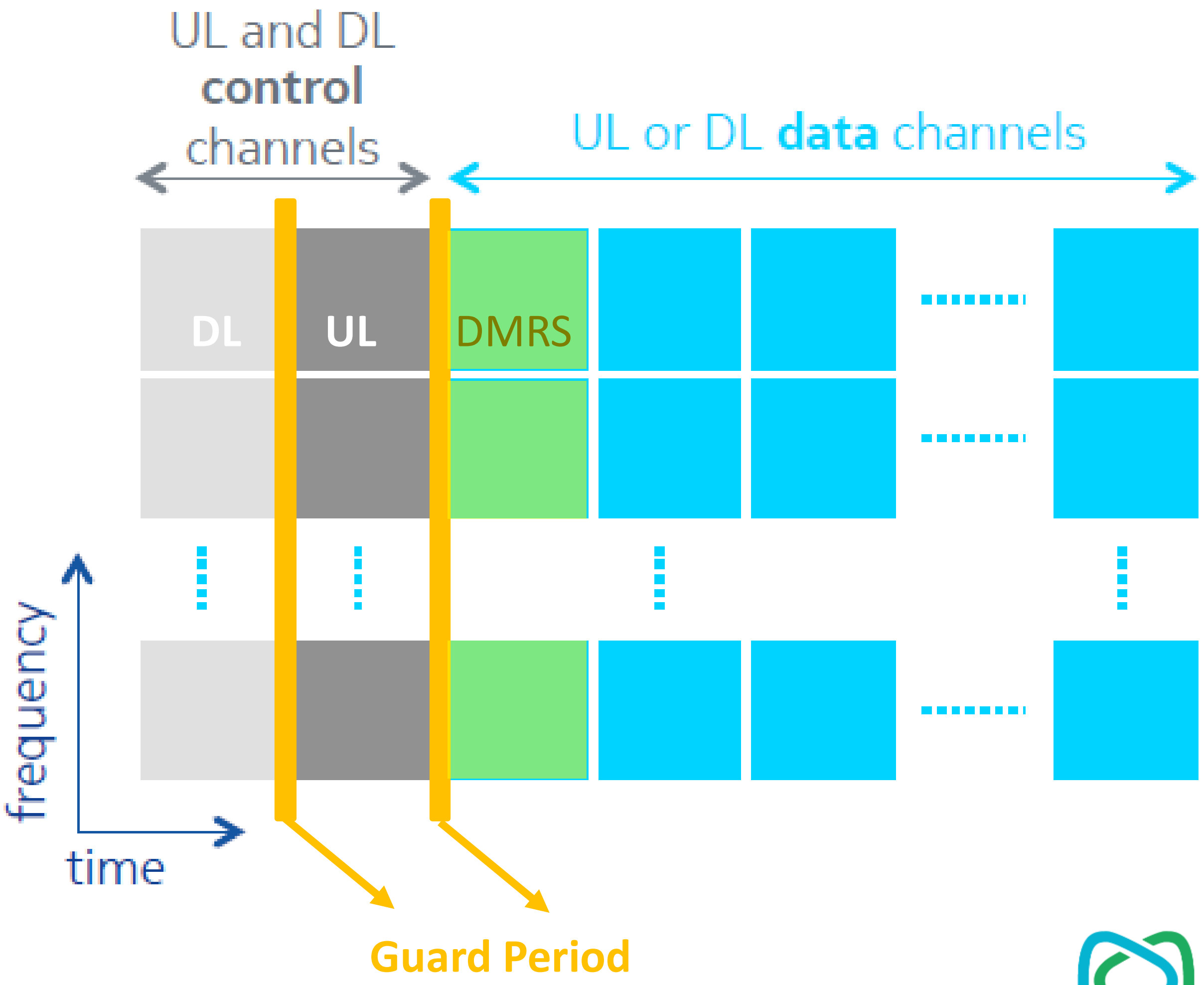
- The proportion of UL and DL frames is not fixed. Any configuration is possible.
  - Separation of Control Channels and Data Channels.
    - ✓ Short guard period inserted every switch of transmission direction
    - ✓ Cost-effective pipeline processing at the receiver
    - ✓ Reduced Latency
  - The first symbol in the data part is reserved for transmission of DMRS (DeModulation Reference Sequence) : to enable channel estimation at the receiver.



Mogensen, Preben, et al. "Centimeter-wave concept for 5G ultra-dense small cells." *Vehicular Technology Conference (VTC Spring), 2014 IEEE 79th*. IEEE, 2014.

Dynamic TDD

- Frame length is assumed to be 10 times lower than LTE’s
  - Overall latency in the order of 1 ms
- Uses the same access technique for both DL and UL:
  - Easy multihop,
  - self-backhauling
  - direct device-to-device communication in a cost-efficient way
- Challenges
  - Synchronization
  - Interference



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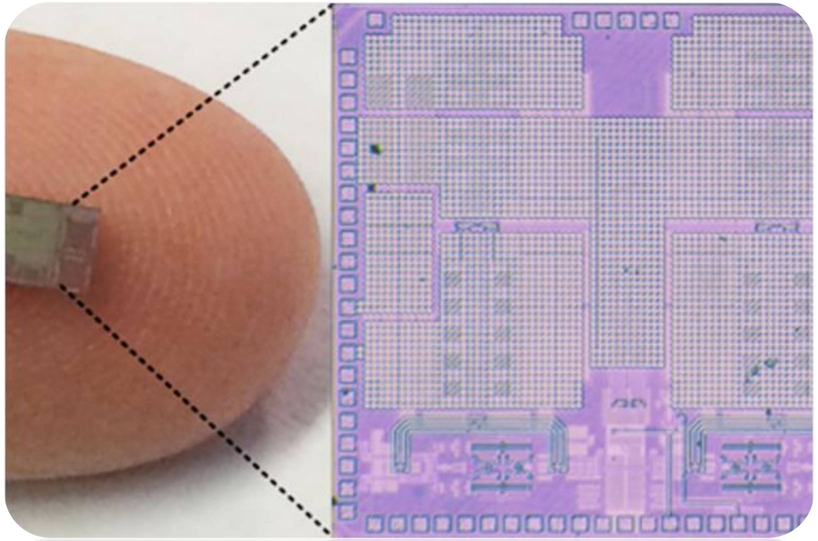
Mogensen, Preben, et al. "Centimeter-wave concept for 5G ultra-dense small cells." *Vehicular Technology Conference (VTC Spring), 2014 IEEE 79th*. IEEE, 2014.

Full Duplexing

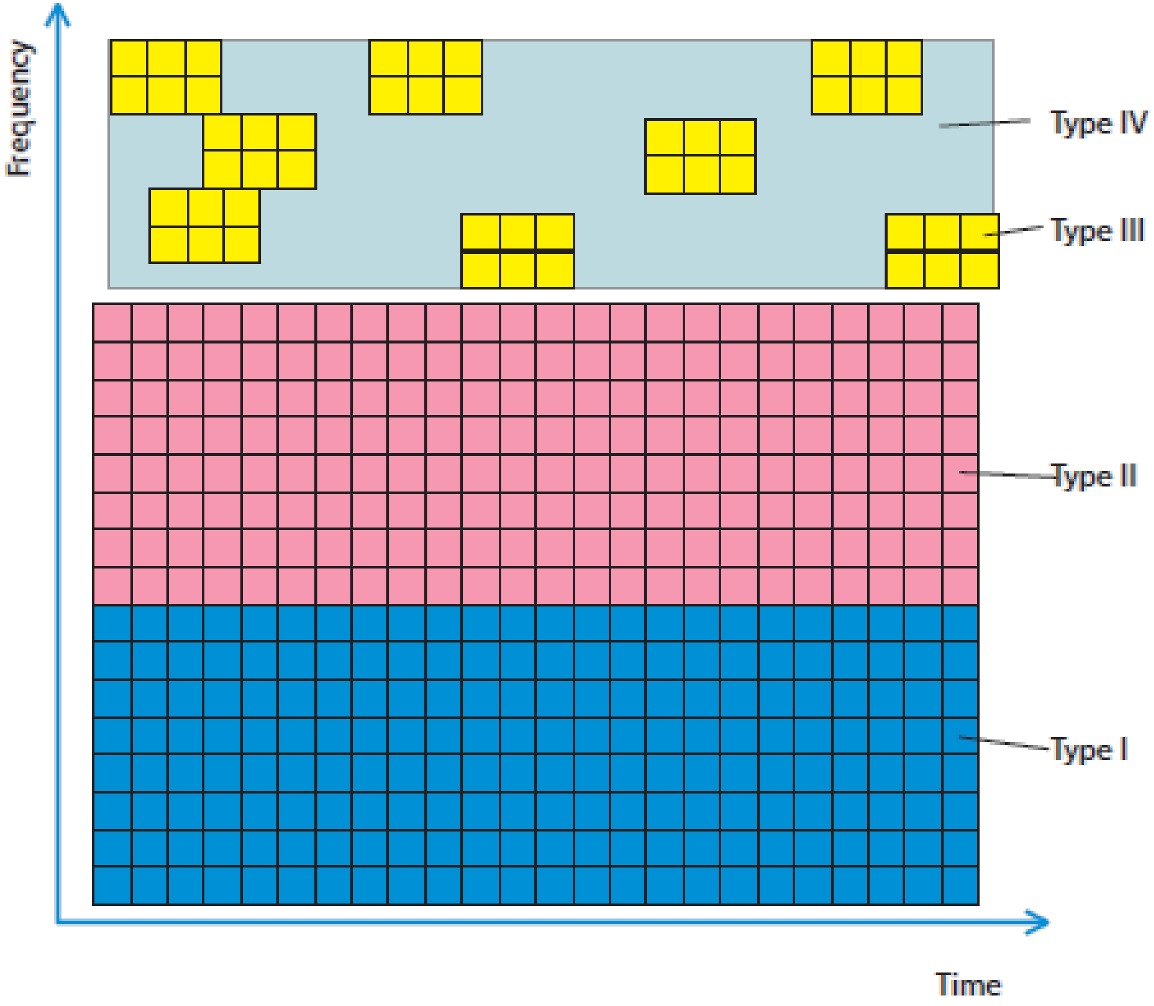


- Another proposal to meet 5G requirements is the use of full duplex radios.
- Challenges
- Self-interference cancellations
  - Antenna Cancellation using asymmetric placement of TX
  - Analog cancellation with cancellation circuits that reconstruct a copy of transmitted signal and subtracts it.
  - Digital cancellation
- DL to UL Interference mitigation
- Battery usage

Han, Shuangfeng, et al. "Full duplex: Coming into reality in 2020?." *Global Communications Conference (GLOBECOM), 2014 IEEE*. IEEE, 2014.
http://www.theregister.co.uk/2015/03/26/full_duplex_transciever_for_mobiles_of_the_future/

Unified uplink frame structure

- Unified uplink frame structure
  - Enables mix of synchronous and asynchronous and orthogonal / non-orthogonal traffic types
  - High volume data transmission and high-end spectral efficiency still exploits orthogonality and synchronism wherever possible (Type 1 and 2).
  - Sporadic traffic type exploits contention-based access technique (Type 3)
  - Sensor type traffic would stretch the transmissions in time, for it is an energy efficient approach (Type 4)

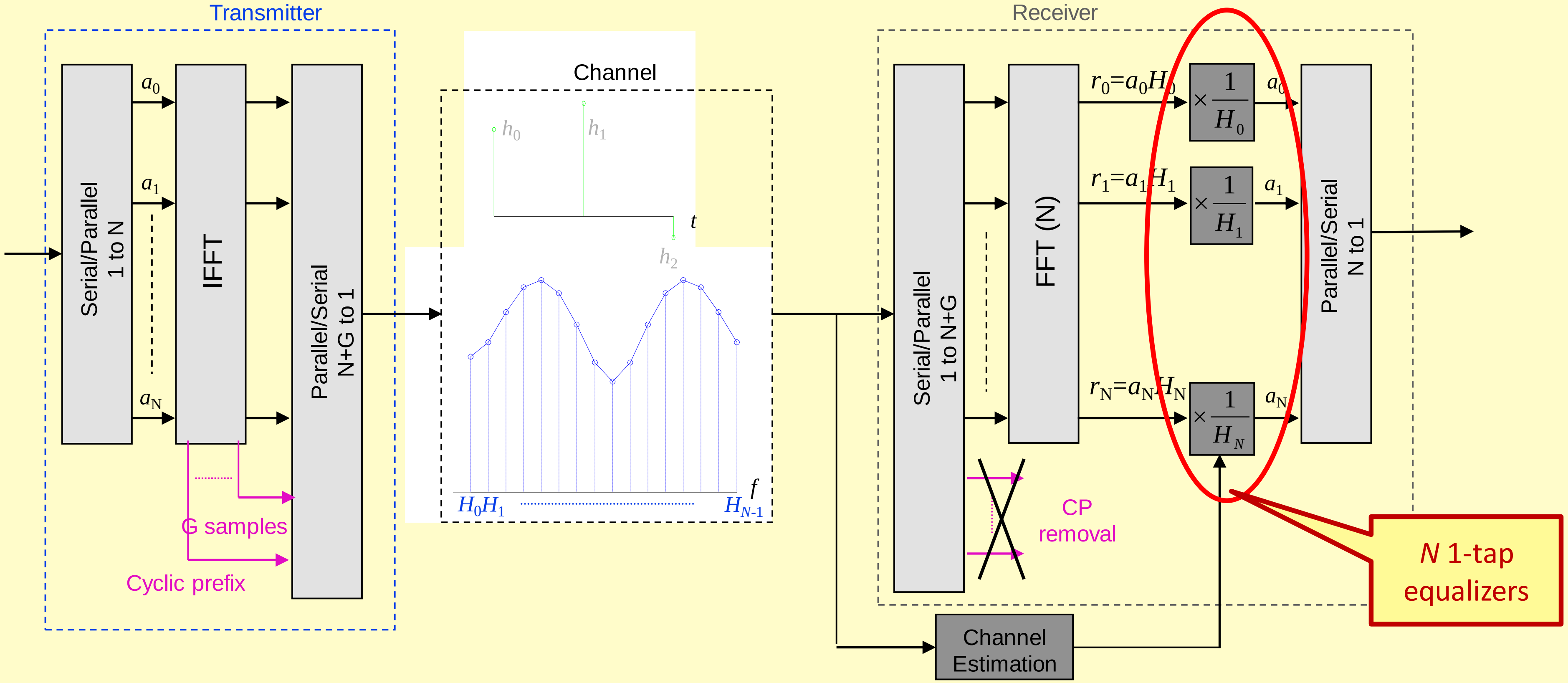


Wunder, Gerhard, et al. "5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications." *Communications Magazine, IEEE* 52.2 (2014): 97-105.

AIR INTERFACE
MODULATION AND CODING

OFDM (Orthogonal Freq. Div. Mux.)

- OFDM is the currently preferred technique for broadband wireless
  - 4G (3GPP-LTE), WiFi (IEEE 802.11), Digital TV (DVB/ISDB), among others
- Reduced and fixed equalization complexity for large number of multipaths (depends on FFT size)



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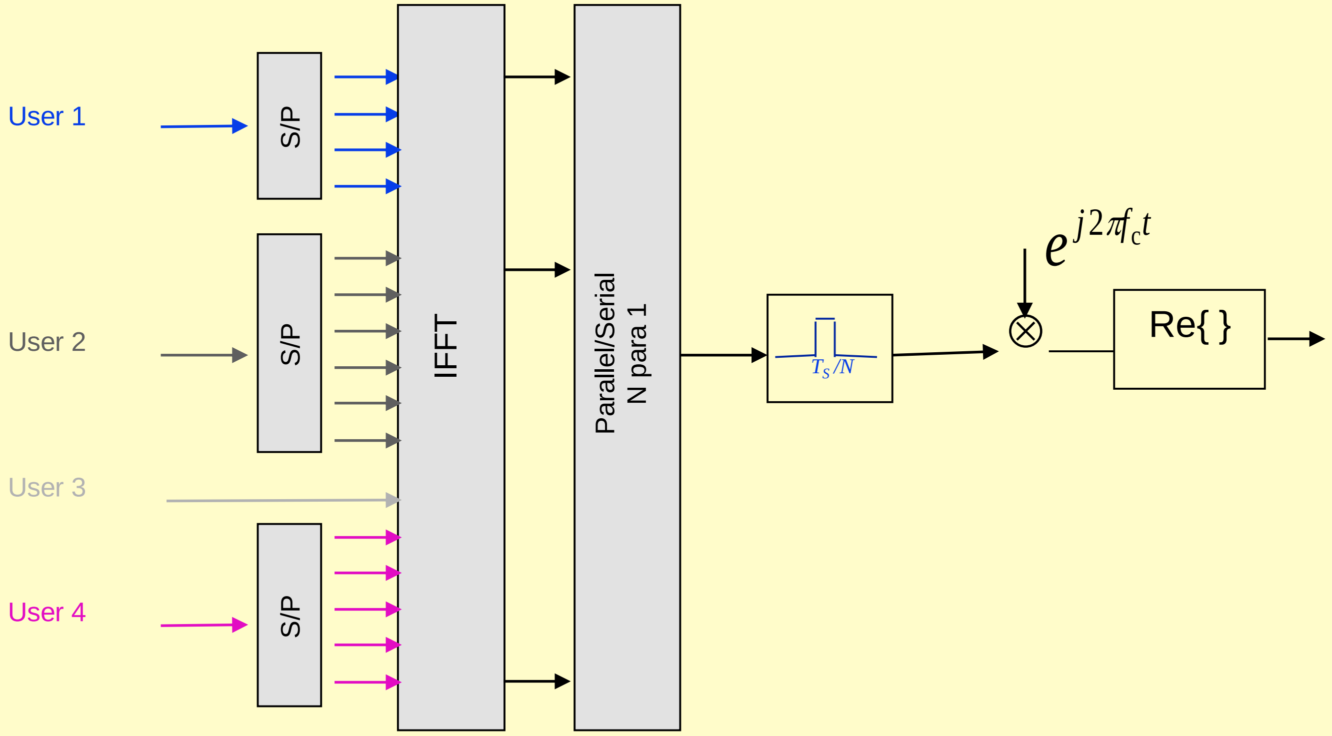
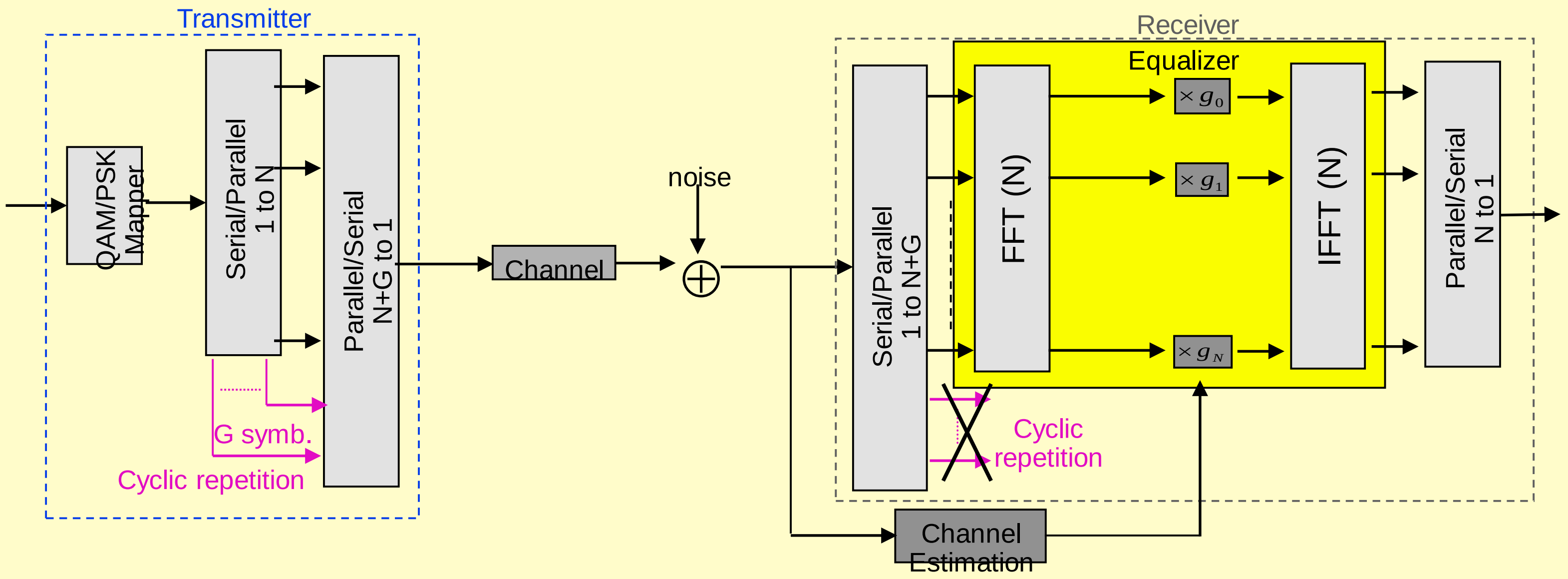
OFDMA (Ort. Freq. Div. Multiple Access)

- Flexible resource allocation
- Frequency-domain resource assignment is possible
  - If channel state information is known
  - Allows multiuser diversity



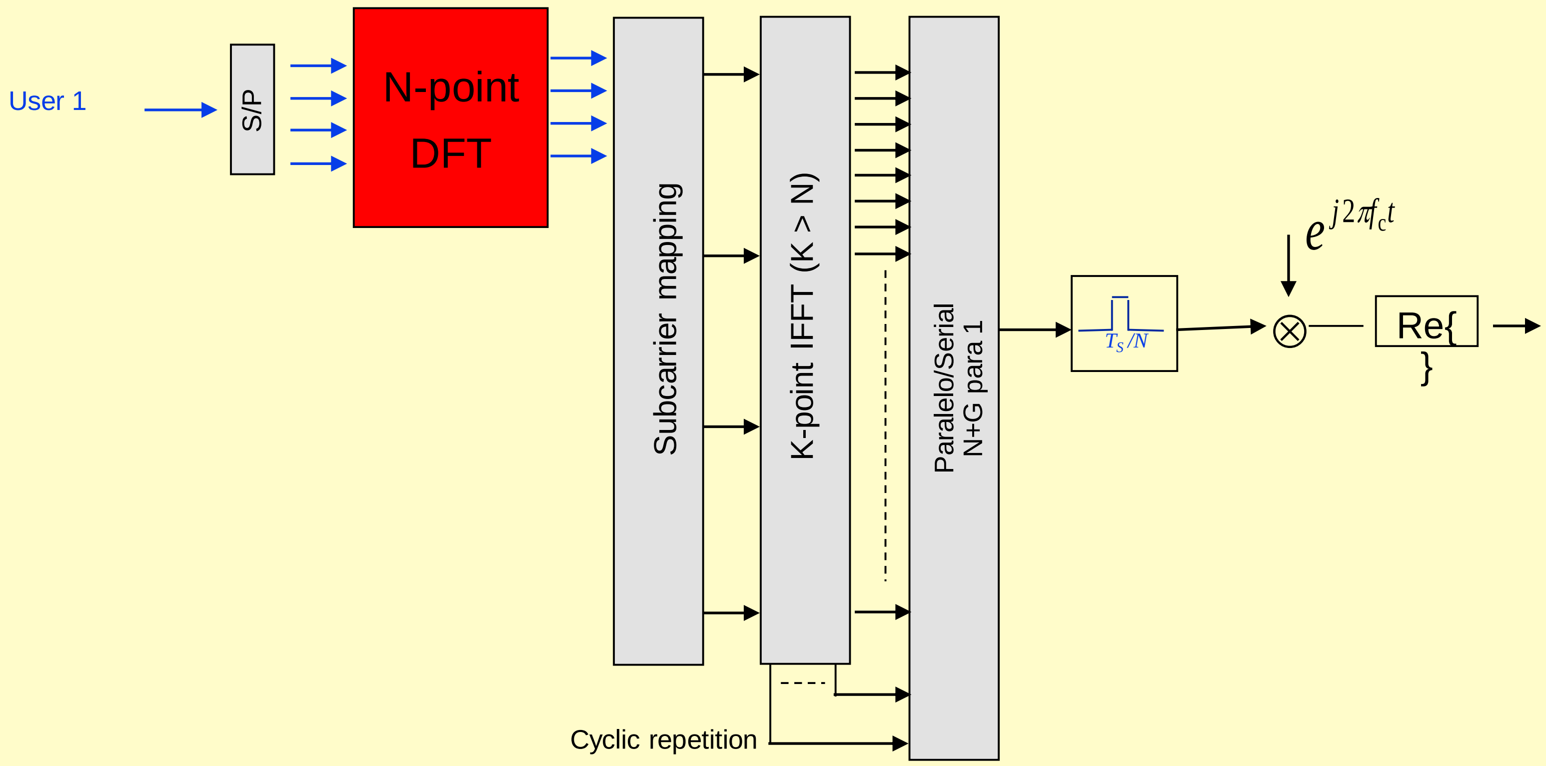
SC-FDE (Single-Carrier Freq. Domain Equalization)

- OFDM has a large Peak-to-Average Power Ratio (PAPR)
  - Power amplifiers must be overdimensioned and operate ineficiently
  - Especially unfavourable for UL, transmitting user equipments (UE)
- Blockwise Frequency-Domain Equalization approach can also be applied to single-carrier modulation (if guard interval is included)



SC-FDMA

- Multiple users can be allocated to different subcarriers by applying a DFT on the single-carrier signal
- Also known as DFT-spread (DS) OFDM
- Used in 4G Uplink

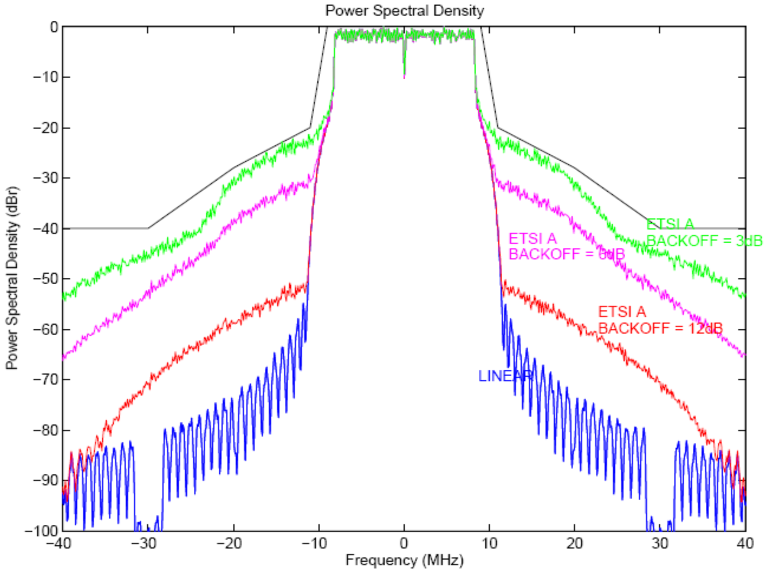


Do we need a new waveform?

- Different scenarios
  - Below 3GHz
    - ✓ “business as usual” (for now)
  - 3GHz< f < 30GHz (cmWaves)
    - ✓ Ultra-dense Networks
    - ✓ Many different types of users
  - >30GHz (mmWaves)
    - ✓ Beamforming
      - Low interference
      - Small delay spread

Do we need a new waveform?

- Motivations
  - Spectral containment
    - ✓ Well-defined sub-bands (flexibility)
  - Loose synchronization requirements
    - ✓ Less PRACH interactions (lower faster signalling)
    - ✓ Particularly relevant for machine-type communications
  - OFDM has some drawbacks
    - ✓ Relatively large sidelobes
    - ✓ Requires time/frequency synchronization to maintain orthogonality



- Most likely one single technique for al links
  - Use of D2D / V2X / multihop eliminates the distinction between UL/DL
  - Makes interference cancellation easier

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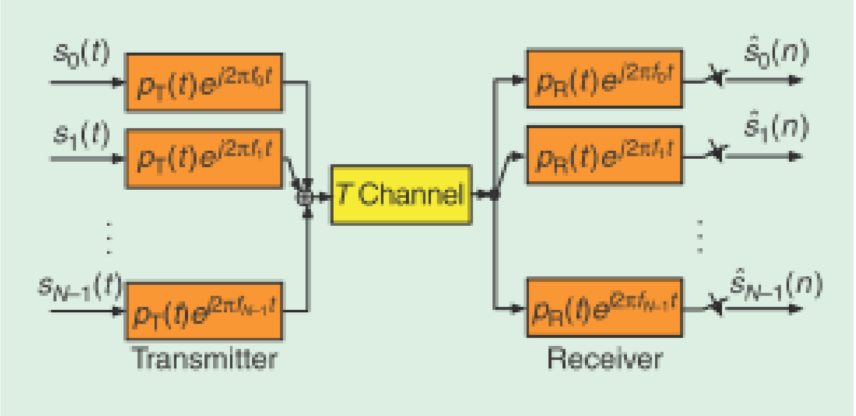
New Waveforms

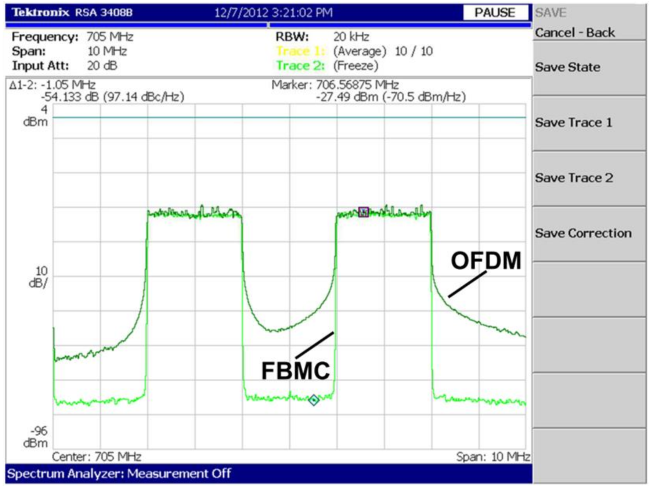
- Several candidates are being proposed in the literature
  - FBMC UFMC
  - GFDM
  - ZT-DS-OFDM
  - Faster-than-Nyquist

FBMC (Filterbank Multicarrier)

- Each subcarrier is filtered by a frequency shifted prototype filter
- OFDM is actually a particular case of filter-bank modulation
  - Prototype filter is a `rect` (in time domain) / `sinc` (in frequency domain)
    - ✓ with large sidelobes
    - ✓ But orthogonal subcarriers
- Other prototype filters with lower out-of-band radiation may be used
  - But orthogonality may be lost
  - More efficient with OQAM



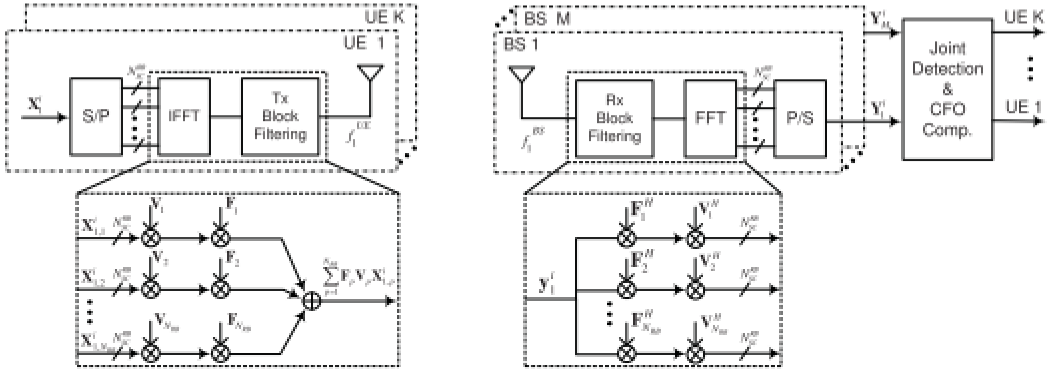
Farhang-Boroujeny, *OFDM versus Filterbank Multicarrier*, IEEE Signal Proc. Mag., 2011.

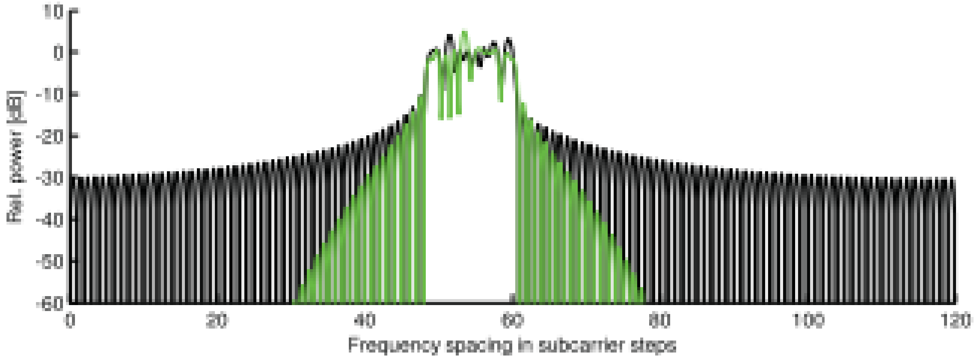


http://www.ict-qosmos.eu/

UFMC (Universal Filterbank Multicarrier)

- It’s an extension of FBMC
- Filter is applied on blocks of OFDM subcarriers instead of on each individual subcarrier

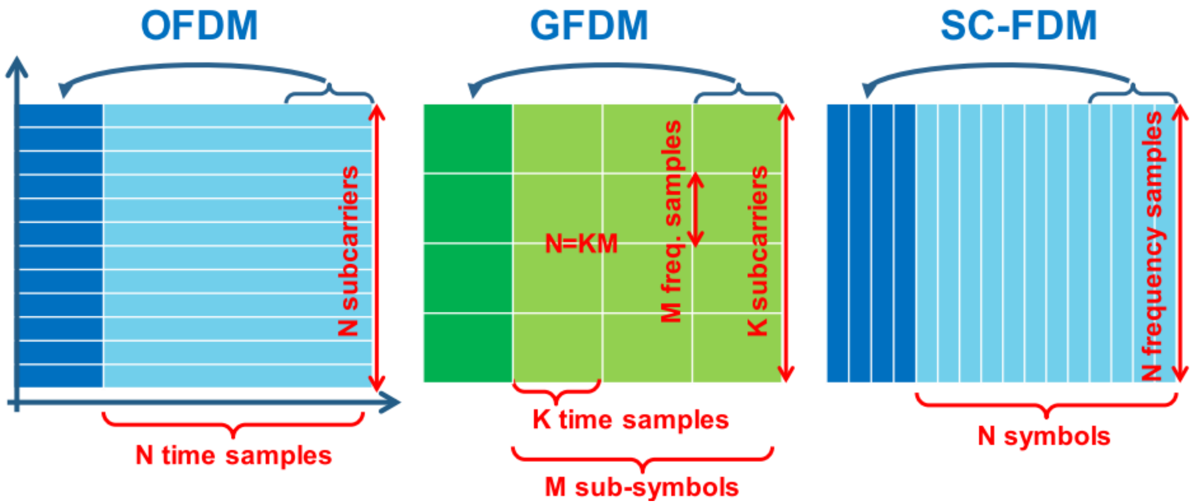




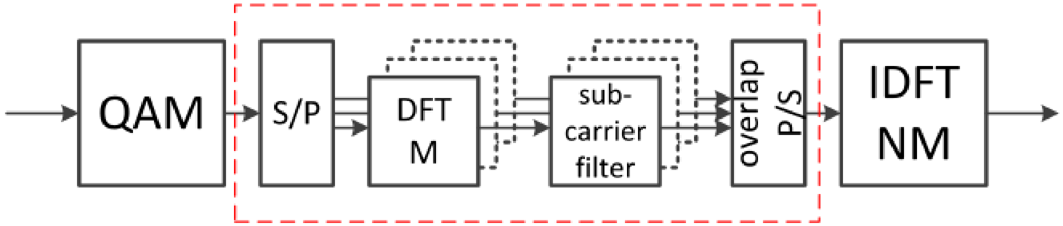
Vakilian, *5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications*, Globecom 2013

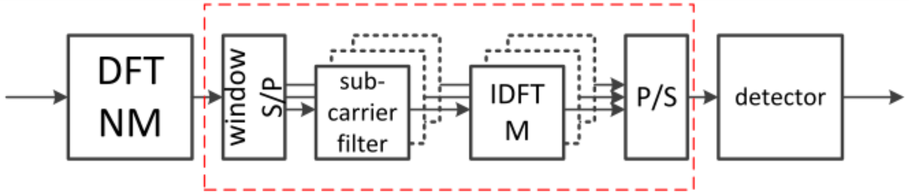
GFDM (Generalized Freq. Div. Multiplexing)

- Block-based approach
  - One cyclic prefix per block of symbols
- Tail-biting (circular) filtering for reduced filter overhead



Fettweis, *Designing A Possible 5G PHY With GFDM*, 5G Workshop, Globecom 2014





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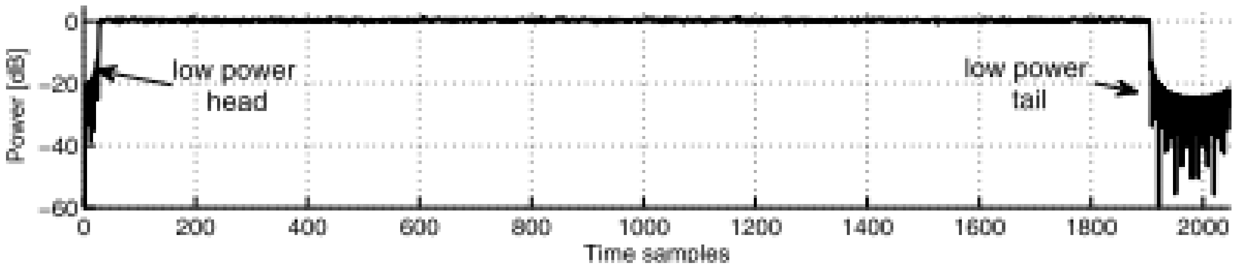
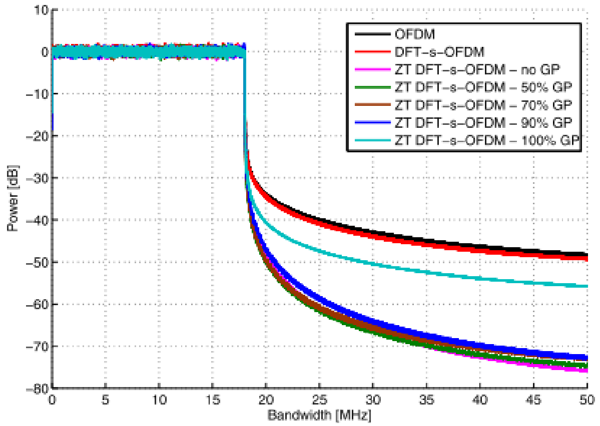
ZT-DS-OFDM (Zero-Tail DFT-Spread OFDM)

- Similar to DS-OFDM (SC-FDMA)
  - With zero-tail instead of cyclic prefix
  - ZT inside FFT length
    - ✓Different users may have diferente guard intervals
  - Low-power head guarantees low out-of-band radiation





Berardinelli et al., *On the potential of zero-tail DFT-spread-OFDM*, VTC-Fall 2014

Faster-than-Nyquist

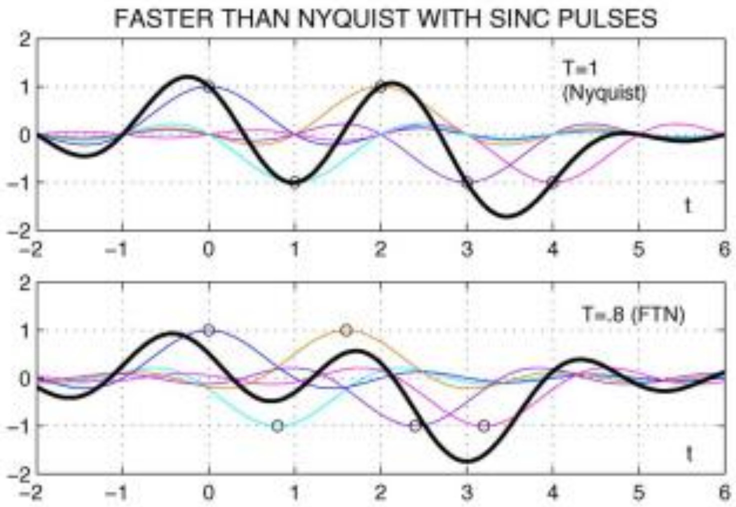
- Nyquist criterion for zero inter-symbol interference

$$\sum_{i=-\infty}^{\infty} P\left(f - \frac{i}{T_S}\right)$$

  - Lowest bandwith can be achieved with `sinc` pulses,
    - ✓ $B = R_S$ (*roll-off* = 0)
- Lower bandwidth can be achieved if ISI is allowed
  - Partial-response signals
  - Capacity increases

$$C_{\text{PSD}} = \int_0^{\infty} \log_2\left[1 + \frac{2P}{N_0}|H(f)|^2\right] df \text{ b/s.}$$

  - But equalization / interference cancellation is needed



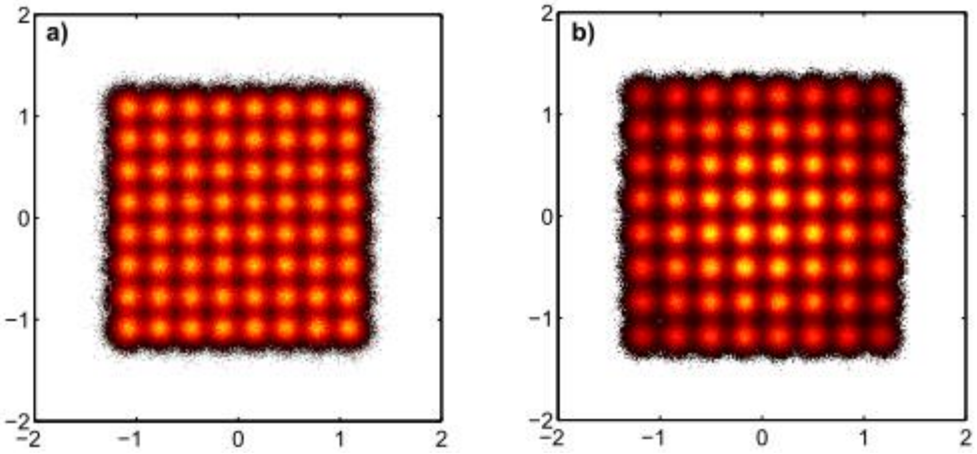
Anderson, *Faster-Than-Nyquist Signaling*, Proc. of the IEEE, 2013

Or OFDM???

- It still not clear whether we really need to abandon OFDM
  - Orthogonality makes MIMO easier...
- Complexity of other techniques is (much) higher
  - This can be a particularly important issue in 5G
    - ✓Very large bandwidths (>200MHz) , consequently large number of subcarriers
    - ✓Cheap and energu-eficiente devices are needed for IoT
    - ✓But, on the other hand, Moore's law is still valid (but for how long?)

Higher-Order Modulation Schemes

- High data rates and high spectral efficiency require
  - Multiple antennas
  - Higher order modulation schemes
    - ✓256 / 512 / 1024 – QAM
      - RF imperfections like I-Q imbalance/phase noise may cause an unacceptable error floor
      - Non-square / non-uniform constellations may be employed



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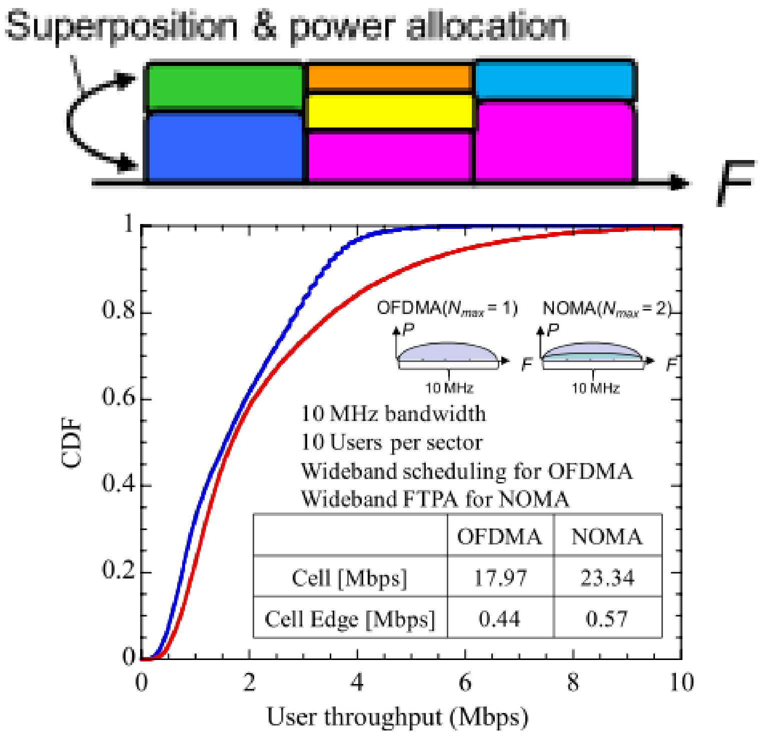
NOMA/SCMA

- Instead of the orthogonal multiple access from OFDMA
- NOMA (Non-Orthogonal Multiple Access)
  - Users are superposed in code and power domain
  - Requires interference cancellation at receiver
- SCMA (Sparse-Code Multiple Access)
  - Multiuser superposition coding using multidimensional codewords
  - Lower-complexity receiver algorithms are possible due to sparse codes
- Higher spectral efficiency



	OFDMA	NOMA
Cell [Mbps]	17.97	23.34
Cell Edge [Mbps]	0.44	0.57

Saito, *Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access VTC-Spring*, 2013

Error control in 4G

- Turbo and LDPC codes are known to get very close to the theoretical Shannon limit
  - Used in LTE (Turbo) and IEEE 802.11n/ac (LDPC)

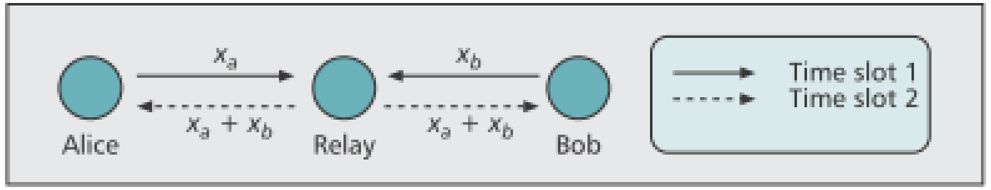
- HARQ can further help achieve low BER with adaptive code rate
- Very low BER can be achieved by ARQ

Do we need new coding schemes?

- Very low BER ($<10^{-10}$) is needed for critical services
  - LDPC/turbo are very efficient for higher BERs, but have an error floor (depending on the code length)
- IoT may use short packets
  - But good codes (LDPC/turbo) usually require long codewords
- Low latency is one of the requirements in 5G
  - HARQ and ARQ cannot be applied in this case
- Energy-efficiency is also a requirement
  - But good iterative decoding algorithms are very power hungry
- Polar Codes have been recently suggested, achieving channel capacity
  - But practical implementations are still a long way

Network Codes

- Coding for a point-to-point link is a (nearly) closed issue
  - LDPC/Turbo/Polar codes
- But on a network level, many gains can still be (possibly) obtained
- Network Codes can bring about potential gains in multihop networks
  - Both at network-level (using binary operations) and PHY-level



Fu et al., *COOPERATIVE WIRELESS NETWORKS BASED ON PHYSICAL LAYER NETWORK CODING*, IEEE Wireless Communications, 2010

INTERFERENCE CONTROL

The interference Problem

"No man is an island …" (John Donne – 17th century English Poet)

"… No **CELL** is either" (Telecom Engineer - 21st century)

- Interference is one big concern in cell network deployments.

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The interference Problem

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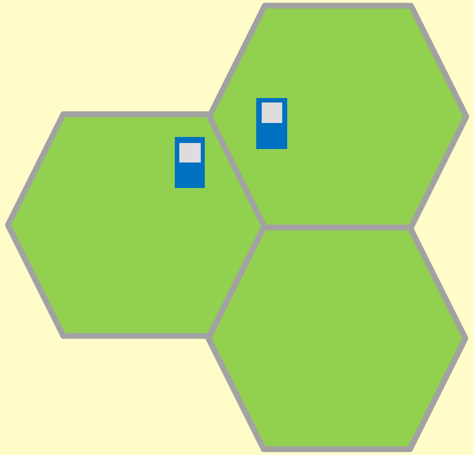
- Interference is one big concern in cell network deployments.
  - Since first generations, interference is a big problem degrading cell-edge performance.
    - ✓ Every cell is surrounded by other network cells
    - ✓ Inter Cell Interference
    - ✓ Reuse Factor



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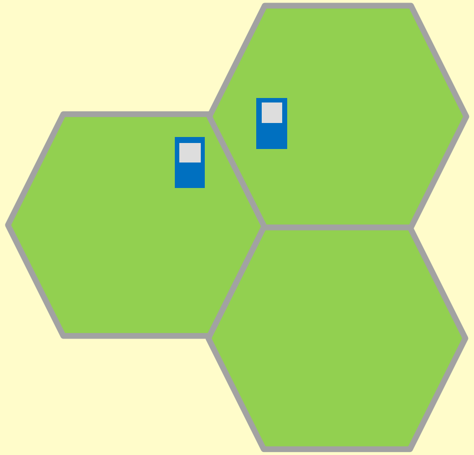
  - Since first generations, interference is a big problem degrading cell-edge performance.
    - ✓ Every cell is surrounded by other network cells
    - ✓ Inter Cell Interference
    - ✓ Reuse Factor
- LTE was designed to reuse all available resources in all its cells (Reuse Factor = 1)
  - At first, LTE relied on fast UE feedback to cope with interference:
    - ✓ Adaptive Modulation and coding
    - ✓ HARQ
    - ✓ Fast Scheduling



But, with increased network traffic the **interference problem** has evolved too.

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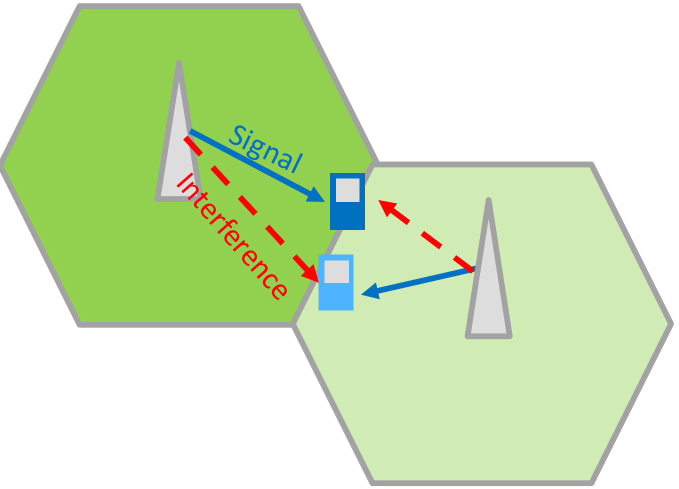
Interference Scenarios

- Increased Traffic. Densification. HetNets. Better Cell-Edge experience.

  …but wait. There is no free lunch! See some examples:

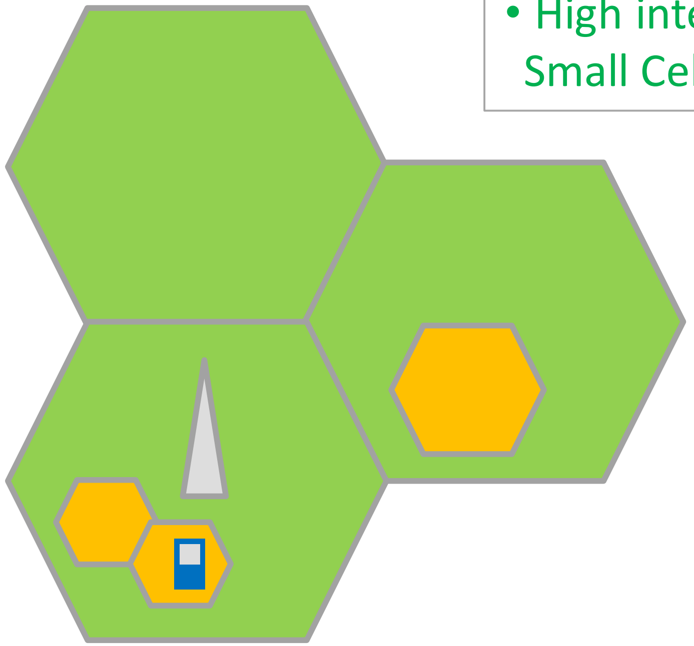
Scenario 1



- Massive Traffic : Several Users
- High interference for cell edge users
- Low SINR
- Impact in throughput

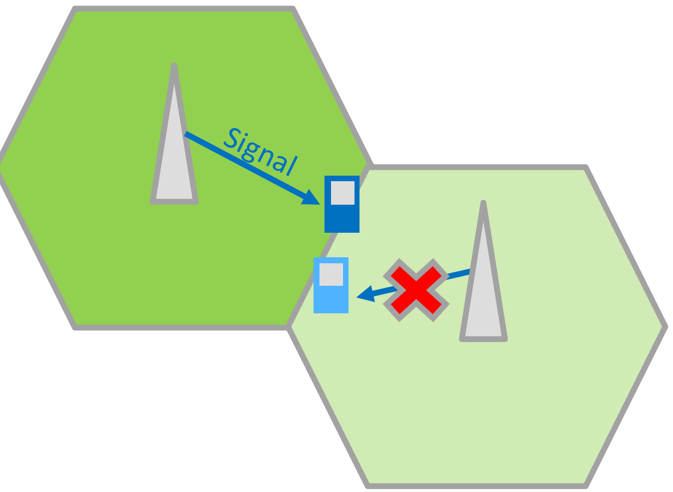
Scenario 2

- Densification: HetNets
- Small Cells coexisting with Macro Cells
- High interference from Macro to Small Cell

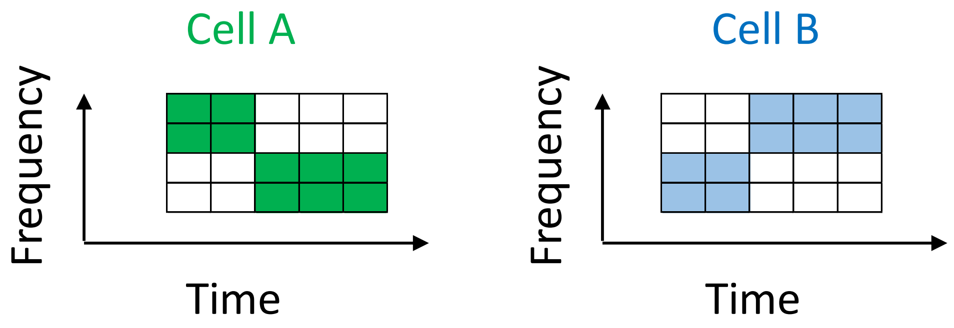


ICIC

- LTE Release 8 presented ICIC (Inter-Cell interference Coordination)
  - ICIC Prevents neighbor cells of using same resources at cell edge to minimize interference.
  - Requires coordination between eNBs via X2 Interface.



- Mutually Exclusive resource reservation for cell-edge users:

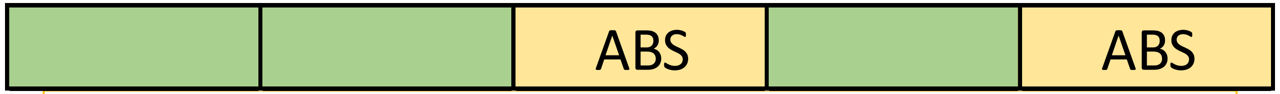


  - Mid-cell users may reuse the same resources in different cells.

- It does not solve the problem for the HetNet Scenario.
- Reduced Cell Throughput

e-ICIC

- LTE Release 10 presented e-ICIC (enhanced ICIC)
  - Allows resource partitioning between macro and small cell.
    - ✓ Almost Blank Subframe (ABS)

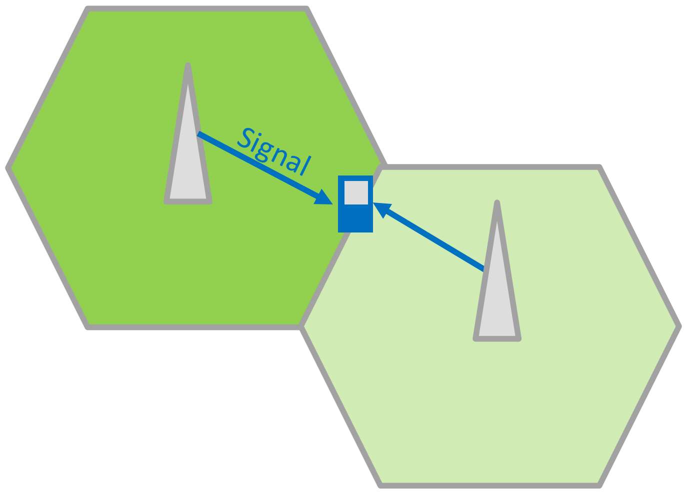


Macro Cell does not send data traffic on ABS.
“Hey, small cell! I will relax a little. I won’t bother you for now” (Macro Cell)

  - HeNB is also expected to adjust its power to avoid interference to other cells
  - Reduced Cell Throughput

COMP

- What if we **USE** the interference instead of trying to cancel it?
  - COMP (Coordinated MultiPoint – Release 10)



- Improve performance by using same resources at cell edge.
  - Joint Processing;
  - Beamforming;
  - COMP Reception (UL)
- Joint Processing:
  - Two cells transmit the SAME information
  - UE Combines the signals
  - Improved SINR
- Coordinated Scheduling and Beamforming (CS / CB)
  - Phase applied in the transmitted signal to make it directive
  - Allows resource reuse: different eNBs transmit in different beams
- COMP Reception:
  - Different eNBs receive UE signal
  - They combine the received signal
  - UE does not need to be aware of COMP

COMP

- COMP Requires Fast Coordination
  - Increased backhaul utilization
  - Scheduling has to be strictly coordinated between Cells:
    - ✓ But there is no RNC in LTE
    - ✓ One eNB will be the controlling eNodeB
  - Near zero delay required between the cells

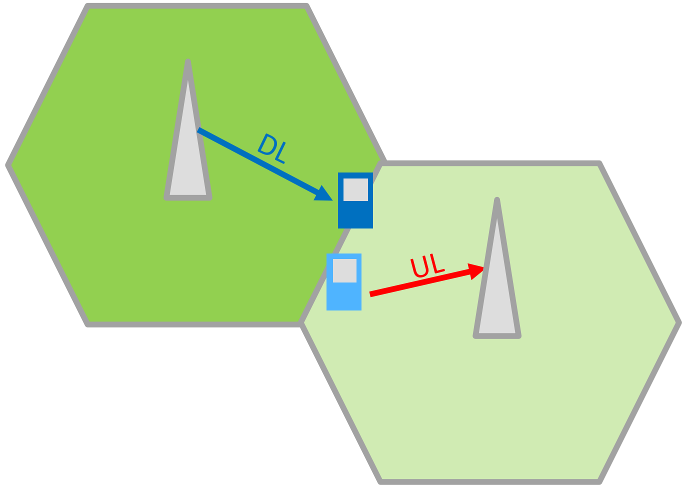
5G Interference Control

- New network architectures: new interference scenarios.

5G Interference Control

- New network architectures: new interference scenarios.
  - Examples:

Dynamic TDD

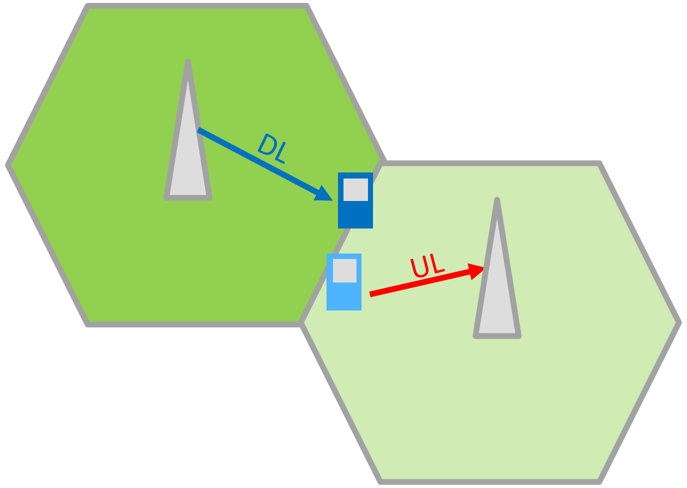


- Worst scenario: Cell Edge UE interferers by transmitting on a UE in the neighbor cell.

5G Interference Control

- New network architectures: new interference scenarios.
  - Examples:

Dynamic TDD



- Worst scenario: Cell Edge UE interferers by transmitting on a UE in the neighbor cell.

In-band Full Duplex

Requires **SELF-INTERFERENCE** Cancellation

5G IC – Other Challenges

- Dynamic TDD or In Band Full Duplexing will increase dramatically the interference between DL/UL Users
  - It requires a robust coordination between the schedulers or;
  - More robust mechanisms to deal with the interference
    - ✓PIC (Parallel-Interference Cancellation)
    - ✓SIC (Sucessive-Interference Cancellation)
    - ✓ IRC (Interference Rejection Combining)

5G IC – Other Challenges

- Dynamic TDD or In Band Full Duplexing will increase dramatically the interference between DL/UL Users
  - It requires a robust coordination between the schedulers or;
  - More robust mechanisms to deal with the interference
    - ✓PIC (Parallel-Interference Cancellation)
    - ✓SIC (Successive-Interference Cancellation)
    - ✓ IRC (Interference Rejection Combining)

    Just remember: Low-latency is a 5G requirement!

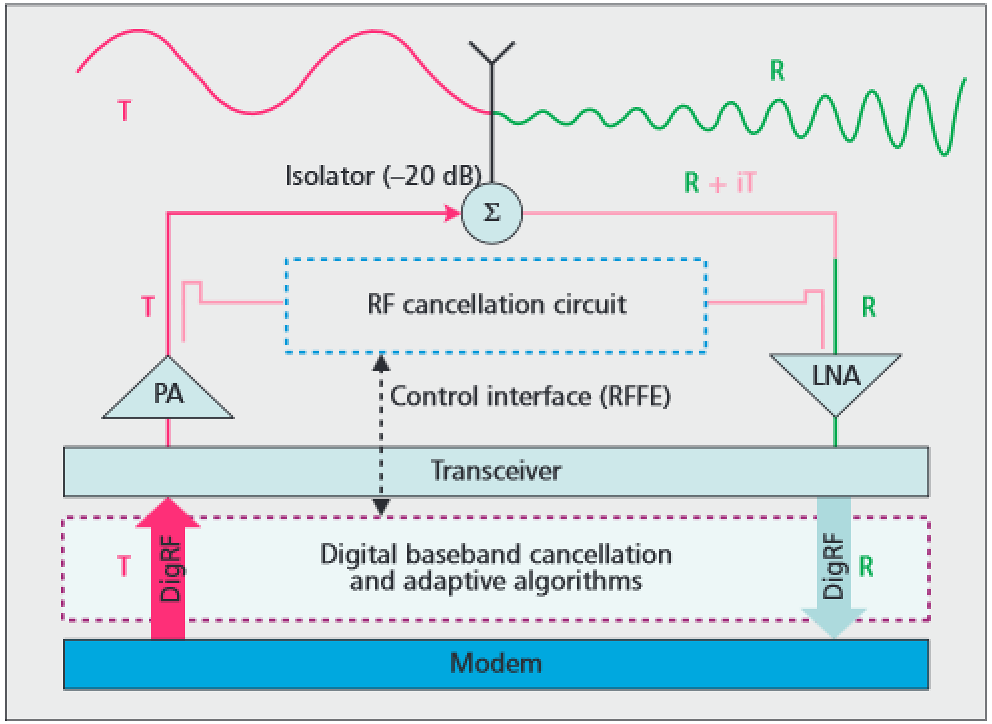
    - ✓ Very Fast Interference estimation needed
    - ✓Rapid data processing: Hardware requirements
    - ✓Coordination?

Self Interference Cancellation

- In-band full duplexing may increase network capacity up to 2x
  - Self-Interference Cancellation
  - Operation principle similar to old telephones
    - ✓Remove the TX signal replica from the Received signal
  - Frequency Agnostic Operation
    - ✓Complexity scales linearly for carrier aggregation
    - ❖ But… it increases battery consumption (a lot …)

Self Interference Cancellation

Uh! It seems simple. I know the tx signal! I just need to remove its version from the received signal.



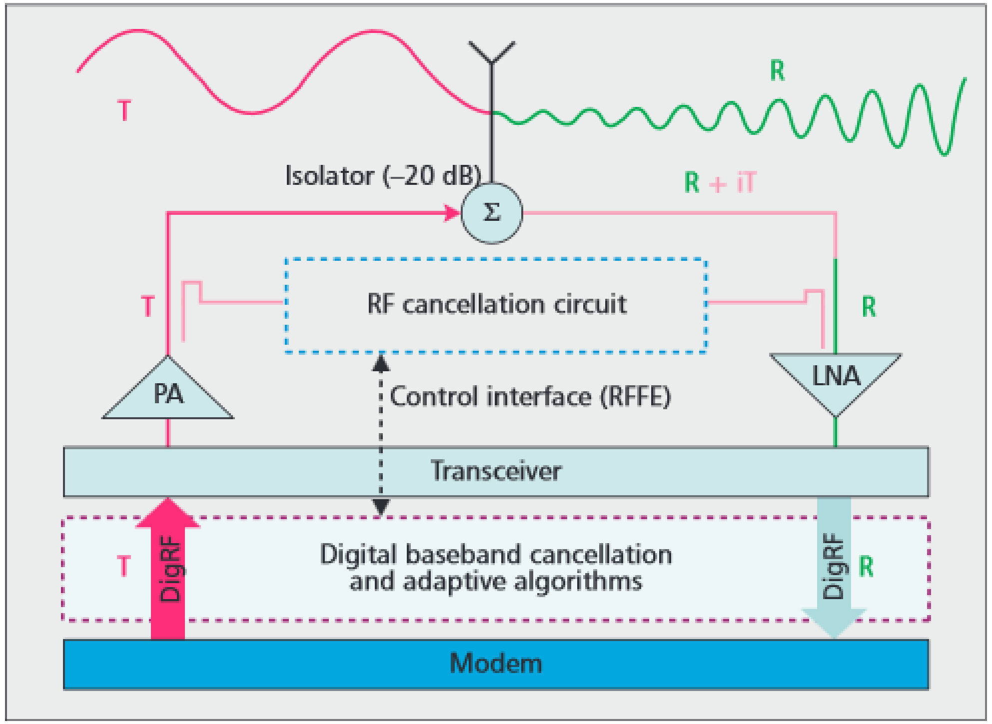
Extracted from:
http://cms.comsoc.org/SiteGen/Uploads/Public/Docs_TC_5GMWI/Applications_of_Self-Interference.pdf

Self Interference Cancellation

Uh! It seems simple. I know the tx signal! I just need to remove its version from the received signal.

But not so fast… The analog up-converted interfering signal is quite different of the known version:

- Affected by non-linearities
  - ✓ Power Amplifier
  - ✓ Receiver Saturation
  - ✓ Phase Noise
  - ✓ ADC Resolution
- Affected by time variation of Self-Interference Wireless Channel



Extracted from:
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The problem of synchronization

- There is an additional challenge for 5G Communication
  - Synchronization!
    - ✓GPS is not a good approach to indoor environments
      - Distributed synchronization is needed
    - ✓Sensors Network: Sensors may be dormant until they trigger a transmission.
    - ✓Inaccuracy of Hardware Clocks
  - Synchronization problems may cause big interference problems.
    - ✓It is necessary to develop a solution with a low response time to solve the synchronization problems

MASSIVE MIMO

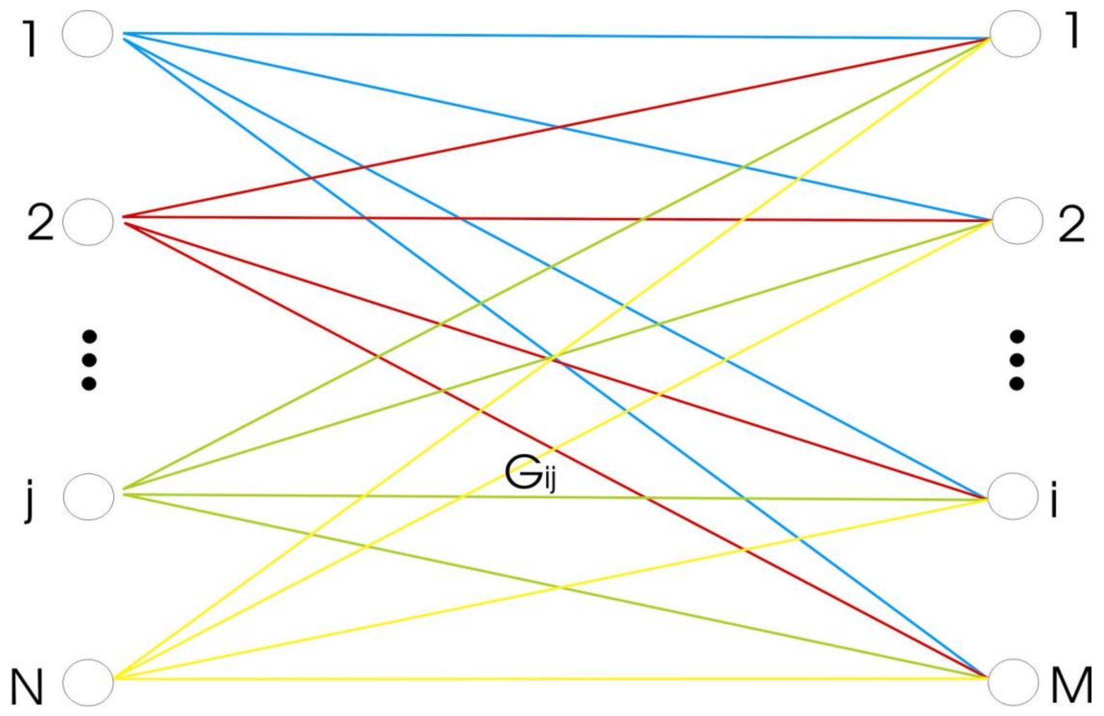
Introduction

- MIMO system

  - **Increasing spectral efficiency** and **quality** with MIMO system opens a new dimension, **space**, offering high bit rates **without increasing transmitted power and bandwidth allocation.**

  - Information theory has shown that with **multipath propagation**, MIMO system can establish essentially **multiple parallel channels** that operate simultaneously, on the same frequency band at the same total radiated power.

MIMO System



$$\{G_{ij}, i = 1,2,\ldots,M, j = 1,2,\ldots N\}$$

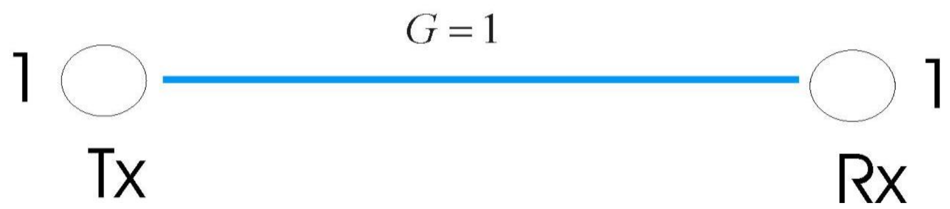
- **Diversity**
- **Adaptive Antennas**
- **Spatial Multiplexing**

The central paradigm is **exploitation** rather than **mitigation** of **multipath** effects.

MIMO System

- Array gain: **increase coverage and QoS.**
- Diversity gain: **increase coverage and QoS.**
- Co–channel interference reduction: **increase cellular capacity.**
- Multiplexing gain: **increase spectral efficiency.**

Capacity analysis: SISO system



$$C = \log_2\left(1 + \frac{P_t}{\sigma^2}\right) = \log_2(1 + SNR) \quad bits/s/Hz$$

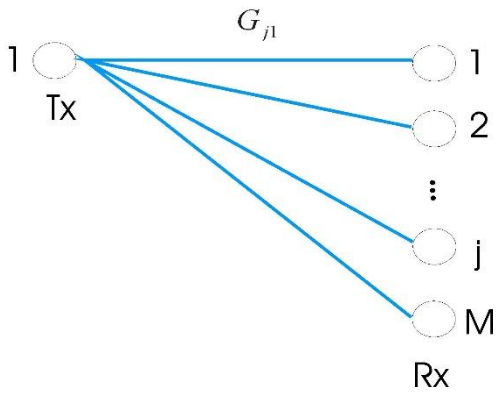
•The information theoretic capacity of single antenna link is limited by the link’s signal to noise ratio (Shannon’s capacity).

•Each extra bits/s/Hz, requires roughly a doubling of TX power (1 bits/s/Hz to 11 bits/s/Hz – Tx power must be increased by ~1000 times).

$$C = \log_2\left(1 + \rho |H|^2\right)$$

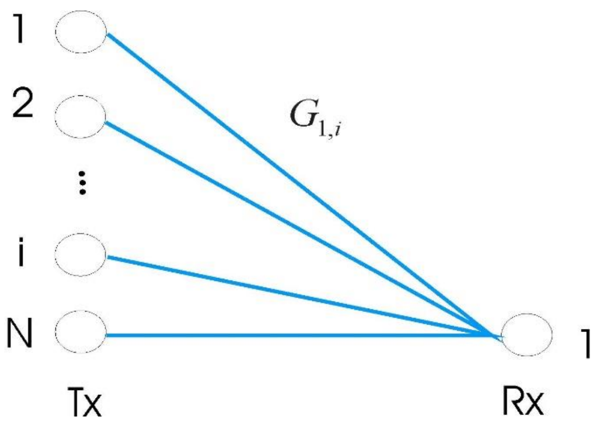
Channel capacity is low - few bits/s/Hz.

Capacity analysis : SIMO, MISO e MIMO



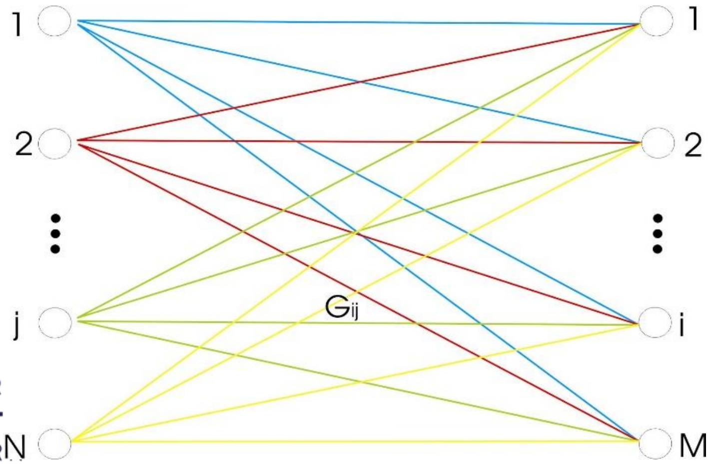
Para qualquer G_{j1}

$$C = \log_2\left(1+\rho\sum_{i=1}^{M}\left|H_{j1}\right|^2\right)\quad b/s/Hz$$



Para qualquer G_{1i}

$$C = \log_2\left(1+\rho\sum_{i=1}^{N}\left|H_{1i}\right|^2\right)\quad b/s/Hz$$



MIMO = SIMO + MISO

Para qualquer G_{ij}

$$C = \log_2\left(1+\rho\sum_{j=1}^{M}\sum_{i=1}^{N}\left|H_{ji}\right|^2\right)\quad b/s/Hz$$

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Capacity Analysis: SIMO,MISO,MIMO

- Goal: to **maximize the channel capacity by maximization of the signal to noise ratio**

  - Increases as the log of n - very slowly!
  - Channel capacity is still low (few bits/Hz/s).
  - Fading is smaller but still large (10-20 dB).
  - Space-domain signal processing - partially .
  - phased array, diversity combining, beamforming etc.

Capacity analysis: MIMO system

MIMO systems can be reduced to a parallel channels system.

$$C = \log_2\left[\det\left(\underline{\underline{I}} + \frac{\rho}{N}\underline{\underline{H}}\,\underline{\underline{H}}^H\right)\right] \quad \text{b/s/Hz}$$

$$H = UDV^H$$

$$C = \sum_{i=1}^{m} \log_2\left(1 + \frac{\rho}{N}\lambda_i\right) \qquad m = \min(M, N)$$

$$D = \begin{bmatrix} \sqrt{\lambda_1} & \cdots & \cdots & 0 \\ 0 & \ddots & \cdots & 0 \\ 0 & \cdots & \ddots & 0 \\ 0 & \cdots & \cdots & \sqrt{\lambda_{MN}} \end{bmatrix}$$

- Enormous channel capacity ~ 10 fold increase has been demonstrated.
- Full space-domain signal processing.
- More complex design is fully compensated by huge advantages.

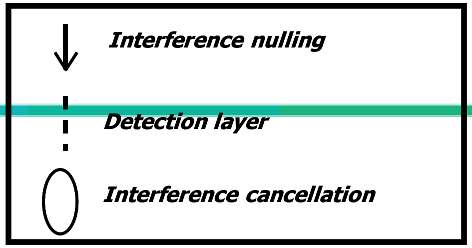
Multi-Antenna Techniques

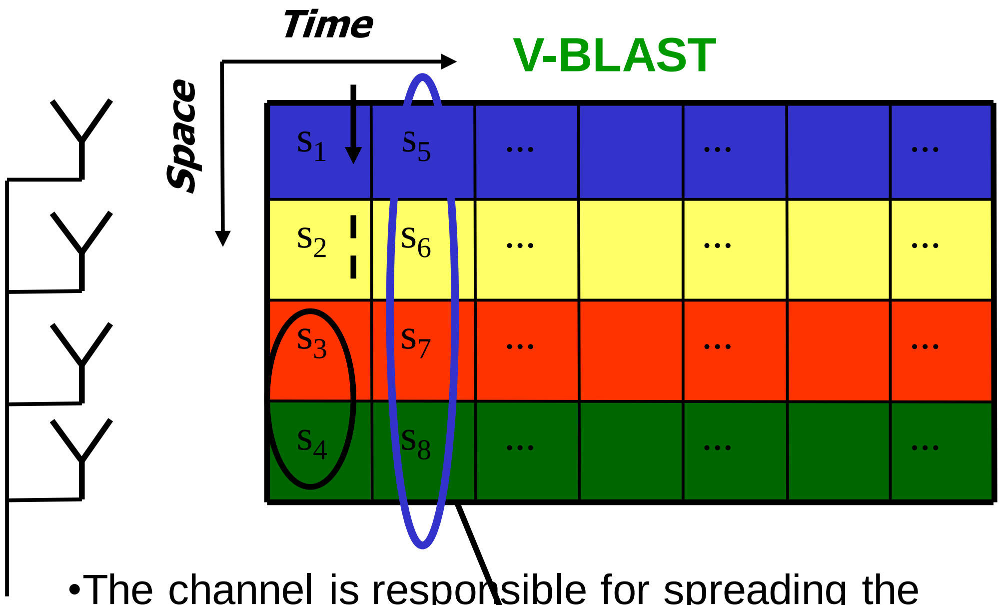
- Multi-Antenna Techniques:
  - Beamforming Techniques
  - Diversity Techniques
    - ✓ Receive Diversity
      - MRC
      - MMSE
    - ✓ Transmit Diversity
      - Open-Loop Techniques
        - » Space-Time Trellis Codes (STTC)
        - » Space-Time Block Codes (STBC): Alamouti
    - ✓ Closed-Loop Techniques
      - Partial/Complete CSI or CQI Techniques
  - Spatial Multiplexing
    - ✓ Open/Closed Loop
  - Hybrid Techniques (Spatial Multiplexing/Diversity)

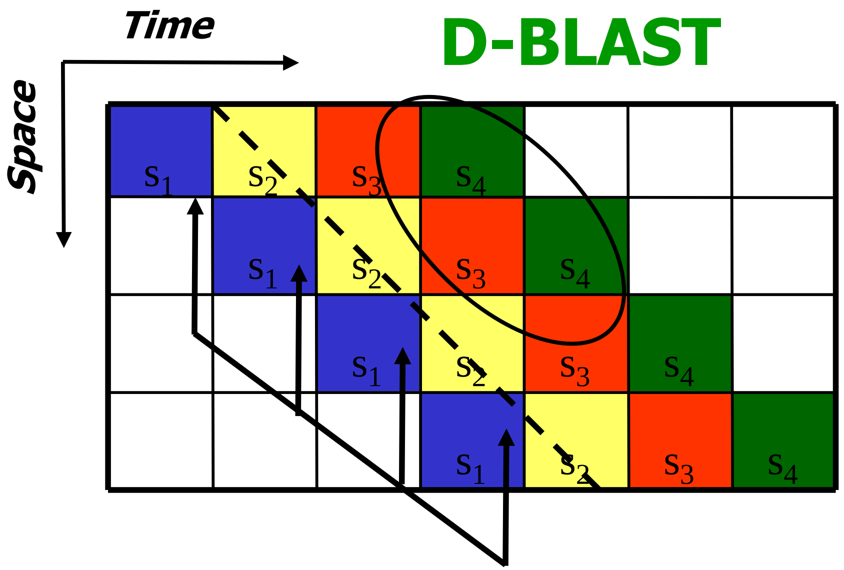
Multi-Antenna Techniques: Transmitter

- Spatial Multiplexing: **Bell Labs Layers Space Time** (BLAST) developed by G. J. Foschini
  - **V-BLAST (Vertically-BLAST)**
  - **D-BLAST (Diagonally-BLAST)**
- Transmit Diversity: **Space-Time Block Codes**
  - Spread the symbols in time and space in a block-by-block Fashion
  - Based on orthogonal Structure
    - ✓ Reduce decoding complexity
  - Important Schemes:
    - ✓ **Alamouti** (1998) - (2Tx-1Rx)
    - ✓ Tarokh *et al* (1998) - STBC (> 2Tx)

V-BLAST vs. D-BLAST Schemes







- The channel is responsible for spreading the signal
- Each sub-stream experiments a different a channel condition
- Error Propagation

Spatial Multiplexing

- A spatial cycle in the sub-stream is done among the antennas
- Every "sub-stream" experiments the *m* possible different channels
- High Delays in the decoding

Alamouti STBC

space-time codeword

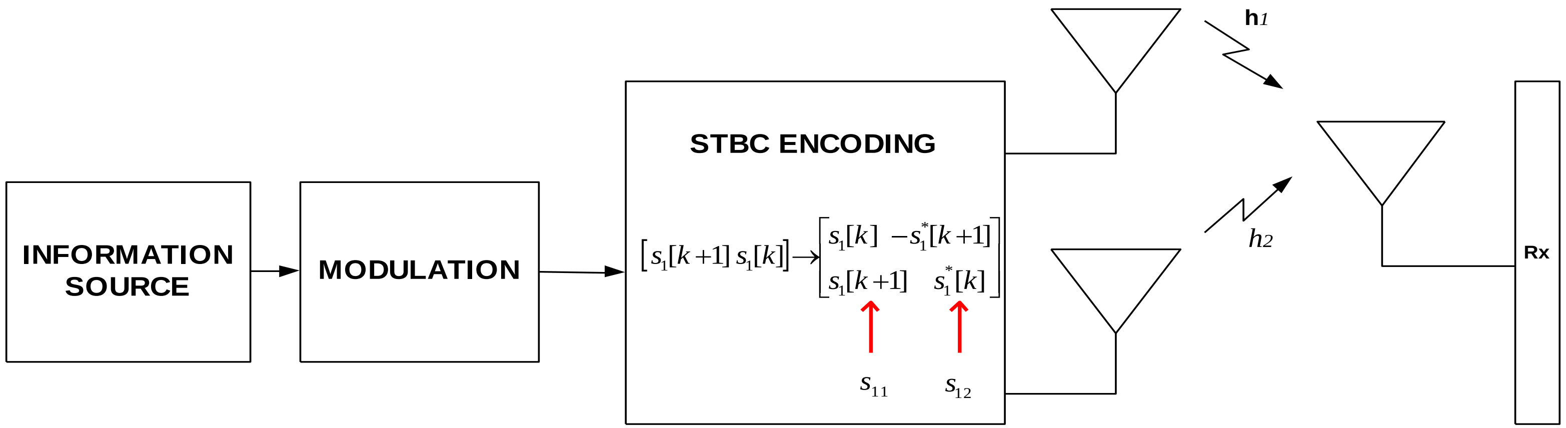
$$\{\ldots \quad s_1[k+1] \quad s_1[k]\} \rightarrow \begin{bmatrix} s_1[k] & s_1[k+1] \\ -s_1^*[k+1] & s_1^*[k] \end{bmatrix}$$

space (→) **time** (↓)

- Detection based on a linear processing in the receiver
- Alamouti provided a STBC scheme for 2 transmitter antennas
- Tarokh extended the Alamouti's scheme for more than 2 transmitter antennas

Alamouti STBC - Transmitter

- Model



$r_1[k] = h_1 s_1[k] + h_2 s_1[k+1] + \eta_1$ ⟶ **signal received at time** k

$r_1[k+1] = -h_1 s_1^*[k+1] + h_2 s_1^*[k] + \eta_2$ ⟶ **signal received at time** $k+1$

conjugate r_1**[k+1]**

$$\mathbf{r} = \begin{bmatrix} r_1[k] \\ r_1^*[k+1] \end{bmatrix} = \underbrace{\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}_{\tilde{\mathbf{H}}} \cdot \underbrace{\begin{bmatrix} s_1[k] \\ s_1[k+1] \end{bmatrix}}_{\mathbf{s}} + \underbrace{\begin{bmatrix} \eta_1 \\ \eta_2^* \end{bmatrix}}_{\boldsymbol{\eta}} \Rightarrow \mathbf{r} = \tilde{\mathbf{H}}\mathbf{s} + \boldsymbol{\eta}$$

Alamouti STBC - Decoding

$$\mathbf{z} = \begin{bmatrix} z_1[k] \\ z_1^*[k+1] \end{bmatrix} = \underbrace{\begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix}}_{\tilde{\mathbf{H}}^H} \cdot \begin{bmatrix} r_1[k] \\ r_1^*[k+1] \end{bmatrix} = \underbrace{\begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \cdot \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}_{\tilde{\mathbf{H}}^H \tilde{\mathbf{H}}} \cdot \begin{bmatrix} s_1[k] \\ s_1[k+1] \end{bmatrix} + \underbrace{\begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \cdot \begin{bmatrix} \eta_1 \\ \eta_2^* \end{bmatrix}}_{\boldsymbol{\eta}'}$$

noise term is still white

$$\tilde{\mathbf{H}}^H \tilde{\mathbf{H}} = \begin{bmatrix} |h_1|^2 + |h_2|^2 & 0 \\ 0 & |h_1|^2 + |h_2|^2 \end{bmatrix} \Rightarrow \begin{cases} z_1[k] = \left(|h_1|^2 + |h_2|^2\right) s_1[k] + \eta_1' \\ z_1[k+1] = \left(|h_1|^2 + |h_2|^2\right) s_1[k+1] + \eta_2' \end{cases}$$

$z_1[k]$ and $z_1[k+1]$ are independent !

$$z = \left(|h_1|^2 + |h_2|^2\right) s + \eta'$$

Diversity gain

Orthogonally reduces the decoding complexity via linear processing

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Multi-antenna Schemes in LTE

- Receive diversity
  - User Equipment (UE) must support receive diversity
  - Base station (eNB) typically supports receive diversity
- Transmit diversity
  - DL: broadcast and control channels use transmit diversity
  - Space-Frequency Block Code (SFBC) is used –a version of the Alamouti scheme
- Beamforming
  - Used in data channels and enhanced control channels
    - ✓ Based on Channel State Information (CSI) feedback or channel reciprocity (in TDD)
- Spatial multiplexing
  - Either closed loop (based on CSI feedback) or open loop
  - It has different spatial layers for a single user (SU-MIMO)
  - It has different spatial layers for multi-users (MU-MIMO)

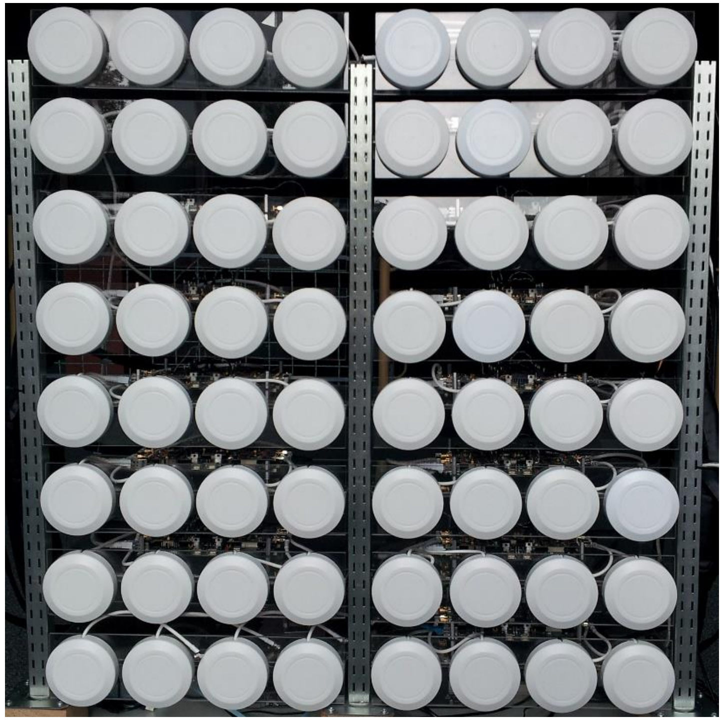
What is Massive MIMO ?

- Other names
  - Large-Scale Antenna Systems
  - Very Large MIMO
  - Hyper MIMO
  - Full Dimension MIMO

- M-MIMO is an array with **few hundreds antennas**

- Basic premise behind M-MIMO
  - Reap all the benefits of the conventional MIMO, but on a **much greater scale**

- M-Massive relies on **Spatial Multiplexing**
  - Extra antennas help by focusing energy into smaller regions of space to bring huge improvements in throughput and radiated energy efficiency



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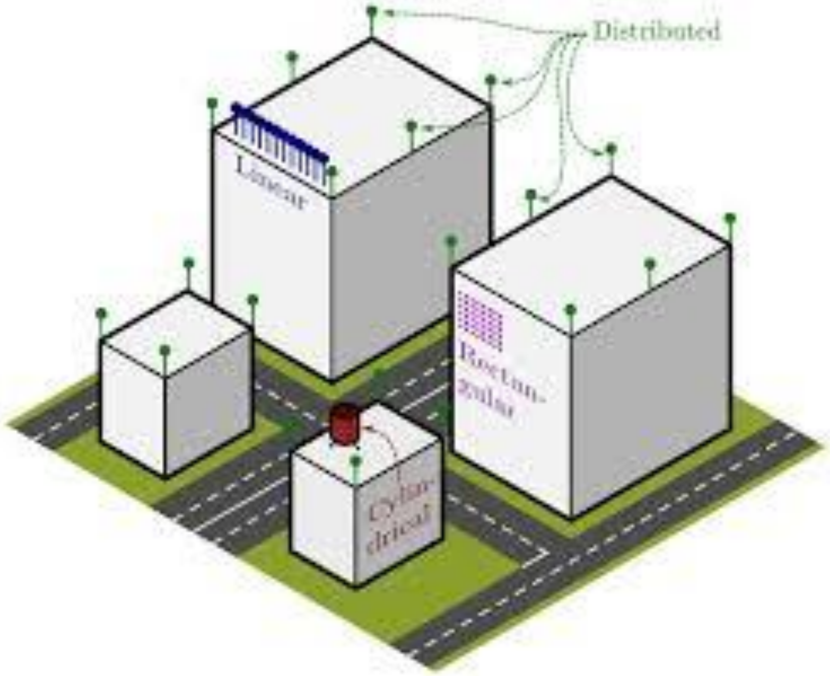
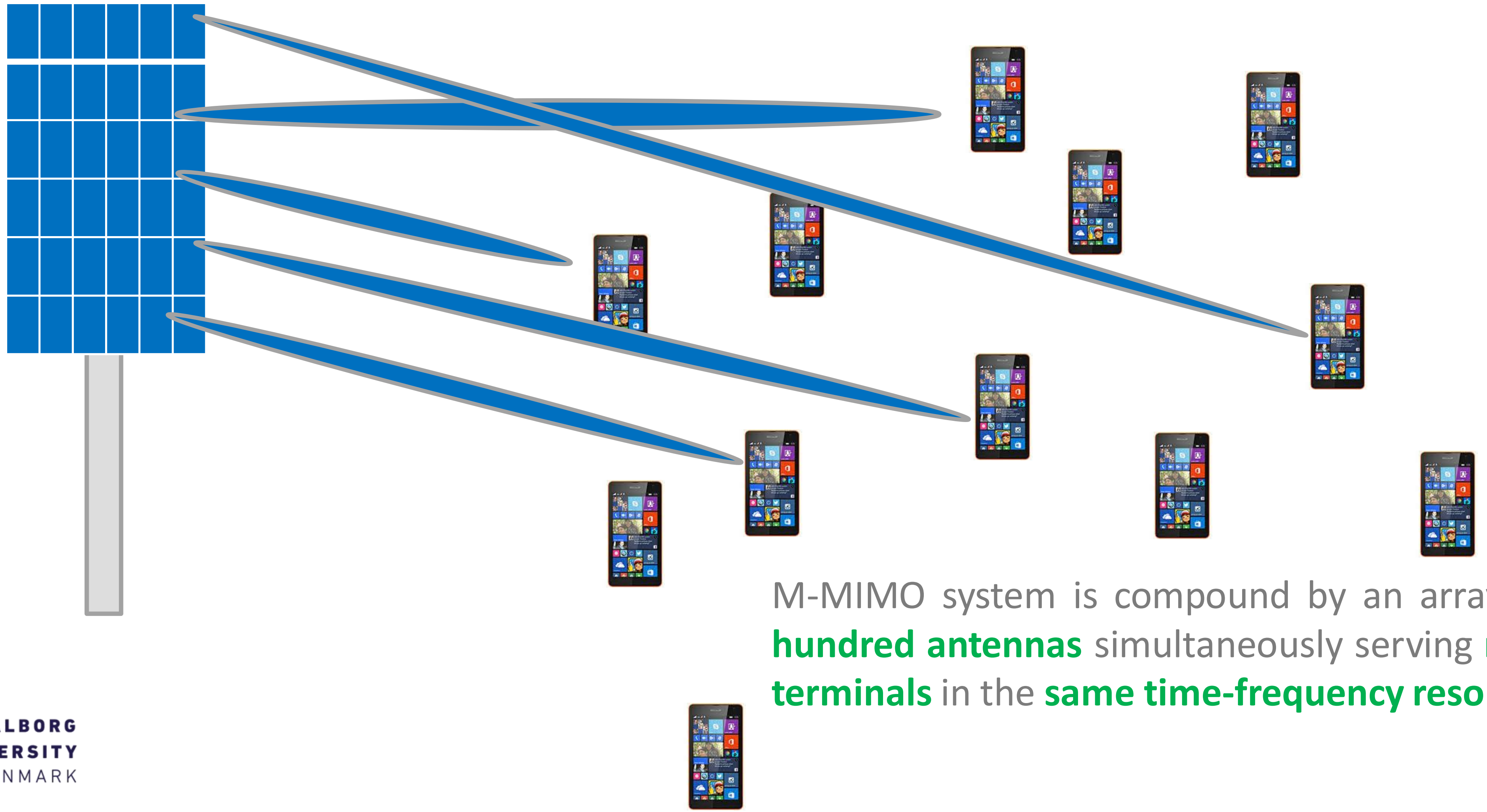
5G and Massive MIMO

- M-MIMO is one key **enabler for future Wireless Broadband** which will be
  - Energy Efficient,
  - Secure and
  - Robust



- M-MIMO is also an important enabler for the future digital society that will Connect **the Internet People and IoT with Clouds**.

M-MIMO System



M-MIMO system is compound by an array with a **few hundred antennas** simultaneously serving **many tens of terminals** in the **same time-frequency resource.**

M-MIMO Benefits

- **M-MIMO can increase the capacity 10 times or more**
  - Capacity increase results from the aggressive spatial multiplexing
    - ✓ Energy can be focused with extreme sharpness into small regions
    - ✓ MmW requires directivity gain from large arrays to overcome high path loss and noise
  - Large antenna arrays serving tens of users
  - Simple signal processing becomes near-optimal with large arrays

- **M-MIMO improve the radiated energy efficiency on the order of 100 times**
  - Expensive ultra-linear 50 W amplifiers are replaced by hundreds of low cost amplifiers with output power in the milli-Watt range
  - M-MIMO reduce the constraints on accuracy and linearity of each individual amplifier and RF chain

M-MIMO Benefits

- **M-MIMO simplifies the multiple access layer**
  - Since fading and noise become minor with large arrays, in OFDM system each subcarrier will have the same channel gain
  - PHY and MAC control signaling redundant can be avoided.

- **M-MIMO enables to reduce of latency on the air interface**
  - Fading is one key issue to build low latency wireless link
  - With M-MIMO
    - ✓ Fading and noise become minor with large arrays
    - ✓ Out-of-cell interference reduced due to directional transmission and blockage (in mmW)

Limiting Factors of M-MIMO

- Channel Reciprocity
  - TDD Operation relies on channel reciprocity
    - ✓ It is a consensus that the propagation channel itself is essentially reciprocal
  - Problem
    - ✓ Hardware chains in the base station and terminal transceivers may not reciprocal between the uplink and downlink
  - Solution
    - ✓ Calibration pf hardware chains

- Pilot Contamination
  - What is Pilot contamination?
    - ✓ There is maximum number of orthogonal pilot sequence in a system.
    - ✓ The effect of reusing pilots from one cell to another and the associated negative consequences is termed pilot contamination.
  - Problem
    - ✓ Channel estimative suffer “contamination” generated by the interference pilot
    - ✓ DL Beamforming generate an interference at those terminals that share the same pilot sequence
  - Solution
    - ✓ Allocation pilot waveform optimization
    - ✓ Clever channel estimation algorithms or blind techniques
    - ✓ New Precoding techniques that take into account the pilot contamination

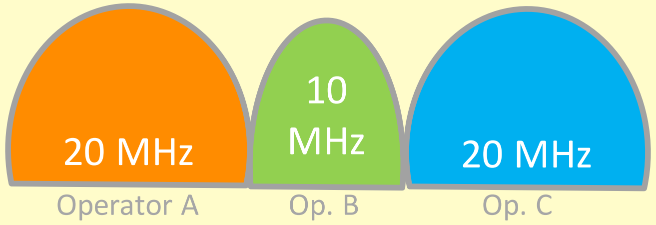
M-MIMO Research Problems

- Fast and Distributed Coherent Signal Processing
- Build Low Cost Hardware
- Hardware Impairments
- Channel Characterization
- HW Reciprocity Calibration
- Pilot Contamination
- Small Cell and Heterogeneous Design Solutions
- Prototype

SPECTRUM

4G Bandwidth

- LTE Predefined Bandwidths: Up to 20 MHz.



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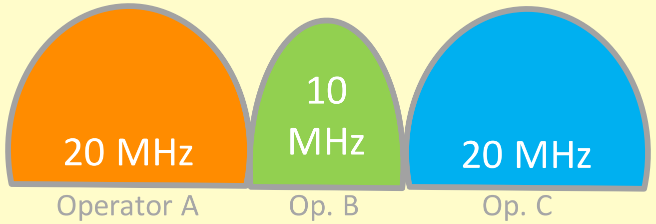

Uh-Oh! Physical Limitation:

Amount of **information symbols** that can be conveyed over a limited channel bandwidth.

- Shannon-Hartley Theorem

4G Bandwidth

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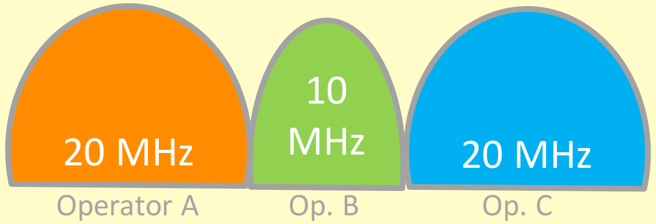

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*" We need to scale up the amount of transmitted data! We need to **increase** the bandwidth "*

4G Bandwidth

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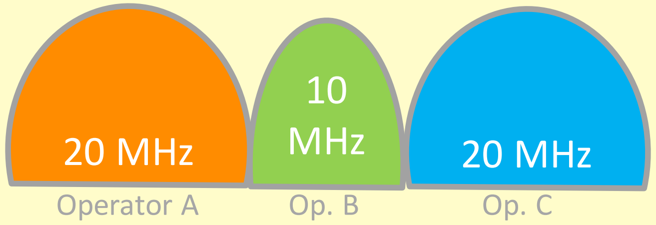

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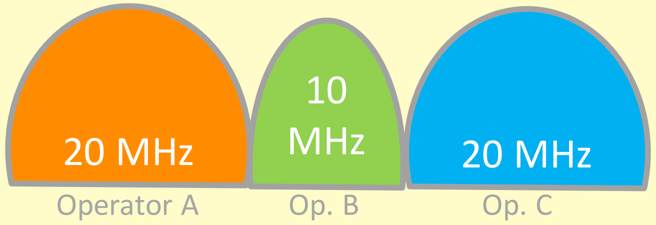
What if we aggregate the operator's bands?

4G Bandwidth

- LTE Predefined Bandwidths: Up to 20 MHz.



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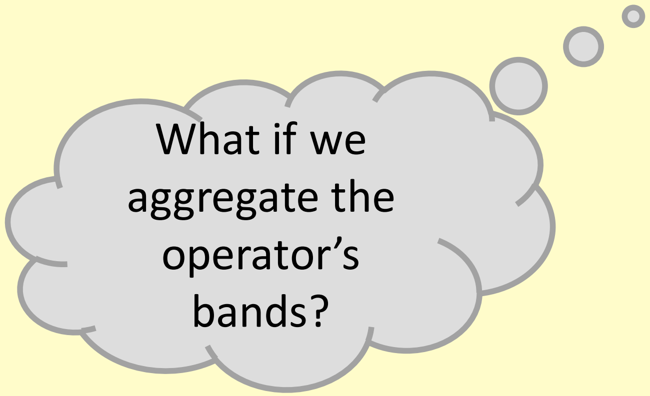
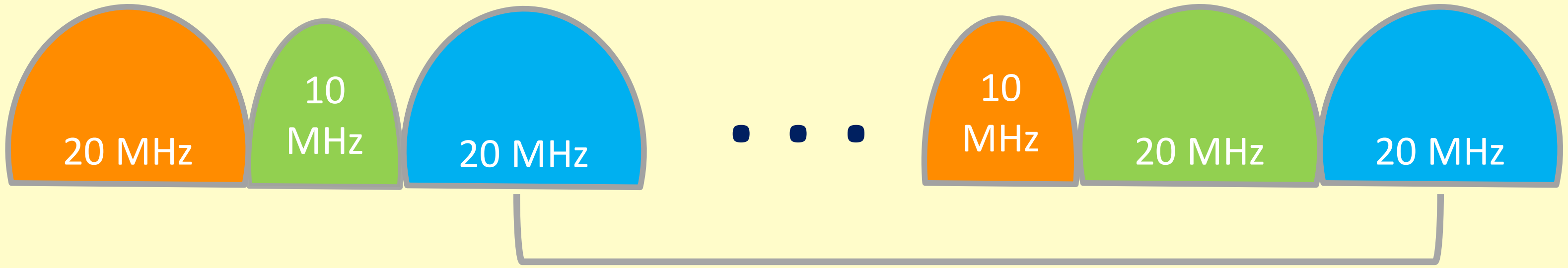
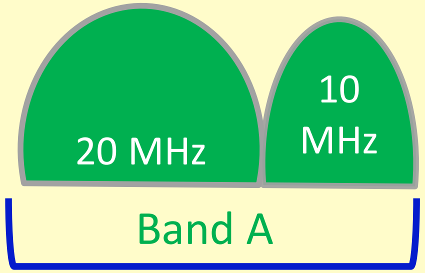




Operator C may aggregate its two bands to create a 40 MHz Bandwidth.

4G Bandwidth

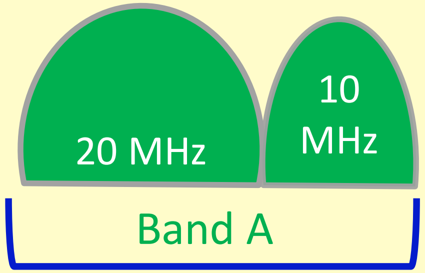
- There are different types of Carrier Aggregation



1. Intraband Contiguous

4G Bandwidth

- There are different types of Carrier Aggregation



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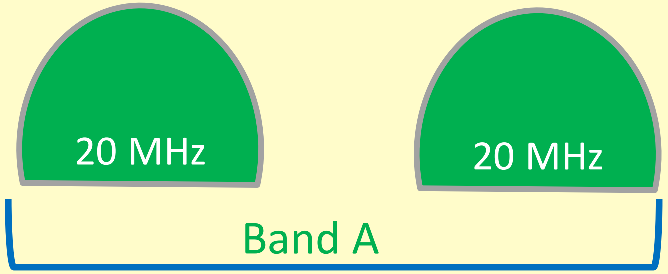
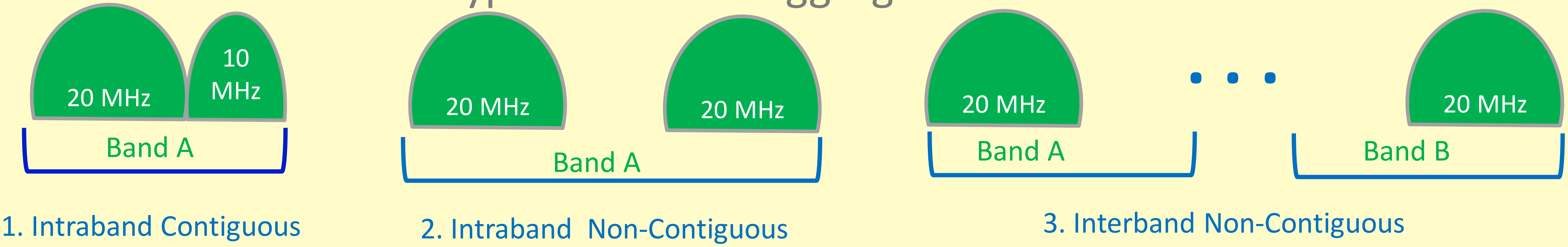


2. Intraband Non-Contiguous

4G Bandwidth

- There are different types of Carrier Aggregation



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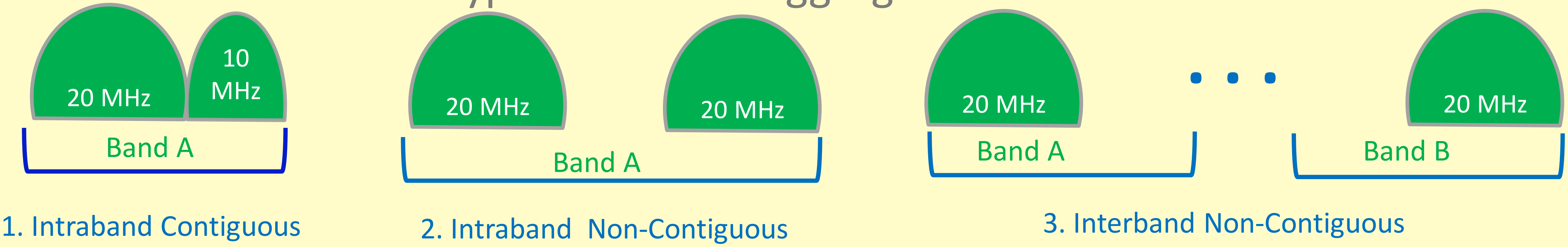
4G Bandwidth

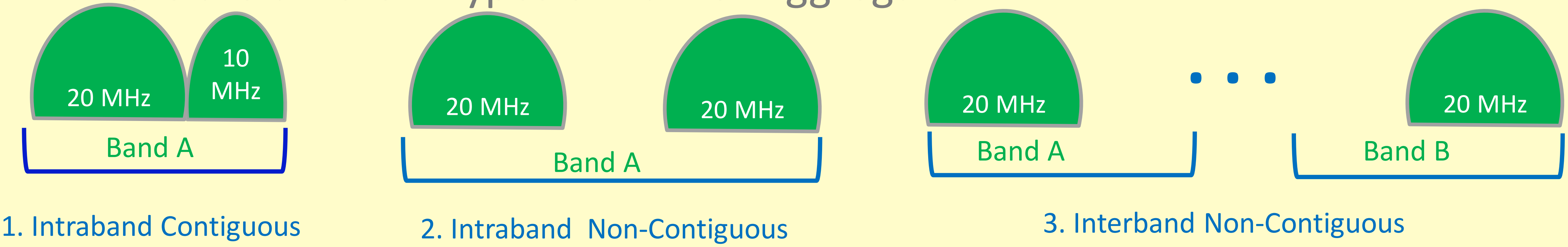
- There are different types of Carrier Aggregation



- 3GPP has planned CA with up to 5 Carriers.
  - The number of carriers does not need to be the same in DL/UL

4G Bandwidth

- There are different types of Carrier Aggregation



- 3GPP has planned CA with up to 5 Carriers.
  - The number of carriers does not need to be the same in DL/UL

$$5\ x\ 20 = 100\ MHz$$

Maximum Bandwidth

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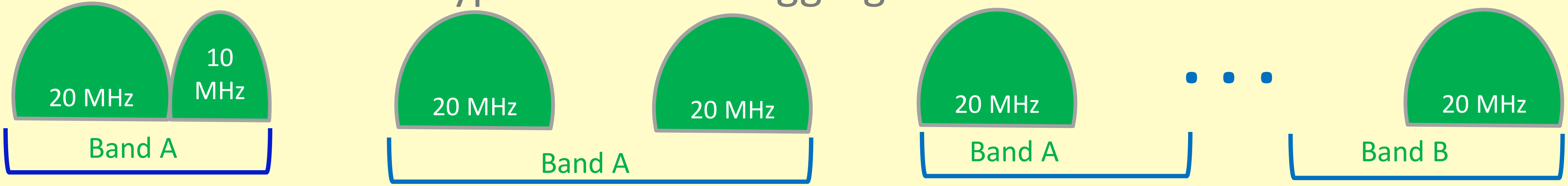
4G Bandwidth

- There are different types of Carrier Aggregation



1. Intraband Contiguous

2. Intraband Non-Contiguous

3. Interband Non-Contiguous

- 3GPP has planned CA with up to 5 Carriers.
  - The number of carriers does not need to be the same in DL/UL

$$\mathbf{5\ x\ 20 = 100\ MHz}$$

Maximum Bandwidth

Problem Solved?

4G Bandwidth

Problem Solved?

- Not really. There are complications.
  - Radios do not support all band combinations yet
    - ✓ Band Combinations are being standardized by 3GPP.
  - Intermodulation
  - Limited Cellular Spectrum disputed by several operators
    - ✓ LAA: Licensed Access Assisted.
    - ✓ LTE users may compete for unlicensed bands: Wi-Fi Competition.

Carrier Aggregation Evolution

3GPP Release 10	3GPP Release 11	3GPP Release 12	Beyond Release 12
• DL Intra Band Contiguous • DL Interband • Maximum 2 DL CA	• DL Intra Band Non Contiguous	• 3 Downlink CA • 2 Uplink CA • FDD+TDD • Dual Connectivity	• LAA • Four DL CA

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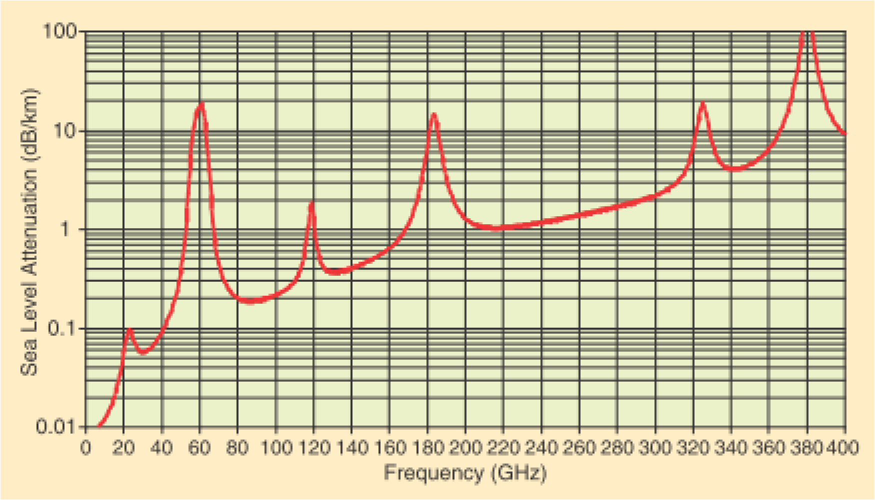
WE NEED ANOTHER SOLUTION:
SEEK EMPTY PORTIONS OF THE SPECTRUM…

mmWave and cmWave

cm/mmWaves

- Available UHF Cellular Spectrum is around: 600MHz.
  - Several ongoing initiatives to optimize its usage
    - Spectrum refarming
    - Cognitive Concepts (TVWS, ASA, LSA)
  - But still not enough
  - Spectrum is too crowded, difficult to maintain QoS
- cm/mmWave: a huge amount of spectrum
  - Much of it unused/underutilized
  - 3-30 GHz(cmWave)
  - 30-300GHz (mmWave)
  - Potential ranges: 28-30GHz, 60GHz, 81-86GHz and 92-95GHz
  - Spectrum Policy needed



Wells, *Faster than fiber: The future of multi-G/s*, IEEE Microwave Mag., 2009

Radio Propagation Considerations

- Radio Propagation is the key factor in all the wireless systems.
- Mobile HetNets + new 5G scenarios + new Spectrum (cmwave & mmwave frequency bands) are relatively unexplored.
- Radio channel measurements and modeling are still necessary (and more important than ever) due to the new scenarios, the new frequency constraints and the future antenna designs (large arrays and massive MIMO).
- Many different measurement activities and contributions around the world towards an unified 5G channel model.

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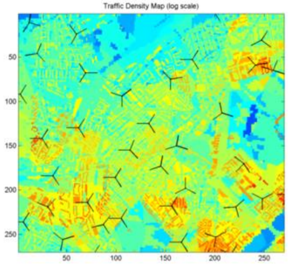
HetNets (from a Radio Propagation Perspective)

		**Macro:** BS antenna deployed in elevated positions above rooftop level. Propagation above rooftop + diffraction from rooftop to street level.	Low frequency bands < 3 GHz for overall coverage and mobility
		**Outdoor Small Cell (Micro):** BS antenna deployed below rooftops close to street level (e.g. lamppost). Street canyon guiding (multiple reflections over the buildings) + diffraction on corners.	Co-channel with Macro < 3 GHz Or dedicated spectrum: 3.5 & 5 GHz
		**Indoor Small Cell (Femto):** indoor BS deployment. Very complex indoor propagation: reflections, diffraction, multi-wall transmission,... * WiFi APs are also Indoor Small Cells… … from a radio propagation perspective ☺	Coverage holes and capacity hotspots!

Main propagation mechanisms vary with the type of cell and the frequency of operation!

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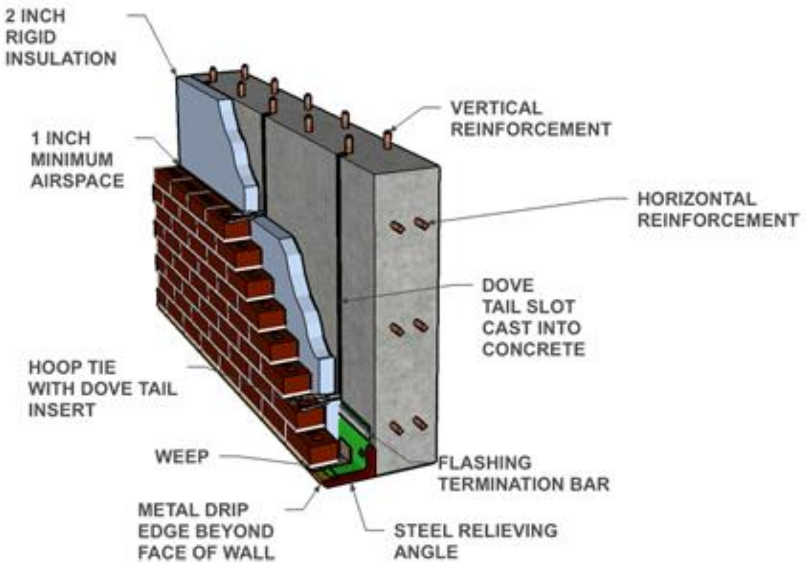
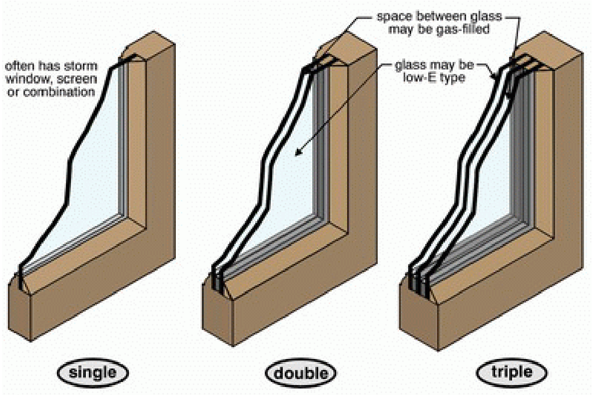
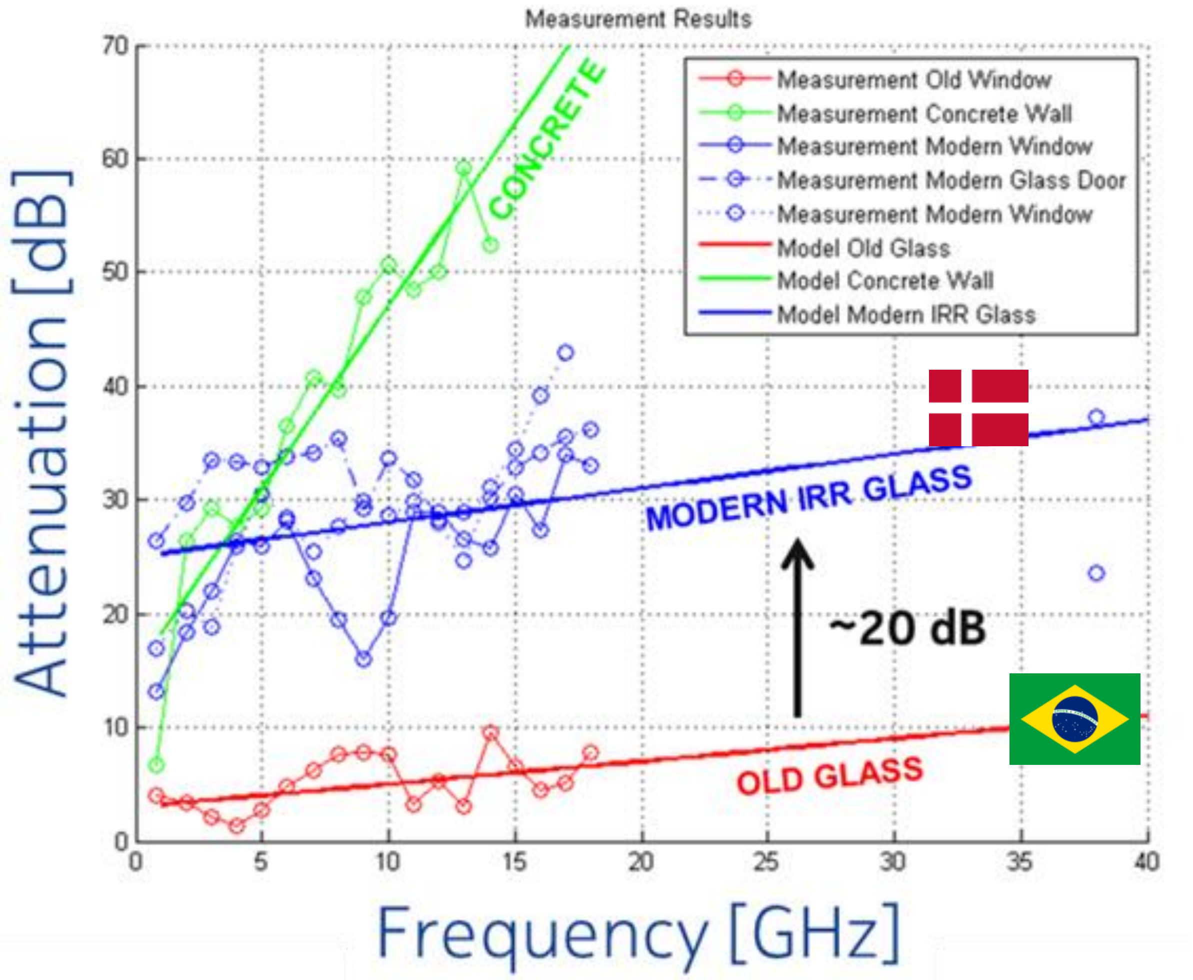
What happens with Outdoor-to-Indoor?



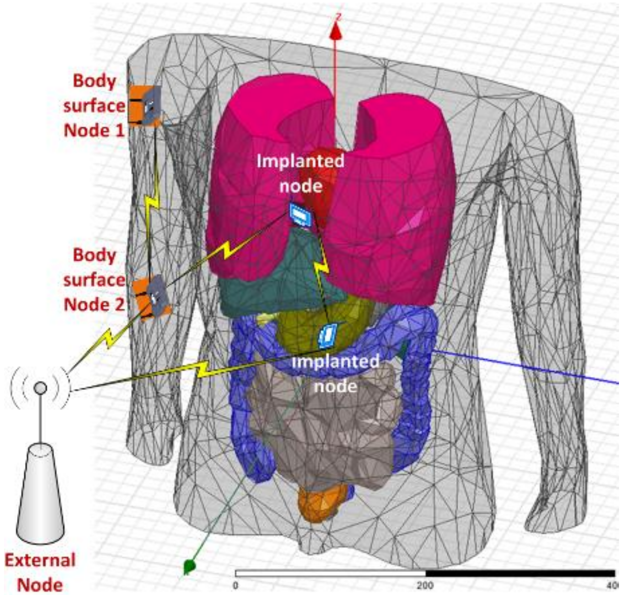


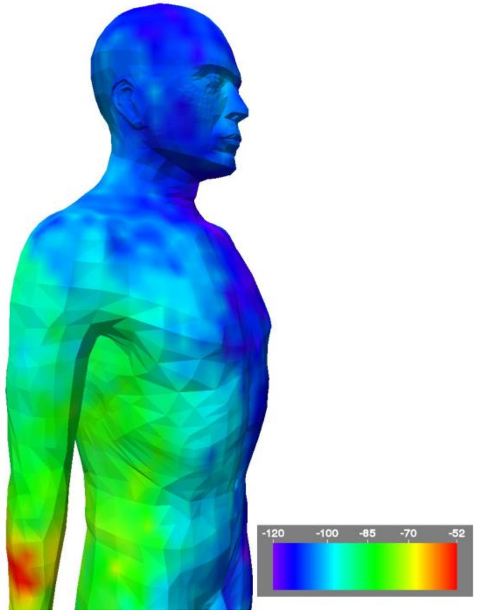


Big impact in outdoor-to-indoor coverage in cold countries, where good thermal isolation is necessary

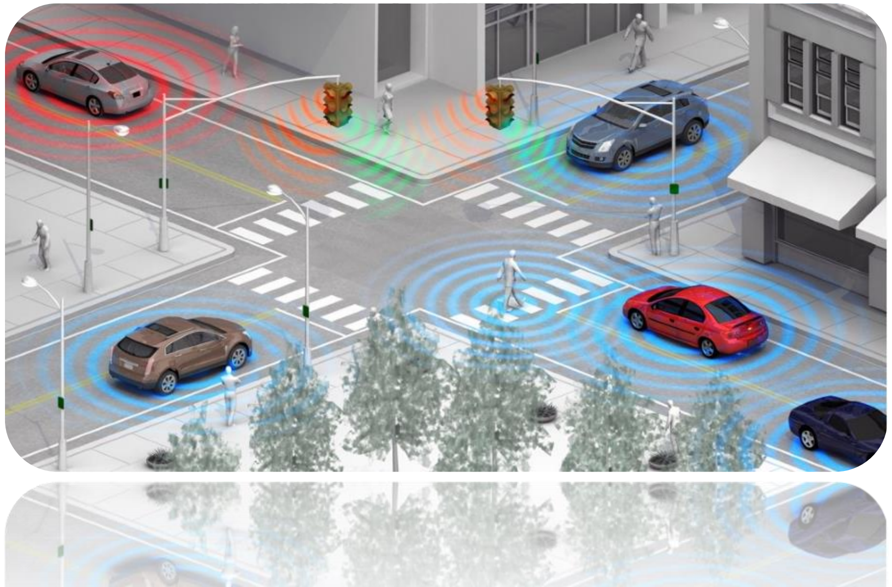
New 5G Scenarios

- Telemedicine:
  - BAN (Body Area Network) for wireless sensors: movement detection, human shadowing.





- Vehicular scenarios:
  - V2V & I2V/V2I
  - HS (high speed)



Propagation is quite unexplored in these scenarios

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Spectrum Requirements

- Typical spectrum used by an European operator (December 2014):
  - 2G: (2 x 9 MHz) @900 + (2 x 11.8 MHz) @1800 / ~ 40 MHz
  - 3G: (2 x 15 MHz)@2100 + (1 x 5 MHz)@1900 / 35 MHz
  - 4G: (2 x 20 MHz) @800 + (2 x 20 MHz) @2600 + (2 x 10 MHz)@1800 / 100 MHz

TOTAL BANDWIDTH ~ 175 MHz (“only”)

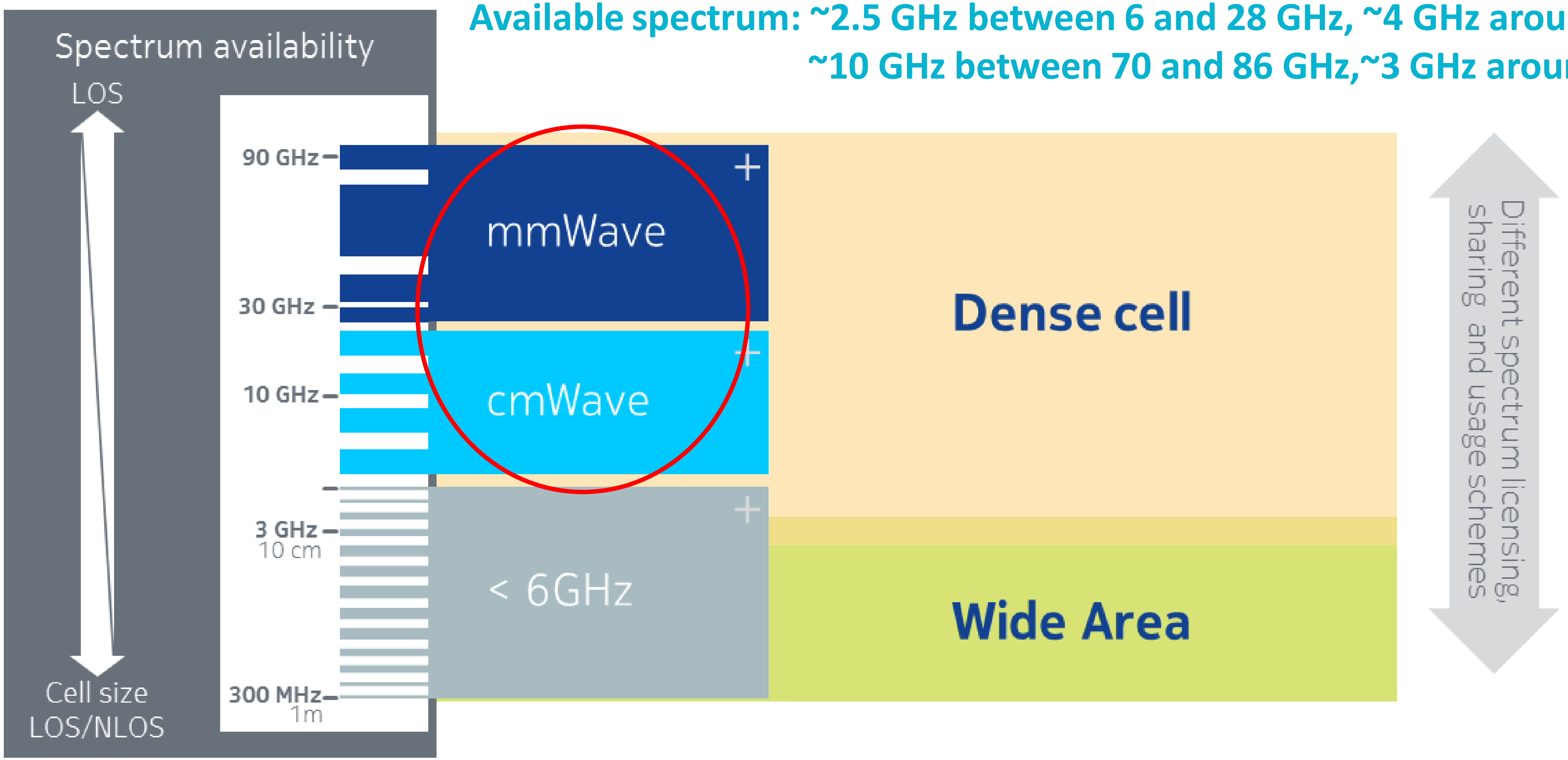
$$C = W \log_2 (1 + S/N)$$

- Bandwidth matters!
- Traditional spectrum below 6 GHz is limited.

More spectrum is needed for future RATs & applications
Refarming? GSM for M2M? We will see…

Spectrum Utilization

Available spectrum: ~2.5 GHz between 6 and 28 GHz, ~4 GHz around 38 GHz, ~10 GHz between 70 and 86 GHz,~3 GHz around 90 GHz.



Large contiguous bandwidth opportunities!

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5G Channel Modeling Activities

- There is a huge interest from both industry and academia in accurately characterizing radio propagation in frequency bands above 6 GHz.

METIS cost IC1004 ITU ETSI NIST National Institute of Standards and Technology

- It is expected that interested groups are likely to collaborate in the future on developing a unified channel model for 3GPP.

5G Channel Modeling Requirements

- A unified/standardized 5G channel model is missing.
- Main requirements:
  - Spatial and temporal consistency (especially for non-stationary scenarios, with fast mobility).
  - Wideband characterization.
  - 3D extension (for both outdoor and indoor scenarios).
  - Should cover M2M scenarios.
  - Should be applicable in all frequency bands from low frequencies up to cmwave and mmwave.
  - Large antenna arrays and Massive MIMO.

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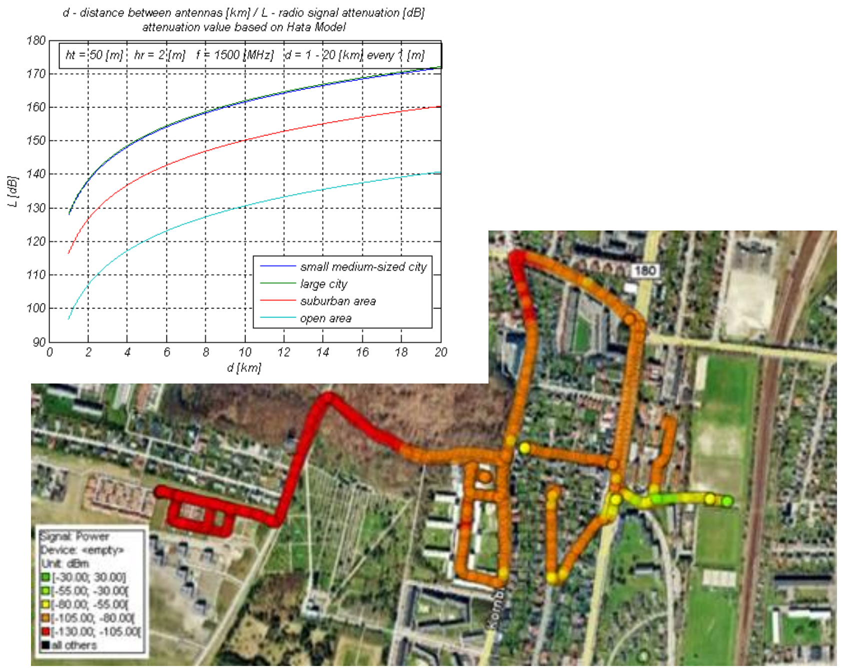
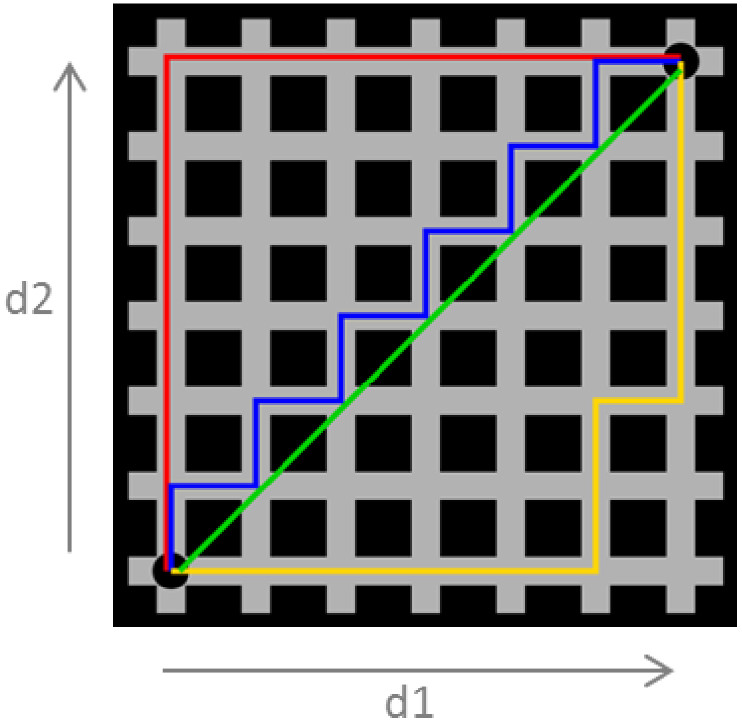
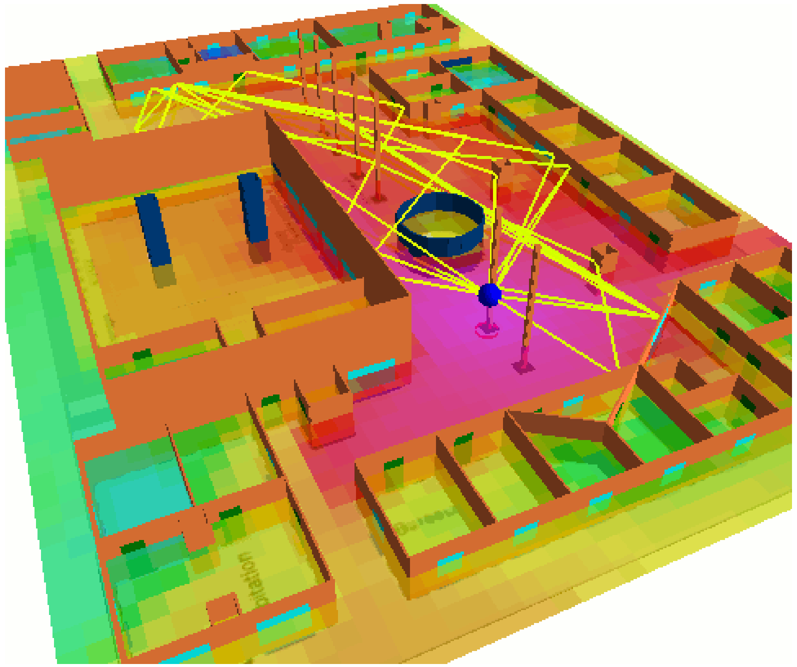
“Old” Path Loss Modeling







Empirical statistical: frequency, height & distance. Extensive measurement campaign needed in order to achieve statistical significance

Semi-deterministic geometrical: frequency, height, distance & scenario distribution.

Fully deterministic (Ray-Tracing): height, distance, scenario distribution, electromagnetic properties,… (Not that big measurement campaign are required, but very accurate and time consuming)

+ level of detail/complexity/accuracy

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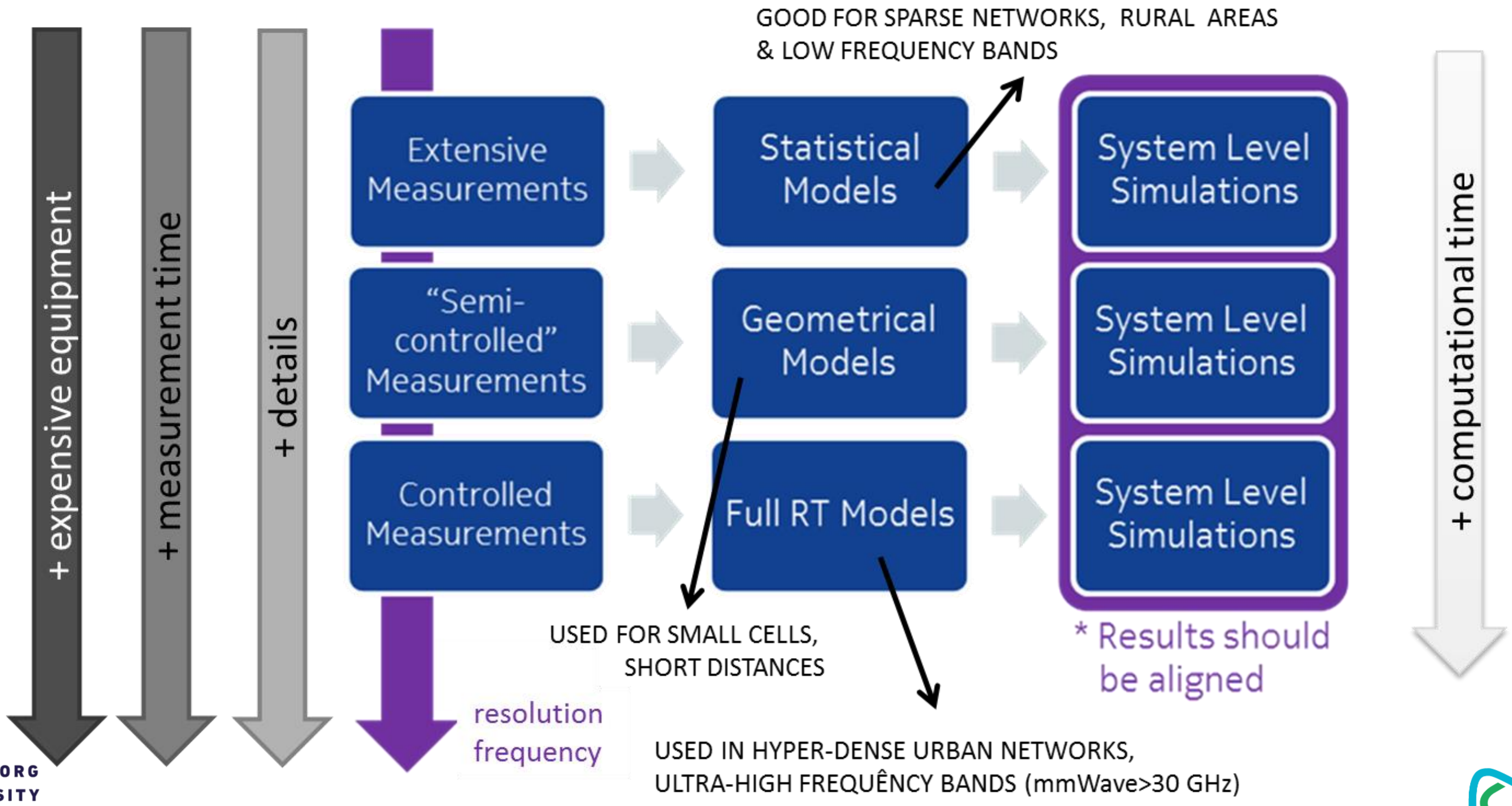
Path Loss Modeling Approaches & Challenges



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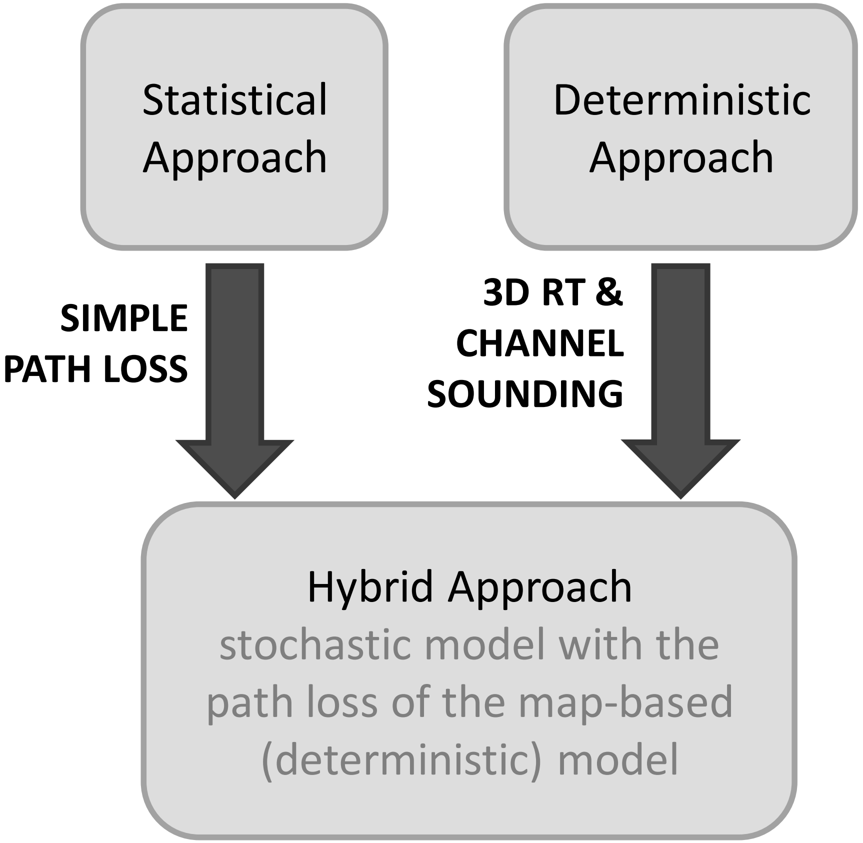
New “5G” Modeling Approaches

- Now is more than path loss. There is a need for directional 3D channel models for large array antennas (massive MIMO) and mmWave.
- The future is not “narrowband”. GHz bandwidths should be considered.
- New scenarios to be considered: M2M.
- A lot of channel sounding still needed.



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Standardized Models vs. METIS Objectives

Feature	3GPP SCM	WINNER II / WINNER+	IMT-Advanced	3GPP D2D	3GPP 3D	IEEE 802.11ad	METIS Model	
							stochastic	map-based
Frequency Range (GHz)	1 – 3	1 – 6	.45 – 6	1 – 4	1 – 4	60 – 66	up to 70 GHz	up to 100 GHz
Bandwidth (MHz)	5	100	100	100	100	2000	100 MHz < 6 GHz, 1 GHz @ 60 GHz	10 % of the centre frequency
Support massive-MIMO	no	limited	no	no	limited	yes	no	yes
Support spherical waves	no	no	no	no	no	no	no	yes
Support extremely large arrays beyond stationarity interval	no	no	no	no	no	no	no	yes
Support dual mobility	no	no	no	limited	no	no	limited	yes
Support Mesh networks	no	no	no	no	no	no	no	yes
Support 3D (elevation)	no	yes	no	no	yes	yes	yes	yes
Support mmW	no	no	no	no	no	yes	partly	yes
Dynamic modelling	no	very limited	no	no	no	limited	no	yes
Spatial consistency	no	no	no	no	no	no	SF only	yes

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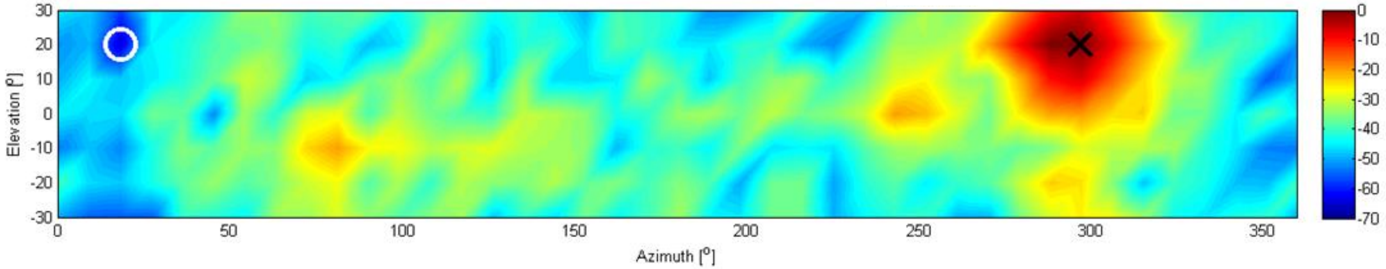
24 GHz Measurement Activities

- Characterization of the radio propagation at 24 GHz (cm-wave) in urban & suburban Brazilian-like scenarios:
  - Identification and characterization of dominant propagation mechanisms (diffraction, reflection, scattering, transmission).
  - Analysis of the number of “strong” received components for spatial diversity characterization.
  - Impact of vegetation.
  - Path loss analysis and modeling.

Directional Measurement Setup

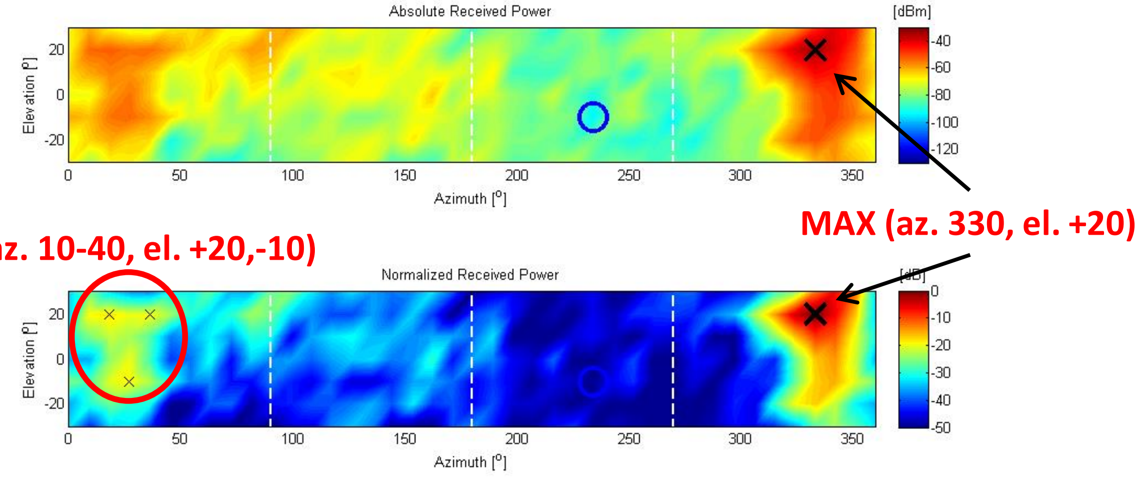
- CW radio transmission at 24 GHz.
- Fixed TX rooftop antenna.
- Automatized directional measurements at the RX side in order to characterize the received power in full azimuth (0-360 degrees) and +/- 30 degrees in elevation.

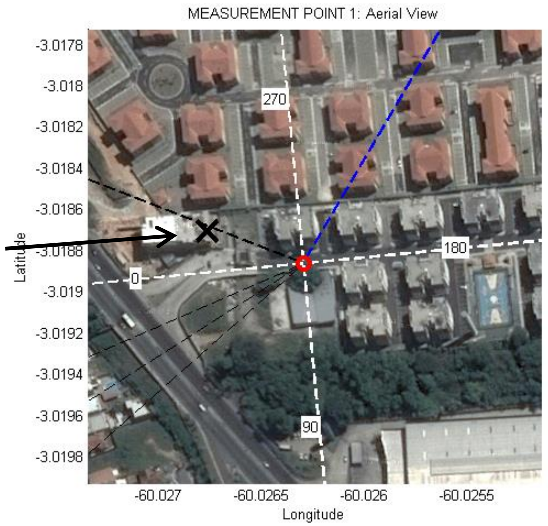


Some Preliminary Results

ABSOLUTE RECEIVED POWER

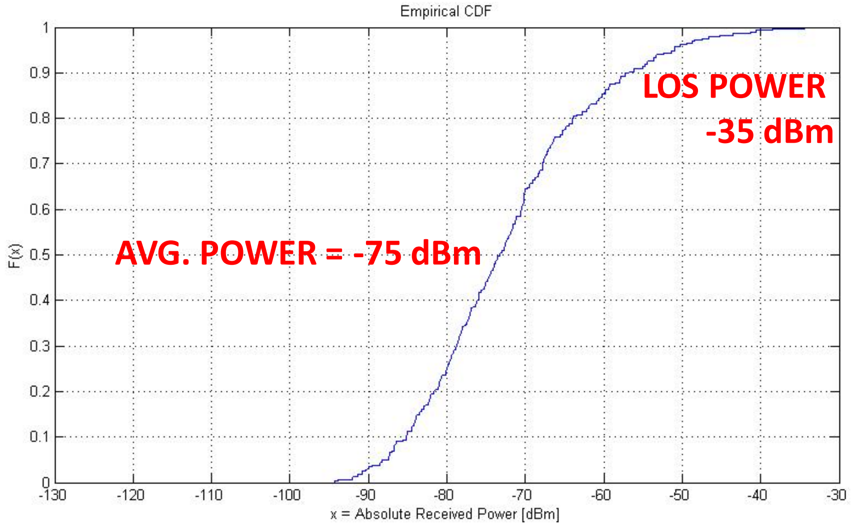
NORMALIZED RECEIVED POWER

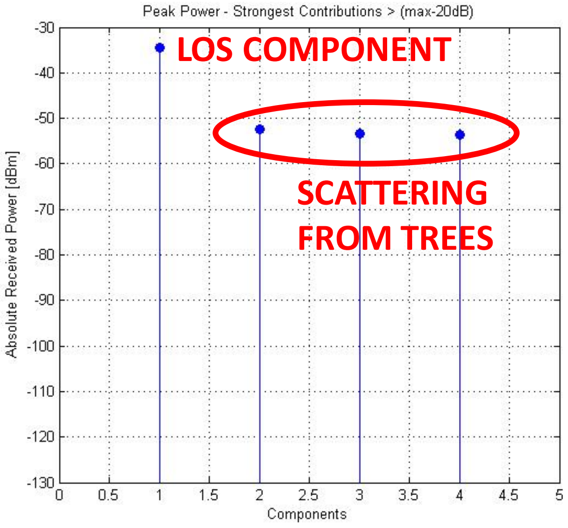




TOP VIEW WITH DIRECTIONAL INFORMATION (azimuth)

CDF ABSOLUTE RECEIVED POWER





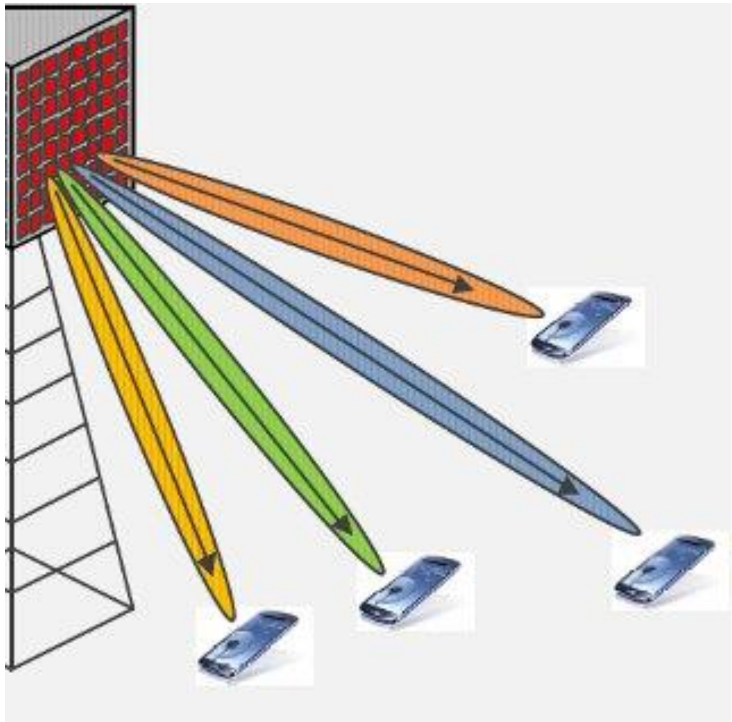
“STRONG” RECEIVED COMPONENTS

LOS position, 40 m distance to BS

MILLIMETER WAVE COMMUNICATION

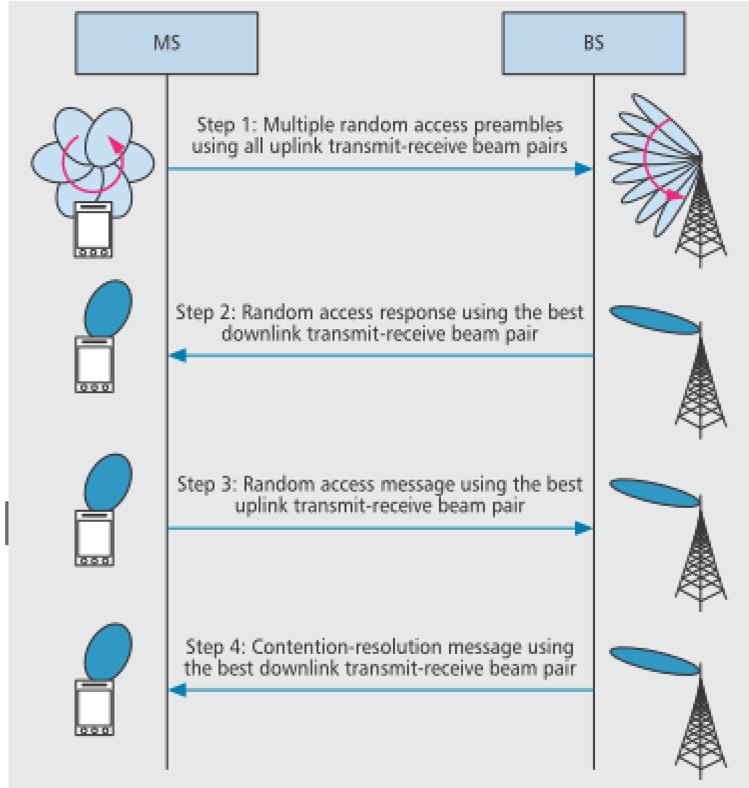
mmWave + Massive MIMO

- Signal suffers very strong attenuation
- Massive MIMO and beamforming are key Technologies to increase range



mmWave – MAC challenges

- New protocols are needed to manage the beam directions
  - How to provide a beacon?
  - How to discover devices?
  - How to react quickly to obstructions?
  - How to adapt the beam?
  - Do we need feedback?
  - Interference is likely to be low most of the times, but can l
    times, how to deal with it?



Jeong et al., *Random Access in Millimeter-Wave Beamforming Cellular Networks: Issues and Approaches,* IEEE Comm. Mag., 20015

mmWave – PHY challenges

- MIMO is used mostly for beamforming, hence spectral efficiency arises from
  - Very wide band signal (a few GHz)
    - ✓ How does channel/beamforming behave in this condition?
  - High SNIR ⇒higher-order modulation schemes
    - ✓ But RF imperfections and ADC resolution tend to be significant at these frequencies
- Can equalization needs be relaxed on account of narrow beamwidths (particularly for not very wide bands)?
- Do we still need multicarrier?
  - challenging with low ADC resolution
  - PAPR

Beyond mmWave

- Beyond mmWave
  - THz – submillimeter Waves
- High cost of hardware (for now)
- Possibly for very short links

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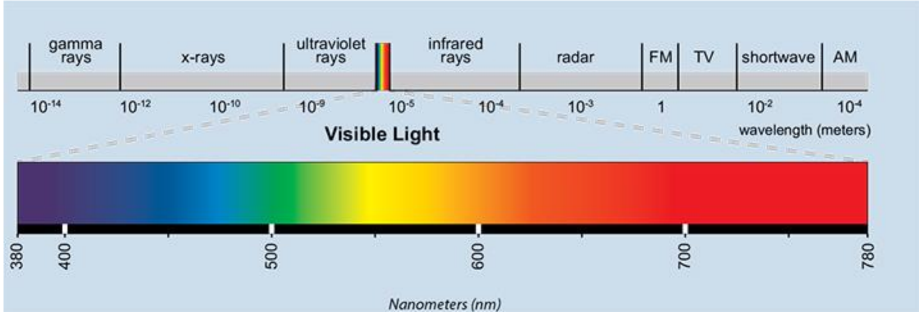
VLC – VISIBLE LIGHT COMMUNICATION

VLC (Visible Light Communications)

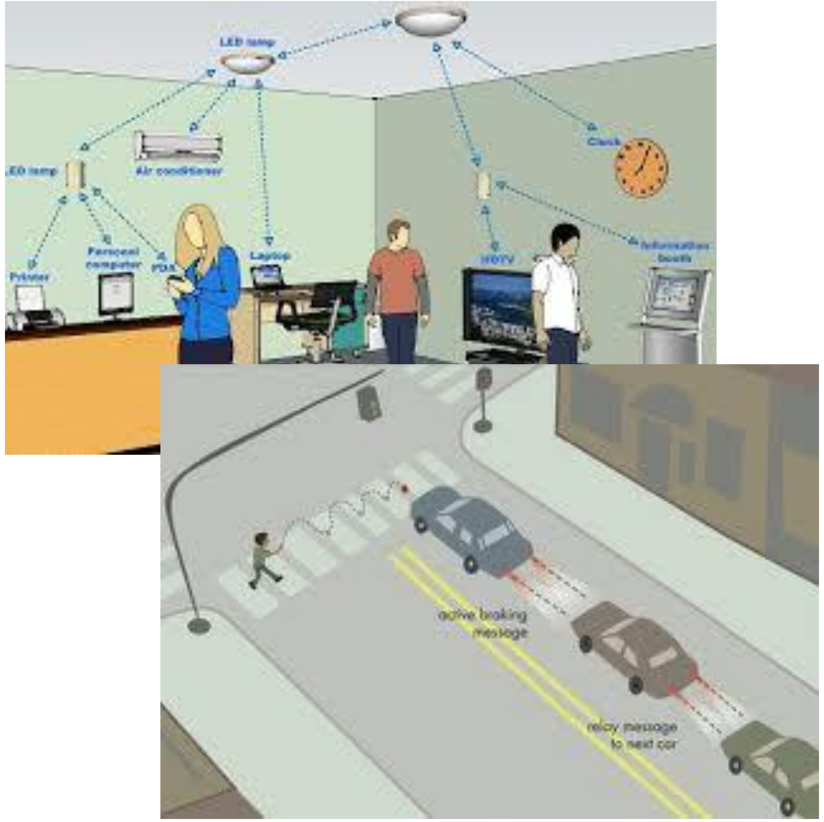
- Visible Light Spectrum (between 430 and 790 THz) largely unexploited for data transmission
  - Cheap and widely available components (LEDs and photodetectors)
  - Line-of-Sight only, hence,
    - ✓Short range,
    - ✓but very little interference
  - may serve as a complement to radio networks, particularly in the downstream

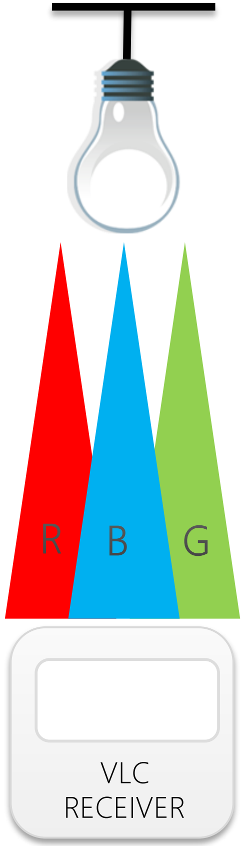


http://www.eyelighting.com

VLC

- Different applications
  - Home / office (indoors)
  - V2X
- Standards available
  - IEEE 802.15.7 (LiFi)
  - Up to 96Mbps in standard
    - ✓But multi-Gbps rates in labs





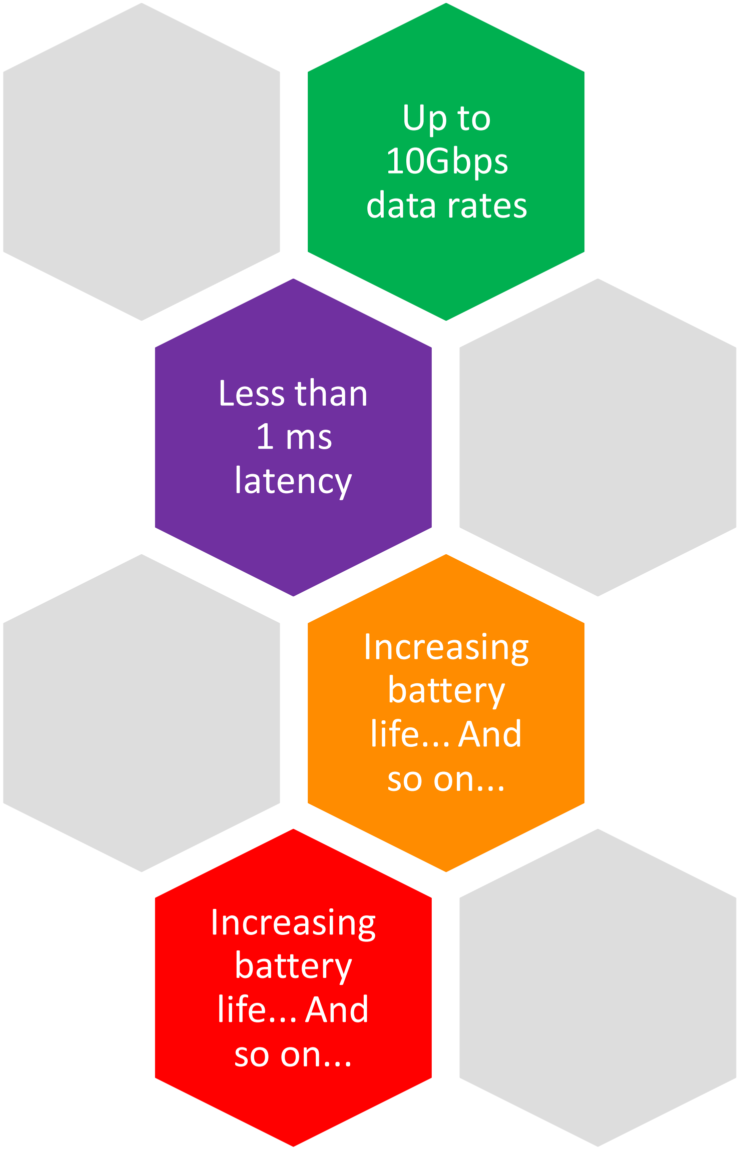
FSO (Free-Space Optical Links)

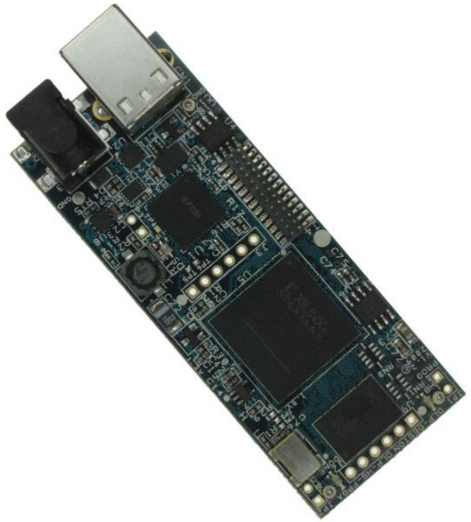
- Directional links can be created using lasers
- Can be a possible solution for wireless backhaul
- Challenges:
  - Tx/Rx modems must be aligned
  - Signal is attenuated by fog/heavy rain
  - Transmission is interrupted by physical obstructions (e.g., birds)

HARDWARE IMPLEMENTATION

Hardware Implementation

- 5G imposes tough requirements. Some of them are even contradictory.
- Let’s revisit some challenging requirements for 5G





Hardware Implementation

- But what does this mean in terms of implementation?

New techniques in advanced waveform modulation, coding, multiple access and full-duplex radios.

Complex baseband algorithms must run on highly efficient processing architecture to cope with throughput and latency requirements

Use of mmWave frequencies and physically small antennas.

SDR technologies need to be integrated in 5G architectures to allow flexible use of spectrum and access technology

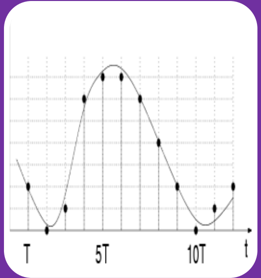
Flexible and cost-effective RF front-ends

Hardware Implementation

- In mobile communications the adoption of an advanced technology depends on the status of CPU, DSP, A/D Converters, RF, analog passive components like antennas and others...
- Hardware, Integrated Circuits (IC) and other components of the radio transceiver must evolve to meet those requirements

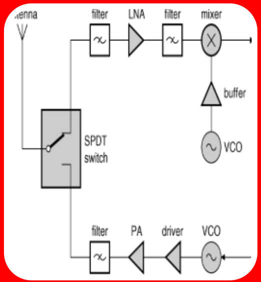
High speed digital processing systems

- DSPs
- FGPAs
- GPU



High Speed D/A Converters

- Suitable for Direct RF Sampling



RF Front-End enhancements

- Low jitter, clock recovery, synchronization
- Wider operating ranges, multi-band

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Hardware Implementation

- Semiconductor vendors are offering a huge number of processing platforms from highly specialized HW to general purpose applications
- Some times an optimal base-band algorithm is not realizable in real world because of implementation complexity or time complexity.
- So the key question is...

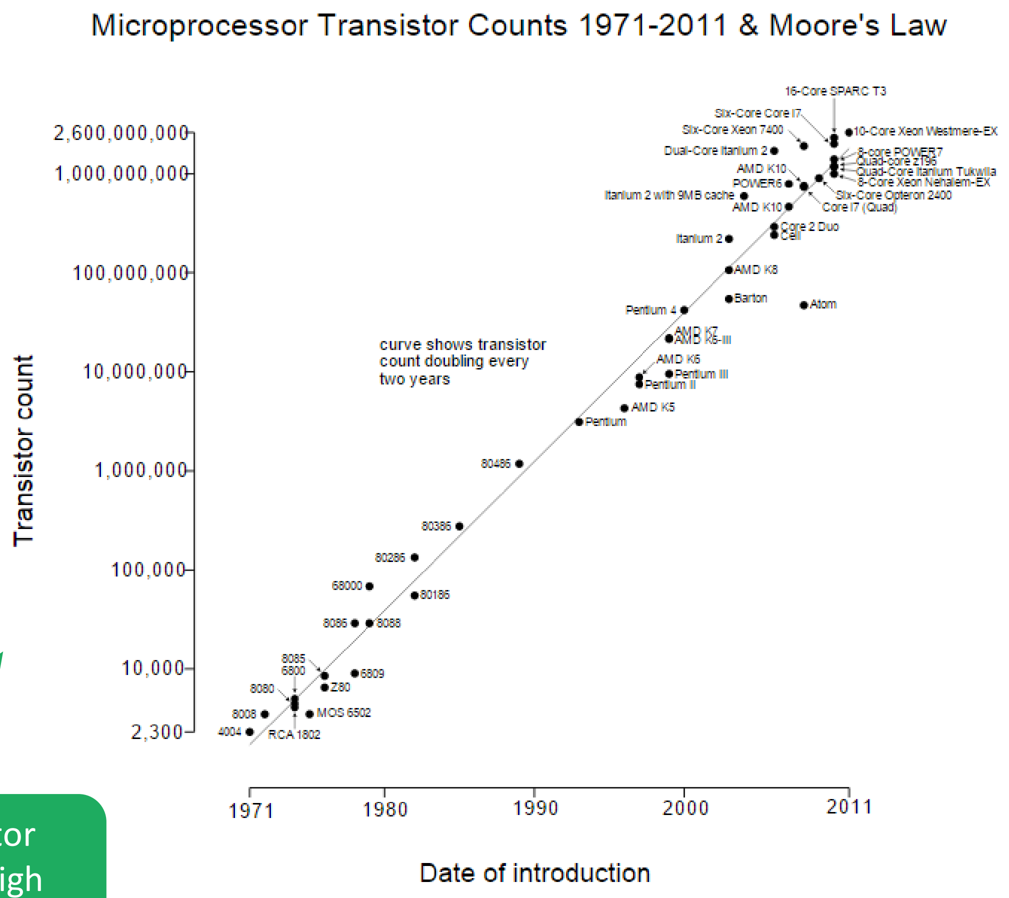
Hardware Implementation

- ...how to achieve high performance with low power consumption in a small form-factor?
  - FPGA technology evolved a lot and implementation has become easier with use of IP blocks. But they are still power hungry.
  - DSPs consumes less power and are easy to program, but processing speed is an issue for some algorithms and bit-wise computation
  - GPU has it’s niche in image processing and are gaining attention on SDR design. Power consumption is an issue here also.

Hardware Implementation

- Base-band processing and algorithm execution. How fast are we going??
  - Highly specialized DSPs, FPGA other computing architectures are evolving quite fast in recent years.
- The good news is that Moore's Law is not that saturated

We can rely on Moore's Law so IC development will drive technical progress in 5G!



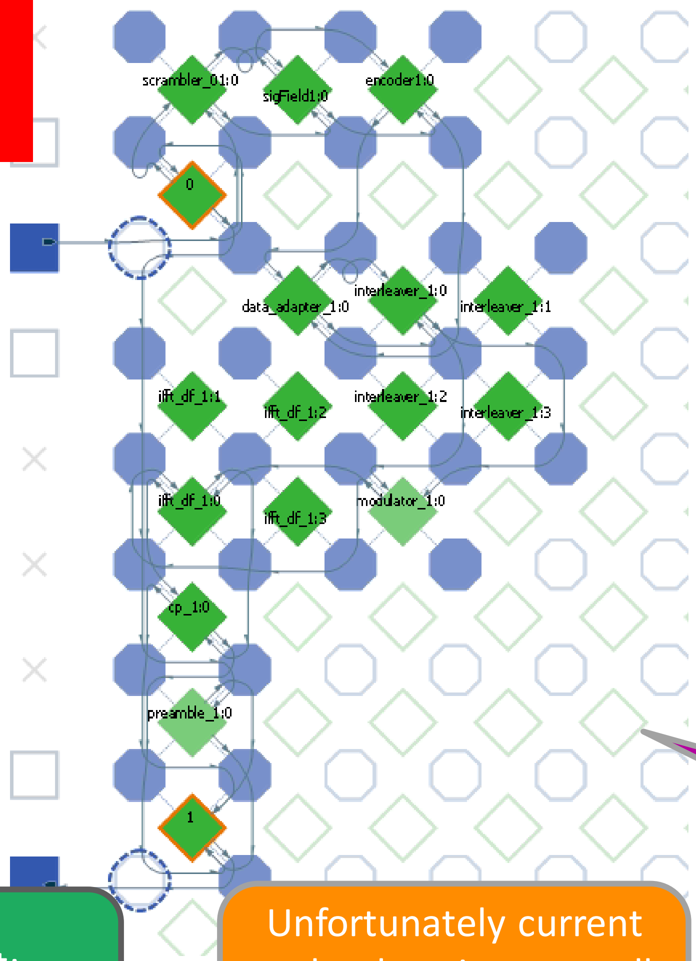
Increase in transistor count and transistor density. Some architectures support a high degree of parallelism

Hardware Implementation

There are some Massive Parallel Architectures out there that combine the power and programmability of DSPs with parallelization using a grid of hundreds of Processing Elements.

	5G
Bandwidth (MHz)	200
Subcarrier Spacing (kHz)	60
Symbol length (µs)	16.67
FFT Size	2048
Effective Subcarriers	3200
Sampling Frequency (MHz)	245.76
CP duration (µs)	1
Waveform	ZT-DS-OFDM

Requirement:
~3 Mega MAC/s



Example of a Network on Chip (NoC) processor with 10x10 PE grid.

This example shows a Tx chain NoC that achieves those processing constraints

Each diamond shape is a Processing Element

Unfortunately current technology is not small enough for mobile or sensor equipment

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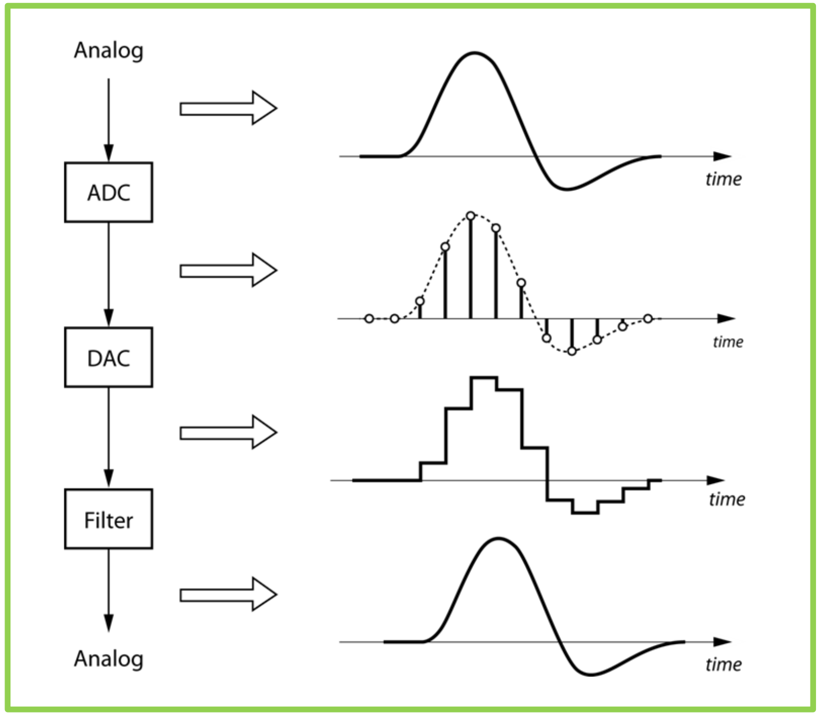
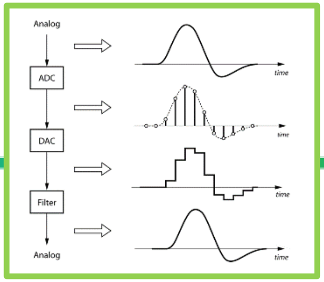
Hardware Implementation

- RF signal must be in digital form before processing. This is were DACs come into place.
- With higher bands the sampling rate of DACs must increase in magnitudes of order.



Hardware Implementation



- Direct RF sampling is one of the development areas for 5G.
  - With direct RF sampling the RF signals are digitally generated and sent directly to DACs for transmission without up-conversion.
    - ✓ It implies lower overall system complexity and cost: don't need multiple stages of filtering, synthesizers and mixers – no image rejection.
    - ✓ Better flexibility in modulation schemes and bands
    - ✓ Simplification of the challenges associated with Carrier Aggregation...
- Some GSamples/s ADC are being offered (TI for example) but they're still expensive and power hungry for mobile devices application

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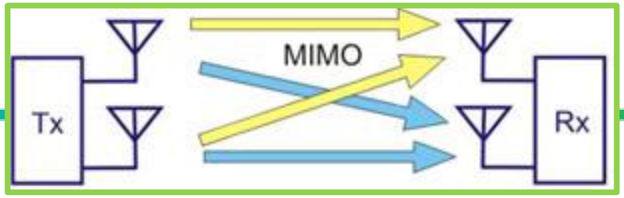
Hardware Implementation



- Multi-antenna transceiver and massive MIMO are key technologies to achieve high throughputs in 5G
- A massive MIMO system requires important attributes like:
  - Accurate time and frequency synchronization
  - High throughput BUS to interconnect processing elements
  - High performance processing for PHY execution to meet real-time constraints and execute MIMO precoding extremely fast!
- The industry already presented some test-bed equipment for developing innovative solutions and waveforms for 5G. But they are far for being in a small form-factor suitable for mobile equipment.

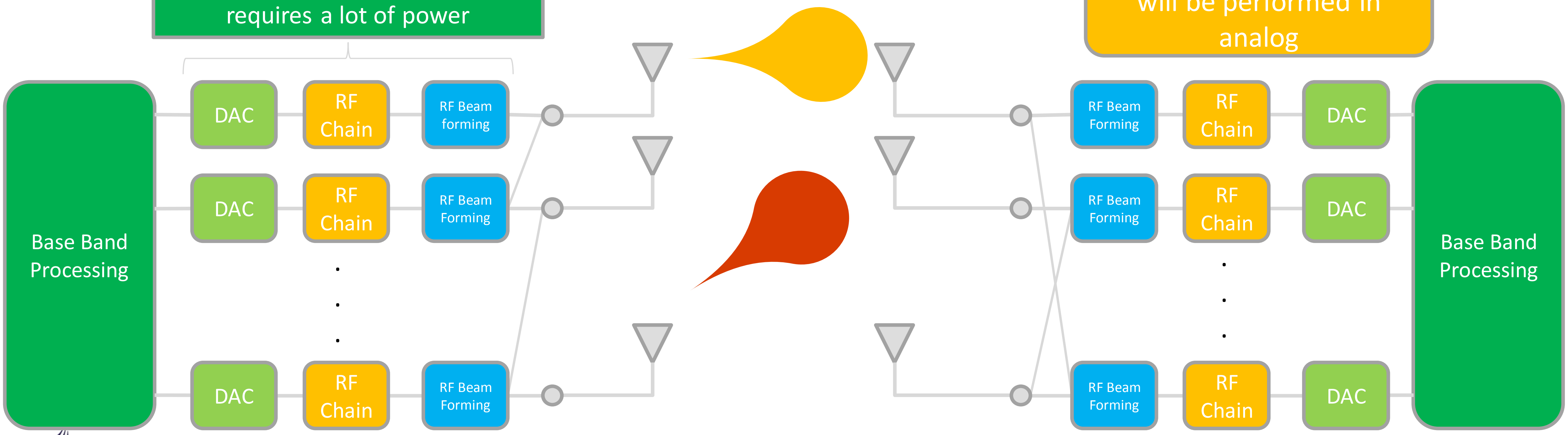
Hardware Implementation

Large antenna systems
Cost and power of components are high

Hybrid precoding: Analog phase shifters controlled digitally.
Need lots of processing speed!

Dedicate a separate RF chain for each antenna is costly and requires a lot of power

Some MIMO processing will be performed in analog



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Hardware Implementation

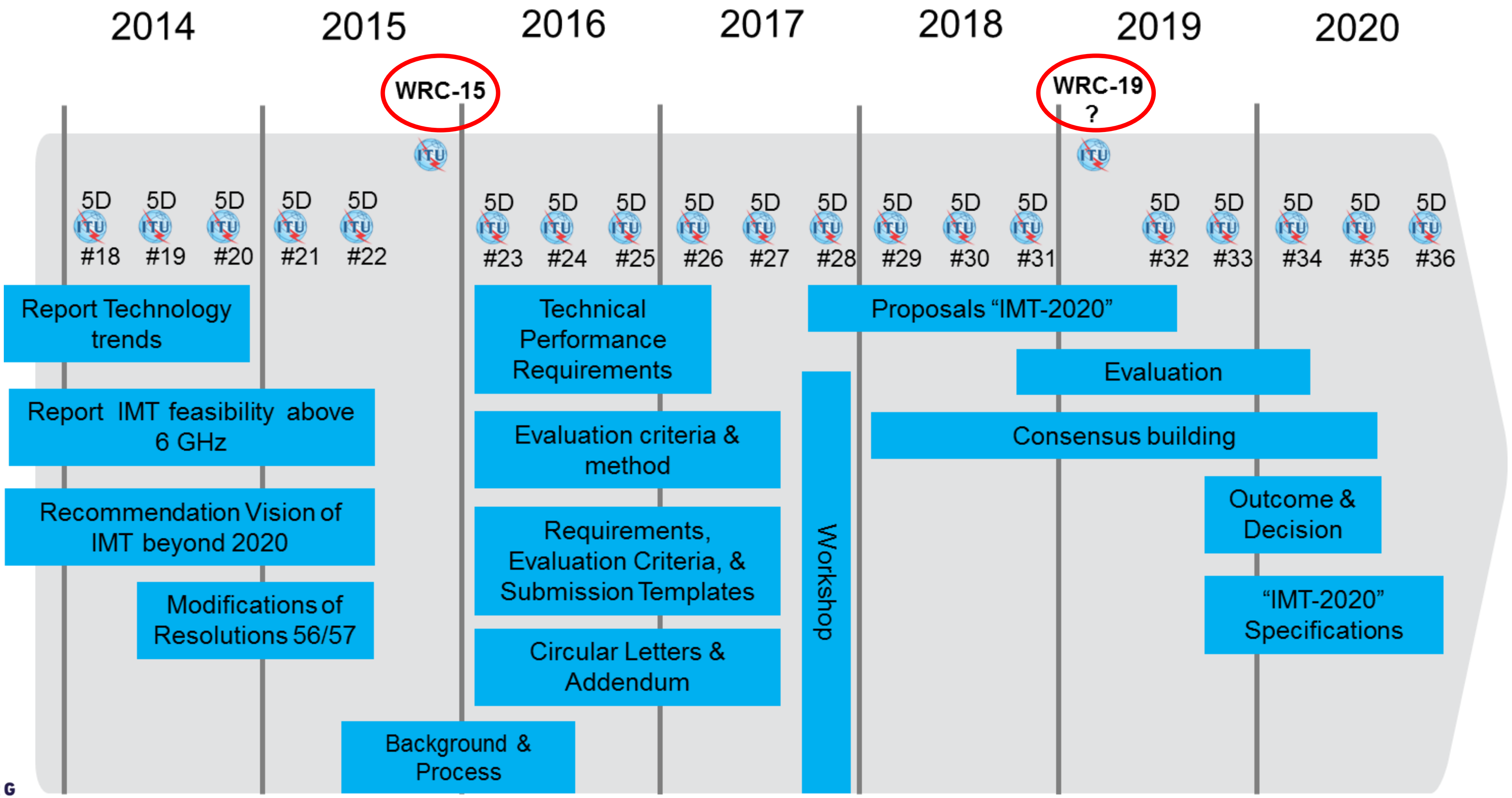
- Other HW impairments...
  - For large BW Power Amplifier Non-linearity becomes an issue
  - In high frequencies, imperfections of oscillators are much more evident.
  - Fitting a large number of antennas in small equipment is challenging engineering problem.
  - Design of PCB with high frequency BUS is challenging.

Hardware Implementation

- Conclusions
  - 5G communication shows potential to offer orders of magnitude of capacity over current communication systems
  - However architectures and protocols must be redesigned to meet the tight requirements of 5G.
  - Integrated Circuit, system, algorithms and RF components must evolve to promote the technology necessary for 5G.

STANDARDIZATION

ITU – Workplan for IMT 2020



3GPP and 5G

3GPP
A GLOBAL INITIATIVE

The Mobile Broadband Standard

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Tentative 3GPP timeline for 5G

March 17, 2015

By Dino Flore, Chairman of 3GPP RAN and Balazs Bertenyi, Chairman of 3GPP SA

Last week, 3GPP endorsed a tentative timeline for the standardization of next generation cellular technology, also known as "5G" [1]. The tentative timeline is shown in the picture below. This article briefly summarizes some of the key milestones and how the work is expected to proceed in 3GPP working groups.

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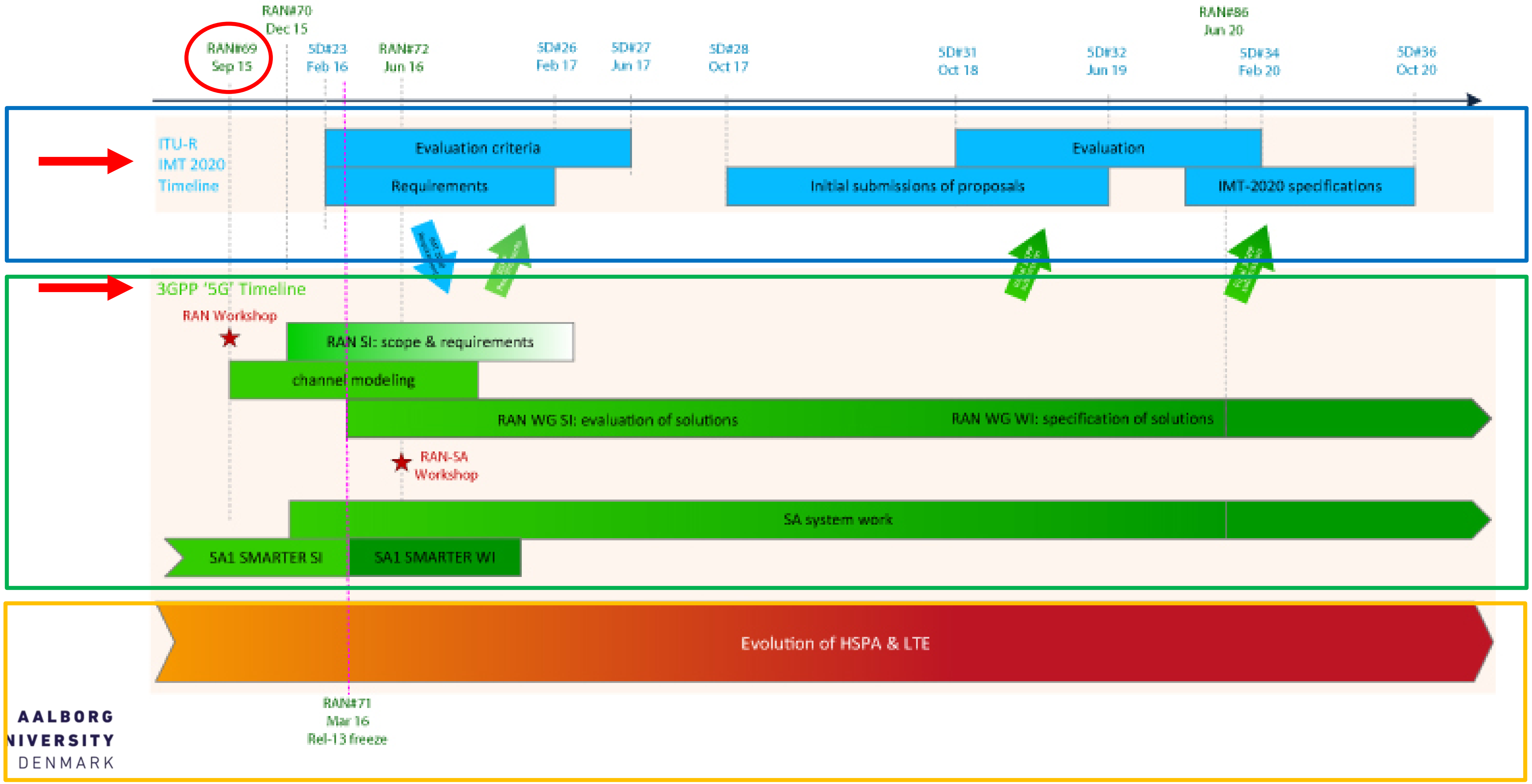

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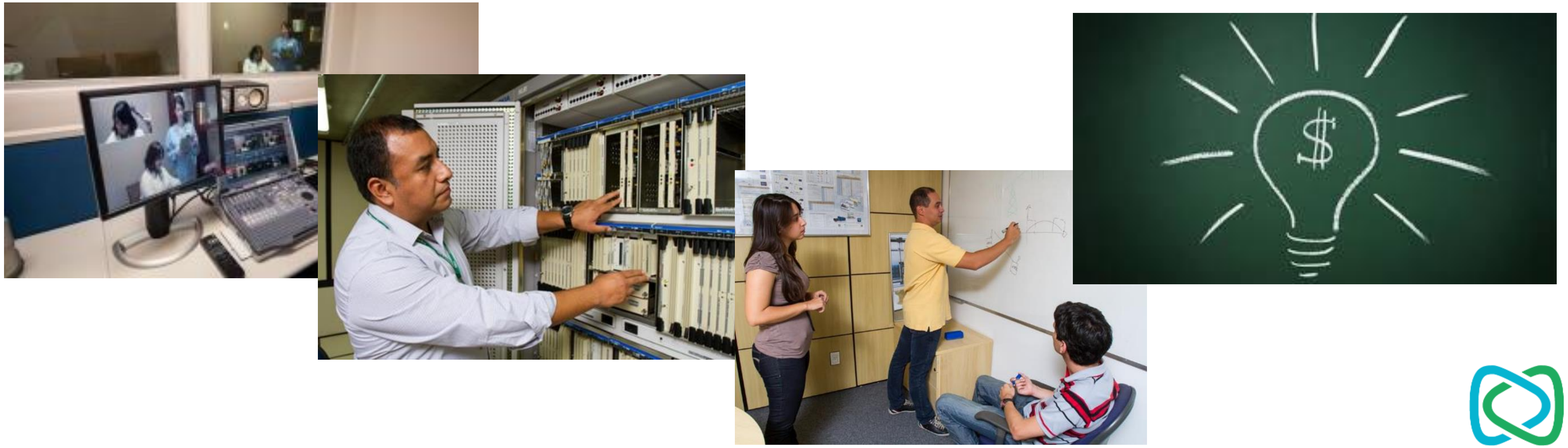
SUMMARY

Summary

- Requirements for new IoT and large-scale broadband wireless are very demanding
- 5G will not be just an evolution of 4G!
- A whole set of new Technologies are needed
  - Architectural changes
  - Communications theory challenges (modulation/coding/signal procesing)
  - Novel Hardware
  - New spectrum

Summary

- It is not going to be an easy task (and profit margins tend to be low)
- Good News is
  - Plenty of research work to be done until 2020
  - hopefully jobs, research grants, start-up opportunities and fun ...



THANK YOU

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