NOKIA

Nokia Networks

5G mmWave Revolution & New Radio

Expanding the human possibilities of technology to make our lives better

IEEE Webinar

September 20th , 2017

Dr. Amitabha Ghosh

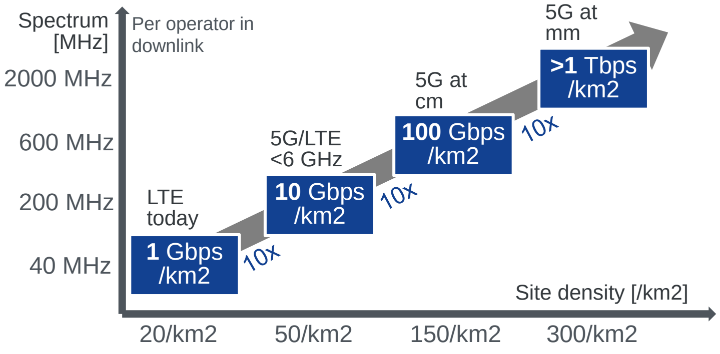
Head of Small Cell Research, Nokia Fellow, IEEE Fellow

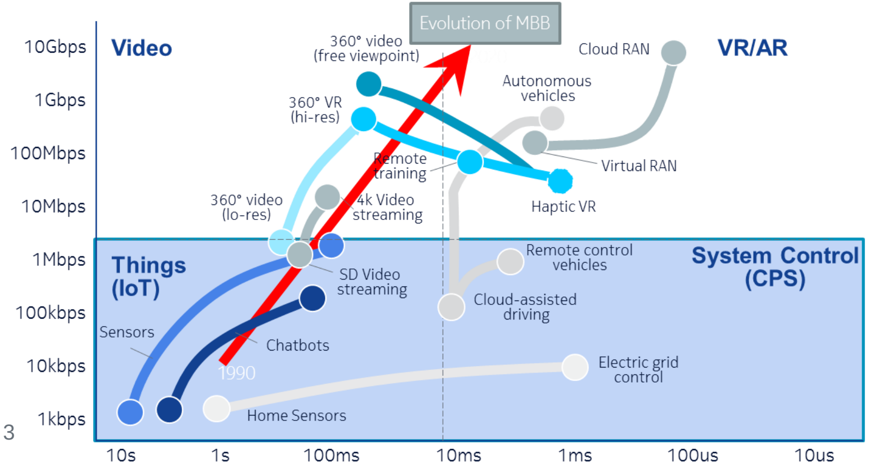
Nokia Bell Labs

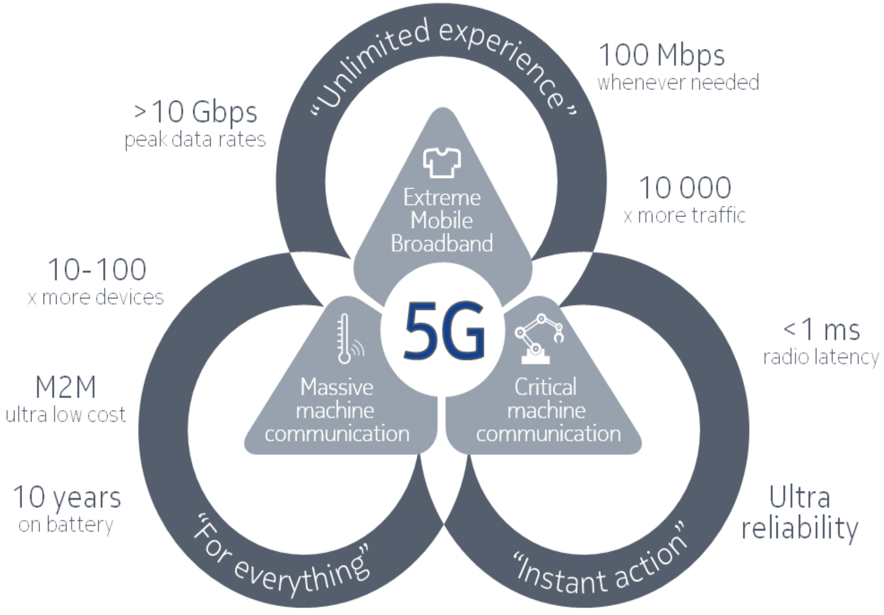
mmWave Use cases, Challenges and Proof Points

Value capture from 5G Evolution and Revolution towards 1 Tbs/km2 …

Three-pronged requirements for 5G networks







NOKIA

5G mmWave Challenges & Proof Points

- **Unique difficulties that a mmWave system must overcome**
  - Increase path loss which is overcome by large arrays (e.g., 4x4 or 8x8)
  - Narrow beamwidths, provided by these high dimension arrays
  - High penetration loss and diminished diffraction

- **Two of the main difficulties are:**
  - Acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
  - Mitigating shadowing with base station diversity and rapidly rerouting around obstacles when user device is shadowed by an opaque obstacle in its path

- **Other 5G aspects a mmWave system will need to address**:
  - High peak rates and cell edge rates (>10 Gbps peak, >100 Mbps cell edge)
  - Low-latency (< 1ms)

NOKIA

5G Peak Rates

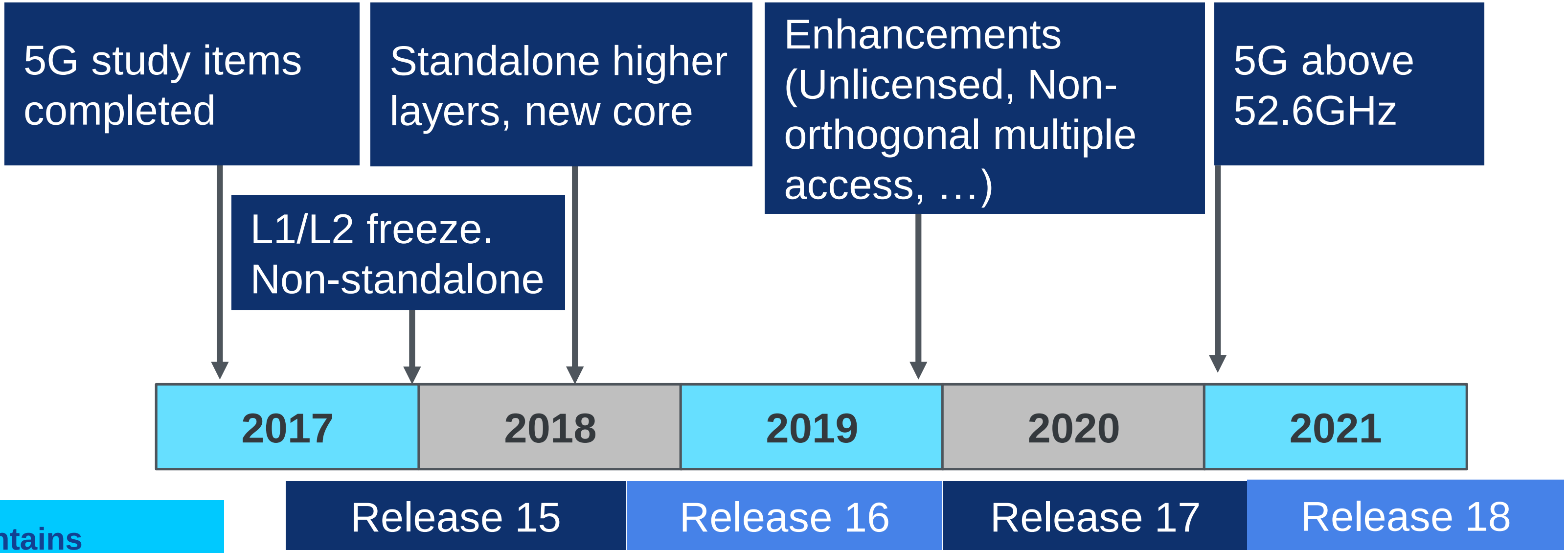
- 4G achieved 10-15% of the target bit rate in the first deployment and the full target four years later.
- Extrapolating to 5G would give 5 Gbps by 2020 and 50 Gbps by 2024

	Target bit rate	3GPP specs	1st deployment	Wide-scale Adoption
		2011	2013	2017
4G = LTE-Advanced	1 Gbps	3GPP Release 10	150 Mbps	1 Gbps
		2018	2020	2024
5G	50 Gbps	3GPP Release 14	5 Gbps	50 Gbps

NOKIA

3GPP Schedule, mmWave Spectrum & Channel Models

5G (New Radio) Schedule in 3GPP



- **Release 15 contains intermediate ASN.1 freeze for Non-standalone in March 2018**
- **Full ASN.1 freeze September 2018 for full 5G feature set**

5G Schedule based on LTE History

LTE

3GPP Release 8 March 2009	Telia LTE launch December 2009	12 LTE launches 2H/2010

2008	2009	2010

5G

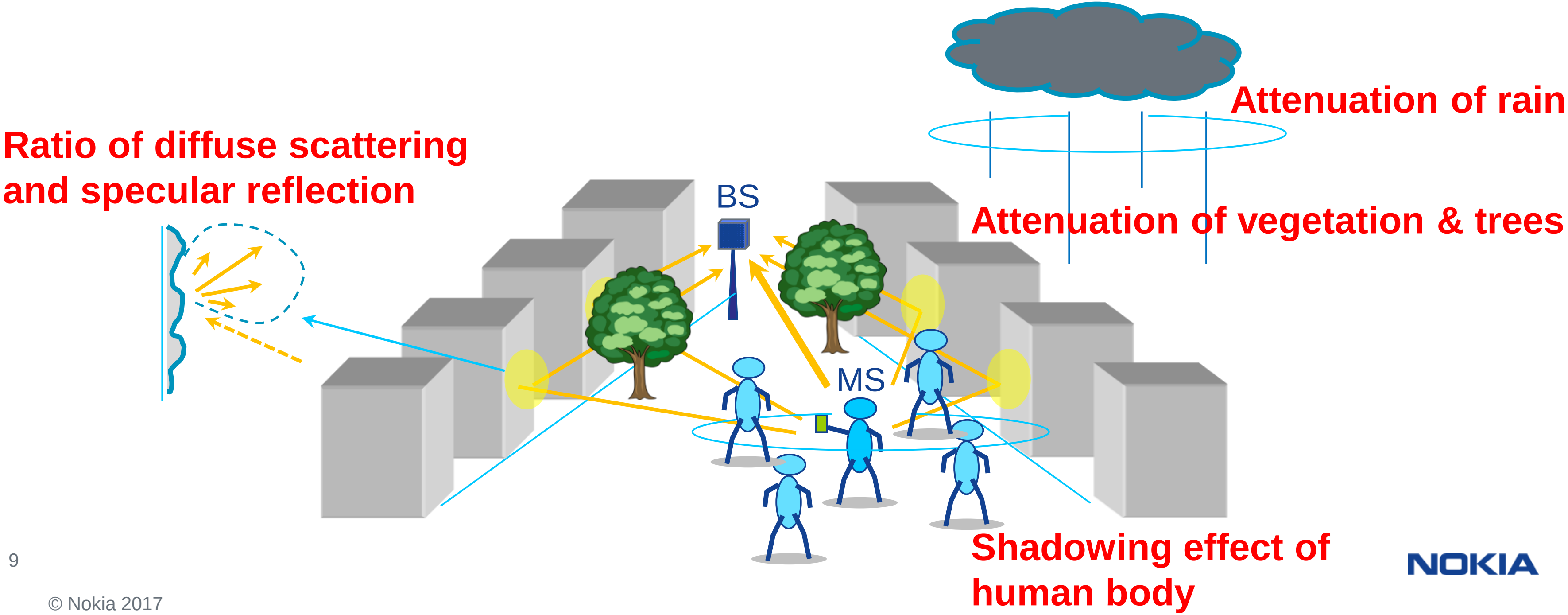
3GPP Release 15 March 2018	5G launch by end-2018	Several 5G launches 2019

2017	2018	2019

- First 3GPP LTE was launched by Telia December 2009. That was 8 months after 3GPP completed Release 8. Total 12 LTE launches during 2H/2010.
- Note the planned std phase in 3GPP for 5G is very short, only 9 months after study, which gives less development time compared to LTE specification time

Key Propagation Phenomena at Higher Frequencies

To develop channel model for frequency range above 6 GHz, frequency dependency of path loss and channel properties need to be understood.

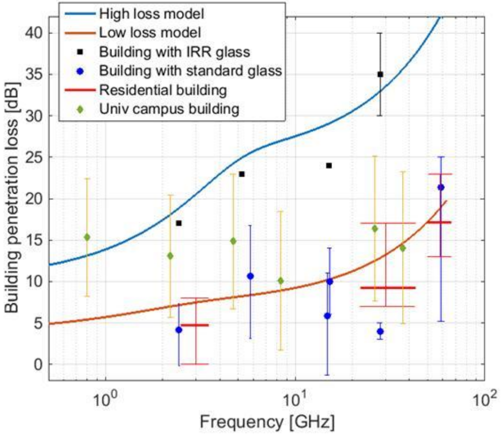


Propagation Challenges for 5G (less than 100 GHz)

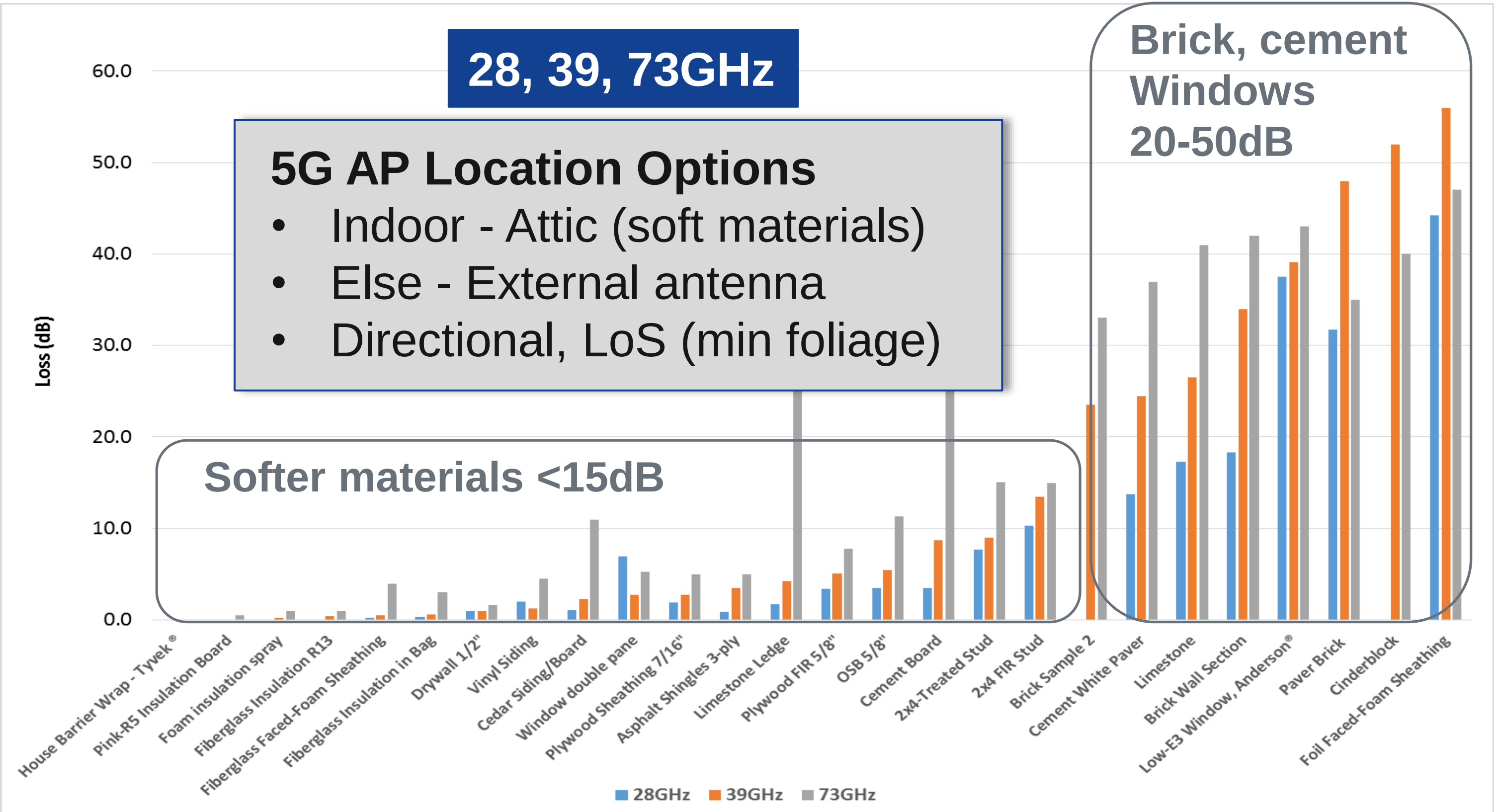
- **Path loss** increases with frequency
  - However, wavelength decreases with frequency
  - Larger number of antennas possible in the same area
  - Leverage large scale arrays to mitigate the larger path loss
- **Diffraction** (e.g., the bending of rays around building corners/roofs) loss increases with frequency
  - No longer a dominant effect after around 10 GHz in outdoor channels
- **Atmospheric/rain losses** are frequency dependent
  - However: small (less than around 2.0 dB for worst-case rain) for cells radii less than 100 m even at 100 GHz
- **Reflections** seem to increase with frequency going from 6 to 100 GHz
  - Smaller objects like lamp posts more reflective as frequencies increase
  - Seems to make up for loss in diffraction in outdoor environments
- **Scattering** increases with frequency,
  - Current measurements are not showing a significant impact below 73 GHz
  - Diffuse scattering more pronounced at higher frequencies
- **Penetration loss** tends to increase with frequency
  - Highly material dependent
  - Certain materials allow even higher frequencies to pass through without much attenuation (e.g., standard glass)

Spatial Consistency:

Penetration Loss:



Penetration Loss : cm/mmWave



5G AP Location Options

- Indoor - Attic (soft materials)
- Else - External antenna
- Directional, LoS (min foliage)

Note: +5dB if not 90 degrees

Note: 3GPP SIG channel model for 6-100GHz urban done

3GPP: 5G Channel Models

- 3GPP 5G channel model is based on 3D channel model with certain enhancements:
  - More Scenarios (RMa, UMa, UMi-Street Canyon, UMi-Open Square, Indoor-office, Indoor-Shopping mall)
  - Frequency dependent pathloss, penetration and large scale parameters are introduced
  - Additional features:
    - Large antenna and large bandwidth modelling
    - Spatial Consistency (for MU-MIMO and beam tracking simulation)
    - Blockage modelling (for mobility simulation)
    - Oxygen Absorption (for frequency in between 53GHz and 66GHz)
    - Multi-frequency correlation model (for dual-connectivity)
    - Ground reflection modelling (for LOS links when ground reflection may be significant)
- ITU Channel Model captured in ITU-R M.[IMT-2020.EVAL]
- 5G channel model is captured in TR38.901
  http://www.3gpp.org/ftp//Specs/archive/38_series/38.901/38901-e11.zip

3GPP TR 38.901 V14.1.1 (2017-07)

Technical Report

3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Study on channel model for frequencies from 0.5 to 100 GHz
(Release 14)

A GLOBAL INITIATIVE

The present document has been developed within the 3rd Generation Partnership Project (3GPP ™) and may be further elaborated for the purposes of 3GPP.
The present document has not been subject to any approval process by the 3GPP Organizational Partners and shall not be implemented.
This Report is provided for future development work within 3GPP only. The Organizational Partners accept no liability for any use of this Specification.
Specifications and Reports for implementation of the 3GPP ™ system should be obtained via the 3GPP Organizational Partners' Publications Offices.

3GPP New Radio

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)

5G NR Numerology : Overview

Numerologies with normal CP (subframe = 1msec)

	Slot Configuration 0					
Subcarrier spacing [kHz]	15	30	60	120	240*	480**
Symbol duration [us]	66.7	33.3	16.6	8.33	4.17	2.08
Nominal CP [us]	4.7	2.41	1.205	0.60	0.30	0.15
Nominal max BW [MHz]	49.5	99	198	396	397.4	397.4
Max FFT size	4096	4096	4096	4096	2048	1024
Min scheduling interval (symbols)	14	14	14	14	14	14
Min scheduling interval (slots)	1	1	1	1	1	1
Min scheduling interval (ms)	1.0	0.5	0.25	0.125	0.0625	0.0312

*SS Block only

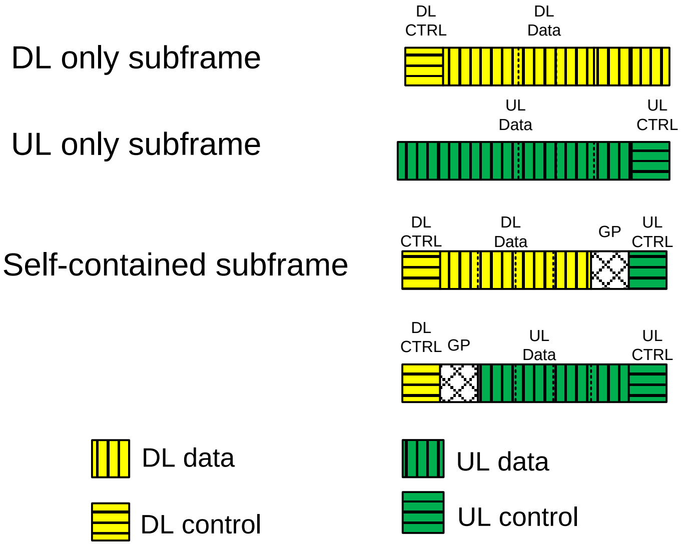
**Not supported

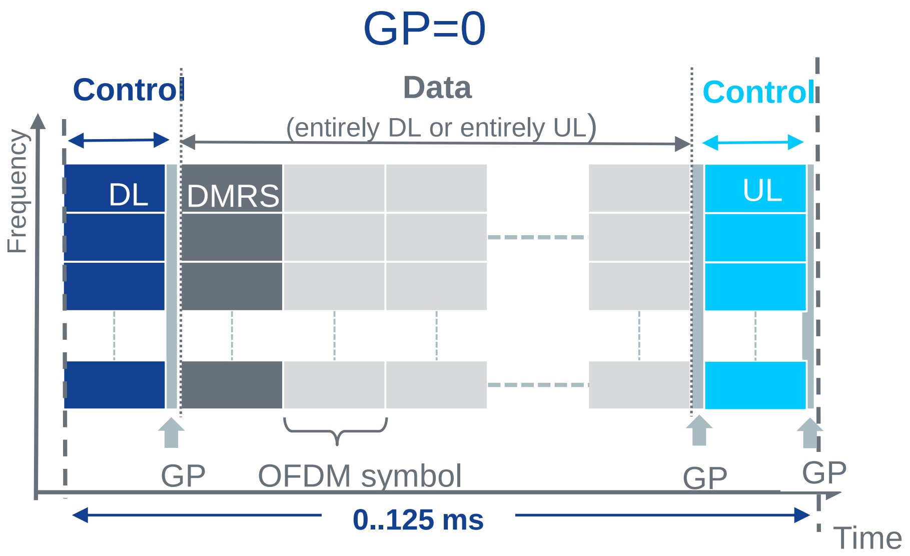
Numerologies with extended CP (subframe = 1msec)

Subcarrier spacing [kHz]	Symbol Duration[us]	Ext CP[us]	Nom max BW	FFT Size	Sched Interval (sym)	Sched Interval (slot)	Sched Interval (ms)
60	16.6	4.2	198	4096	12	1	0.25

NOKIA

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

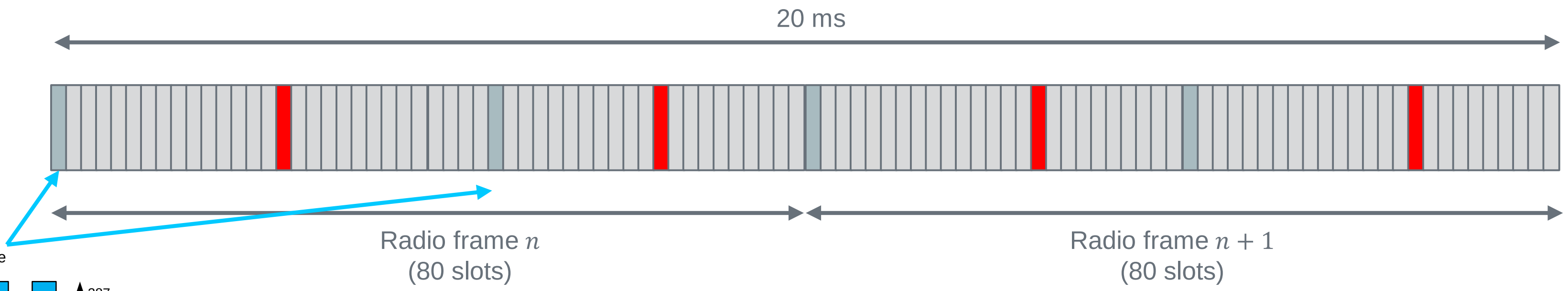
Flexible UL/DL

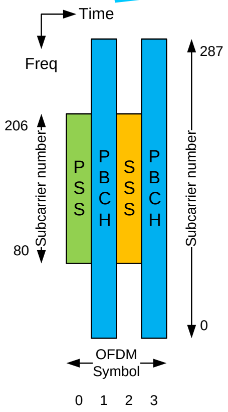
Control channel just before data

Energy-effective processing

NOKIA

NR TDD Frame structure (120 KHz SC)





PSS → Used for beam training, timing and frequency synchronization

SSS → Used for beam training, timing and frequency synchronization

PBCH → Contains system information block containing essential information for initial access

PRACH → Random access, scheduling request

PUCCH/PUSCH/PDCCH/PDSCH → Uplink/ Downlink control and data channels

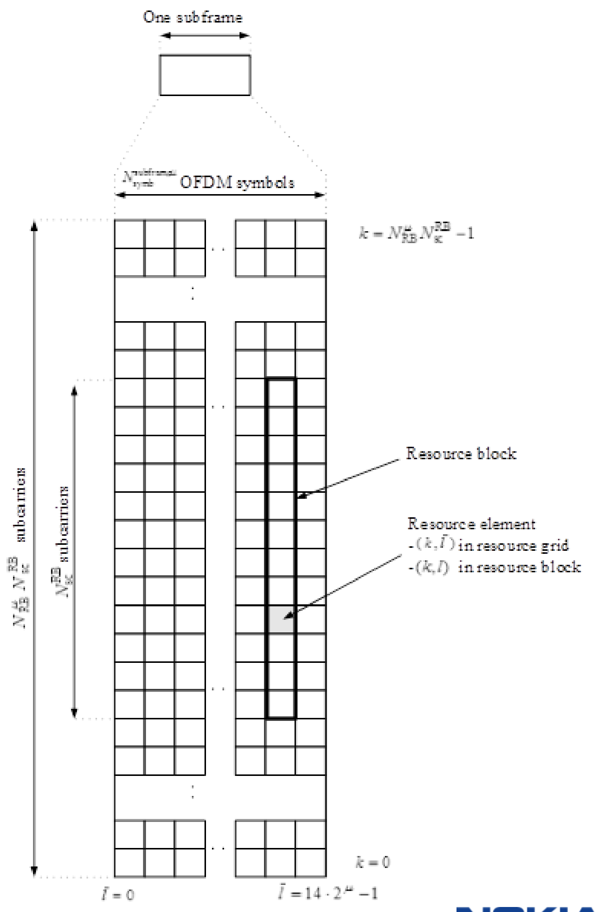
SS/PBCH Blocks : 4 OFDM Symbols and 24 PRB's

NOKIA

Frame Structure (120 KHz SC) & Modulation

- 80 slots/10 ms frame
- 14 OFDM symbols/slot
- 24-275 PRBs/slot
- 12 subcarriers/PRB
- Occupied BW
  - Minm = 24x12x120 = 34.56 MHz
  - Maxm = 275x12x120 = 396 MHz

Modulation scheme	UL /DL
π/2-BPSK	UL only, In combination with transform precoding only
QPSK	UL/DL
16QAM	UL/DL
64QAM	UL/DL
256QAM	UL/DL



NOKIA

Downlink Channels & Signals
PDSCH and PDCCH

	PDSCH (5G)	PDSCH (LTE)	PDCCH (5G)	PDCCH (LTE)
Purpose	Transmit DL Data	Transmit DL Data	Transmit DL Control	Transmit DL Control
Waveform	OFDM	OFDM	OFDM	OFDM
Bandwidth	Numerology Dependent	Max: 1.4 / 3 / 5 / 10 / 15 / 20 MHz	Flexible, Numerology Dependent	Fixed: 1.4 / 3 / 5 / 10 / 15 / 20 MHz
Reference signals	UE-specific	Cell specific or UE-specific (Release 10)		
Phase noise compensation	Yes	No		
Modulation	Up to 256QAM	Up to 256QAM	QPSK	QPSK
Coding scheme	LDPC	Turbo	Polar	TBCC

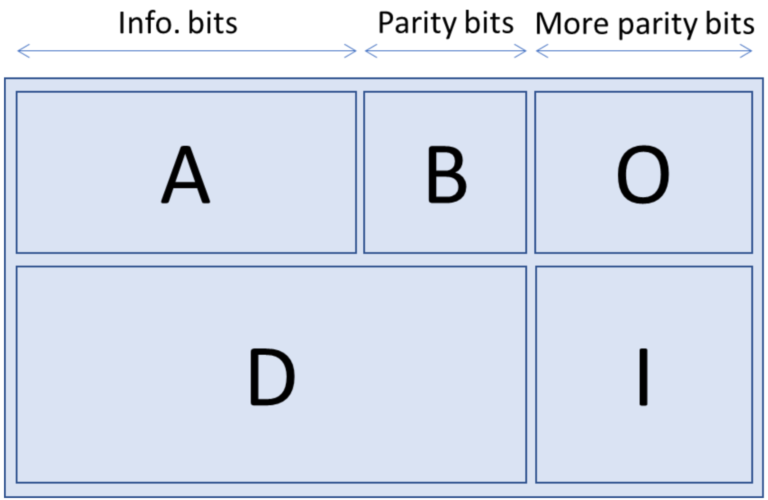
NOKIA

Uplink Channels & Signals
PUSCH – Uplink shared channel

	PUSCH (5G)	PUSCH (LTE)
Purpose	Used to transmit uplink data and control information	Used to transmit uplink data and control information
Waveform	OFDM/SC-FDMA (Optional)	SC-FDMA
Bandwidth	See numerology	Max: 1.4 / 3 / 5 / 10 / 15 / 20 MHz
Phase noise compensation	Yes	No
Modulation	Up to 256 QAM & $\pi/2$–BPSK	Up to 64QAM
Coding scheme	LDPC	Turbo

Channel Coding
eMBB Data Channel

- NR eMBB data channel adopts LDPC codes
  - Defined by parity check matrices with a structure depicted on the right
- Quasi-cyclic design
  - The parity check matrices are defined by much smaller base matrices
  - Each base matrix is either zero or a shifted identity matrix
- Enables high-throughput and low-latency hardware implementation
- Supports both Incremental Redundancy (IR) and Chase Combining (CC) HARQ

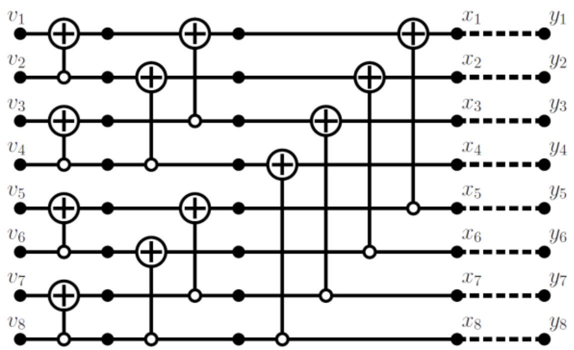


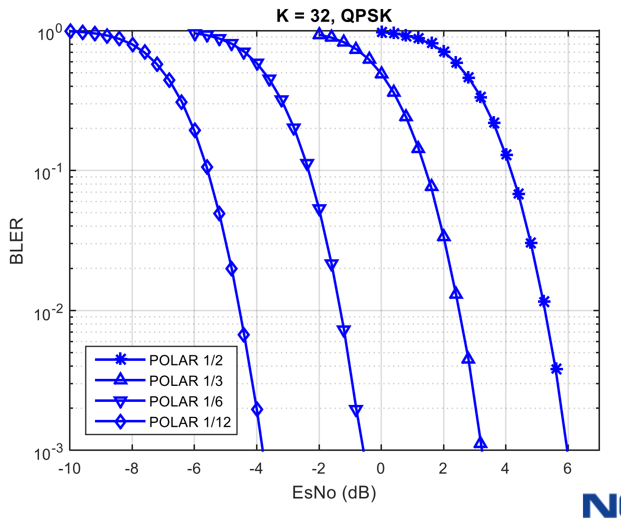
- A corresponds to (systematic) information bits
- B contains a dual diagonal structure
- O is a zero matrix
- I is an identity matrix

Channel Coding

eMBB Control Channel

- NR eMBB control channel uses polar codes, except for very small payloads
- Polar codes are relatively new, discovered by Prof. Arıkan in 2008
- Pure polar codes need to be concatenated with outer codes to achieve superior performance
  - Outer codes could be as simple as CRC codes
- List decoding is common and effective





Massive MIMO

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)

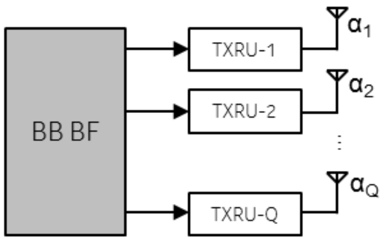
NOKIA

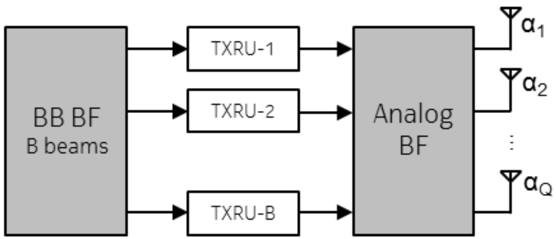
Massive MIMO: Why Now?

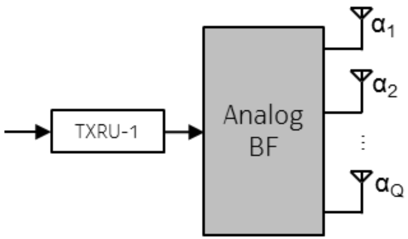
Capacity Requirements	Coverage Requirements	Technology Capability	3GPP Spec Support
Most Macro Networks will become congested	Below 6GHz: desire to deploy LTE/NR on site grids sized for lower carrier frequencies	Active Antennas are becoming technically and commercially feasible	3GPP supports Massive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

NOKIA

Antenna Array Architectures for scalable flexible MIMO







Digital (Baseband) beamforming	Hybrid beamforming	Analog beamforming
Adaptive TX/RX weights at Baseband	Adaptive TX/RX weights at both Analog and Baseband domains	Adaptive TX/RX weights at RF to form a beam
Each antenna element or antenna port has a transceiver unit High number (8->) of transceiver units	Each RF beam has a transceiver unit; Moderate number of transceiver units for capacity (e.g. up to 8)	One transceiver unit and one RF beam with high antenna gain (coverage)
“Frequency-Selective” beamforming	Combination of Analog and Baseband beamforming	“Frequency-Flat” beamforming
Best for capacity and flexibility (subject to high power consumption & cost characteristics when bandwidth increases)	Optimization between both coverage and capacity	Best for coverage (low power consumption & cost characteristics)

NOKIA

MIMO in 3GPP

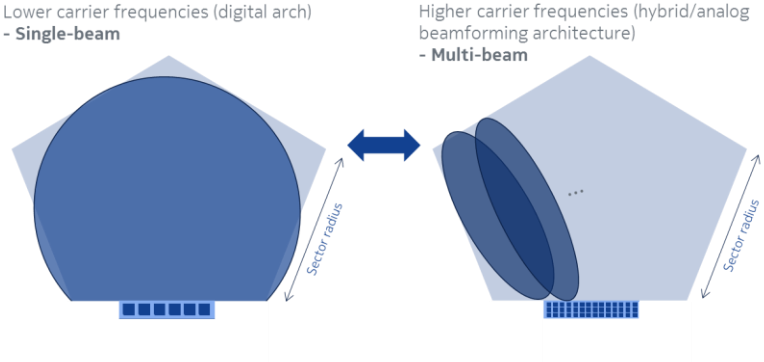
Release 8	Release 9	Release 10	Release 11
• 4x4MIMO • 4x2MIMO • 8RX uplink • Uplink CRAN	• 8TX TM8	• 8TX TM9	• Downlink CoMP (TM10)

Release 12	Release 13	Release 14	Release 15+
• Downlink eCoMP • New 4TX codebook	• Massive MIMO 16TX	• Massive MIMO 32TX	• 5G massive MIMO 64TX+

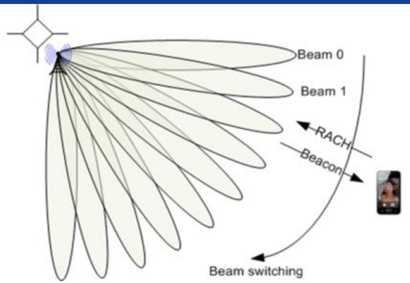
NOKIA

Massive MIMO in 3GPP New Radio – Beam Based Air Interface

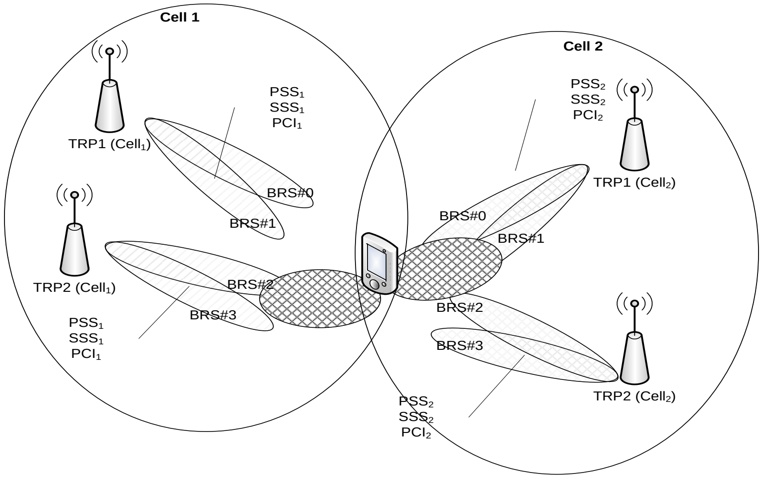
Beamformed Control Channels



Beam Scanning



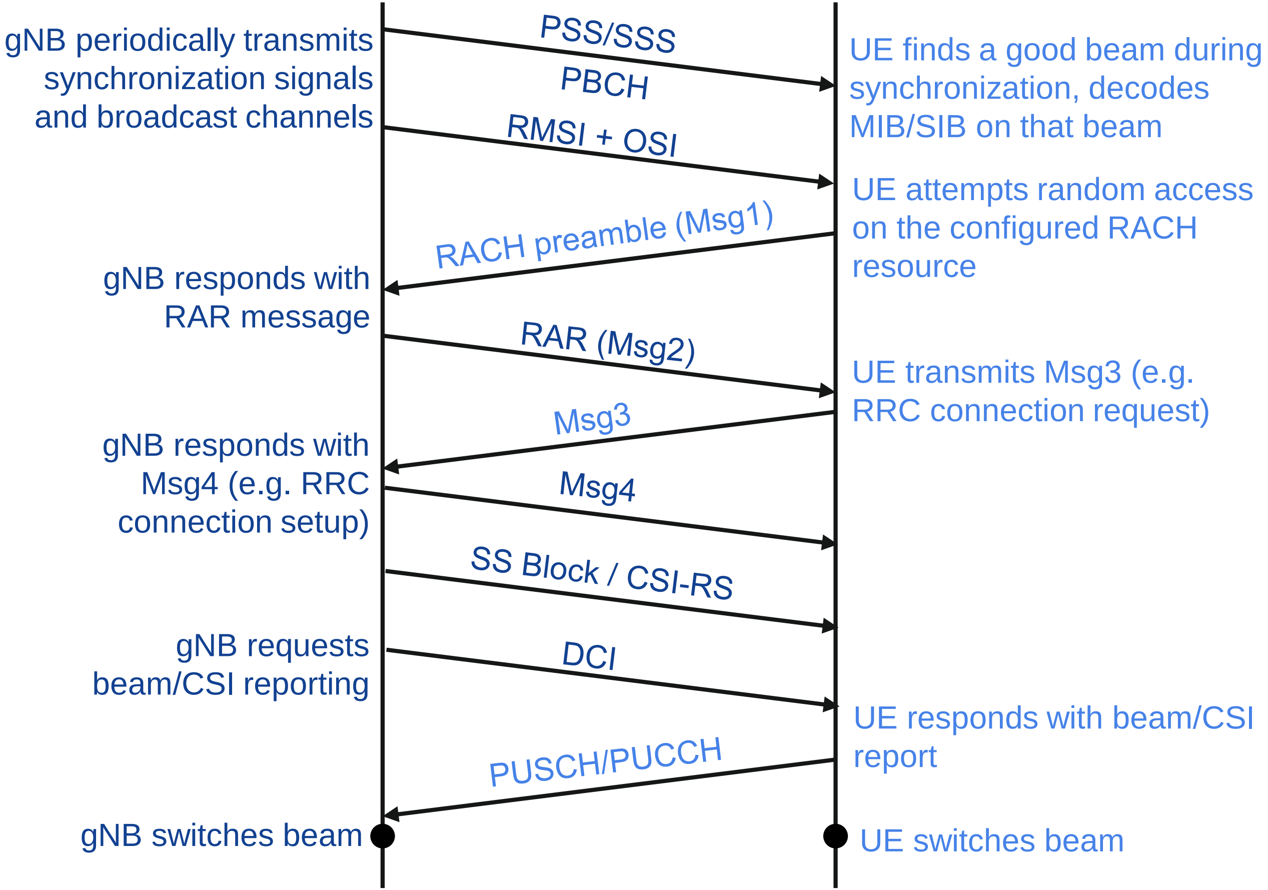
Beam Management



- Acquisition and maintenance of a set of beams for TX and RX at base and UE
- CoMP is built in

NOKIA

Initial Access



Beam Management and CSI

Downlink Codebook Overview

Type I Codebooks:

- Standard resolution CSI feedback
- Single panel and multi-panel

Type II Codebooks:

- High resolution CSI feedback targeting MU-MIMO
- Non-precoded and precoded CSI-RS
- Designed for cross-polar antennas

Supported Antenna Ports

Ports	Type I		Type II	
	Single Panel	Multi-Panel	Non-precoded CSI-RS	Precoded CSI-RS
2	✓			
4	✓		✓	✓
8	✓	✓	✓	✓
12	✓		✓	✓
16	✓	✓	✓	✓
32	✓	✓	✓	✓

NOKIA

Beam Management and CSI

Codebook Comparison

Type I Single Panel Codebook:

- SU-MIMO/MU-MIMO
- 1-8 MIMO layers
- Two-stage:
  - WB beam group selection (1 and 4 beam configurations)
  - SB beam selection and co-phasing
- Precoded & non-precoded CSI-RS supported

Type I Multi-Panel Codebook:

- Builds on single panel codebook (1 beam), adding inter-panel co-phasing
- 1-4 MIMO layers
- Supports 2 or 4 antenna panels
- Low and high resolution SB co-phasing is available with 2 panels

Type II Non-precoded CSI-RS Codebook:

- Forms a linear combination of 2, 3, or 4 DFT beams selected from an orthogonal basis
- WB beam amplitudes, SB phase, optional differential SB amplitudes
- 1-2 MIMO layers

Type II Precoded CSI-RS Codebook:

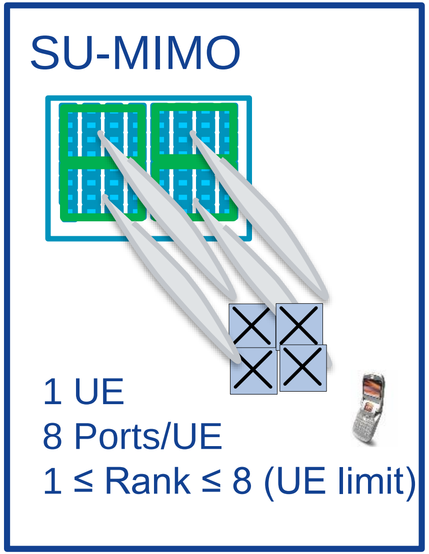
- Selects a subset of the beamformed ports and forms a linear combination of the selected beams
- WB beam amplitudes, SB phase, optional differential SB amplitudes
- 1-2 MIMO layers

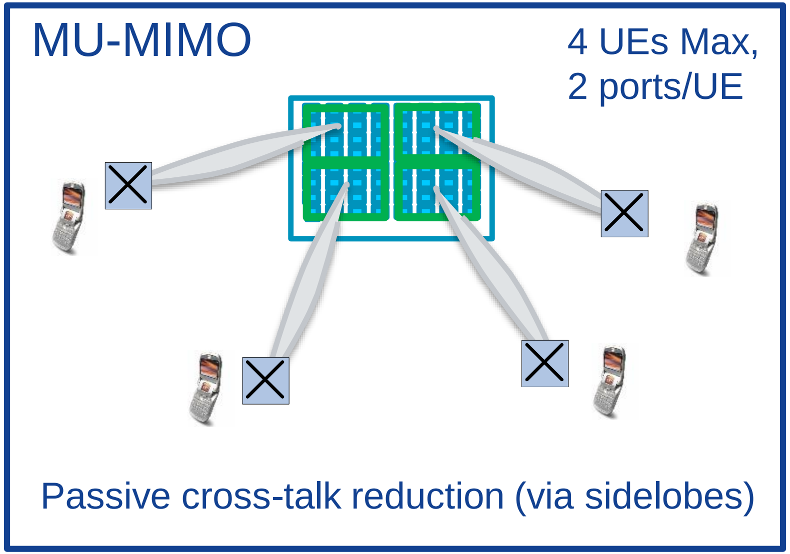
NOKIA

CSI Feedback
mmWave

For mmWave:

- Use beam management to select the best beam for each UE
- Apply the Type I single-panel codebook to select the transmit weights





CSI Feedback

DL Codebook Overhead Example

Type I		Type II			
Single Panel	Multi-Panel	Non-precoded		Precoded	
L=2: 9/1	Mode 1: 10/1	L=2:	31/12-24	L=2:	25/12-24
L=4: 7/3	Mode 2: 10/3	L=4:	59/28-48	L=4:	51/28-48

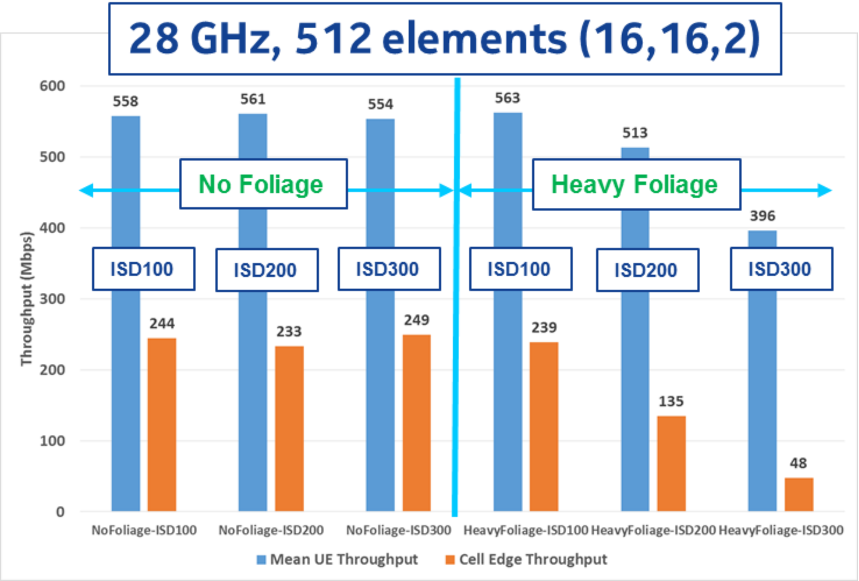
M/N indicates M wideband bits and N bits per subband (Type II entries indicate the range of possible bits per SB)

- L – Number of beams configured in the codebook
- 16 ports, 2 layers assumed
  - Single panel and non-precoded: N_1=4, N_2=2
  - Multi-panel: 2 panels, N_1=2, N_2=2
  - Precoded: Selection sampling factor (d) = 1

NOKIA

mmWave Performance

Early 5G use case: Extreme broadband to the home (mmWave)

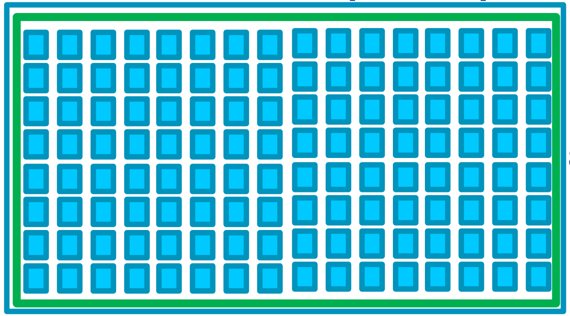


Antenna Array Comparisons - AP Antenna Aperture Constant vs. Frequency

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

AP

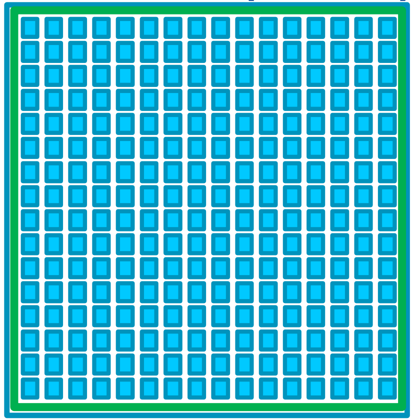
28 GHz
256 elements (8x16x2)



2 TXRUs

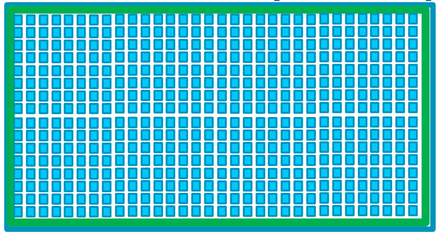
Max EIRP ≈ 60.2 dBm

39 GHz
512 elements (16x16x2)



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

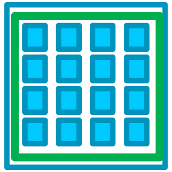
73 GHz
1024 elements (16x32x2)



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

UE

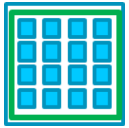
28 GHz, 32 elements, (4x4x2)



2 TXRUs

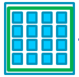
Max EIRP ≈ 36.1 dBm

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

NOKIA

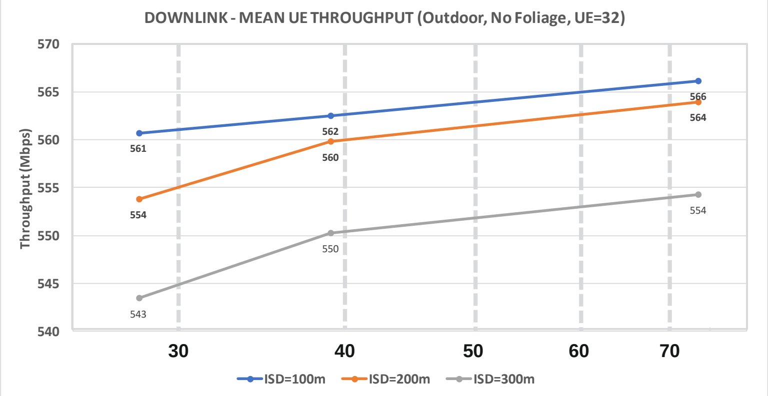
System Simulation Results for the Suburban Micro Environment

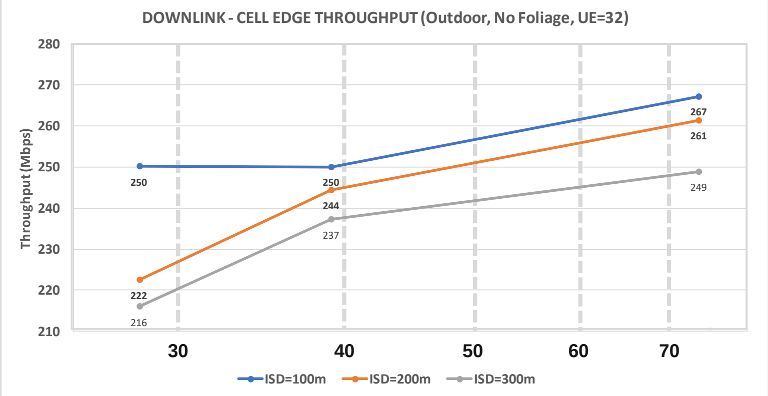
Constant Antenna Aperture for 28 GHz, 39 GHz and 73 GHz

Mean UE Throughput

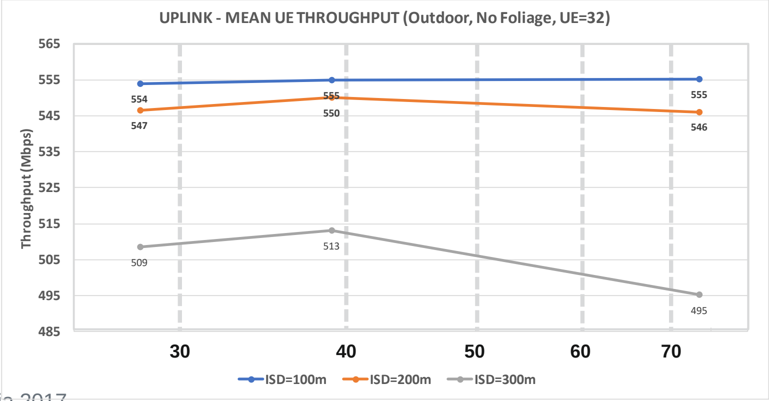
Cell Edge Throughput

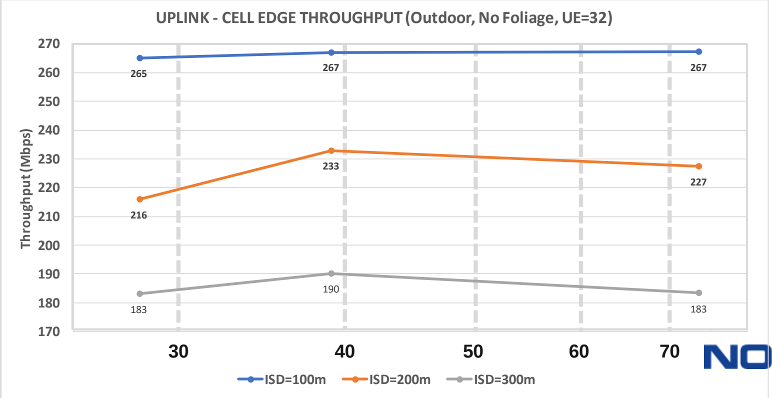
Downlink





Uplink





System Simulation Results

Summary

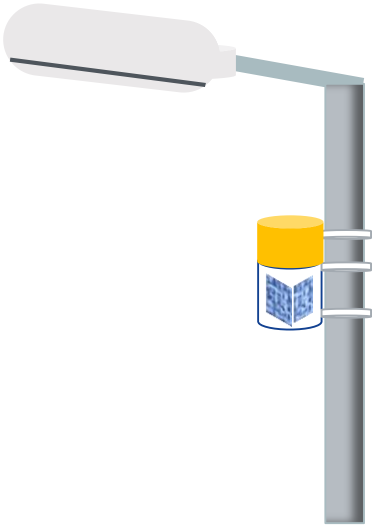
- Antenna array size will decrease for given array configuration and number of elements
  - Reduced antenna aperture is the primary reason for decreasing performance with higher frequency
  - Little degradation is seen at 100m ISDs as systems are not path loss limited
  - Some degradation is seen for larger ISDs as systems become more noise limited
- Keeping antenna aperture constant can mitigate differences at higher frequencies
  - Increasing the number elements as frequency increases will keep the physical array size and antenna aperture constant
  - Performance is nearly identical at all frequencies and ISDs with constant physical array size (antenna aperture)
  - Slight improvements in downlink performance if power per element is held constant as number of elements is increased
- Foliage poses challenges at all mmWave frequencies and is not dramatically higher at 70 GHz as compared to 28 GHz or 39 GHz

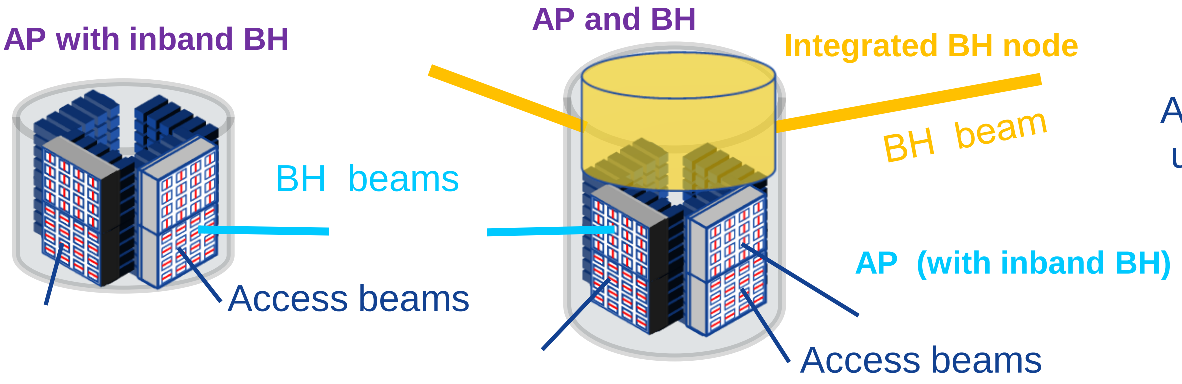
NOKIA

Self Backhauling and PoC

Basic Network Building blocks

- 5G mmW basestation and integrated wireless backhaul will be a small box which is easy to install to lamp posts, walls or small masts.
- The cost of the box is mainly in RF, antennas and BB-SoC, of course some cost goes for cover mechanics and power supply.
- Investigating how to arrange the creation and manufacturing of the RF and antenna components.
- Multi-sector sBH is the assumption



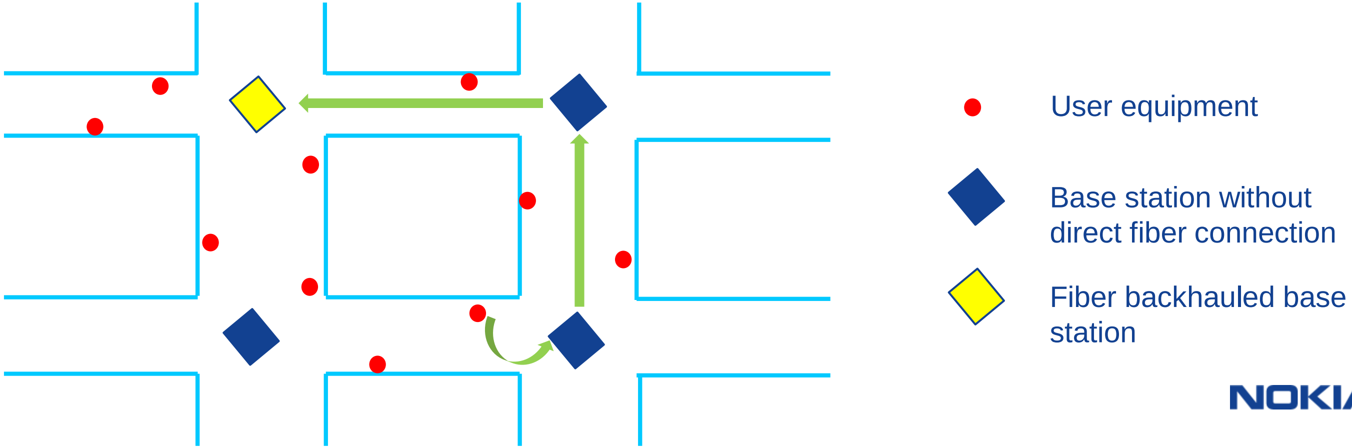


AP and Integrated BH
use quite similar technologies

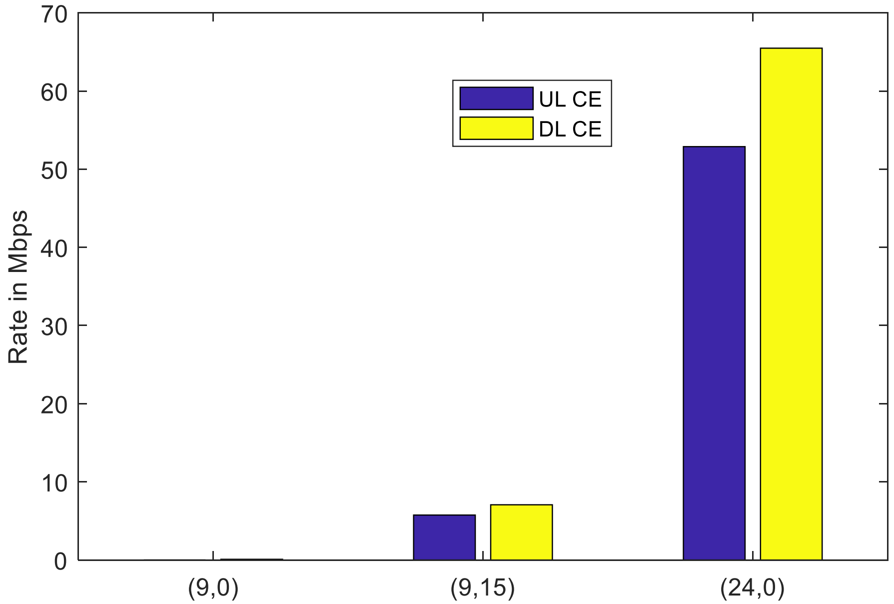
NOKIA

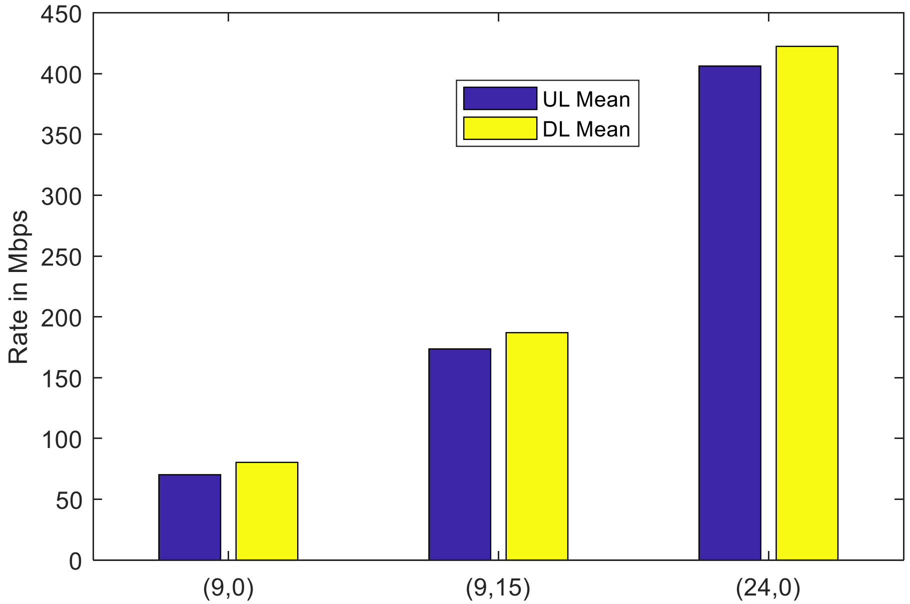
Self-backhauling Needed for Millimeter Wave Cellular

- New radio would likely require **dense deployments right from the initial phases** to get sufficient coverage (esp. for frequency > 20 GHz).
- 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.



Comparison of Rates: 3MB scenario





More than **100x gain in cell edge rates** and about **2x to 3x gain in mean rates** by adding 15 relays to (9,0)

NOKIA

5G mmWave Proof-of-Concept @70 GHz

Features

1) Feature 1: 1 GHz BW Single Link @ 70 GHz √

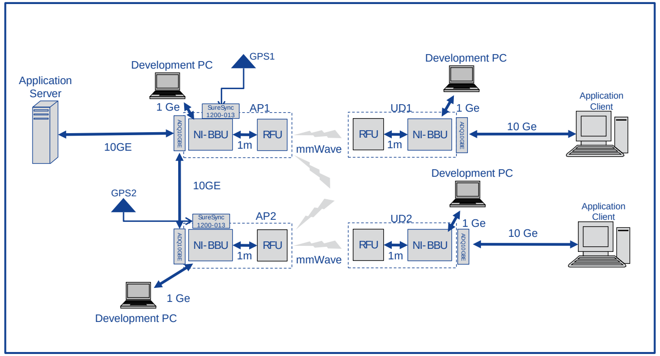
- Single-user acquisition and tracking Collaborate on field testing at YRP
- Mobile World Congress 2015

2) Feature 2: 1 GHz BW Multi Link @ 70 GHz

- Low latency application support < 1 ms
- Multi-user acquisition and tracking
- Dynamic TDD allocation
- Rapid Rerouting – Access Point Diversity

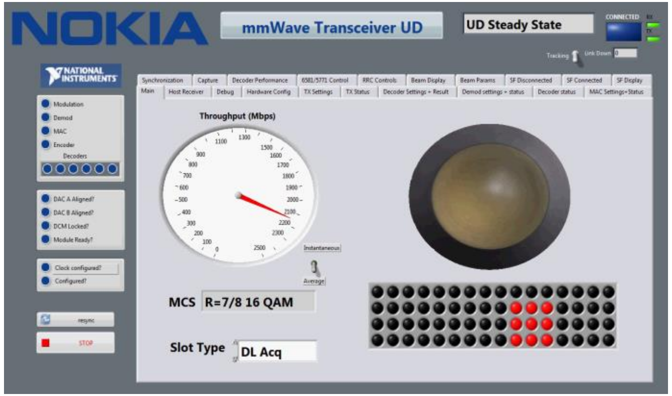
3) Feature 3: 2 GHz BW @ 70 GHz

- BBU based on new platform
- **2x2 MIMO with 64 QAM modulation**
- **Peak Rate : 15 Gbps**



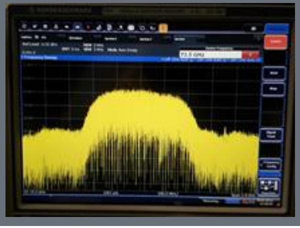
Nokia 5G mmWave beam tracking demonstrator (70 GHz)

First 5G demos
CEATEC 2014

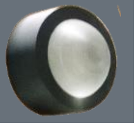


- 70 GHz PoC System
  - 1 GHz BW (2.5 Gbps Peak Rate)
  - 2 GHz BW (2x2 MIMO, 15 Gbps Peak Rate)

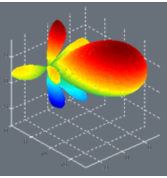
70 GHz band
1 GHz bandwidth



Lens antenna with 64-beam switching



3˚ beam width

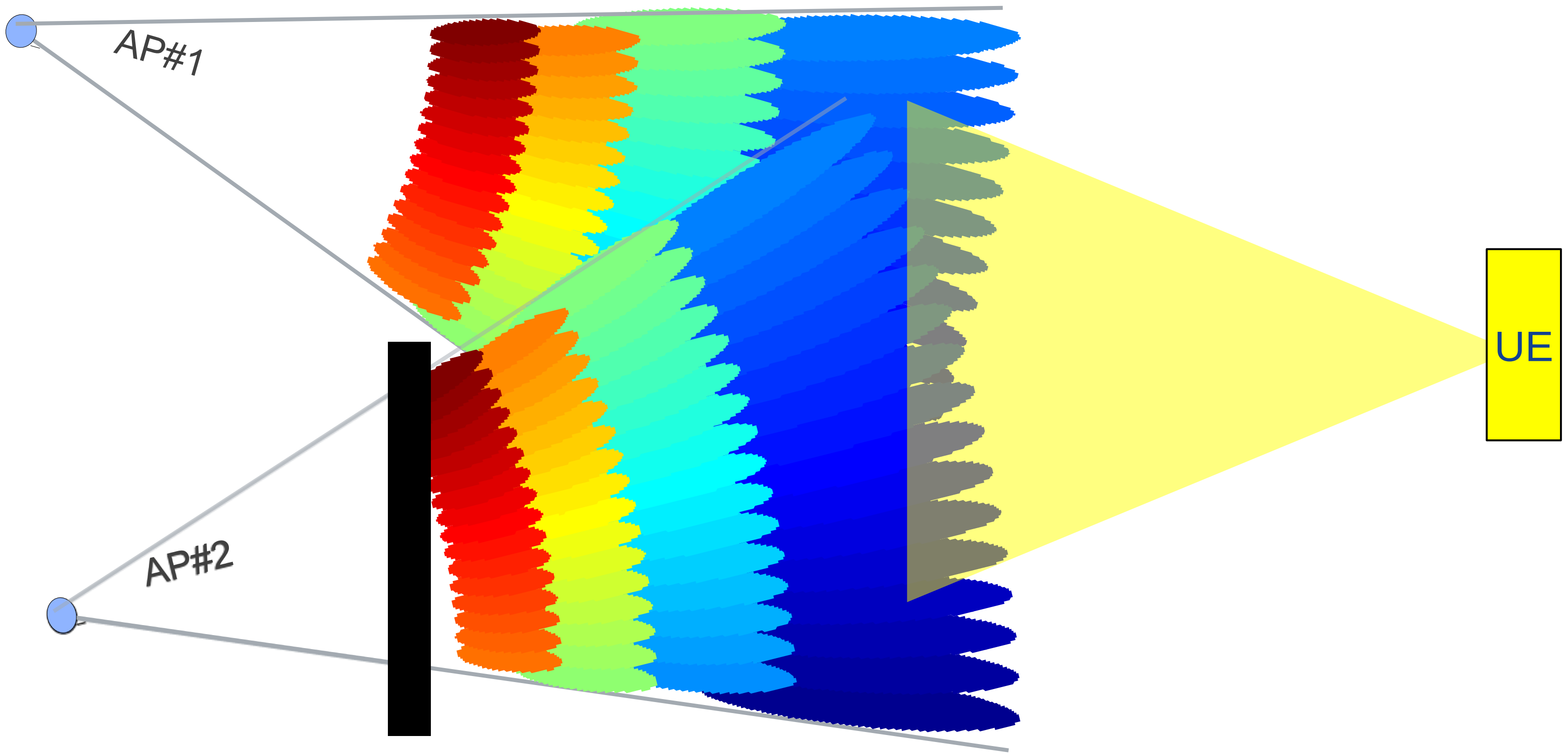


Nokia 5G mmWave beam tracking demonstrator (70 GHz)

Rapid Rerouting Feature

- **Scenario: 2 APs and 1 UD**
  - APs are configured for overlapping coverage creating a triangle between AP1, AP2 and the UD
  - UD is positioned such that it can detect both APs. UD will display the detected beams from both APs. The UD will maintain connectivity to both the serving and alternate AP.
- **TCP/IP throughput**
  - Iperf application running over the mmWave will be used to demonstrate throughput
  - The throughput will be displayed on the User Device (UD) display showing the raw of PHY throughput of 2 Gbps.
  - Rapid re-routing between APs will show minimal TCP/IP throughput degradation depending on type of re-route.
- **Rapid Rerouting demonstrations:**
  - **Blockage Detection (BD)**: Serving AP is blocked by demonstrator using a mmWave opaque device (many different physical items are suitable).
  - **Make Before Break (MBB)**: UD is rotated slowly to favor the alternate AP initiating a re-route.
  - **Break Before Make (BBM)**: An abrupt change where both APs are blocked and the UD must re-initialize the connection.

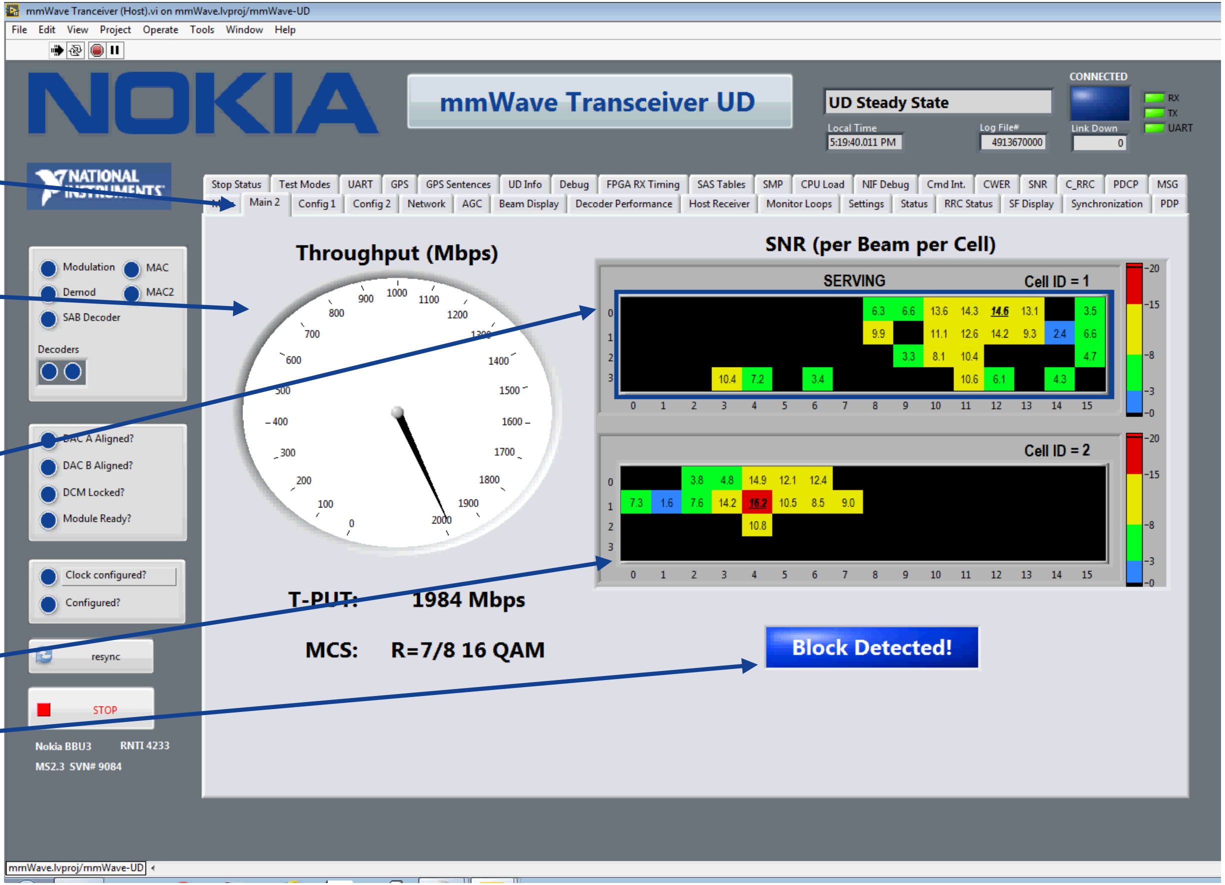
mmWave Rapid Rerouting
Blockage Detection



mmWave Rapid Rerouting

Demo Display – “Main 2” tab

- New “Main 2” Tab
  - Main 2 can be used for demonstrations showing physical layer throughput, serving cell and detected beam SNR
- Throughput Gauge
  - Duplicated from the “Main” tab shows the downlink throughput of the UD visible to observers. Throughput and active MCS are visible below in text.
  - Reflects the application throughput running over the link. Recommend Iperf session running over the mmWave link
- SNR (per Beam per Cell)
  - Shows the beam SNR per cell for all 64 beams: 16 QAM 7/8 is in red; 16 QAM ½ is in yellow, QPSK ½ is green and BPSK 1/5 is blue. Undecoded beams are left blank
  - The serving cell is identified by the text “SERVING” and by a blue border
- Blockage Detection
  - When the UD RRC detects an abrupt drop in detected beams, the link will be rerouted and the “Block Detected!” LED will be illuminated for 1 second.



NOKIA

Contributors

Mark Cudak, Fred Vook, Rapeepat Ratasuk, Jie Chen, Bill Hillery, Jun Tan, Eugene Visotsky, Jun Tan, Frank Hsieh, Karri Ranta Aho, Mandar Kulkarni, Nokia PoC Team, Nokia Standards Team, National Instruments

Q&A