The First International Conference on Advances in Signal, Image and Video Processing
SIGNAL 2016 | June 26 - 30, 2016 | Lisbon, Portugal

IARIA

Multi-gigabit Data Radio Transmission: **When will we get to 5G?"**

Prof. Rafael F. S. Caldeirinha

INSTITUIÇÕES ASSOCIADAS

TÉCNICO LISBOA

universidade de aveiro

UNIVERSIDADE DE COIMBRA

PT Inovação

nsn Nokia Solutions Network

UNIVERSIDADE DA BEIRA INTERIOR
Covilhã | Portugal

U.PORTO

ISCTE IUL
Instituto Universitário de Lisboa

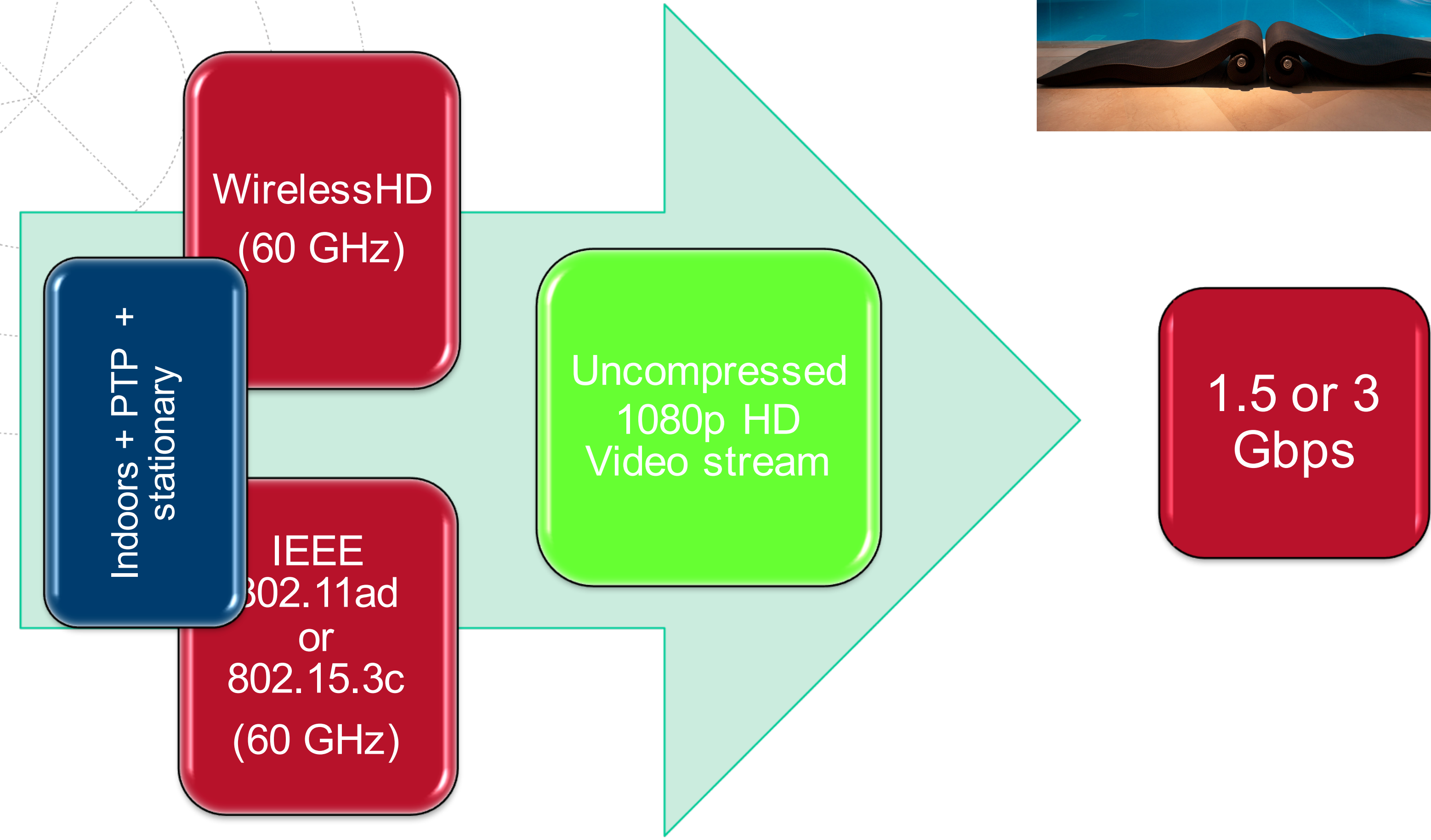
IPL
instituto politécnico de leiria

it
instituto de telecomunicações

Agenda

1. Brief presentation of my research group
2. Uncompressed video streaming
3. 5G:
   - *5G Vision*
   - *5G Requirements*
   - *5G Key Enabling Technologies*
4. Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Uncompressed video streaming - indoors



Uncompressed 1080p HD video stream

- 1 frame (1080 x 1920 pixels)
- 3 (RGB) 8 bits x 1080 x 1920 x 30/60 fps = **1.5** / **3 Gbps**

enhanced mode

Real-time video streaming - outdoors

Outdoors + PTP (<300 m) + stationary

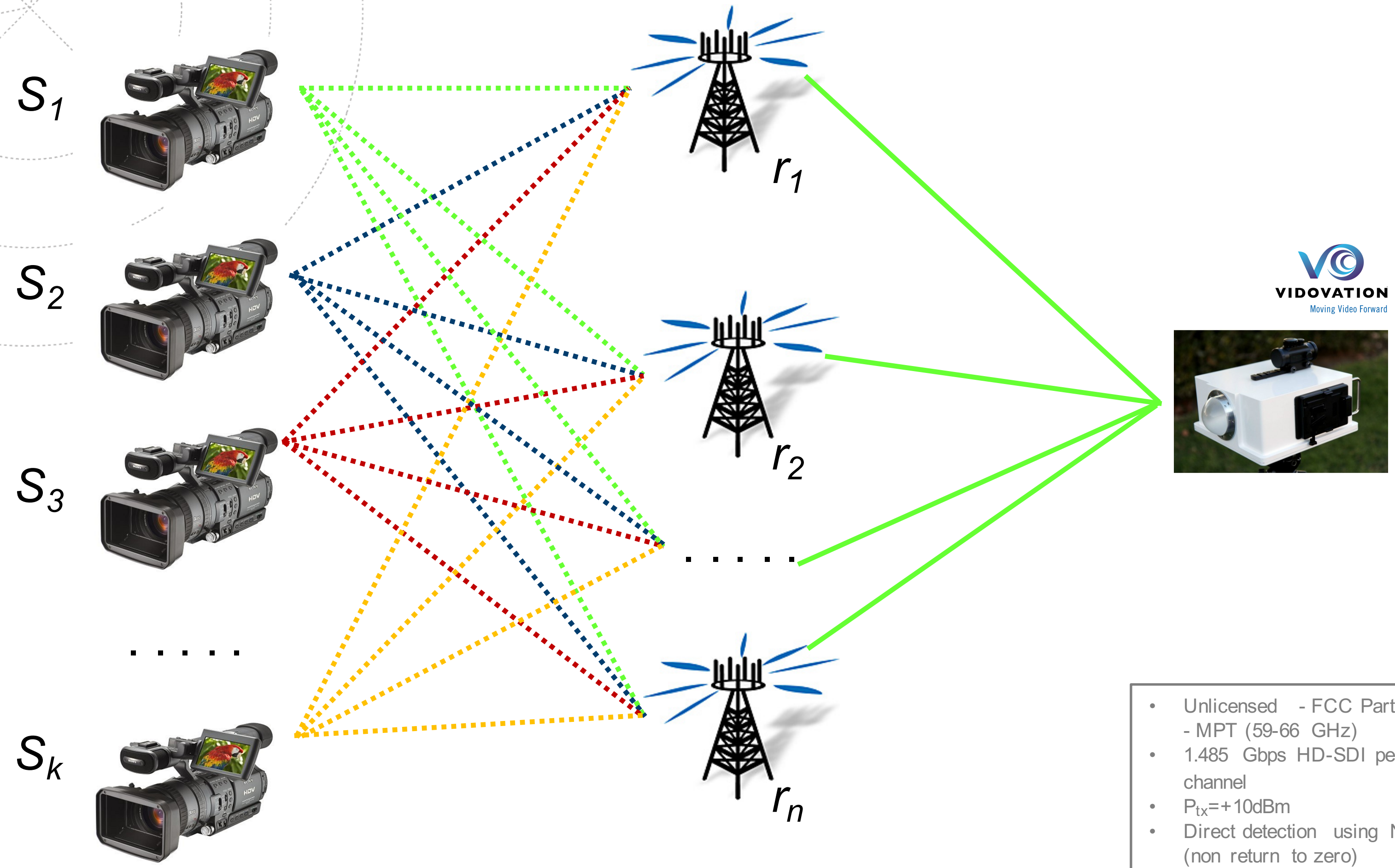
5G using relaying (60 GHz) ?

Scalable video coding (SVC)

< 1 Gbps

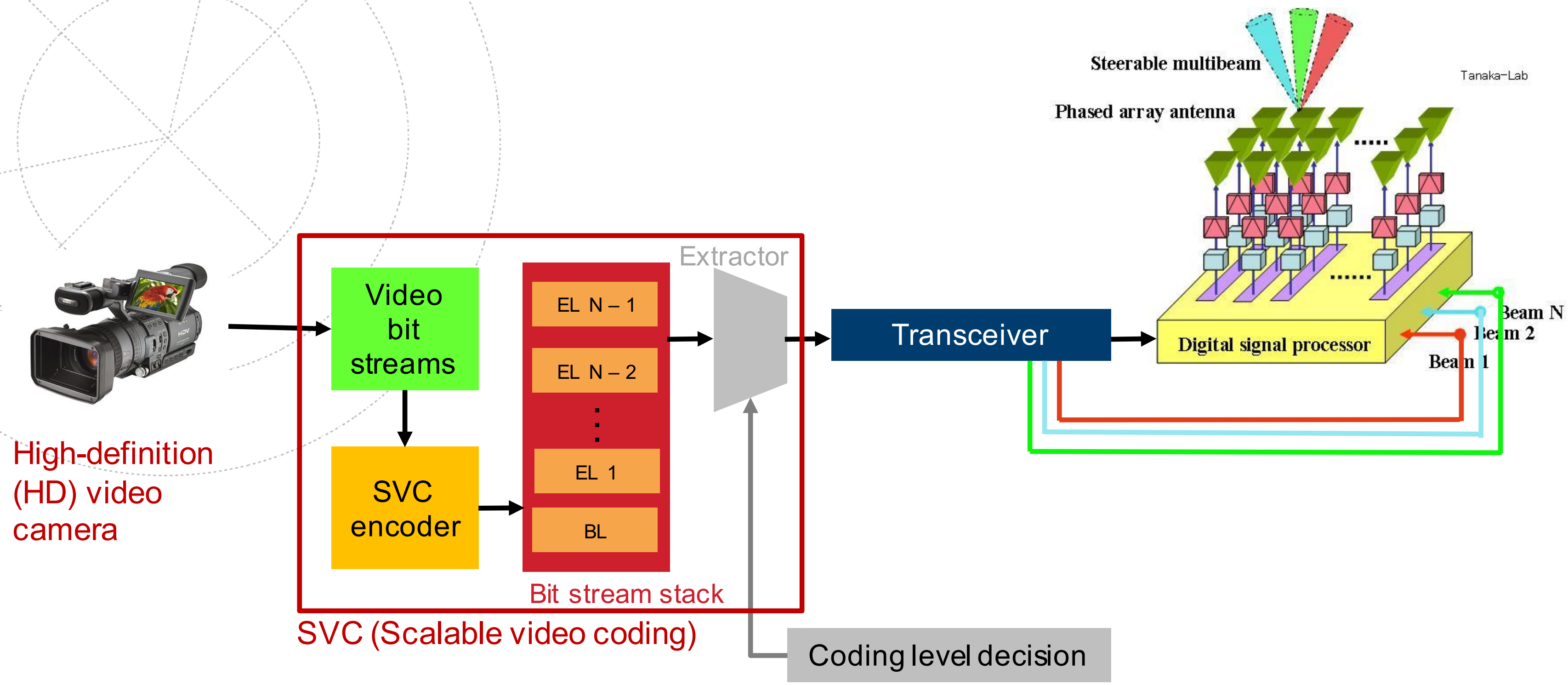
Real-time video streaming - outdoors

Two-hop outdoor mmWave streaming networks

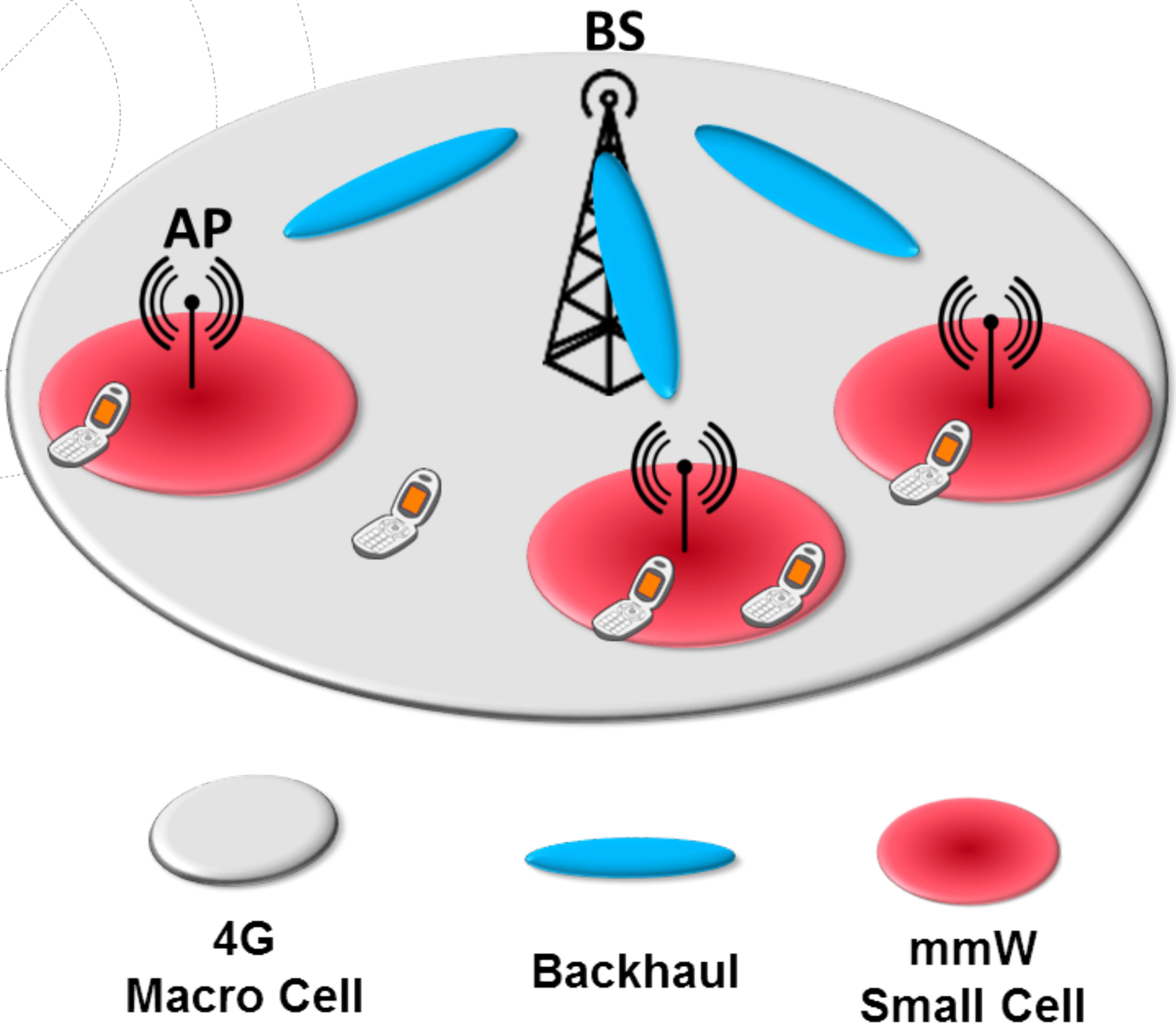


- Unlicensed - FCC Part 15.255 - MPT (59-66 GHz)
- 1.485 Gbps HD-SDI per channel
- P_{tx}=+10dBm
- Direct detection using NRZ (non return to zero)

Source devices in outdoor mmWave streaming platforms



mmWave small cell networks



INSTITUIÇÕES ASSOCIADAS

IPL instituto politécnico de leiria

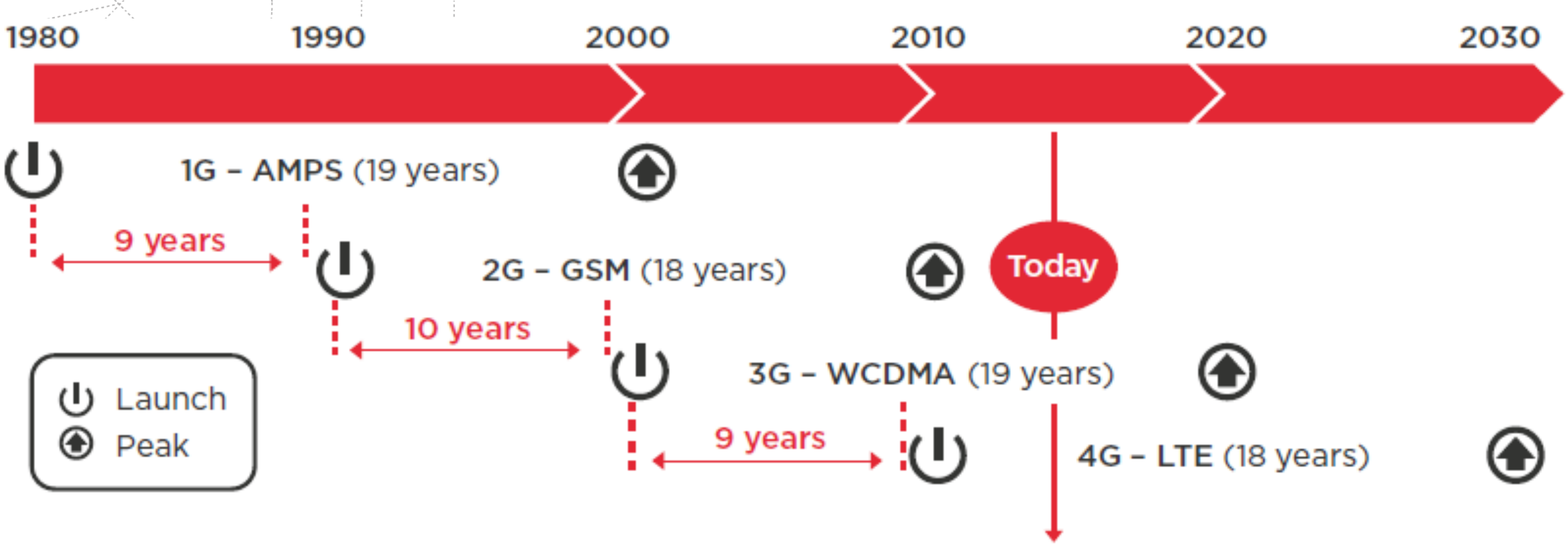
instituto de telecomunicações

And now?


Will uncompressed video transmission be a reality for relatively long distances?
Will we be able to achieve multi-gigabit data radio transmissions?

5G Vision

Evolution of mobile technology by generation, 1980 onwards



Approximate 20-year cycle from launch to peak penetration, with around ten years between the launch of each new technology

[Source: GSMA Intelligence]

Now

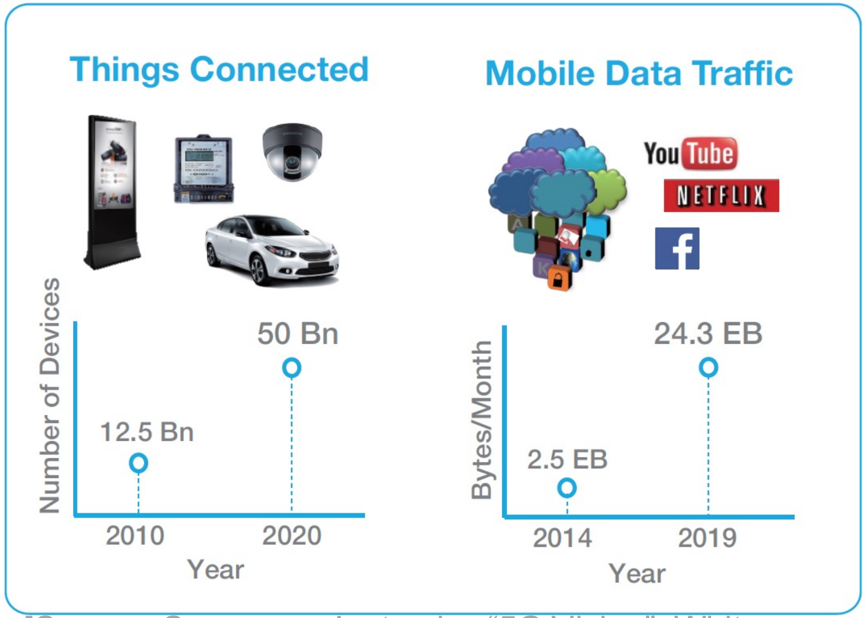
[Source: http://www.nydailynews.com/news/world/check-contrasting-pics-st-peter-square-article-1.1288700]

5G Vision

Dawn of the 5G Era

5G Era can be expected to revolutionize the way we communicate by supporting **immersive applications** that demand exceptionally:

- high-speed wireless connections;
- a fully-realized IoT;
- experience lower latency; and
- promote both spectrum and energy efficiency.



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

Growth in Mobile Traffic and Connected Devices

Exabyte = 10^{18} Bytes
Petabyte = 10^{15} Bytes
Terabyte = 10^{12} Bytes

5G Vision

5G Service Vision

[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Vision

5G Service Vision

- Internet of Things:
  - Up to 1Mn simultaneous connections per km^2;
  - M2M communications:
    - » *wireless metering; mobile payments; smart grid and critical infrastructure monitoring; connected home; smart transportation; and telemedicine.*
- Smart Home:
  - Dishwashers will fix themselves using information from peers of the same model while home appliances at home and in the neighboring homes may cooperate to extinguish a fire;
  - A smart refrigerator recommending a recipe of cuisine to be cooked with ingredients that are already in the refrigerator ….

[Source: Samsung electronics “5G Vision”, White Paper [Online] 2015.]

5G Vision

5G Service Vision

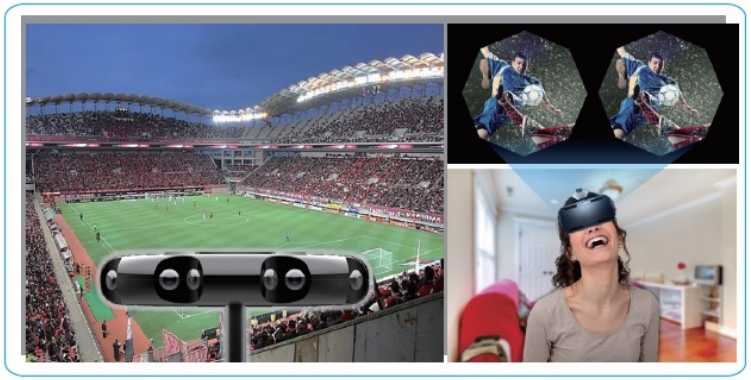
- Fitness & Healthcare:
  - Connected health and fitness related wearable devices will record your athletic performance while you exercise, its duration and frequency per day;
  - Will send vital signs such as brainwave, blood pressure and heartbeat to an expert system in the hospital in real-time … (latency is an issue)…
- Smart Store
  - Alerts of low priced products to the user's device as the user is detected in the vicinity (latency is an issue)
- Smart Office
- Connected car

[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Vision

Immersive Multimedia Experience

- Users will experience life-like multimedia streams anytime and anywhere, e.g. users will feel as if they are part of the scene (virtual reality and augmented reality)



Watching Sport Events with VR

Driving a Car with AR Navigation

[Source: Samsung electronics “5G Vision”, White Paper [Online] 2015.]

5G Vision

Everything on the Cloud

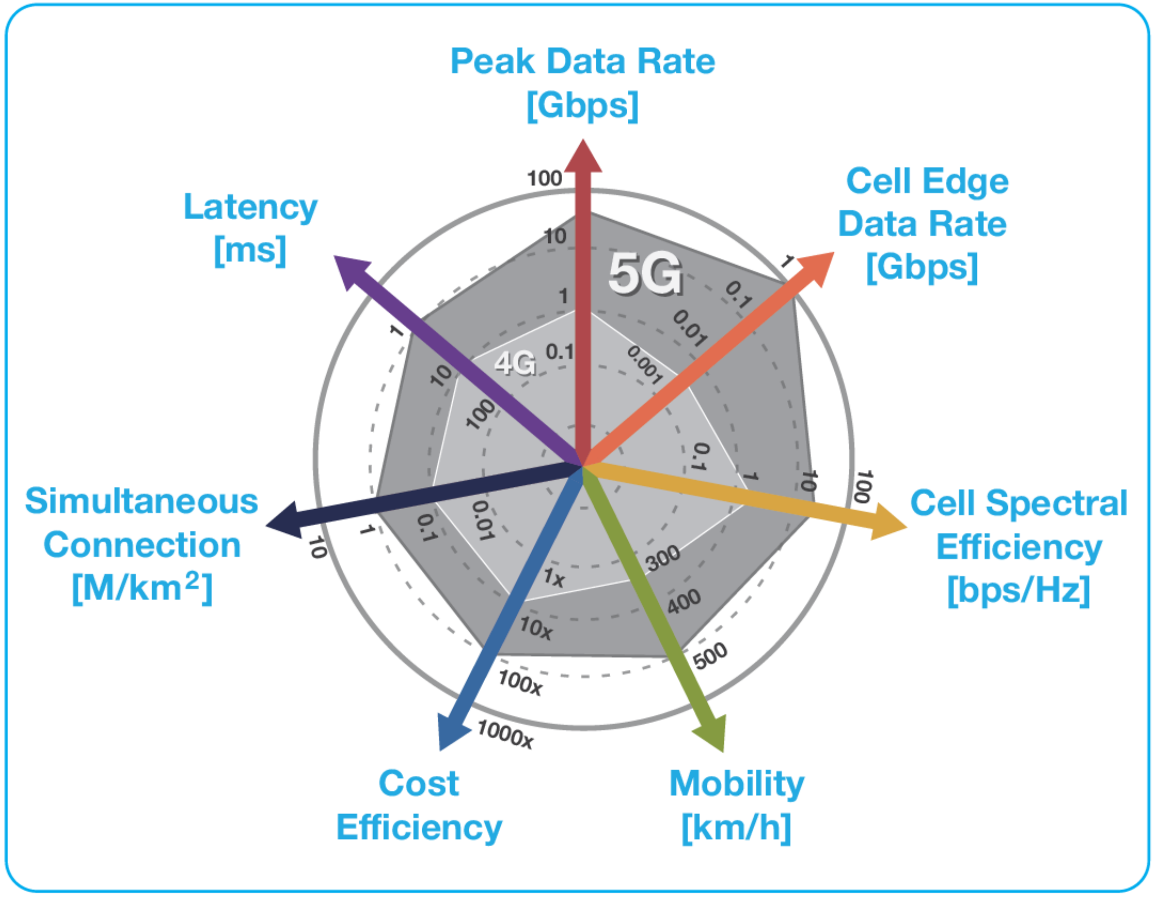
- 5G will provide users with a desktop-like experience based on the cloud computing
  - » *only simply input and output interfaces on mobiles devices are needed » making them lighter, thinner, fancier, and more eco-friendly…*

Intuitive Remote Access

- Users will be able to control remote machines and appliances as if they are right before them, even from thousands of miles away.

5G Requirements

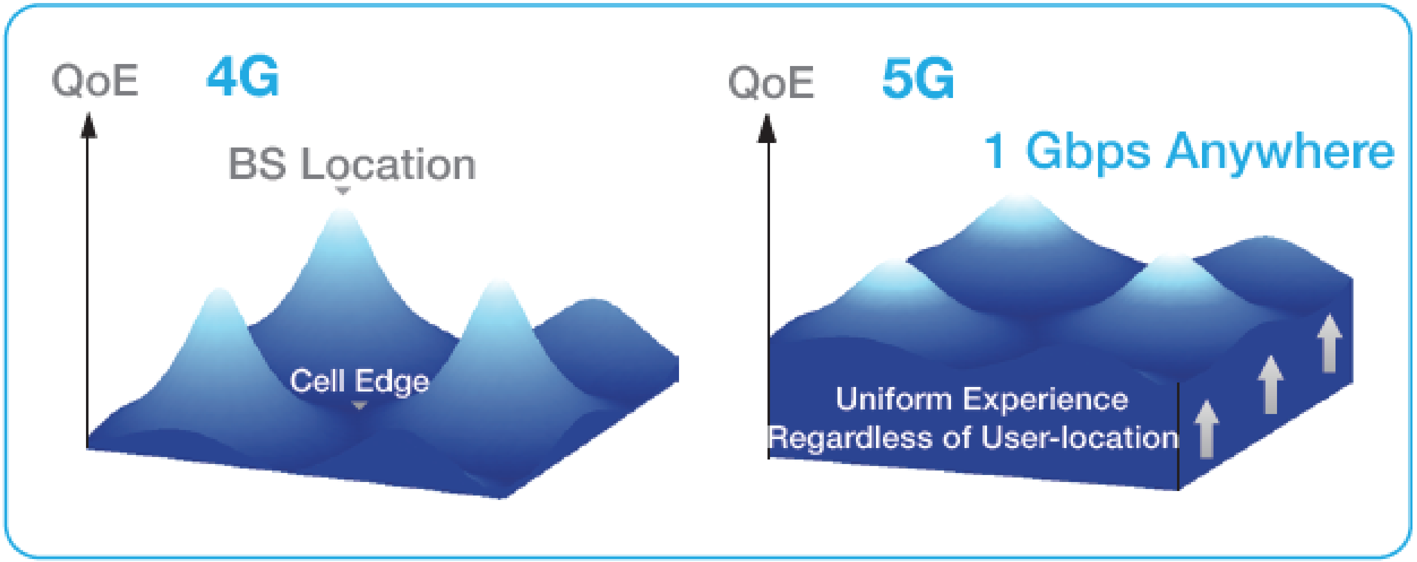
5G rainbow requirements consisting of 7 Key Performance Indices (KPIs)



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Requirements

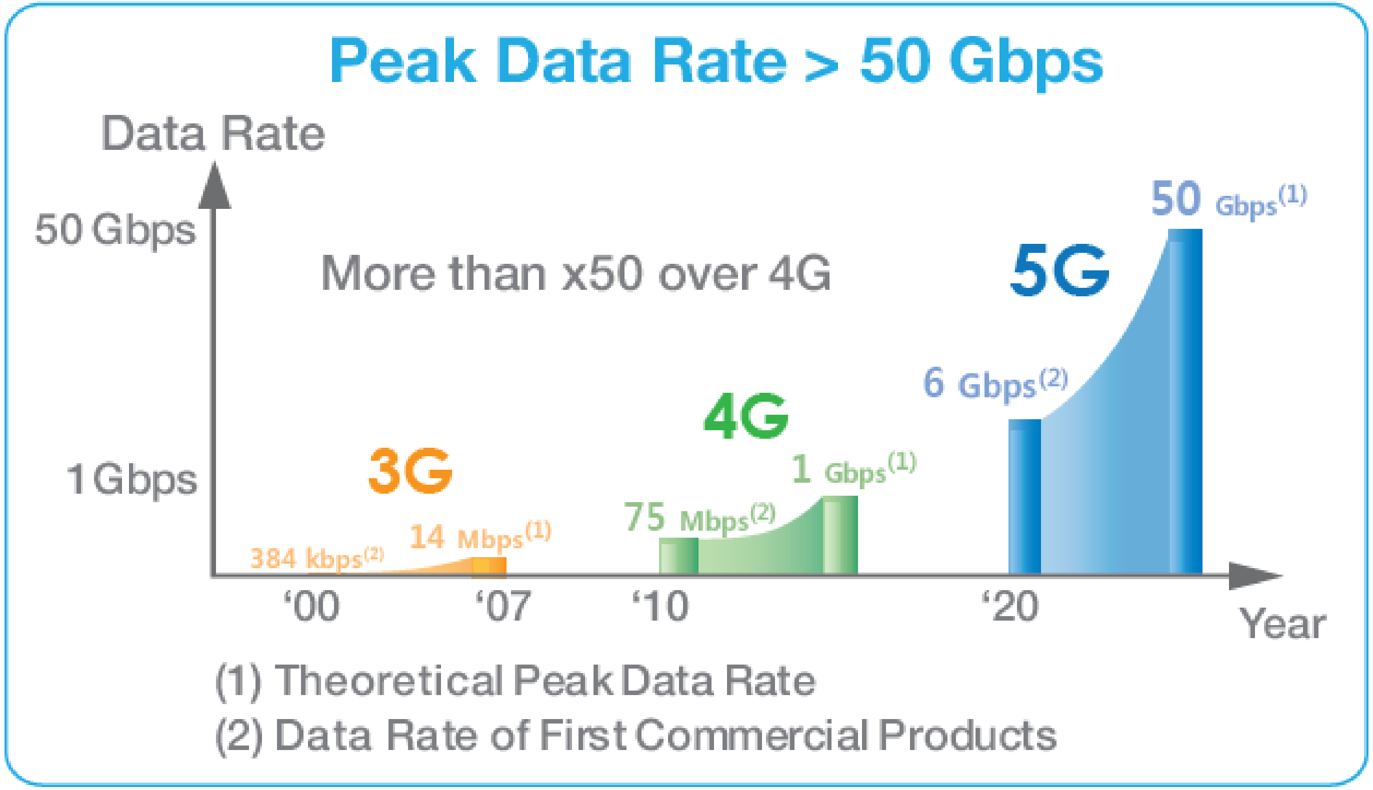
Edgeless RAN - 1 Gbps Anywhere



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Requirements

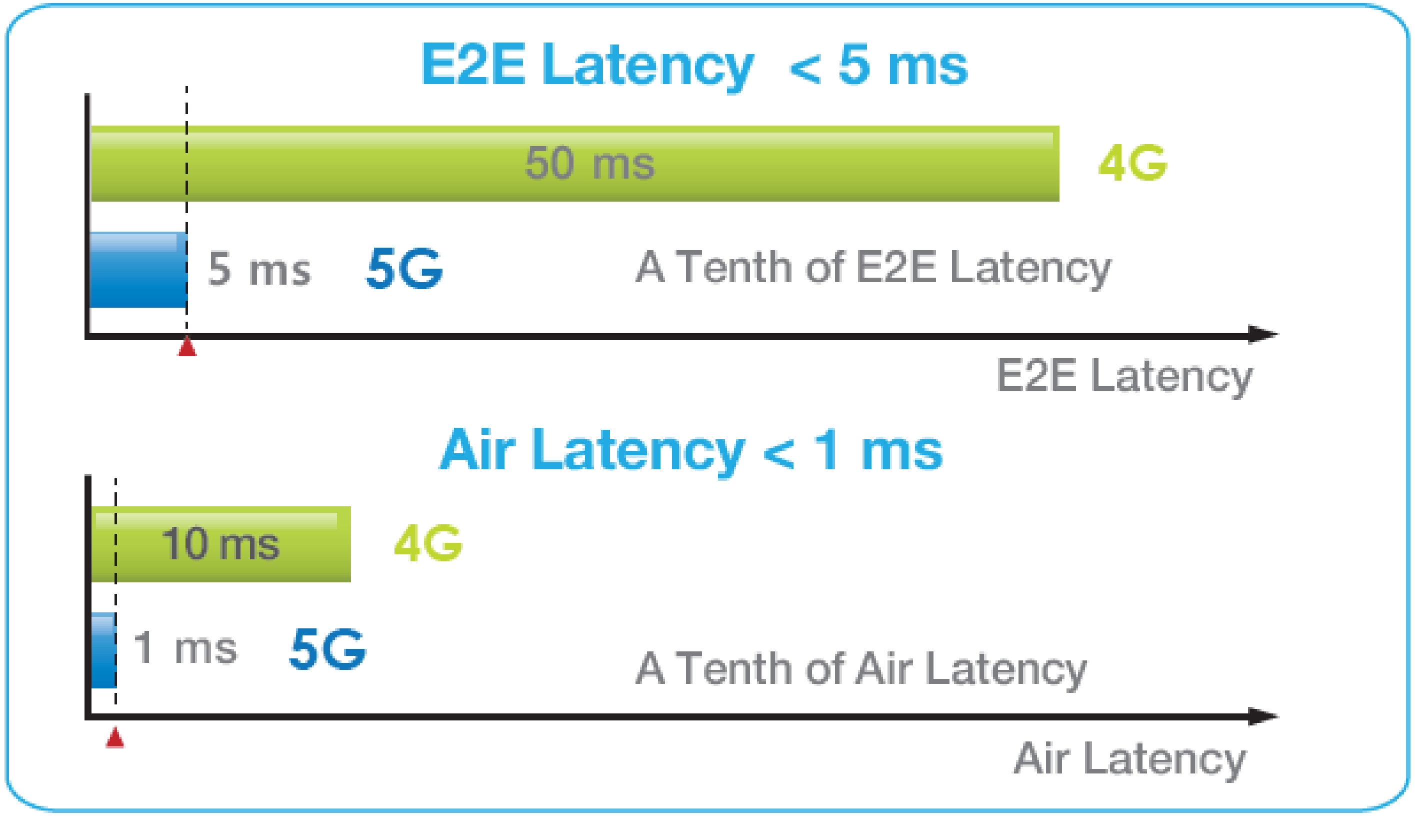
Data Rate Comparison of 5G with 3G and 4G



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Requirements

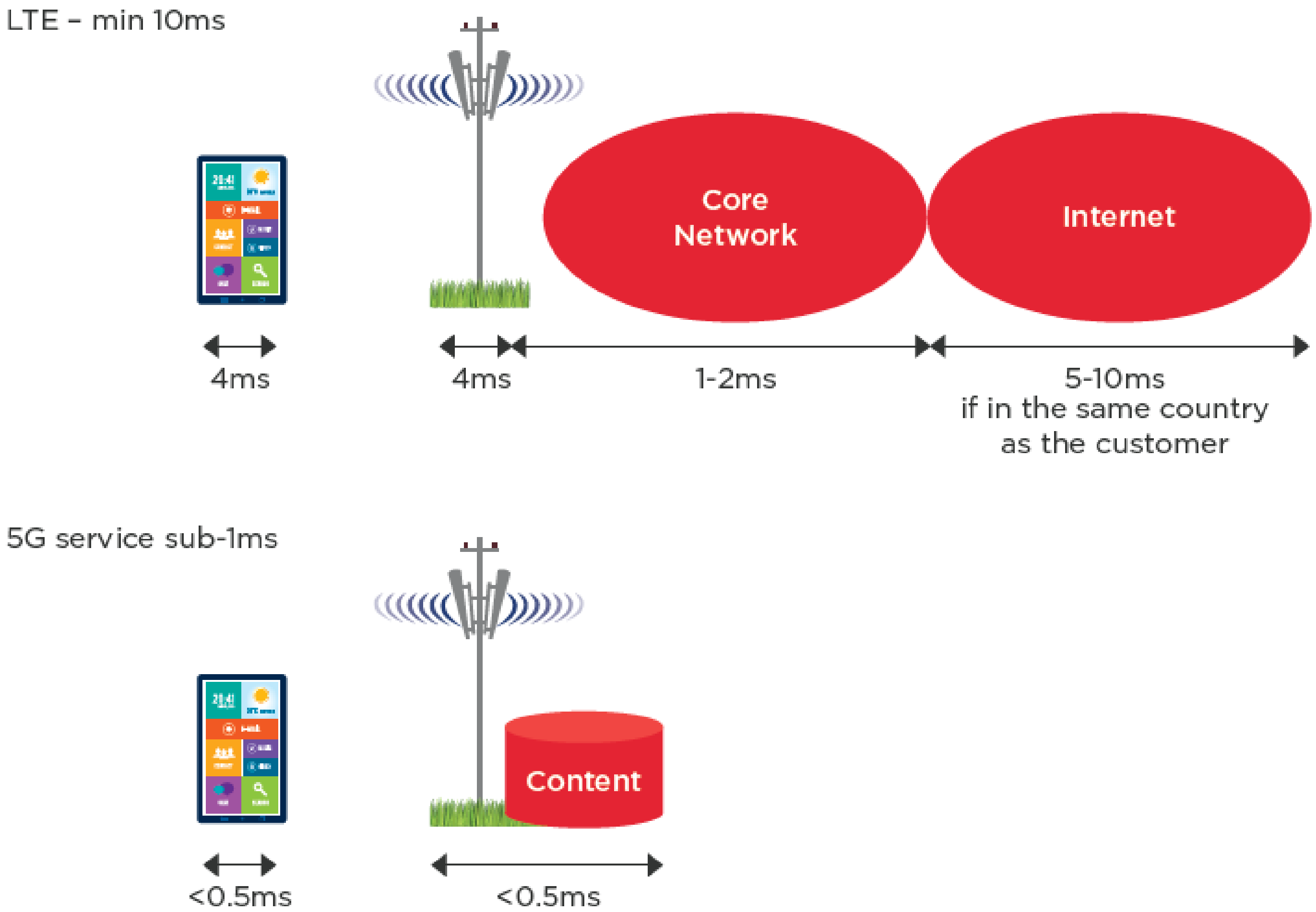
Ultra Low Latency of 5G



[Source: Samsung electronics “5G Vision”, White Paper [Online] 2015.]

5G Requirements

Ultra Low Latency of 5G



[Source: GSMA Intelligence]

5G Requirements

Spectral efficiency requirements:

- set to 10 bits/s/Hz (in contrast to the 1-3 bits/s/Hz on 4G networks),
- Efficient use of the spectrum by using MIMO, advanced coding and modulation schemes and new waveform designs

new

MAY 2016 » 5G Researchers Set New World Record For Spectrum Efficiency

University of BRISTOL

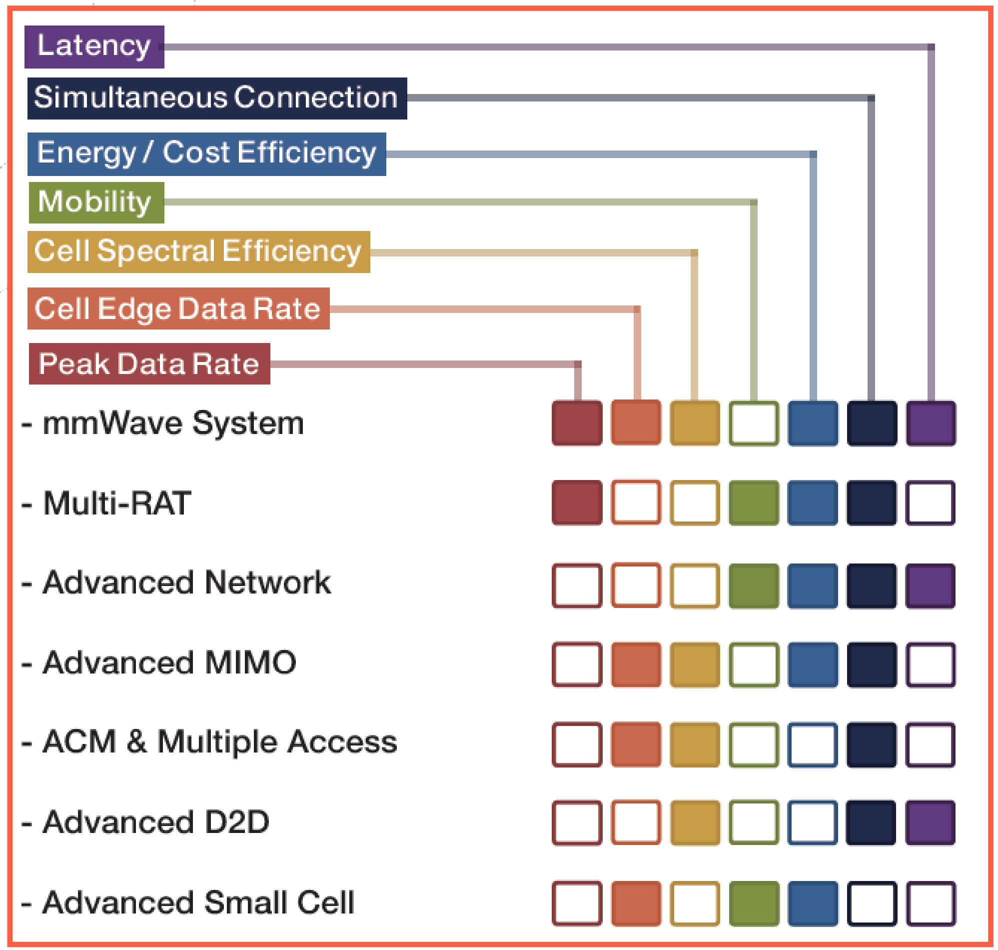
LUND UNIVERSITY

- 145,6 bits/s/Hz for 22 users
- 256 – QAM
- shared 20 MHz at 3.51 GHz
- 128-antenna massive MIMO

22-fold increase in spectrum efficiency over today's existing 4G networks.

5G Key Enabling Technologies

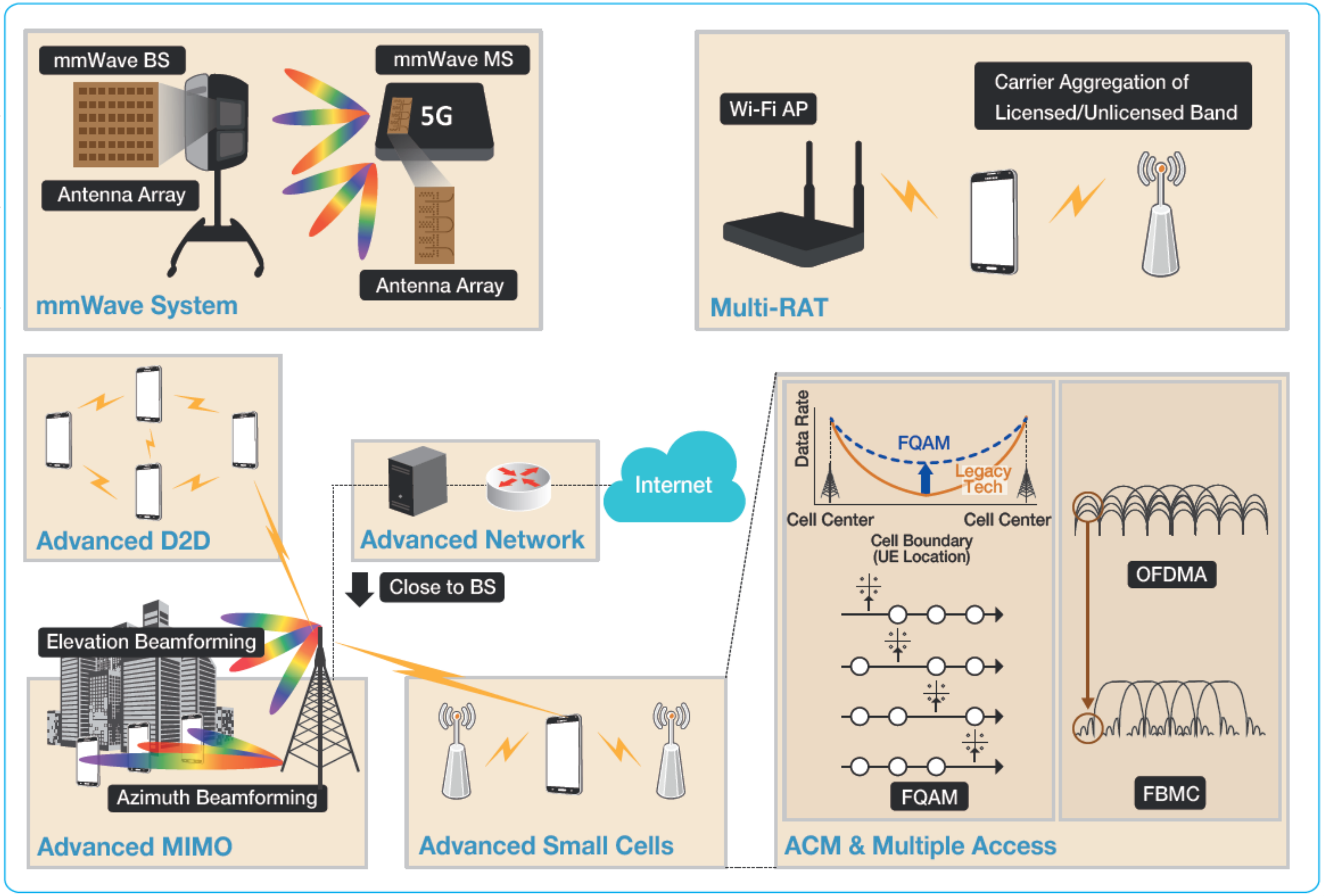
Future 5G systems will encompass fundamentally new designs to boost wireless capacity



[Source: Samsung electronics “5G Vision”, White Paper [Online] 2015.]

5G Key Enabling Technologies

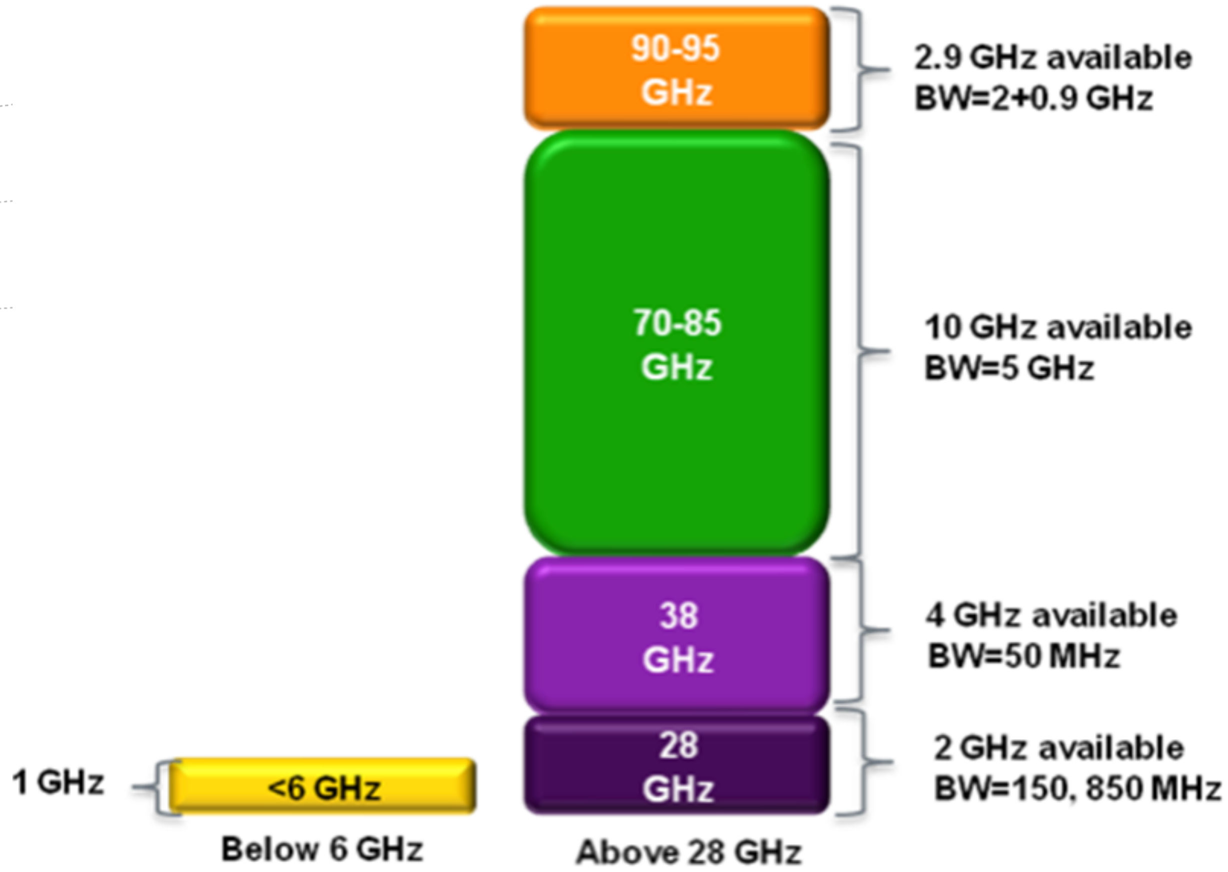
Future 5G systems will encompass fundamentally new designs to boost wireless capacity



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Key Enabling Technologies

Using millimeter wave spectrum for 5G telecommunications

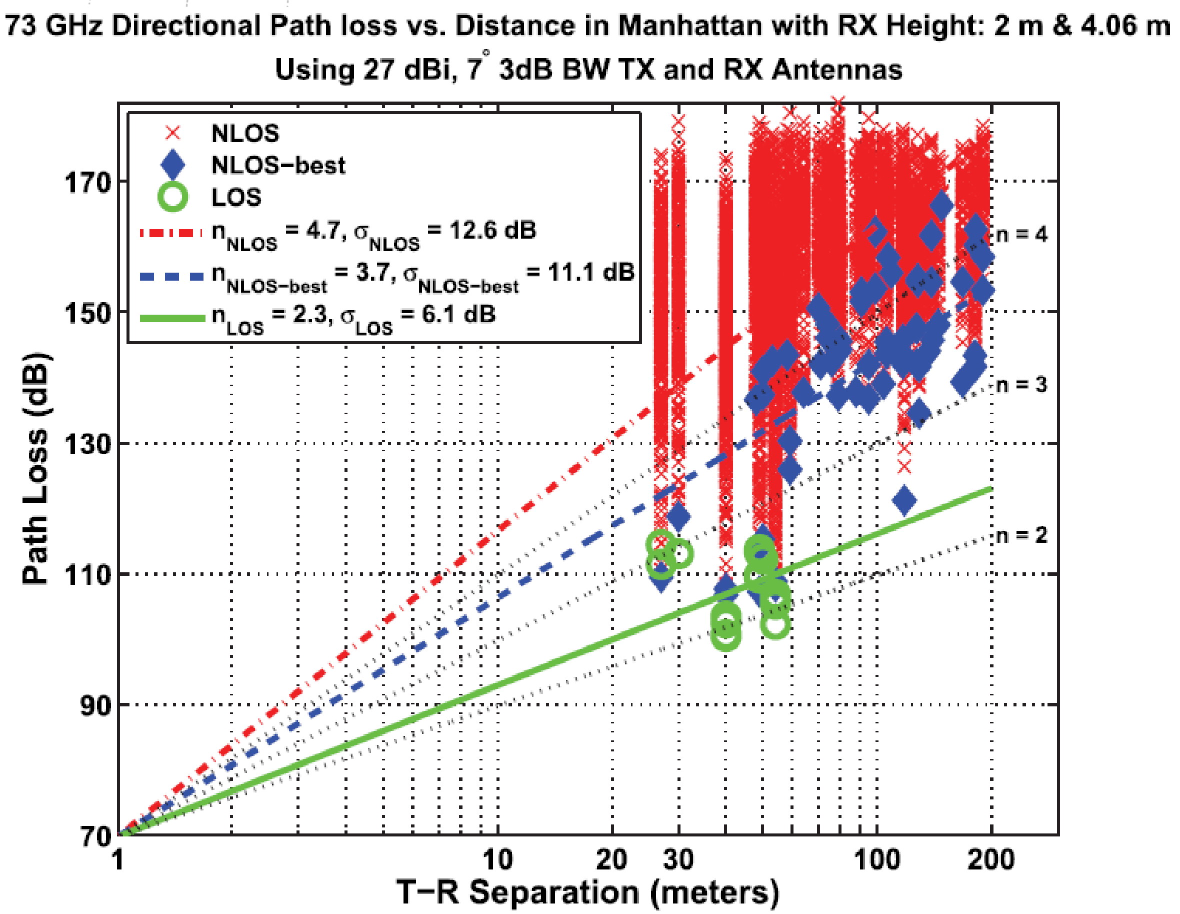


[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Key Enabling Technologies

Propagation channel

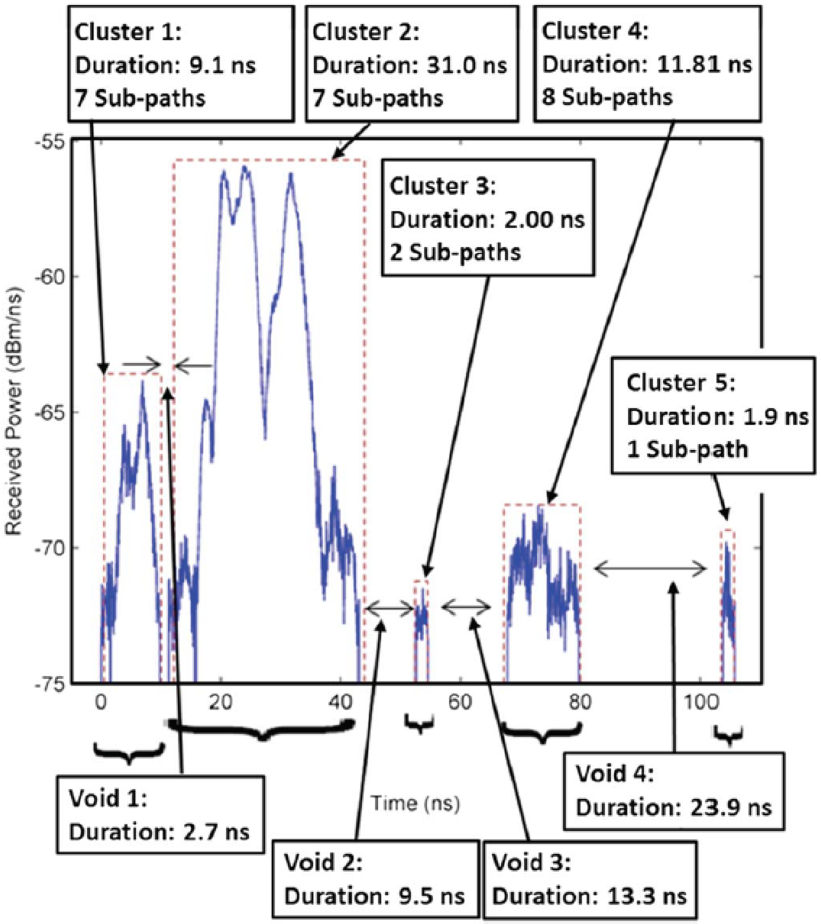
$$PL(d)[dB] = PL(d_0) + 10\bar{n}\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

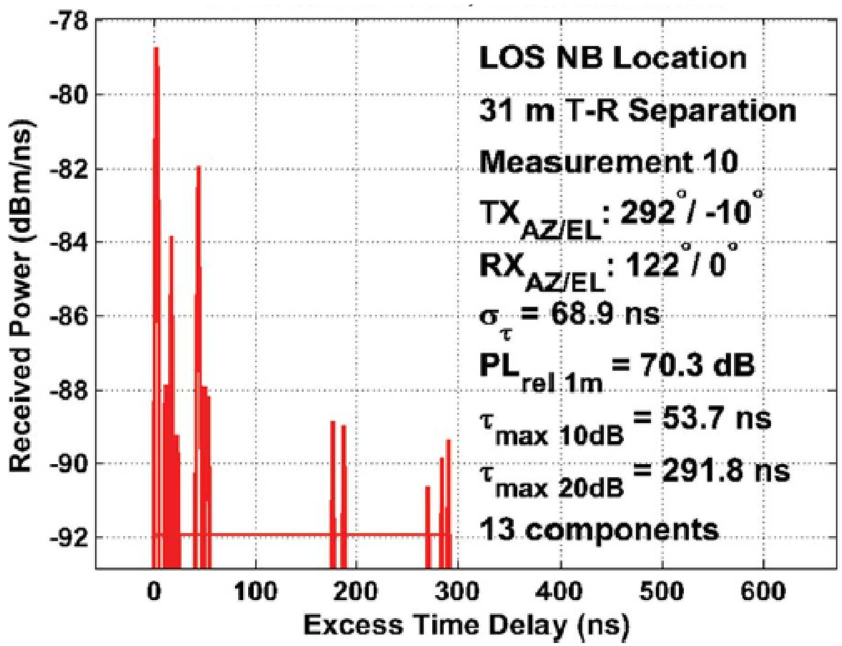


[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

Typical measured power delay profile (PDP)

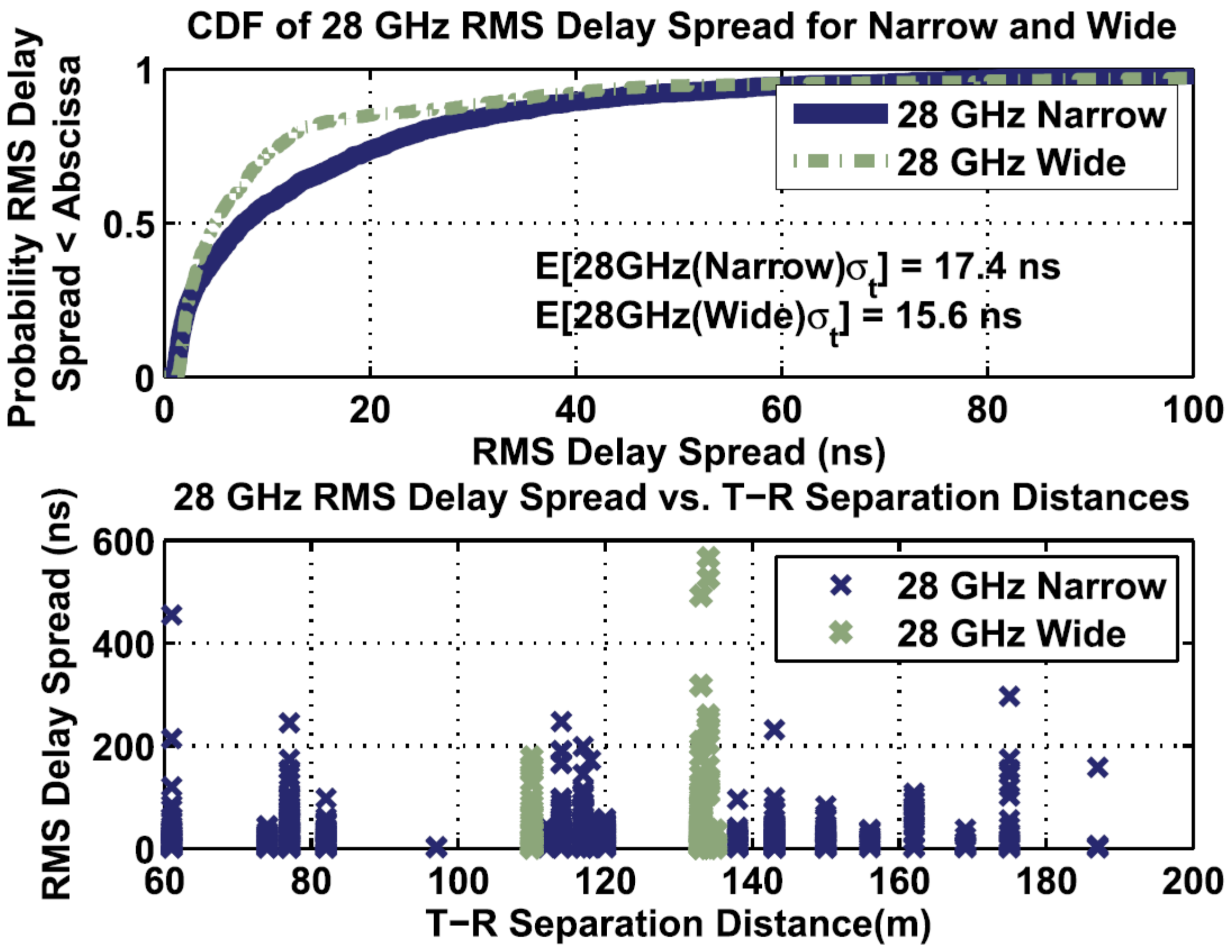




[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

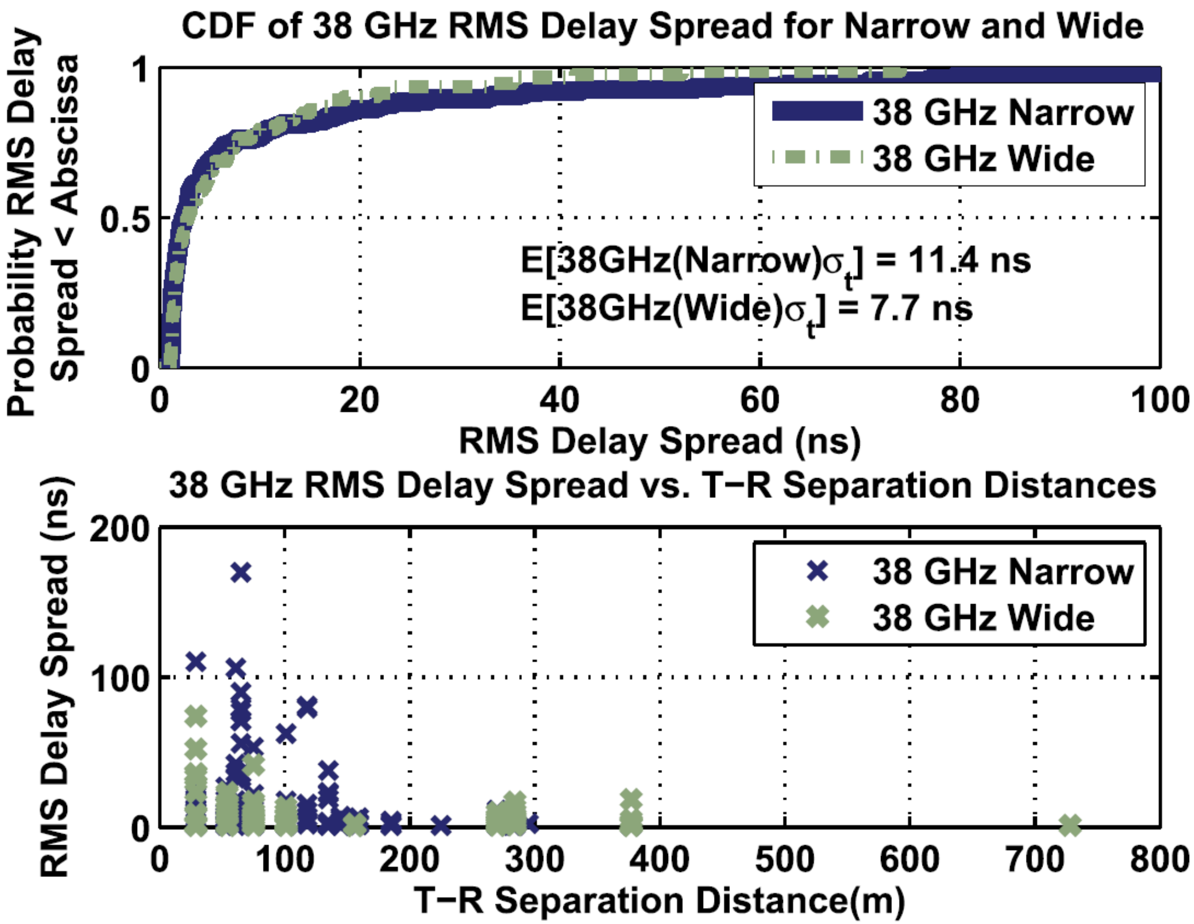
Propagation channel » outdoor



[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

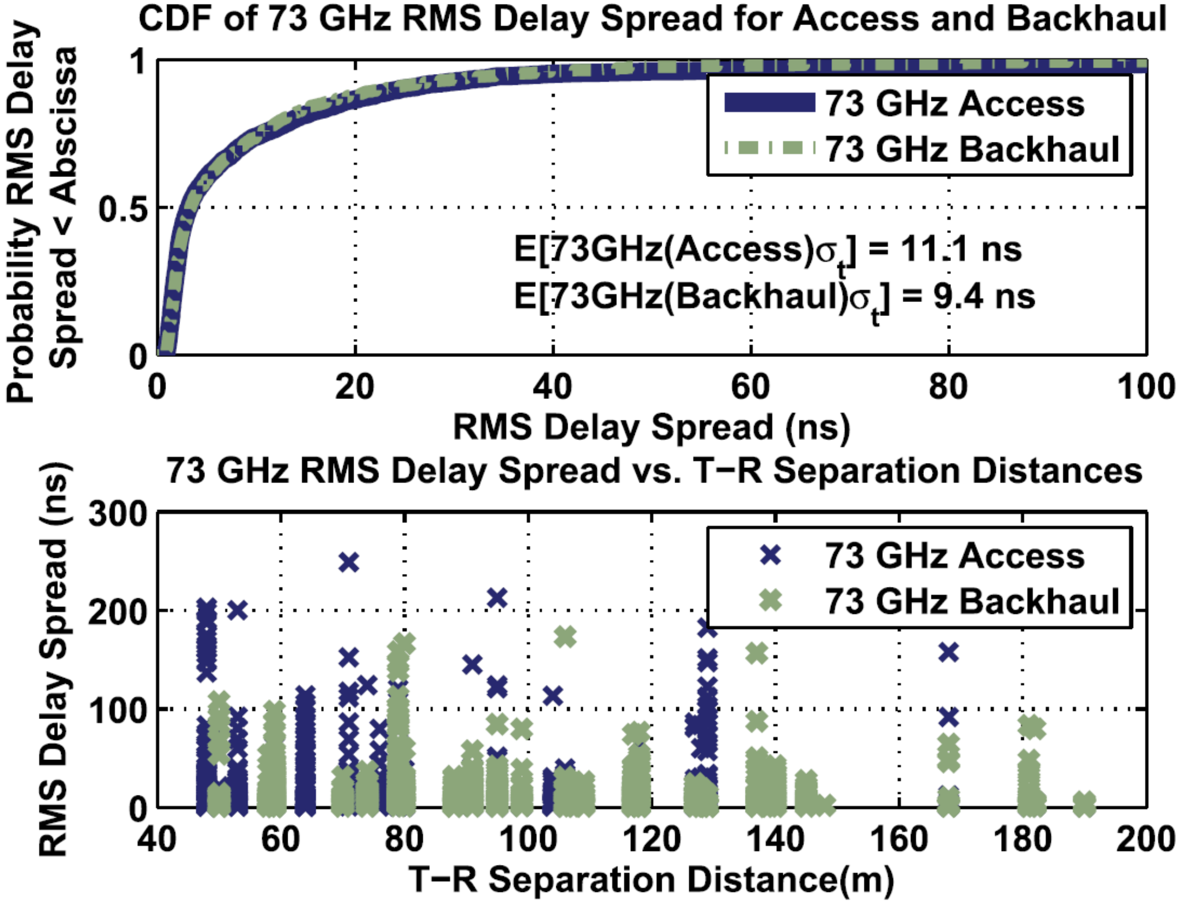
Propagation channel » outdoor



[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

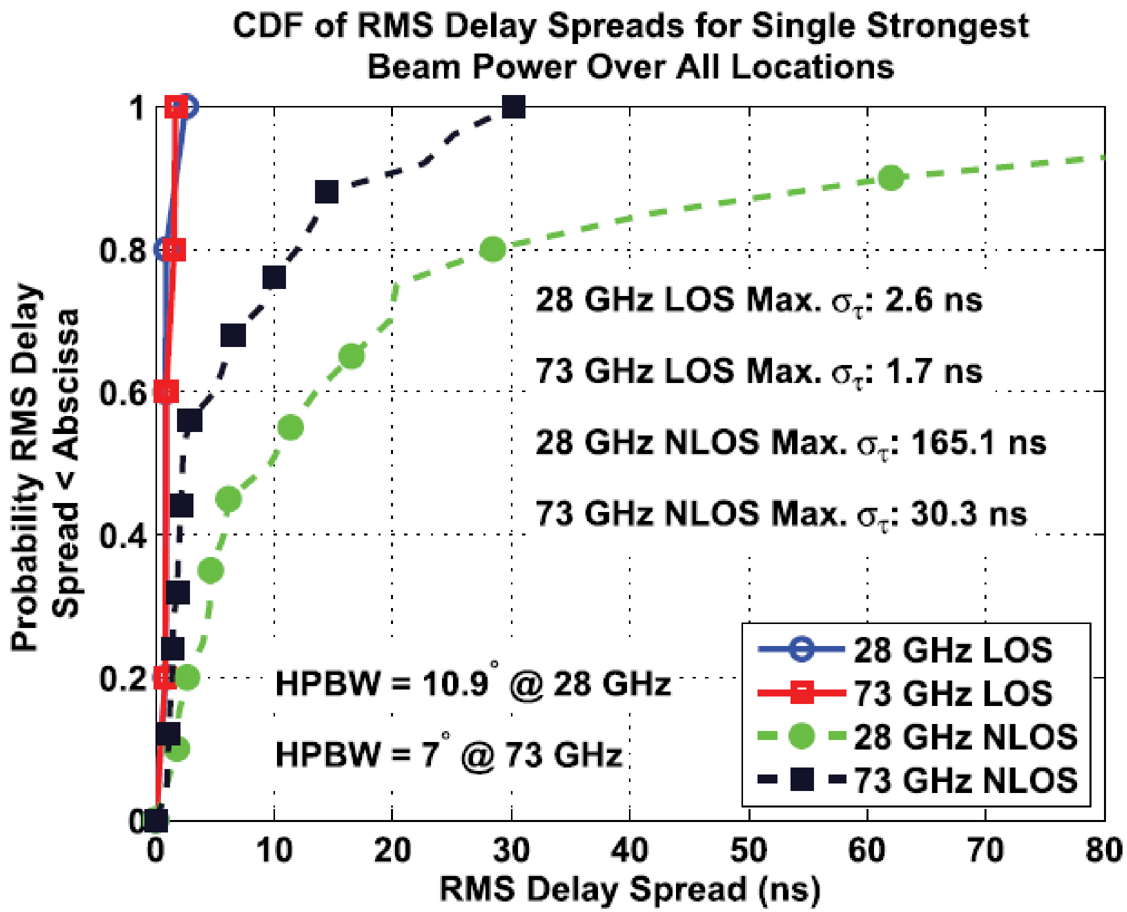
Propagation channel » outdoor



[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

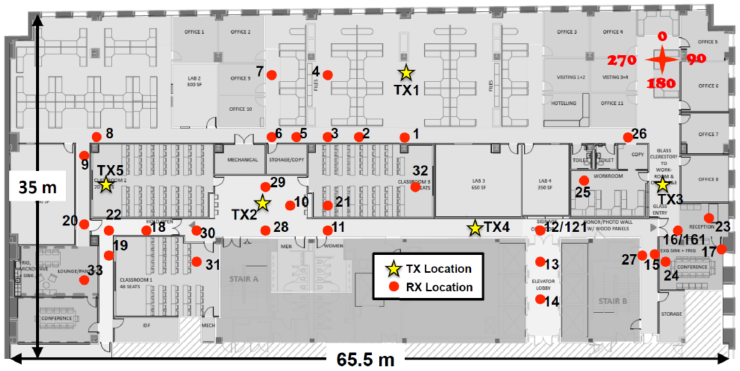
Propagation channel » outdoor



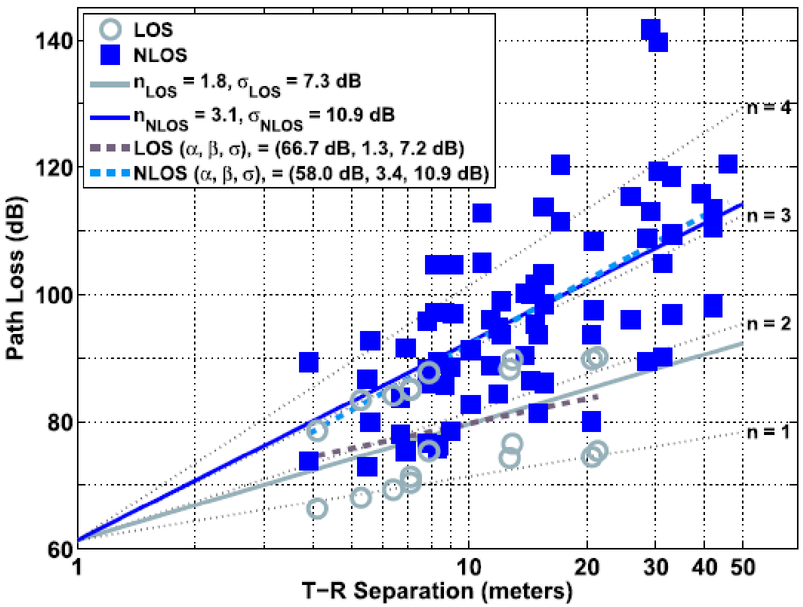
[Source: Rappaport *et al*, IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 63, NO. 9, SEPTEMBER 2015.]

5G Key Enabling Technologies

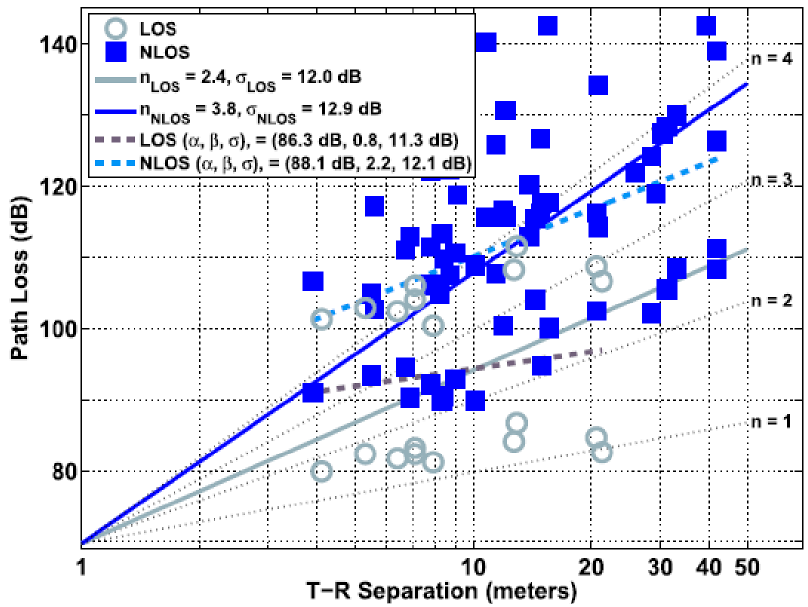
Propagation channel » indoor office



28 GHz Indoor Combined Polarization Omnidirectional Path Loss Models
with TX Height: 2.5 m and RX Height: 1.5 m



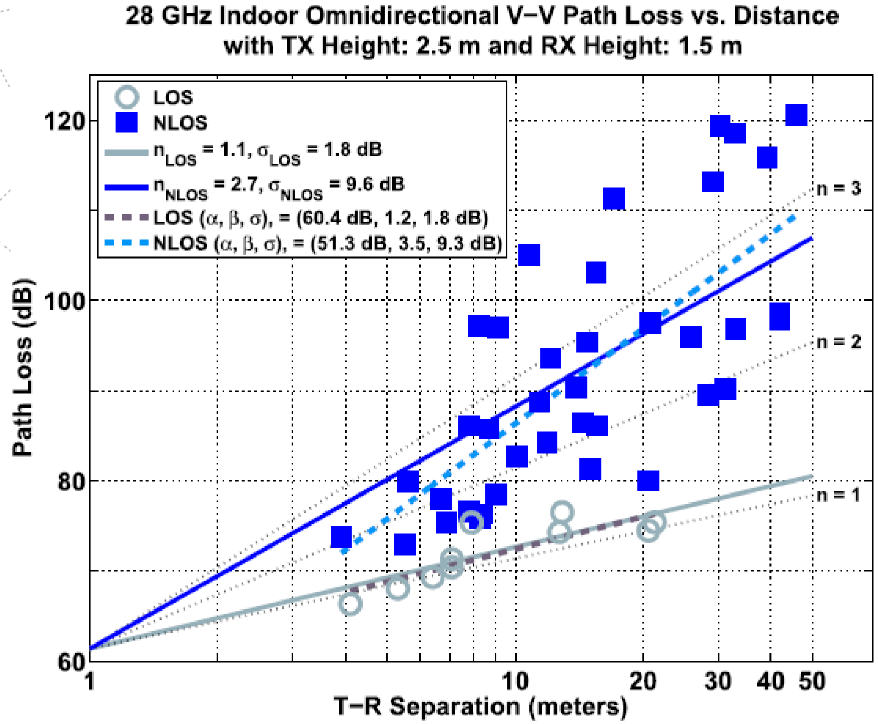
73 GHz Indoor Combined Polarization Omnidirectional Path Loss Models
with TX Height: 2.5 m and RX Height: 1.5 m

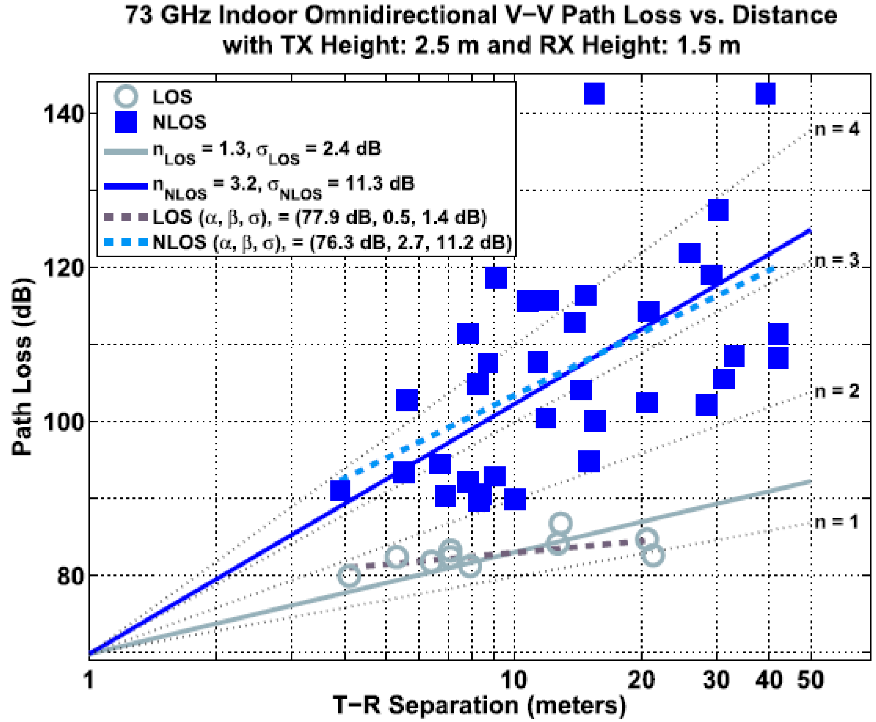


[Source: Rappaport *et al*, IEEE ACCESS, December 2015.]

5G Key Enabling Technologies

Propagation channel » indoor office





[Source: Rappaport *et al*, IEEE ACCESS, December 2015.]

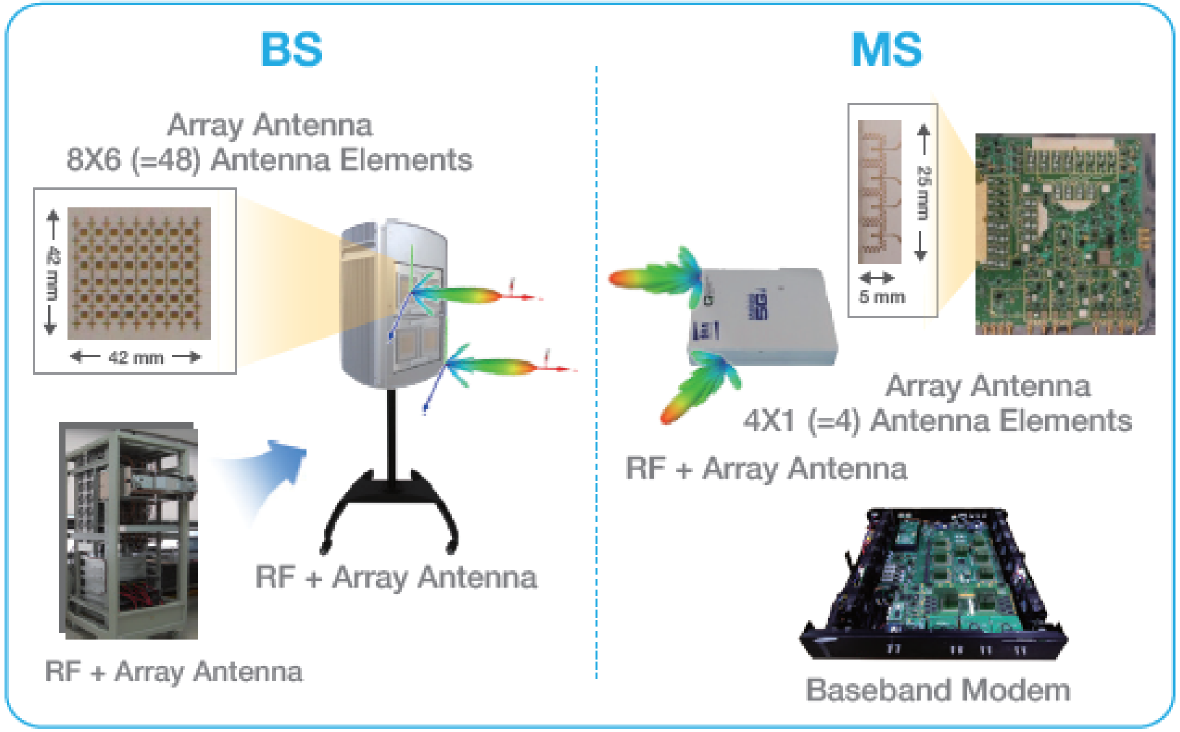
5G Key Enabling Technologies

Propagation channel » Key challenge: RANGE

- Friis' Law: $$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$$
  - Path loss can be overcome with beamforming, independent of frequency!
- Shadowing: Significant transmission losses possible:
  - Brick, concrete > 35 dB
  - Human body: Up to 35 dB
  - But channel is rich in scattering and reflection, even from people
- It works! NLOS propagation uses reflections and scattering
  - Rappaport, et. al, "Millimeter wave mobile communications for 5G cellular: It will work!" IEEE Access, 2013

5G Key Enabling Technologies

Antenna systems » Adaptive Pencil Beamforming



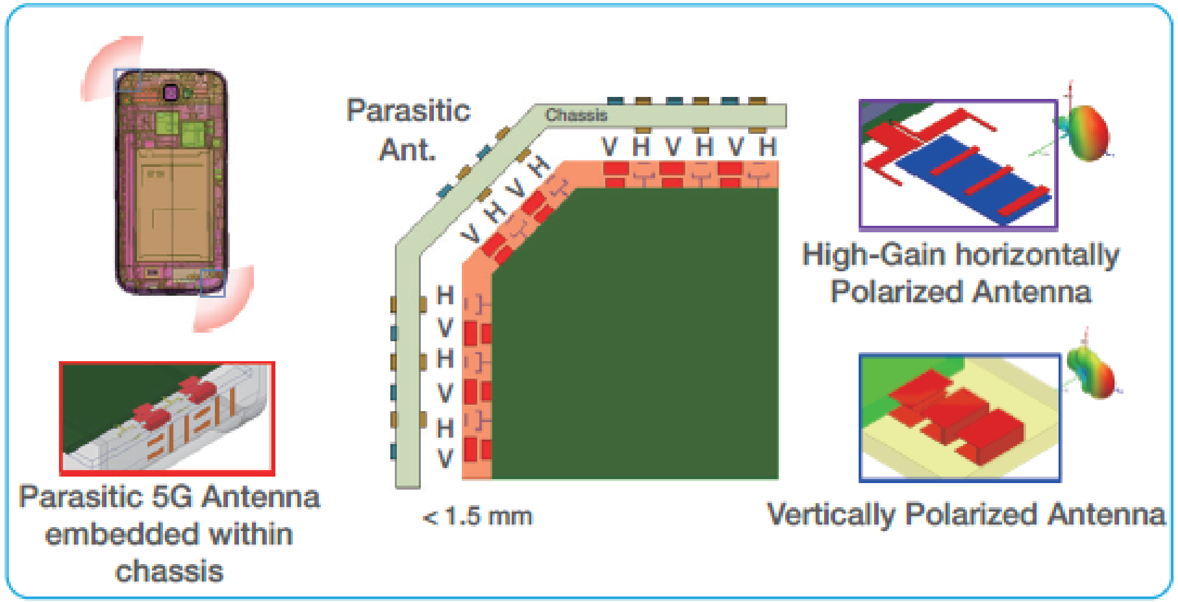
[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

Simulation Results:

- 4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage;
- 8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage;
- Outage can be reduced by denser cells, smart repeaters/relays

5G Key Enabling Technologies

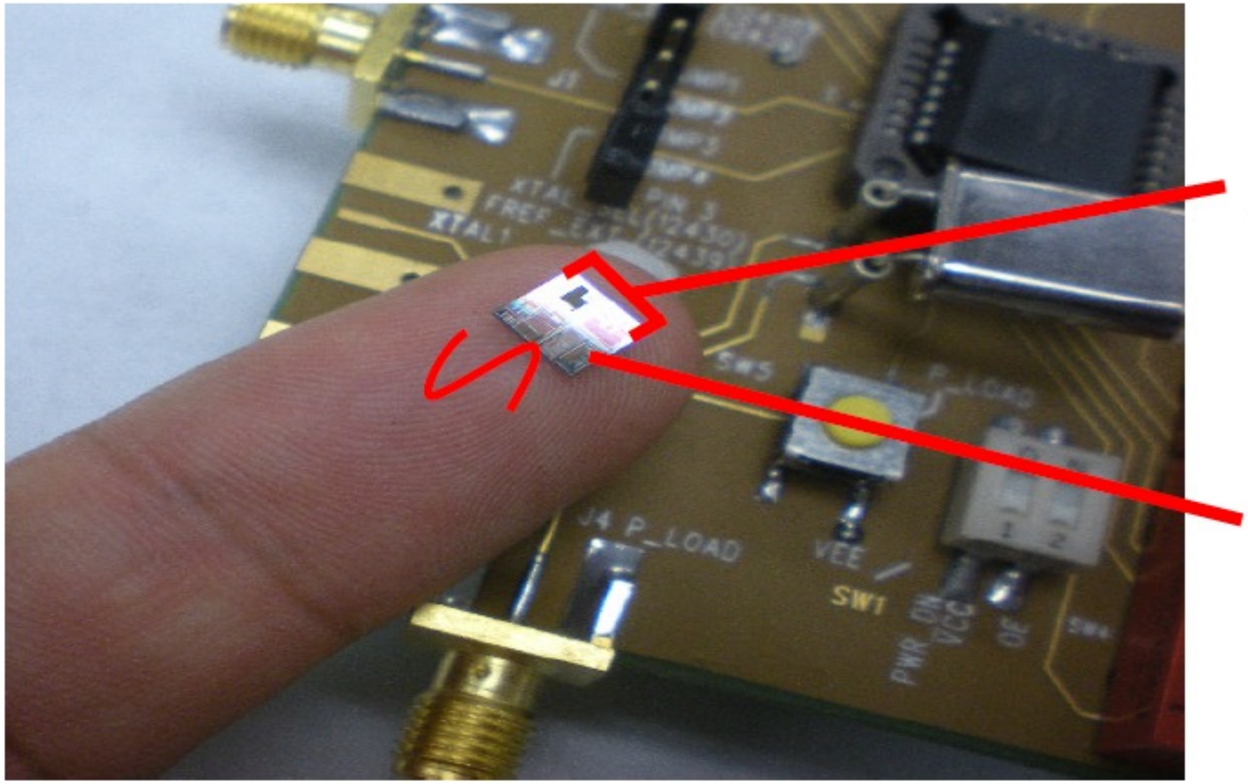
Antenna systems » Reconfigurable 5G Phased-array Antenna



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Key Enabling Technologies

Antenna systems » Reconfigurable 5G Phased-array Antenna



5 millimeters
16 antennas

Integrated Circuit

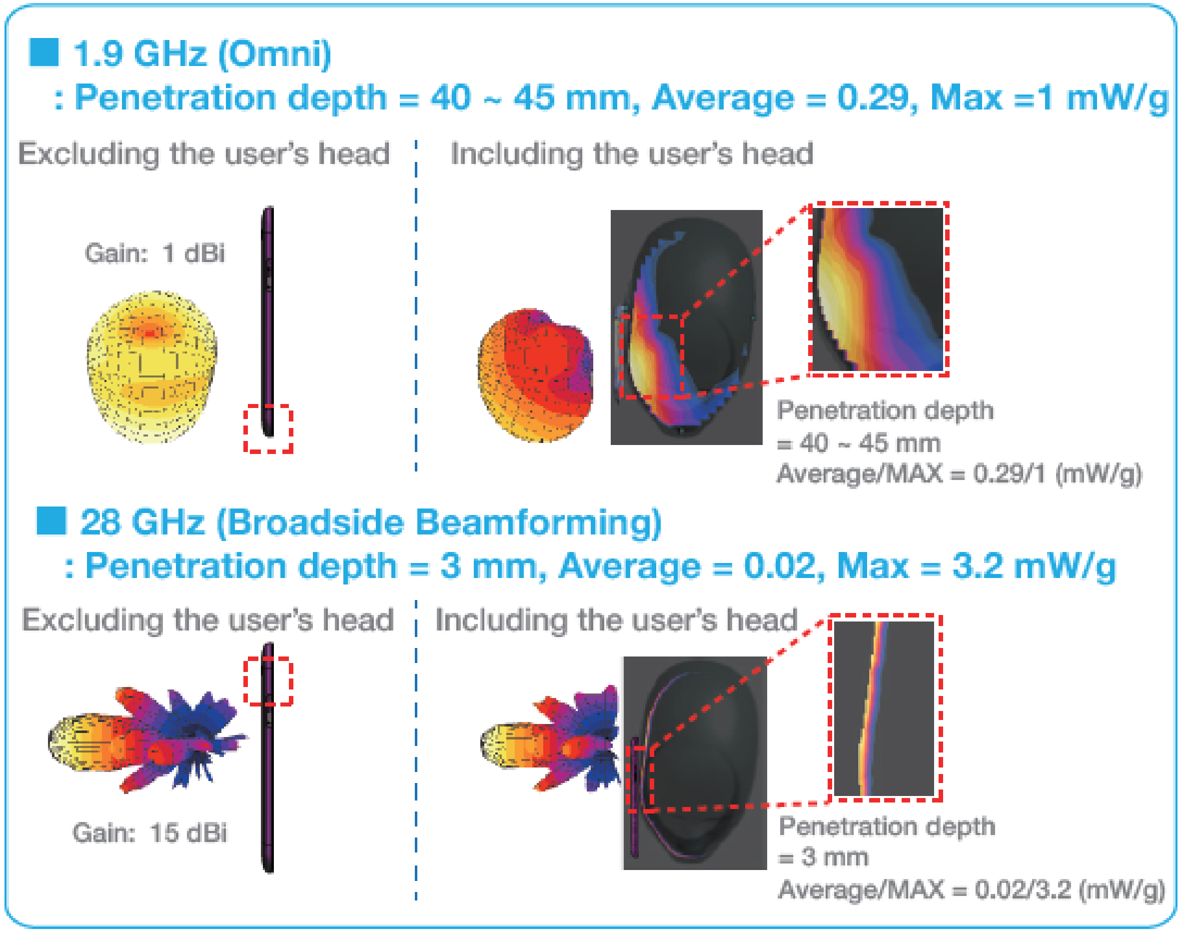
INSTITUIÇÕES ASSOCIADAS

IPL instituto politécnico de leiria

instituto de telecomunicações

5G Key Enabling Technologies

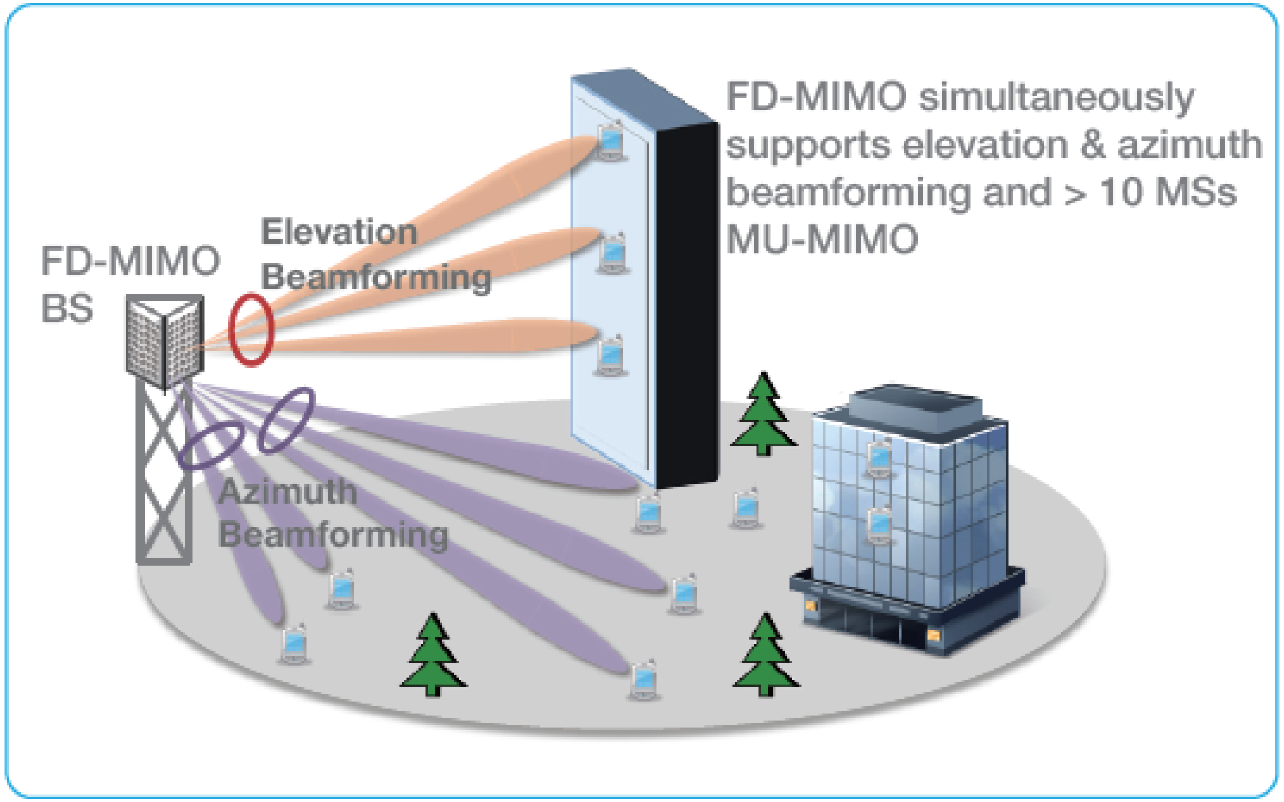
Antenna systems » Biological Implications on the User's Body



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

5G Key Enabling Technologies

Antenna systems » Full-Dimension (FD) MIMO Deployment



[Source: Samsung electronics “5G Vision”, White Paper [Online] 2015.]

5G Key Enabling Technologies

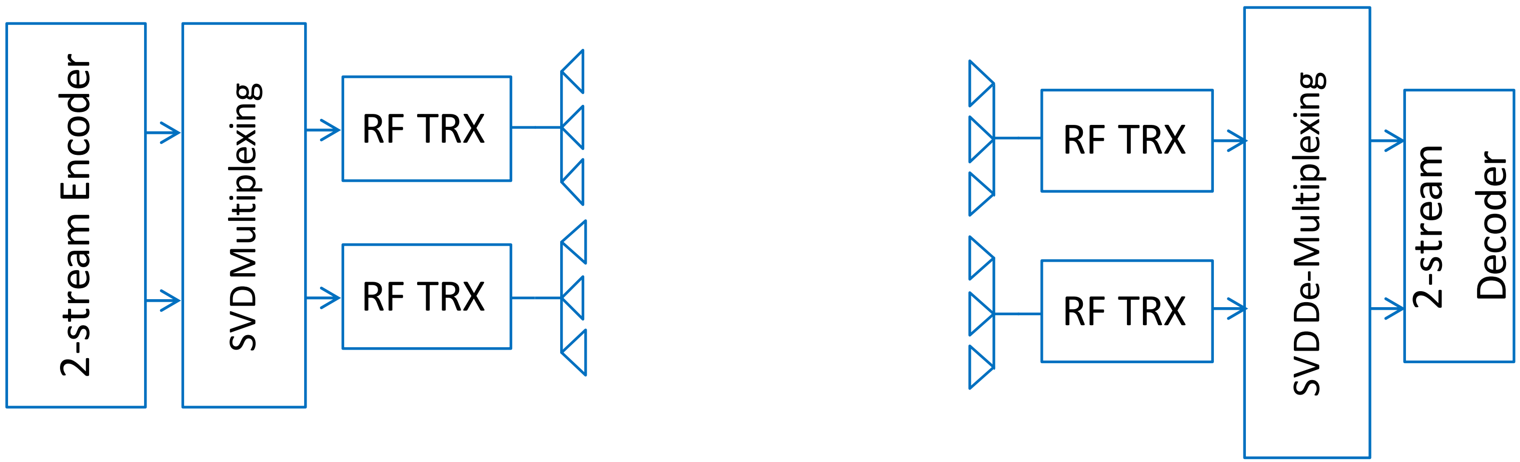
Antenna systems » Applicability of MIMO to mmWave

- A 2x2 mmWave system deploys 2 TX arrays and 2 RX arrays.
    - *Each array may have N elements, but only two data feeds are available.*
- Each array has a programmable phase shifter that can be leveraged to change the MIMO channel seen by the 2x2 system.
    - *A major difference with sub-5GHz systems where omni elements are used;*
    - *Additional knob available through changing array patterns.*

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

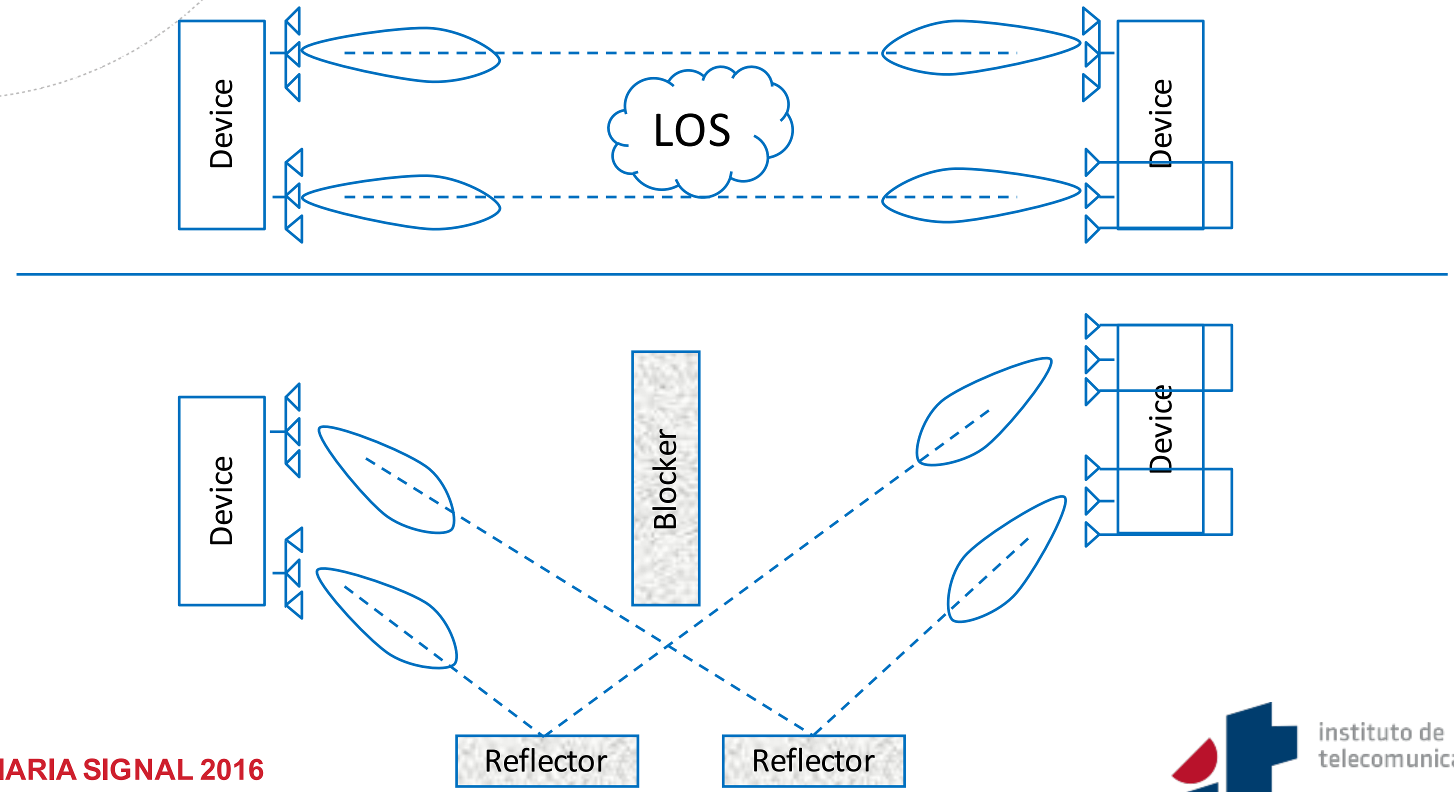
- Scenario 1: SVD Multiplexing (SM)
  - *Form a 2x2 MIMO System*
  - *Apply SVD with/without waterfilling*
  - *Due to narrow beam patterns, the propagation will look like a LOS (AWGN) MIMO channel.*
  - *Can we expect a significant multiplexing gain in LOS (AWGN) MIMO channels?*



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

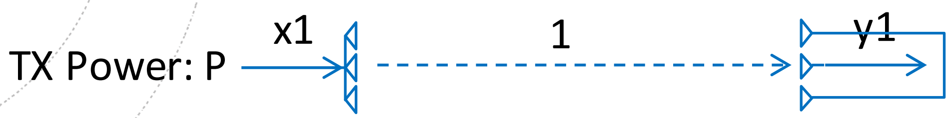
- Scenario 1: SVD Multiplexing (SM)
  - *Two example usage cases*
  - *High cross-interference between the streams (LOS MIMO & AWGN MIMO scenarios)*
  - *These two scenarios can be common in outdoor deployments.*



5G Key Enabling Technologies

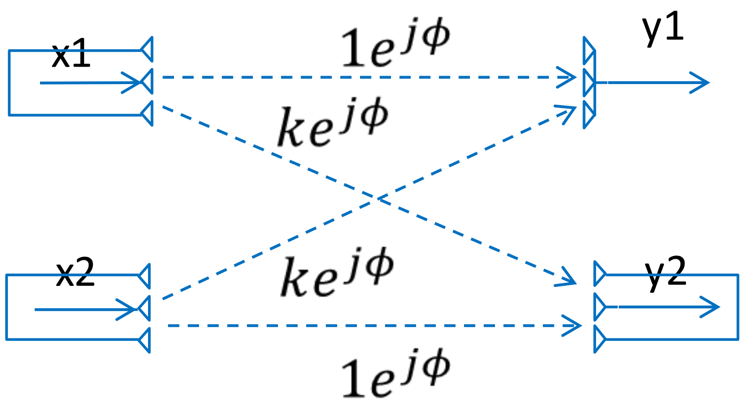
Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)
  - ***SISO Capacity***



$$C_{SISO(P)} = \log(1 + \frac{P}{N})$$

  - ***Line-of-Sight MIMO Capacity***



$$C_{MIMO} = \max_{\mathbf{R_x}:Tr(\mathbf{R_x})=2P} log\left(\det\left(\mathbf{I} + \frac{\mathbf{HR_xH}^*}{N}\right)\right)$$

$$\mathbf{HH}^* = \begin{bmatrix} 1+k^2 & k\left(e^{j(+\phi_{11}-\phi_{21})} + e^{j(+\phi_{12}-\phi_{22})}\right) \\ k\left(e^{j(-\phi_{11}+\phi_{21})} + e^{j(-\phi_{12}+\phi_{22})}\right) & 1+k^2 \end{bmatrix}$$

Above C_{MIMO} can be realized through SVD when CSI is available at TX.

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

  - ***MIMO capacity will depend on the following value:***

    Phase delta (function of distance): $\phi_d = +\phi_{11} - \phi_{12} + \phi_{22} - \phi_{21}$

  - ***MIMO capacity without waterfilling:***

$$C_{MIMO} = log\left(\left(1 + \frac{P}{N}(1 + \mathrm{k}^2)\right)^2 - 2\left(k\frac{P}{N}\right)^2 (1 + \cos(+\phi_{11} - \phi_{12} + \phi_{22} - \phi_{21}))\right)$$

  - ***MIMO capacity with waterfilling***

$$C_{MIMO} = \max_{P_i:\mathrm{sum}(P_i)\leq 2P} \sum_i log\left(1 + \frac{P_i}{2P}\gamma_i\right)$$

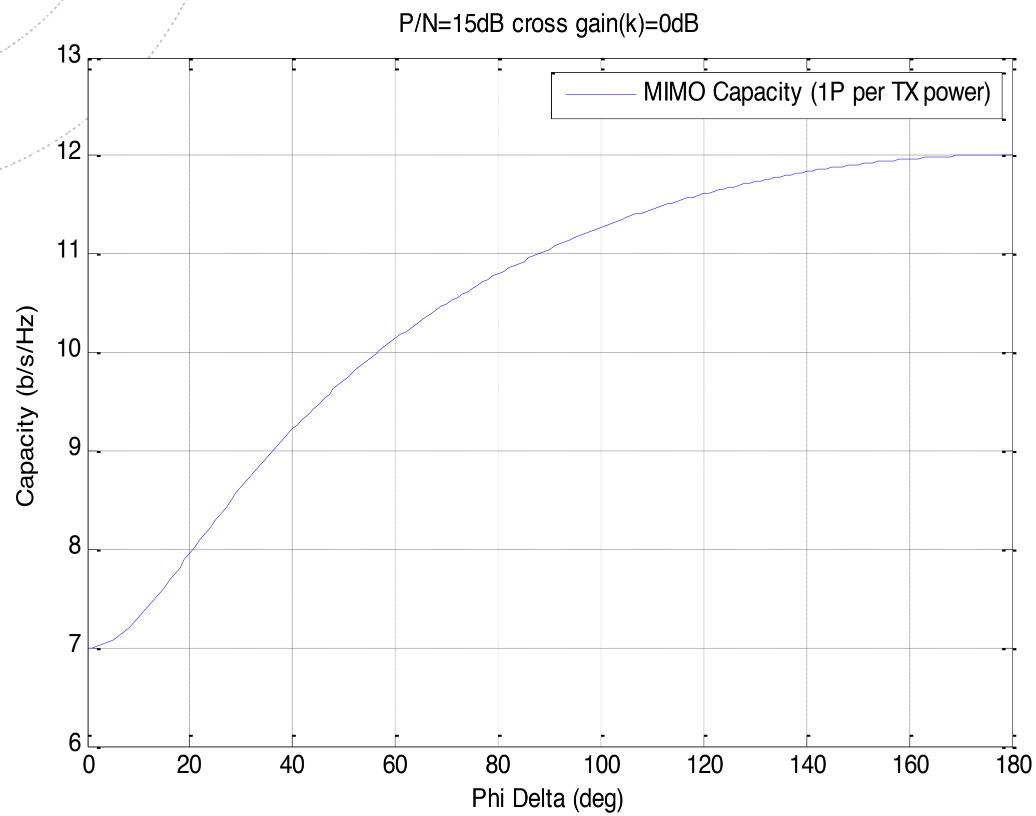
Where $\gamma_i = \frac{2P}{N} e_i$, and e_i are the eigenvalues of $\mathbf{HH}^*$

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

  - ***MIMO Capacity vs Phase Delta ϕ_d***

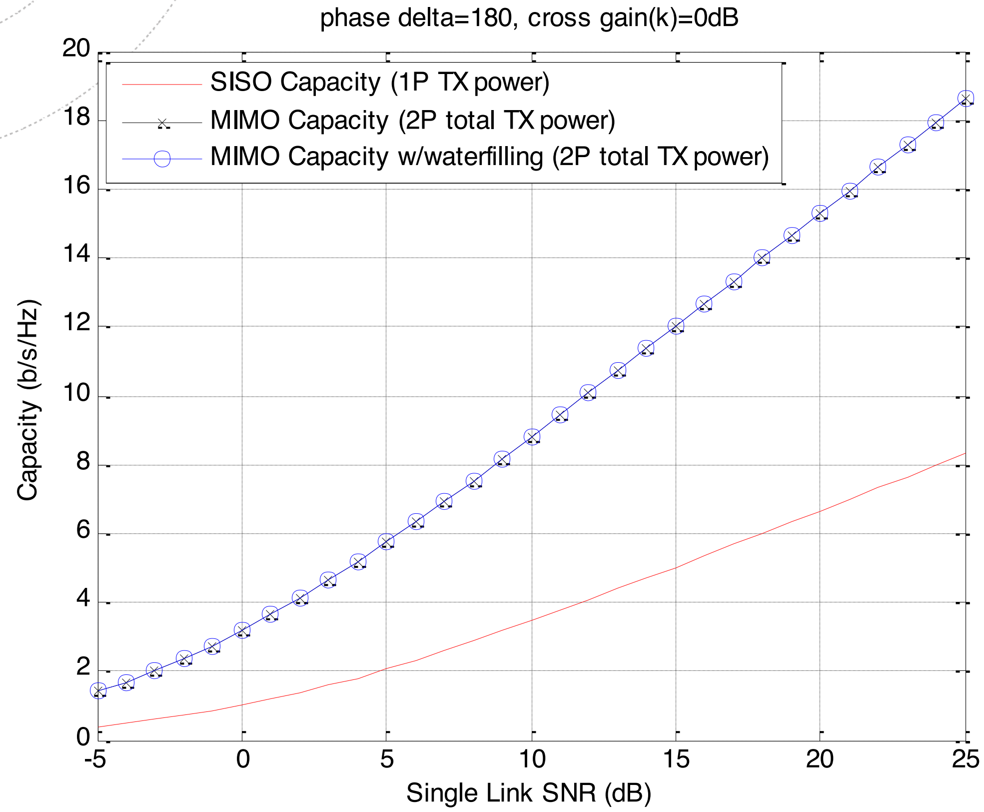


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

  - ***Phase delta=180 deg (maximizes capacity)***
  - ***K=0dB***

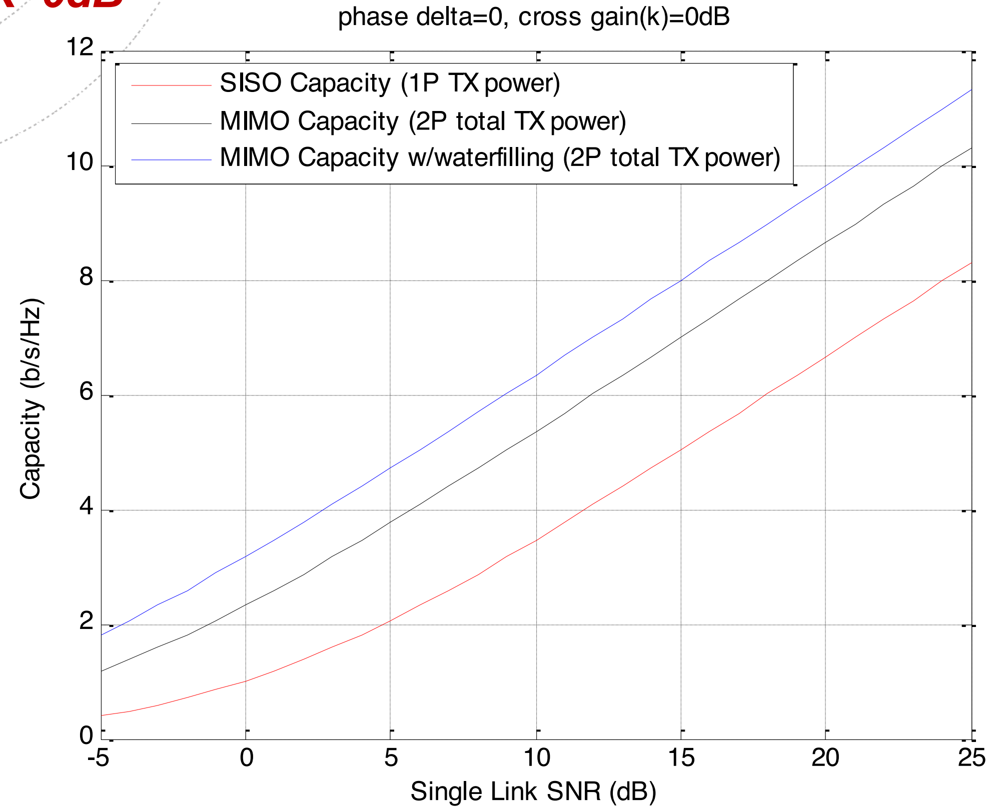


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

  - ***Phase delta=0 deg (minimizes capacity)***
  - ***K=0dB***

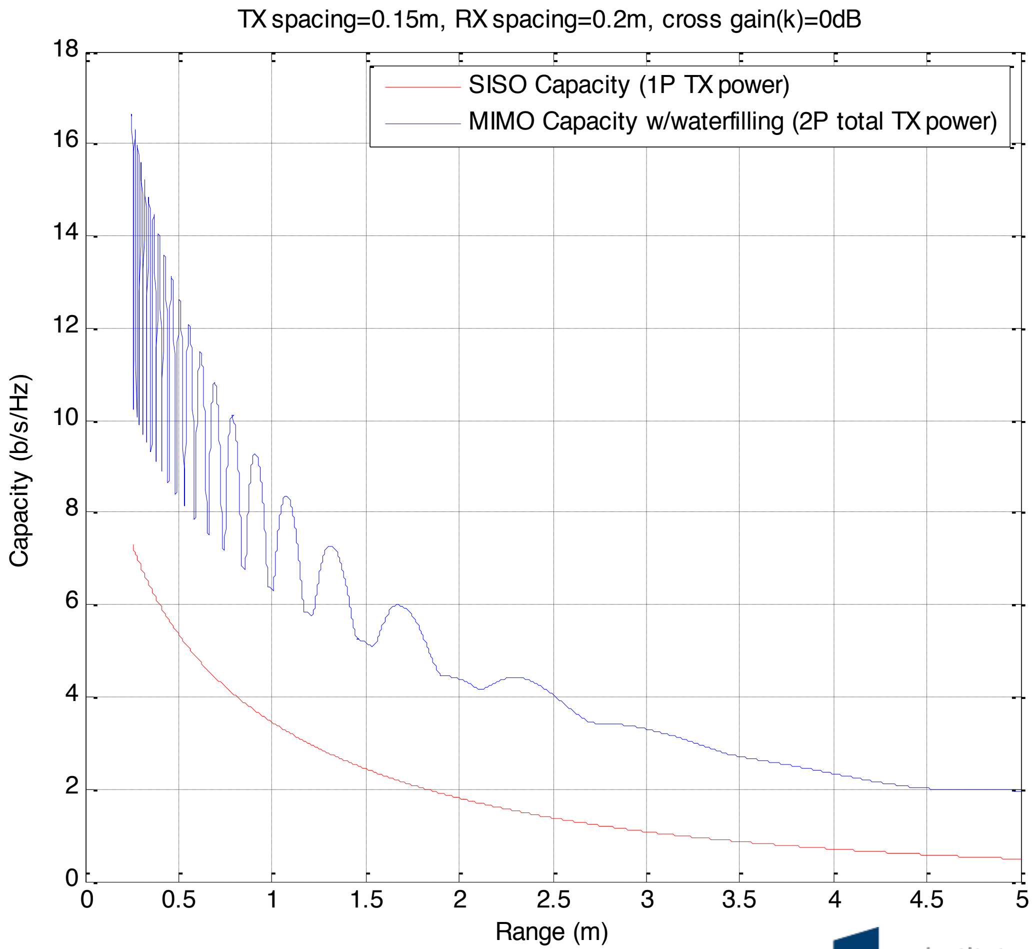


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

- **TX arrays spacing=15cm**
- **RX arrays spacing=20cm**
- **K=0dB**
- **Short range (small # of elements)**

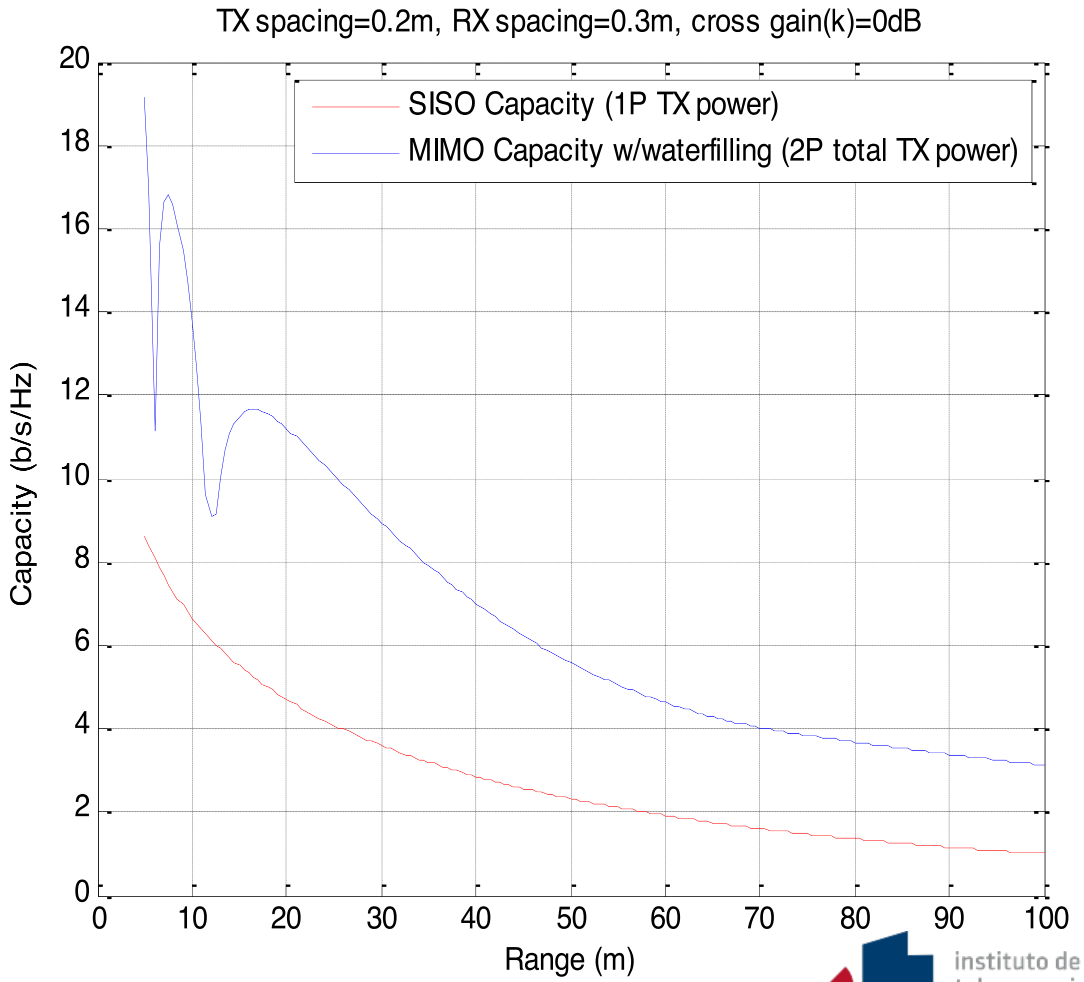


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 1: SVD Multiplexing (SM)

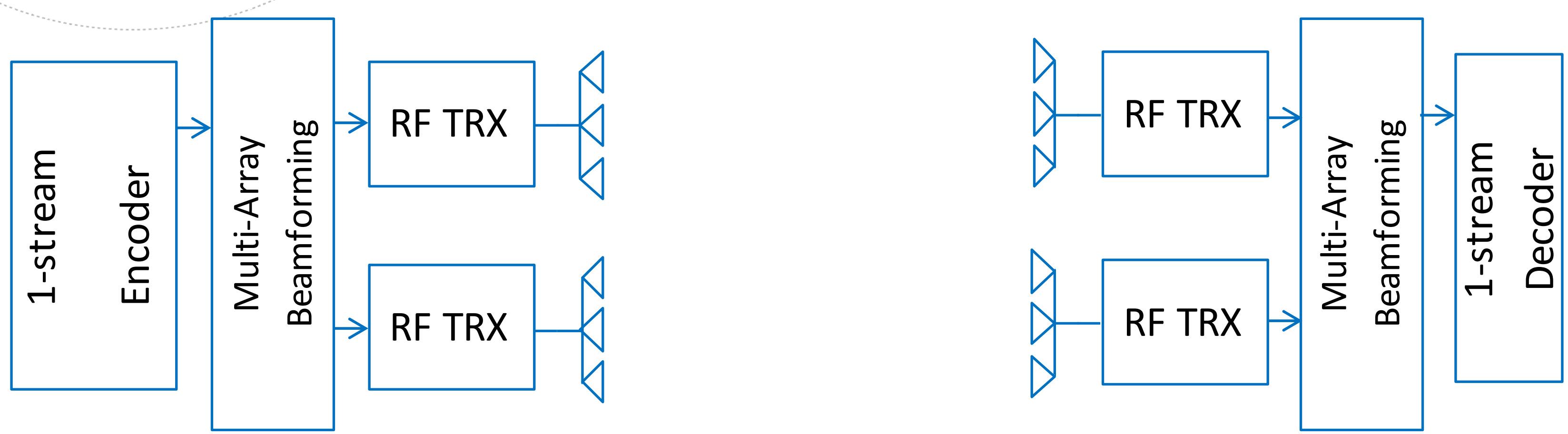
- **TX arrays spacing=15cm**
- **RX arrays spacing=20cm**
- **K=0dB**
- **Long range (high # of elements)**



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

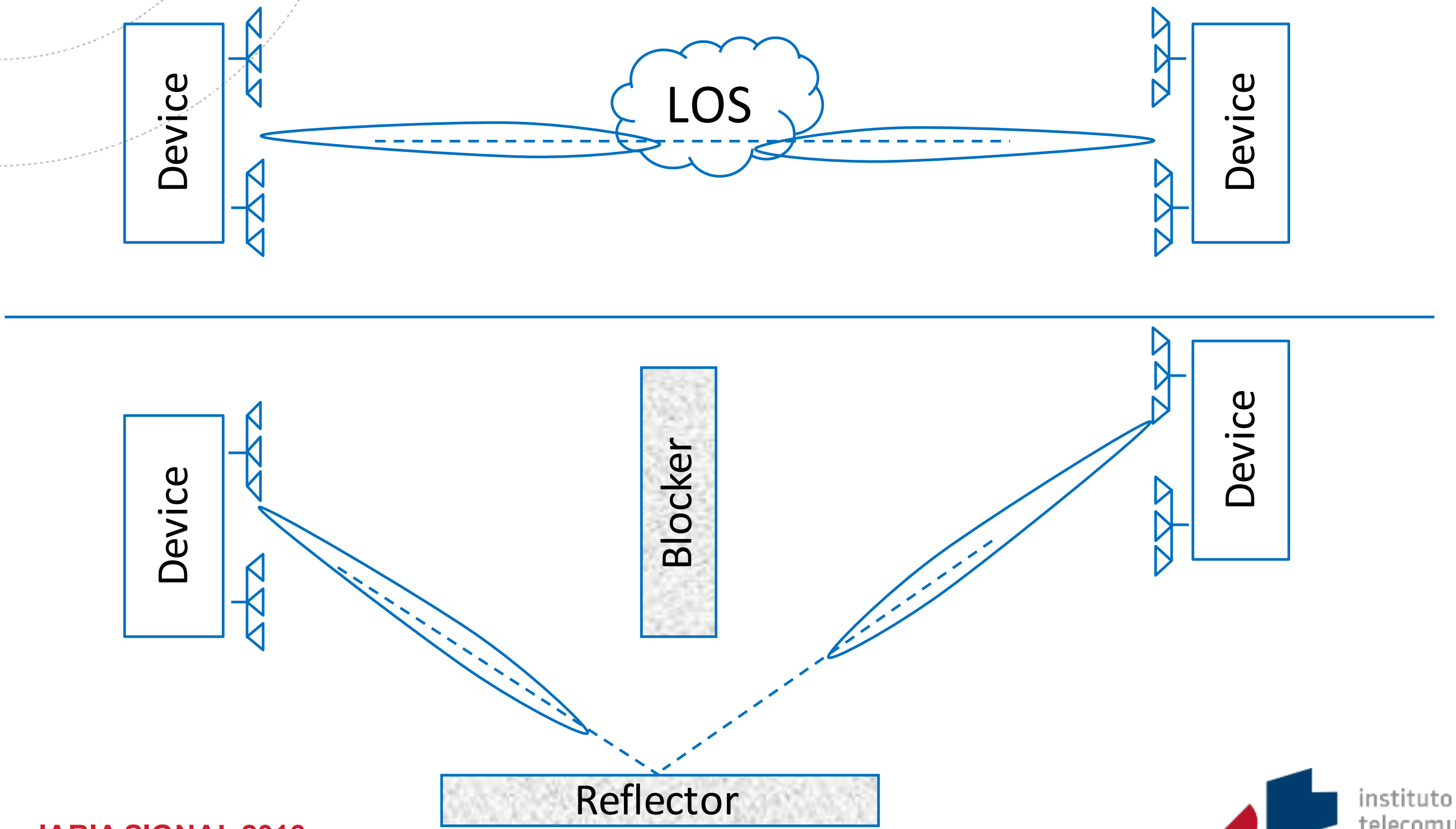
- Scenario 2: Multi-Array Beamforming (MAB)
  - *Form a larger single array by phase-aligning the two arrays*
  - *Transport a single stream at higher SNR*
    - 2 TX arrays and 2 RX arrays: 9dB higher total SNR compared to SISO case



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

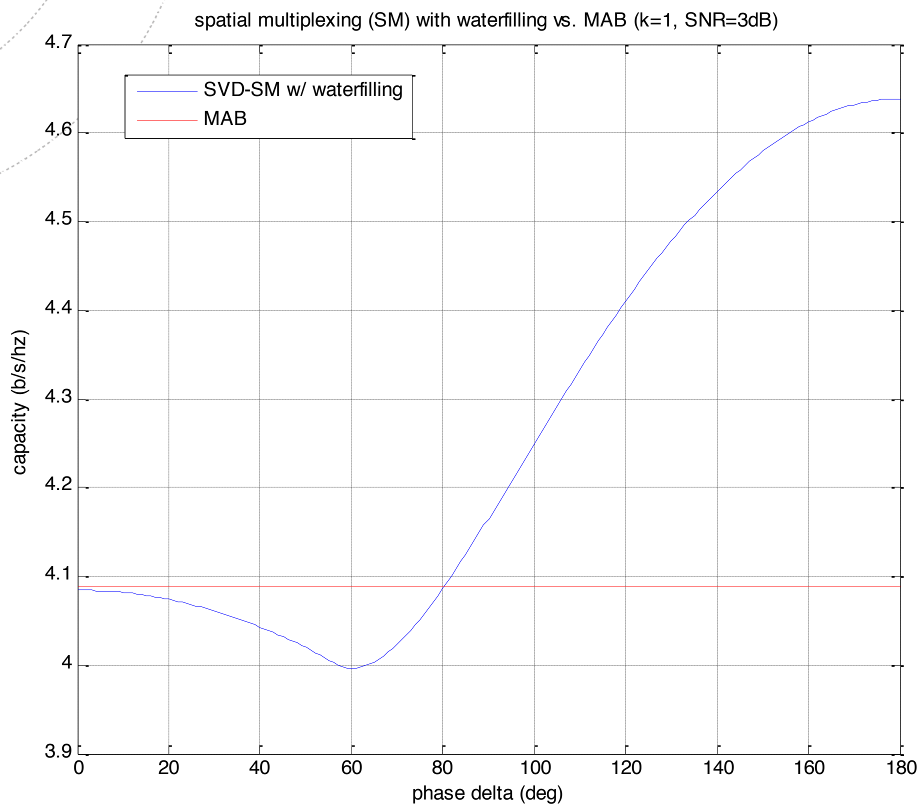
- Scenario 2: Multi-Array Beamforming (MAB)
  - *Two example usage cases*
  - *9 dB SNR gain compared to single array case (6 dB from TX and 3 dB from RX)*



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

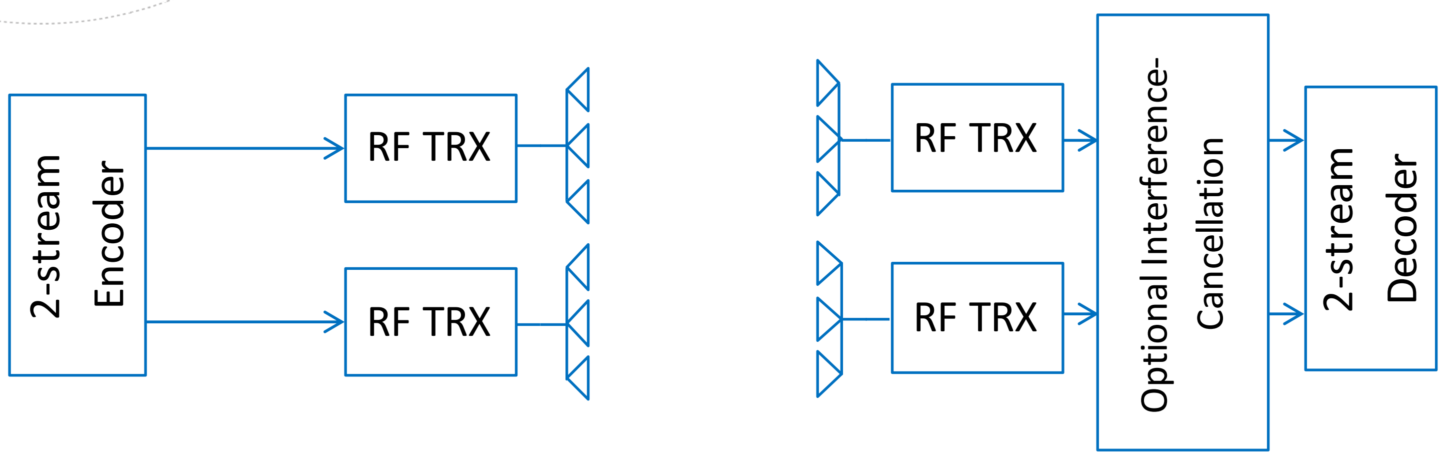
- Scenario 2: Multi-Array Beamforming (MAB)
  - *SVD-Multiplexing can reach MAB performance at low SNR only with the help of waterfilling*



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 3: Spatial Aggregation (SA)
  - *SVD can be eliminated if sufficiently separated beams can be identified.*
  - *Simplified TX and RX implementation*
  - *May be defined as a baseline MIMO mandatory mode (while making SVD-Multiplexing optional)*



INSTITUIÇÕES ASSOCIADAS

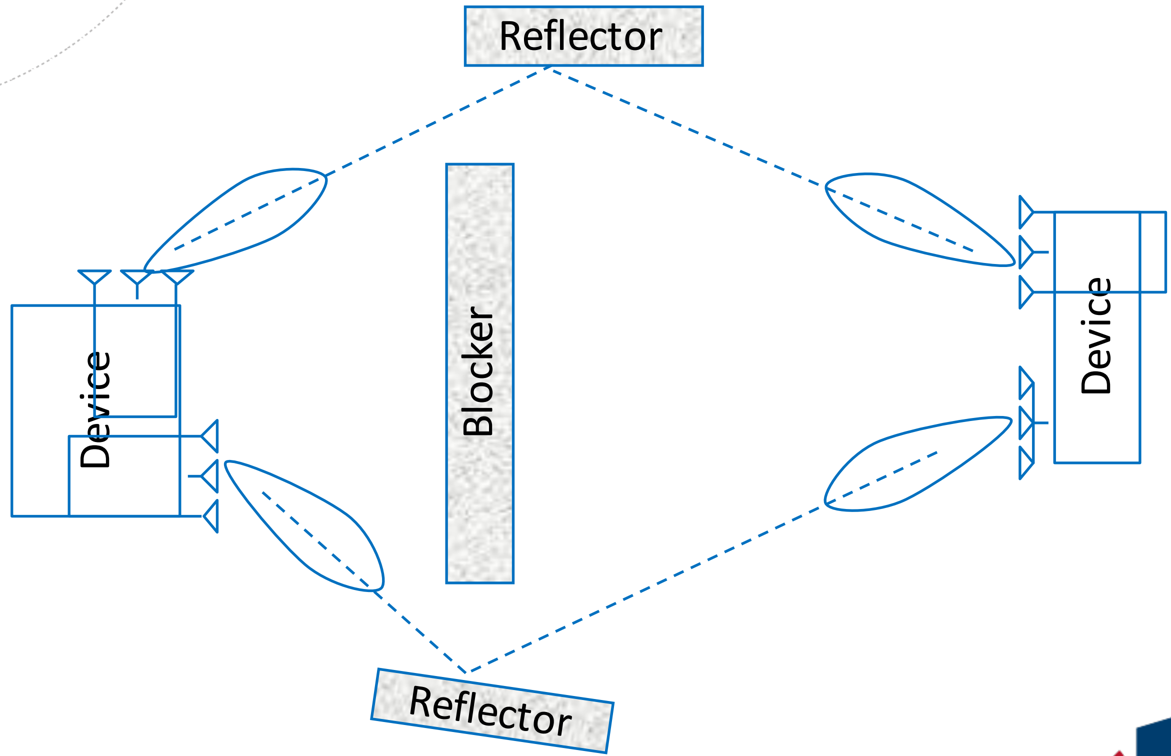
IPL instituto politécnico de leiria

instituto de telecomunicações

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

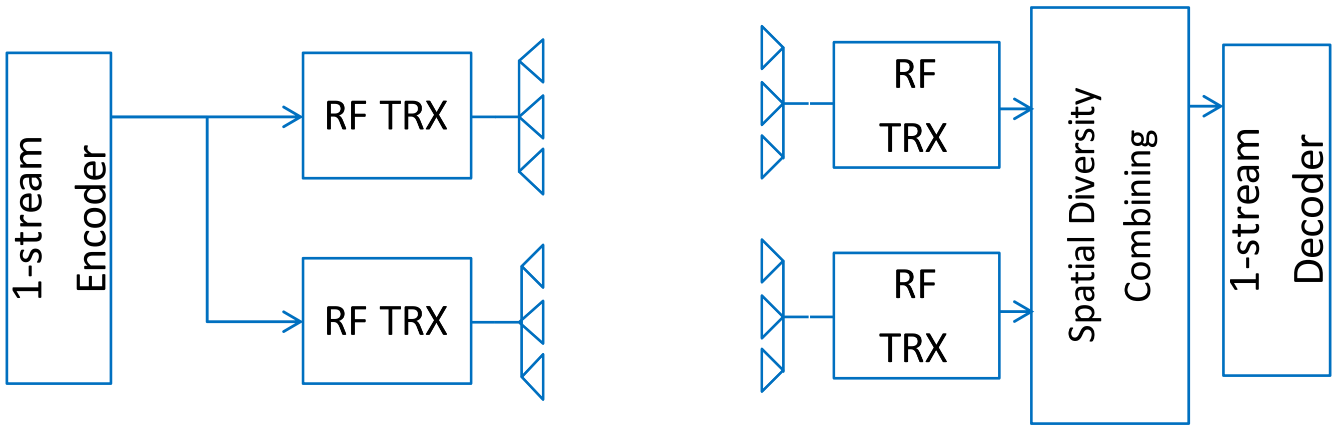
- Scenario 3: Spatial Aggregation (SA)
  - *Example usage case*
  - *SA is a subset of SVD-Multiplexing*
  - *Use of interference cancellation in RX side is implementation and vendor choice.*



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 4: Multi-Array Diversity (MAD)
  - *Transport the same streams across two arrays.*
  - *A sub-optimal configuration to MAB when MAB is not applicable.*
    - SNR is low for significant gain out of SVD-SM
    - Link reliability/redundancy is a key metric
    - Cross-interference between the multiple beams is relatively high
  - *3dB diversity/energy combining gain compared to a single array case.*

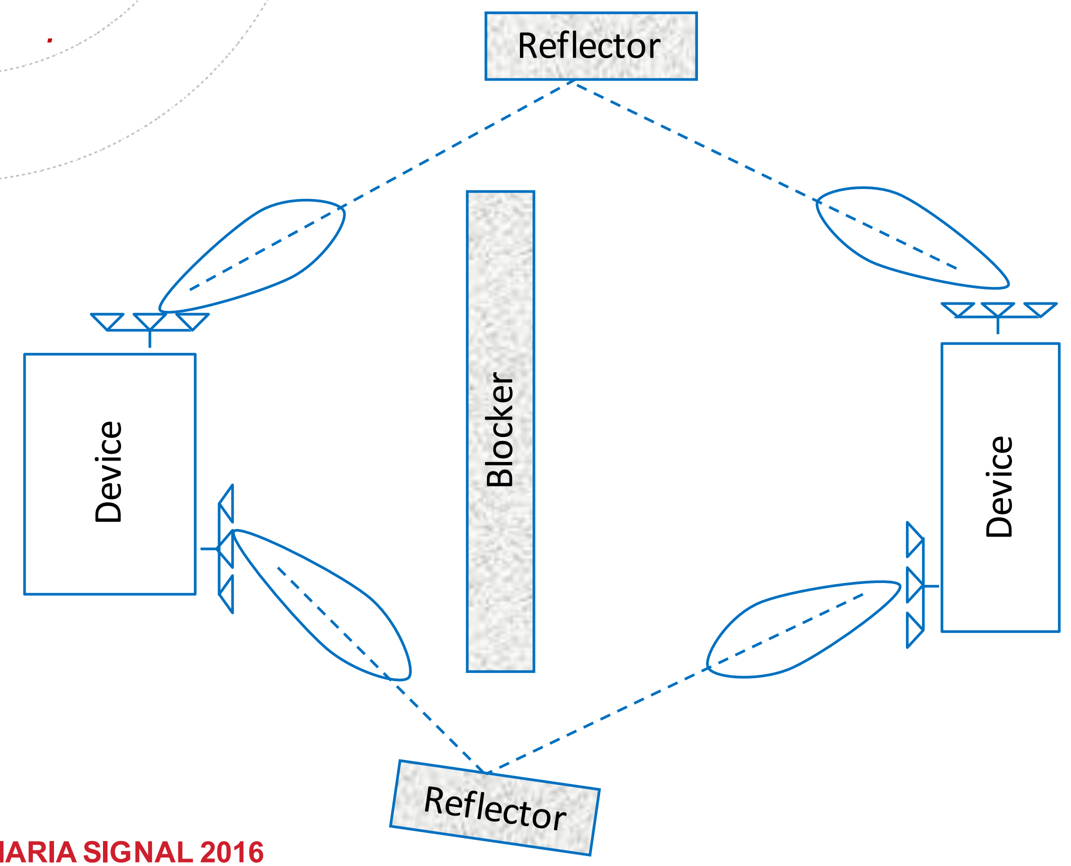


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Scenario 4: Multi-Array Diversity (MAD)
  - *Example usage case*
    - Simple reliability improvement
    - Energy combining gain.

.



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Summary of MIMO Scenarios

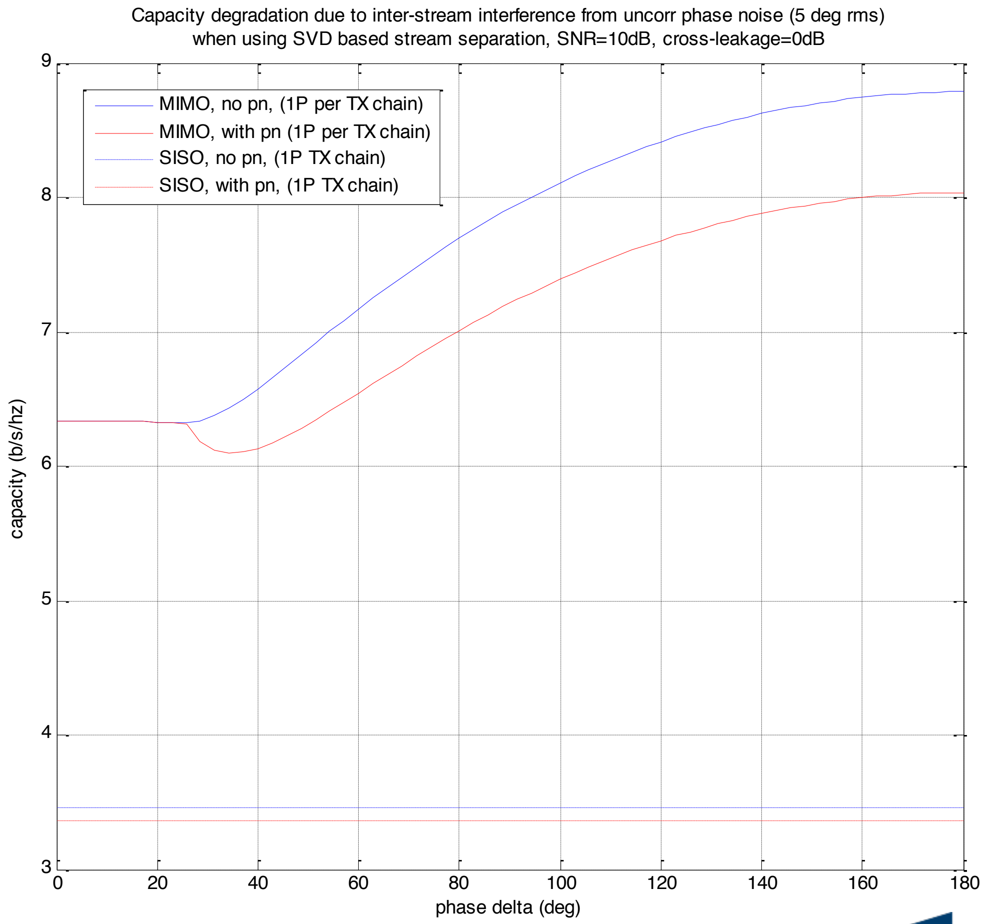
Mode	Number of data streams (Constellation -Level)	True MIMO Coding	Improved Merit of Figure	Some applicable usages
SVD Multiplexing (SM) - Closed Loop using CSI	Two	Yes	Throughput	Backhaul capacity, adjacent arrays, high SNR, polarization multiplexing
Multi-Array Beamforming (MAB)	Single	No	SNR	Backhaul range, adjacent arrays, low SNR
Spatial Aggregation (SA) -Open Loop	Two	No	Throughput	Indoor/Outdoor, polarization multiplexing when good separation available
Multi-Array Diversity (MAD)	Single	No	SNR	Indoor, distant arrays

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Phase Noise Impact on SVD Multiplexing

Integrated uncorrelated phase noise = 5deg



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

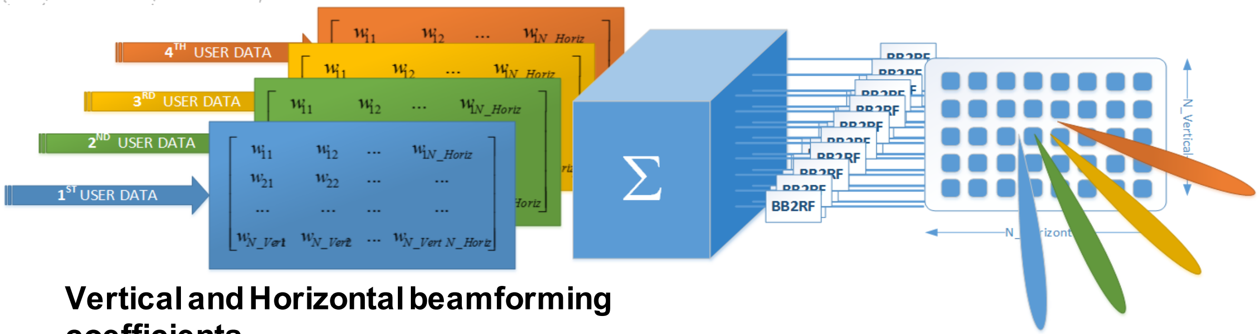
- All four "multi-radio" scenarios can be implemented using a common PHY standard framework.
- Possible standard framework:
  - *Ability to generate 2 to 4 independent streams (no cross coding)*
    - Enables two modes of operation: transport data streams over the same frequency channel (spatial aggregation) or over different frequency channels (carrier aggregation)
  - *Ability to apply some form of "SVD coding" to generate 2 to 4 coded data streams*
  - *This "waveform generation" framework enables following usages: SVD multiplexing (LOS/AWGN MIMO), polarization multiplexing, multi-array beamforming, spatial aggregation, carrier aggregation, multi-array diversity.*

	Same channel	Different channels
No TX cross-coding	Spatial aggregation	Carrier aggregation
TX cross-coding	SVD multiplexing	N/A

5G Key Enabling Technologies

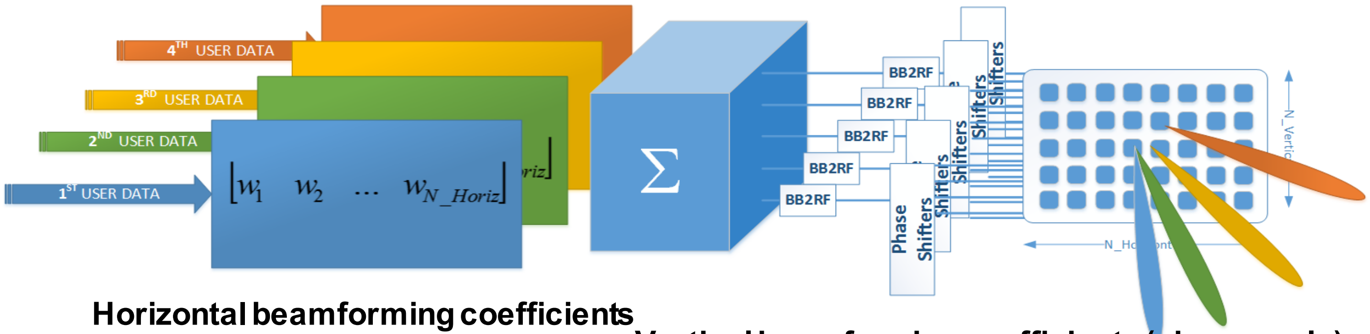
Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *Fully adaptive array (**FAA**) requires one RF chain per each antenna element*



Vertical and Horizontal beamforming coefficients

  - *Modular antenna array (**MAA**) implements the hybrid beamforming technique: coarse analog beamforming using RF phase shifters in sub-arrays and fine beamforming in the BB*



Horizontal beamforming coefficients

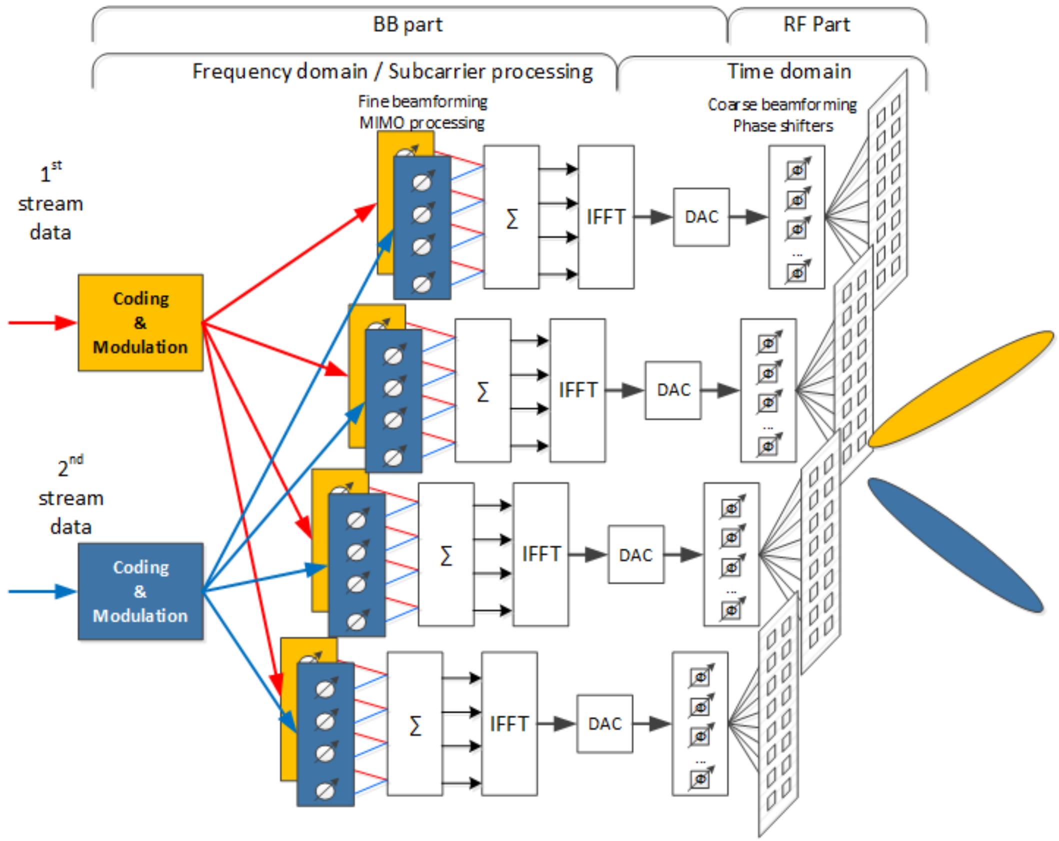
Vertical beamforming coefficients (phases only)

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *MAA MU-MIMO mode implementation: Hybrid beamforming*

- The Hybrid beamforming on the base of the MAA reduces the number of RF chains
- Coarse analog RF beamforming is the same for entire BW
- Fine beamforming (MIMO processing) in BB may be performed for OFDM mode in frequency domain (per subcarrier or per subband)

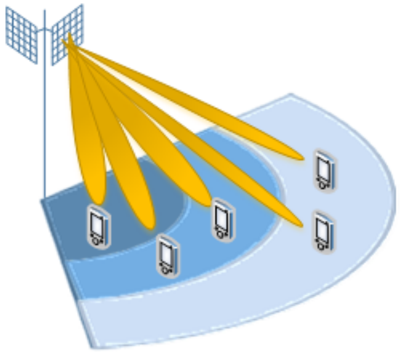


INSTITUIÇÕES ASSOCIADAS
IPL instituto politécnico de leiria
instituto de telecomunicações

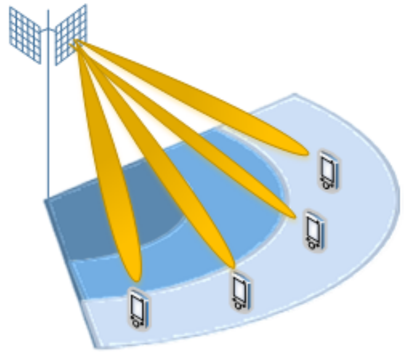
5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *MAA vs. FAA in MU-MIMO mode*
    - FAA allows flexible UE grouping for MU scheduling over the whole cell without limitations
    - MAA with vertical sub-array modules placement allows coarse elevation angle adjustment (by phase shifters) and fine horizontal separation by BB processing:
      - There is almost no difference between FAA and MAA in SU mode
      - In MU-MIMO mode due to limited ability for beam adjustment in elevation, all UEs in MU group should exploit the beams with same elevation angles → MU groups should be arranged by distance from AP (ring structure)



MU grouping with FAA: whole cell



MU grouping with MAA: ring placement

5G Key Enabling Technologies

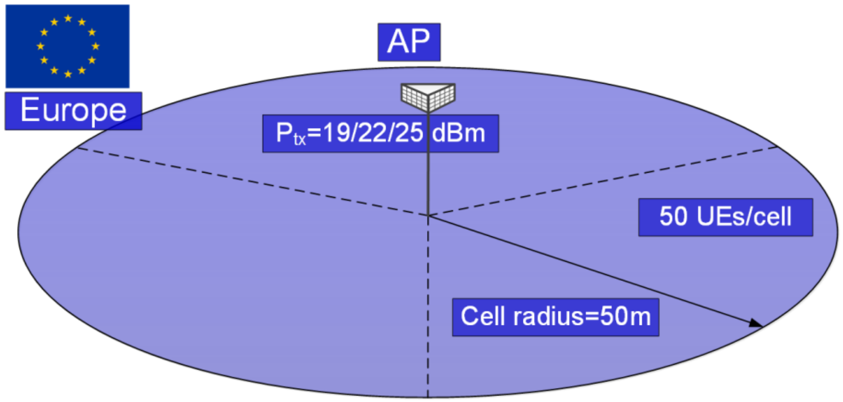
Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *DL MU-MIMO performance evaluation*
    - Basic scenario: outdoor hot-spots
    - Difference in emission regulations in different countries requires:

European: EIRP is limited to **41 dBm**

» Such limitation lead to cell radius up to 100m, with 50m near-optimal value

» 50 UE/cell selected for small cell with 50m radius (1 UE per $50m^2$)

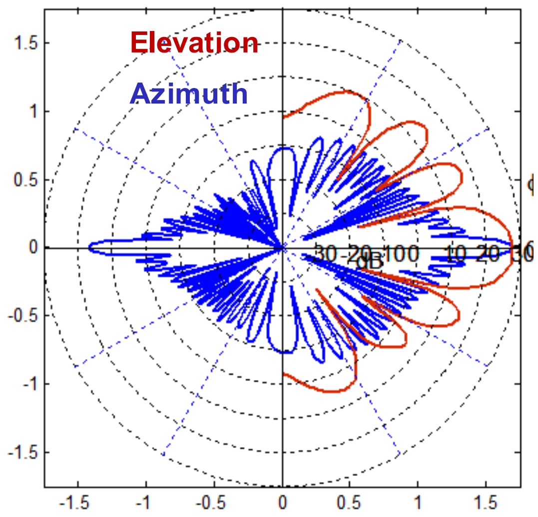


5G Key Enabling Technologies

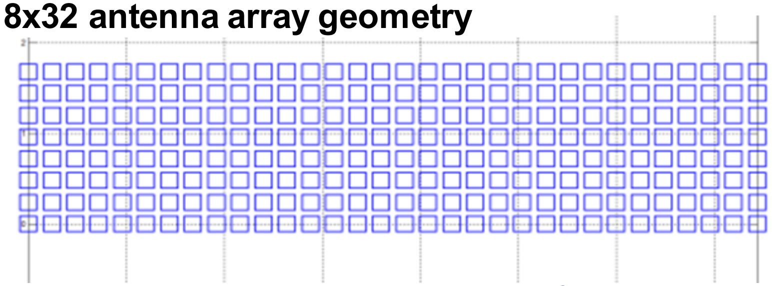
Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *DL MU-MIMO performance evaluation*
    - AP antenna arrays configurations
      - 8x16, 8x32 and 8x64 antenna arrays configurations used in the simulations
      - For the case of modular array (MAA) 8x1 elements sub-array modules placed vertically
      - For MAA elevation adjustment was performed by phase shifters only, while azimuth steering and MIMO processing performed in the BB for 16, 32 and 64 channels respectively

Azimuthal (blue) and elevation (red) antenna patterns for zero direction

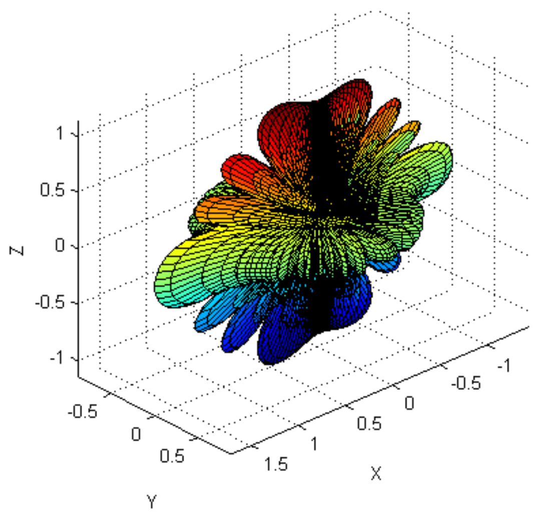


8x32 antenna array geometry



Azimuth HPBW: 3.3°
Elevation HPBW: 13°

3D antenna pattern

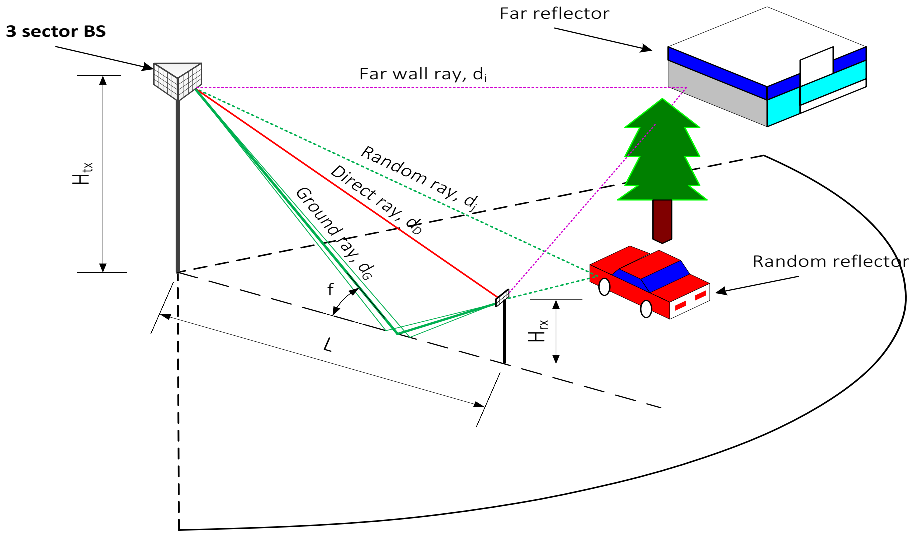


5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *DL MU-MIMO performance evaluation*
    - Open-area scenario

Parameters		Assumption
D-rays	Number	2 (LOS and reflected)
	Power	Friis / Fresnel equations
R-rays	Number	3
	Arrival rate	Poisson, 0.05 ns^{-1}
	Power decay	Exponential, 15 ns
	K-factor	10 dB
	AoA/AoD range (az., el.)	[-60°:60°; -20°:20°]
Intra-cluster rays	Number	3
	Arrival rate	Poisson, 0.3 ns^{-1}
	Power decay	Exponential, 4.5 ns
	K-factor	[9, 6] dB
	AoA/AoD range (az., el.)	[-10°:10°; -10°:10°]



5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- MU-MIMO schemes
  - *DL MU-MIMO performance evaluation*
    - Simulation results

Ant. Conf.	Ant. type	AP throughput, Gbps	
		Isolated cell	Dense hexagonal deployment
		EU scenario	**EU scenario**
8x16	FAA	8.0	5.5
	MAA	**7.0 (-12,5%)**	**4.9 (-11%)**
8x32	FAA	16.4	10.9
	MAA	**15.7 (-4%)**	**10.4 (-5%)**
8x64	FAA	32.1	21.4
	MAA	**31.1 (-3%)**	**20.5 (-4%)**

5G Key Enabling Technologies

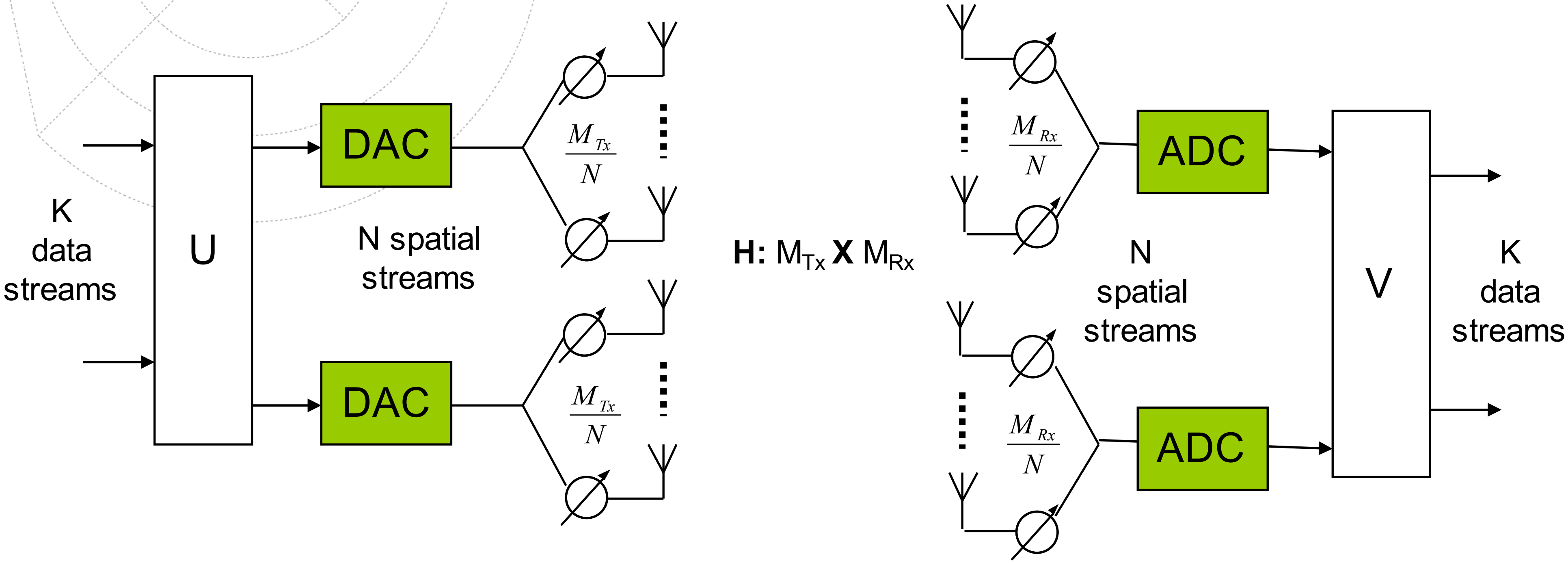
Antenna systems » Applicability of MIMO to mmWave

- Shared MIMO Architecture for 802.11ay
  - *Spatial Multiplexing Using MIMO Architecture*
    - MIMO architecture can be used to multiplex multiple data streams over different spatial streams in the wireless channel, consequently increasing the data rate
  - *Split-Array Multi-Stream Architecture*
  - *Shared-Array Multi-Stream Architecture*

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Shared MIMO Architecture for 802.11ay
  - *Split-Array Multi-Stream Architecture*



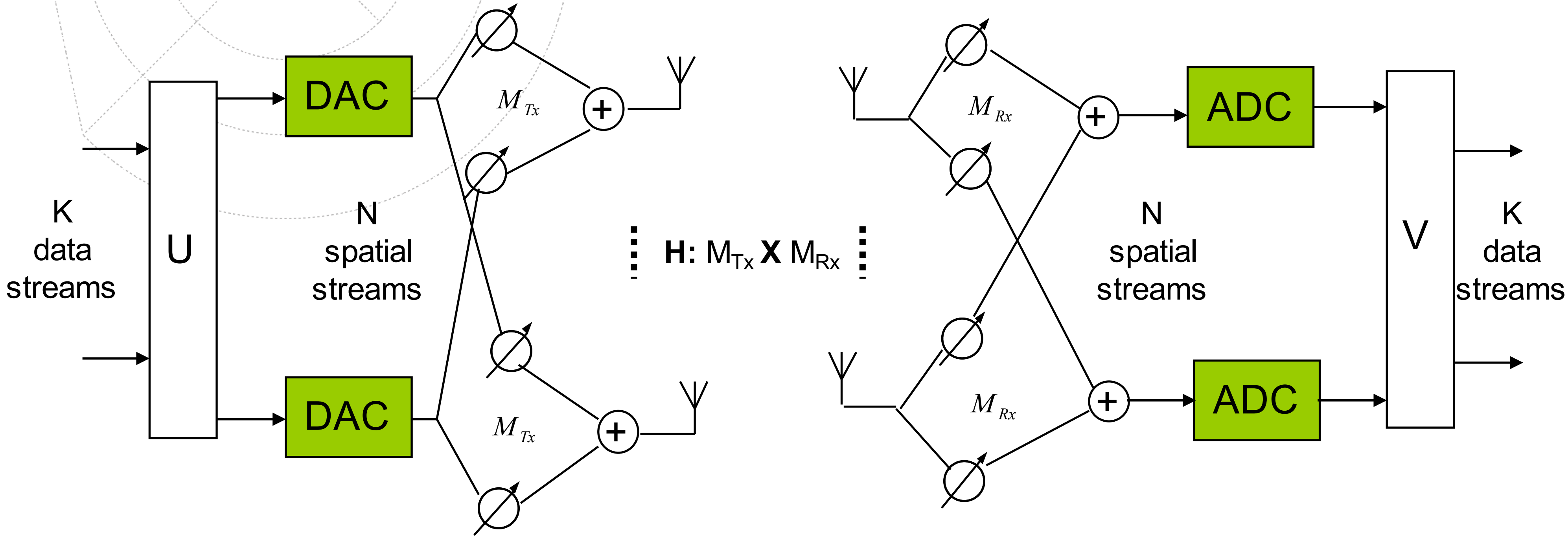
- MTx and MRx antennas split across N(xN) spatial streams such that each antenna is associated with a single spatial stream
- Effective array size for each stream is MTx/N and MRx/N
- Number of data streams may be less than number of spatial streams, K ≤ N (down to K = 1)

INSTITUIÇÕES ASSOCIADAS
IPL instituto politécnico de leiria
instituto de telecomunicações

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Shared MIMO Architecture for 802.11ay
  - *Shared-Array Multi-Stream Architecture*

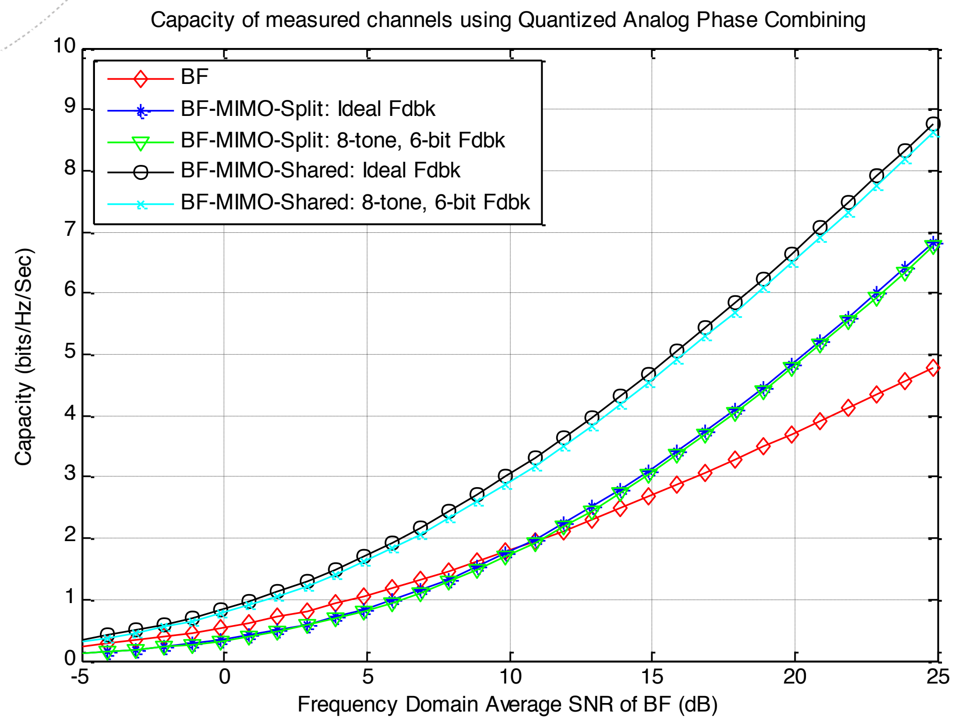


- MTx and MRx antennas shared across N(xN) spatial streams.
  - Full array used for each beam.
  - Fair comparison must assume constant total TX power per TX antenna.
- Increases number of phase shifters and associated feedback.
- More flexibility in allocating antenna groups to the streams.

5G Key Enabling Technologies

Antenna systems » Applicability of MIMO to mmWave

- Shared MIMO Architecture for 802.11ay
  - *Performance*
    - Using field-measured 60 GHz channel.
    - OFDM modulation scheme, two spatial streams over 36 antenna ($M_{Tx}=M_{Rx}=36$).
    - Shared architecture providing larger beam-forming gain per stream.

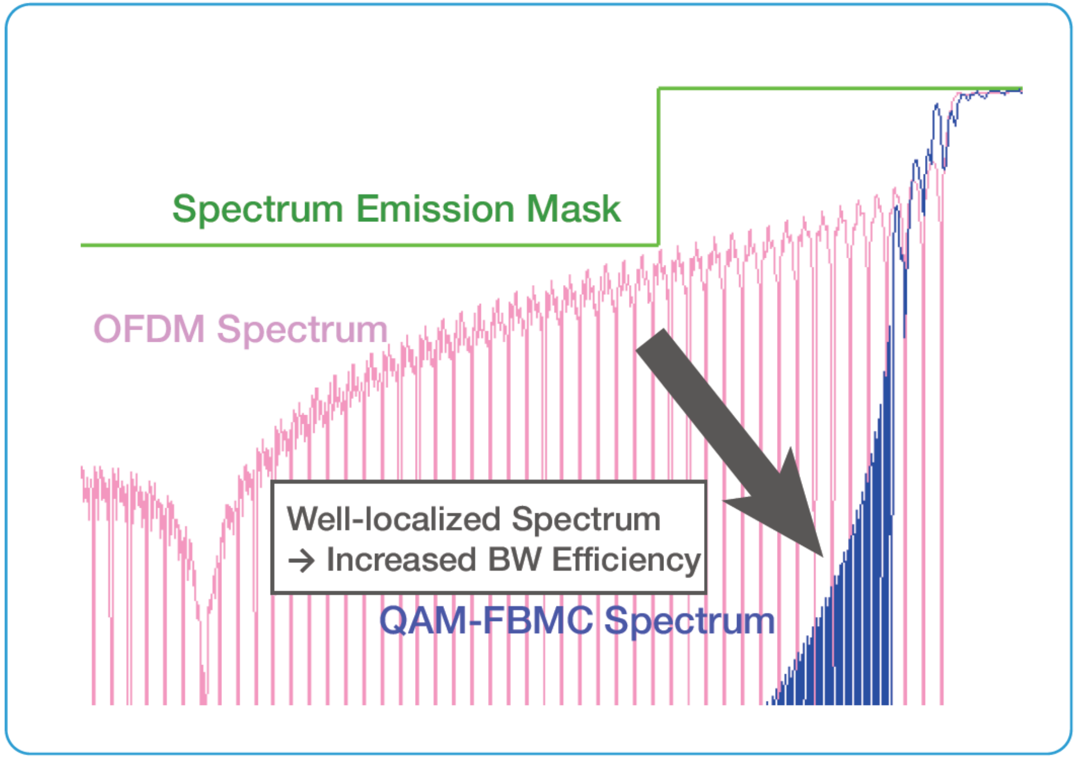


INSTITUIÇÕES ASSOCIADAS
IPL instituto politécnico de leiria
instituto de telecomunicações

5G Key Enabling Technologies

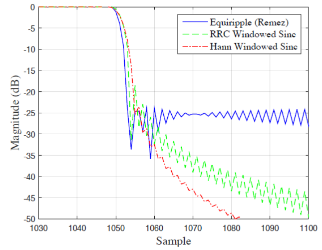
ACM & Multiple Access» New Waveforms (Post OFDM) » FBMC

- Pulse shaping per subcarrier
- Reduced Cyclic Prefix overhead
- OQAM required better channel estimation algorithms and MIMO schemes

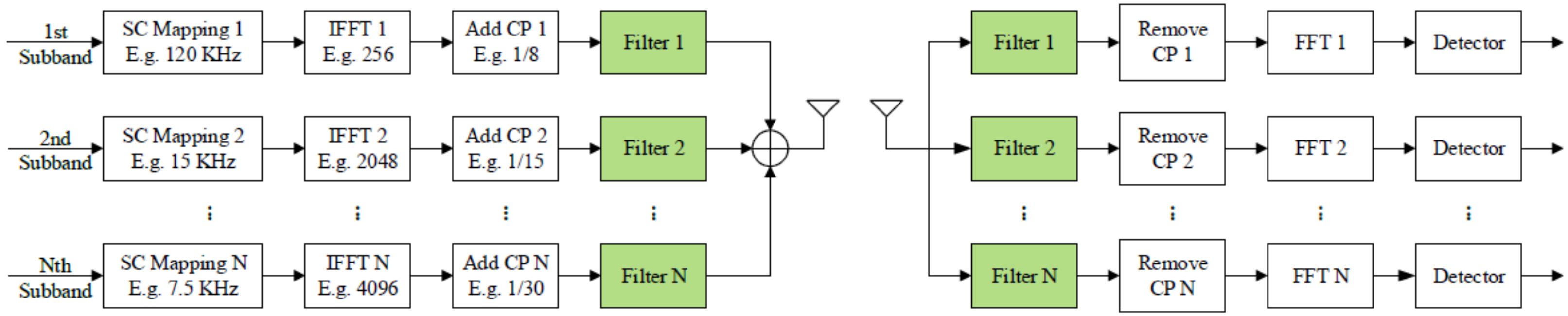


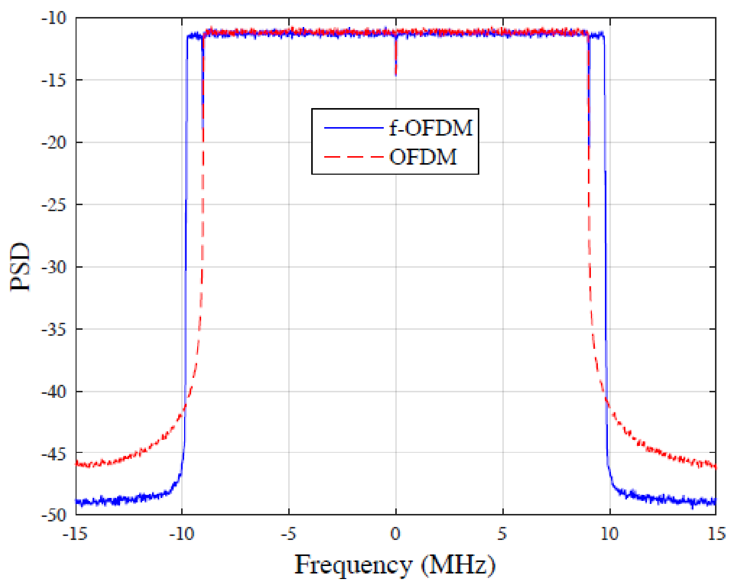
[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

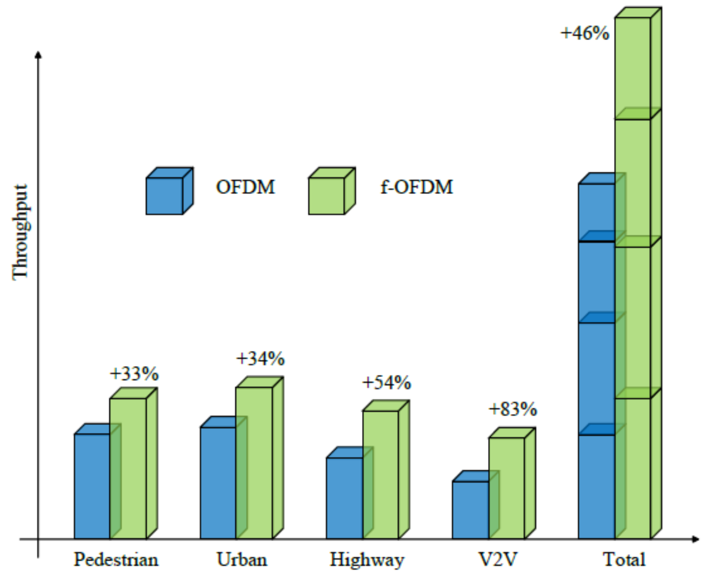
5G Key Enabling Technologies



ACM & Multiple Access» New Waveforms (Post OFDM) » f-OFDM

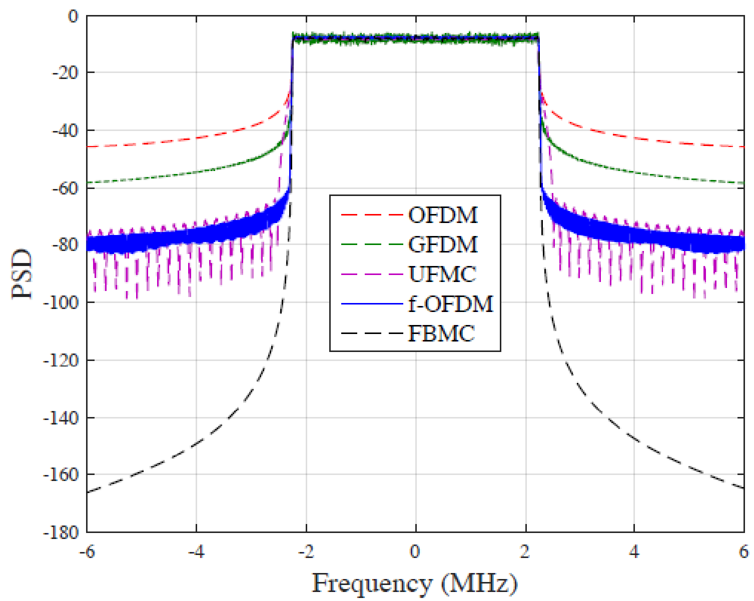






5G Key Enabling Technologies

ACM & Multiple Access» 5G waveform candidates

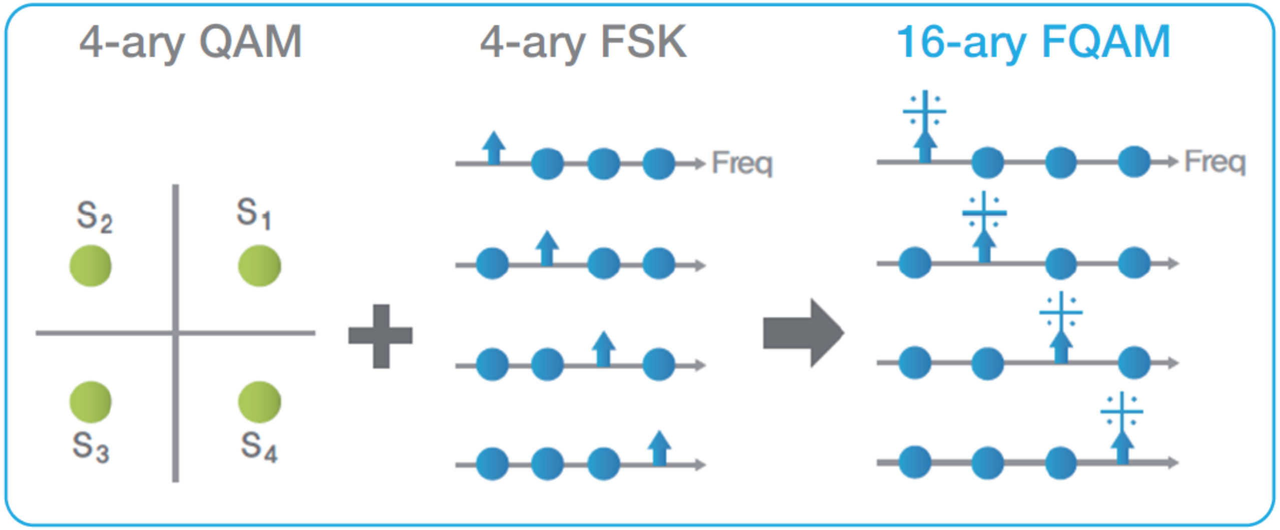


Waveform	Filter Granularity	Typical Filter Length	Time Orthogonality	Frequency Orthogonality	OOBE
OFDM	Whole band	$\leq$ CP length	Orthogonal	Orthogonal	Bad
GFDM	Subcarrier	$\gg$ Symbol duration	Non-orthogonal	Non-orthogonal	Good
FBMC	Subcarrier	$= (3, 4, 5) \times$ Symbol duration	Orthogonal in real domain	Orthogonal in real domain	Best
UFMC	Subband	$=$ CP length	Orthogonal	Quasi-orthogonal	Good
f-OFDM	Subband	$\leq 1/2 \times$ Symbol duration	Non-orthogonal	Quasi-orthogonal	Better

5G Key Enabling Technologies

ACM & Multiple Access» New Modulation » FQAM

- Improves the cell-edge performance
- With FQAM, the statistical distribution of ICI is likely to be non-Gaussian, especially for cell-edge users.
- Higher transmission rates **(x3)** when compared with QAM-based OFDMA



[Source: Samsung electronics "5G Vision", White Paper [Online] 2015.]

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

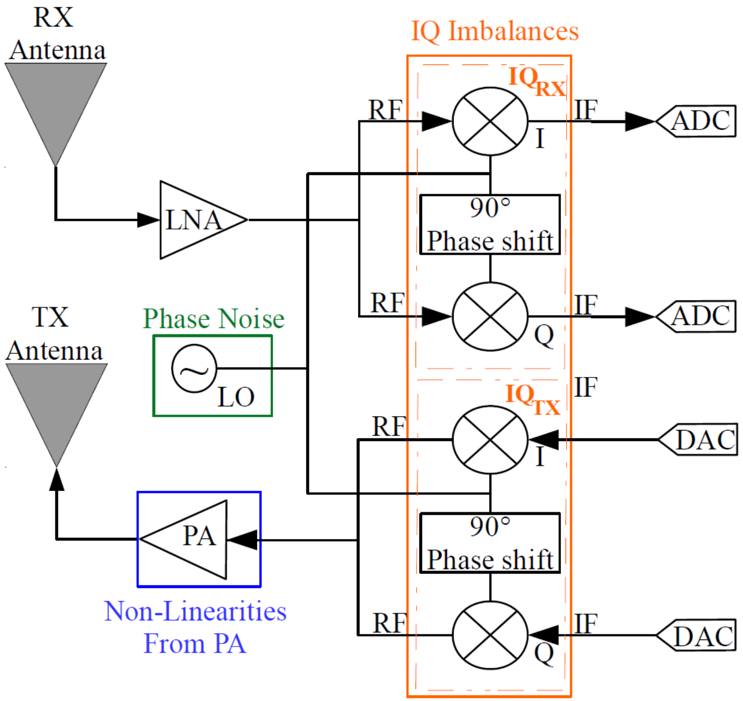
This research project involves the design of appropriate digital baseband modulation schemes that will be implemented on FPGA platform based on the standard 802.15.3c.

The identification of RF non-idealities that should be considered in the 60 GHz design and providing efficient mitigation methods.

Orthogonal Frequency Division Multiplexing (OFDM) and Single Carrier Frequency Domain Equalization (SC-FDE) are the transmissions schemes adopted by this standard.

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

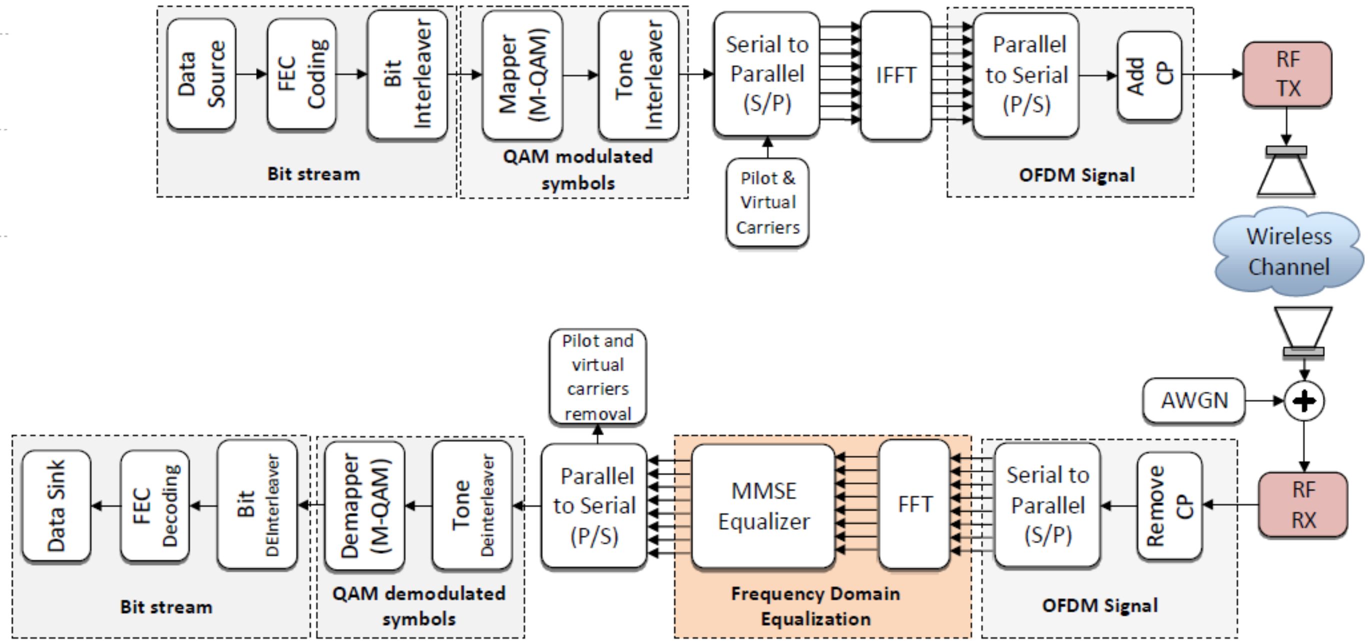
RF Impairments Models for 60 GHz Communications Systems



Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Simulation Framework for mmWave systems

OFDM block diagram



INSTITUIÇÕES ASSOCIADAS

IPL instituto politécnico de leiria

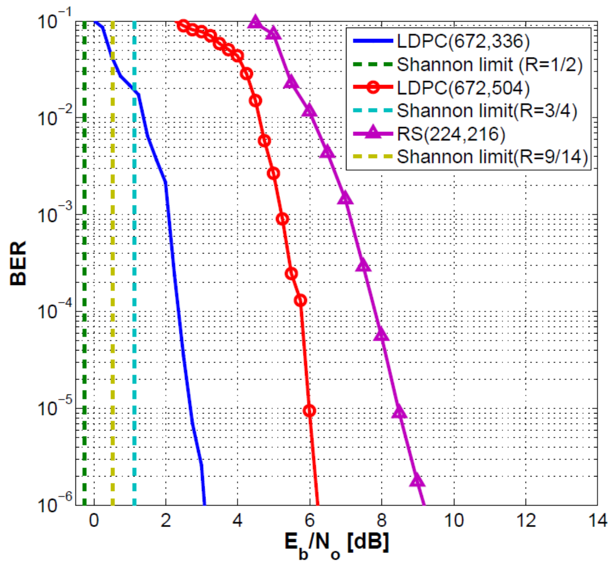
instituto de telecomunicações

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

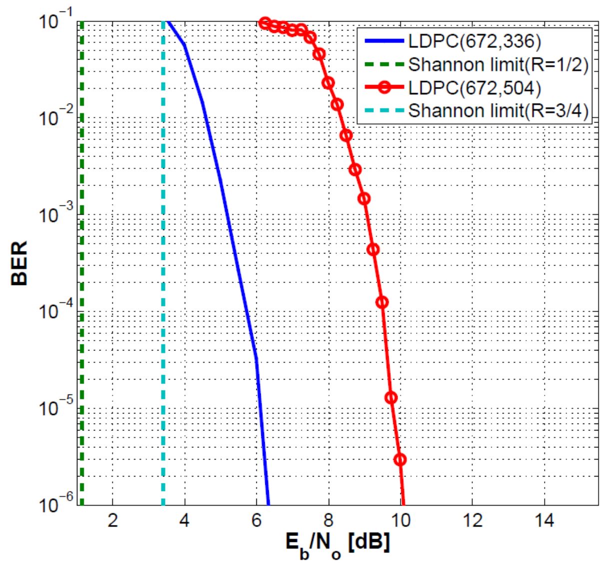
Simulation Framework for mmWave systems

Coded OFDM

FEC	Overall code rate	Modulation	Throughput [Gbps]
RS (224,216)	9/14	16 QAM	3.96
LDPC (672,336)	1/2	16 QAM	3.08
		64 QAM	4.62
LDPC (672,504)	3/4	16 QAM	4.62
		64 QAM	6.93



16 QAM



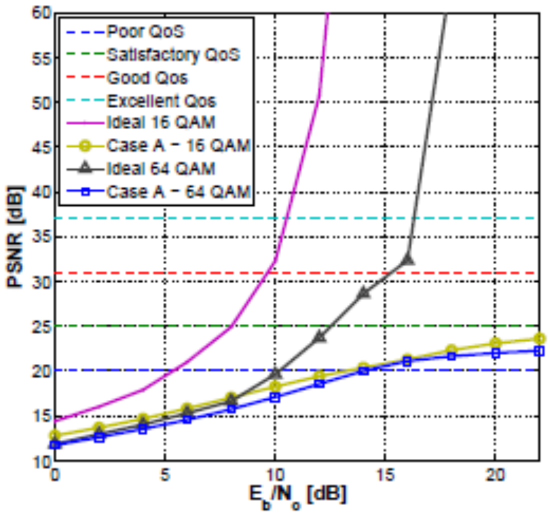
64 QAM

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

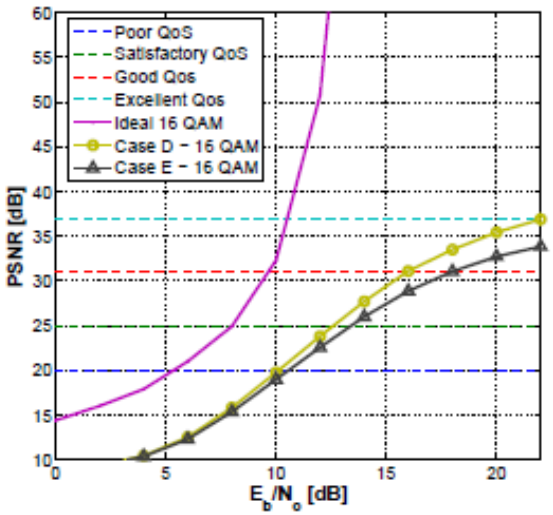
PSNR Simulations Results

- PA non-linearities impact on the subject quality of a transmitted video frame.

Reference frame from the Full HD Cactus.yuv video sequence for the PSNR calculation.



Uncoded



coded

INSTITUIÇÕES ASSOCIADAS

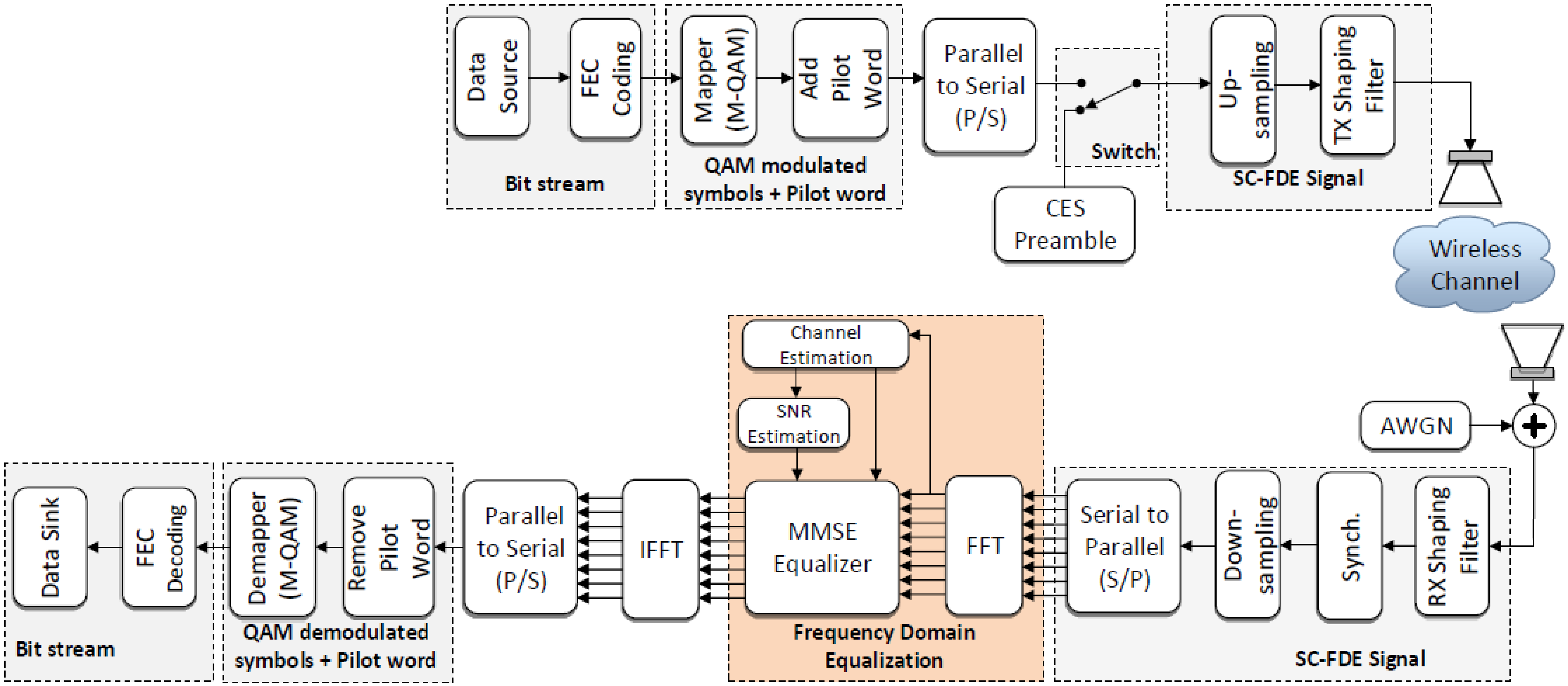
IPL instituto politécnico de leiria

instituto de telecomunicações

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Simulation Framework for mmWave systems

SC-FDE block diagram



INSTITUIÇÕES ASSOCIADAS

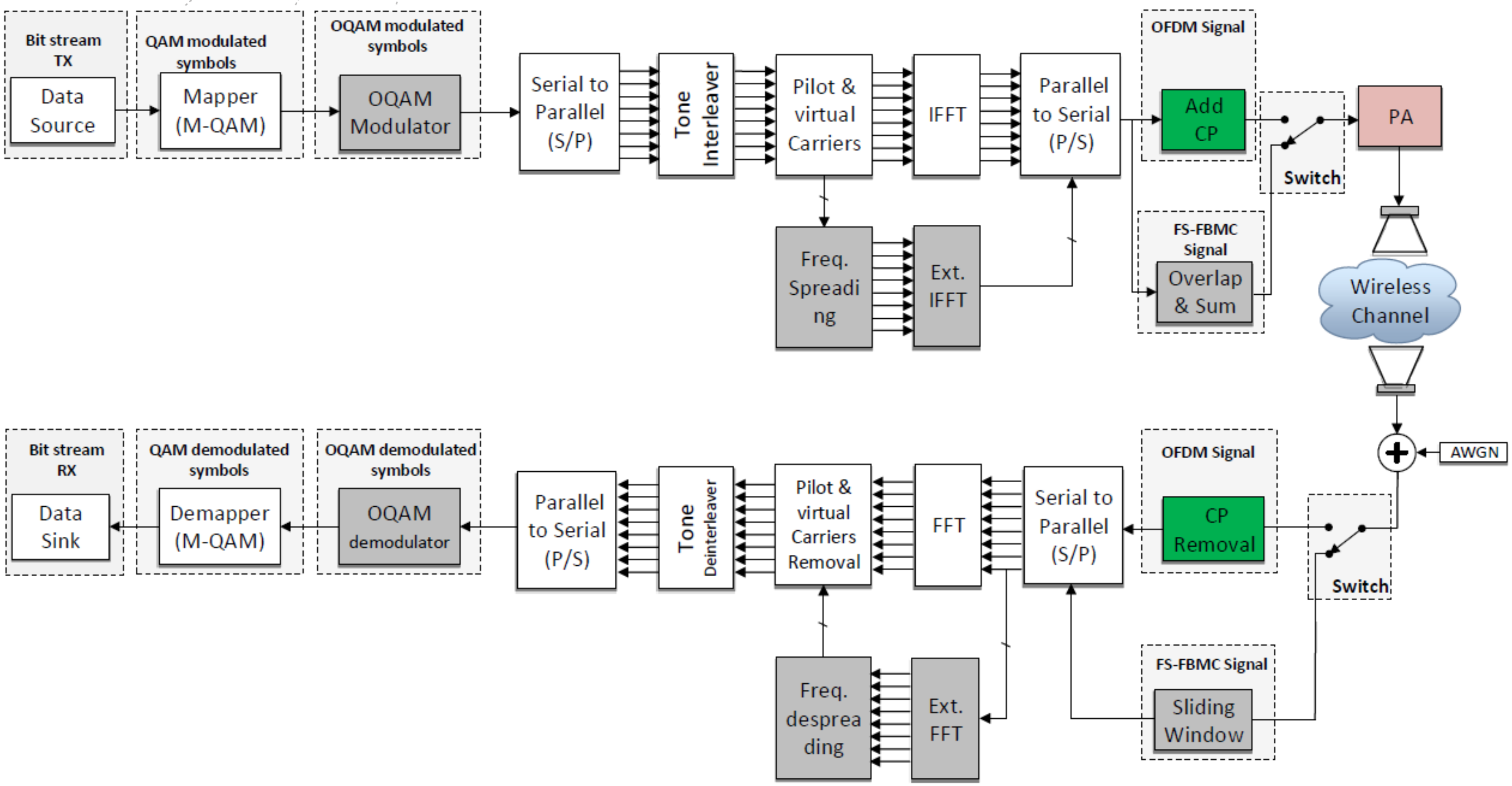
IPL instituto politécnico de leiria

instituto de telecomunicações

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Simulation Framework for mmWave systems

OFDM/FS-FBMC block diagram



INSTITUIÇÕES ASSOCIADAS

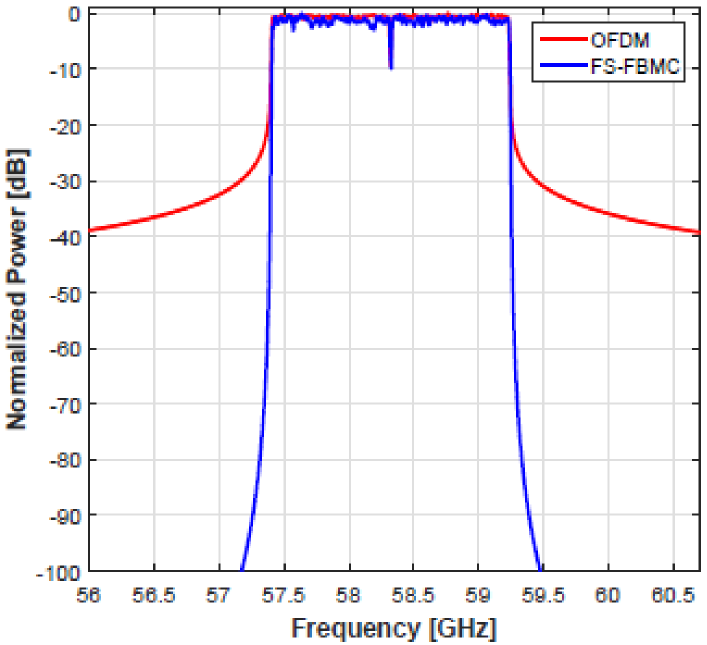
IPL instituto politécnico de leiria

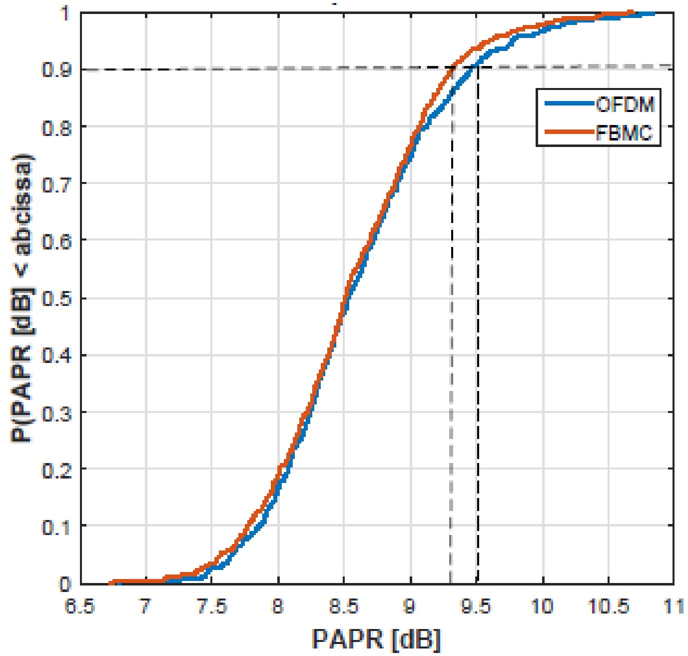
instituto de telecomunicações

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Simulation Framework for mmWave systems

OFDM/FS-FBMC



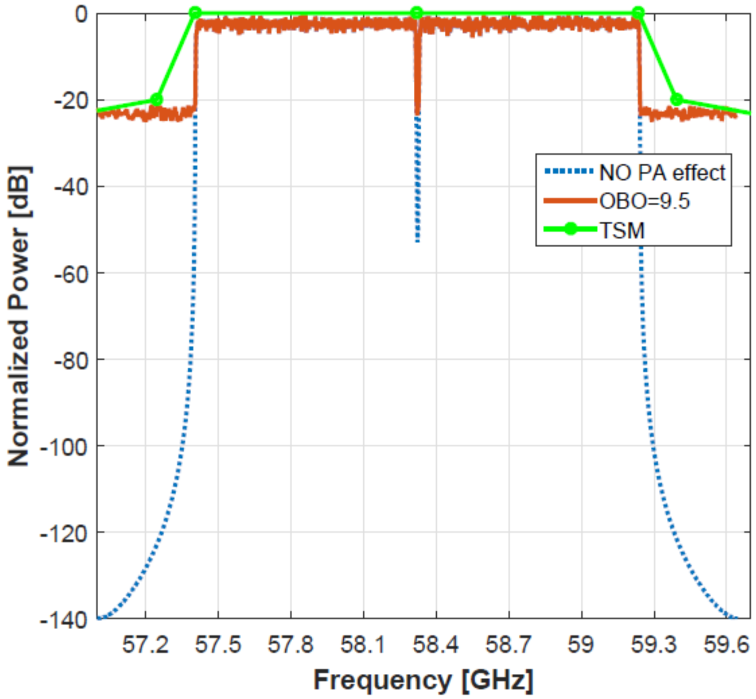


Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

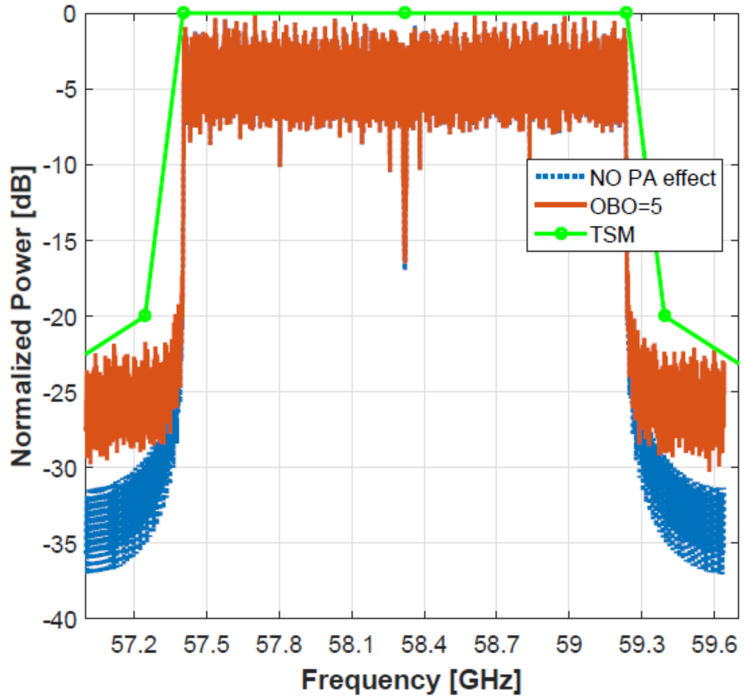
Simulation Framework for mmWave systems

OFDM/FS-FBMC

Estimated out-of band emission using the GaAs PA model employing 16



FS-FBMC



OFDM

INSTITUIÇÕES ASSOCIADAS

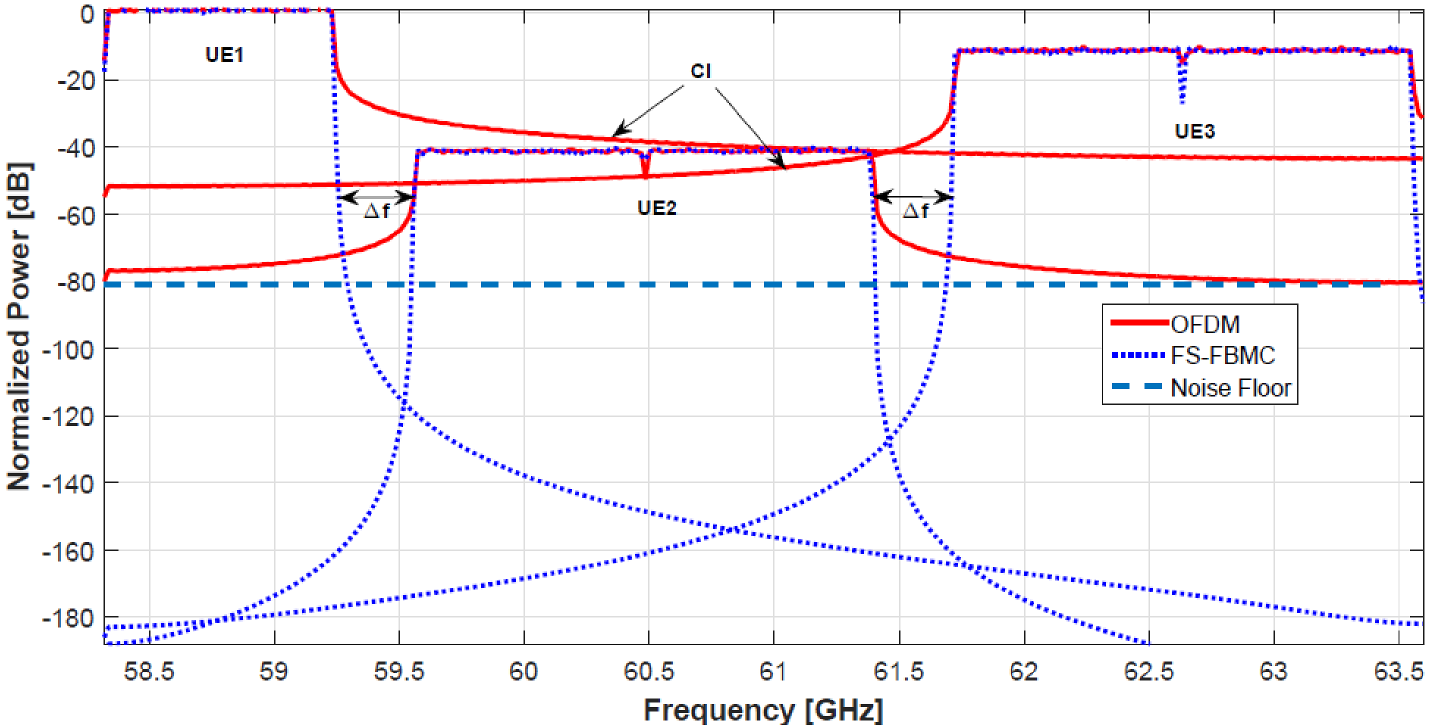
IPL instituto politécnico de leiria

instituto de telecomunicações

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Simulation Framework for mmWave systems

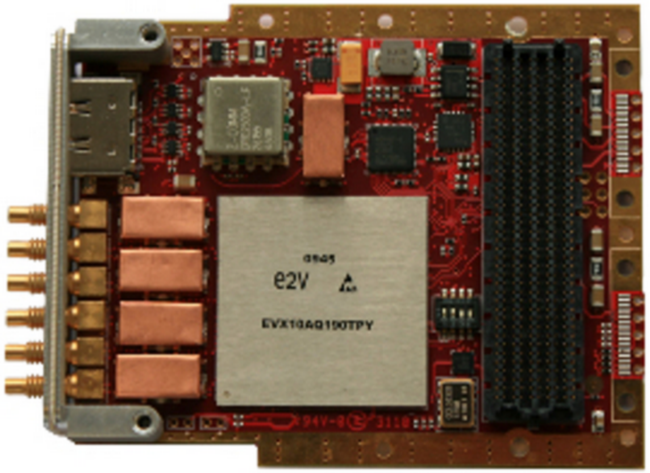
OFDM/FS-FBMC



Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Xilinx Virtex-7 FPGA VC707 Evaluation Kit.

Vubiq V60WGD03.



ADC FMC module.

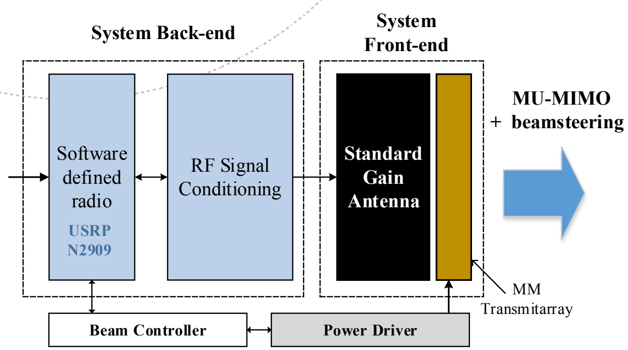
ADC specs - FMC 126:

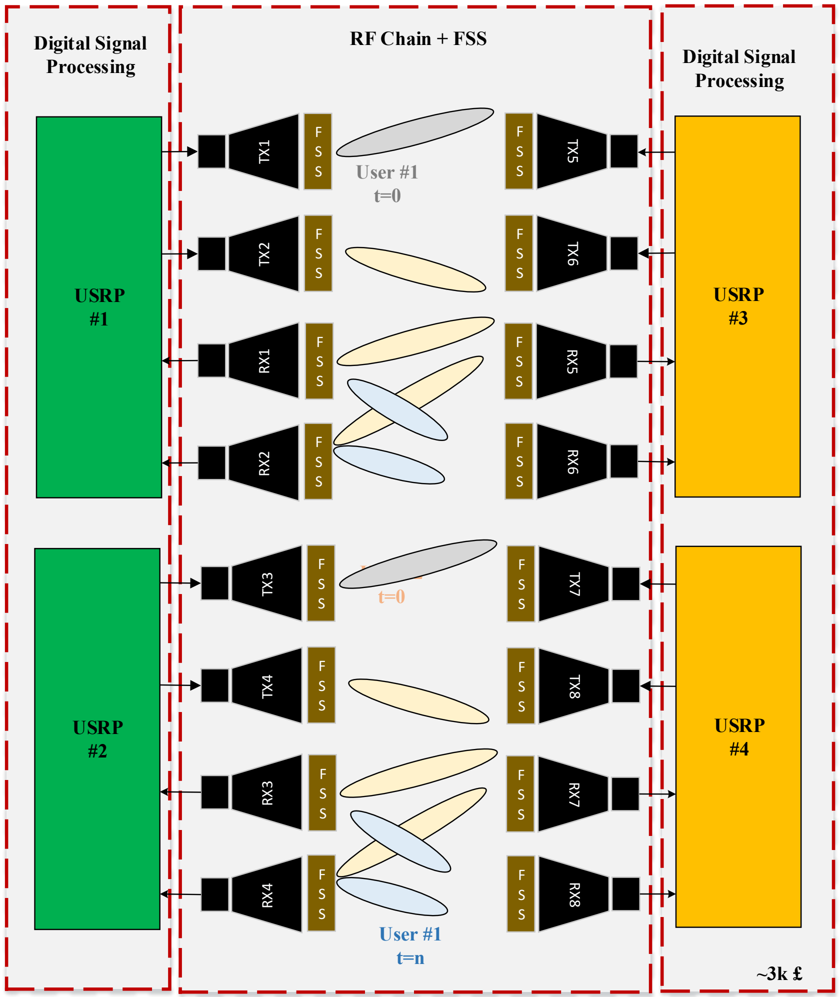
- 10 bit resolution;
- 1.25 GSPS using two channels;
- **Maximum signal bandwidth: 625 MHz.**

Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application **[our work]**

Under prototyping

MIMO multi-user 4x4 @ 6 GHz – Full duplex communication

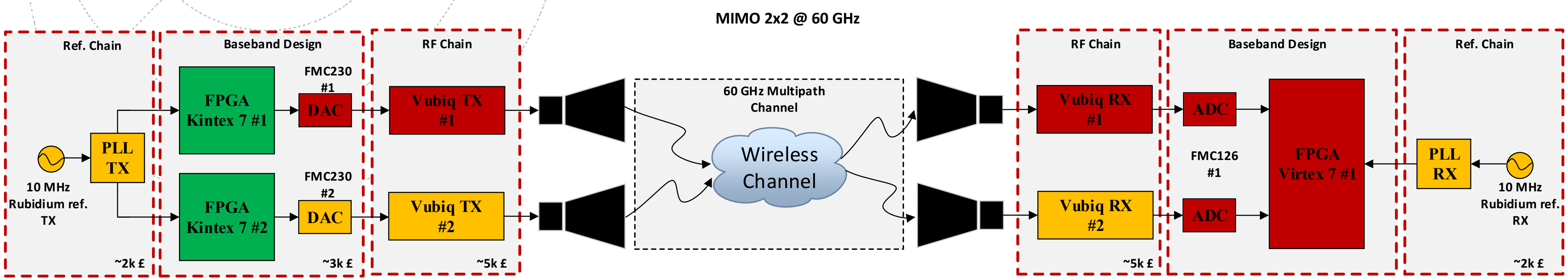




Millimetre Wave Wireless Radio System Prototype for Giga-bit/s Multimedia Application [our work]

Under prototyping

MIMO 2x2 @ 60 GHz




THANK
YOU