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5G New Radio (NR) : Physical Layer Overview and Performance

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5G New Radio : Key Features

Feature	Benefit	Feature	Benefit
Usage of sub 6GHz and mmWave spectrum	10x..100x more capacity	**Advanced Channel Coding**	Large data block support with low complecxity
UE agnostic Massive MIMO and beamforming	Higher Capacity and Coverage	**Aggregation of LTE + 5G carriers**	Higher data rate with smooth migration
Lean carrier design	Low power consumption, less interference	**Integrated Access and Backhaul**	Greater coverage @ mmWave with lower cost
Flexible frame structure	Low latency, high efficiency	**Flexible connectivity, mobility and sessions**	Optimized end-to-end for any services
Scalable OFDM based air-interface	Address diverse spectrum and services	**Beamformed Control and Access Channels**	Greater Coverage
Scalable numerology	Support of multiple bandwidths and spectrum	**Higher Spectral Usage**	Enhanced Efficiency

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Potential 5G Bands in (Early) 5G Deployments

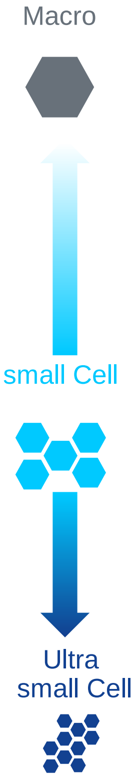
600 MHz	LTE/5G	North America
700 MHz	LTE/5G	APAC, EMEA, LatAm
3.3-3.4	LTE/5G	APAC, Africa, LatAm
3.4-3.6	LTE/5G	Global
3.55-4.2	LTE/5G	US
3.6-3.8	5G	Europe
4.5	5G	Japan China
28	5G	US, Korea Japan
39	5G	US
24.25-27.5	5G	WRC-19 band
31.8-33.4	5G	WRC-19 band (Fra, UK)
~40,~50,~70	5G	WRC-19 bands

Full coverage with <1 GHz

Dense urban high data rates at 3.5 – 4.5 GHz

Hotspot 10 Gbps at 28/39 GHz

Future mmwave options



Most of the 3.5Ghz already awarded – Spectrum re arrangement to happen to support larger block

5G Coverage Footprint – Combination of Low and High Bands

Let's make 3.7-4.2 GHz available

- High bands for capacity
- Low band for IoT and low latency critical communication

5G mm-waves

1000x local capacity

20 Gbps / 1000 MHz

5G 3500 mMIMO

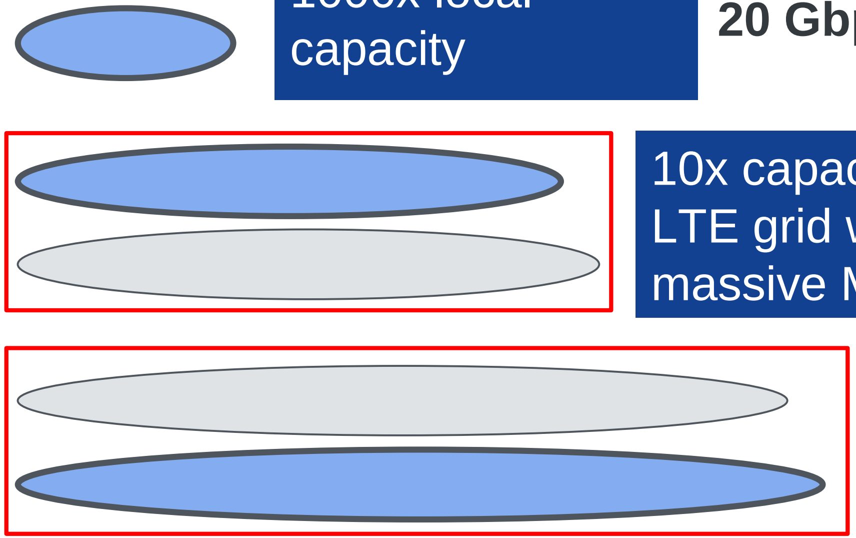
LTE-AWS

10x capacity with LTE grid with massive MIMO

2 Gbps / 100 MHz

LTE700

5G600



IoT and critical communication with full coverage

200 Mbps / 10 MHz

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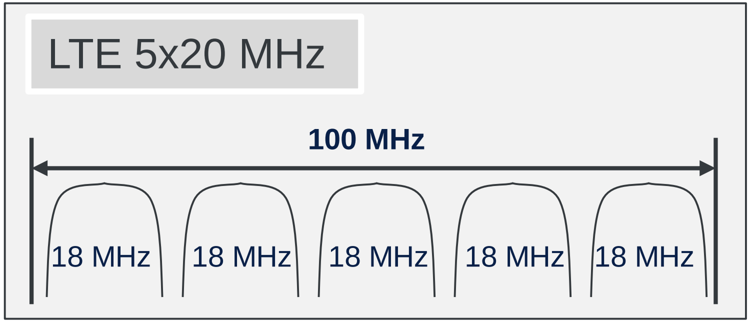
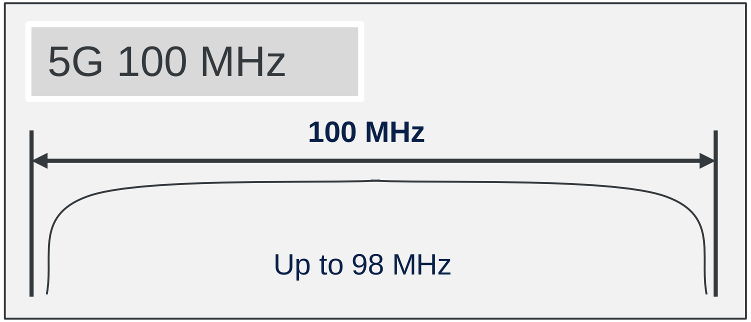
5G Enhances Spectral Utilization





- Wideband 5G carrier is more efficient than multicarrier LTE
- Faster load balancing
- Less common channel overhead
- No unnecessary guard bands between carriers. LTE uses 10% for guard bands.

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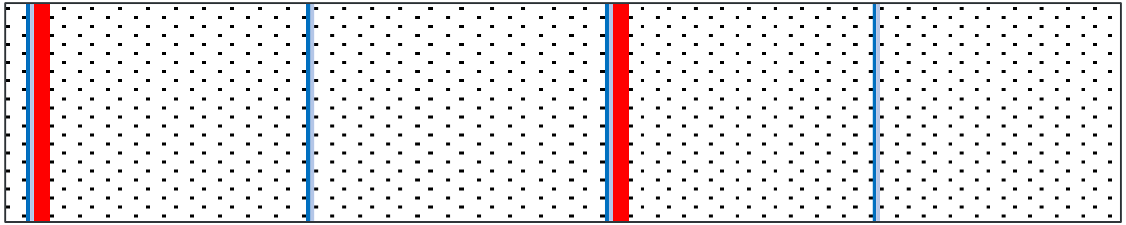
5G Lean Carrier for Enhanced Efficiency

= Primary synchronization
= Secondary synchronization
= Broadcast channel
= LTE cell reference signals

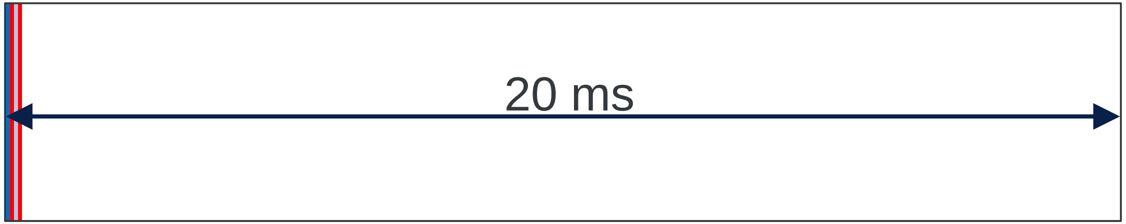
LTE



- Cell specific reference signal transmission 4x every millisecond
- Synchronization every 5 ms
- Broadcast every 10 ms

Very limited capability for base station power savings due to continuous transmission of cell reference signals

5G



- No cell specific reference signals
- Synchronization every 20 ms
- Broadcast every 20 ms

5G enables advanced base station power savings

Physical Channels & Physical Signals

PDSCH
DL shared channel

PBCH
Broadcast channel

PDCCH
DL control channel

GNodeB

PUSCH
UL shared channel

PUCCH
UL control channel

PRACH
Random access channel

User Equipment

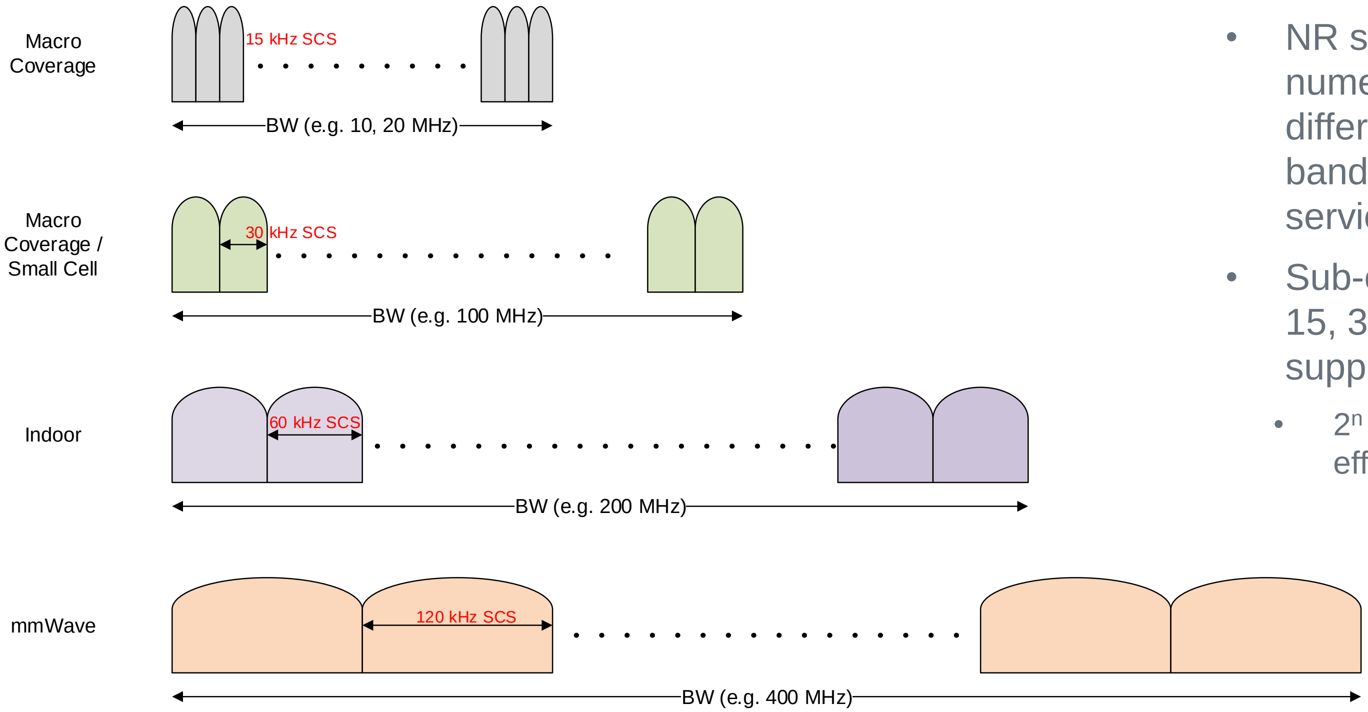
DL Physical Signals

Demodulation Ref (DMRS)
Phase-tracking Ref (PT-RS)
Ch State Inf Ref (CSI-RS)
Primary Sync (PSS)
Secondary Sync (SSS)

UL Physical Signals

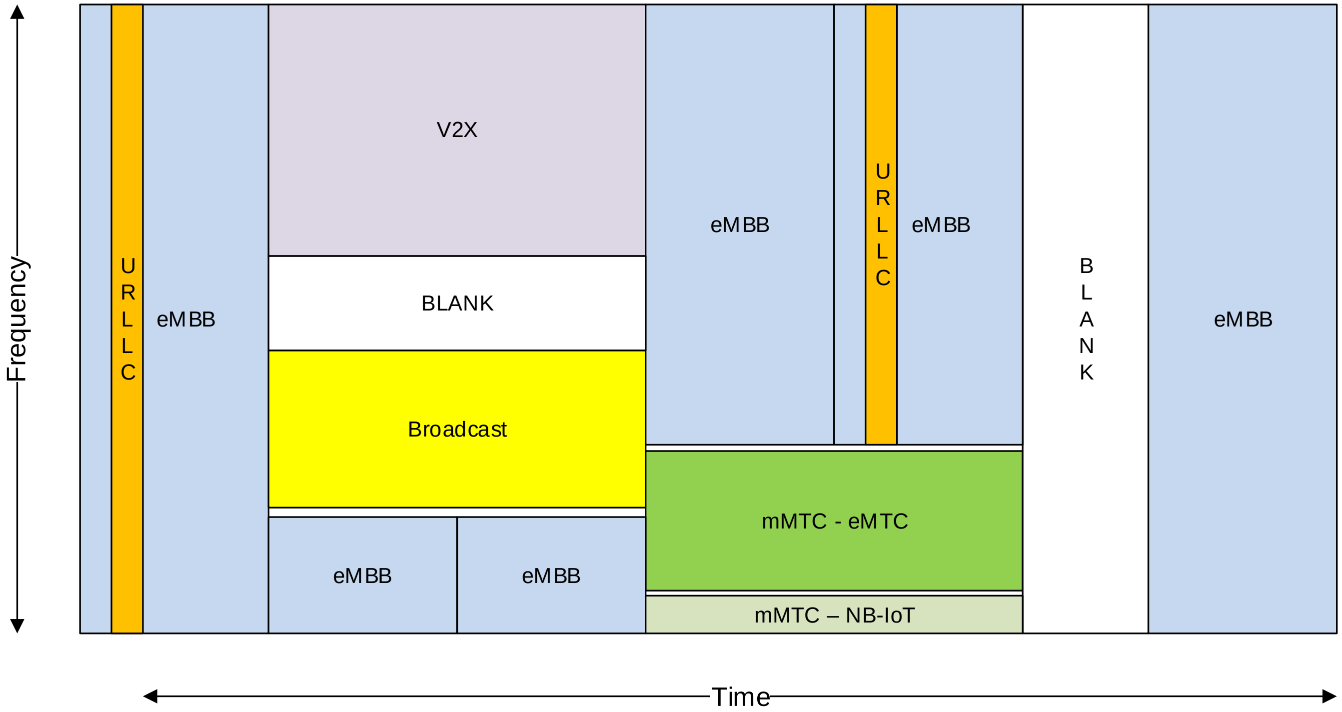
Demodulation Ref (DMRS)
Phase-tracking Ref (PTRS)
Sounding Ref (SRS)

Scalable NR Numerology



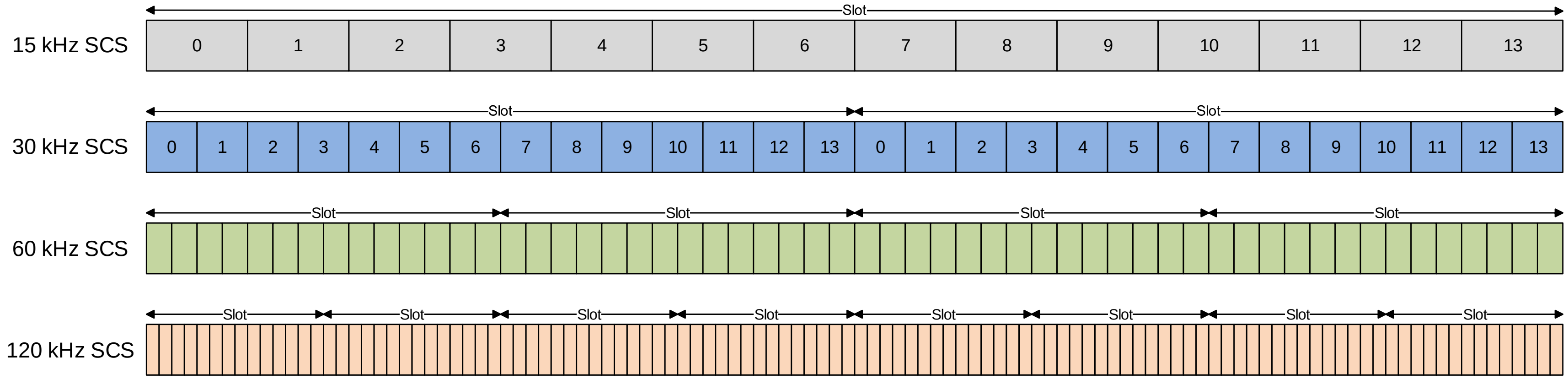
- NR supports scalable numerology to address different spectrum, bandwidth, deployment and services
- Sub-carrier spacing (SCS) of 15, 30, 60, 120 kHz is supported for data channels
  - 2^n scaling of SCS allows for efficient FFT processing

Flexible NR Framework



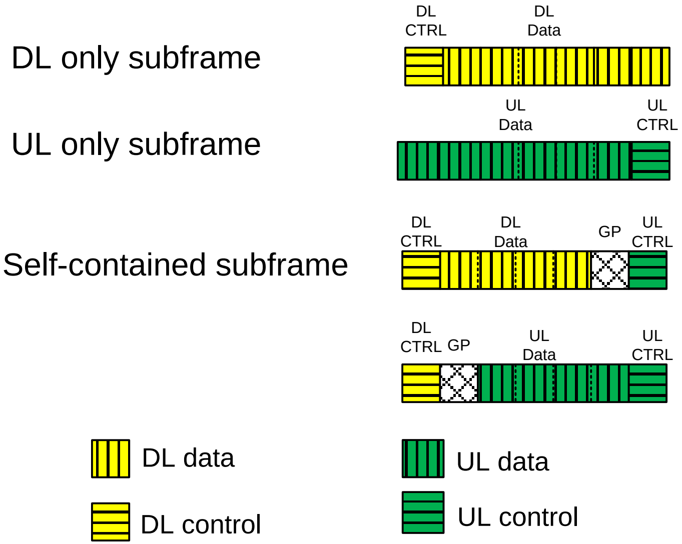
- NR provides flexible framework to support different services and QoS requirements
  - Scalable slot duration, mini-slot and slot aggregation
  - Self-contained slot structure
  - Traffic preemption for URLLC
  - Support for different numerologies for different services
- NR transmission is well-contained in time and frequency
  - Future feature can be easily accommodated

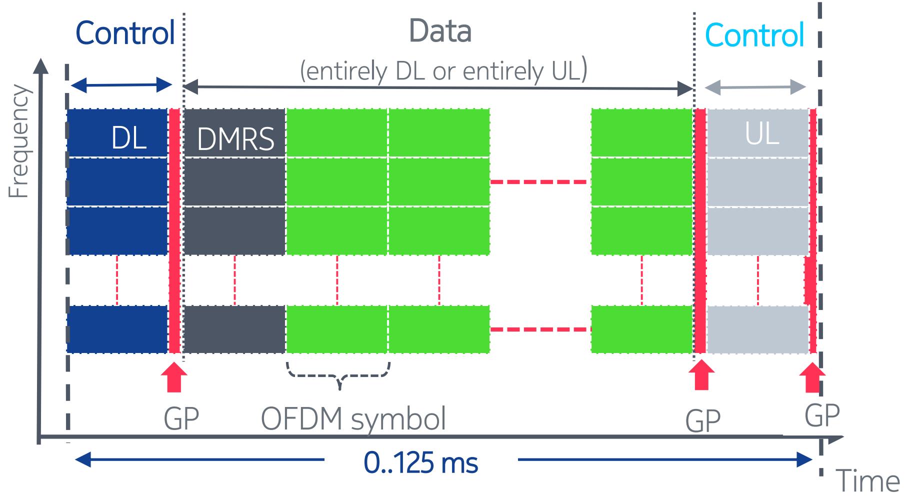
Scalable NR Slot Duration



- One slot is comprised of 14 symbols
  - Slot length depends on SCS – 1ms for 15 kHz SCS to 0.125ms for 120 kHz SCS
- Mini-slot (2,4, or 7 symbols) can be allocated for shorter transmissions
- Slots can also be aggregated for longer transmissions

NR frame/subframe structure





0.125ms frame with cascaded UL/DL control signals (120 KHz SC)

1.0 ms user plane latency
GP = 0

Same physical layer in UL and DL

Scalable Slot Duration

Flexible UL/DL

Control channel just before data

Energy-effective processing

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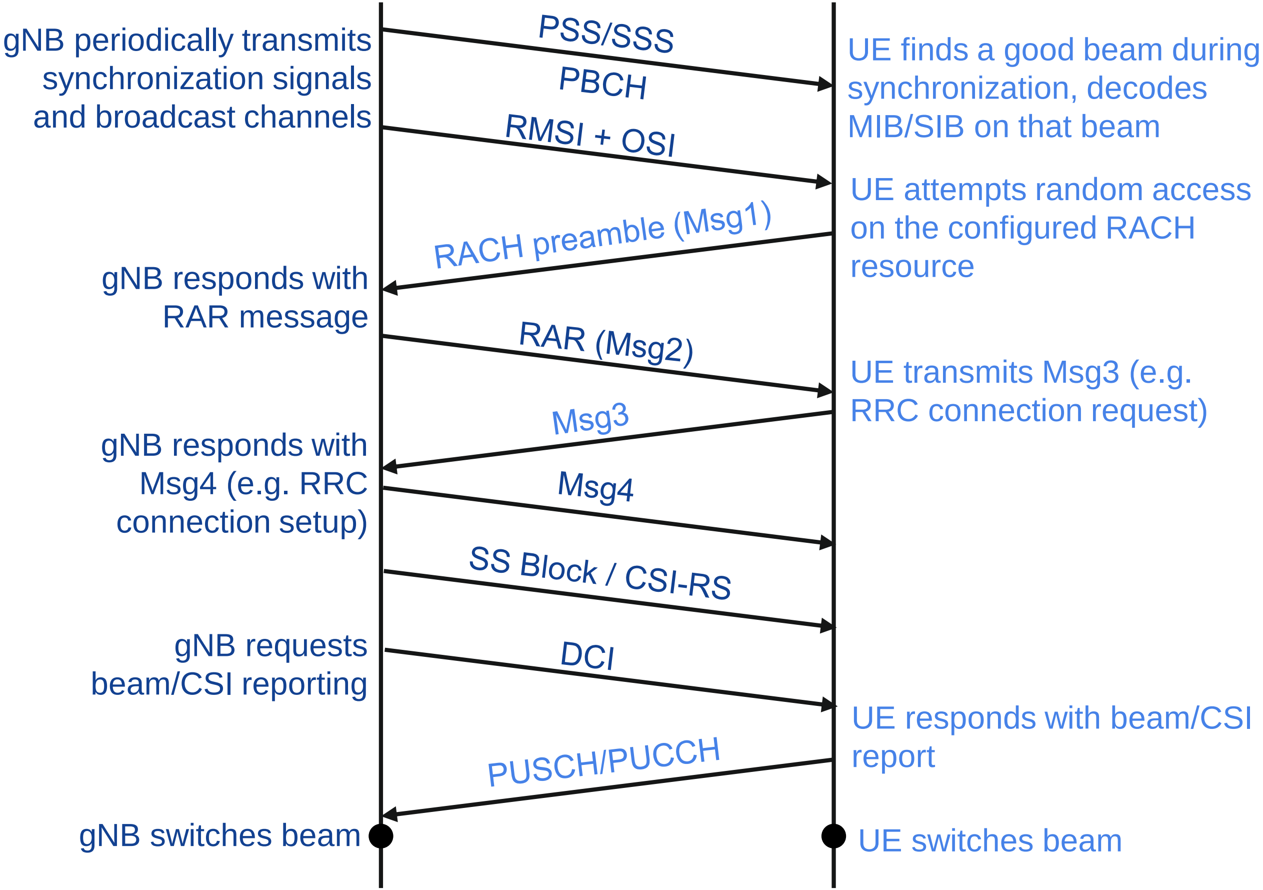
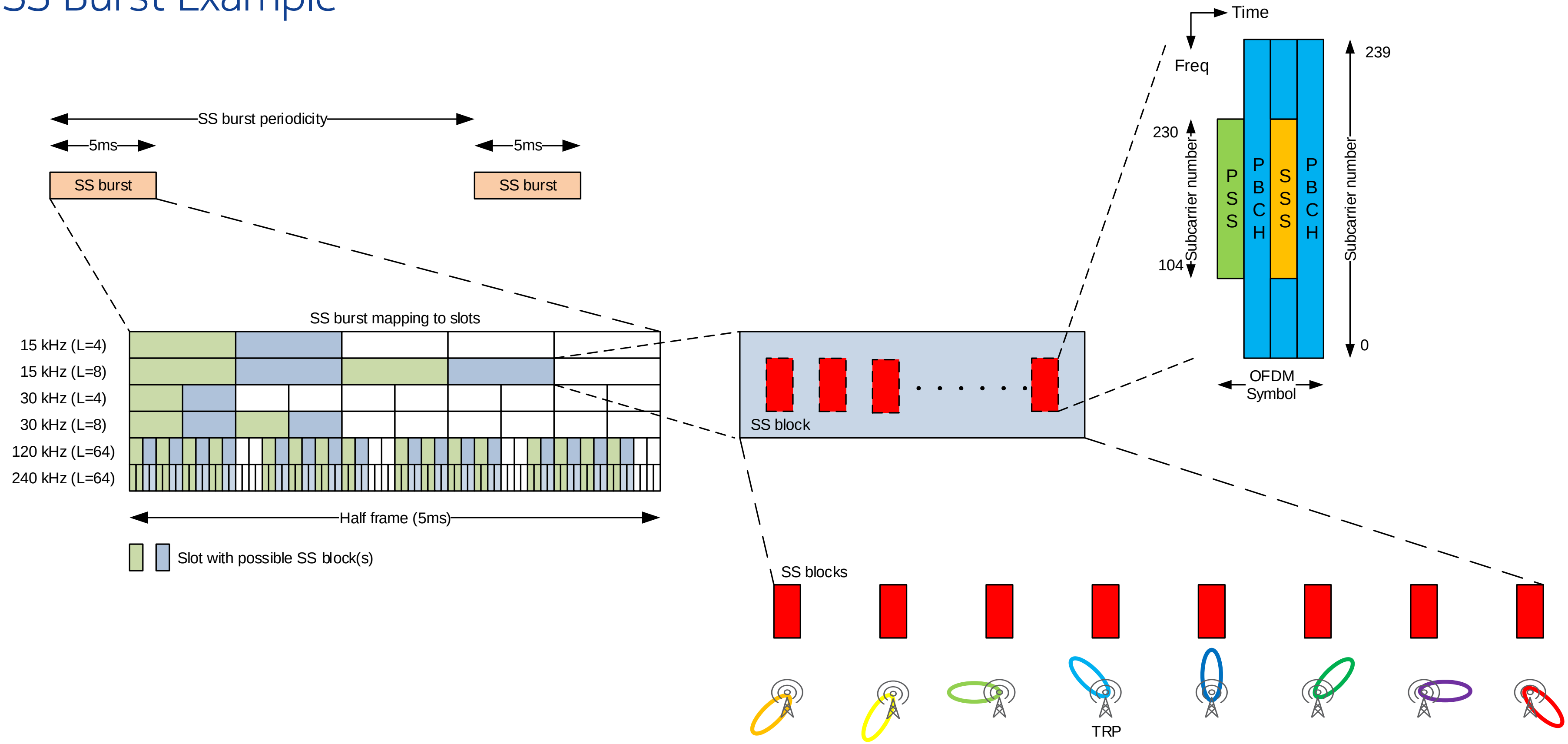
Initial Access



SS Burst Example



Overview of NR eMBB coding schemes

LDPC

- Data channel
  - BG1 and BG2
  - Quasi-cyclic (QC)
  - Covers a wide range of coding rates and block sizes
  - Full IR-HARQ support
- Benefits
  - High throughput (parallel decoding in hardware)
  - Good performance

Polar codes

- Control channel
  - DL: CRC-distributed polar codes
  - UL: CRC-aided and PC polar codes
- Benefits
  - Best performed short codes
  - Low algorithmic complexity
  - No error floor

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What is "Massive MIMO"

Massive MIMO is the extension of traditional MIMO technology to antenna arrays having a **large** number (>>8) of controllable antennas

Transmission signals from the antennas are **adaptable** by the physical layer via gain or phase control

Not limited to a particular implementation or TX/RX strategy

Enhance Coverage:
High Gain Adaptive Beamforming
➔ Path Loss Limited (>6GHz)

Enhance Capacity:
High Order Spatial Multiplexing
➔ Interference-limited (<6GHz)

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MIMO in 3GPP

Release 8	Release 9	Release 10	Release 11
• 4x4MIMO • 4x2MIMO • 8RX uplink • Uplink CRAN	• 8TX TM8	• 8TX TM9	• Downlink CoMP (TM10)

Release 12	Release 13	Release 14	Release 15+
• Downlink eCoMP • New 4TX codebook	• Massive MIMO 16TX	• Massive MIMO 32TX	• 5G / NR Massive MIMO 32TX+

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Massive MIMO: Why Now?

Capacity Requirements	Coverage Requirements	Technology Capability	3GPP Spec Support
Most Macro Networks will become congested Spectrum < 3GHz and base sites will run out of capacity by 2020	<u>Below 6GHz</u>: desire to deploy LTE/NR on site grids sized for lower carrier frequencies <u>Above 6GHz</u>: Large Bandwidths but poor path loss conditions	Active Antennas are becoming technically and commercially feasible Massive MIMO requires Active Antenna technology	3GPP supports Massive MIMO in Rel-13/14 for LTE and Rel-15 for NR/5G 3GPP-New-Radio will be a “beam-based” air interface

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Massive MIMO at Higher Carrier Frequencies (>>6 GHz)

Poor path loss conditions	Cost & power consumption	Antenna array implementation	Beam based air interface
Large number of antennas needed to overcome poor path loss Obtaining channel knowledge per element is difficult	Full digital solutions require transceiver units behind all elements Wide bandwidths: A/D and D/A converters are very power hungry	Smaller form factors Distributed PA solutions → Hybrid arrays Beamforming at RF with baseband digital Precoding	Single sector-wide beam may not provide adequate coverage → Beamform all channels! → Support analog and hybrid arrays

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NR-MIMO in the 3GPP New Radio

Main Drivers of NR-MIMO Development

Deployment	Scalable, Flexible Implementation	Purpose
• Support frequencies both below and above 6GHz • Support both FDD and TDD	gNB: • support full digital array architectures (<6GHz) • hybrid/analog architectures (>6GHz), • arbitrary TXRU configurations • arbitrary array sizes UE: • support traditional UE antenna configurations • higher numbers of antennas • UEs operating above 6GHz (hybrid/analog architectures)	• Enhance capacity (interference-limited deployments) • Enhance coverage (coverage-challenged deployments)

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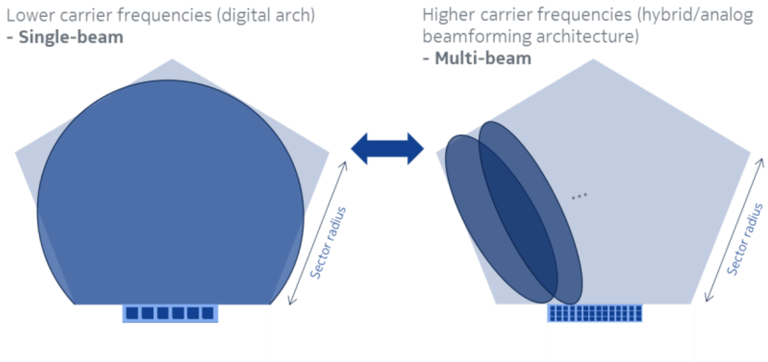
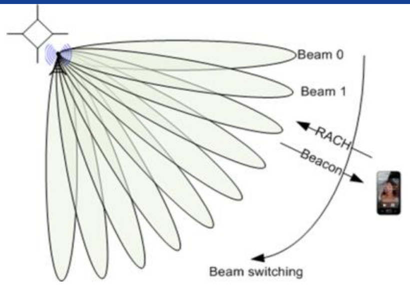
Massive MIMO in 3GPP New Radio – Beam-based air-interface

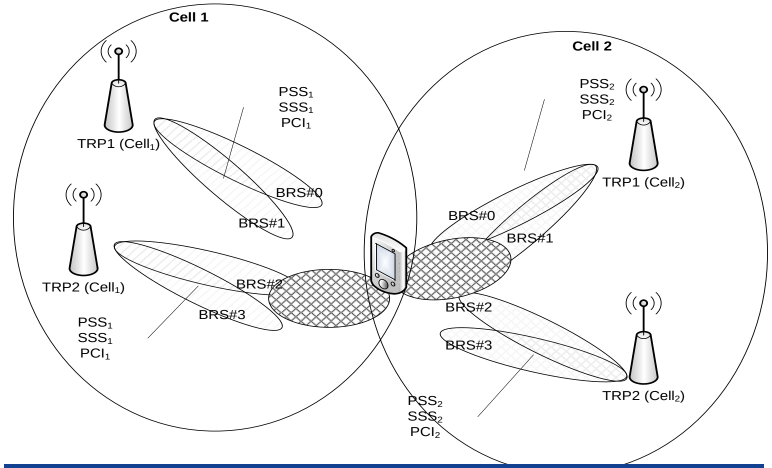
Beamformed Control Channels



Beam Scanning



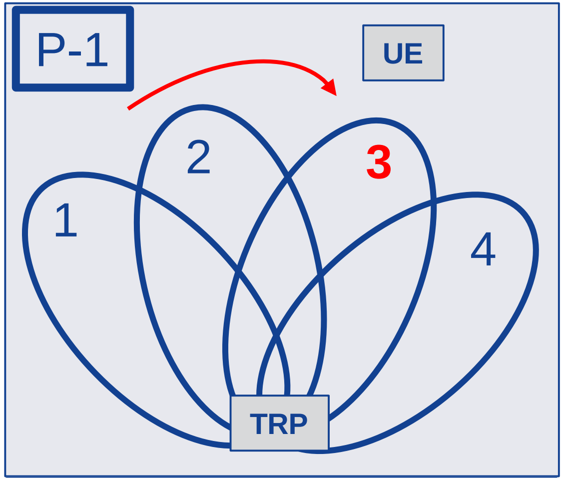
Beam Management



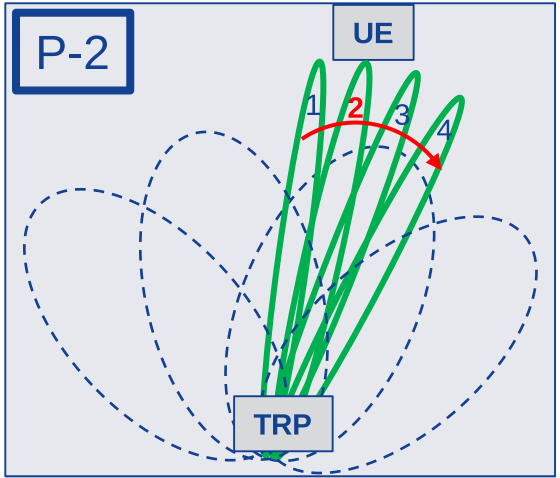
Key features for beam-based AI

- Scalable and Flexible CSI Acquisition Framework
- High performing CSI Acquisition Codebooks
- Improved UL framework

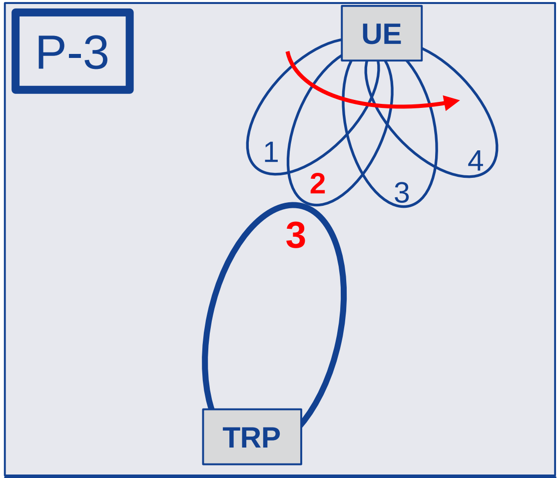
Downlink MIMO Framework: Beam Management



- Initial gNB Beam Acquisition
- SSB or CSI-RS



- gNB Beam Refinement
- E.g., CSI-RS



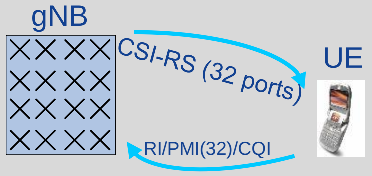
- UE Beam Refinement

Forming beam ports for MIMO transmission (TX and RX)

DL-MIMO Operation – Sub-6GHz

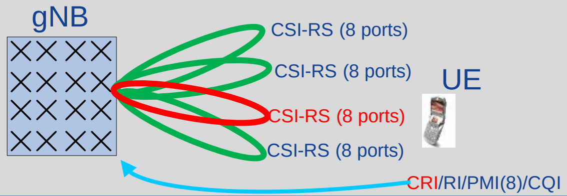
Single CSI-RS

- CSI-RS may or may not be beamformed
- Leverage codebook feedback
- Analogous to **LTE Class A**
- Process:
  - gNB transmit CSI-RS
  - UE computes RI/PMI/CQI
- Maximum of 32 ports in the CSI-RS (codebooks are defined for up to 32 ports)
- Typically intended for arrays having 32 TXRUs or less with no beam selection (no CRI)



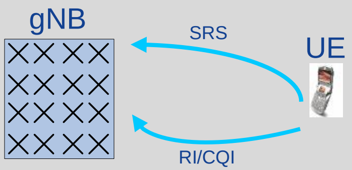
Multiple CSI-RS

- Combines beam selection with codebook feedback (multiple beamformed CSI-RS with **CRI** feedback)
- Analogous to **LTE Class B**
- Process:
  - gNB transmits one or more CSI-RS, each in different "directions"
  - UE computes CRI/PMI/CQI
- Supports arrays having arbitrary number of TXRUs
- Max 32 ports per CSI-RS



SRS-Based

- Intended for exploiting TDD reciprocity
- Similar to SRS-based operation in LTE
- Supports arrays having an arbitrary number of TXRUs.
- Process:
  - UE transmits SRS
  - Base computes TX weights



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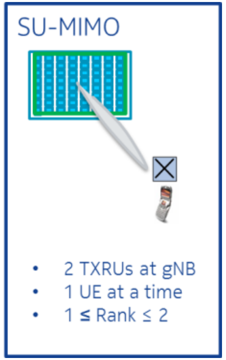
Disclaimer: NR-MIMO is flexible enough to support many variations on what is described on this slide

DL-MIMO Operation – Above 6GHz

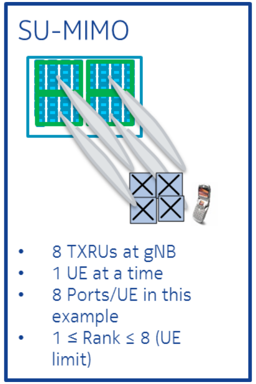
Single Panel Array

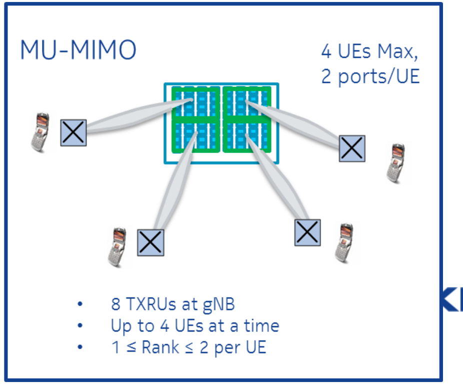
- Combination of RF Beamforming and digital precoding at baseband
- RF Beamforming is typically 1RF BF weight vector per polarization: a single “Cross-Pol Beam”
- 2 TXRUs, Single User MIMO only
- Baseband Precoding Options:
  - None (rank 2 all the time)
  - CSI-RS based (RI/PMI/CQI)
  - SRS-based (RI/CQI)



Multi-Panel Array

- Combination of RF beamforming and digital precoding at baseband
- RF Beamforming is typically 1RF BF weight vector per polarization per panel:
- One “Cross-Pol Beam” per sub-panel
- Number of TXRUs = 2 x # of panels
- Baseband Precoding Options:
  - CSI-RS based (RI/PMI/CQI)
  - SRS-based (RI/CQI)
- SU- and MU-MIMO (typically one UE per Cross-Pol Beam)





CSI Framework: major components

Report Settings

What CSI to report and when to report it

- **<u>Quantities to report</u>**:
  CSI-related or L1-RSRP-related
- **<u>Time-domain behavior</u>**: Aperiodic, semi-persistent, periodic
- **<u>Frequency-domain granularity</u>**:
  Reporting band, wideband, sub-band
- **<u>Time-domain restrictions</u>**
  for channel and interference measurements
- **<u>Codebook configuration</u>**
  parameters
  Type I
  Type II

Resource Settings

What signals to use to compute CSI

- A Resource Setting configures S>1 **<u>CSI Resource Sets</u>**
- Each CSI Resource Set consists of:
  ** **<u>CSI-RS Resources</u>**
  (Either NZP CSI-RS or CSI-IM)
  ** **<u>SS/PBCH Block Resources</u>**
  (used for L1-RSRP computation)
- **<u>Time-domain behavior</u>**: aperiodic, periodic, semi-persistent
  ** Periodicity and slot offset
- **<u>Note</u>**: # of CSI-RS Resource Sets is limited to S=1 if CSI Resource Setting is periodic or semi-persistent.

Trigger States

Associates
What CSI to report and when to report it
with
What signals to use to compute the CSI

- Links Report Settings with Resource Settings
- Contains list of associated CSI-ReportConfig

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Summary : UL MIMO

- **Two transmit schemes are supported for NR uplink MIMO**
  - Codebook based transmission
    - Up to 4Tx codebooks are defined for both DFT-S-OFDM and CP-OFDM
  - Non-codebook based transmission
    - UE Tx/Rx reciprocity based scheme to enable UE assisted precoder selection

- **Diversity schemes are not explicitly supported in NR specification**
  - No diversity based transmission schemes are specified in Rel-15 NR
  - UE can still use “transparent” diversity transmission scheme.
    - UE may use 1Tx port procedure for specification-transparent diversity Tx schemes

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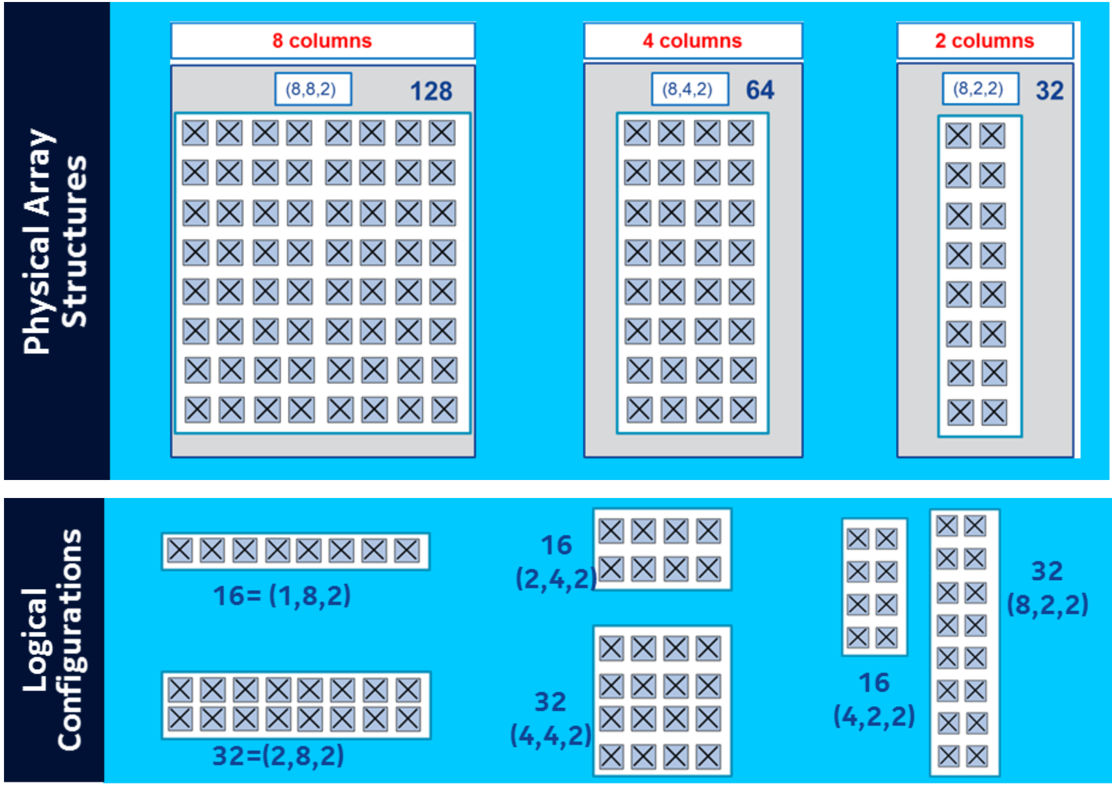
Downlink Massive MIMO: NR vs LTE: 16 and 32 TXRUs, Full Buffer Traffic

LTE:

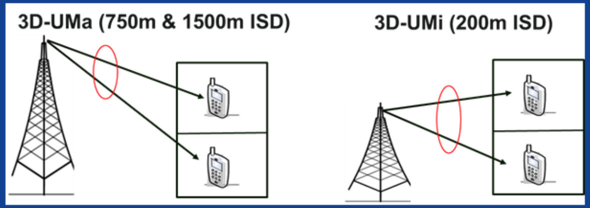
- Rel-13 Codebook
  - 16 Ports and 32 Ports, Maximum Rank = 8
  - (32 ports=Rel-13 extension CB approved in Rel-14)
- Rel-14 codebook
  - 16 Ports and 32 Ports, Maximum Rank = 2

NR:

- NR Codebook Type I
  - 16 Ports and 32 Ports, Maximum Rank = 8
- NR Codebook Type II
  - 16 Ports and 32 Ports, Maximum Rank = 2



- Scenarios at 2GHz



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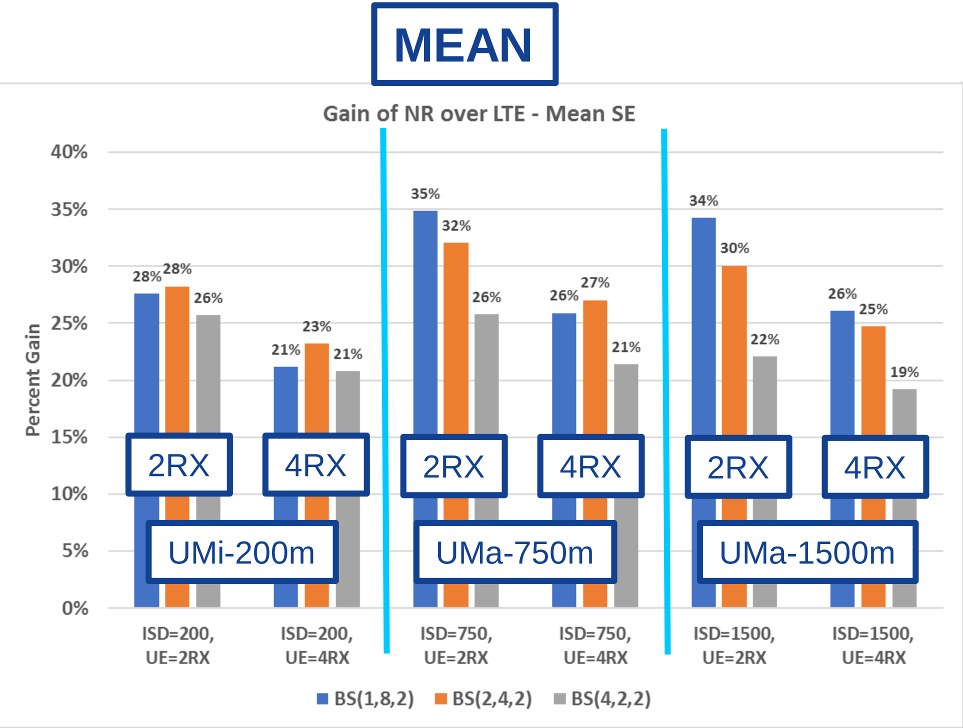
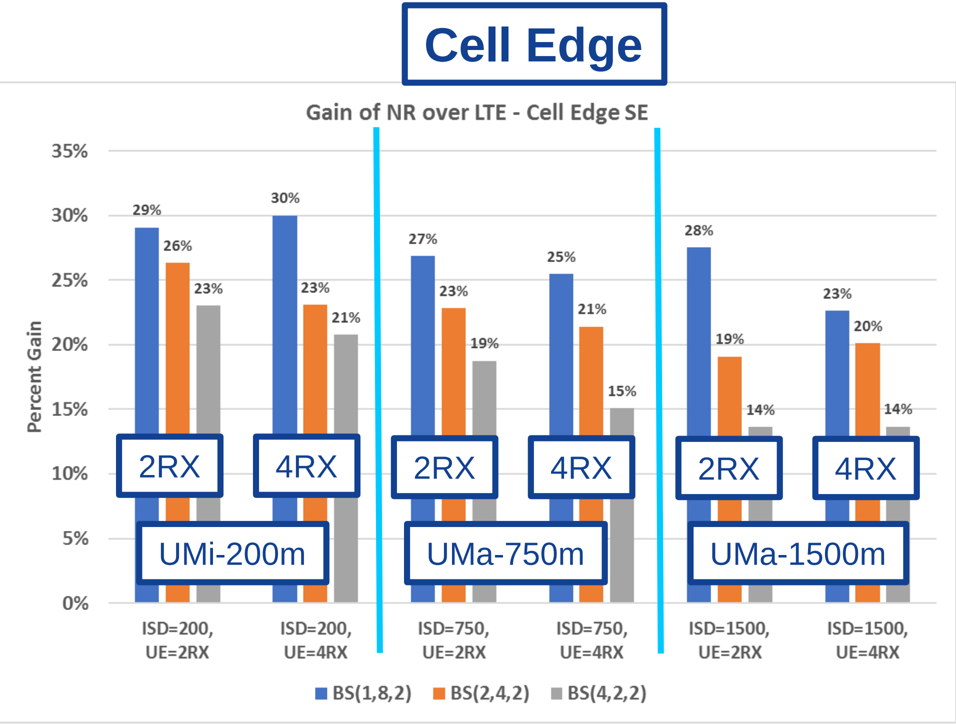
Gain of NR over LTE: 16 Ports – Full Buffer, 2GHz, DL





- Gain of NR over LTE is roughly 19-35% in Mean SE, 14%-30% in cell edge (Full Buffer)
- Gains in bursty traffic will be higher

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5G vs. 4G Capacity per Cell at 2GHz – 16x4 MIMO

LTE
2GHz
750m ISD
16x4
eNB=(1,8,2)

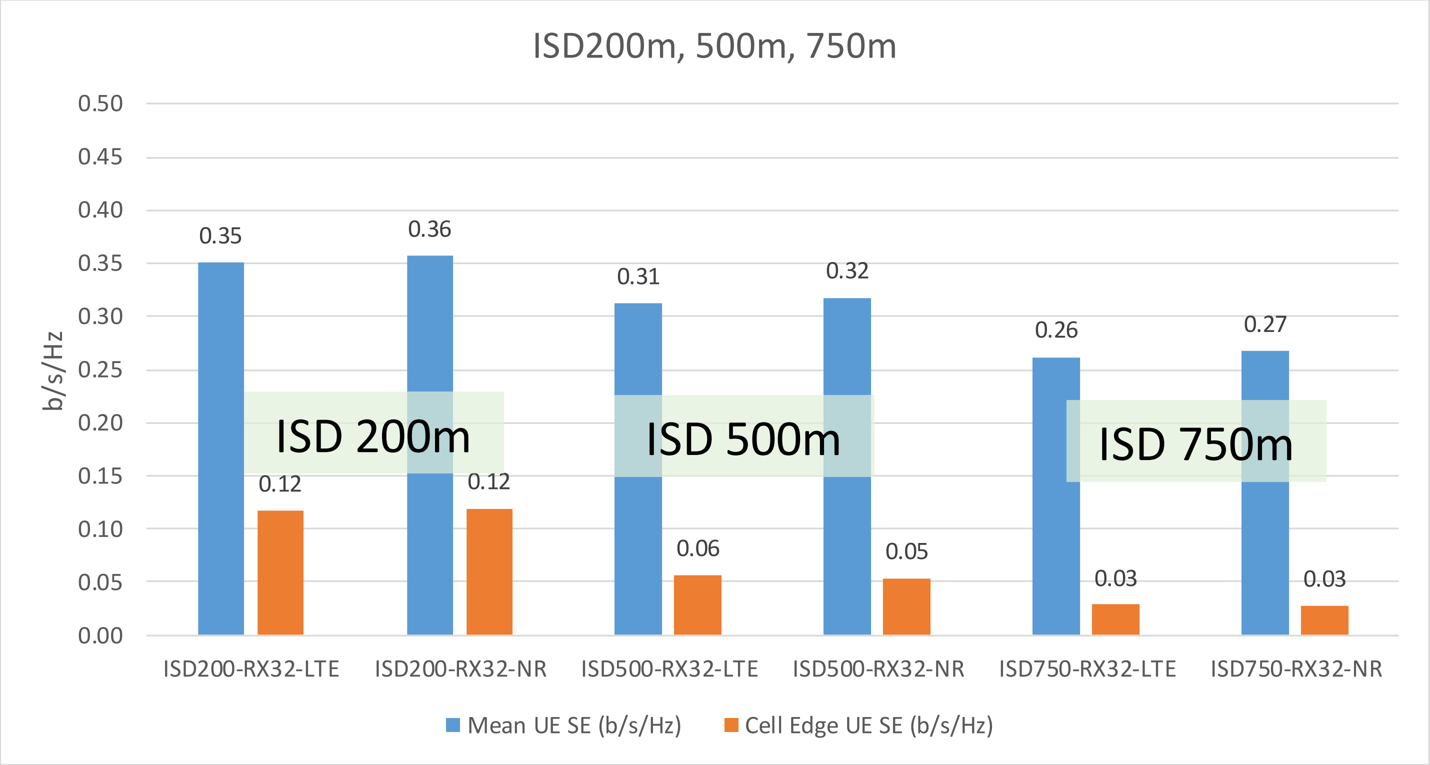
LTE		NR
2GHz		2GHz
20MHz	1.5 x	20MHz
5.12 bps/Hz		7.73 bps/Hz *
102 Mbps cell throughput		155 Mbps cell throughput

NR
2GHz
750m ISD
16x4
gNB = (1,8,2)

- **In Full Buffer, NR Codebooks show significant gains over LTE Codebooks**
  - **Mean UE throughput: 26%**
  - **Cell edge: 25%**

* Includes 20% improvement due to lean carrier in NR

Uplink Performance: 32 Rx – Full Buffer, 2GHz



- Cell Edge Performance of UL degrades significantly as ISD is increased from 200m to 750m.
- No major differences in UL performance with NR vs LTE

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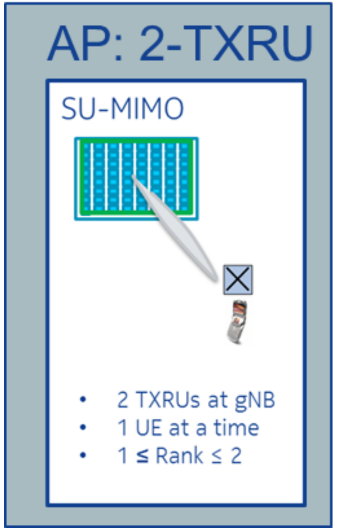
Detailed Simulation Parameters: 28GHz

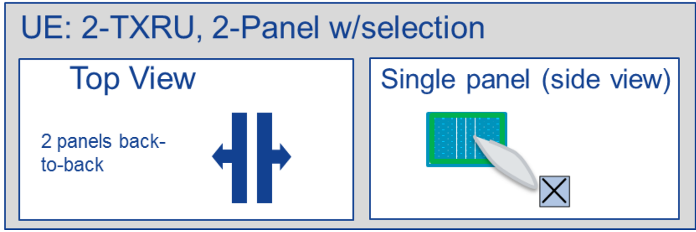
Access Point Parameters:

- AP512: cross-pol array with 512 physical antenna elements (16,16,2), 256 elements per polarization
- Physical antenna elements: 5dBi max gain per physical element, Half wavelength spacing between rows and columns, elements have 3dB beamwidth of 90 degrees.
- Max EIRP = 54dBm and 60dBm (assuming polarizations are not coherently combined), Noise figure of 5dB
- Single TXRU per polarization → 2TXRUs: SU-MIMO with open-loop rank 2 per UE on DL and UL



UE:

- UE32: Dual panel cross-pol array, 2 panels oriented back-to-back with best-panel selection at UE. Each panel is (4,4,2) with 32 physical elements per panel, 16 physical elements per polarization per panel, TX power fed to active panel element = 23dBm
- Physical elements in antenna array panel: 5dBi max gain per physical element, half wavelength spacing between rows and columns, elements have 3dB beamwidth of 90 degrees.
- Max EIRP = 40dBm in all cases (assuming all antenna elements can be coherently combined), Noise figure of 9dB
- Single TXRU per polarization → 2 TXRUs: SU-MIMO with open-loop rank 2 per UE on DL and UL



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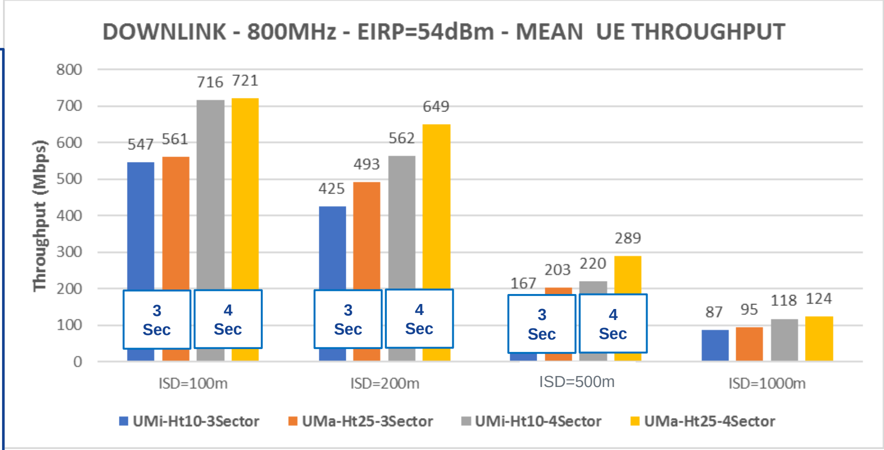
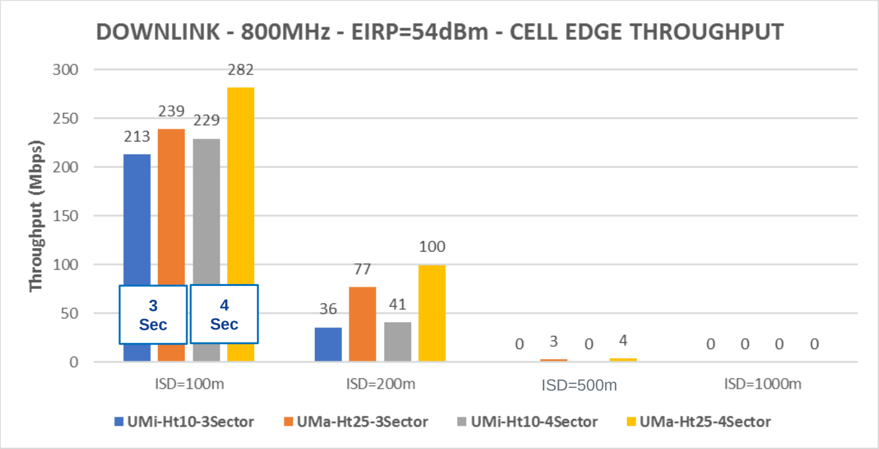
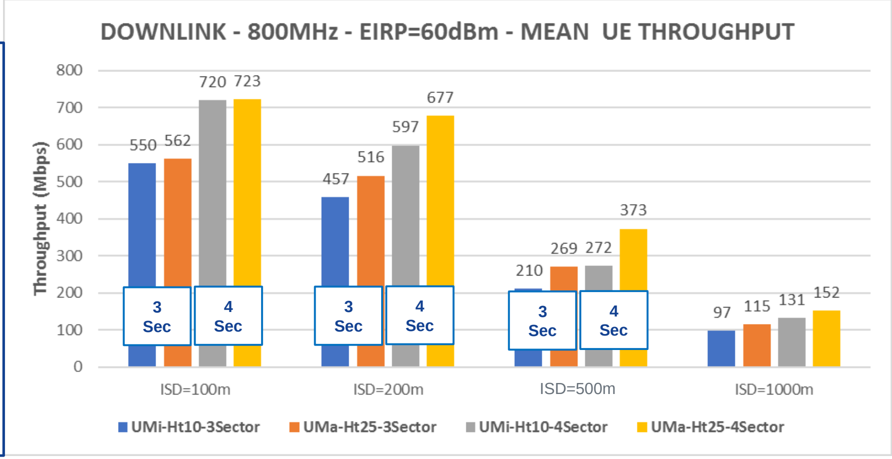
Downlink (800MHz): Mean & Cell Edge Throughput (Non Ideal RX)

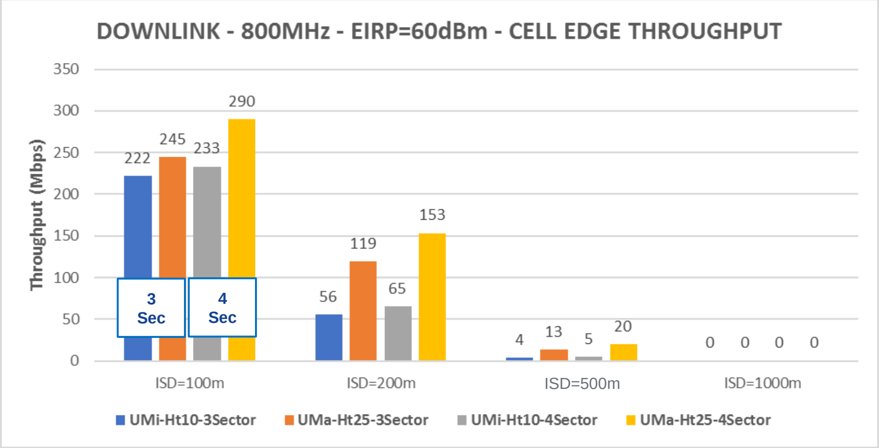
EIRP = 54dBm





EIRP = 60dBm





Mean UE Throughput

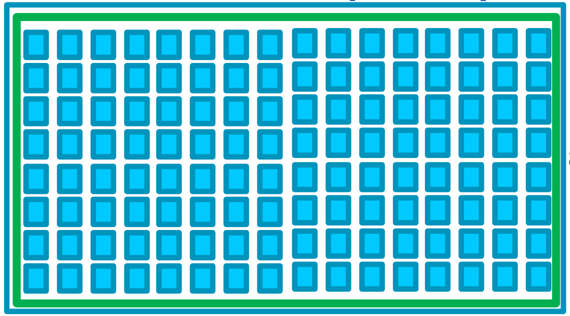
Cell Edge Throughput

Antenna Array Comparisons - AP Antenna Aperture Constant vs. Frequency

5dBi ant element gain, 7dBm AP Pout per element, 1dBm UE Pout per element, shown to scale

AP

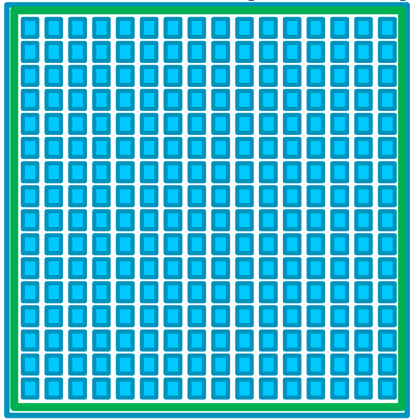
28 GHz
256 elements (8x16x2)



2 TXRUs

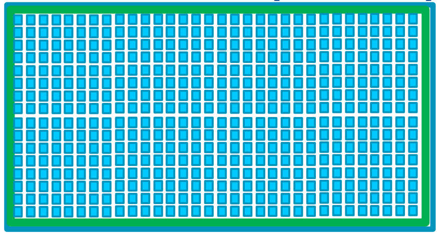
Max EIRP ≈ 60.2 dBm

39 GHz
512 elements (16x16x2)



Max EIRP ≈ 66.2 dBm
103% area relative to 28GHz

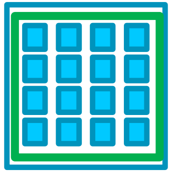
73 GHz
1024 elements (16x32x2)



Max EIRP ≈ 72.2 dBm
59% area relative to 28GHz
Room to grow…normalized array size is ~4.5dBm more than above

UE

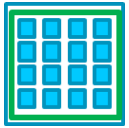
28 GHz, 32 elements, (4x4x2)



2 TXRUs

Max EIRP ≈ 36.1 dBm

39 GHz, 32 elements, (4x4x2)



Max EIRP ≈ 36.1 dBm
52% area relative to 28GHz

73 GHz, 32 elements, (4x4x2)

Max EIRP ≈ 36.1 dBm
15% area relative to 28GHz

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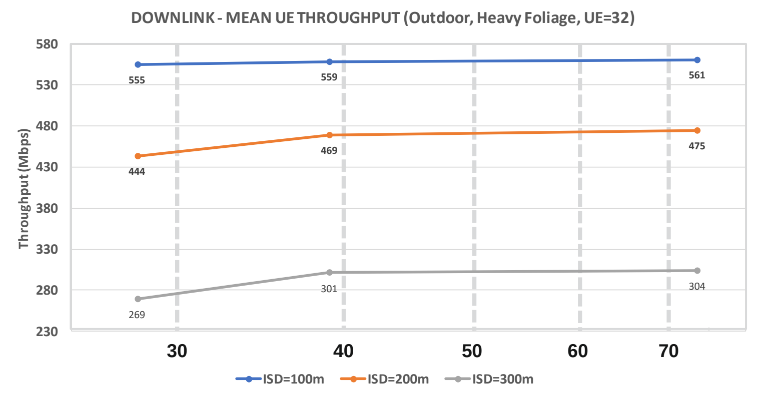
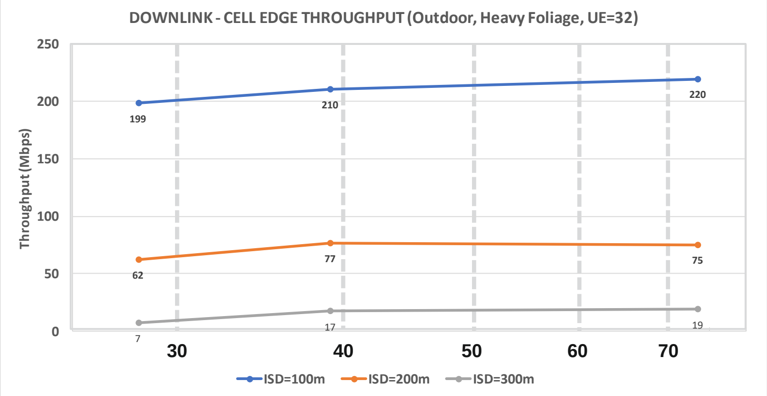
System Simulation Results for the Suburban Micro Environment (Heavy Foliage)

Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

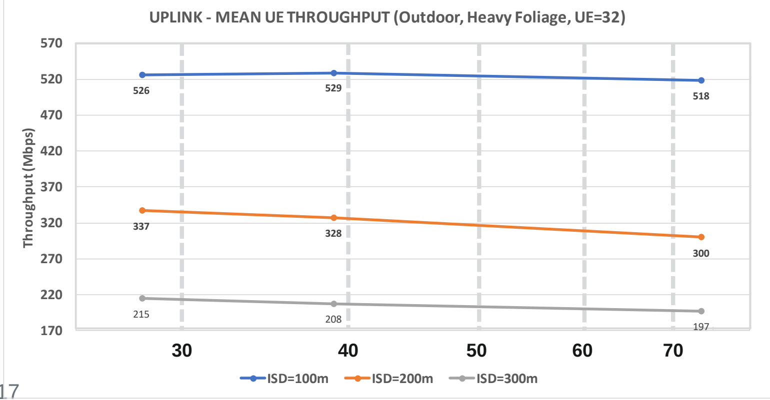
Mean UE Throughput | Cell Edge Throughput

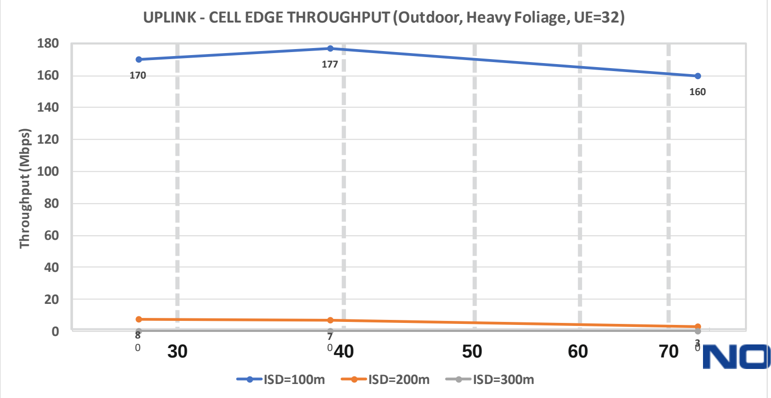
Downlink



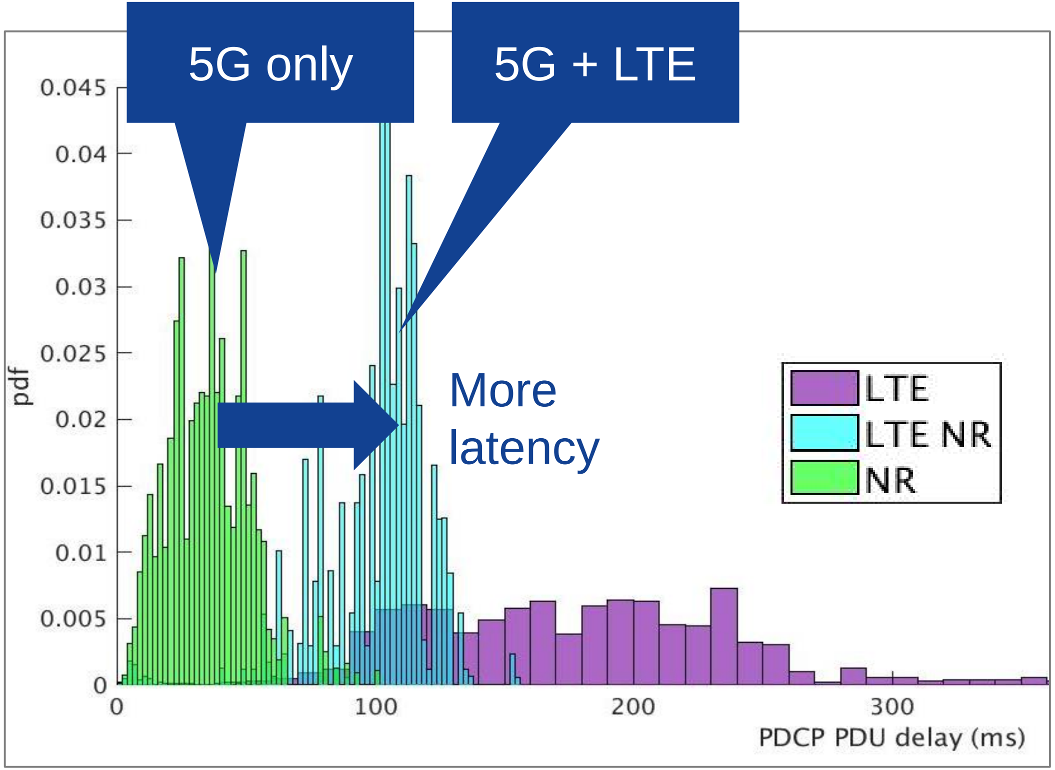


Uplink





5G – LTE Dual Connectivity and Application Performance



- 5G (=NR) gives lowest latency for the packets = best application performance
- 5G + LTE aggregation increases latency and degrades performance
- Conclusions: use 5G for user plane without LTE aggregation as long as 5G is available

Radio assumptions on average

- 5G: 400 Mbps and 3 ms
- LTE: 100 Mbps and 30 ms

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3GPP Release 16 outlook – RAN1 led items

On-going	High Priority	Medium Priority	Need unclear
Non-orthogonal multiple access	MIMO enhancements	NR-based V2X below 6.4 GHz	Air-to-ground
Non-terrestrial networks	URLLC enhancements	MBMS for 5G / EN-DC	Flexible duplex
eV2X evaluation methodology	Dual Connectivity optimization	High speed UE	Full Duplex
Unlicensed spectrum	Location enhancements*	Spectrum Efficiency Enhancements	
	Dynamic TDD	5G Above 52.6 GHz	
	NR based IoT UE categories		
	Initial access enhancements		
	UE power saving & Wake-up		

* High priority applies for items with relevance for E911 accuracy requirements

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5G mmWave Integrated Access and Backhaul (IAB)

Problem Statement

New radio would likely require **dense deployments right from the initial phases** to get sufficient coverage @ mmWave frequencies

Economically not feasible to provide fiber connectivity to each site until the new radio deployments become mature.

Self-backhauling is enabling multi-hop networks with shared access-backhaul resources.

Key disruption

Self-backhaul using same antenna arrays to dynamically switch between access and backhaul with optimized scheduling and dynamic TDD enabling deployment cost reduction and improving system performance

Topics

Topology management for single-hop/multi-hop and redundant connectivity

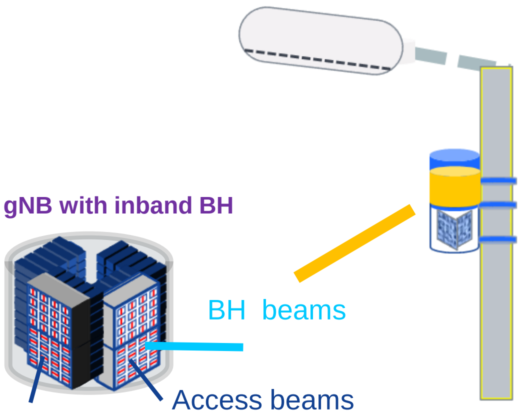
Route selection and optimization

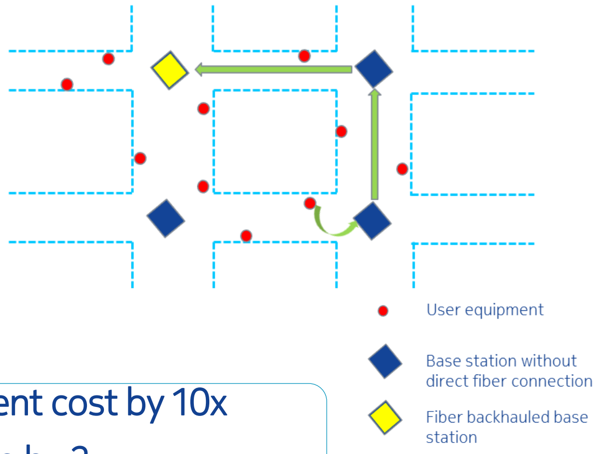
Dynamic resource allocation between the backhaul and access links

Physical layer solutions to support wireless backhaul links with high spectral efficiency

3GPP Study Item

In Progress complete by Dec 2018





Reduce deployment cost by 10x

Improve Coverage by 2x

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Q&A

3GPP Standardization on 5G vs available spectrum?