The road to 5G
LTE-A evolution, Internet of Things and first 5G aspects

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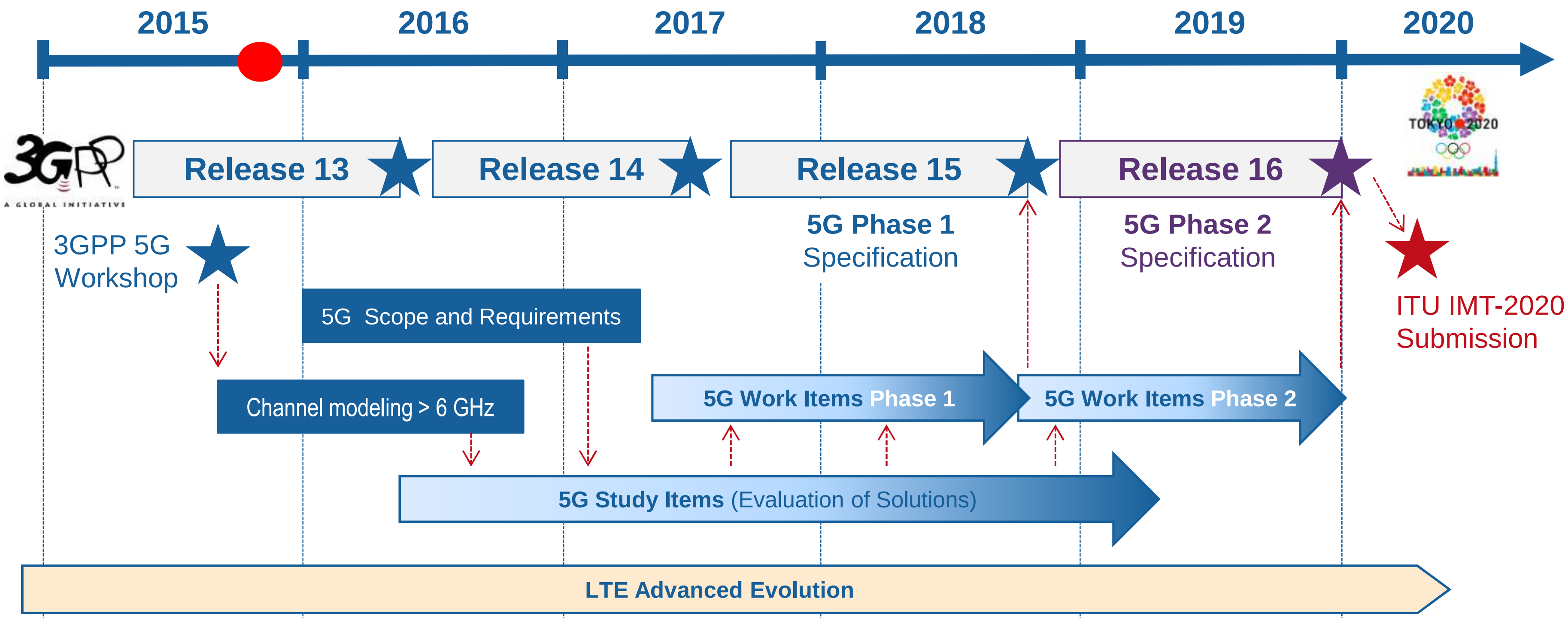
5G Standardization

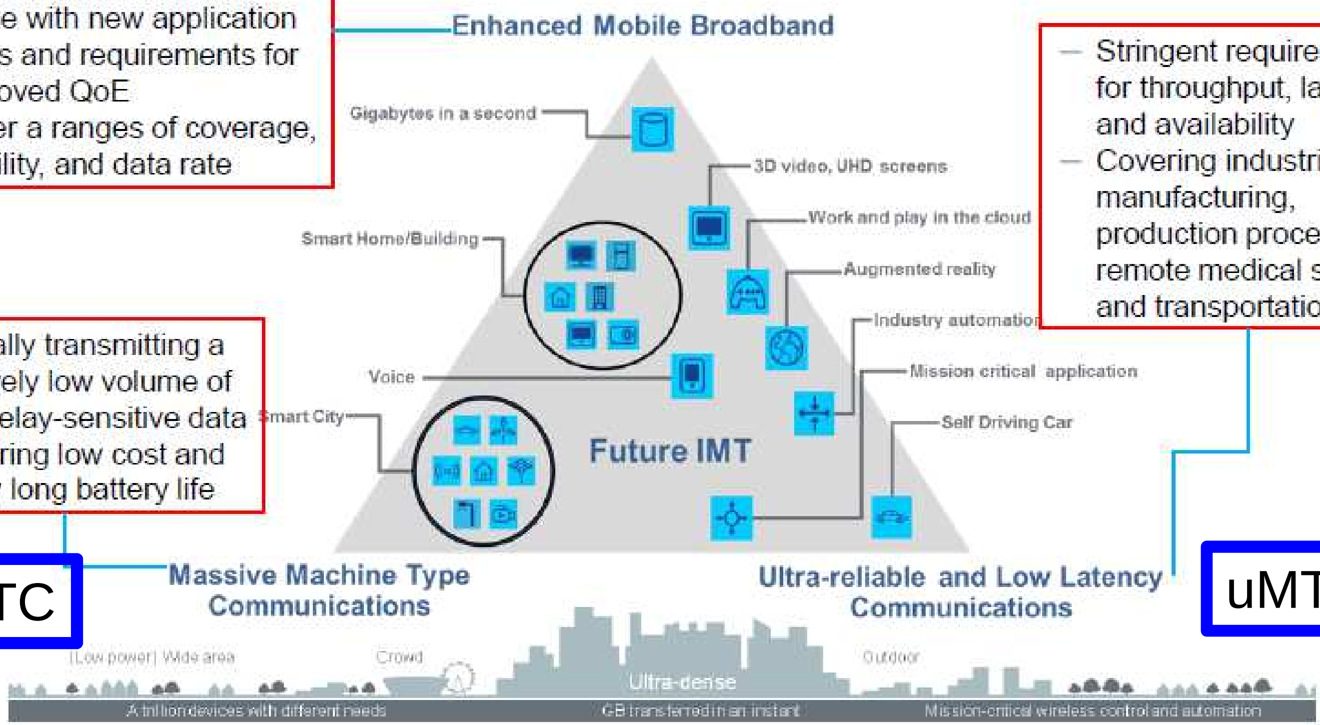
3GPP 5G Standardization Schedule



IMT 2020 - services

eMBB

- Human-centric use cases for multi-media content
- Come with new application areas and requirements for improved QoE
- Cover a ranges of coverage, mobility, and data rate



- Stringent requirements for throughput, latency and availability
- Covering industrial manufacturing, production processes, remote medical surgery, and transportation safety

uMTC

- Typically transmitting a relatively low volume of non-delay-sensitive data
- Requiring low cost and a very long battery life

mMTC

From Link Efficiency to System Efficiency

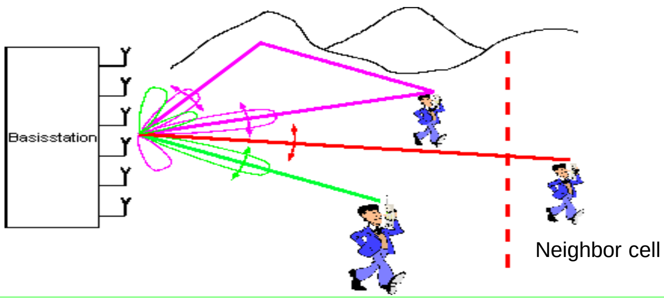
Legacy focus

Link Efficiency

Future focus

System Efficiency

One RAT: link adaptation with coding + modulation to send as much data as possible



System adaptation, to select the RAT that offers the best data transmission according to the requested quality of service for each service

Air interface framework for 5G

Duplex method

- FDD
- TDD
- Flexible duplex
- Full duplex

Wave-forms

- High + low frequencies
- OFDMA
- Single carrier
- FBMC
- UFMC
- GFDM
- F- OFDM
- …

Multiple antenna

- Massive MIMO
- Beamforming
- Centralized
- Distributed
- NxN MIMO

Multiple access

- OFDMA
- SCMA
- NOMA
- PDMA
- MUSA
- IDMA

Modulation coding

- Polar codes
- LDPC
- APSK
- Network coding
- Turbo codes
- FTN

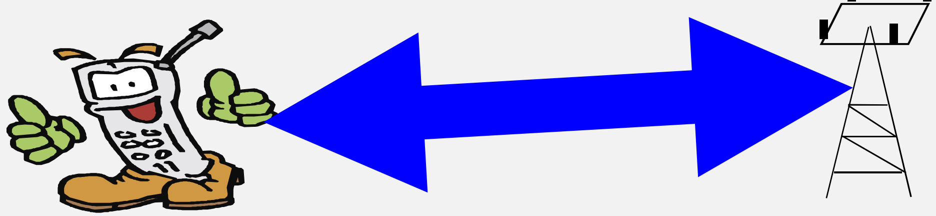
Protocol aspects

- Split C/U plane
- Adaptive HARQ
- Grant free access
- Low energy mode

Various combinations of above methods to fulfill multiple scenarios

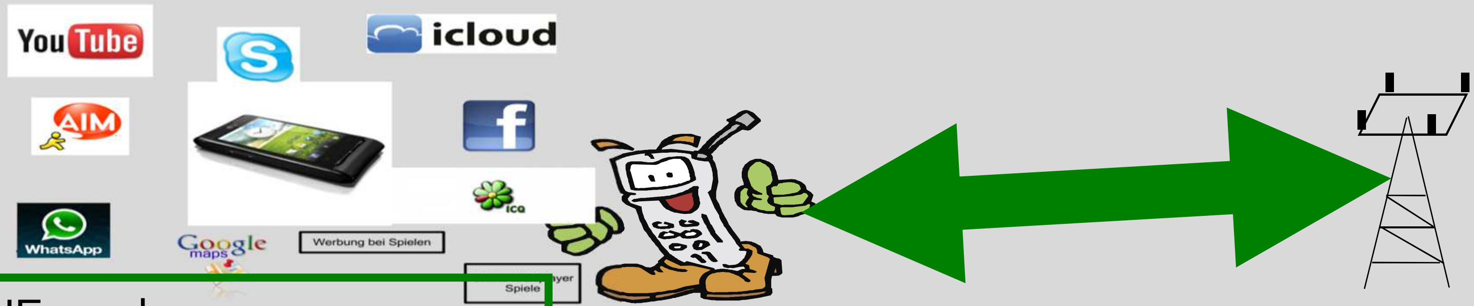
Information about UE

UE sends
Capability information
to the network



e.g. max power,
RAT support,
bands supported
etc. mainly RF
aspects

today

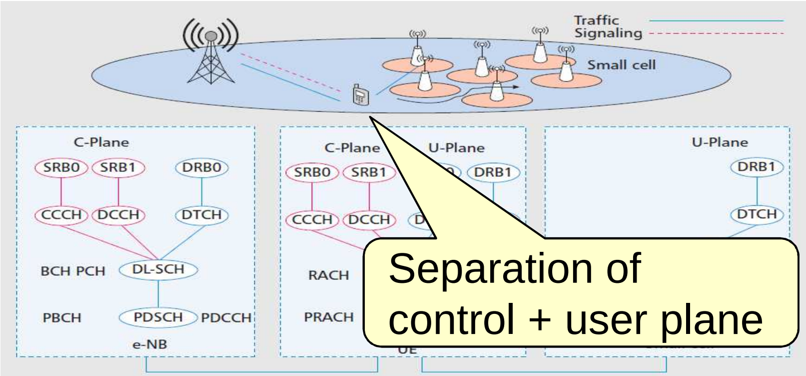


UE sends
Information about installed
applications and behavioural
aspects

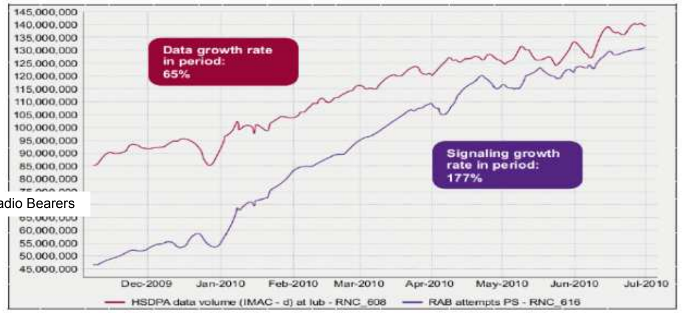
Network may
now conclude
how the UE
may behave,
e.g. mobility,
activity,
bursted traffic

future

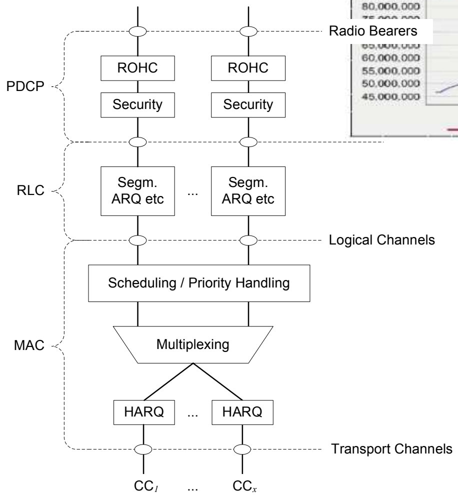
Technology framework: Protocol aspects / targets

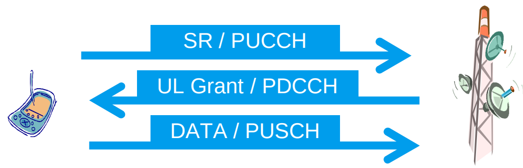


→ Multiple radio connections in parallel

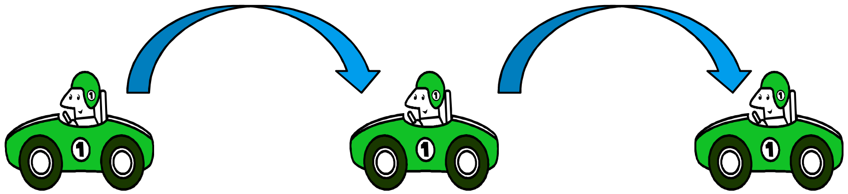


→ Reduce signaling





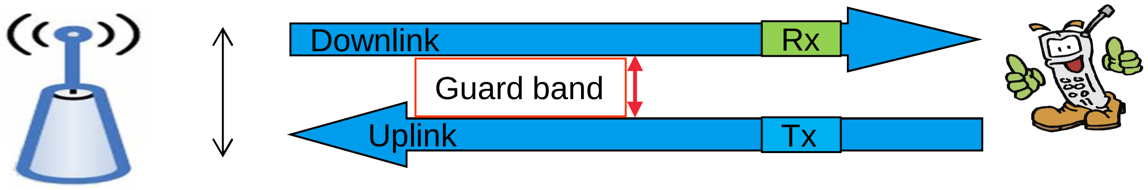
→ Grant free access



Mesh networks: multihop and device to device

→ Light MAC and RRM
for energy saving modes

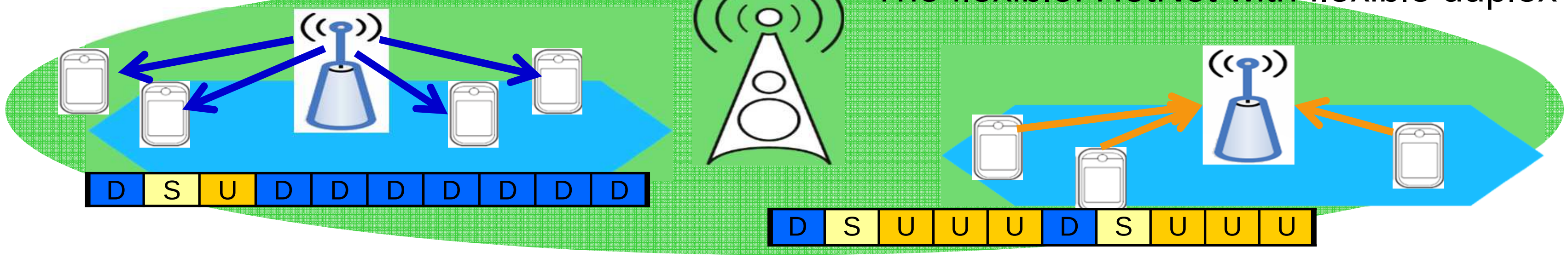
Technology framework: Duplex methods



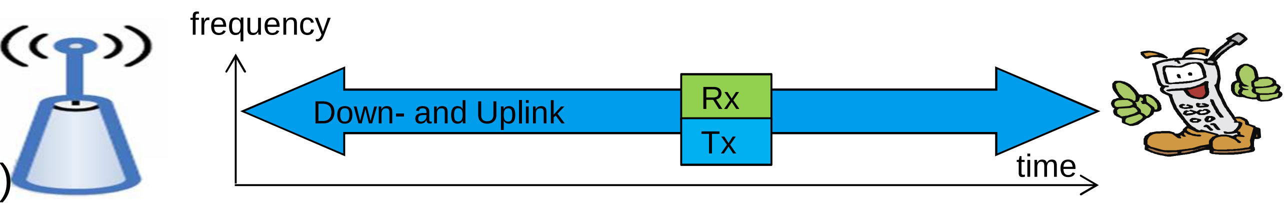
The classics: FDD (guard band) and TDD (guard time)

Duplex = how to separate Rx and Tx?

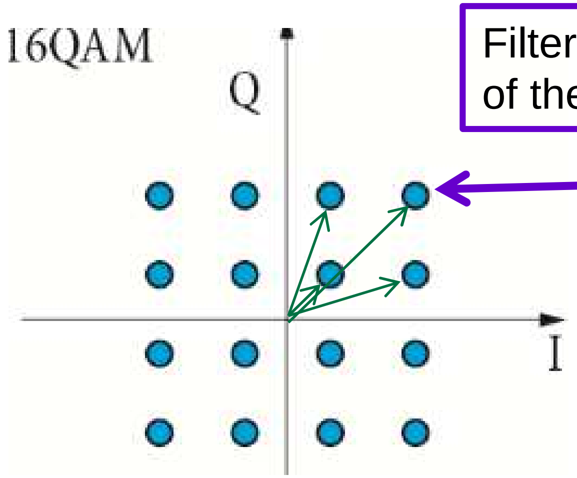
The flexible: HetNet with flexible duplex



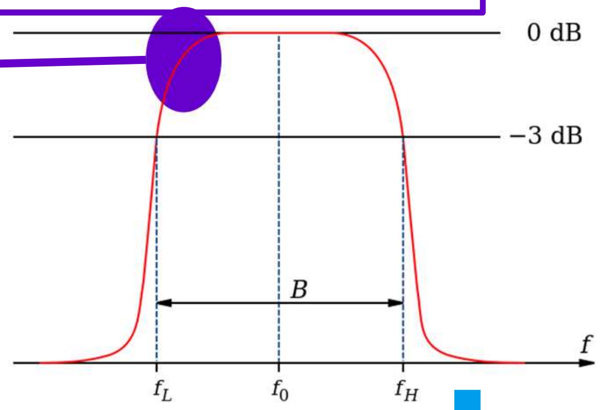
The future outlook:
Full duplex to obtain higher Capacity
(at costs of higher complexity)



Technology framework: Modulation & Coding

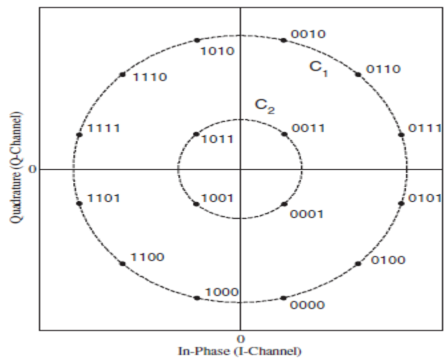


Filter edges may curtail the constellation of the QAM symbols



Example: in QAM there are multiple amplitude values
→ dynamic range of power amplifer + Crest factor

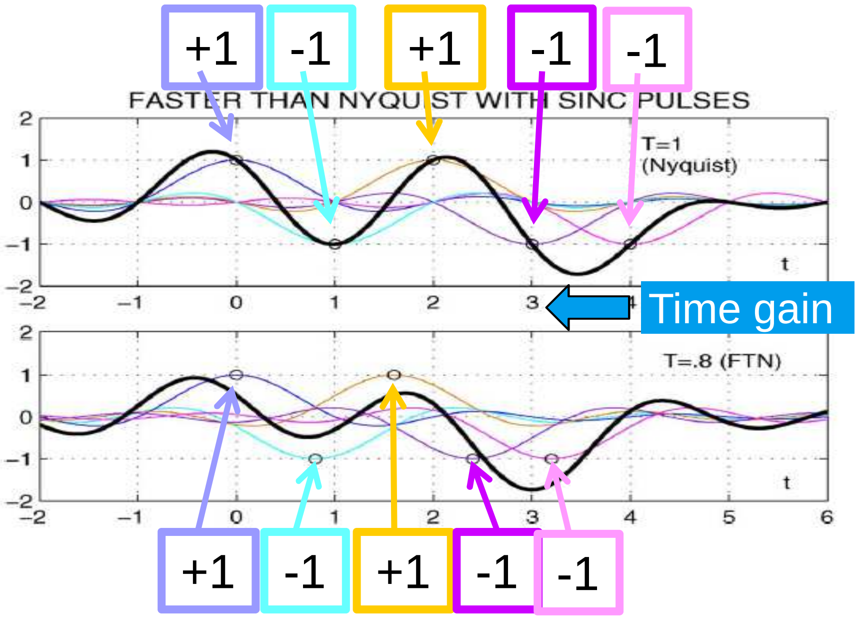
Compare to
e.g. 12 + 4 PSK
→ less amplitude values



Technology framework: Modulation & Coding

Inter-symbol Interference free in time,
Pulses fulfill Nyquist criterion.

Pulses are no longer orthogonal.



Coding trends:

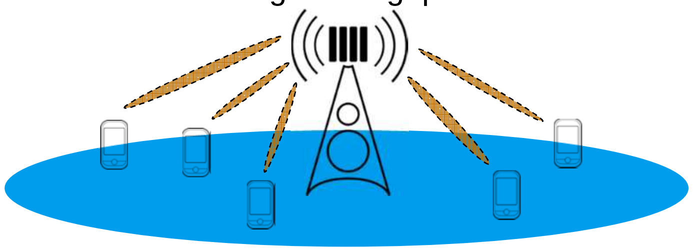
- low complexity → energy efficient
- fast decoding → high data rate
- hardware implementation → low latency

But: there is no code supporting all the requests → it looks like multiple codes will coexist depending on the service: LDPC codes, Turbo codes; Polar codes etc.

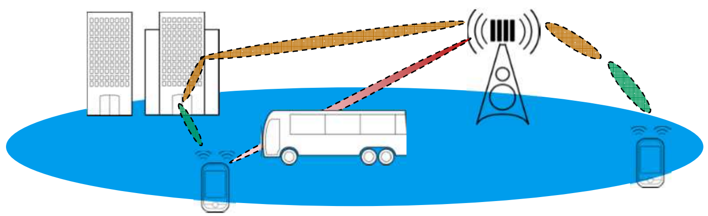
Pulses are no longer orthogonal, faster symbol rate → Receiver has to remove ISI !
Faster than Nyquist → idea to shorten pulse length and send more data per spectrum

Massive MIMO / mm-Wave MIMO
Beamforming is one important aspect

- **Massive MIMO characterized by**
  - Very large (i.e. number of Tx elements) antenna array at the base station.
  - Large number of users served simultaneously (choosing the right group of antenna elements for the specific users)
  - TDD allows channel estimation without UE feedback.
  - Leveraging the multiplicity of (uncorrelated) propagation channels to achieve high throughput.

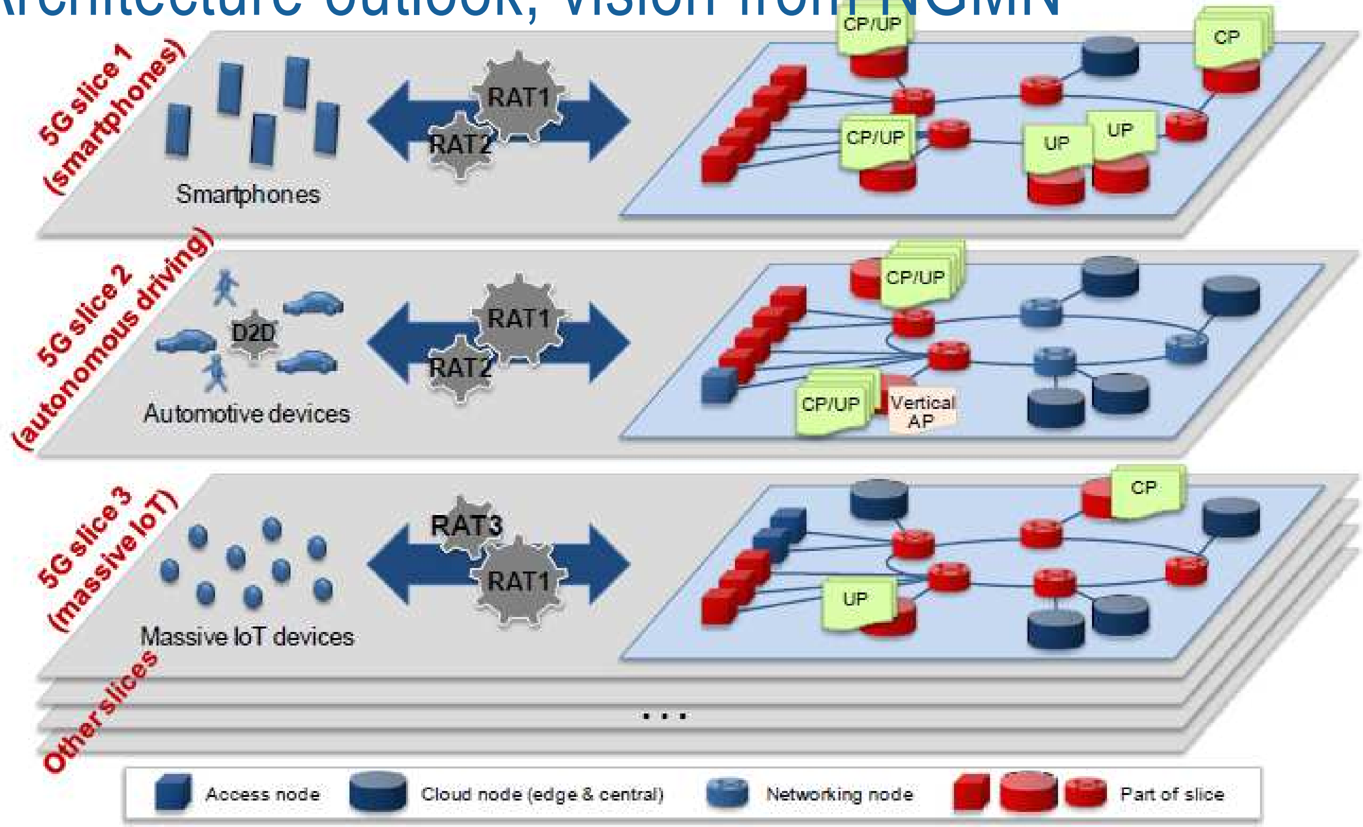


- **mm-Wave MIMO/beamforming characterized by**
  - Very small (in terms of dimensions) antenna arrays possible
  - Highly directional transmission is needed to compensate severe path loss (beamforming used at Tx and Rx)
  - Dynamic beam adaptation is essential



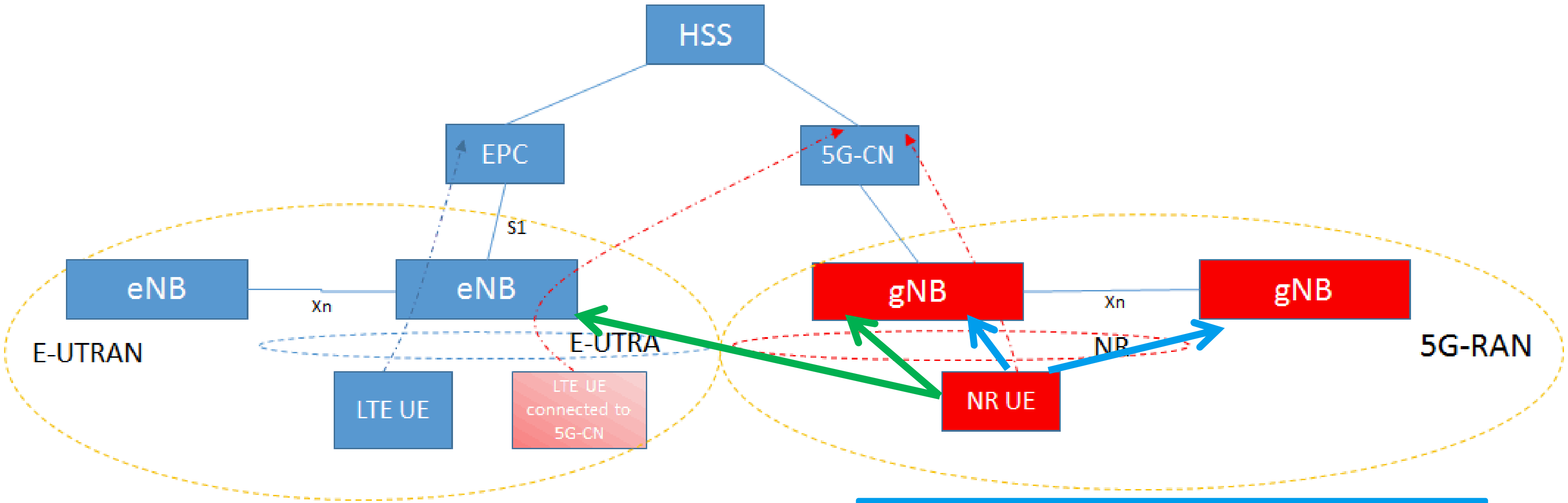
► **Over the air measurements will become much more important**
► **Dynamic beamforming verification requires enhancement of the existing test procedures**

Architecture outlook, vision from NGMN



idea of network slicing

3GPP terminology



NR DC = new radio dual connectivity

EN- DC = EUTRA + new radio dual connectivity

Deployment scenarios

Source: 3GPP TR 38.913 Version 0.3.0 (2016-03)

Scenario	Indoor hotspot	Dense urban	Rural	Urban macro	High speed[6] (500 km/h)
Carrier frequency range (aggregated system BW)	4GHz (200MHz) 30GHz[3](1GHz) 70GHz[4](1GHz)	4GHz (200MHz) 30GHz (1GHz)	700MHz+2GHz (20MHz) 4GHz (200MHz)	2GHz (TBD) 4GHz (200MHz) 30GHz (1GHz)	4GHz (200MHz) 30GHz (1GHz) 70GHz (1GHz)
BS / UE antenna elements[2]	256/32 256/8 (4GHz)	256/32 (30GHz) 256/8 (4GHz)	256/8 (4GHz) 64/4 (700MHz)	256/32 (30GHz) 256/8 (4GHz)	256/32 256/8 (4GHz)
Coverage range (indoor/outdoor user distribution in %)	20 m 100%/0%	200 m Macro (3 micro TRPs[5] per macro) 80%/20%	1732 / 5000 m 50%/50%	500 m 80%/20%	1732 m 100% users in train
Scenario	**Extreme rural[7]**	**Urban overage for mMTC**	**Highway**	**Urban grid for connected car[9]**	**Air to Ground**
Carrier frequency range (aggregated system BW)	< 3GHz (40MHz)	700 MHz (TBD) 2.1GHz (TBD)	< 6GHz (200MHz)	< 6GHz (200MHz)	tbd
BS / UE antenna elements[2]	<TBD>	2, 4, 8 (optional) / 1	32/32 (RSU[8]) 32/8 (in vehicle UE)	32/32 256/8 (4GHz)	[40MHz]
Coverage range (indoor/outdoor user distribution in %)	100 km (even up to 300 km)	500 / 1732 m 80%/20%	500 m 100% in vehicles	500 m Vehicles, bicycles, pedestrian	[100km]

- Frequency range beyond 6 GHz:
- 24 – 40 GHz and 66 – 86 GHz
- Maximum total modulation BW:
- 1 GHz
- Maximum number of UE
- antenna elements: 32
- Maximum number of BS
- antenna elements: 256

FCC opens up cm- and mm-Wave spectrum for 5G

- FCC adds additional spectrum for 5G wireless by an anonymously vote on July 14, 2016
- Total of 10.85 GHz will be made available:
  - 28 GHz: 27.5 to 28.35 GHz
  - 37 GHz: 37.0 to 38.6 GHz
  - 39 GHz: 38.6 to 40 GHz
  - 64 to 71 GHz.

Licensed

Unlicensed

2x 425 MHz blocks for the 28 GHz band, country-wide available. Remaining, licensed bands are organized as 200 MHz blocks.

Source: http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0714/DOC-340310A1.pdf

Frequency spectrum considerations for 5G in Europe

European Commission

Measures to support 5G roll-out in EU

"A 5G-ready Europe": Key pre-requisites - spectrum & fibre connectivity

- *Fast track for EU spectrum identification, pioneer bands based on RSPG opinion, 2016;*
- *Full set of bands by end of 2017, technical usage options*
- *Mapping required fiber capillarity towards coordinated investment planning to increase fibre capacity for 5G backhauling, using political target for 5G connectivity along route corridors and train connections by 2025*
- *Best practice for cost reduction of dense cell deployment (emission limits, local taxes, etc), leveraging CODE general authorisations*

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Info from NGMN at Brussel, EU commission conference, Oct 16

Frequency spectrum considerations for 5G in Europe

"The RSPG agreed that the next phase of the multiannual spectrum policy program should be more a **generic programme addressing the spectrum needs of various sectors and not be mainly focussed on wireless broadband only"**
"The RSPG recommends maintaining the possibility to trade and lease the rights of spectrum use in the following frequency bands: 790-862 MHz, 880-915 MHz, 925-960 MHz, 1 710-1 785 MHz, 1 805-1 880 MHz, 1 920-1 980 MHz - 2 110-2 170 MHz, 2.5-2.69 GHz, and 3.4-3.8 GHz (see Article 6.8 of the current RSPP). The RSPG recommends adding any new ECS harmonised band to that list so that every new harmonised band can benefit from this regime."
"The RSPG will continue its efforts and develop recommendations to support the development of 5 G."
"The RSPG recommends the following actions to prepare Europe for new spectrum for 5G above 6 GHz:
- The RSPG should develop before the end of 2017 an Opinion addressing bands suitable for 5G above 6 GHz, focusing on those having the best potential for harmonisation. In addition, the RSPG analysis could address the challenges such as: spectrum sharing, network densification, usage conditions, policy implementation, incentive regulation practices. "

Info from NGMN at Brussel, EU commission conference, Oct 16

Frequency spectrum considerations for 5G in Europe

- **700MHz spectrum in particular for IoT use cases (like sensoring) requiring good coverage**

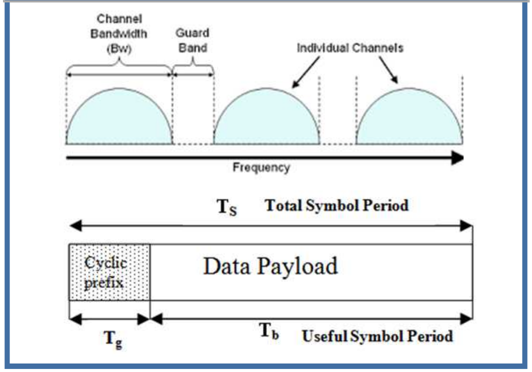
- **3.4 - 3.8GHz spectrum for eMBB use cases supporting existing cell deployments (micro/marco cell deployment)**

- 24.25 - 27.5GHz spectrum for eMBB use cases in small cell deployments

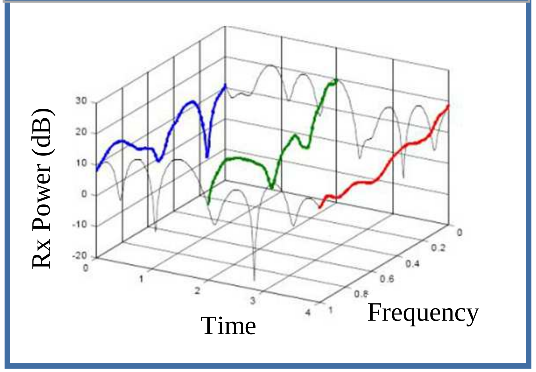
Info from NGMN
at Brussel,
EU commission
conference, Oct 16

5G waveform candidates – some design aspects

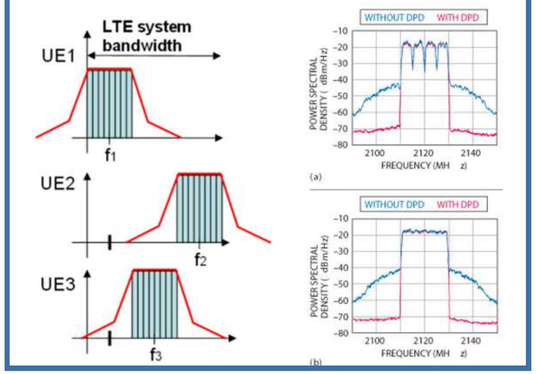
Overhead



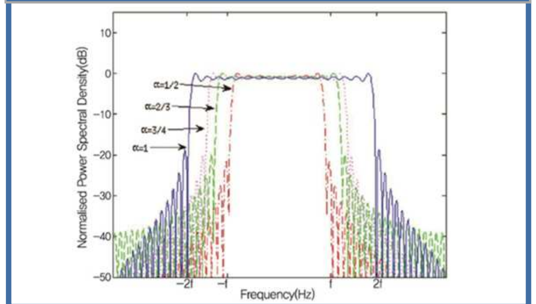
Resistance to Interference



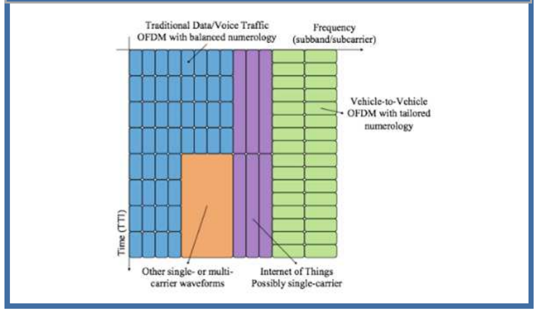
Out of Band Emissions



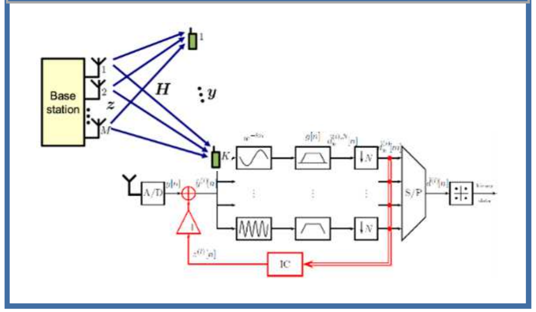
Spectral Efficiency



Flexibility



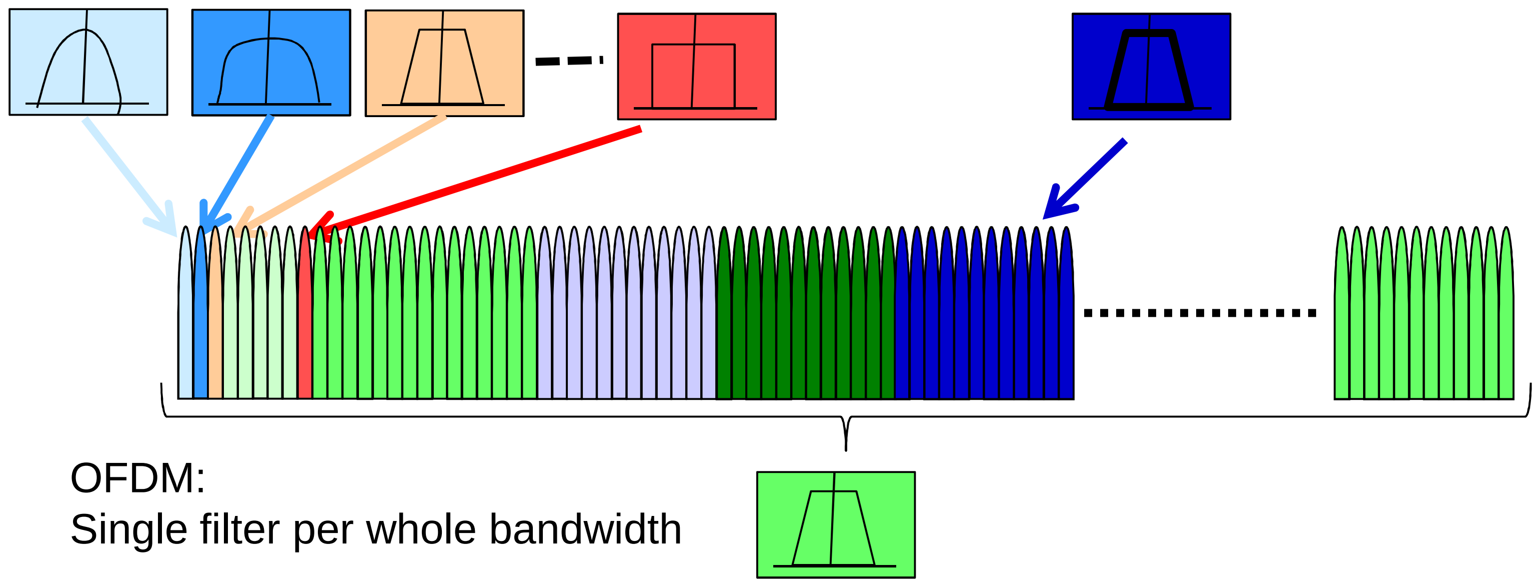
Receiver/MIMO Complexity



New waveform candidates
Comparison: Filter concept

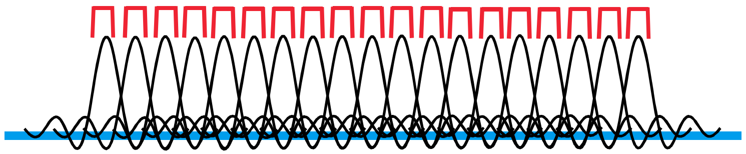
FBMC + GFDM
Individual filter per subcarrier

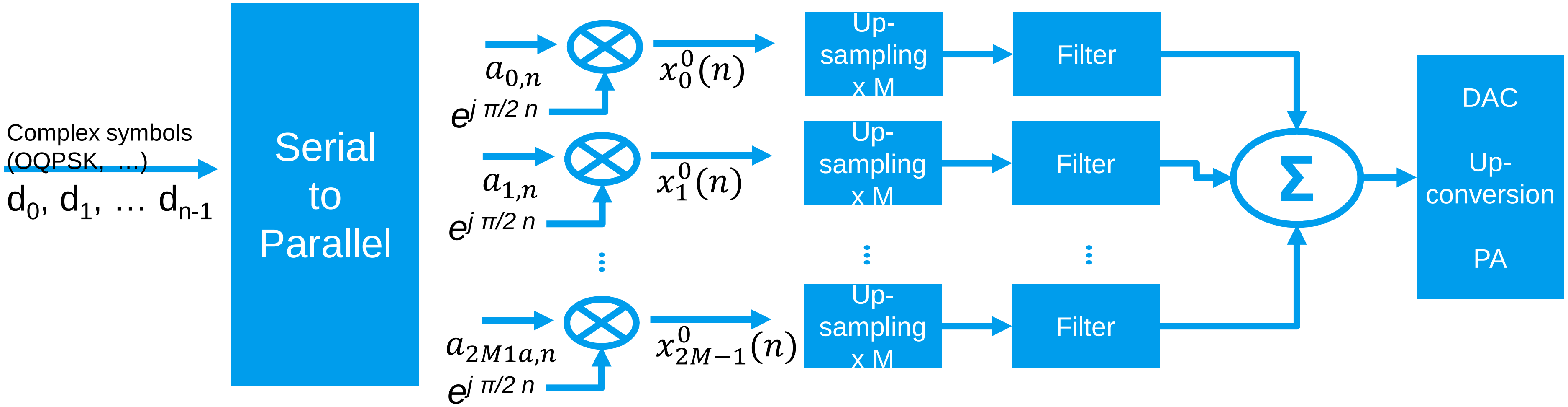
UFMC + F-OFDM
Individual filter per subband



OFDM:
Single filter per whole bandwidth

FBMC
Filterbank Multicarrier

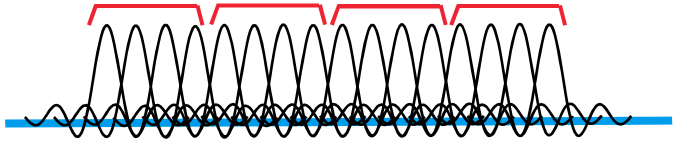


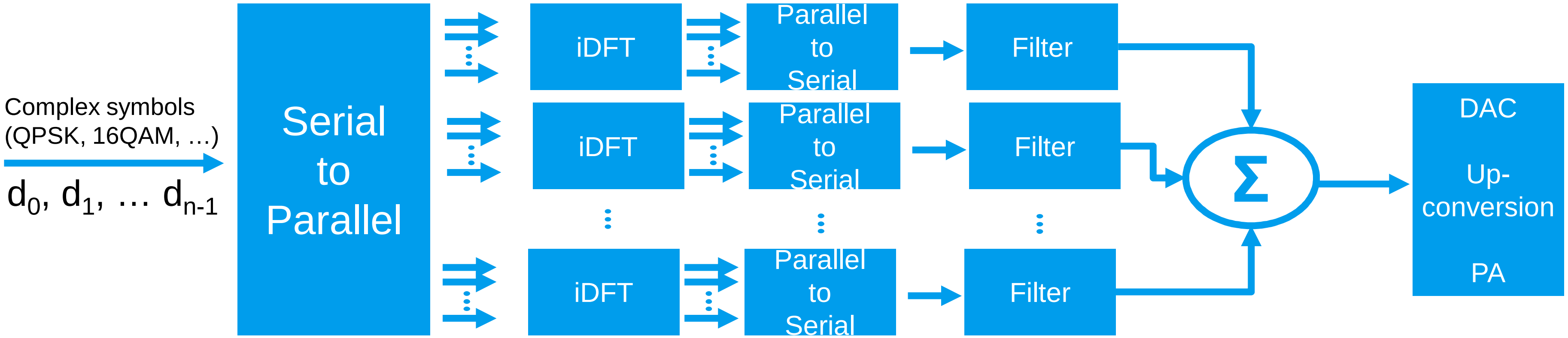


- Each sub-carrier is filtered individually, typically long filter duration
- Typically orthogonality has to be relaxed by using Offset-QAM (OQAM)

UFMC

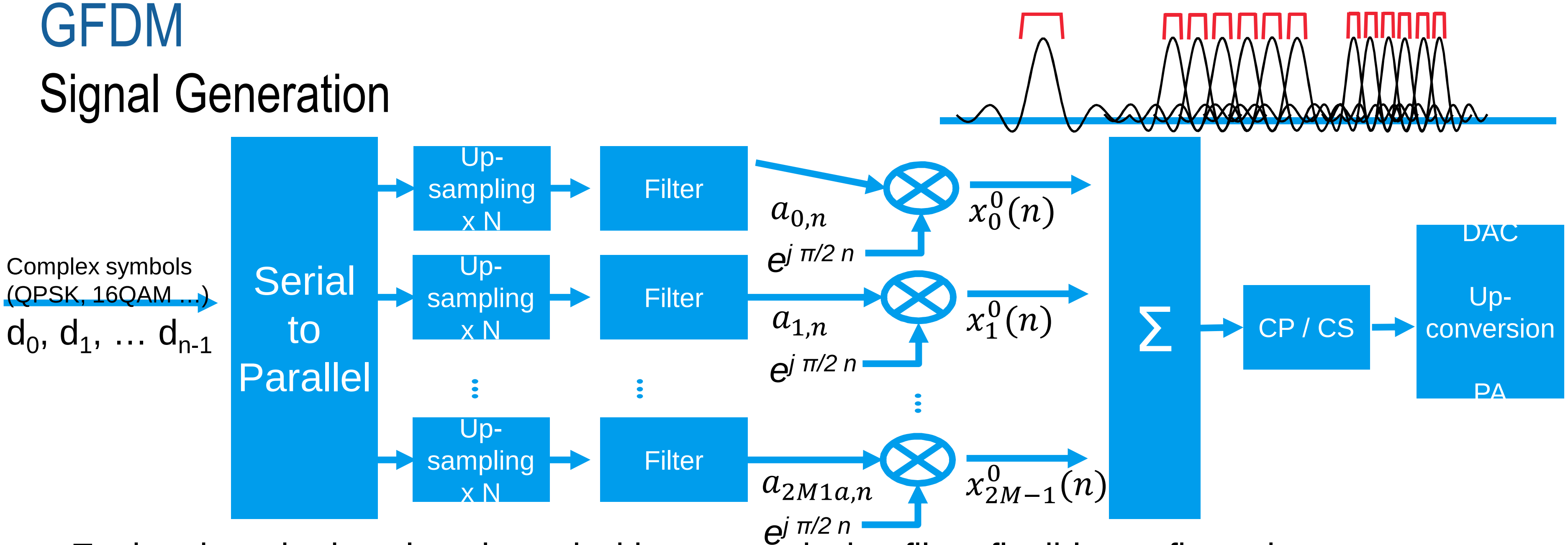
Universal Filtered Multi-Carrier





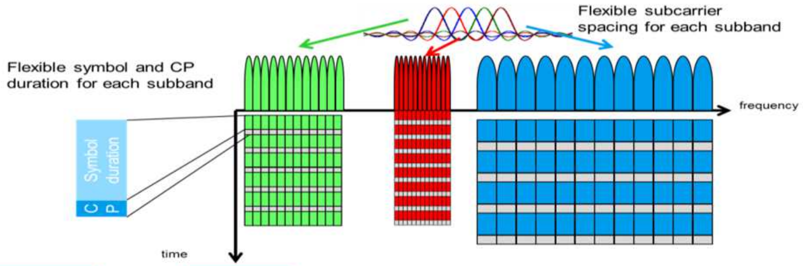
- Groups of carriers (sub-bands) are filtered, typically shorter filters
- Common number of carriers per subband and filter parameters
- Equally sized sub-bands to prevent aliasing
- Non-contiguous sub-bands possible
- Special cases: Only 1 sub-band = OFDM. 1 carrier / sub-band = FBMC

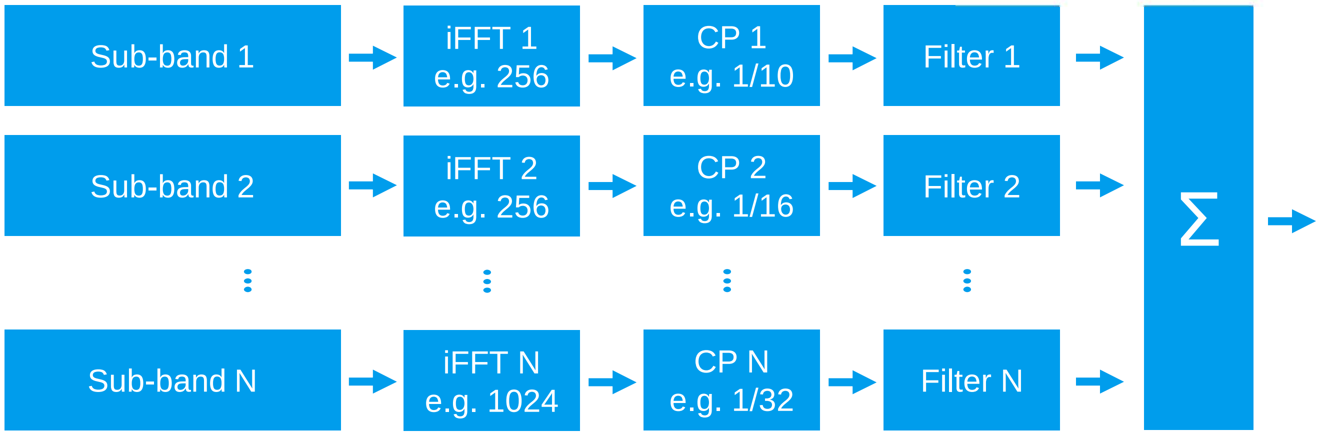
GFDM
Signal Generation



- Each subcarrier is pulse-shaped with a transmission filter, flexible configuration
- Each subcarrier may have a different bandwidth, typical, overlapping -> Rx more difficult
- Filtering by circular convolution to keep sequence length (Tail biting)
- OFDM can be seen as a special case of GFDM.
- Transmission based on a block structure definition, typically short frame length

f-OFDM
Filtered OFDM





- f-OFDM applies subband specific filtering, various characteristics possible
- Based on OFDM numerology
- Completely different parameter set for each sub-band
  - Sub-carrier spacing, FFT-size, filter, cyclic prefix length

Waveform – summary

- “What is the best waveform for 5G?” => it depends on which scenario is prioritized
- Using the same abbreviation does not implicitly mean we have the same waveform

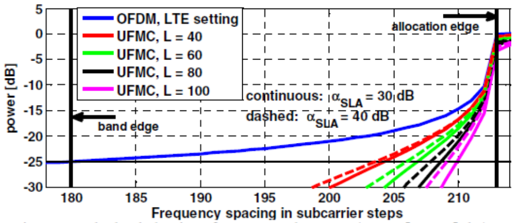
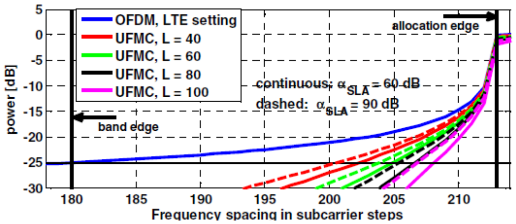
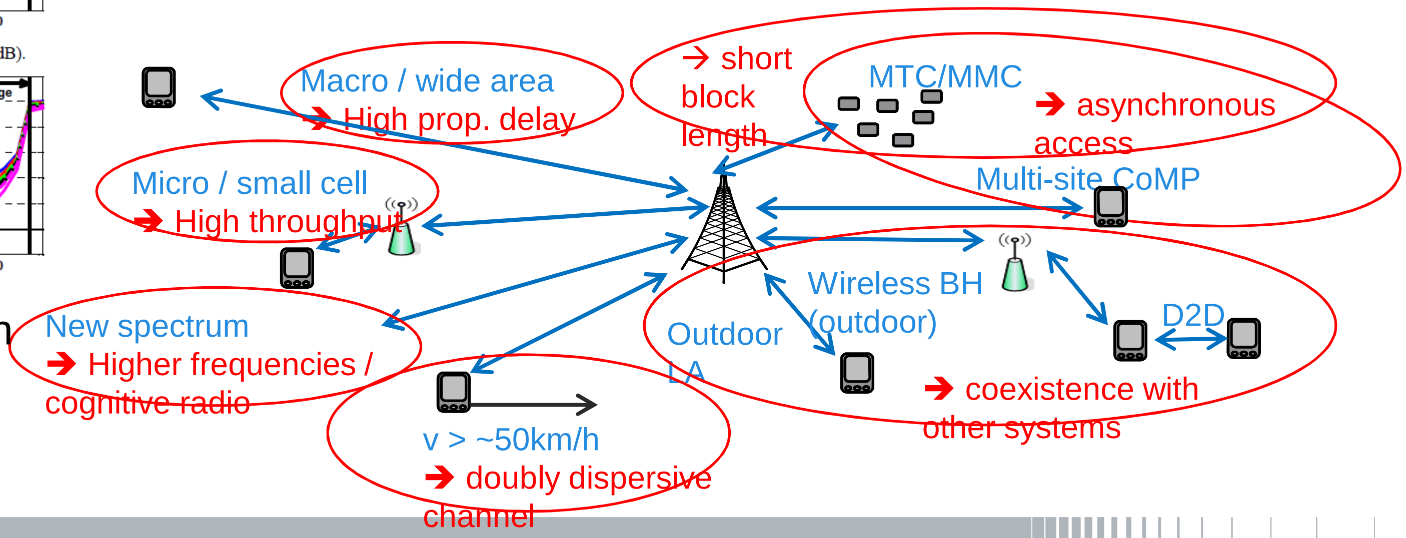


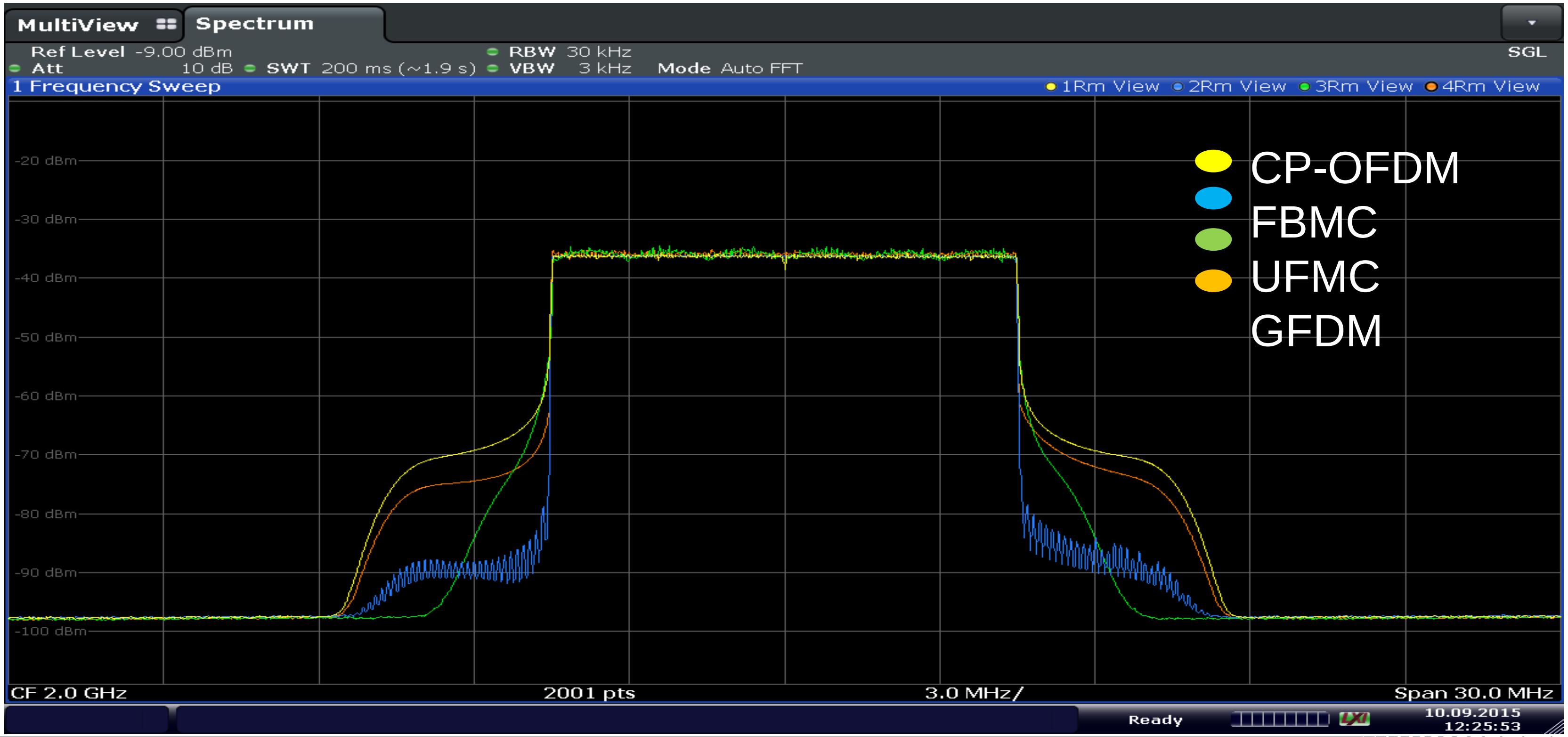
Fig. 6: Band edge behavior of OFDM and UFMC ($\alpha_{SLA} = [30, 40]$ dB).



e.g. out of band emission
UFMC using
different filter types

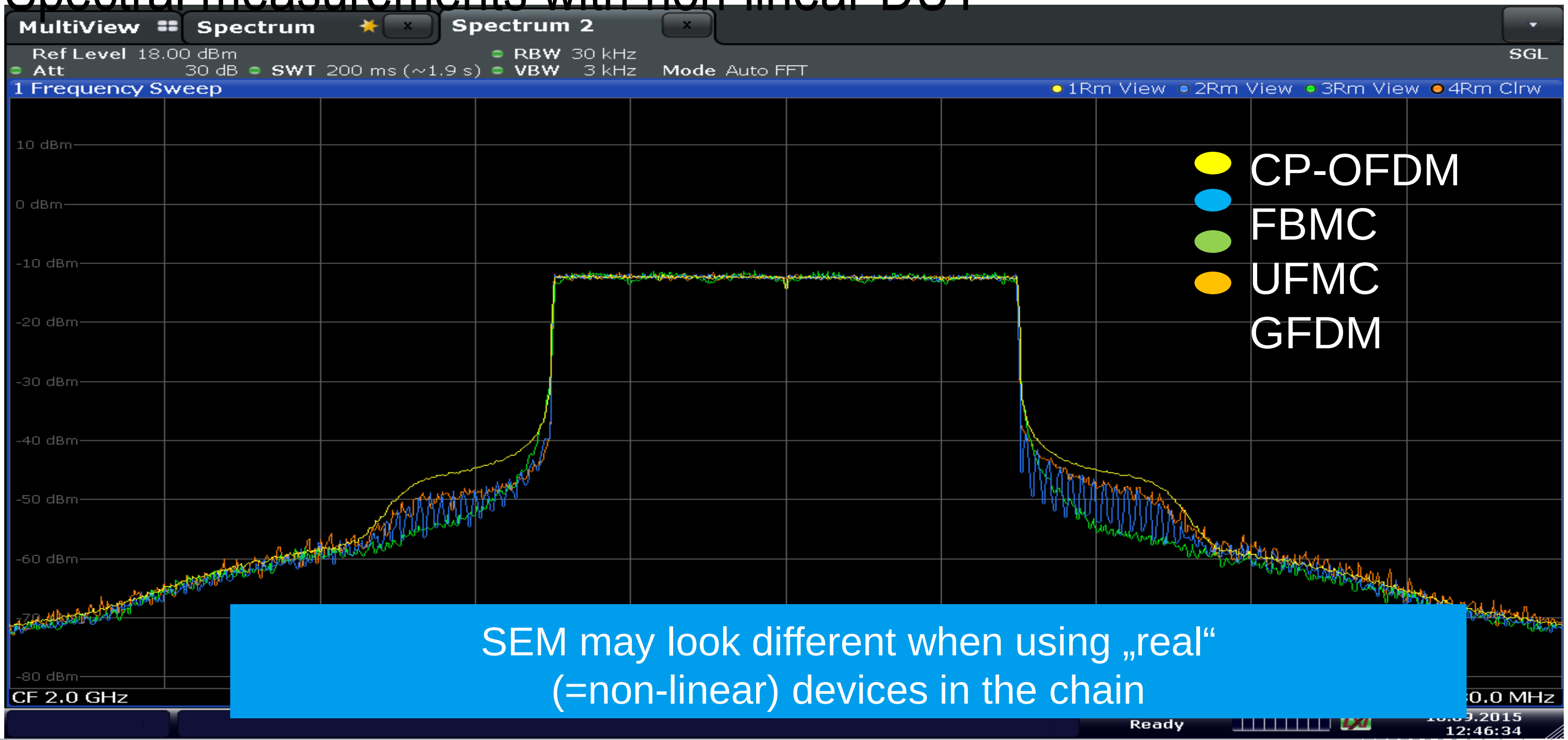


Test Solution for 5G: Waveform candidates



Test Solution for 5G waveform candidates

Spectral measurements with non-linear DUT



SEM may look different when using „real“
(=non-linear) devices in the chain

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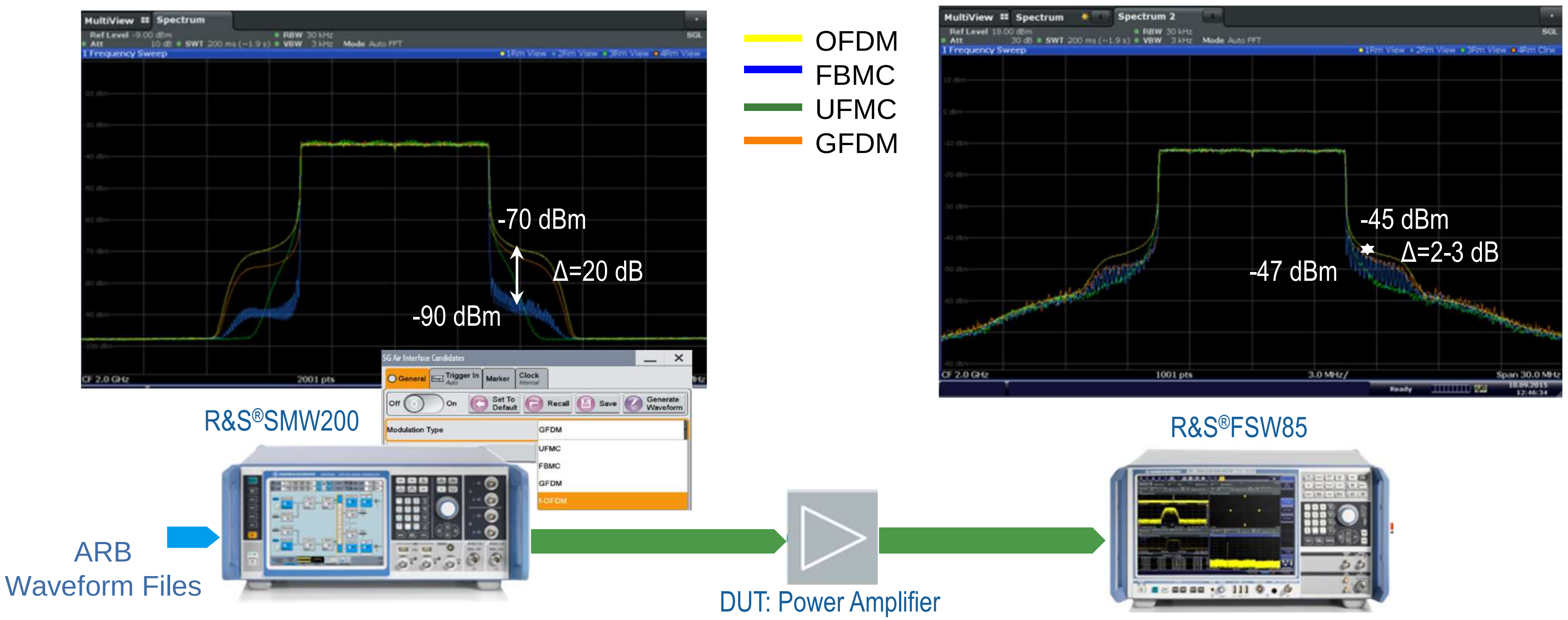
Waveform Gains: From Theory to Reality

From: Waveform theory and simulation

To: Real devices with non-linear elements



Two use cases: 5G Trial Services, Fixed Wireless Access (FWA)

PyeongChang 2018

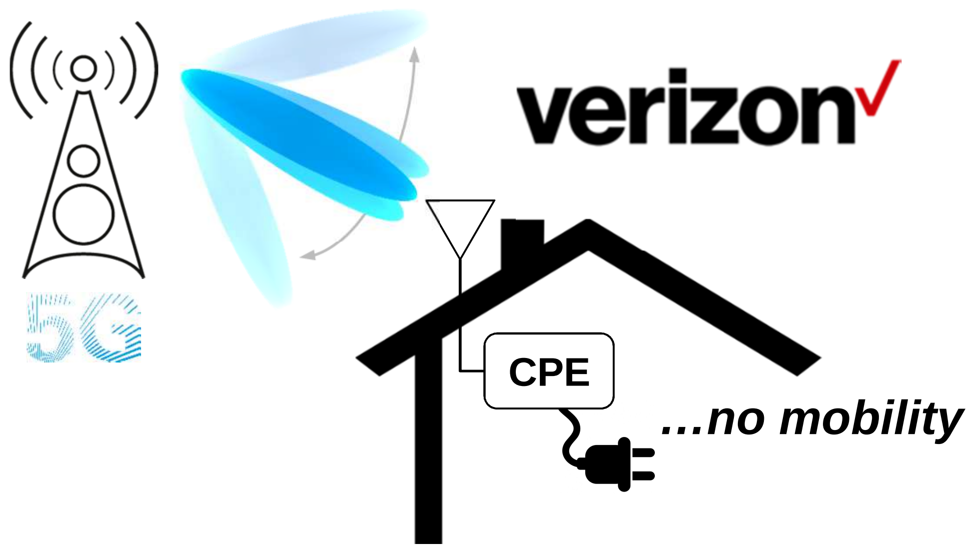
TOKYO 2020 CANDIDATE CITY

...mobility required

SK telecom

kt

NTT docomo

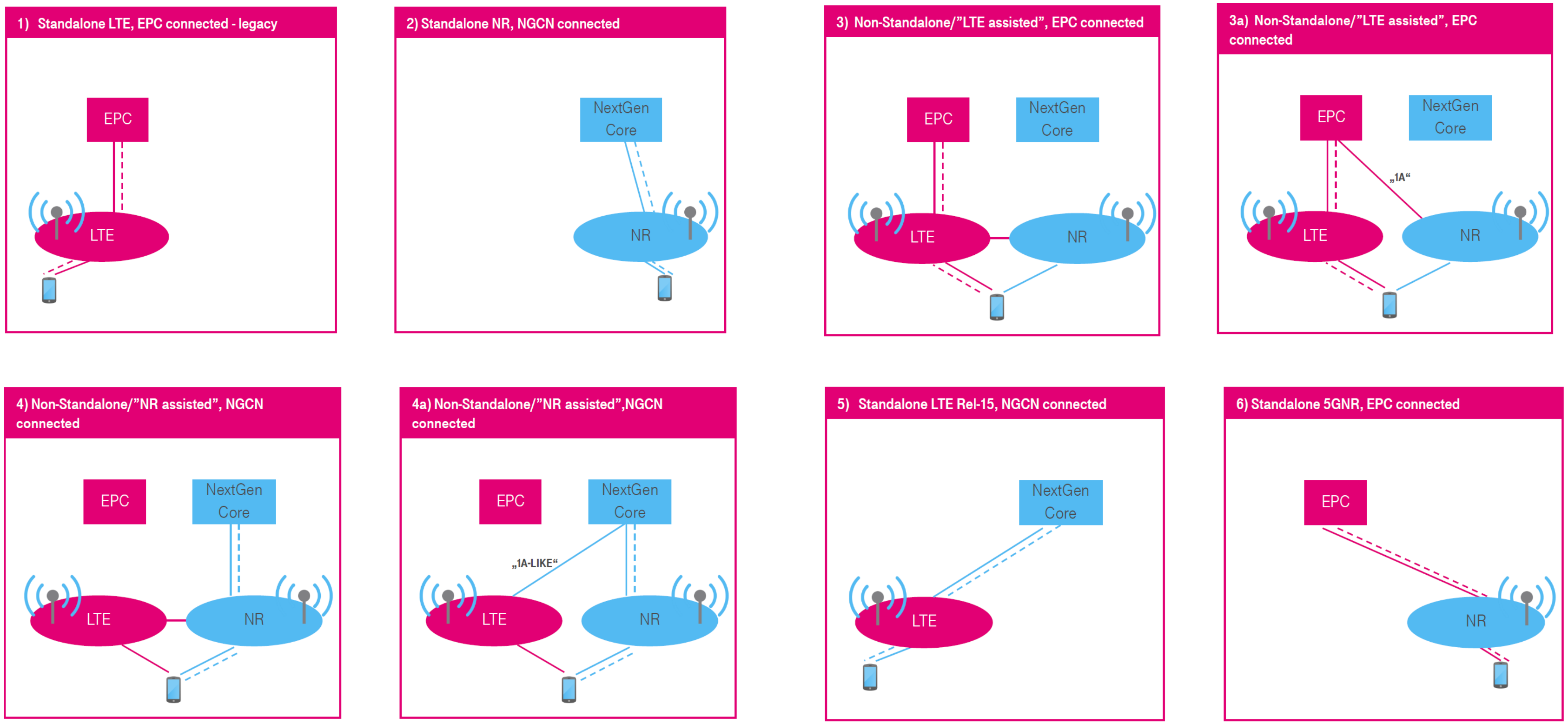


Verizon's Shammo: 5G pilot in 2017 is all about fixed wireless, not mobility

April 21, 2016 | By Monica Alleven

http://www.fiercewireless.com/tech/story/verizons-shammo-5g-pilot-2017-all-about-fixed-wireless-not-mobility/2016-04-21 [April 2016]

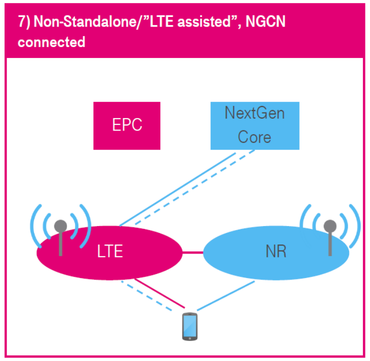
Different network architectures for 5G NR due to SA and NSA (1)

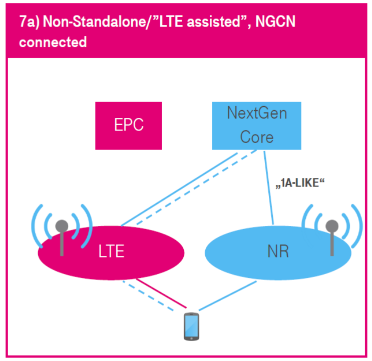


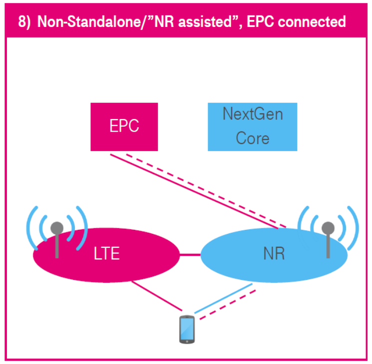
Different network architectures for 5G NR due to SA and NSA (2)

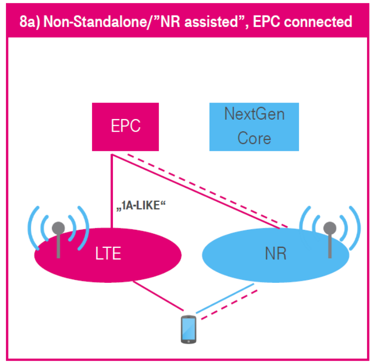
- There are 8 major options possible.
  - Option #1 corresponds to legacy deployed LTE
  - Option #6, #8 will not be studied due to irrelevance, Option #5 is not applicable from RAN2 perspective.
  - Leaves Option #2, #3, #4, #7.

	RAN2	RAN3
Scenario 1	-	-
Scenario 2	YES	YES
Scenario 3 / 3a	YES	YES
Scenario 4 / 4a	YES	YES
Scenario 5	NO	YES
Scenario 6	NO	NO ?
Scenario 7 / 7a	YES	YES
Scenario 8 / 8a	NO	NO

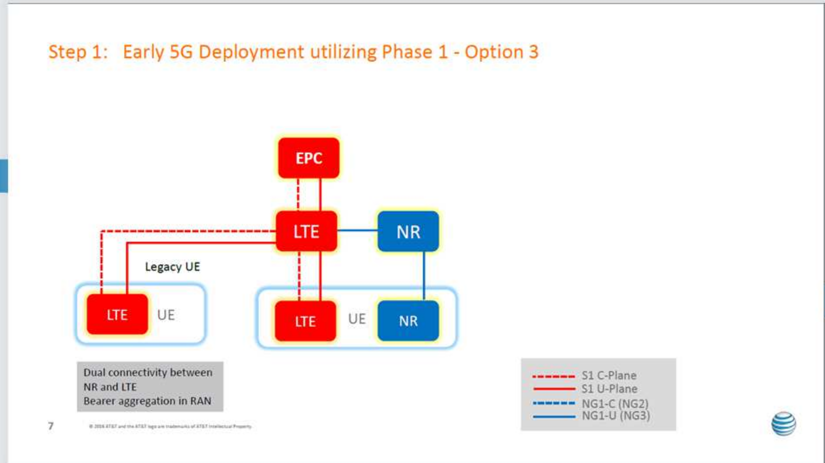




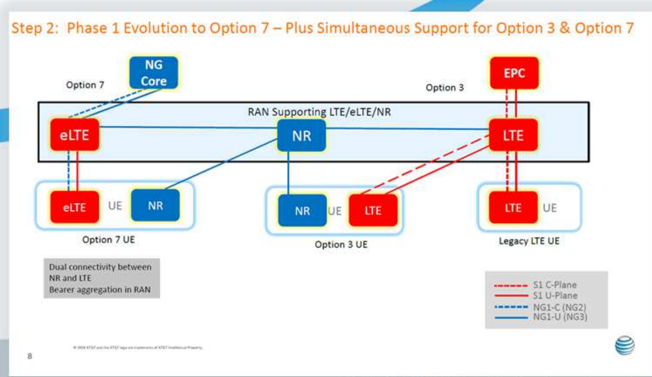


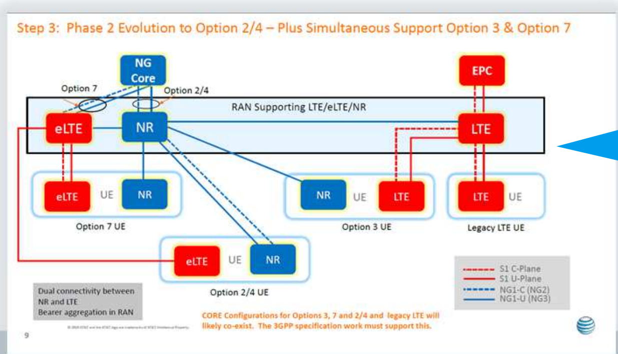


…many operators clearly announce their favor for NSA as a transition from 4G to 5G



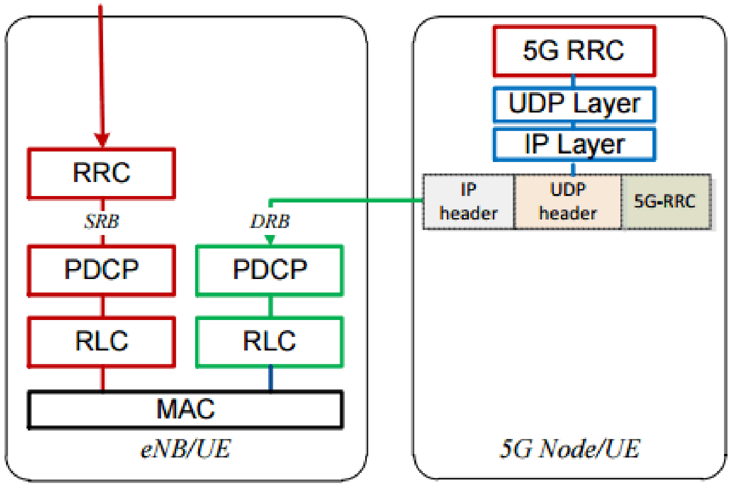
Source: [R3-161772](R3-161772) [June 2016]



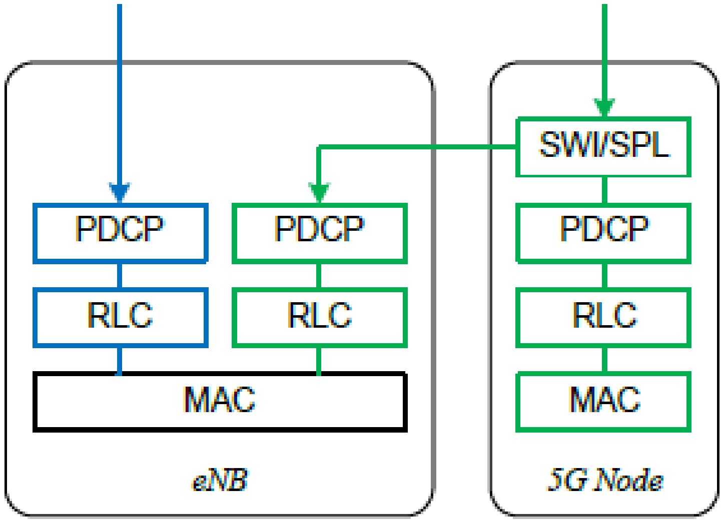


KT's version of 5G Dual Connectivity based on Non-Standalone mode

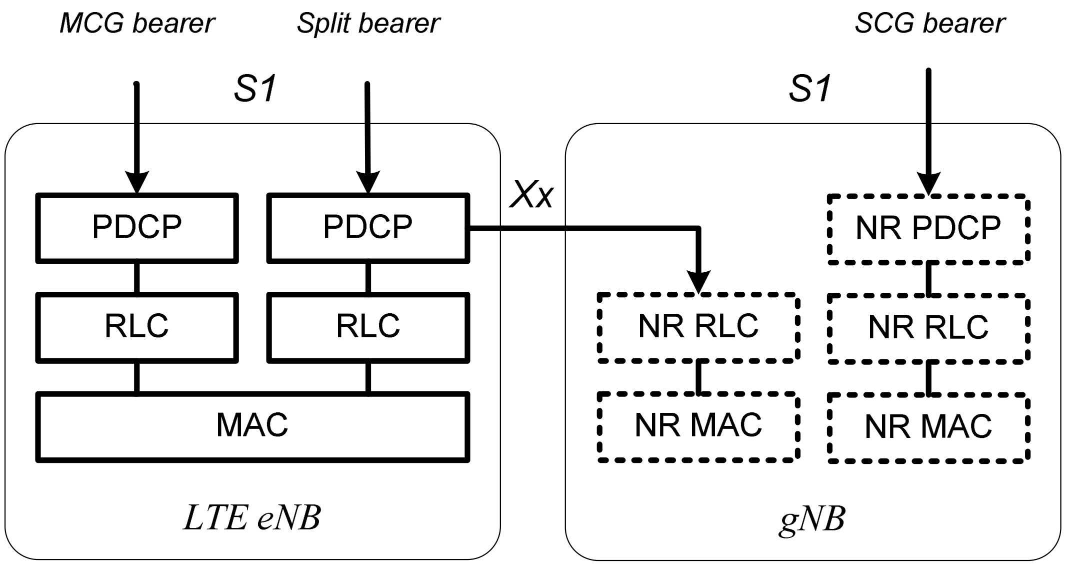
- Control plane



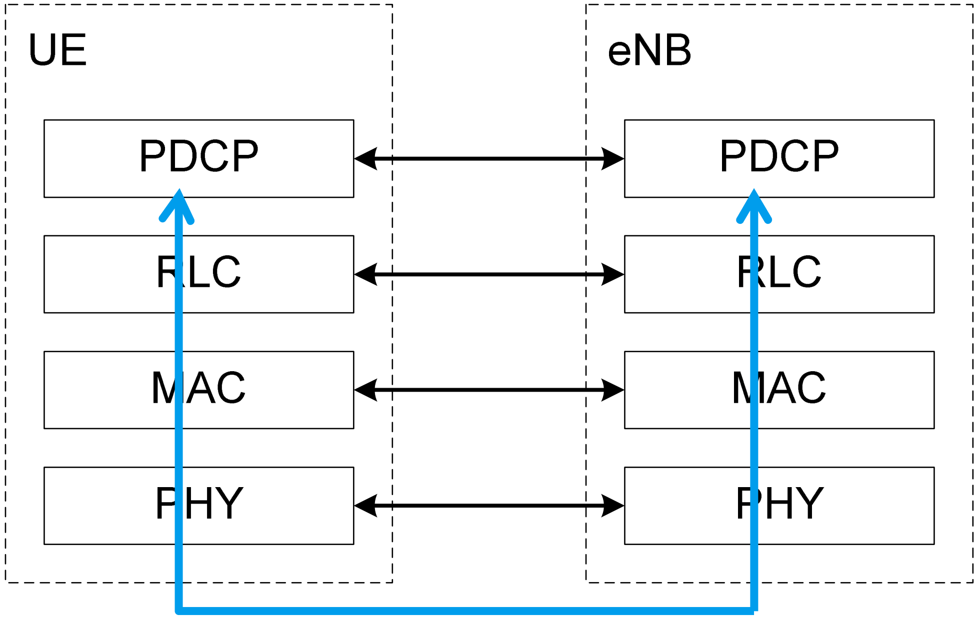
- User plane



…compare 3GPP's version of 5G NR NSA mode using dual connectivity approach (Rel-12)



5G scenarios: latency requirements for URLLC



Latency request: radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point via the radio interface <= 0.5 msec

Latest RAN#86bis (October 2016) Discussion
Channel Coding

- Agreement:
  - The channel coding scheme for eMBB data is LDPC, at least for information block size > X
  - FFS until RAN1#87 one of Polar, LDPC, Turbo is supported for information block size of eMBB data <= X
  - The selection will focus on all categories of observation, including overall implementation complexity, regardless of the number of coding schemes in the resulting solution (except if other factors are generally roughly equal)
  - The value of X is FFS until RAN1#87 (Nov 2016), 128 <= X <= 1024 bits, taking complexity into account
  - The channel coding scheme(s) for URLLC, mMTC and control channels are FFS

- Huawei has a concern on the upper value of the range of X to be considered.

Way Forward on Waveform for NR Uplink (RAN1#86bis)

- Agreement:
  - NR Support DFT-S-OFDM based waveform complementary to CP-OFDM waveform, at least for eMBB uplink for up to 40GHz
    - FFS additional low PAPR techniques
    - CP-OFDM waveform can be used for a single-stream and multi-stream (i.e. MIMO) transmissions, while DFT-S-OFDM based waveform is limited to a single stream transmissions (targeting for link budget limited cases)
    - Network can decide and communicate to the UE which one of CP-OFDM and DFT-S-OFDM based waveforms to use
      - **Note: both CP-OFDM and DFT-S-OFDM based waveforms are mandatory for UEs**
  - RAN1 should target for a common framework in designing CP-OFDM and DFT-S-OFDM based waveforms (without compromising CP-OFDM performance/complexity), e.g., control channels, RS, etc.
  - Discuss further offline for possible refined evaluation assumptions/methodology for waveform evaluations

3GPP covers 5G NR in 38er series

spec number	title	notes
TR 38.801	Study on New Radio Access Technology: Radio Access Architecture and Interfaces	
TR 38.802	Study on New Radio Access Technology Physical Layer Aspects	
TR 38.803	TR for Study on New Radio Access Technology: RF and co-existence aspects	
TR 38.804	TR for Study on New Radio Access Technology Radio Interface Protocol Aspects	
TR 38.900	Study on channel model for frequency spectrum above 6 GHz	
TR 38.912	Study on New Radio (NR) Access Technology	
TR 38.913	Study on Scenarios and Requirements for Next Generation Access Technologies	

5G New Radio (NR) numerology

A GLOBAL INITIATIVE

- Current working assumption (WA) based on 3GPP RAN1#85 is that subcarrier scaling is based on f_0 *2^m with f_0 = 15 kHz and scaling factor is 2^m with m {-2, 0, 1, …, 5}

m =	-2	0	1	2	3	4	5	…
Subcarrier Spacing [kHz]	3.75	15	30	60	120	240	480	…
Symbol Length [µs]	266.67	66.67	33.33	16.67	8.333	4.17	2.08	…
Component Carrier BW [MHz]	FFS							
Cyclic Prefix Length [µs]	FFS							
Subframe Length [ms] (= $1/2^m$)	4	1	0.5	0.25	0.125	0.0625	0.03125	
Radio Frame Length [ms]								

- Agreements based on RAN1#86 (08/2016)
  - More than one CP length should be studied for a given subcarrier spacing
  - The different CP lengths for a given subcarrier spacing can be of substantially different lengths
  - FFS whether all of subcarrier spacing's support more than one CP length or not.

Comparison LTE and Verizon Wireless 5G

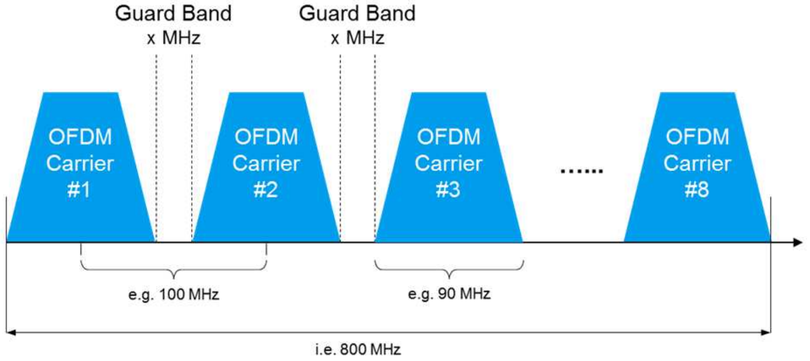
PHY parameterization (1/2)

PHY parameter	LTE (Rel.8-14)	Verizon 5G
Downlink (DL)	OFDM	OFDM
Uplink (UL)	DFT-s-OFDM (SC-FDMA)	OFDM
Subframe Length	1ms	0.2ms
Subcarrier Spacing	15 kHz	75 kHz
Sampling Rate	30.72 MHz	153.6 MHz
Bandwidth	20 MHz	100 MHz
NFFT	2048	2048
OFDM symbol duration, no CP	66.67 us	13.33 us
Frame Length	10 ms	10 ms
#Subframes (#slots)	10 (20)	50 (100)
CP Type	Normal & Extended	Normal Only
Multiplexing	FDD / TDD	Dynamic TDD
Max RBs	6,15,25,50,75,100	100
DL/UL Data coding	Turbo Code	LDPC code

Comparison LTE and Verizon Wireless 5G

PHY parameterization (2/2)

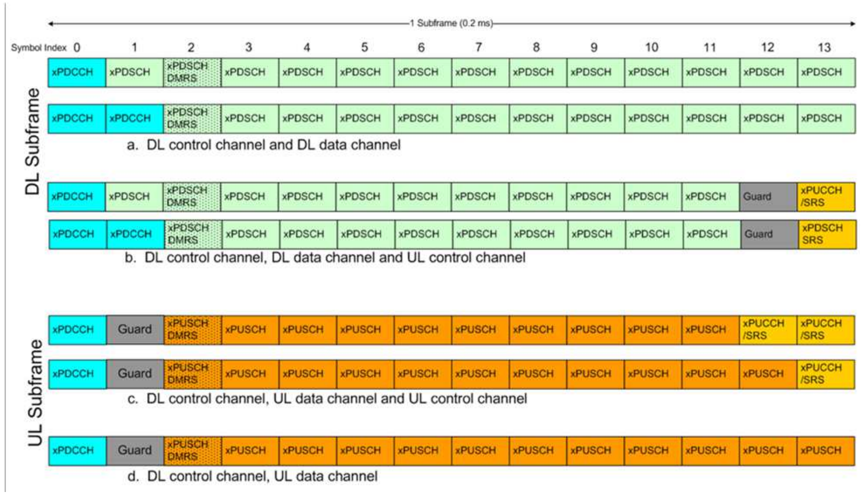
- Aggregation of up to 8 carriers 100 MHz each.
  - LTE: 3GPP Rel.10-12: only 5 carriers 20 MHz each.
  - LTE: 3GPP Rel.13: 32 carriers up to 20 MHz each.



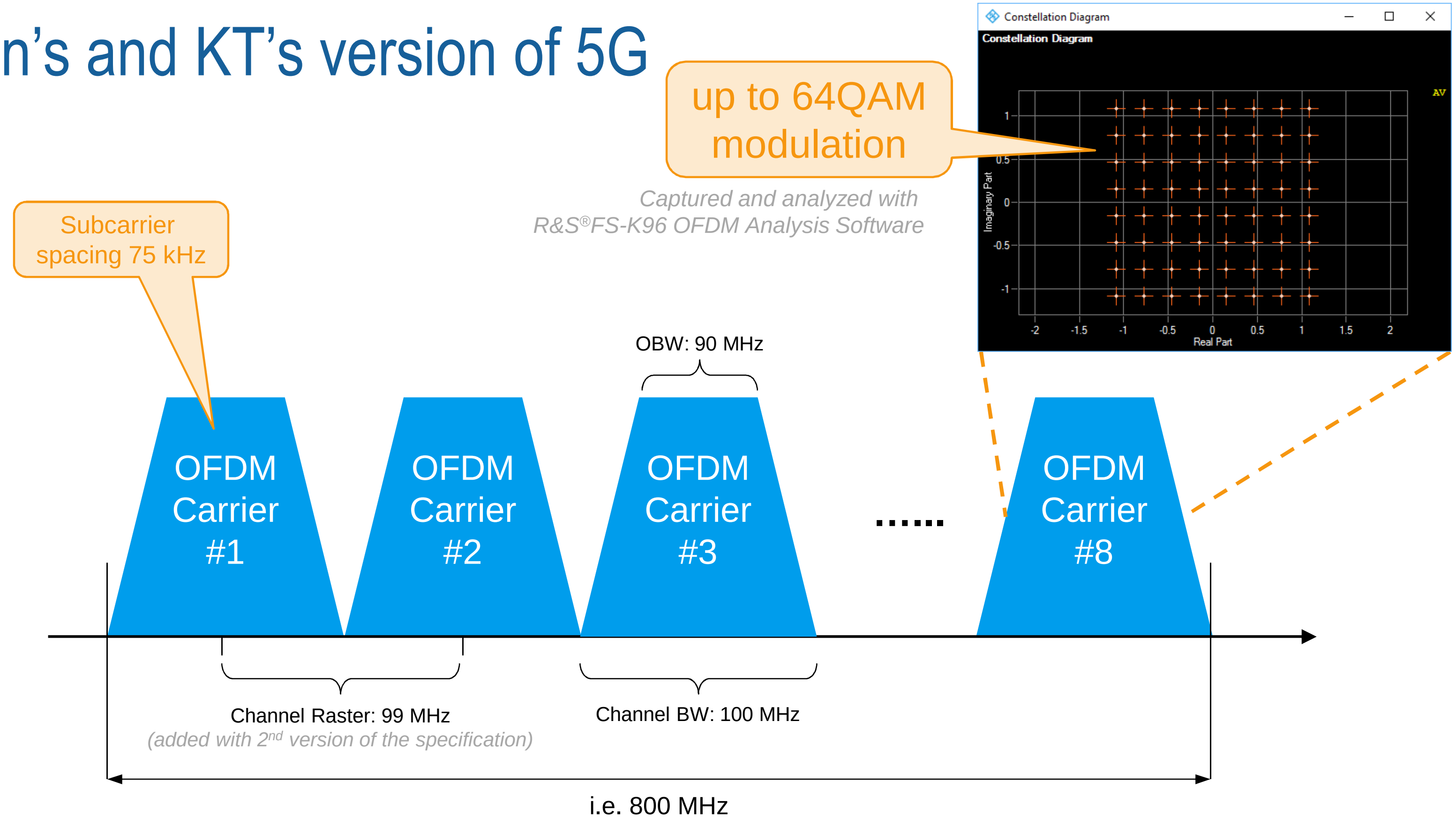
- New PHY signals and new or modified PHY channels, supporting additional capabilities.

Dynamic switch on a subframe basis from downlink to uplink transmission.

- 4 possibilities:

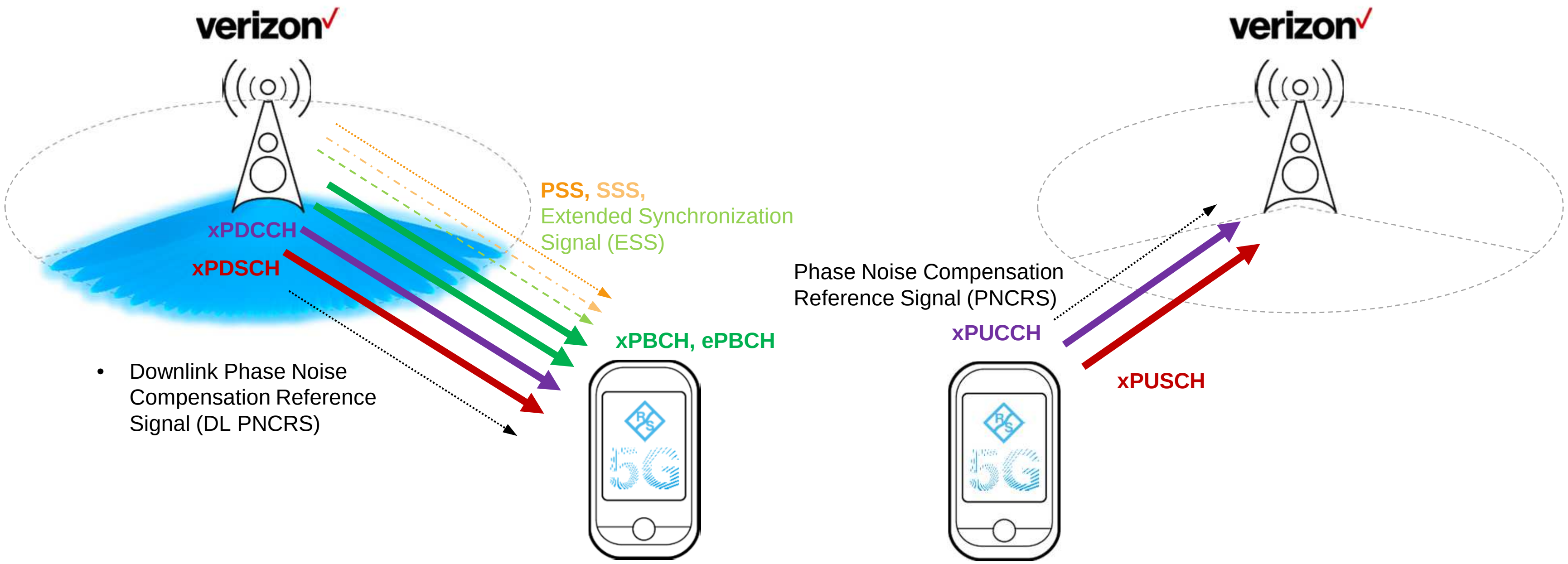


Verizon's and KT's version of 5G

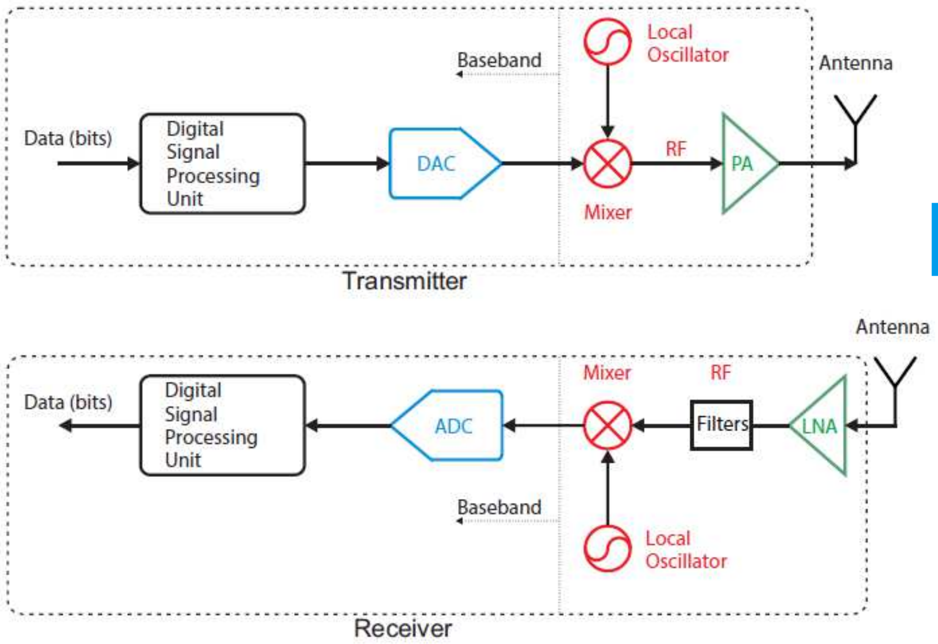


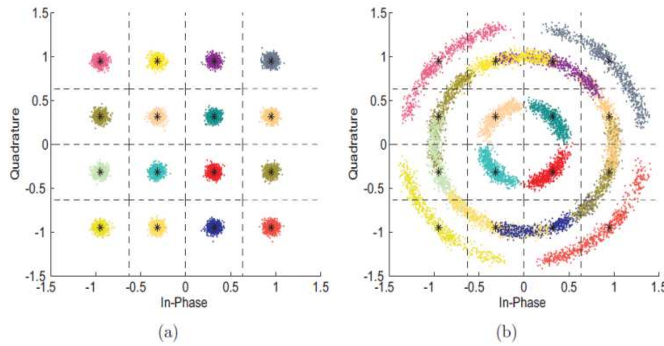
Verizon 5G specification

Basic principles: Downlink and Uplink



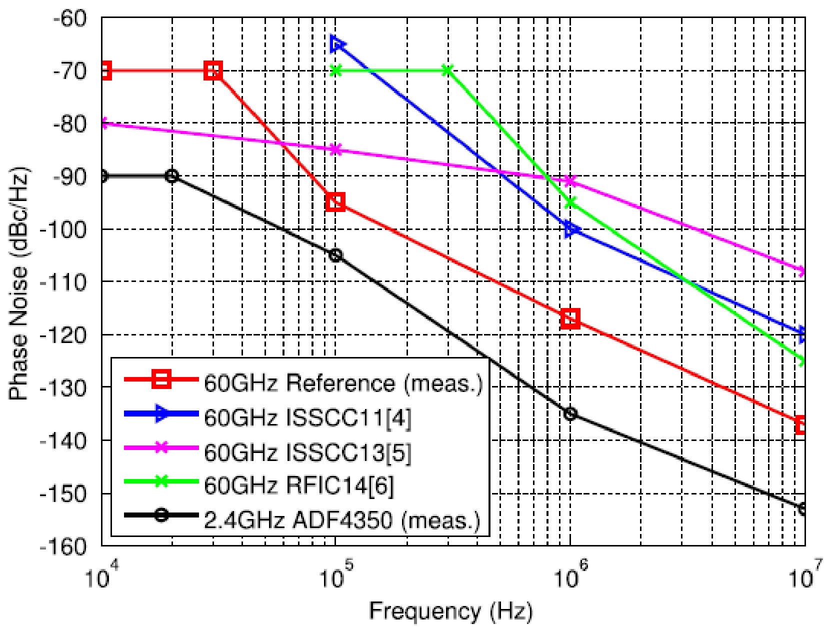
Verizon 5G vision: mapping of phase noise reference signals





effect of phase noise as an example of 16 QAM.

5G scenarios: dual link scenario between LTE and 5G NR



At higher frequencies, the Rx is affected by phase noise

$$r = s * H + n$$

our receiver equation becomes more complex

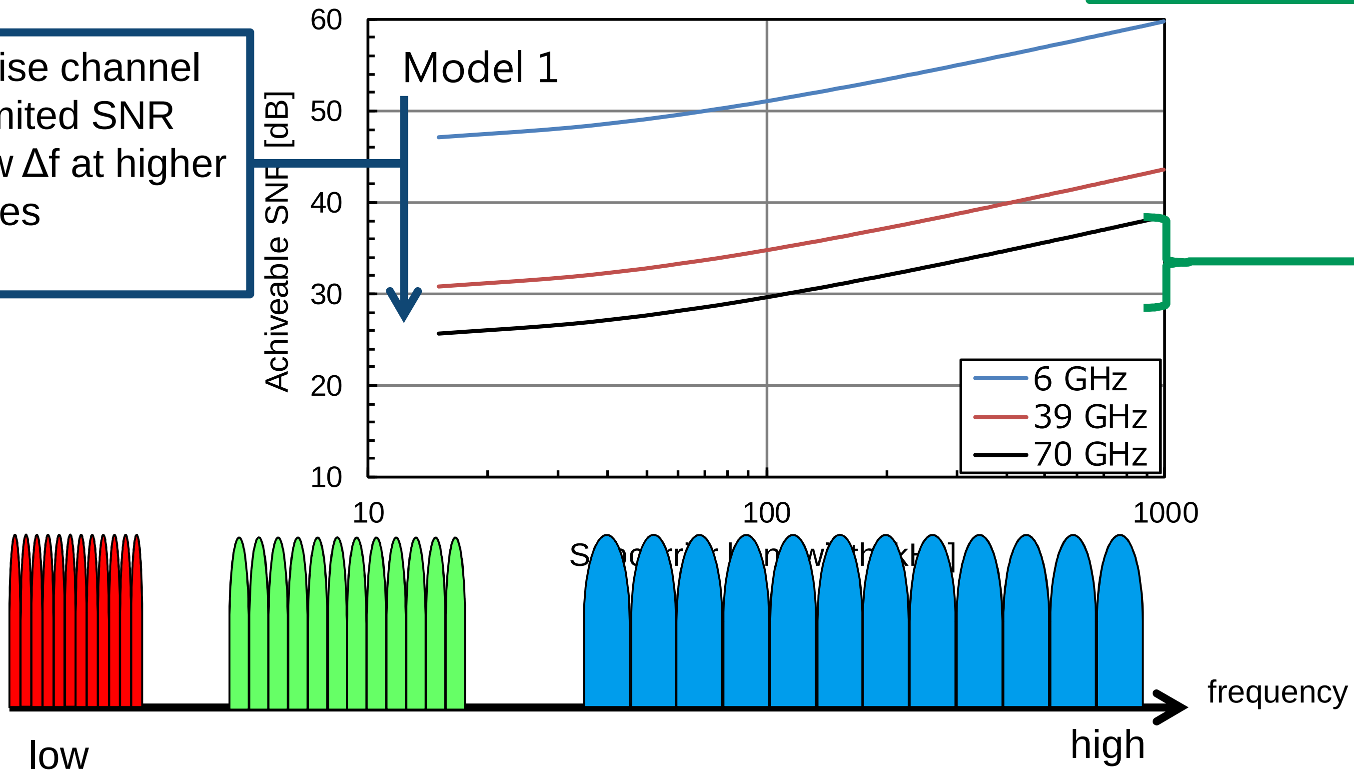
$$r_i = e^{j2\pi\phi_i}\left(\sum_{k=0}^{N_{\mathrm{CIR}}-1} s_i h_{i-k}\right) + w_i,$$

idea is to remove the phase noise influence with the help of additional reference symbols

5G air interface: impact of phase noise

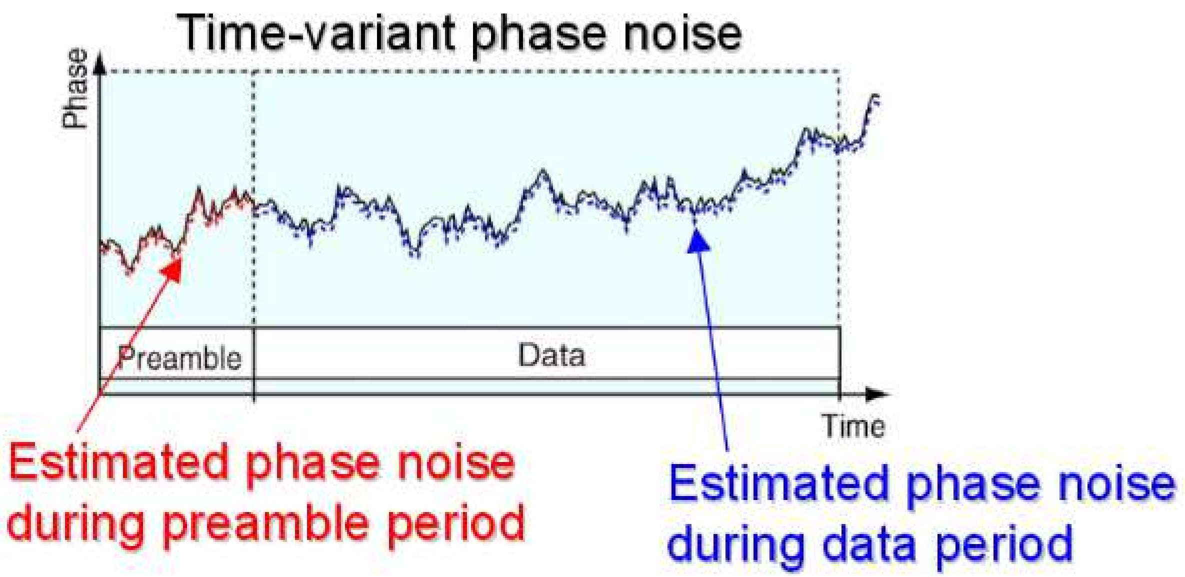
phase noise channel model: limited SNR for narrow Δf at higher frequencies

improving achievable SNR
=> widening Δf



3GPP R1-165177

5G scenarios: dual link scenario between LTE and 5G NR

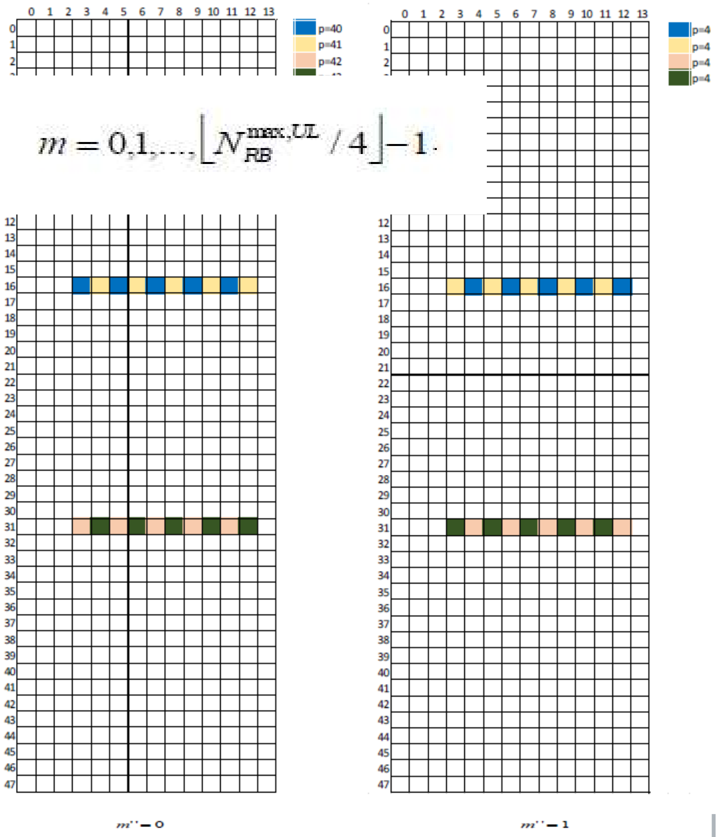


5GTF : mapping of phase noise reference signals, e.g. xPUSCH

$$r(m) = \frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m)) + j\frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m+1)), \quad m = 0,1,\ldots,\left\lfloor N_{RB}^{\max,UL} / 4 \right\rfloor - 1.$$

mapping of a constant envelope demodulation reference signal for phase noise estimation into the data flow

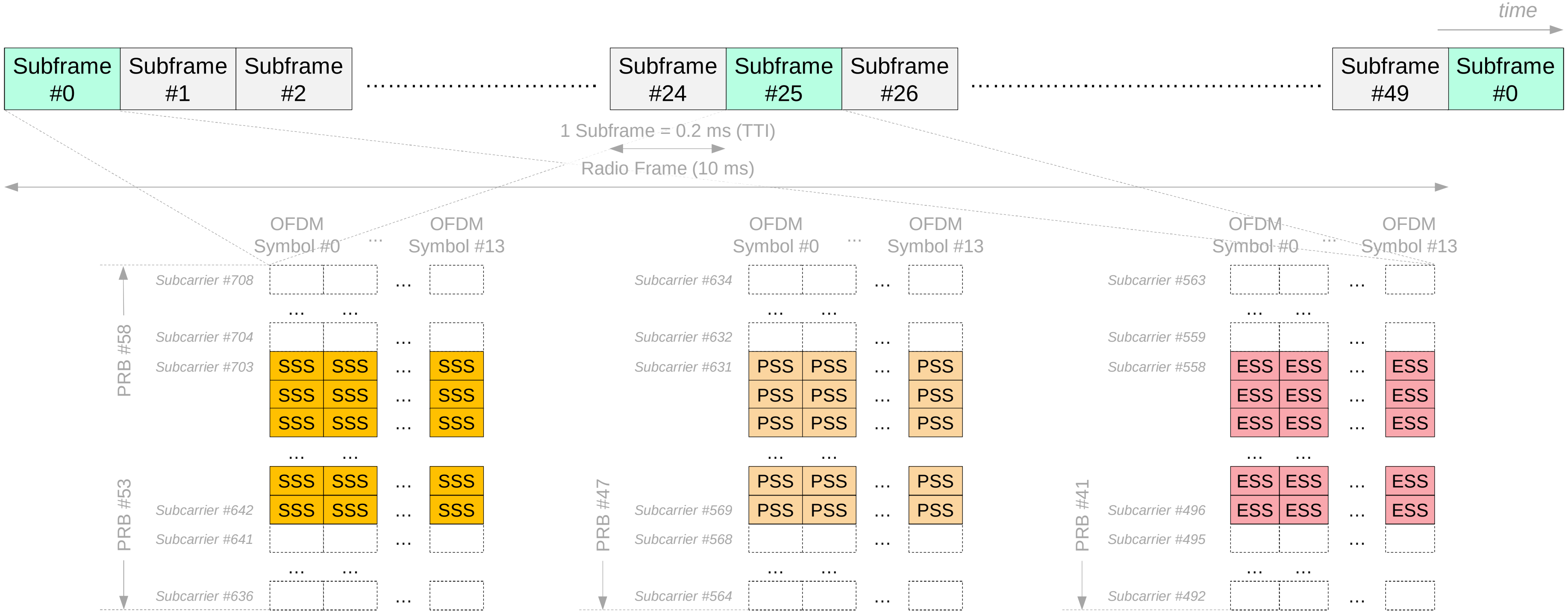
reference signal is based on a PN sequence linked to physical Cell ID



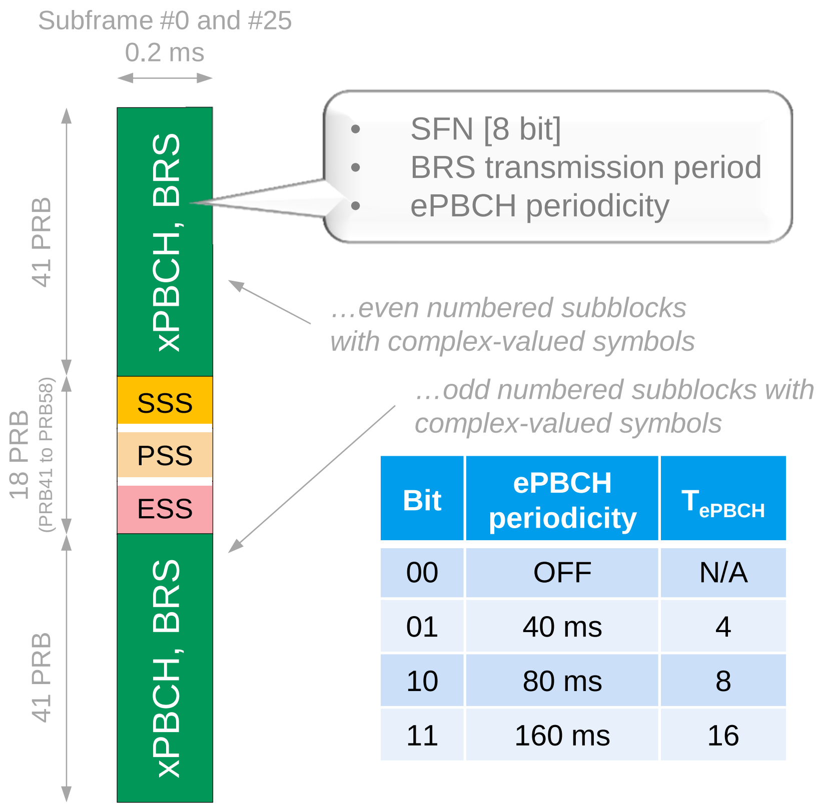
ROHDE&SCHWARZ

Old and new synchronization signals

PSS/SSS, Extended Synchronization Signal (ESS)



xPBCH, ePBCH – Where are the broadcast channels transmitted?

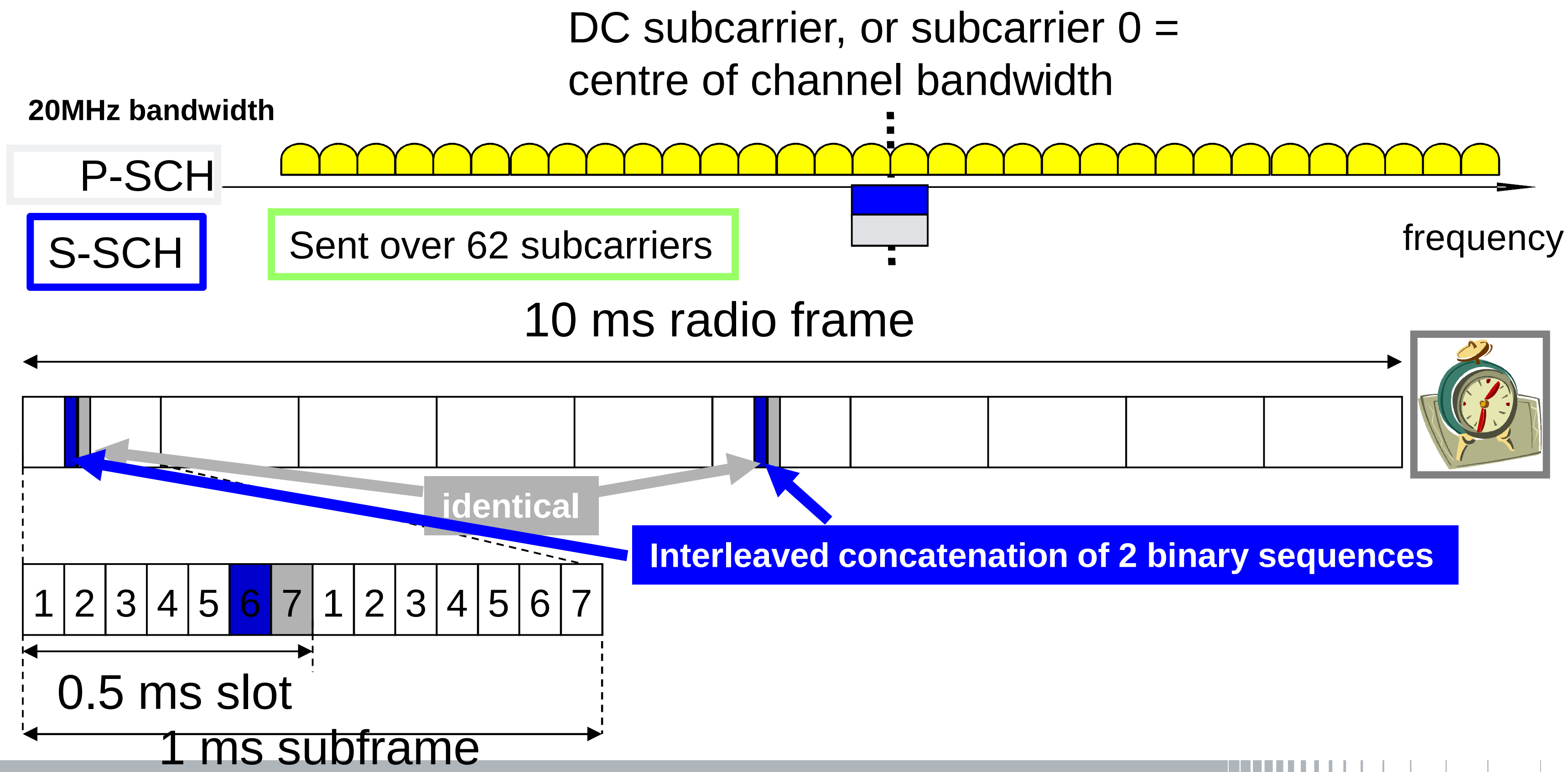


Bit	ePBCH periodicity	T_{ePBCH}
00	OFF	N/A
01	40 ms	4
10	80 ms	8
11	160 ms	16

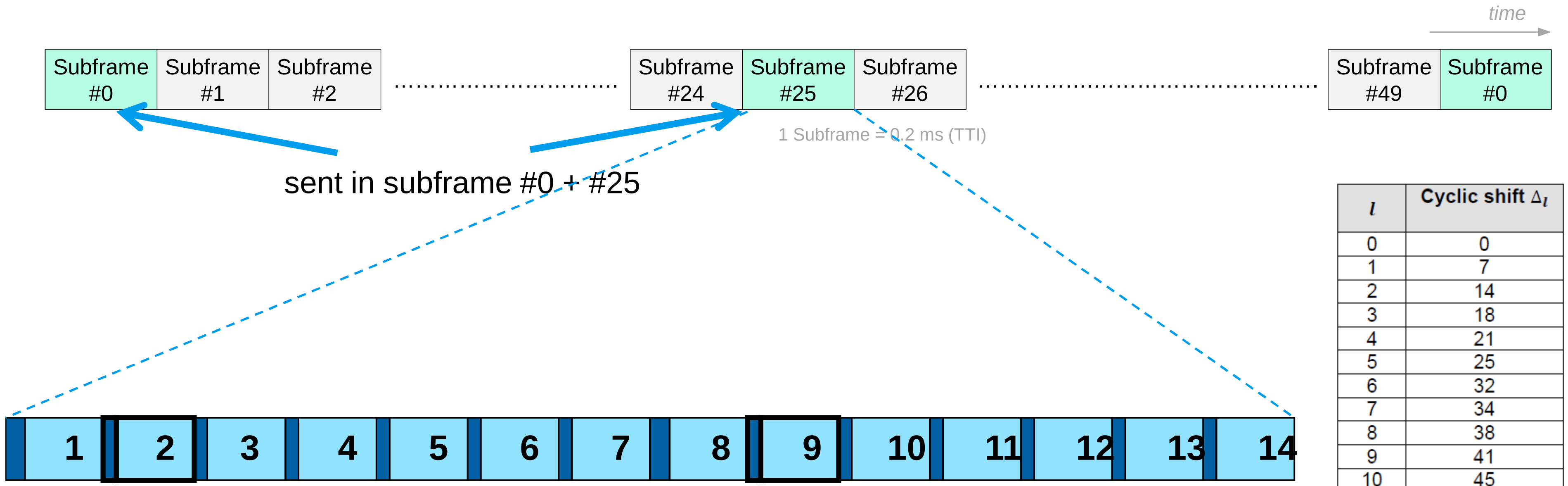
- xPBCH transmitted on 4 consecutive radio frames.
  - Occupies subframe #0, #25 with PSS/SSS/ESS and BRS; BRS are used to demod xPBCH.
  - Transmitted info (MIB): SFN (8 bits), BRS period, ePBCH transmission periodicity.
- ePBCH carries System Information Block (xSIB) and is transmitted on pre-defined or configured subframe.
  - Subframe depends on BRS transmission period.
  - Periodicity is (none, 4, 8, 16) radio frames (xPBCH).

BRS transmission period	# of subframes	Subframes within radio frame
1 slot < 5 ms	1	49th
1 subframe = 5 ms	2	48th, 49th
2 subframes = 10 ms	4	46th, 47th, 48th, 49th
4 subframes = 20 ms	8	42nd, 43th ,… ,48th ,49th

Initial synchronization aspects in 5G NR: LTE reminder



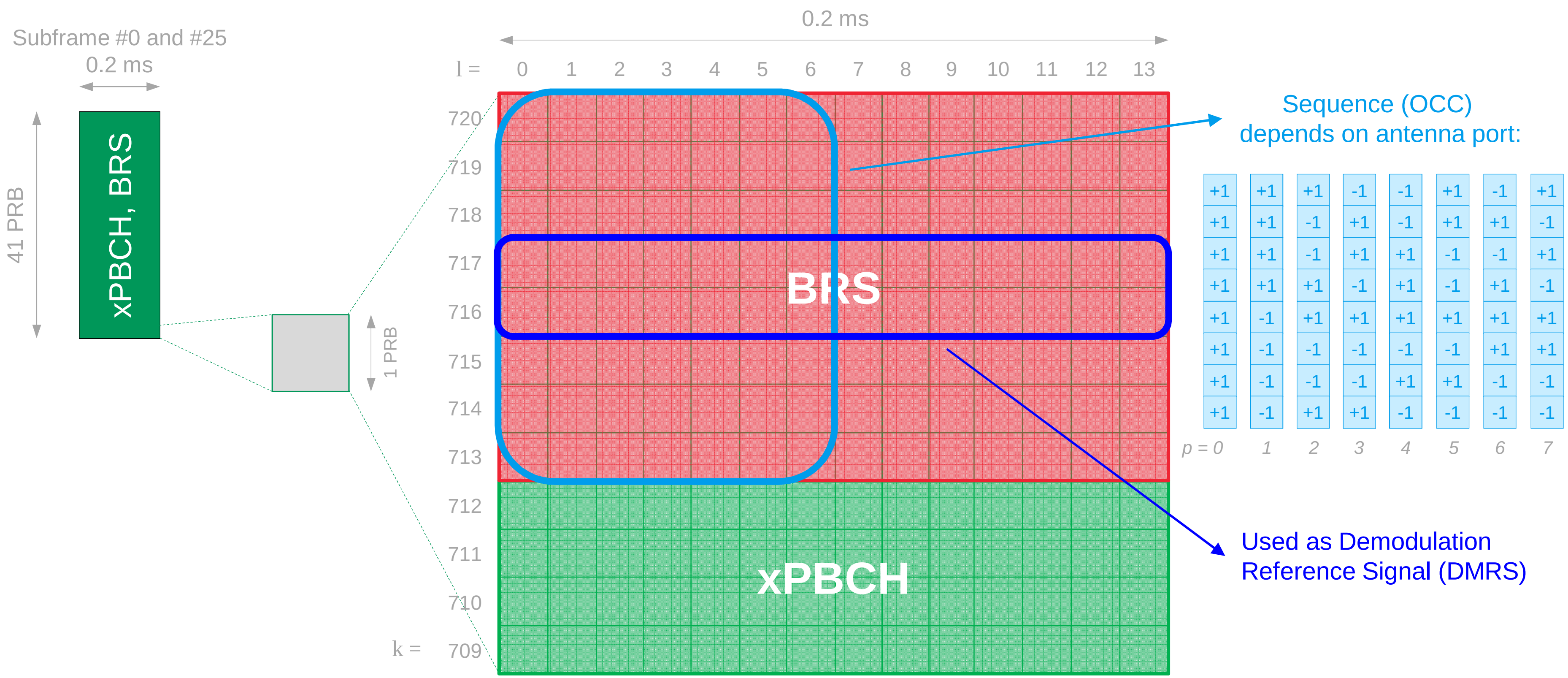
5GTF: concept of extended synchronization signal ESS



l	Cyclic shift Δ_l
0	0
1	7
2	14
3	18
4	21
5	25
6	32
7	34
8	38
9	41
10	45
11	52
12	59
13	61

ESS allows to identify the OFDM symbol index based on a cyclic shift.
That allows the receiver to identify symbol timing, which
is important for the overall beamforming acquisition process

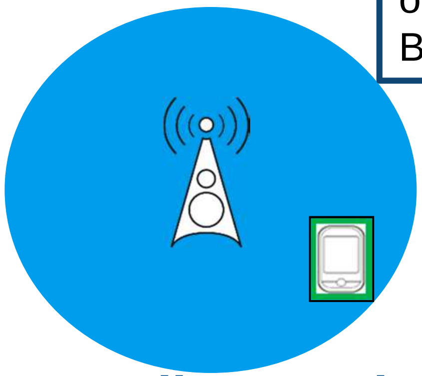
xPBCH, Beamforming Reference Signal (BRS)



p = 0	1	2	3	4	5	6	7
+1	+1	+1	-1	-1	+1	-1	+1
+1	+1	-1	+1	-1	+1	+1	-1
+1	+1	-1	+1	+1	-1	-1	+1
+1	+1	+1	-1	+1	-1	+1	-1
+1	-1	+1	+1	+1	+1	+1	+1
+1	-1	-1	-1	-1	-1	+1	+1
+1	-1	-1	-1	+1	+1	-1	-1
+1	-1	+1	+1	-1	-1	-1	-1

5G air interface aspects: beam sweeping for initial access

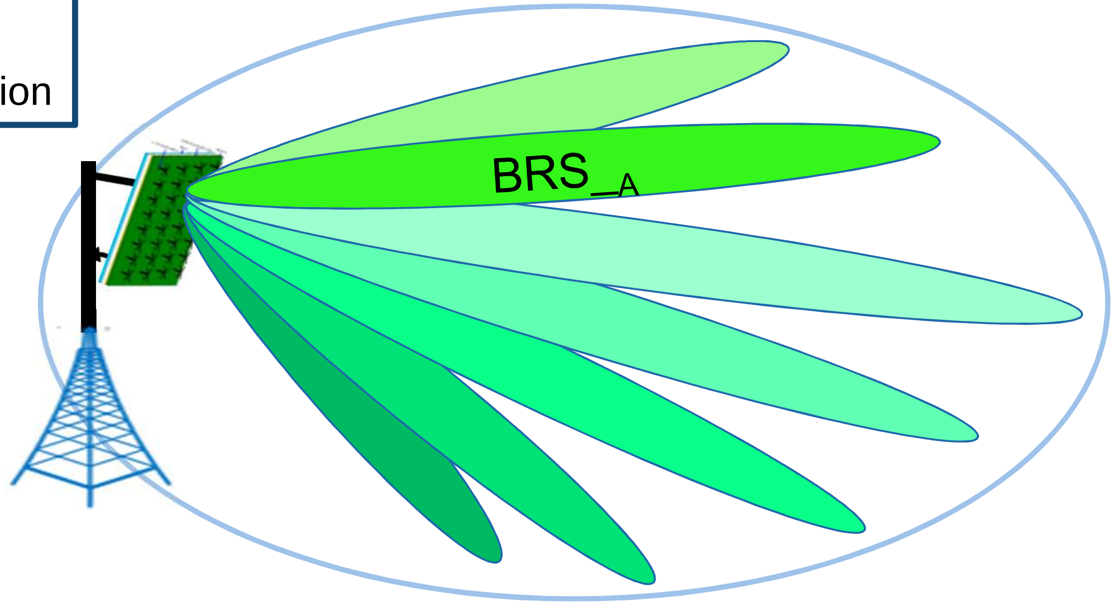
traditional approach: omnidirection Tx of BCCH for cell detection



Friis equation

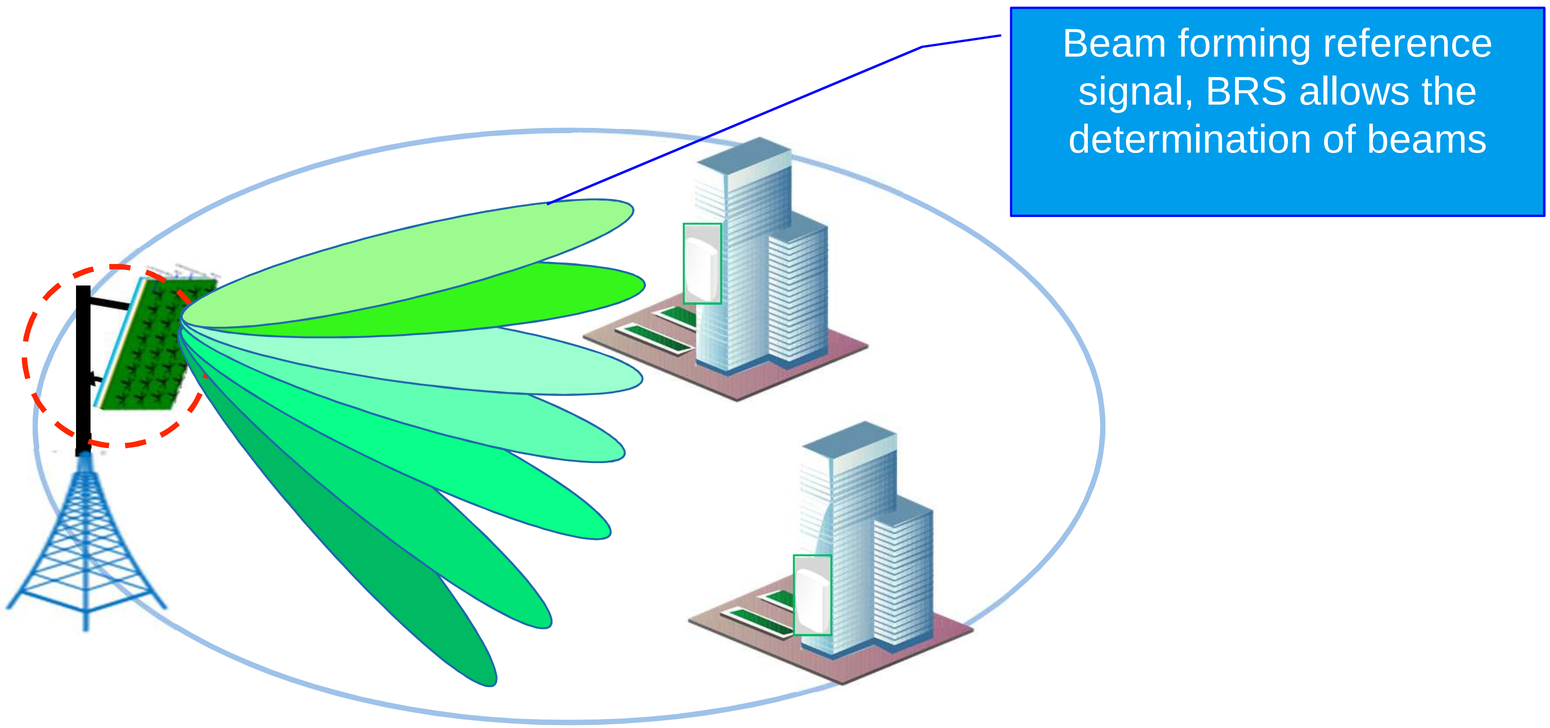
$$\frac{P_{Rx}}{P_{Tx}} = G_{antenna}\left(\frac{c}{4\pi f d}\right)^{\gamma}$$

at higher frequencies: Free space path loss is high -> beamforming with high gain

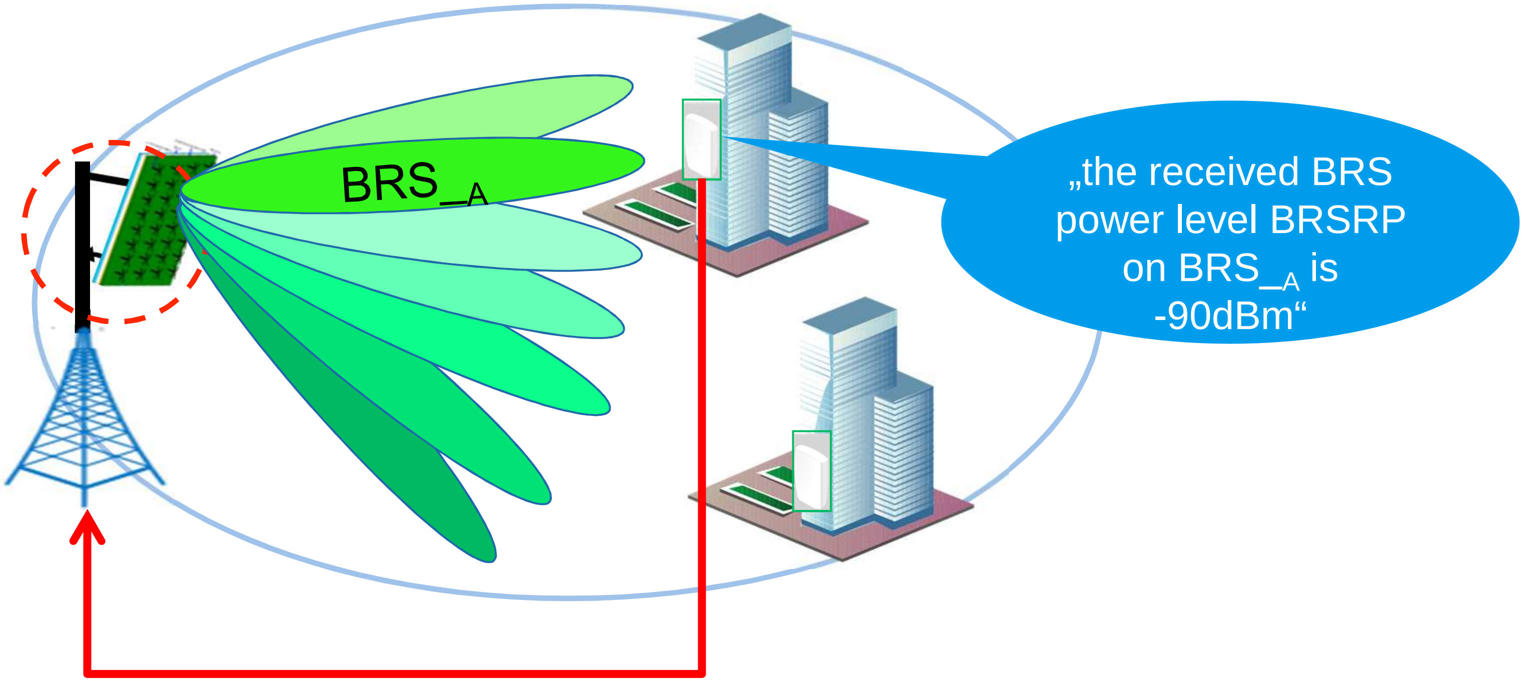


Beam sweeping procedure for power efficiency and cell detection

5G air interface aspects: beam reference signals

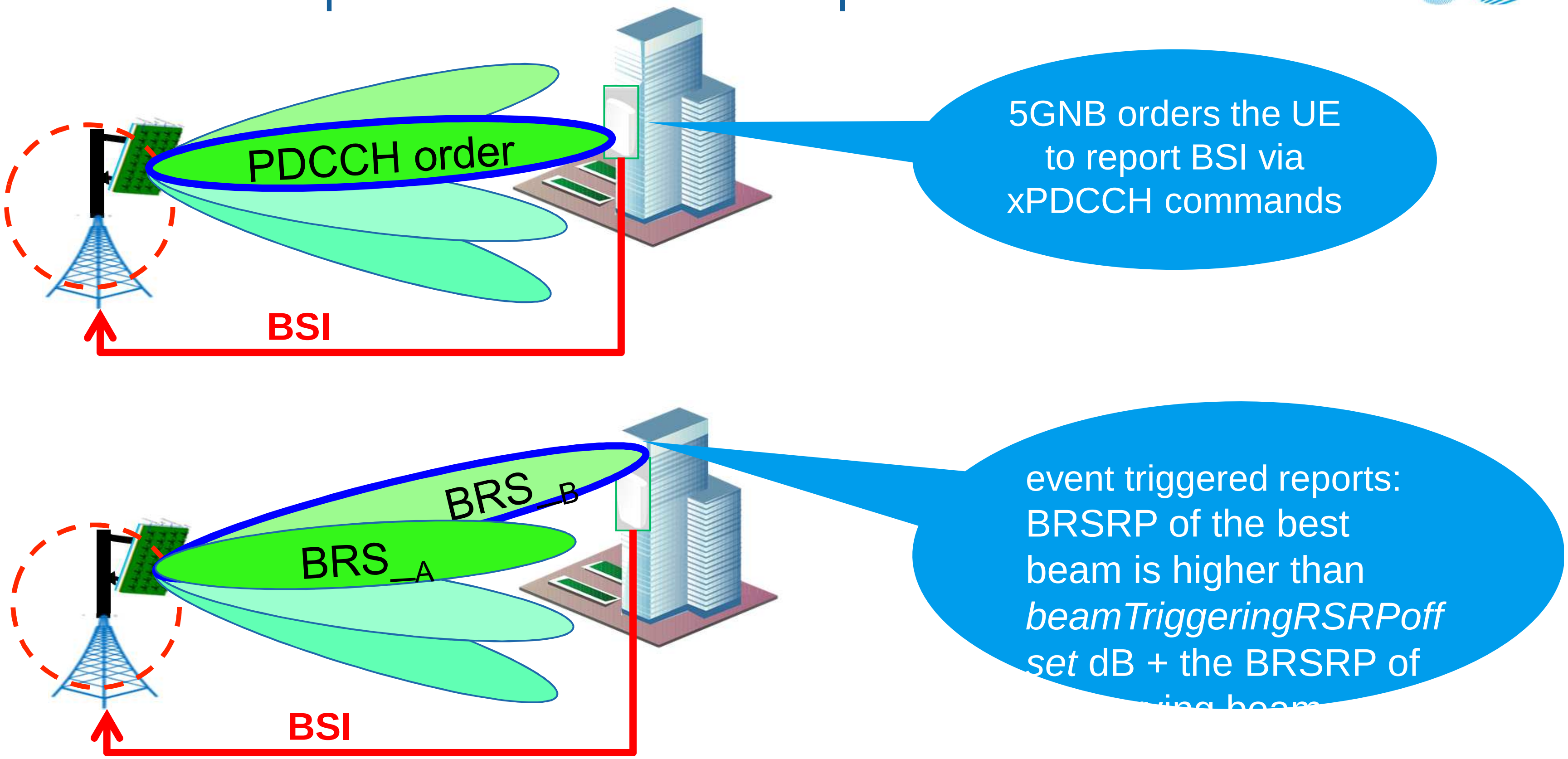


5G air interface aspects: beam reporting

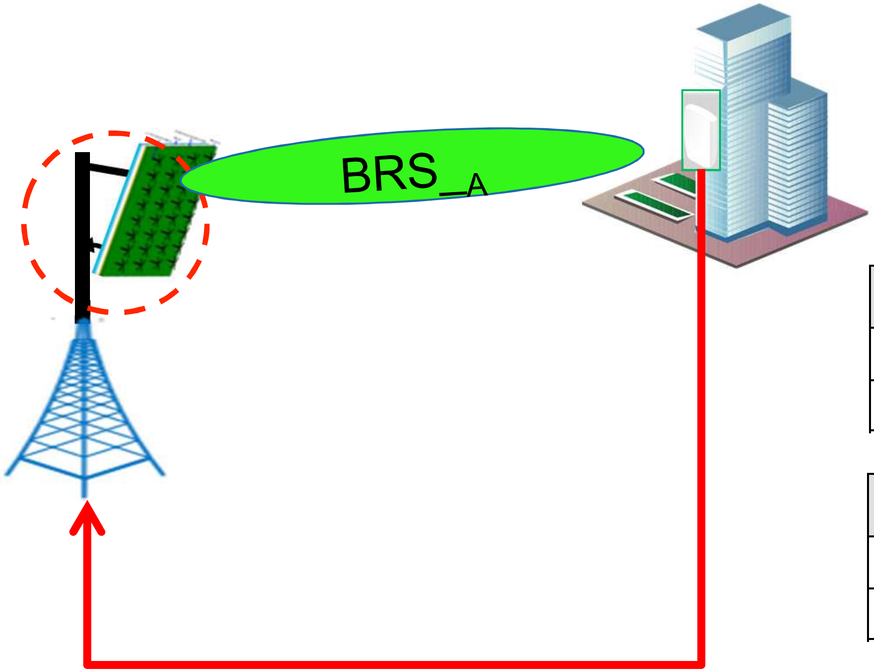


UE reports the beam status indication BSI

5G air interface aspects: beam status reports



5G air interface aspects: beam forming reporting



UE maintains up to 4 BSR sets, each set consist of beam indicators + power indicator

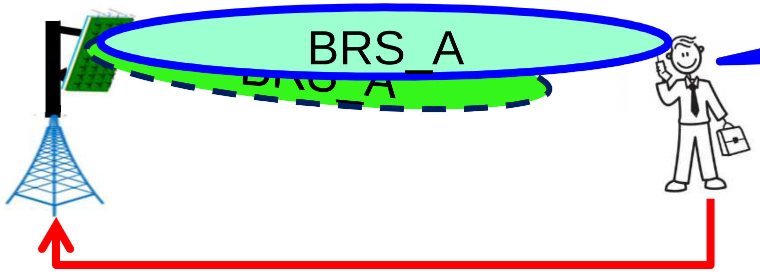
Field	Bit width
Beam index	9*N
Wide-band BRSRP	7*N

Field	Bit width
BRRS-RI	3*N
Wide-band BRRS-RP	7*N

UE reports beam index based on BRS or beam refinement index BRRS-RI and power level (i.e. BRSRP or BRRS-RP)

5G air interface aspects: beam switching procedure

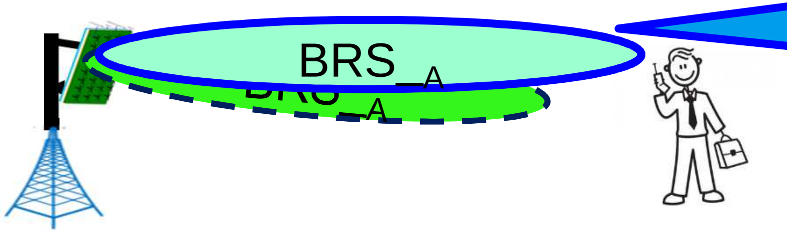
DCI based



Beam switch to strongest BSRP indicated by UE in previous report

BSI report. Strongest BSRP will be new beam index

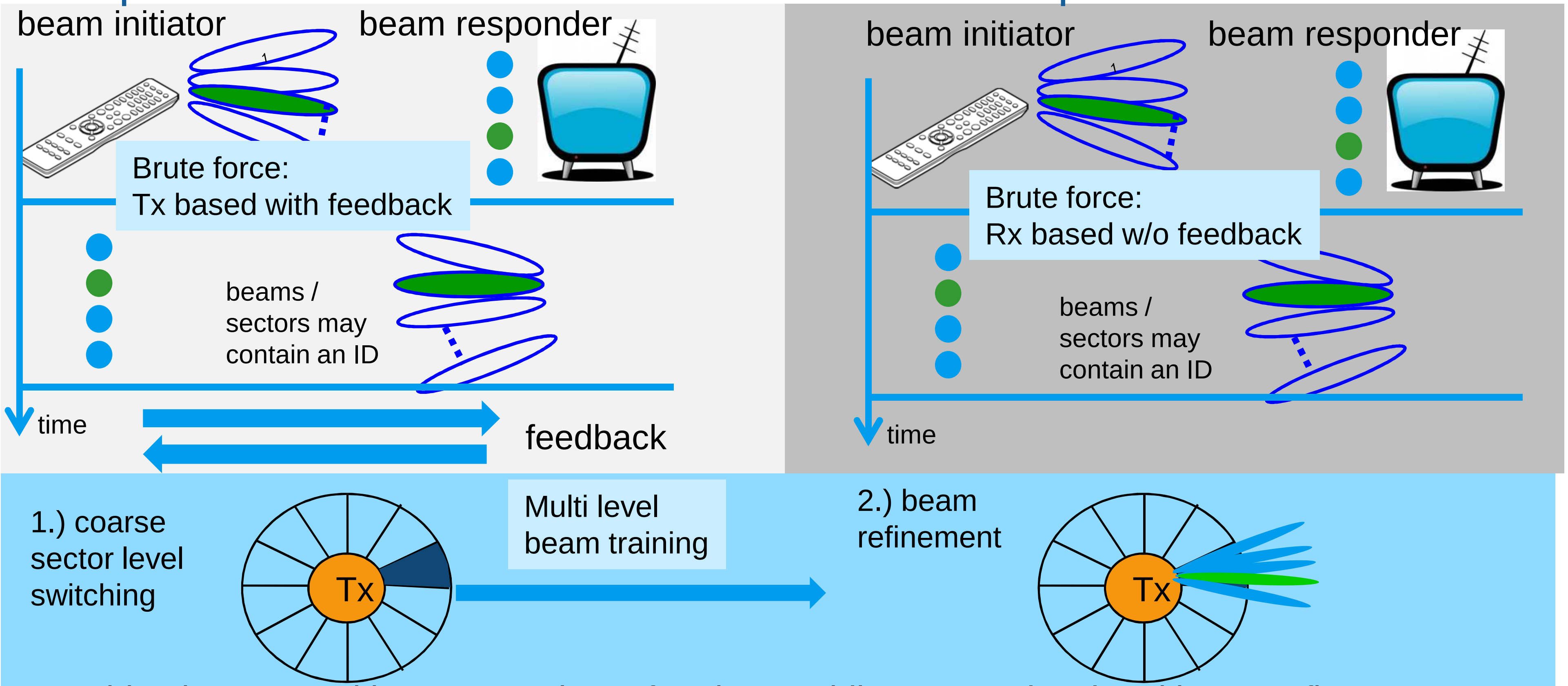
MAC-CE based



Beam switch indicated via MAC-CE signalling, switch to new beam index

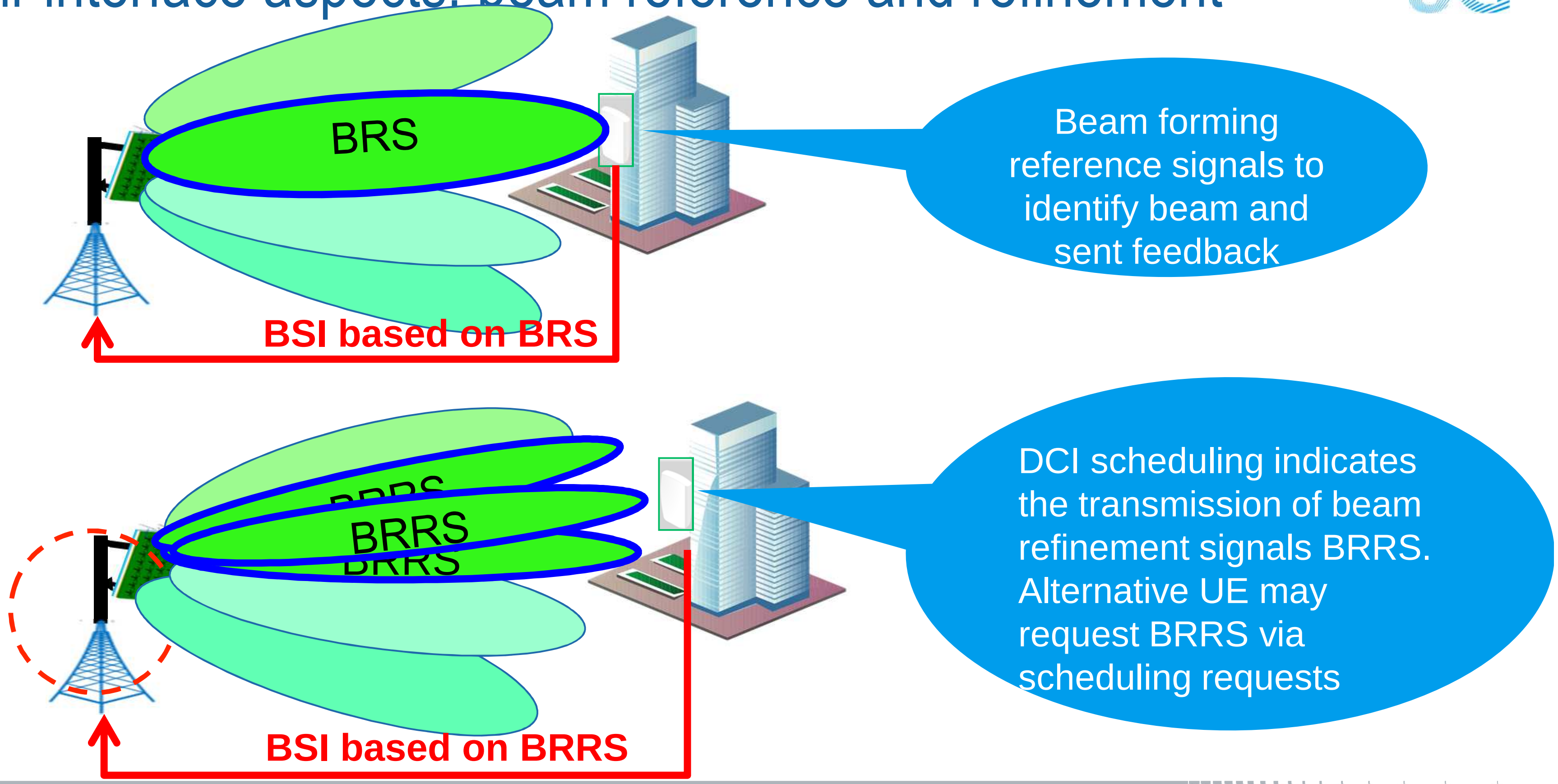
BI								Oct 1
BI	R	R	R	R	R	R	R	Oct 2

Aspects of DoA estimation – motivation for simpler methods

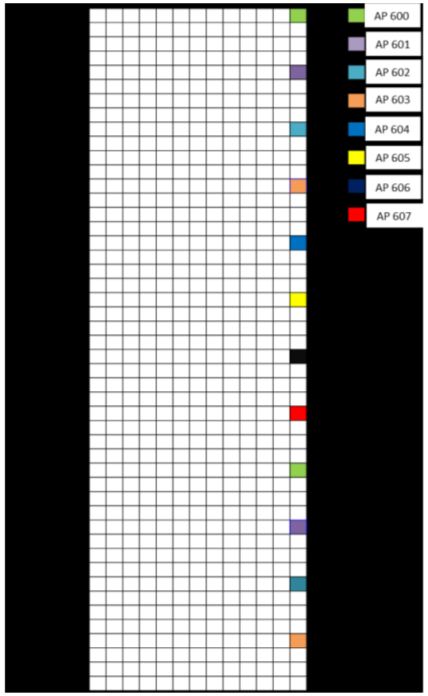


idea in 802.11ad is a 2 stage beamforming enabling: sector level and beam refinement

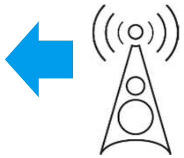
5G air interface aspects: beam reference and refinement



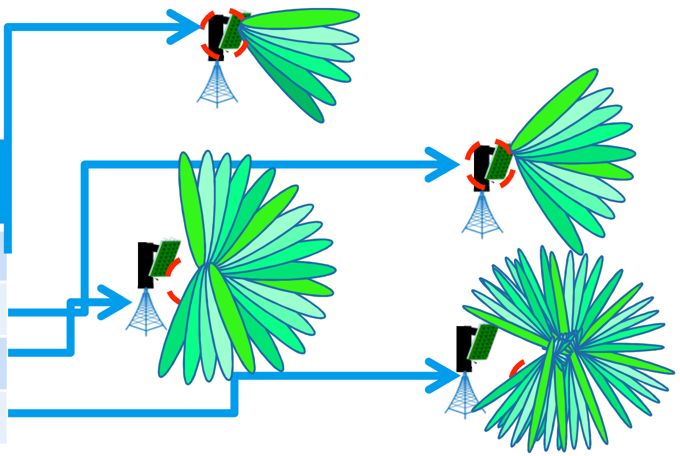
5GTF idea of beam forming reference signals BRS



5GNB supports up to 8 antenna ports,
Additionally beam refinement reference symbols can be sent



BRS transmission configuration allows different #of beams per antenna port
+#beams: 7 .. 56 per port



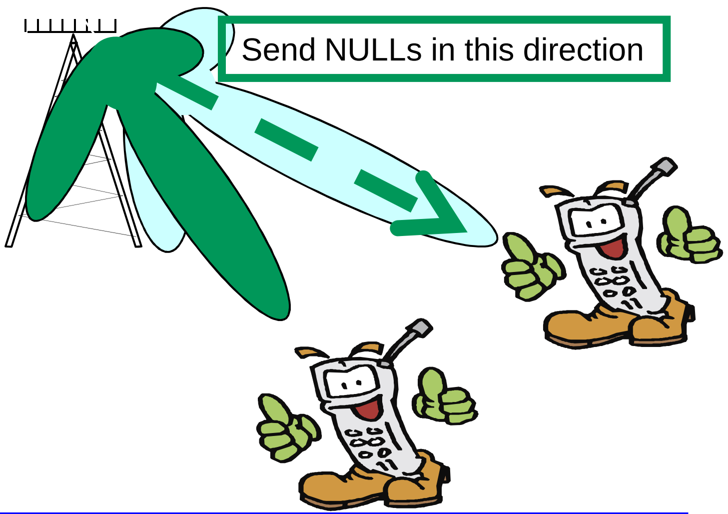
BRS transmission period	# of subframes
1 slot < 5 ms	1
1 subframe = 5 ms	2
2 subframes = 10 ms	4
4 subframes = 20 ms	8

Beam management as per TR38.802

- **Beam management:** a set of L1/L2 procedures to acquire and maintain a set of TRP(s) and/or UE beams that can be used for DL and UL transmission/reception, which include at least following aspects:
  - **Beam determination:** for TRP(s) or UE to select of its own Tx/Rx beam(s).
  - **Beam measurement:** for TRP(s) or UE to measure characteristics of received beamformed signals
  - **Beam reporting:** for UE to report information a property/quality of of beamformed signal(s) based on beam measurement
  - **Beam sweeping:** operation of covering a spatial area, with beams transmitted and/or received during a time interval in a predetermined way.

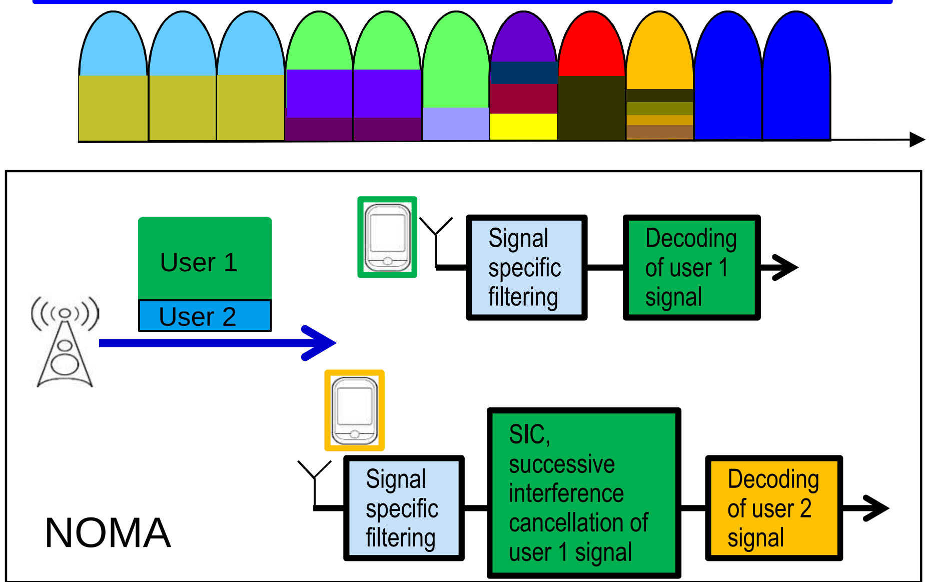
Technology framework: Multiple access schemes

SDMA = Space division multiple access



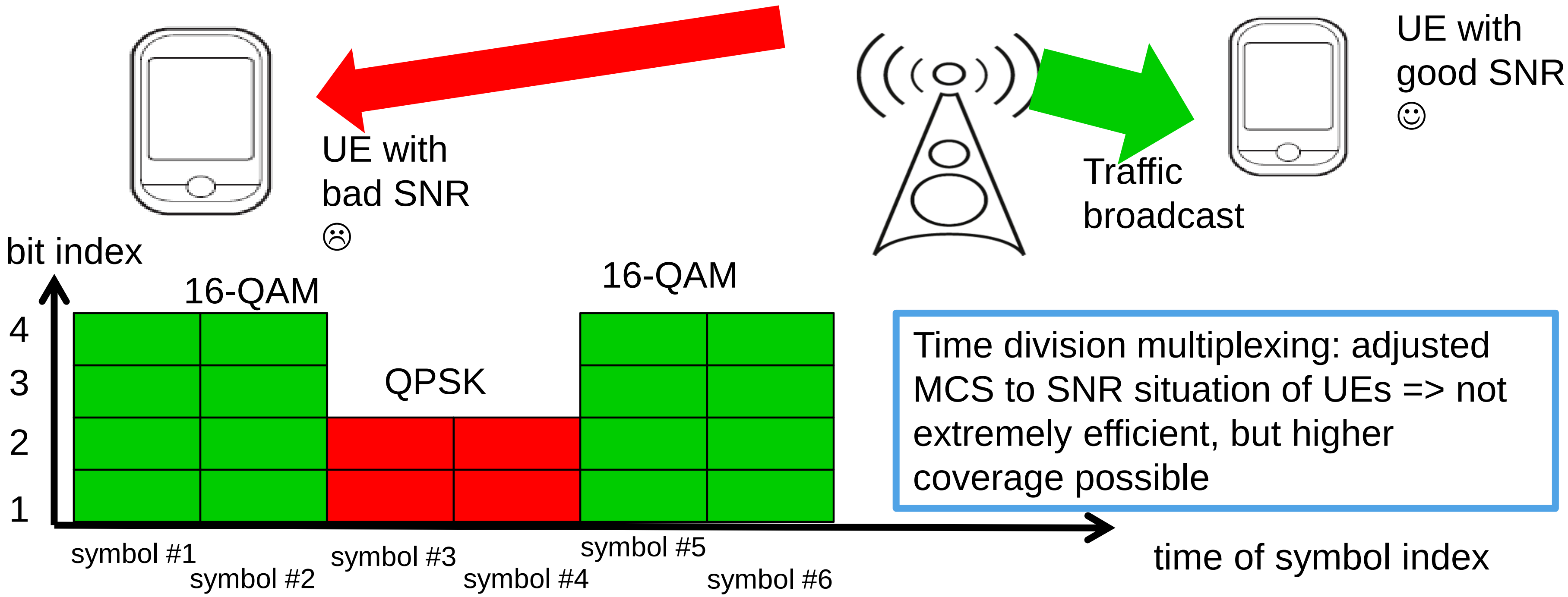
Coordination of pencil beams to steer desired direction & place NULLs in „interfering“ directions

Basic idea is to overlap OFDMA subcarrier principle with code division multiple access
⇒ One subcarrier may contain traffic of multiple users



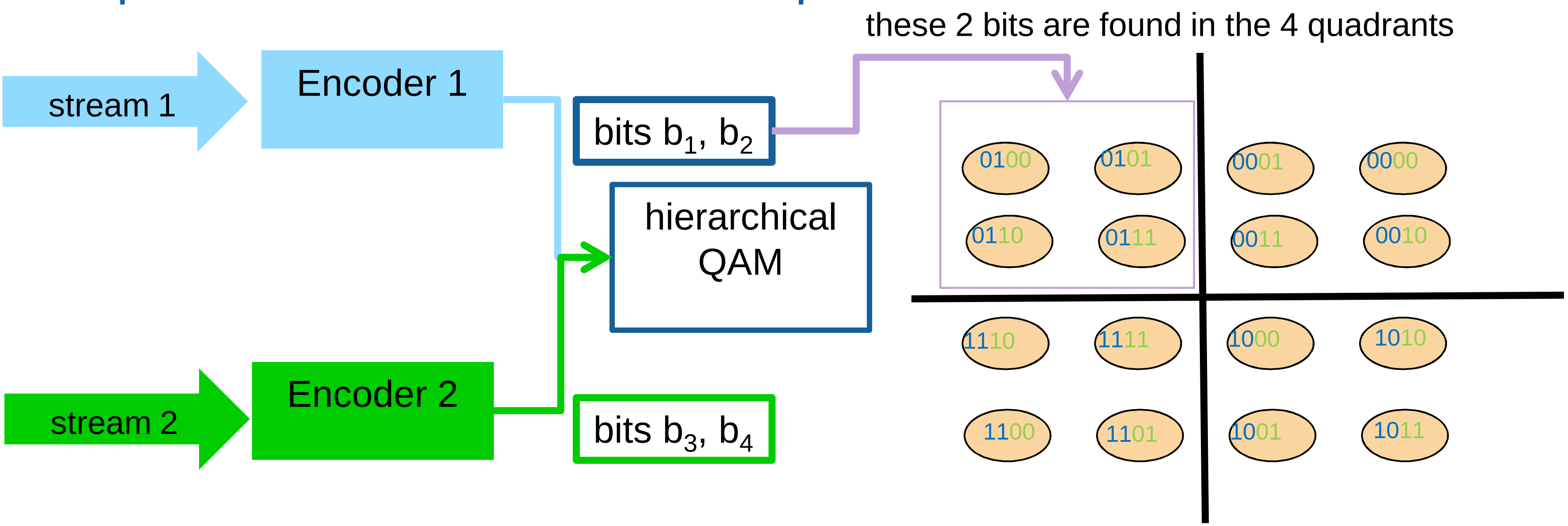
Multiple access – Bit division multiple access BDM

broadcast & multicast problem: tradeoff between coverage & throughput



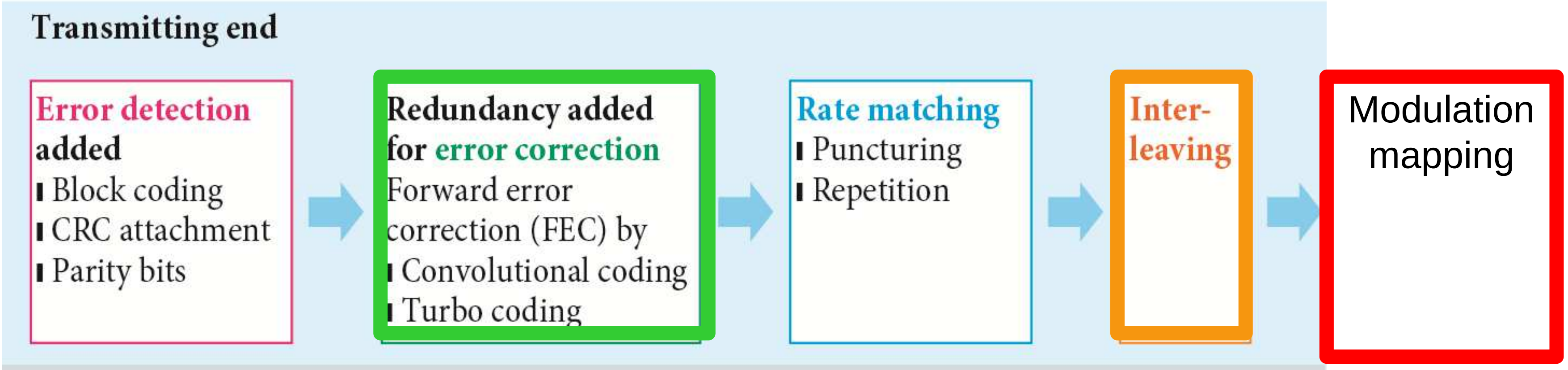
Time division multiplexing: adjusted MCS to SNR situation of UEs => not extremely efficient, but higher coverage possible

Multiple access – Bit division multiple access BDM



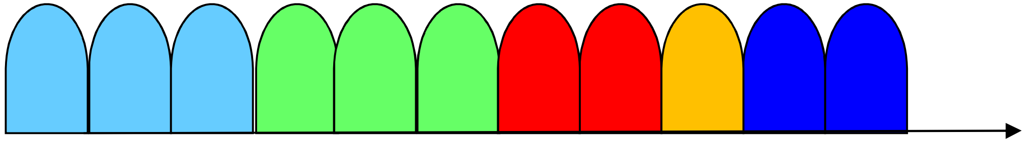
take a closer look into 16-QAM: it can be uniform = same distance between all constellation points or non-uniform. The stream 1, bits b_1 and b_2 are in the 4 quadrants and have thus a better BER as stream 2

Multi-user Bit interleaved coded modulation with iterative decoding

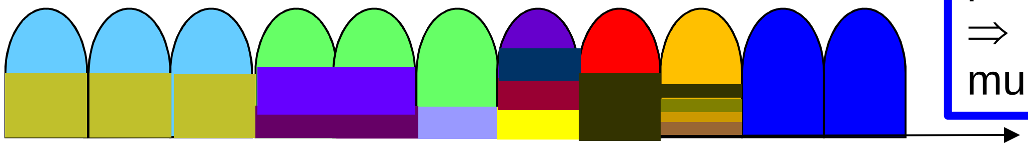


General idea: Is it possible to distinguish different users by different ways of Channel coding, Interleaving and Modulation mapping ? => superimpose the system and approach capacity limit of channel

Multiple access – combination CDMA + OFDMA

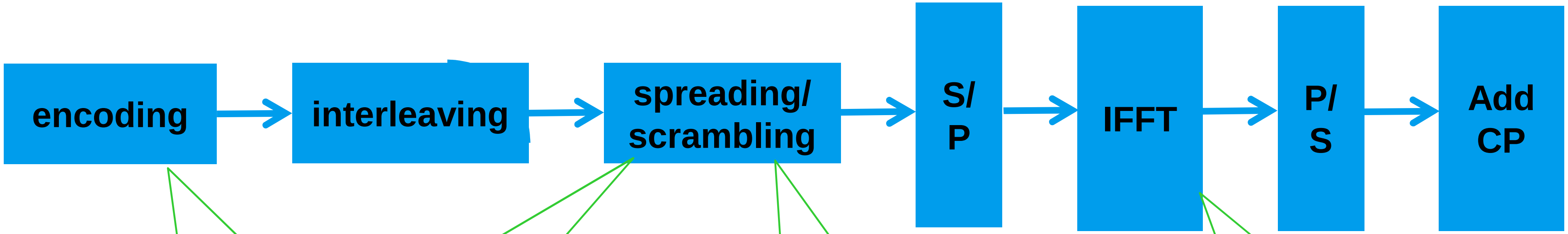


In OFDMA one subcarrier transmits data from one user only



Basic idea is to overlap OFDMA subcarrier principle with code division multiple access
⇒ One subcarrier may contain traffic of multiple users

RSMA – general aspects



possible of using a joint operation of coding + scrambling. not just a simple code like repetition or convolutional coding but an enhanced code where scrambling can be used for error correction as well

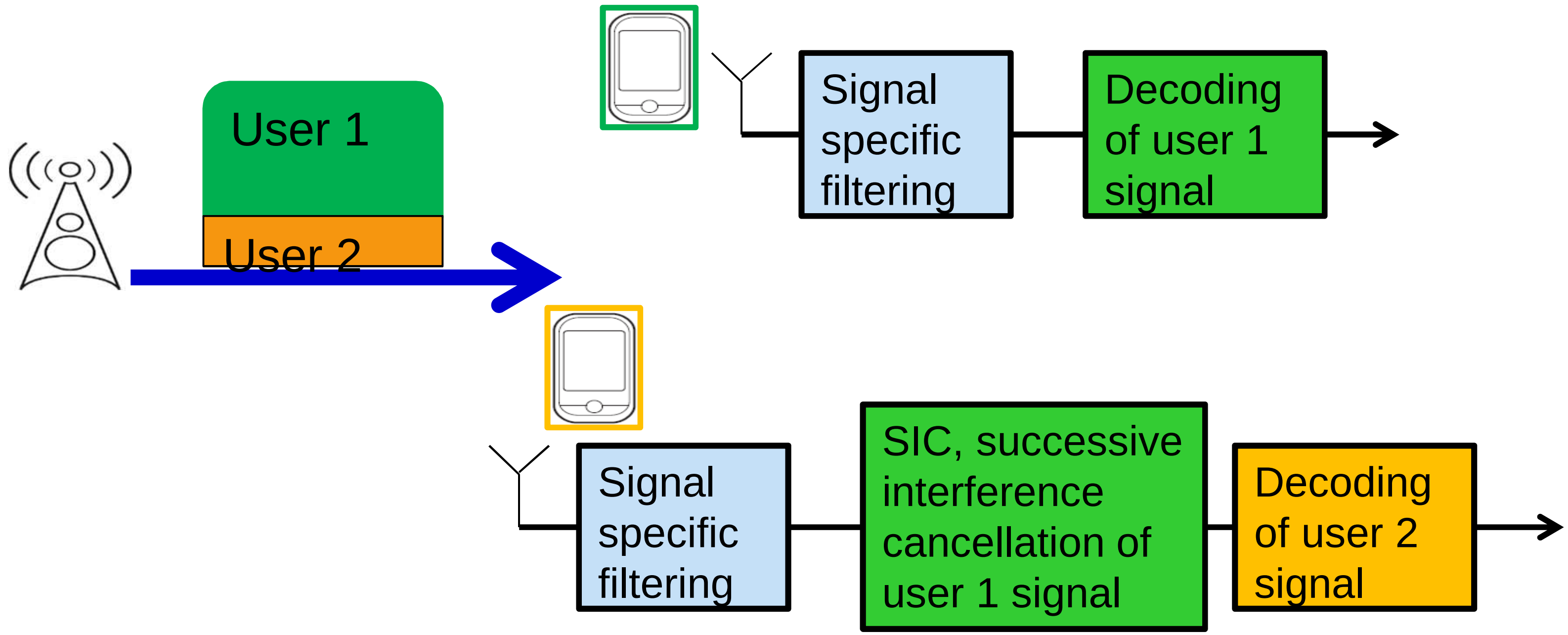
spreading offers a processing gain, better E_{bit}/N_0

Distribution also in frequency domain => better adaptation to frequency selectivity

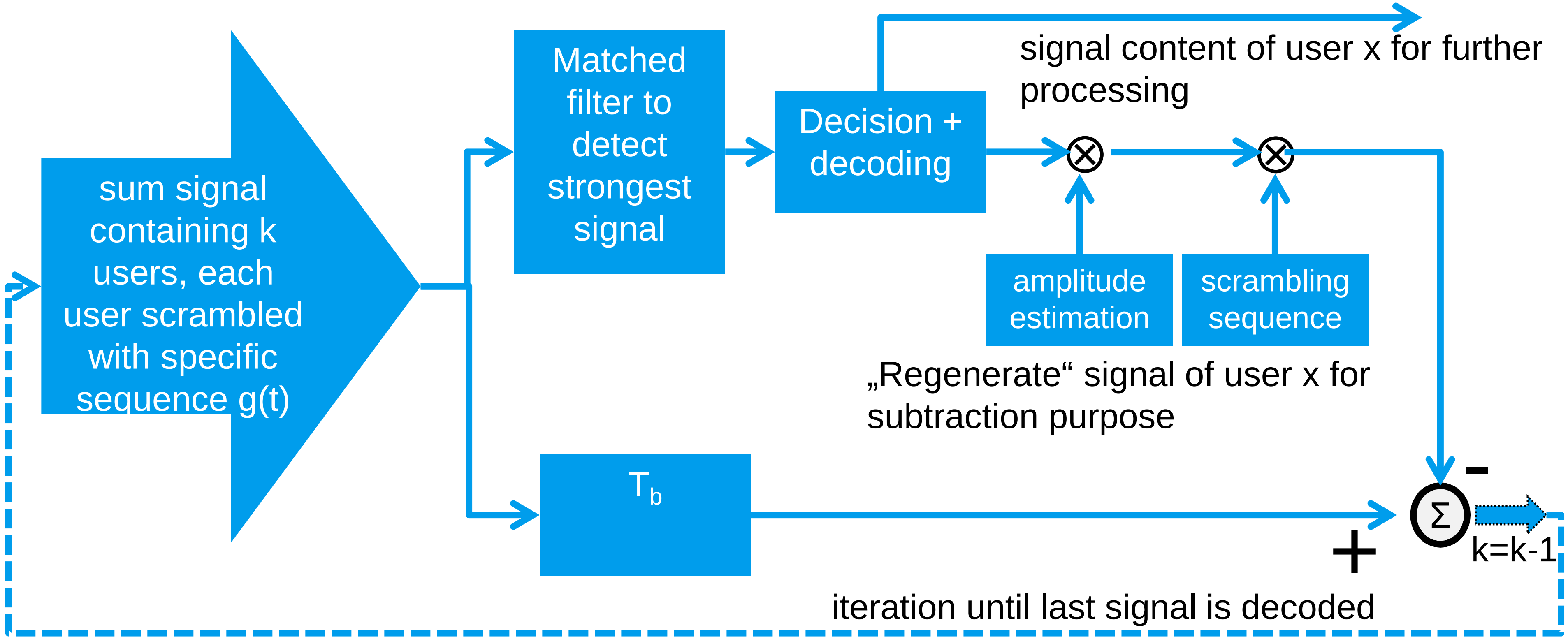
Question: scheduling and (a)-synchronuous multiplexing?

Successive interference cancellation SIC in NOMA

NOMA uses the principle of various power levels that are super-positioned. Each receiver will cancel the stronger signals

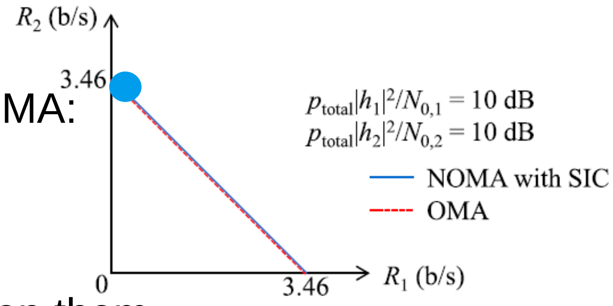


Successive Interference cancellation concept, 1st stage



NOMA – downlink example of performance

Orthogonal multiple access OMA:
2 users where bandwidth is
split amongst them.
channel is symmetric ->
fair sharing of capacity between them.

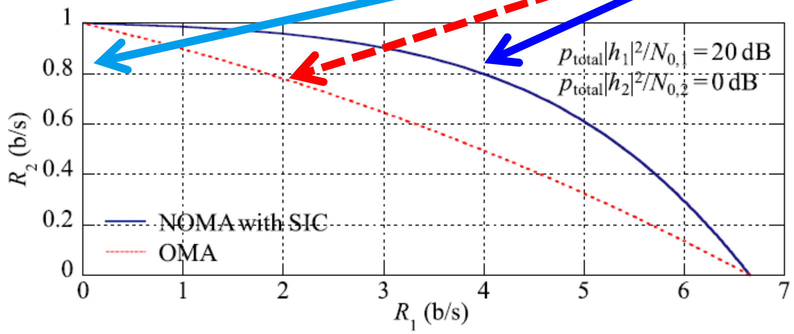


(a) Symmetric channel

● = whole capacity is allocated to user 2 only.

Performance:
if we want to obtain a rate for user 2 of 0.8 bit/sec we can get a rate of ~2 b/s if OMA is used, but we could get ~4b/s if NOMA is used

Non-orthogonal channel:
2 users with different
power levels due to
asymmetric channel
superpositioned

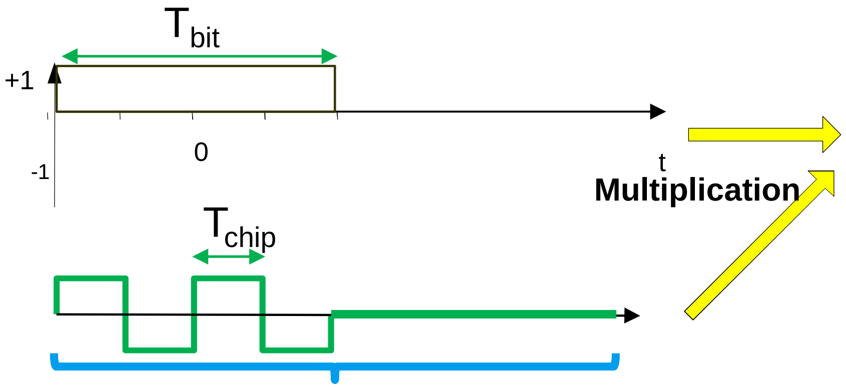


(b) Asymmetric channel

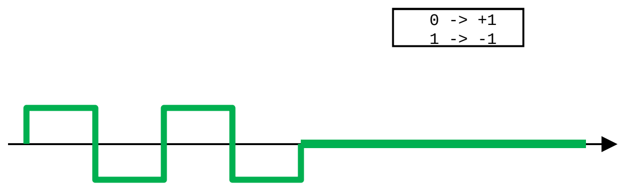
source: NOMA with SIC for future radio access, Higuchi + Benebbour

Low density signature – idea of system overload

Basic idea of low density signature



spreading code has length N
but only d_v < N chips will contain non-zero values



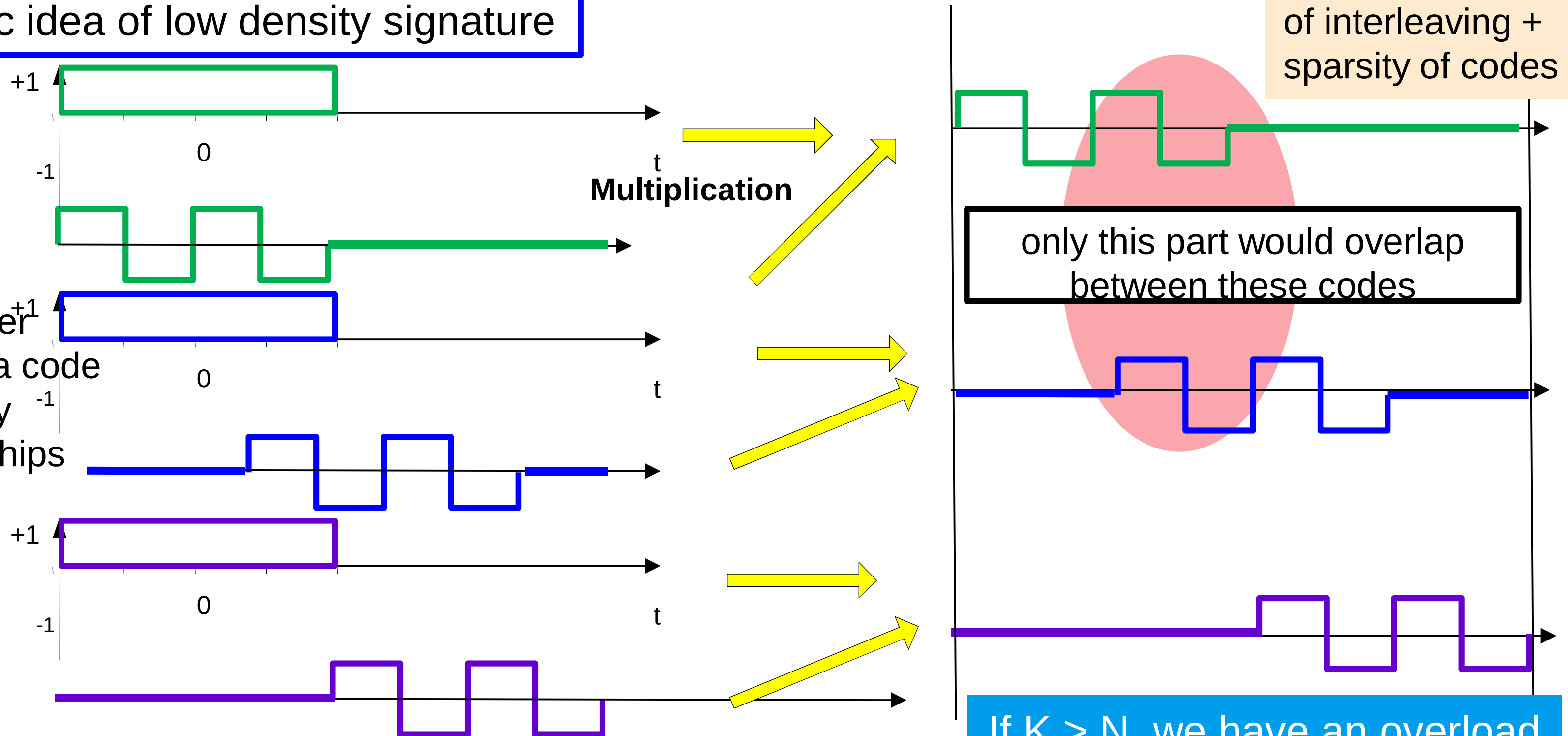
spread signal after channelization
-> only fragment of spectrum is occupied
-> this will result in some kind of sparsity of the code

Low density signature – idea of system overload

The fact that the code has $d_v < N$ chip length will result in some kind of interleaving + sparsity of codes

Basic idea of low density signature

K users, each user will get a code with only $d_v < N$ chips



If K > N, we have an overload situation -> capacity increase

Low density signature codes

example: LDS indicator matrix, one idea how to generate LDS for spreading

2nd rule: d_c = amount of 1s in one row (users simultaneously vs total amount of users) << K

K = 16 users

N = 12 chips

$$\mathbf{F}_{12\times16} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

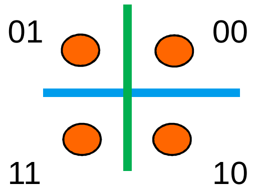
here: at Chip 3 we would have multiple access interference MAI of users 2, 5, 7 and 10

1st rule: d_v = amount of 1s in one column (used chips vs spreading gain) << N

here: user Nr. 11 will spread its data over chip Nr. 4, 11 + 12

SCMA encoding aspects

reminder: QPSK
data bits are mapped onto
constellation symbol



N = dimension of
complex constellation
i.e. here N = 2 (IQ-axis)

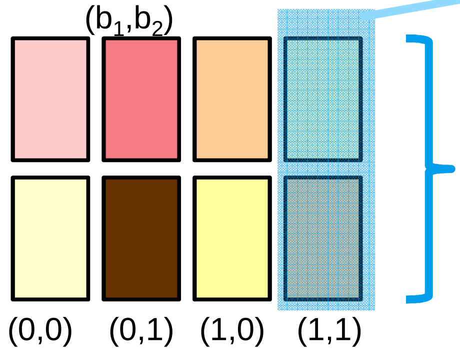
max number of codebooks:

$$J = \binom{K}{N}$$

in encoding also called layer
e.g. if code length = 4 and
2 symbols are used, we
have max = 6 users

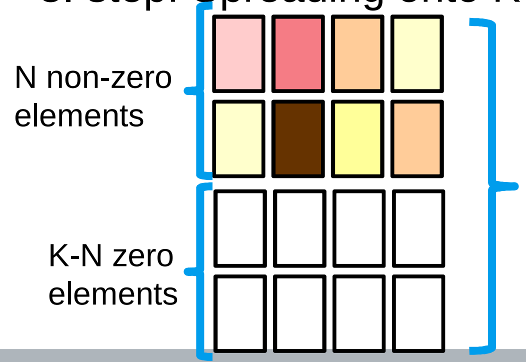
1. step: binary data pattern, e.g. 0100111101011001

2. step: mapping of bits onto a codeword size N (here N = 2)



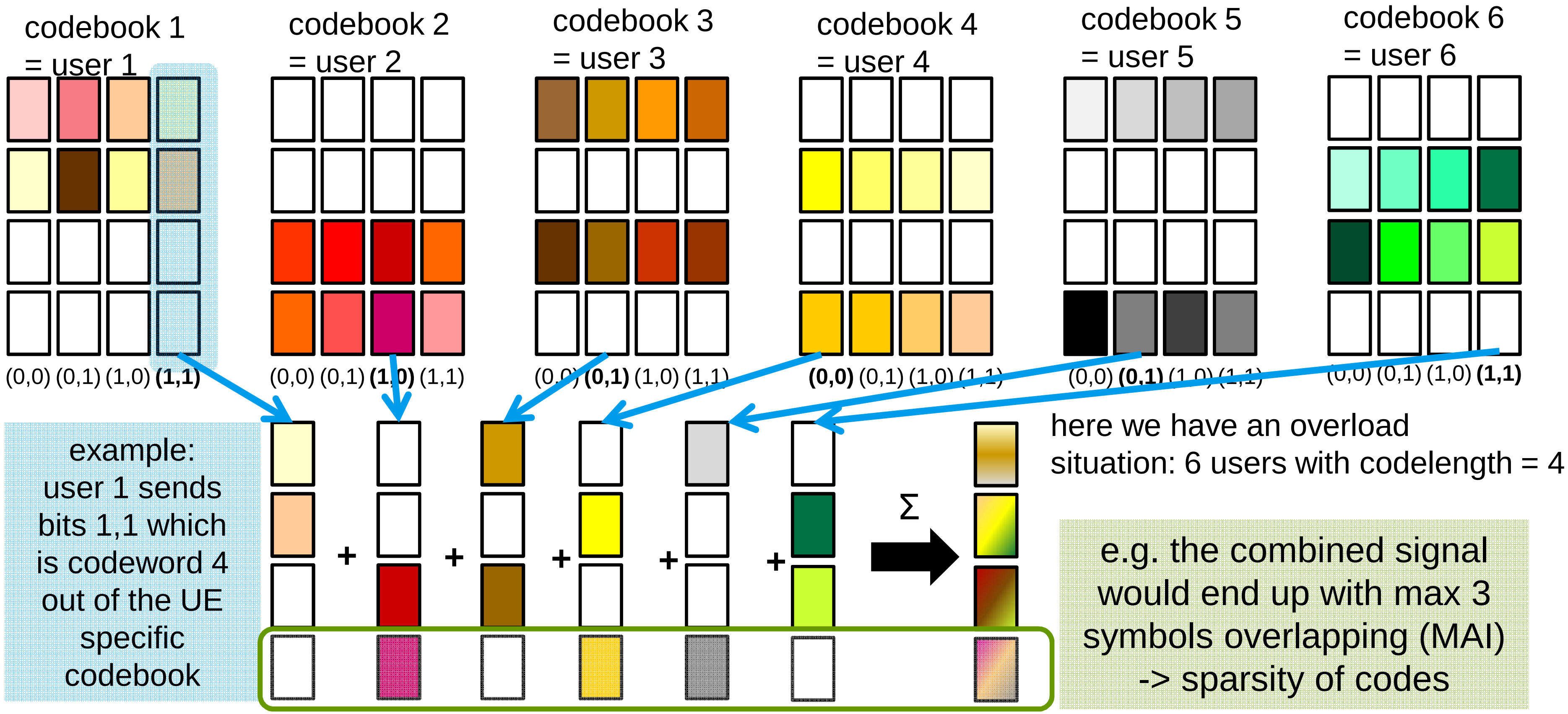
example: codebook
containing codewords
-> codebook is UE specific

3. step: Spreading onto K dimensional codeword. K-N zero rows



example: codebook of size K = 4
(representing 4 constellation symbols
of QPSK) will be spread over 4
OFDM subcarriers (here 4 rows) but
only 2 rows are non zero => sparsity
of the codeword

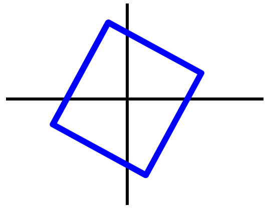
SCMA encoding multiple access by using multiple codebooks



SCMA codebook design, idea of multidimension, rotated + shuffled

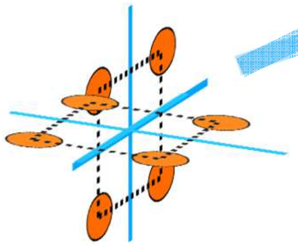
Complexity gets high again as idea is to send more data due to multidimensions:

1.)

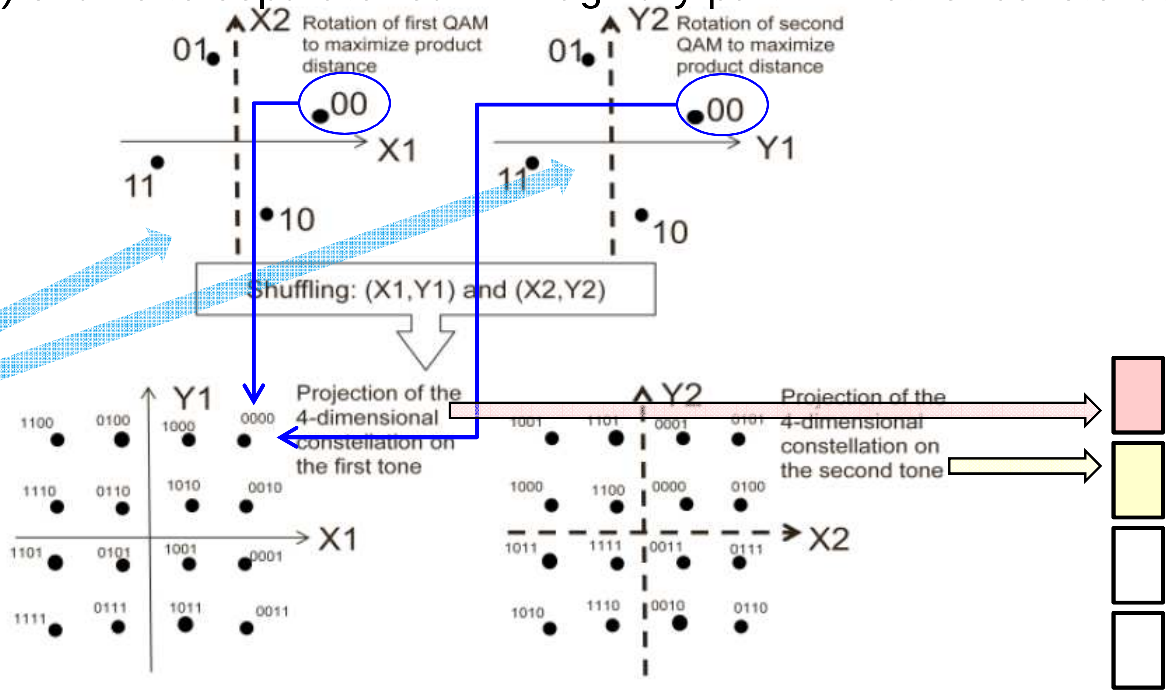


using rotated constellations,
so I and Q axis are independend

2.) rotate each constellation
diagram, e.g. x-y and x-z axis



3.) shuffle to separate real + imaginary part -> mother constellation

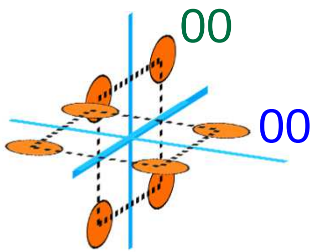


SCMA codebook design, trying to make it simple

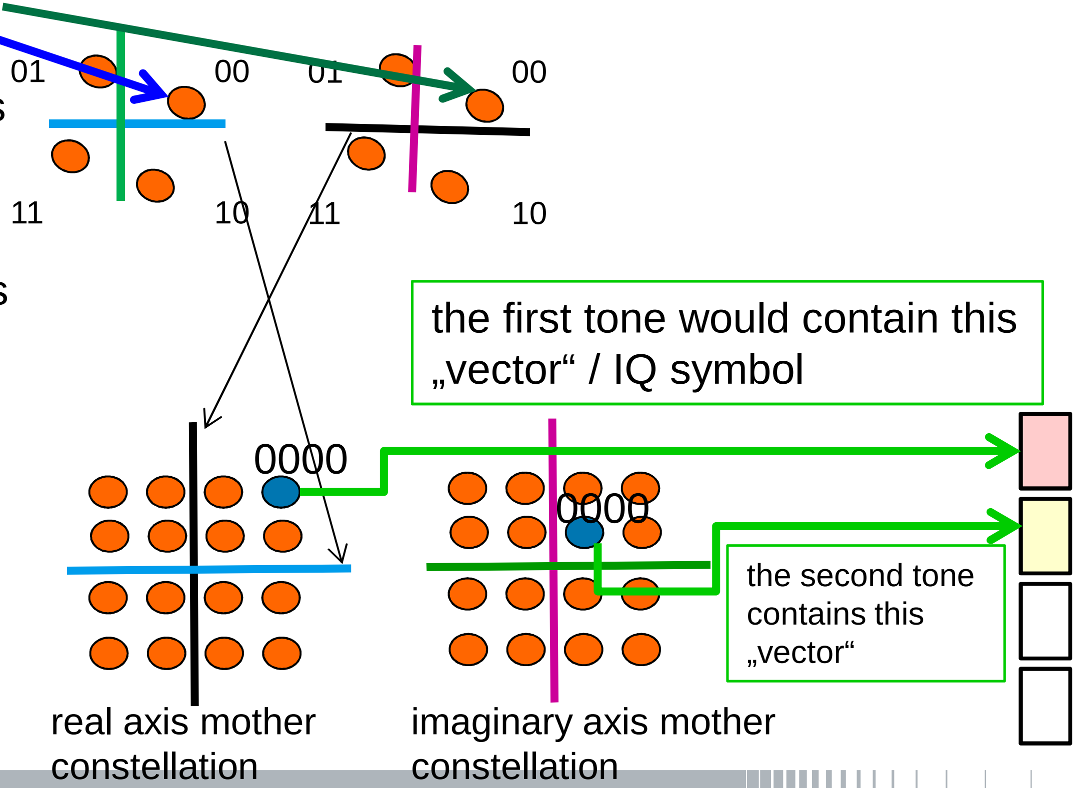
1.) We have a bit pattern, e.g. 0000

2.) e.g. using QAM constellation, here 2 times as we have 2 dimensions

3.) you have to read the constellations as shuffled to get a higher dimension, e.g. one is x-y axis the other is x-z axis



4.) generate the projection of the shuffled as 16-point but 2 dimensions



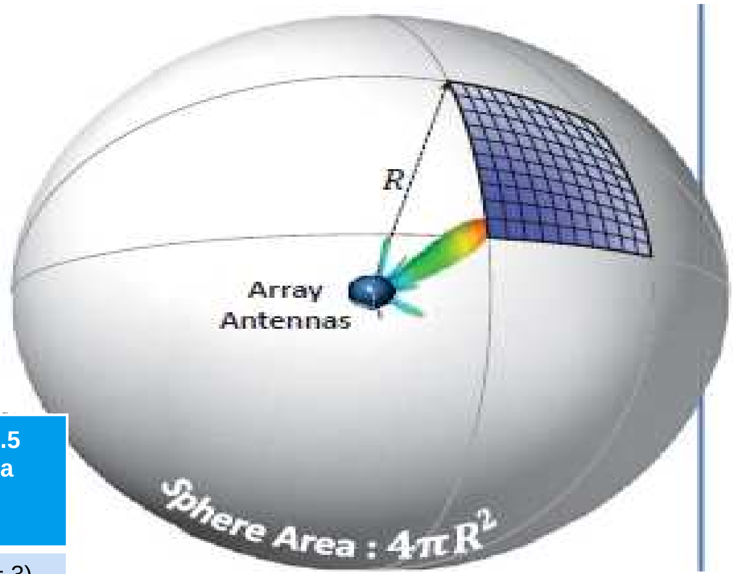
Higher frequencies: path loss issues

Higher frequencies = higher attenuation
Higher frequencies = smaller antennas

Friis equation

$$\frac{P_{Rx}}{P_{Tx}} = G_{antenna}\left(\frac{c}{4\pi f d}\right)^{\gamma}$$

Beamforming



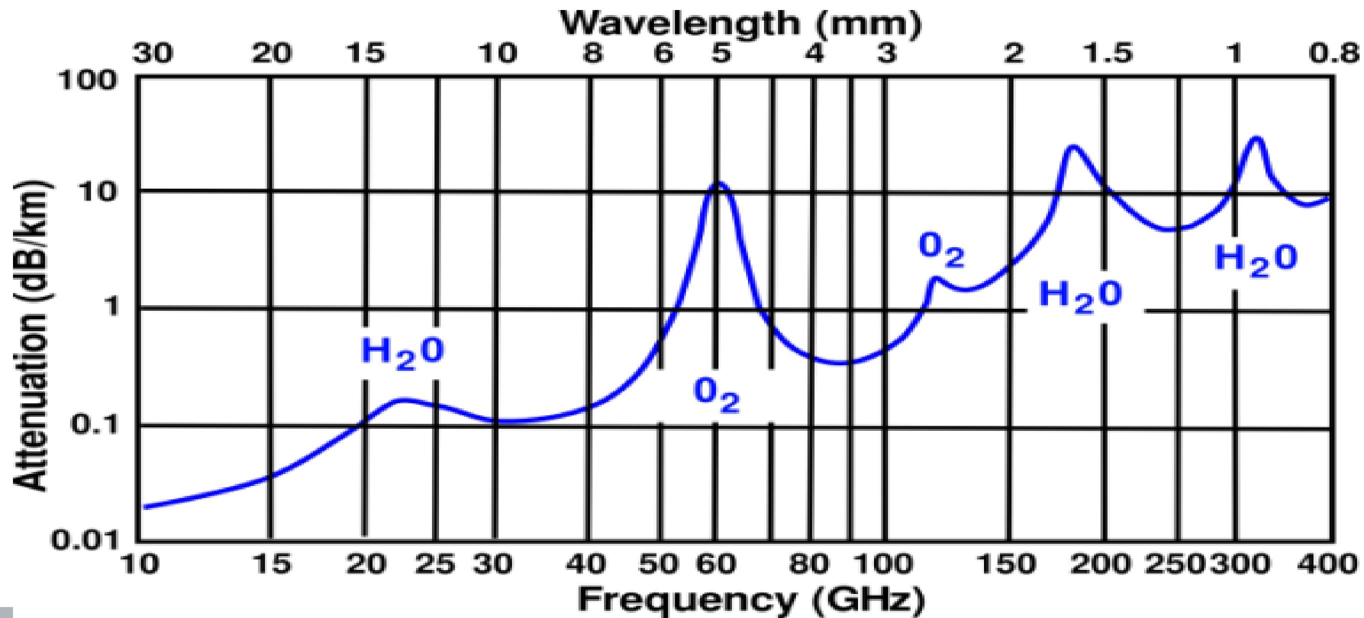
EXAMPLE
@ 28 GHz:

PathLoss 28 GHz	γ = 2 Free Space	γ = 1.6 to 1.8 Indoor LOS	γ = 2.7 to 3.5 Urban Area
1 m	- 61,4 dB	- 52 dB (k=1,7)	-92,1 dB (k = 3)
10 m	- 81,4 dB	-69 dB	-122,1 dB
100 m	- 101,4 dB	-86 dB	- 151,1 dB
1000 m	- 121,4 dB	-103 dB	- 181,1 dB

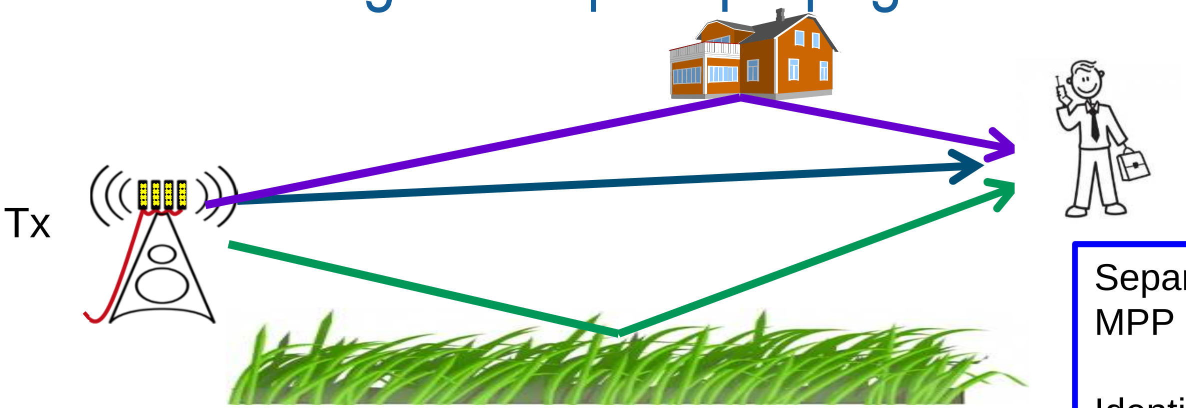
γ = path loss exponent

Channel sounding

Main idea of channel sounding is to understand the wave propagation characteristics
Like attenuation, power delay profile, direction of arrival, correlation aspects etc.
-> especially for the „higher“ frequency ranges



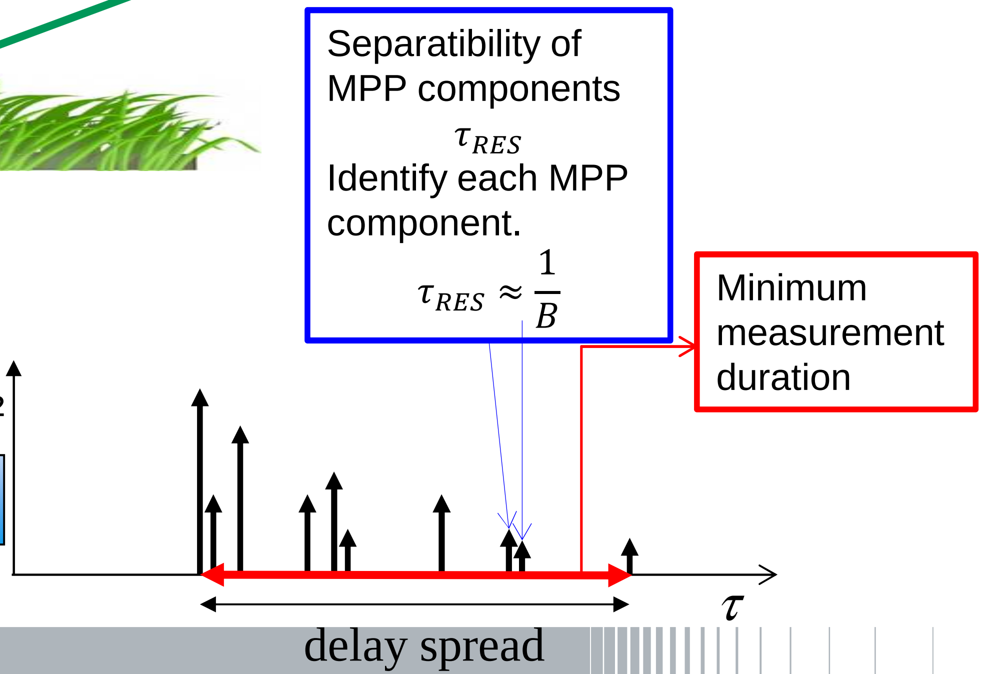
Channel sounding – multipath propagation MPP



Channel impulse response CIR

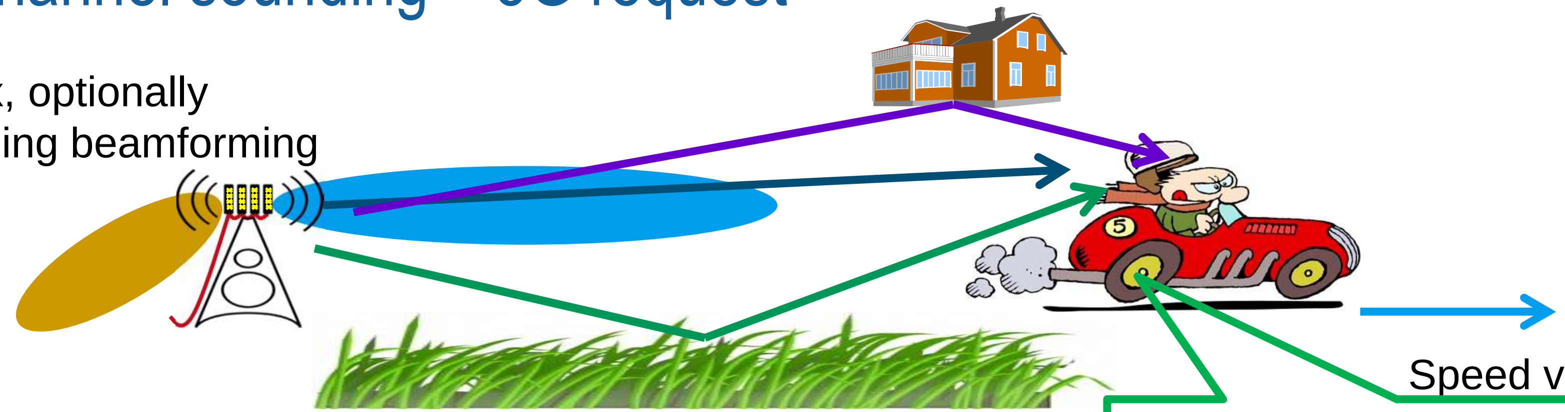
$$h(\tau,t)=\sum_{i=0}^{L-1} a_i(t)\,e^{j\phi_i(t)}\,\delta(\tau-\tau_i)$$

path attenuation | path phase | path delay



Channel sounding – 5G request

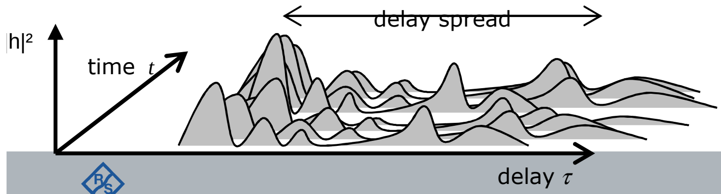
Tx, optionally
using beamforming



Speed v

Channel impulse response CIR: time variant and depending on direction of arrival

$$h(t,\tau,\varphi) = \sum_{\Delta\varphi=0°}^{360°} \Delta\varphi \sum_{i=0}^{L-1} a_i(t) \cdot e^{j\Phi(t)} \cdot \delta(\tau - \tau_i)$$



Each multipath component is characterized by:

- Time t
- Angle of arrival Δφ
- Doppler shift
- Excess delay ΔT
- Phase shift
- In MIMO condition it would end up in a NxM matrix set

Why channel modeling ?

Objectives

- The performance of a radio system is ultimately determined by the radio channel
- The channel models basis for
  - System design
  - Algorithm design, antenna design
- Without reliable channel models, it is hard to design radio systems that work well in real environments.
- New **challenges** within “5 G mm-waves”
  - *Extremely extended frequency range i.e. frequency dependency of parameters (6 – 100 GHz)*
  - *Spatial information / 3D beamforming / spatial consistency*

- Some examples:
  - behavior in time/place?
  - behavior in frequency?
  - directional properties?
  - bandwidth dependency?
  - behavior in delay?

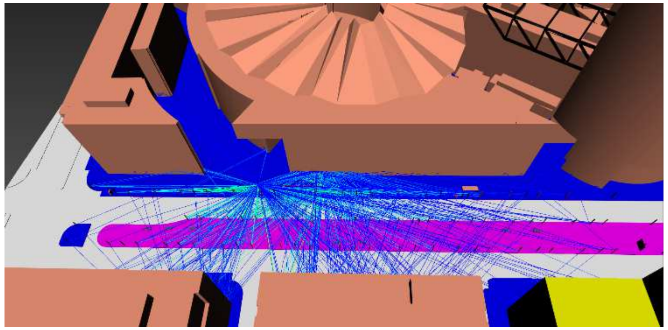
Channel Modeling Approaches

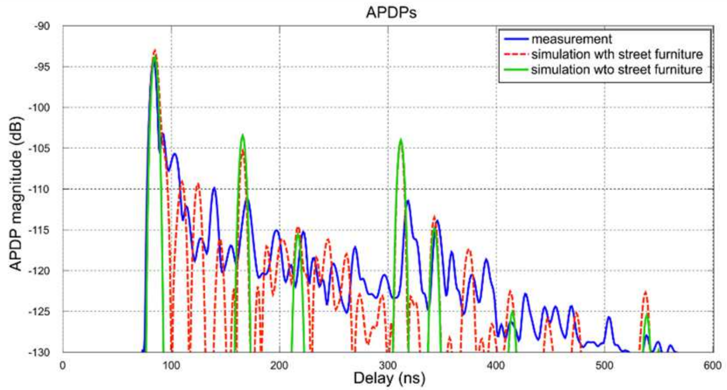
- Full Electromagnetic Solutions => exact geometry, materials

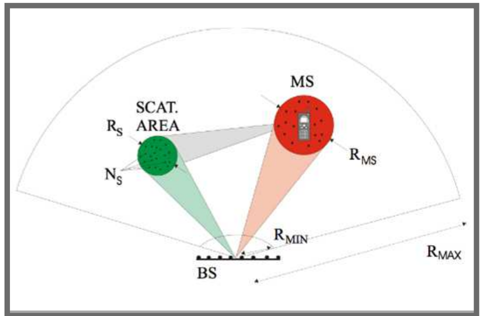
- Deterministic (Raytracing) => exact geometry, materials

- Quasi Deterministic + Stochastic (3D geometry-based stochastic channel models GSCM) => some geometry, large scale parameters needed, complexity at acceptable level

Raytracing

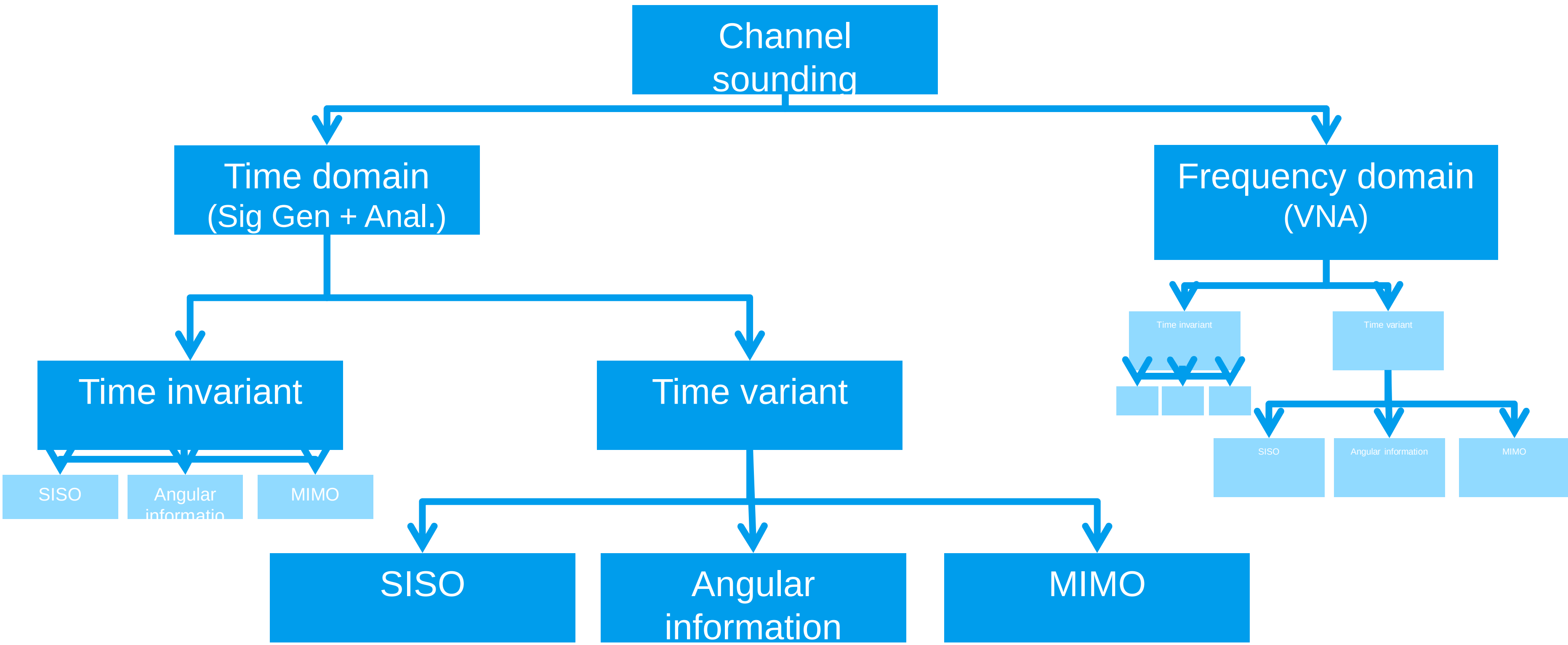






GBSM
Geometry Based Stochastic Model

Channel sounding measurement aspects - structure



Channel measurements in mmWave frequency bands
R&S TS-5GCS channel sounding solution

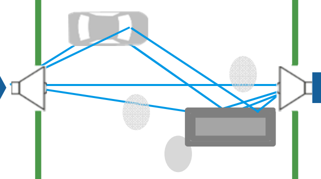
Measurement Setup

Pulsed Correlation Sequence Generation

R&S®SMW200

- High reference frequency stability
- Power Delay Profile
- Freq. Up-converter may be necessary

Real world environment



Direct Measurement of CIR (Channel Impulse Response)

DSSS Channel Sounding

I/Q Data Capturing

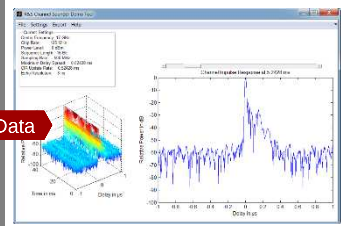
R&S®FSW85

- High receiver sensitivity
- Built-in LNA
- Large dynamic range

Power Angular Profile (Angle of Arrival)

I/Q Data

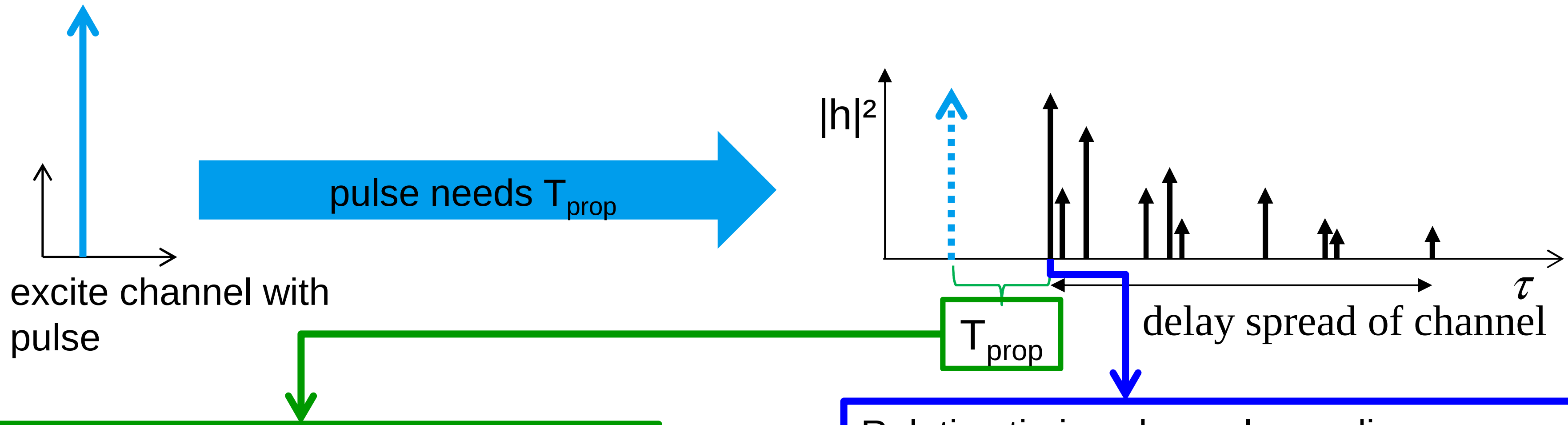
Realtime data analysis software



HHI Synchronomat: absolute propagation time

No synchronization: relative propagation time

Channel sounding: relative or absolute timing information

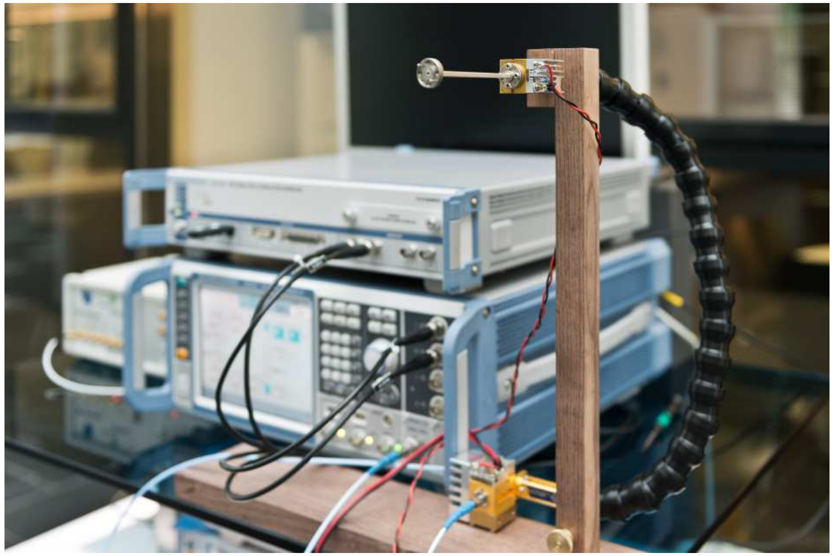


Absolute timing channel sounding:
We want to measure the propagation time between Tx and Rx.
=> some synchronisation will be needed

Relative timing channel sounding:
We do not get any information about the propagation time, the CIR is based on the first pulse received.
=> no synchronisation between Tx and Rx

Sounding @ 82.5 GHz

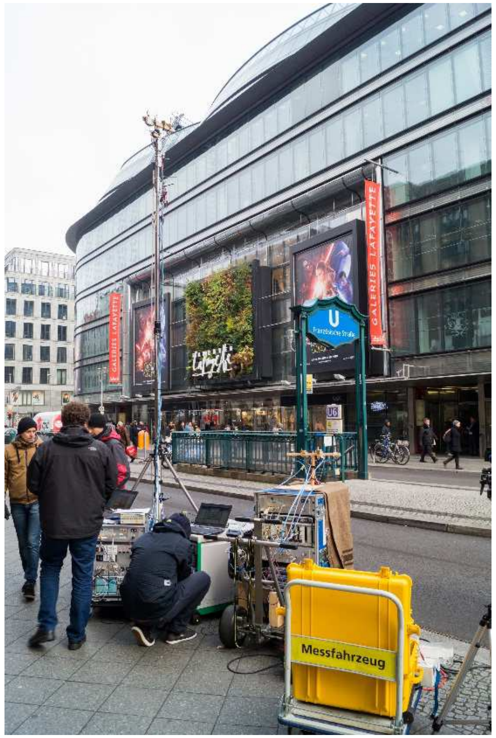
R&S 5G mmWave Expert Day September 2015

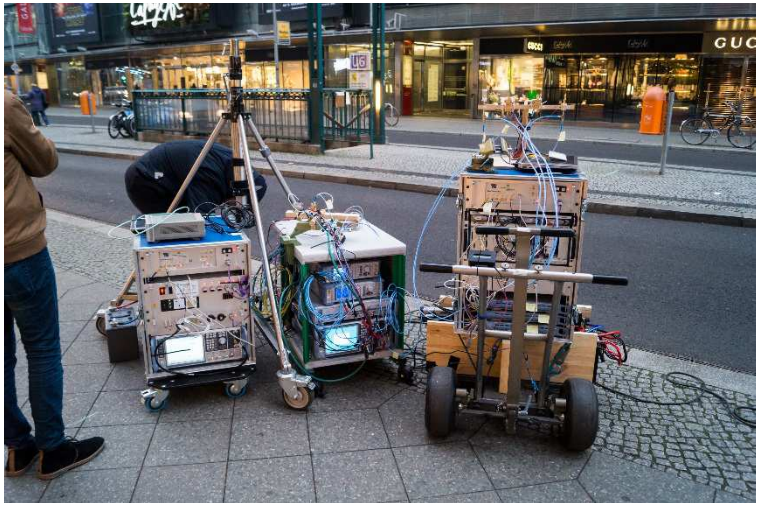


500 MHz BW transmitter AFQ100B + SMW200A

500 MHz BW receiver FSW85

Channel sounding campaign with HHI Fraunhofer (Berlin, Nov. 27th, 2015)

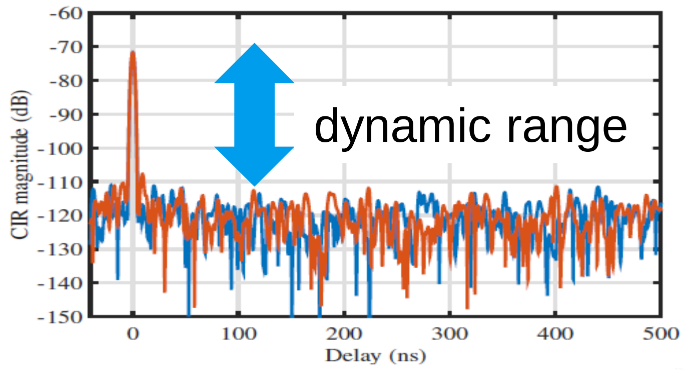




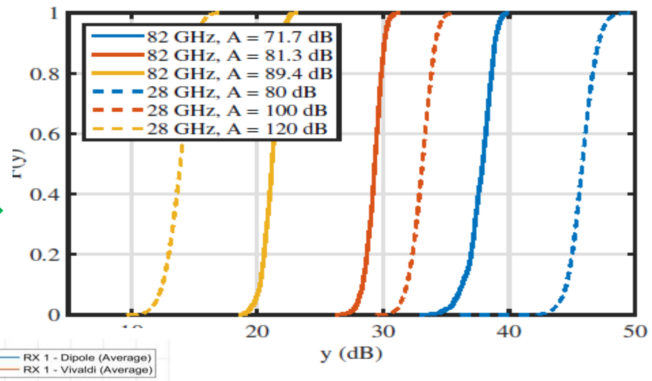
- HHI together with R&S conducted simultaneous measurements at 10 GHz, 28 GHz, 40 GHz and 82 GHz (500 MHz BW for 10 GHz, 1.5 GHz BW for other frequencies).
- Scenarios: Street canyon and shopping mall.
- Evaluation of measurement results under way.

Channel sounding – evaluation aspects

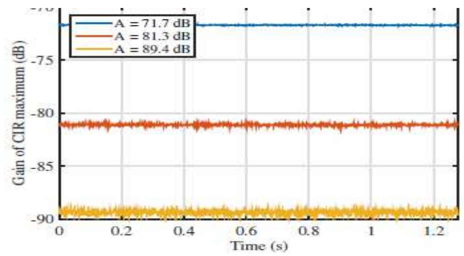
There is no golden setup -> various aspects to consider

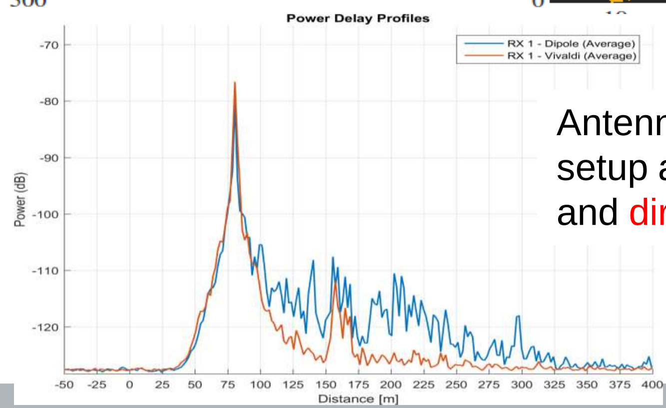


adjustable attenuator: instantaneous dynamic range decreases, when attenuation increases



Amplitude error -> calibration required

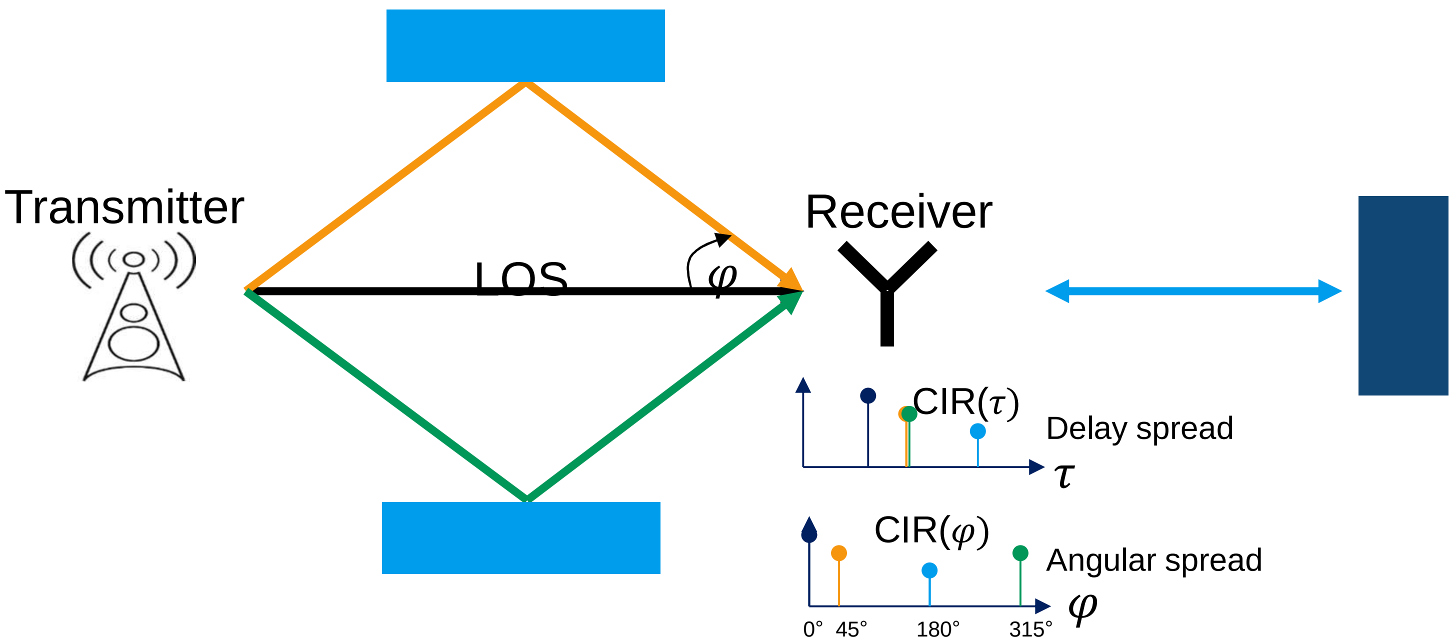




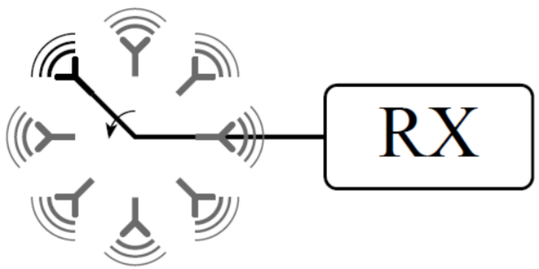
Antenna influence: e.g. outdoor setup at 17 GHz using omnidirectional and directional (Vivaldi) antenna

Source: Characterization of mm-wave Channel sounders (EuCAP2016 paper #1570230959)

Problem: Where does the echo come from?



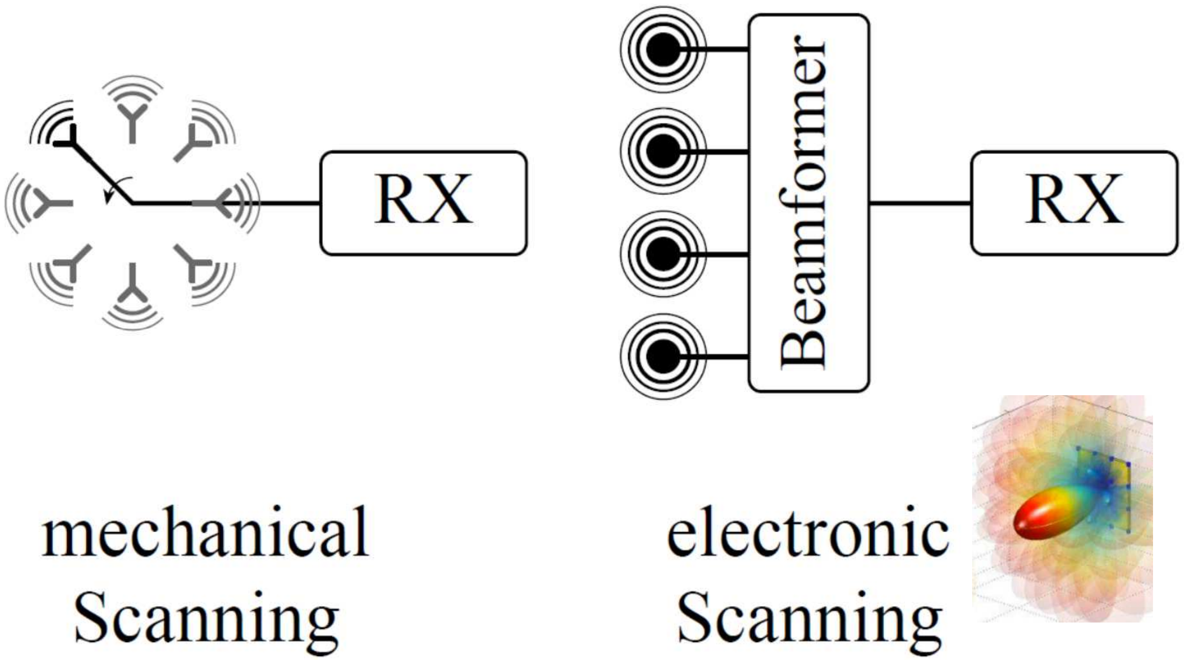
Directional Information: Spatial Filtering



mechanical Scanning

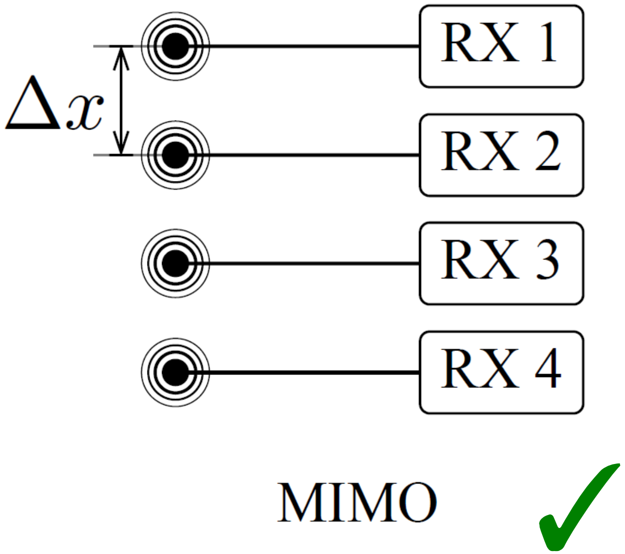
- Direct measurements of angles of arrivals
- Mechanical scanning is very slow, only suitable for static channels
- Mechanical scanning is very simple
- Limited resolution
- Ambiguity through overlapping patterns owing to the antenna characteristic
- difficult for high frequencies as high gain antennas are needed

Directional Information: Spatial Filtering



- Direct measurements of angles of arrivals
- High effort and low performance of electronic scanning
- Electronic scanning is very fast
- Limited resolution
- Ambiguity through overlapping patterns owing to the antenna characteristic
- difficult to obtain phase information

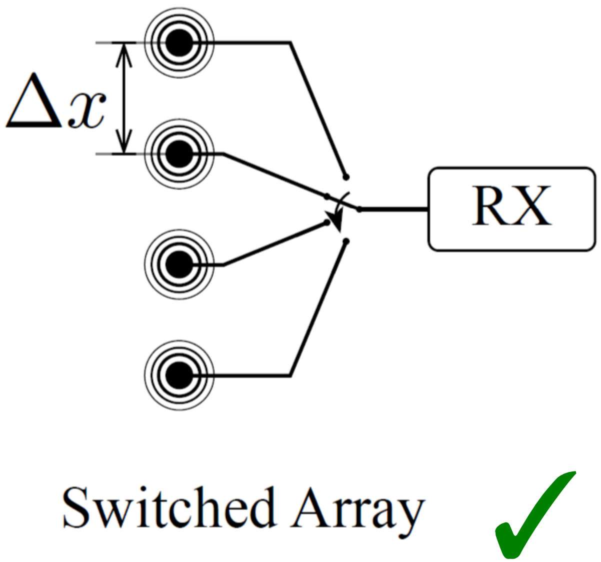
Directional Information: Estimation Algorithm



using amplitude PDP and phase information and apply post-processing, e.g.

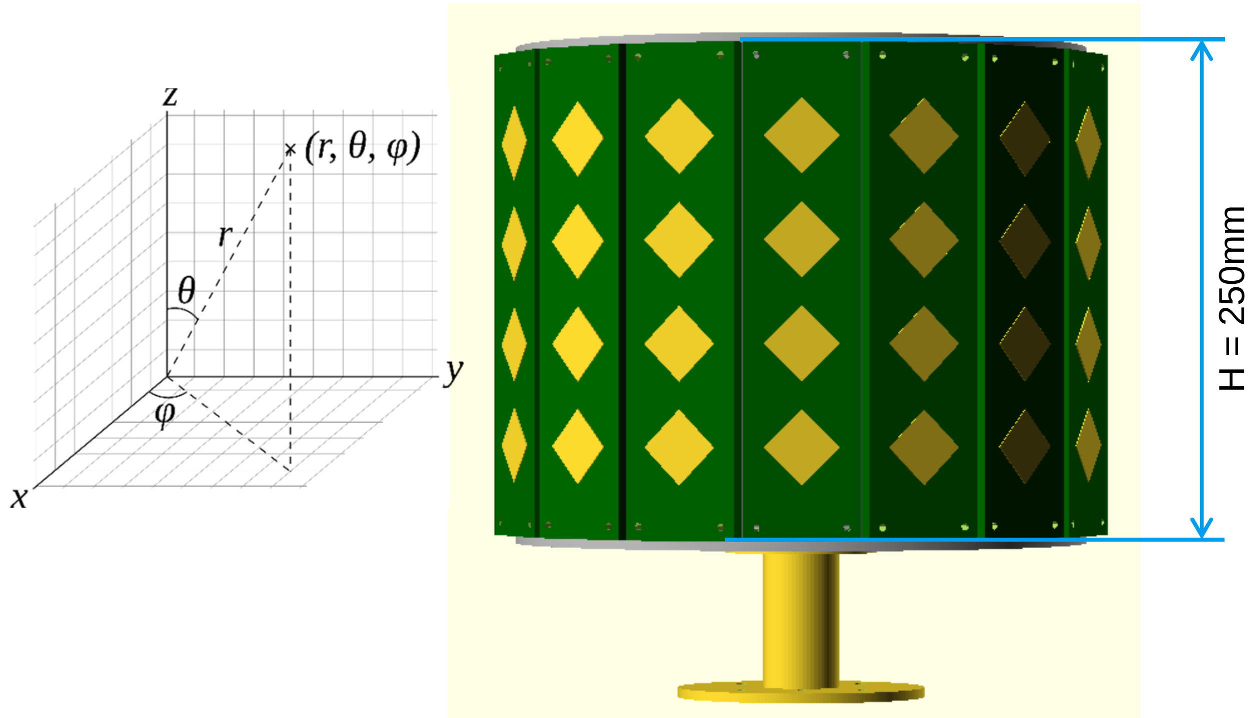
- Estimation of direction of arrival using array signal processing (MUSIC etc.)
- High hardware effort
- High measurement speed
- Sensitive to phase errors

Directional Information: Estimation Algorithm



- Estimation of direction of arrival using array signal processing (MUSIC etc.)
- Less hardware effort (in comparison to mechanical antenna)
- High measurement speed
- Typically cylindrical switched array
- Linear, circular or 3D movements for virtual array
- Calibration needed, for every path!
- Sensitive to phase errors = difficult for high frequencies

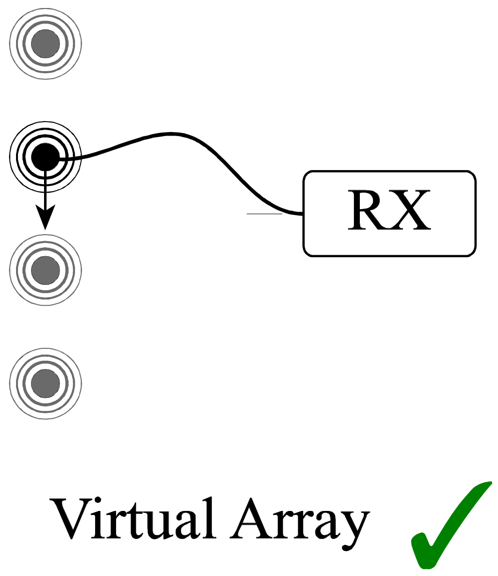
Circular Switched Array Antenna for 3D DoA Measurements



- Design for frequencies up to 18 GHz available
- Uniform cylindrical array
- 16 columns, 4 dual-polarized patch elements per column => 128 elements in total
- Alignment of switching by Synchronomat
- target frequency 3.75GHz
- Target bandwidth 800MHz
- Successfully applied for industry measurements

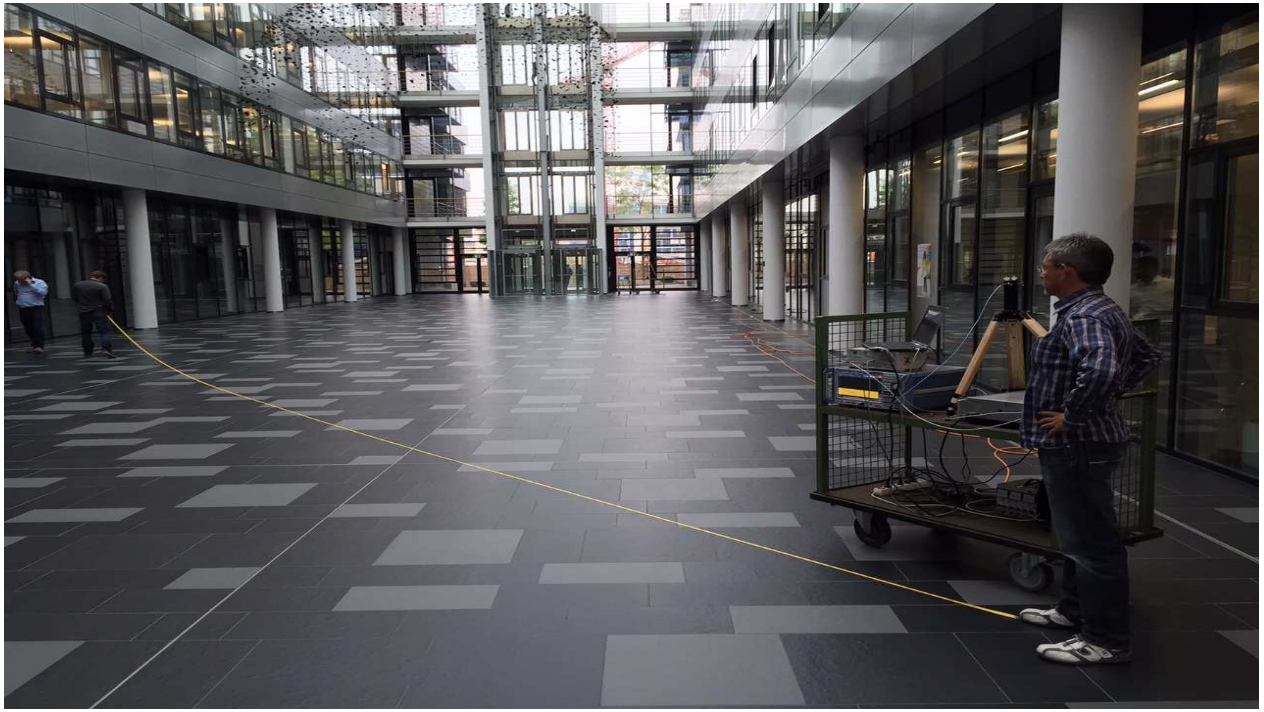
source: HHI Berlin

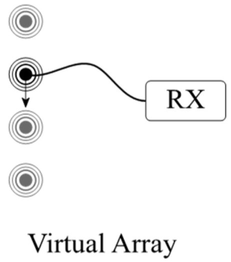
Directional Information: Estimation Algorithm



- Estimation of direction of arrival using array signal processing (MUSIC etc.)
- Less hardware effort (in comparison to mechanical antenna)
- High measurement speed
- Typically cylindrical switched array
- Linear, circular or 3D movements for virtual array
- No calibration needed for virtual array
- Sensitive to phase errors

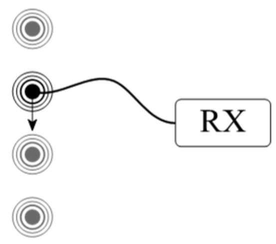
Angular Information from Virtual Arrays: Proof of Concept



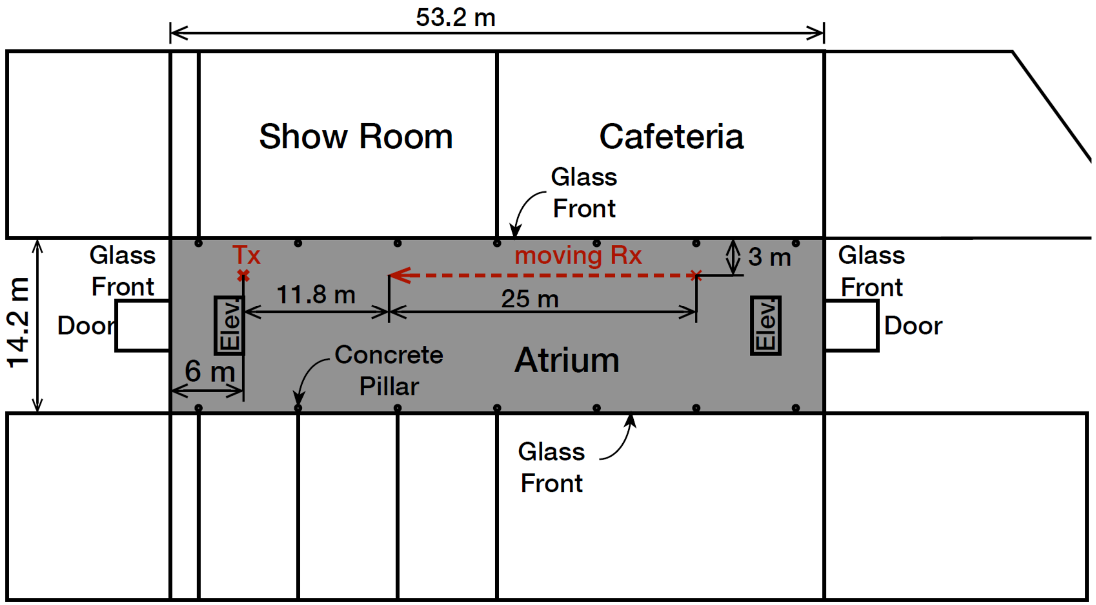


- Indoor measurement in the Rohde & Schwarz R&D center “atrium”
- Frequency: 17 GHz
- Linear moving receiver
- 1 ms snapshot rate
- Measurement bandwidth: 250 MHz

Angular Information from Virtual Arrays: Proof of Concept: Large scale virtual array



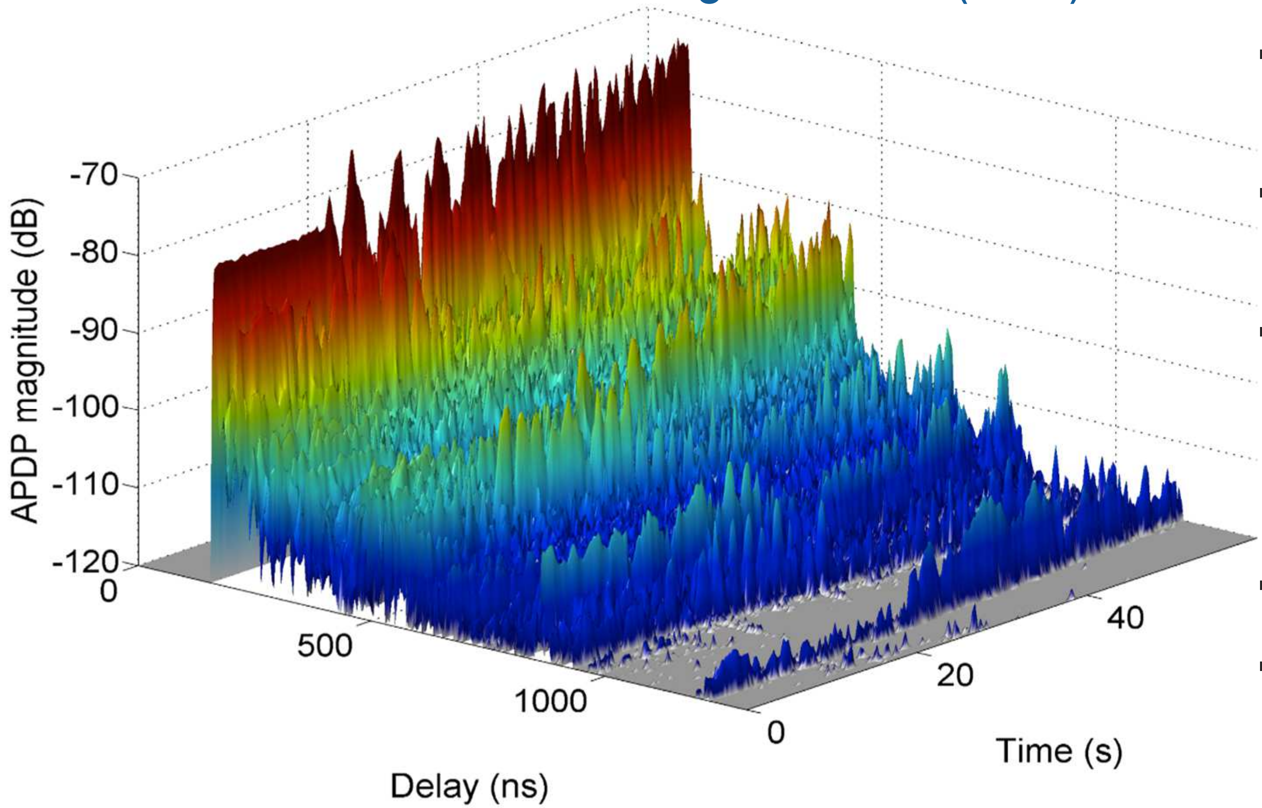
Virtual Array



- Indoor measurement in the Rohde & Schwarz R&D center “atrium”
- Frequency: 17 GHz
- Linear moving receiver
- 1 ms snapshot rate
- Measurement bandwidth: 250 MHz

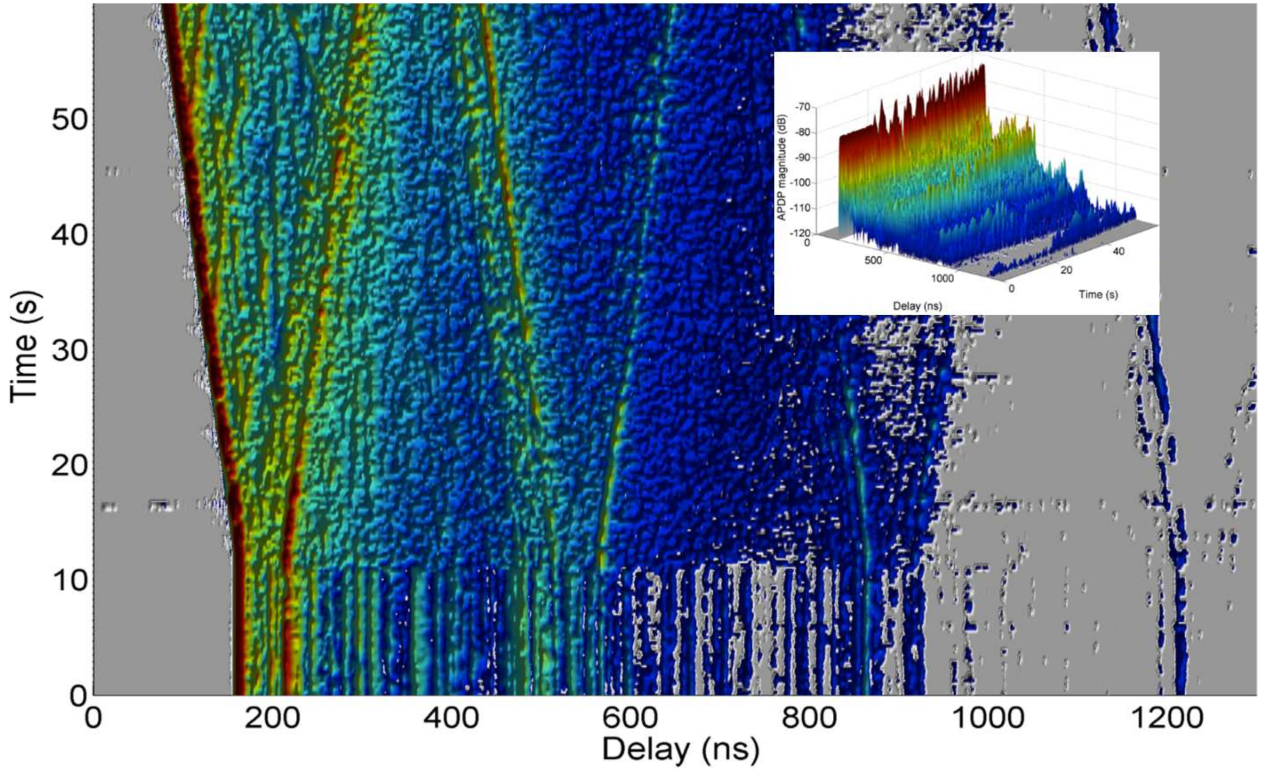
Source: Estimation of DoA based on Large Scale Virtual Array
(EuCAP2016 paper #1570231978)

Evolution of CIRs over moving distance (time)



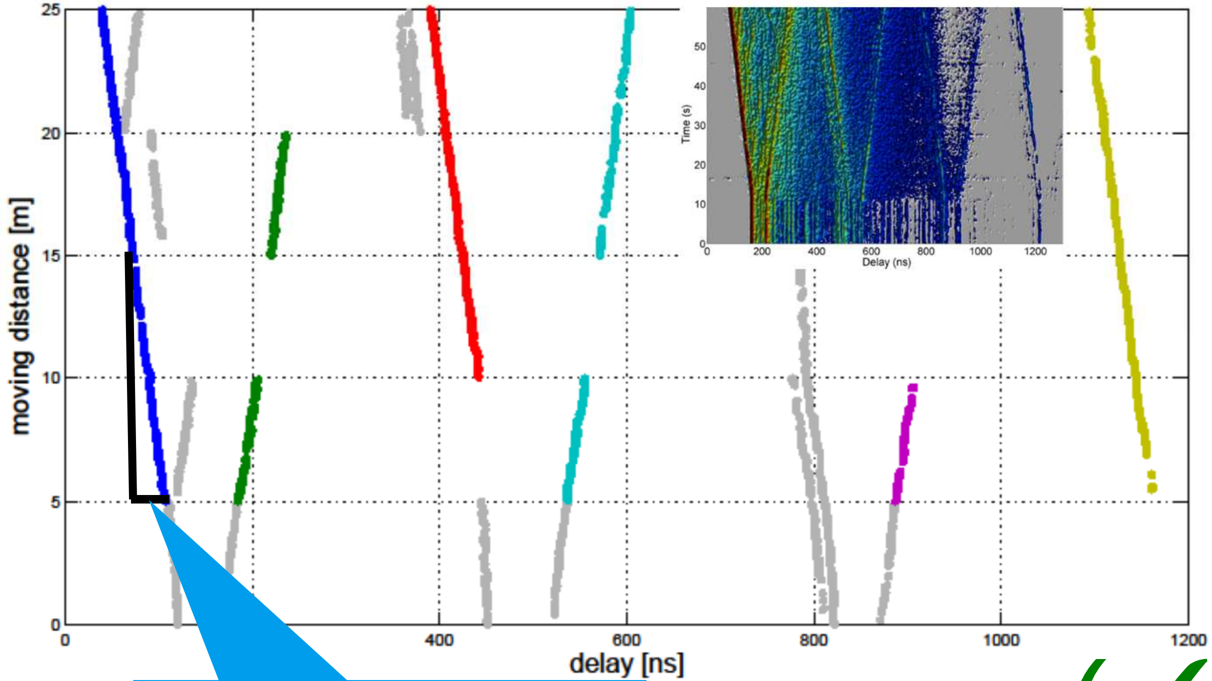
- Direct outcome of measurements at 17 GHz
- 60,000 snapshots in 60s, distance 25m
- In the first 10s no movement
- Line-Of-Sight Path (LOS) and reflected components (multipath contributions: MPC)
- Channel length: 1µs
- Large-scale fading of MPCs due to RX movement

Evolution of the CIRs over moving distance



- Top-view of set of power delay profiles
- Change of delays due to movement (piecewise linear)
- Certain paths (tracks) clearly visible

Path Tracking

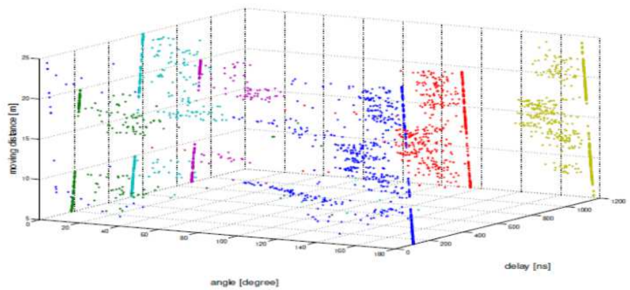


idea: from the steepness of the path we can derive the DoA

- Estimation of the paths by tracking algorithm
- Evolution of delay over time (i.e. distance) yields information about direction of arrival and Doppler shift
- Robust large scale analysis as long as direction of paths do not change during measurement run (farfield assumption)

(✓)

Direction of Arrival DoA Evaluation



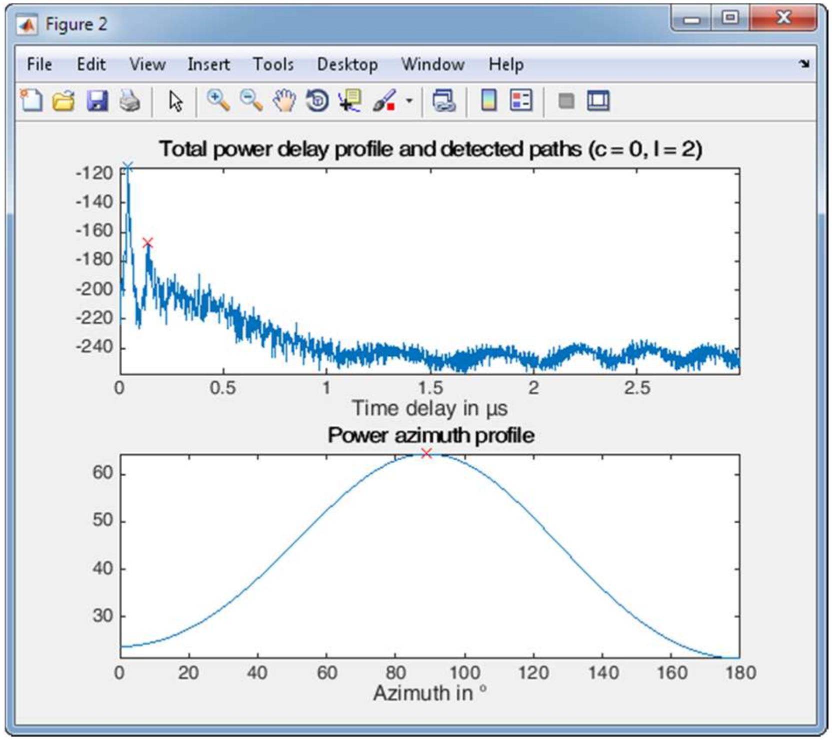
- The relationship between a detected trace and its DoA can be derived from geometry:

$$\phi = \arccos\left(c \cdot \frac{\mathrm{d}\tau}{\mathrm{d}x}\right), \qquad 0 \leq \phi \leq \pi,$$

comparison with MUSIC proofs concept

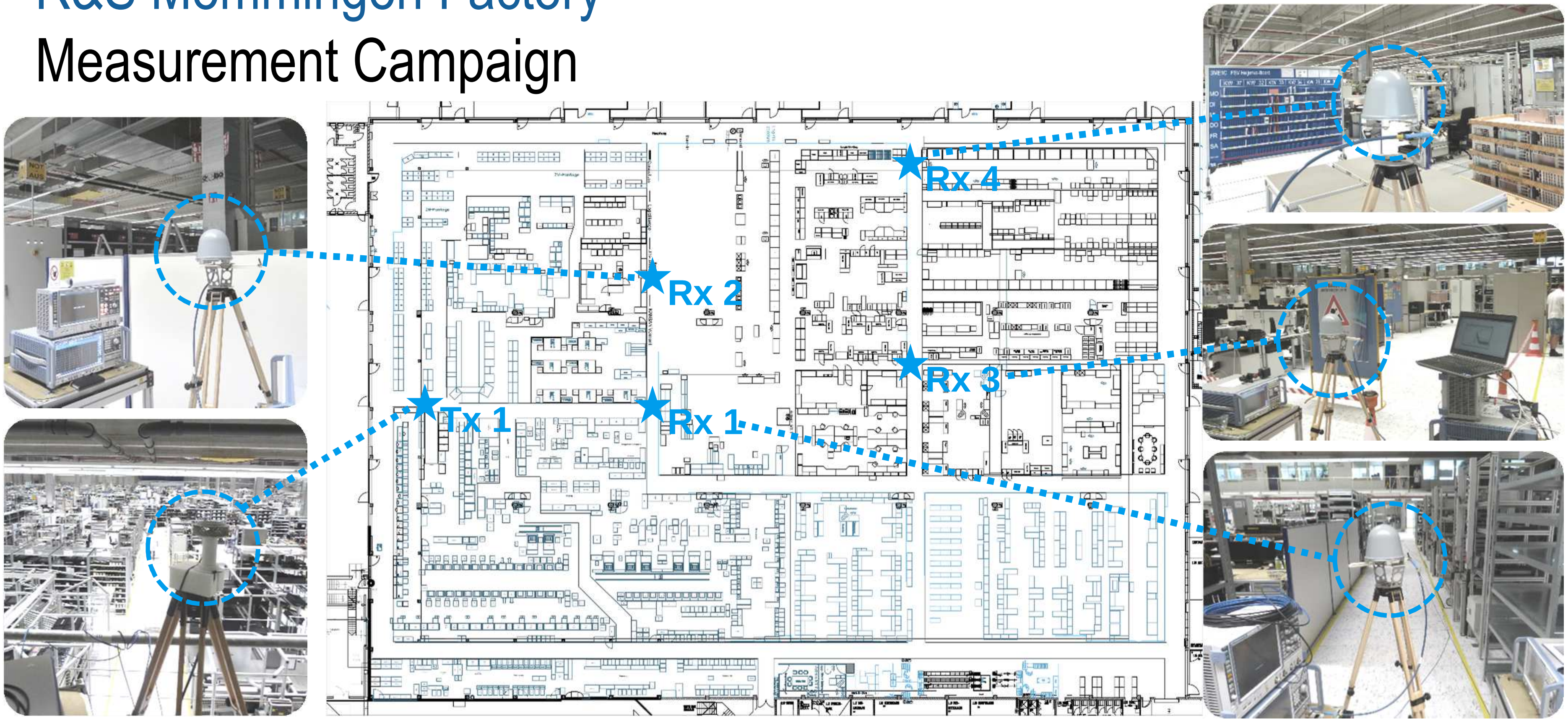
distance [m]	cos(ϕ)							
25 – 20	−1,00	0.92	−0.52	−0.75	−0.96	1.01	−1.13	
15 – 20	−0.97	−0.78	0.94	−1.03	1.08	1.01	−0.99	
10 – 15	−1.03	−1.08	−0.46	−1.02				
5 – 10	−1.09	1.11	1.21	1.24	−1.25	−1.16	1.15	−1.28
0 – 5	−0.65	0.86	−0.33	0.92	−0.81	−0.59	0.90	

Direction of arrival testing
Power Azimuth Profiles



R&S Memmingen Factory

Measurement Campaign

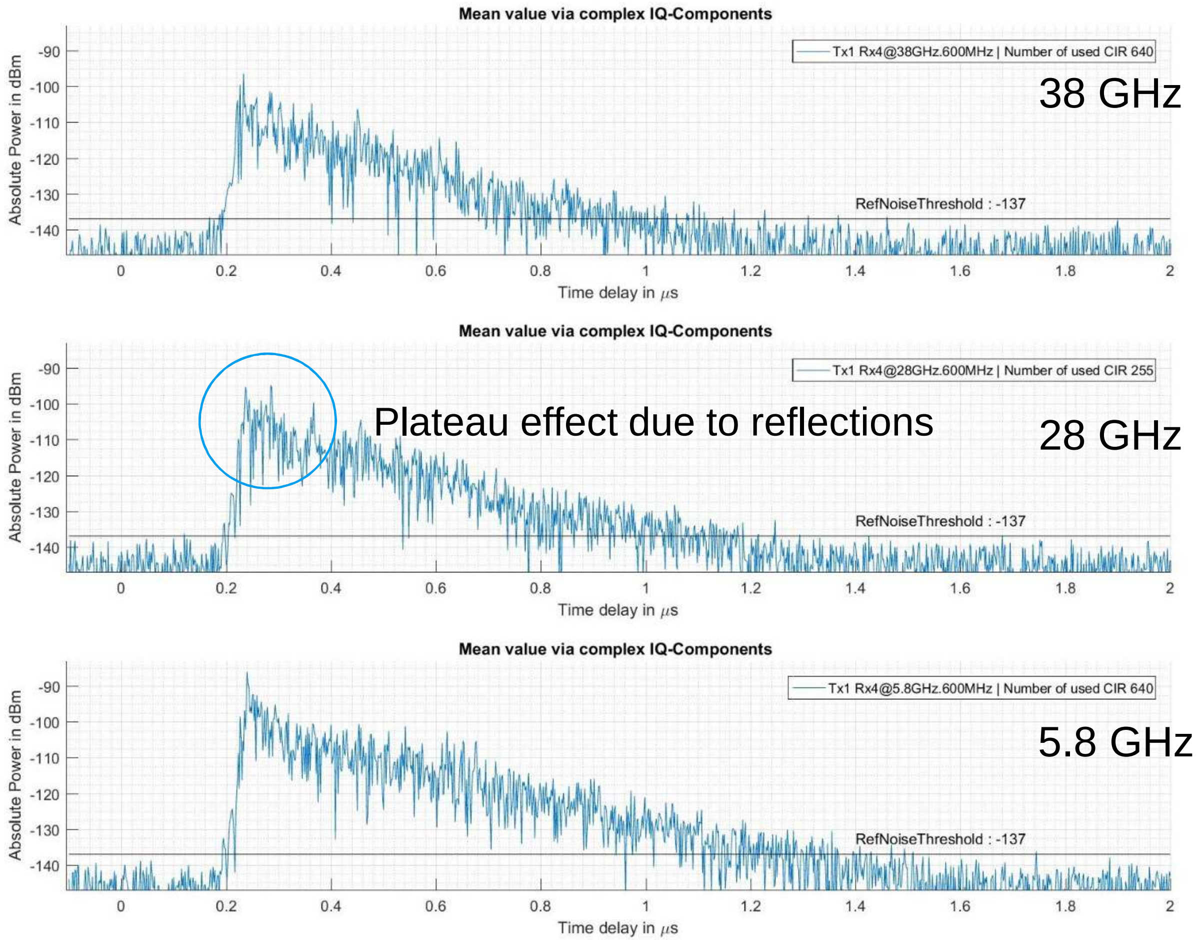


Industry 4.0 channel sounding trial

Position:
Tx1 Rx4 (NLOS)

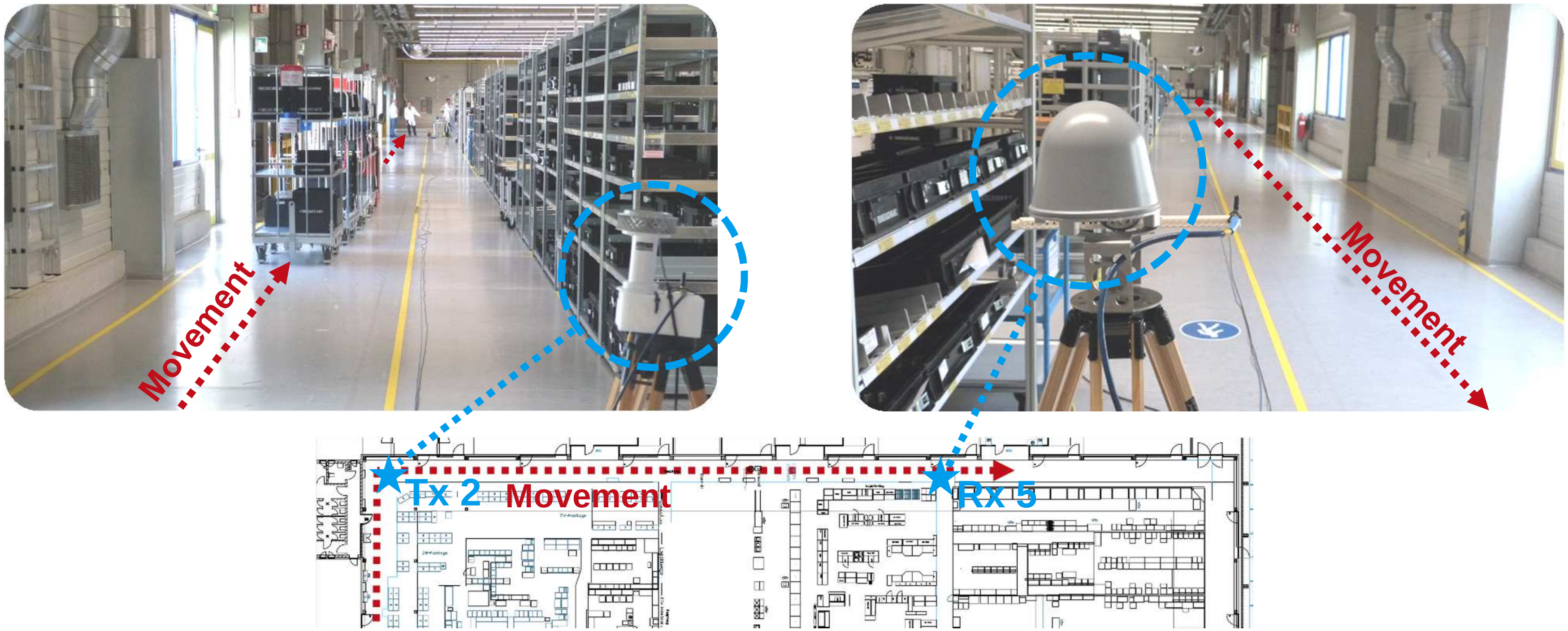
Frequencies:
38 GHz,
28 GHz,
5.8 GHz

Bandwidth:
500 MHz



Industry 4.0 trial: Street in Factory Hall, Moving Vehicle

Setup Description, R&S factory in Memmingen

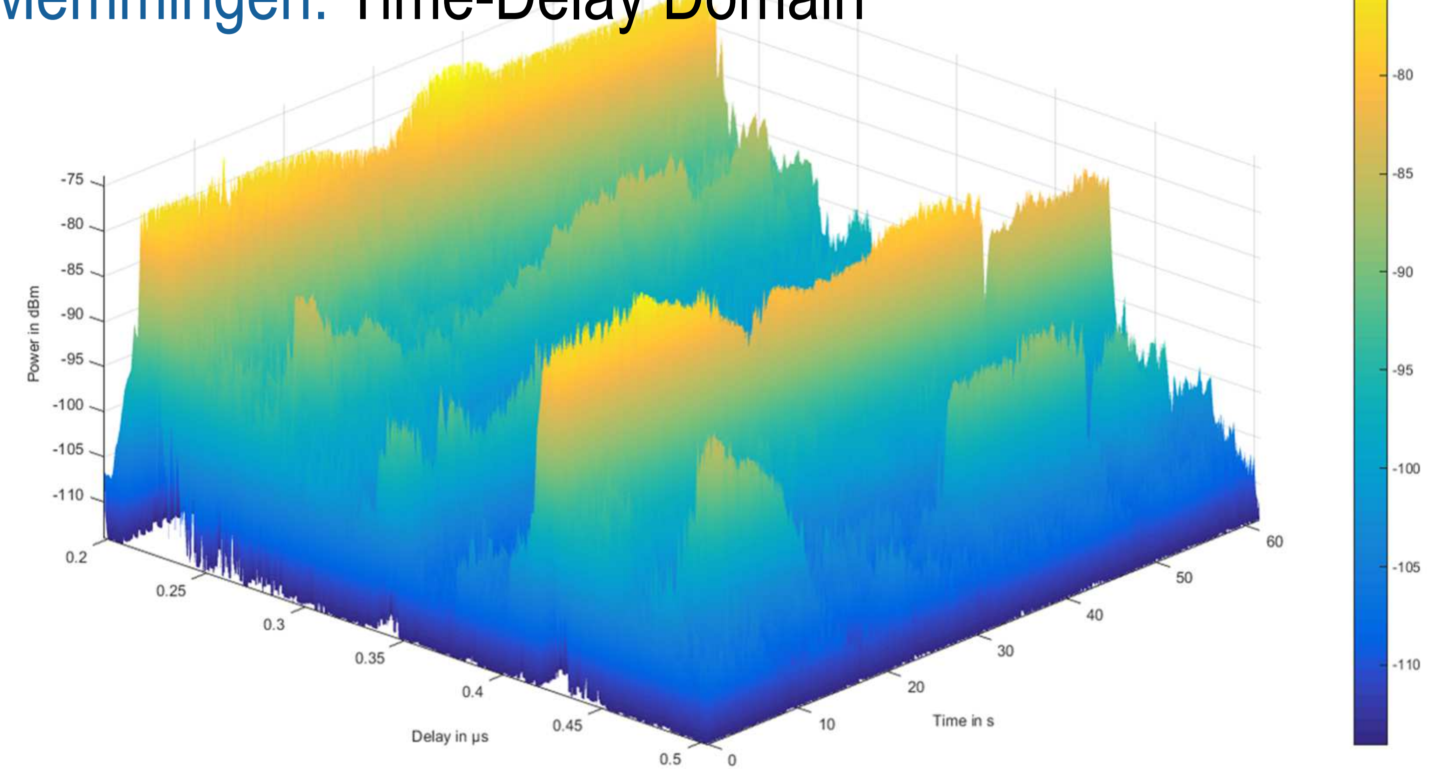


Industry 4.0 trial: Street in Factory Hall, Moving Vehicle
R&S factory in Memmingen: Time-Delay Domain

Positions:
Tx2 Rx5

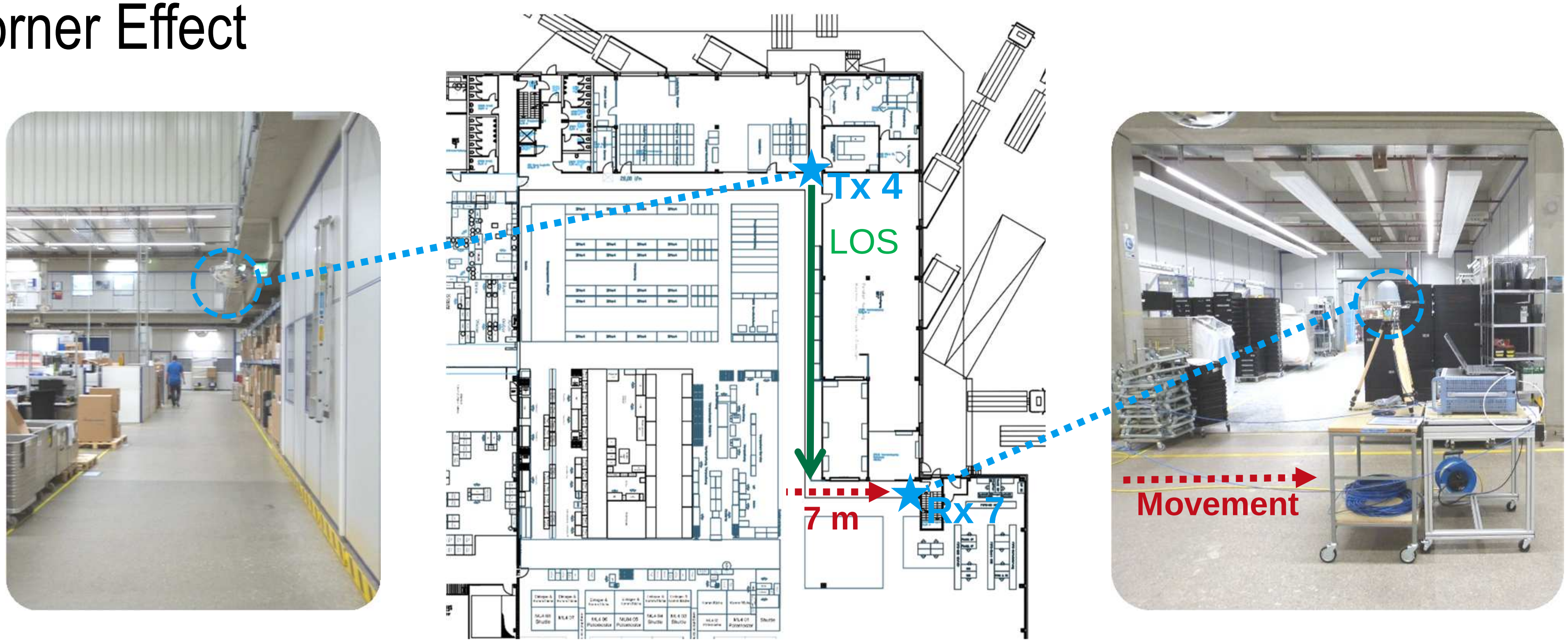
Frequency:
5.8 GHz

Bandwidth:
500 MHz



Industry 4.0 trial: balcony scenario:
LOS and Rx is moved around a corner

Corner Effect

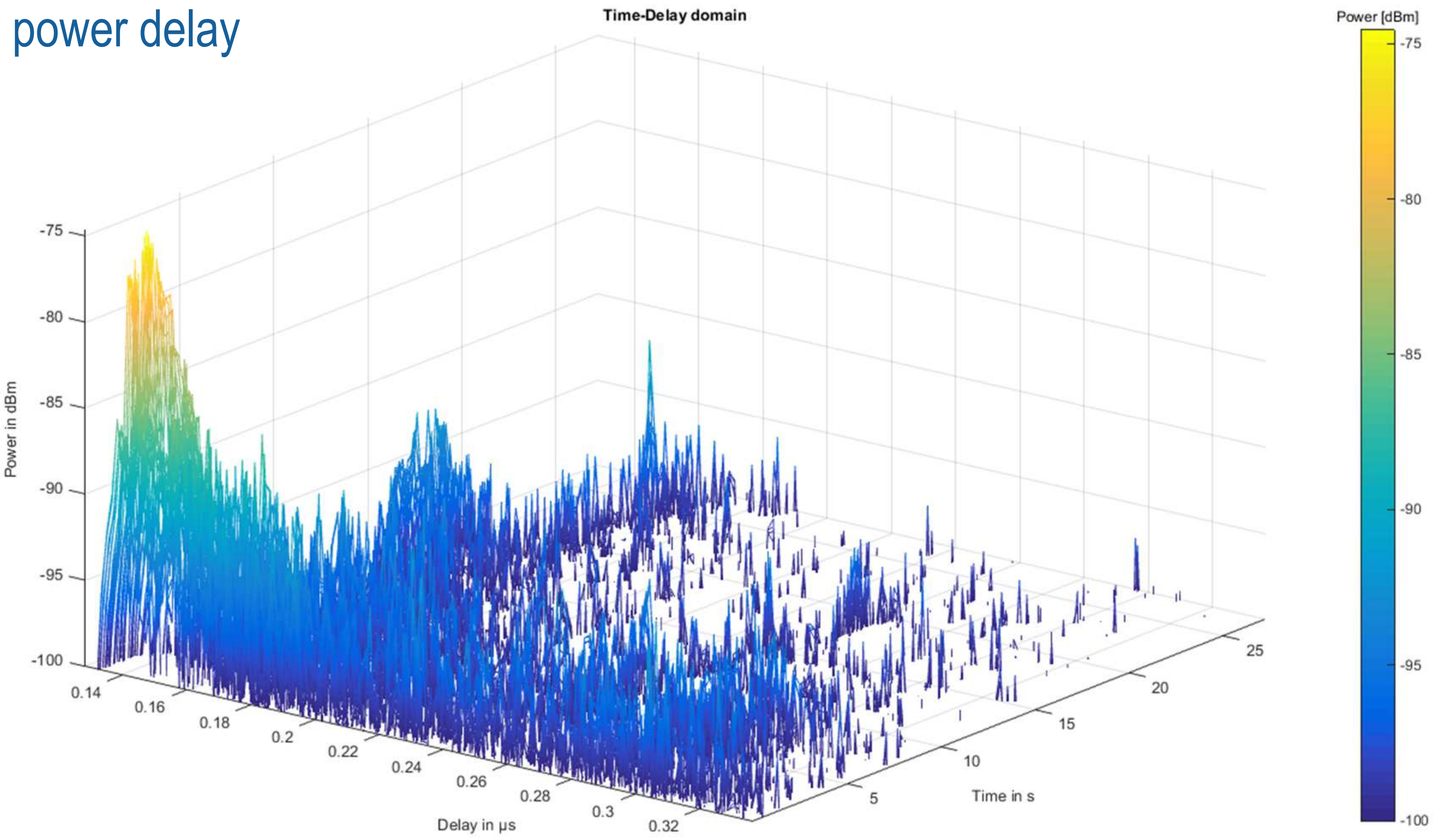


Industry 4.0 trial: power delay profile vs. time

Positions:
Tx4 Rx7

Frequency:
5.8 GHz

Bandwidth:
500 MHz

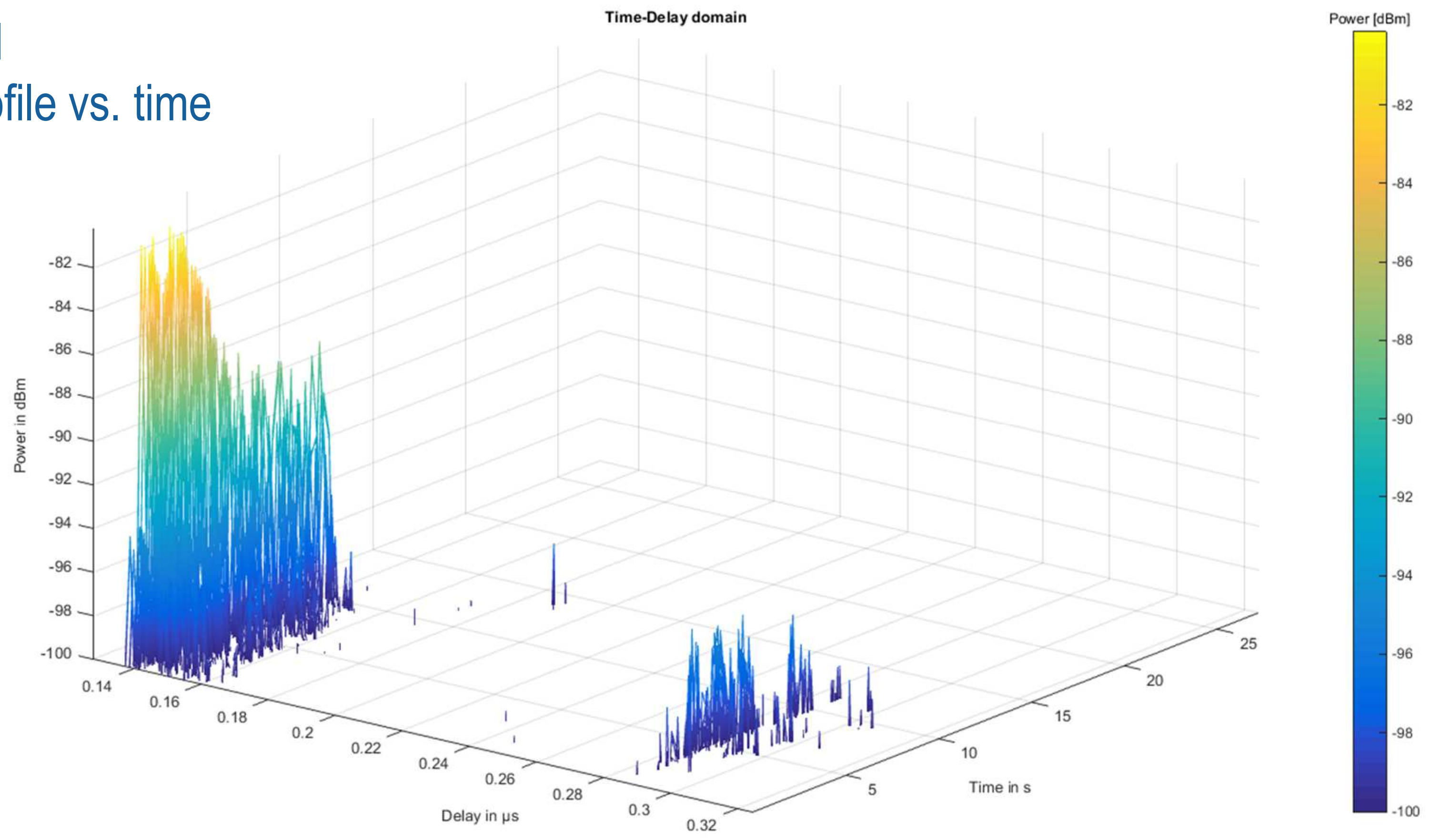


Industry 4.0 trial
power delay profile vs. time

Positions:
Tx4 Rx7

Frequency:
38 GHz

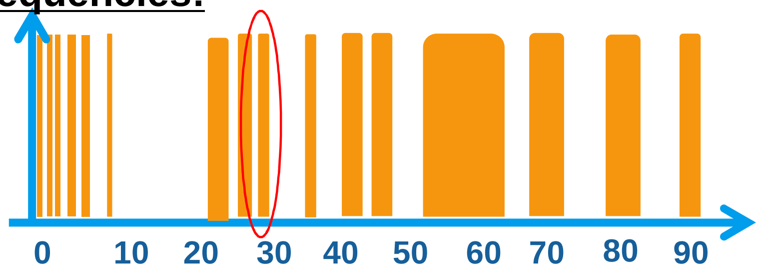
Bandwidth:
500 MHz



Feature comparison 3GPP 5G vs. Pre-5G

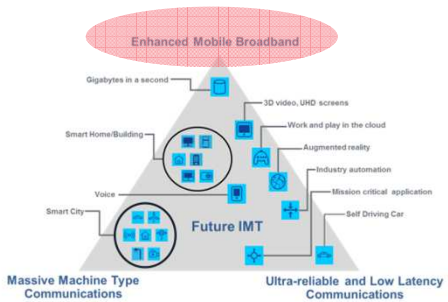
Pre-5G

Frequencies:



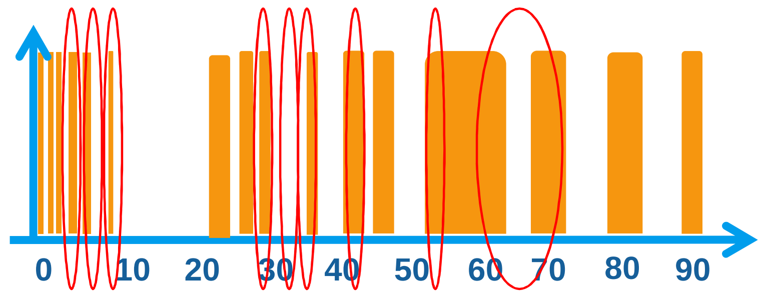
Only 28GHz in focus

Application:

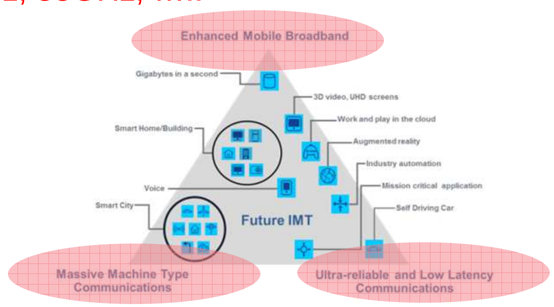


Only focus on eMBB

3GPP 5G + vision



Various frequencies in focus: 700MHz, 3.5GHz, 5.9GHz, 15GHz, 25GHz, 28GHz, 38GHz, …..

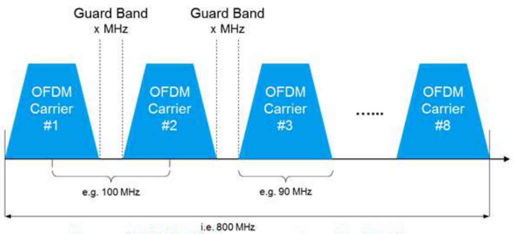


Focus on all: eMBB, mMTC and uRLLC

Feature comparison 3GPP 5G vs. Pre-5G

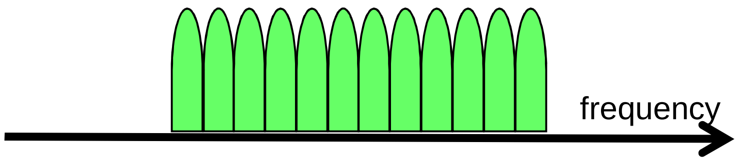
Pre-5G

Bandwidth:



1 channel = 100MHz, up to 8 CCs
800MHz total bandwidth

subcarrier spacing:



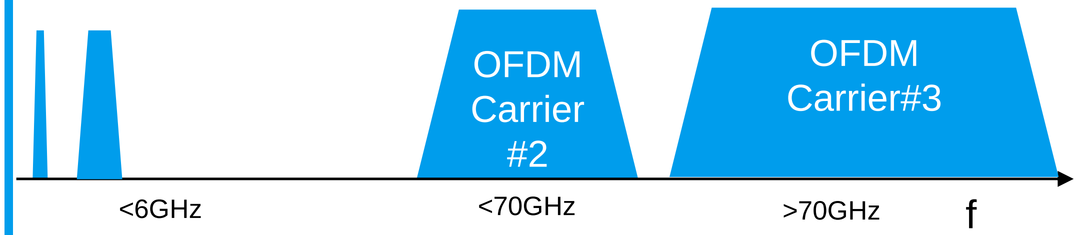
Δf = const = 75kHz

Modulation scheme:

QPSK, 16QAM + 64QAM

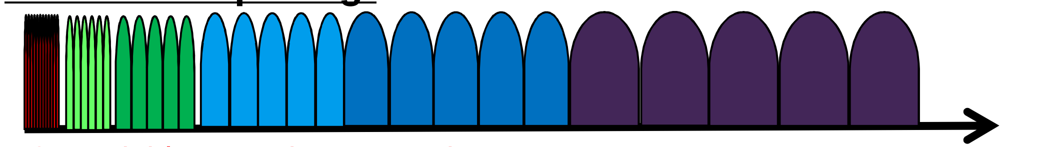
3GPP 5G + vision

Bandwidth:



1 channel = 10 or 20MHz | 1 channel ~80MHz | 1channel ~640Mhz
total bandwidth up to 2GHz

subcarrier spacing:



Δf = variable = 3.75kHz … 240kHz

frequency

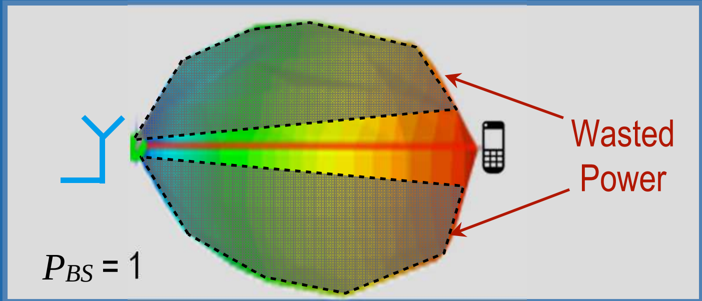
Modulation scheme:

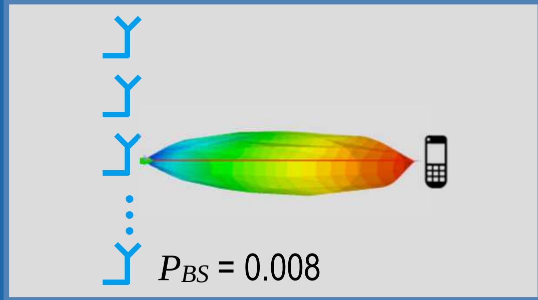
QPSK, 16QAM, 64QAM + 256QAM (higher order tbd + alternative schemes i.e. 12 + 4 PSK or constant envelope)

Massive MIMO Theory & Hardware

ROHDE&SCHWARZ

Energy Efficiency: Why Massive?





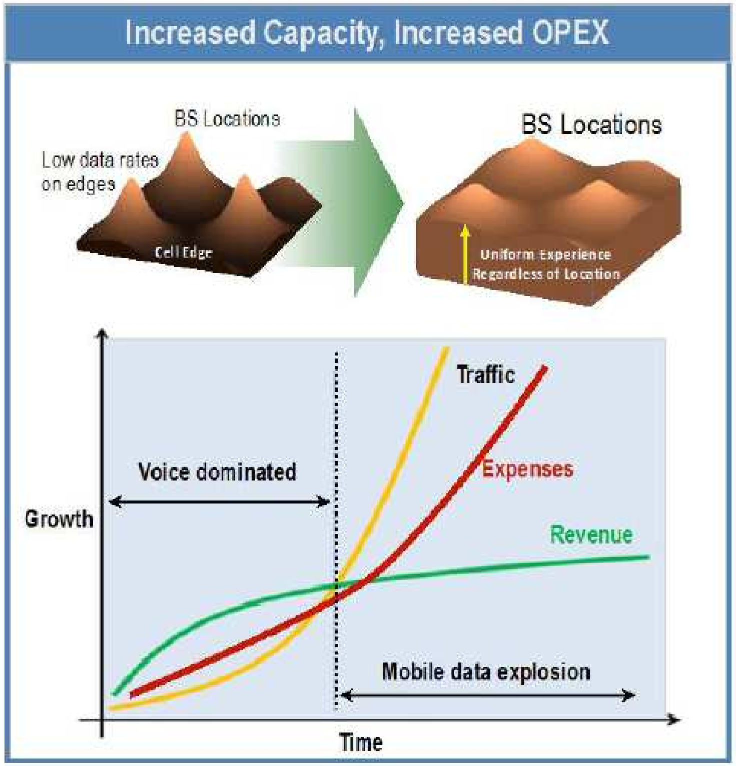
	Number of Antennas = 1	Number of UEs: 1 120 antennas per UE
Number of BS Transmit Antennas	1	120
Normalized Output Power of Antennas	$P_{ant} = \frac{1}{M_t} = 1$	$P_{ant} = \frac{1}{M_t^2}$
Normalized Output Power of Base Station	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^{i} = 1$	$P_{total} = \sum_{i=1}^{M_t} P_{ant}^{i} = 0.008$

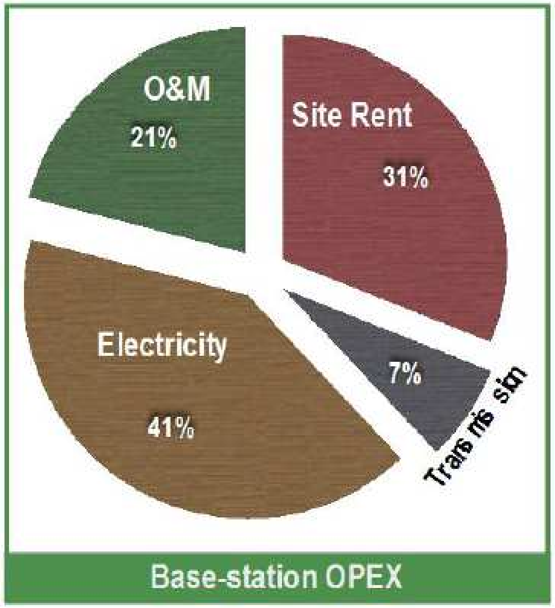
Source: IEEE Signal Processing Magazine, Jan 2013

ROHDE&SCHWARZ

Easiest way to improve energy efficiency: more antennas

Energy Efficiency: energy efficiency vs site installation costs

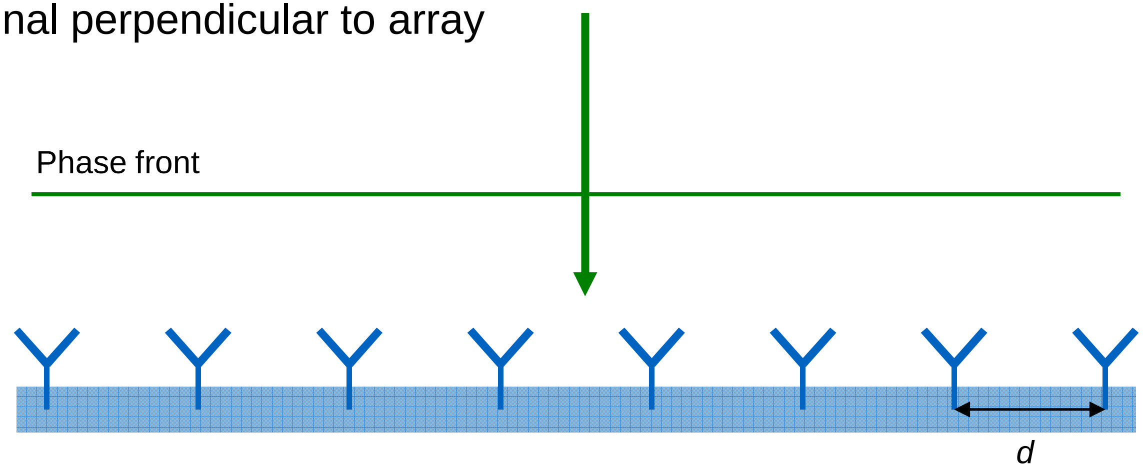




Easiest way to improve energy efficiency: more antennas

Phased Array Antenna Principle

Example: Linear array
- 8 antenna elements
- Equidistant spacing *d*
- Incident signal perpendicular to array

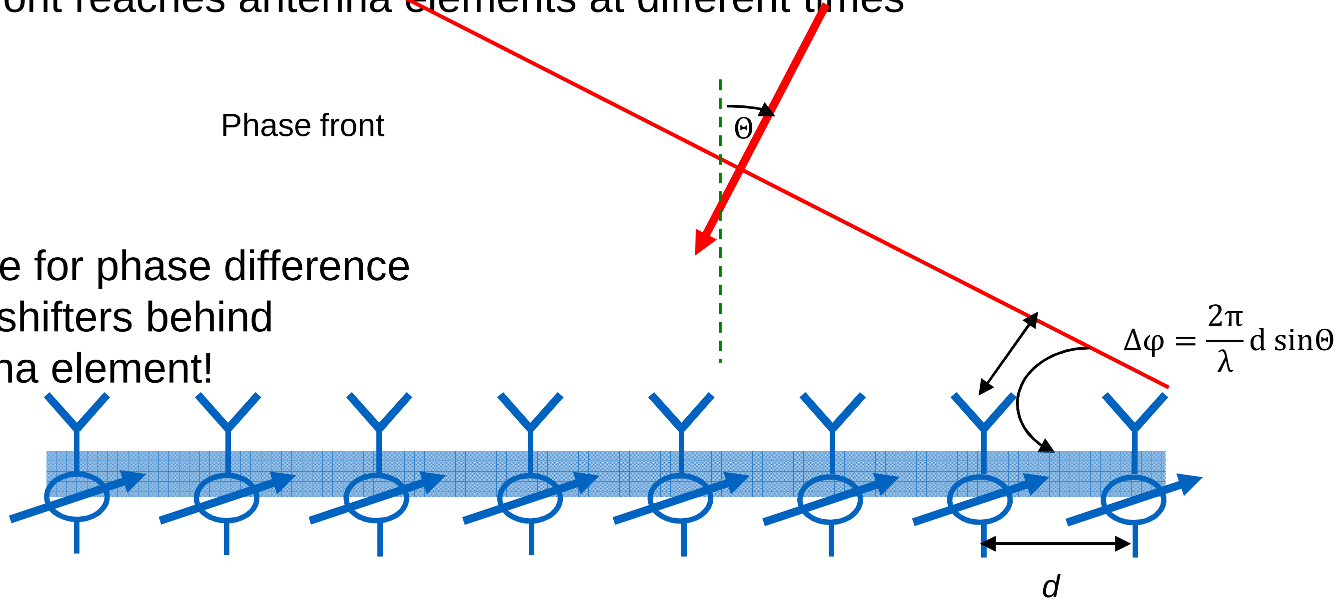


Phase front reaches all antenna elements at same time

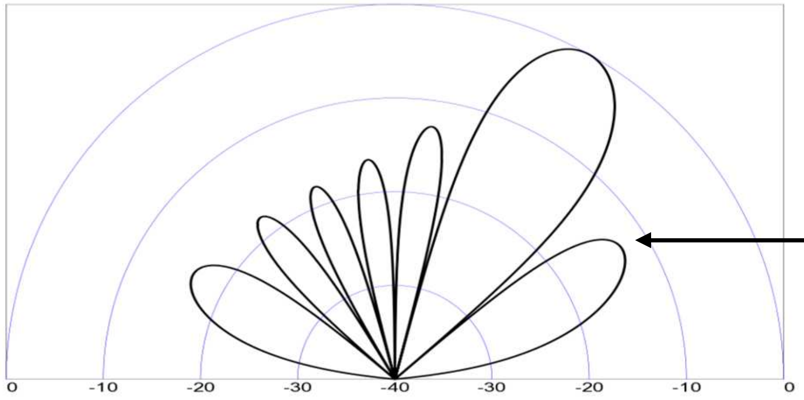
Phased Array Antenna Principle

Example: Linear array
- Direction of incident signal with angle Θ
- Phase front reaches antenna elements at different times

Idea:
- Compensate for phase difference
- Add phase shifters behind each antenna element!



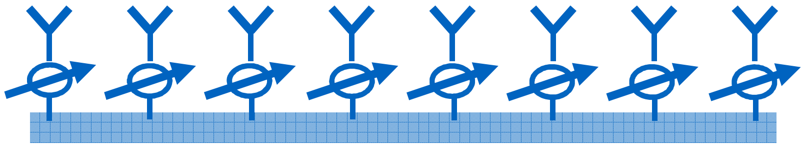
Phased Array Antenna Principle



Advantage:
Main beam direction steerable with phase shifters

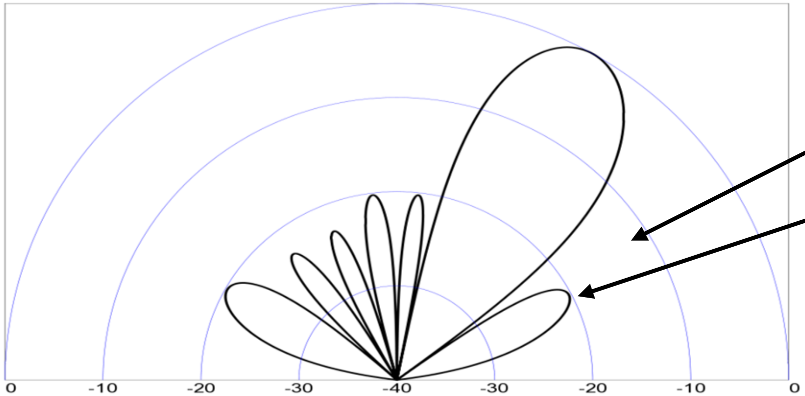
Problem:
Still high side lobe level

How to get side lobe level down?



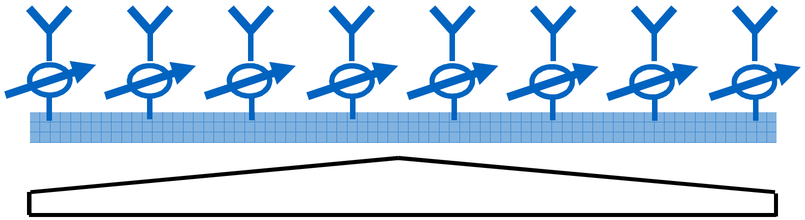
phase shifters:
Weighting by phase

Phased Array Antenna Principle



Question:
How to get side lobe level down?

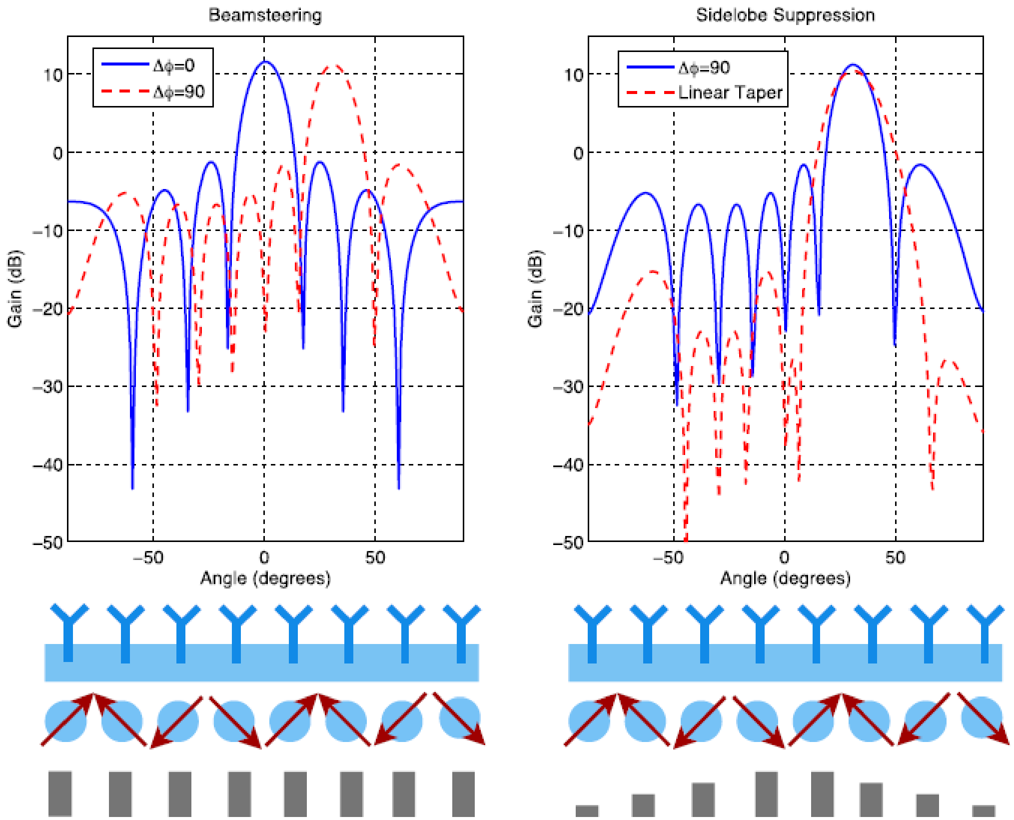
Answer:
Additional weighting by magnitude!



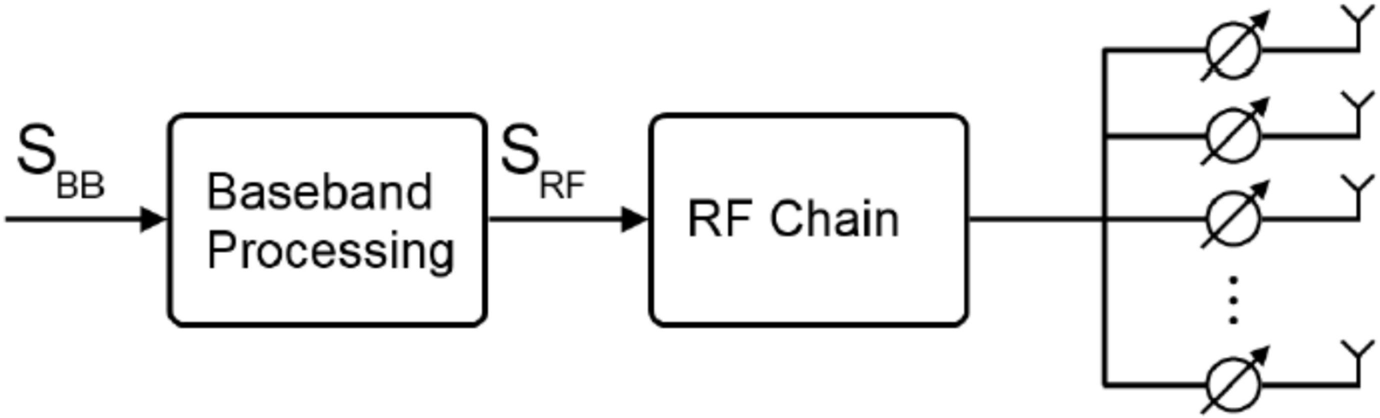
weighting phase and magnitude

Triangular weighting function

beamforming with phased array = phase + amplitude modification

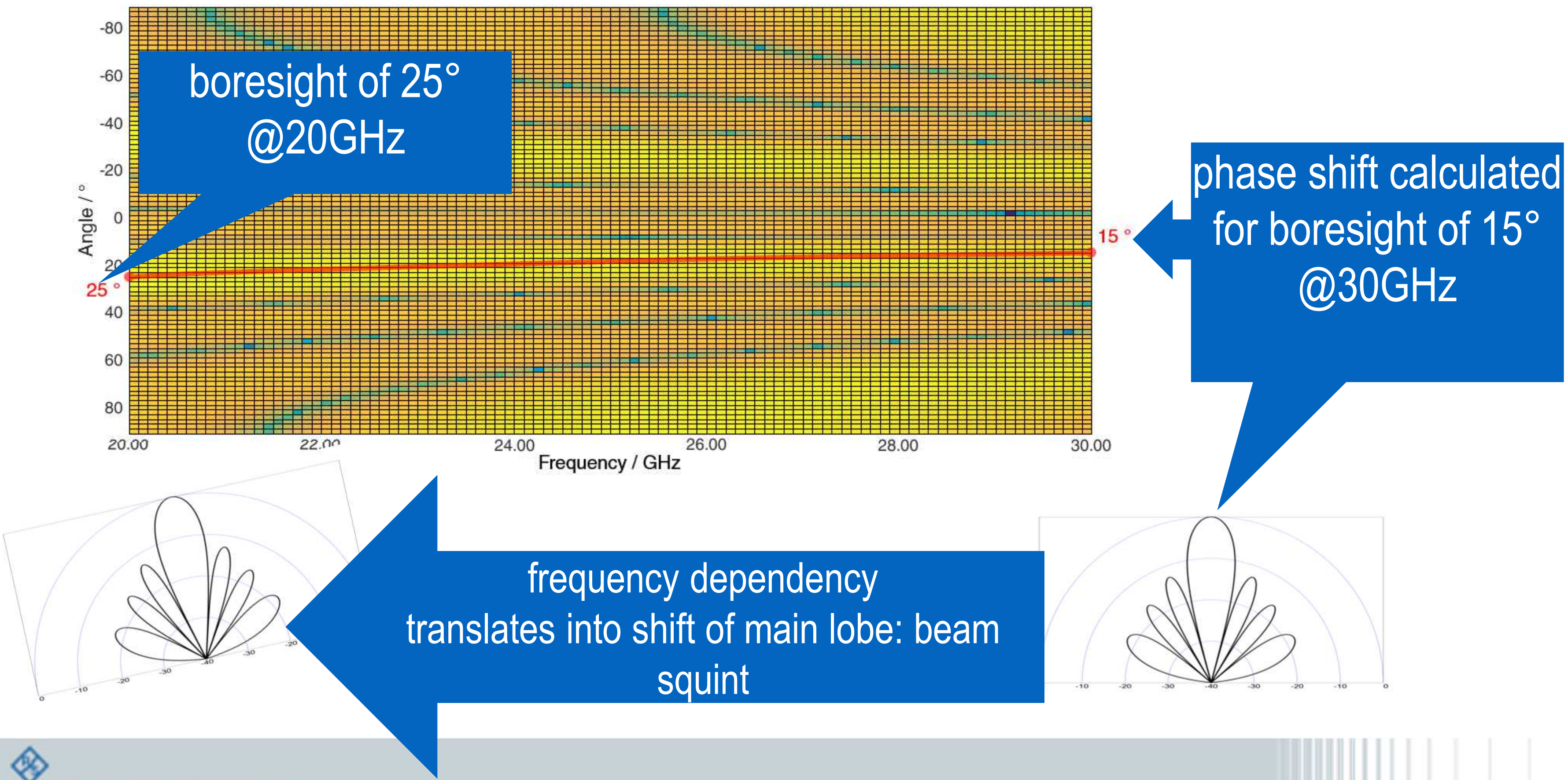


Analog beamforming concept

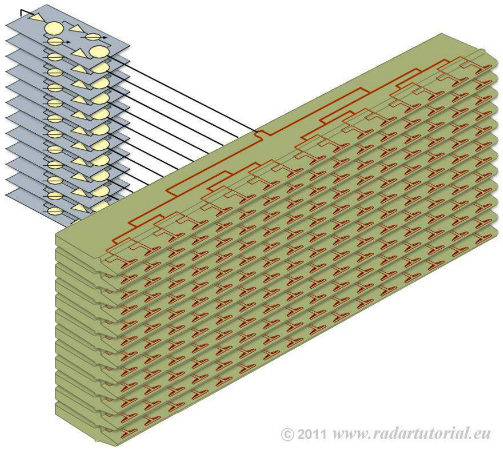


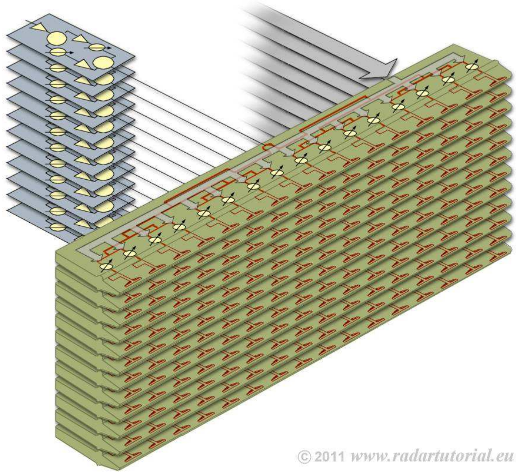
- separate control of the phase of each element
- beam can be steered not only to discrete but virtually any angle using active beamforming antennas
- not as expensive and complex as the other approaches
- On the other hand implementing a multi-stream transmission with analog beamforming is a highly complex task
- one RF chain

Analog beamforming – effect of beam squint



antenna arrays and beamforming scenarios





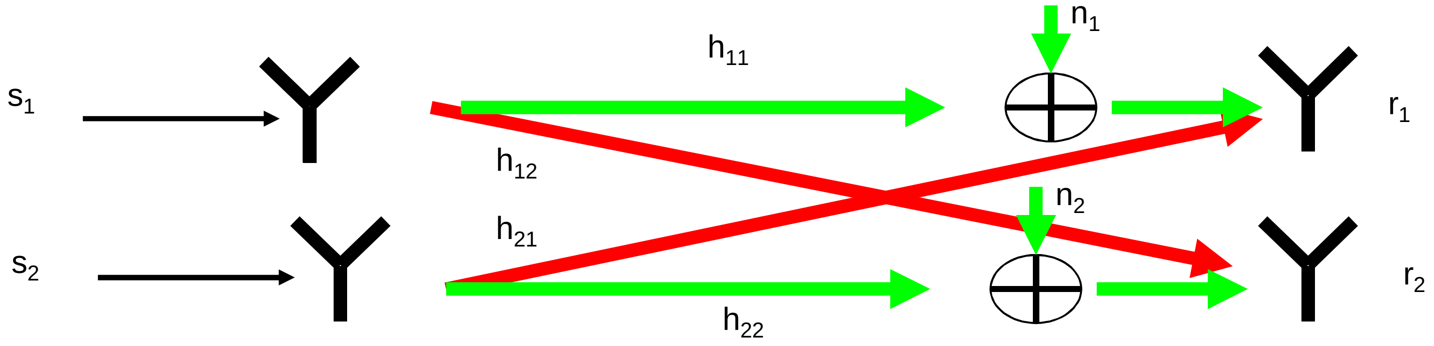
Linear antenna array:

- one phase shifter for antenna element segments
- simpler structure
- beam forming only in one dimension possible

Planar antenna array:

- one phase shift for each antenna element
- structure is more complex
- beam forming in 2 dimensions possible, i.e. horizontal and vertical = 3D beamforming

MIMO reminder – capacity calculations, e.g. 2x2 MIMO



This results in the equations:

$r_1 = s_1*h_{11} + s_2*h_{21} + n_1$

$r_2 = s_2*h_{22} + s_1*h_{12} + n_2$

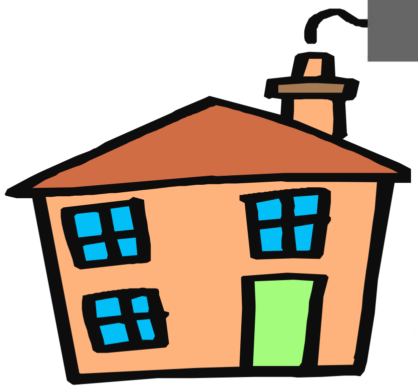
Or as matrix:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} * \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

Generally written as: $r = s*H + n$

To solve this equation, we have to know H

MIMO – work shift to transmitter



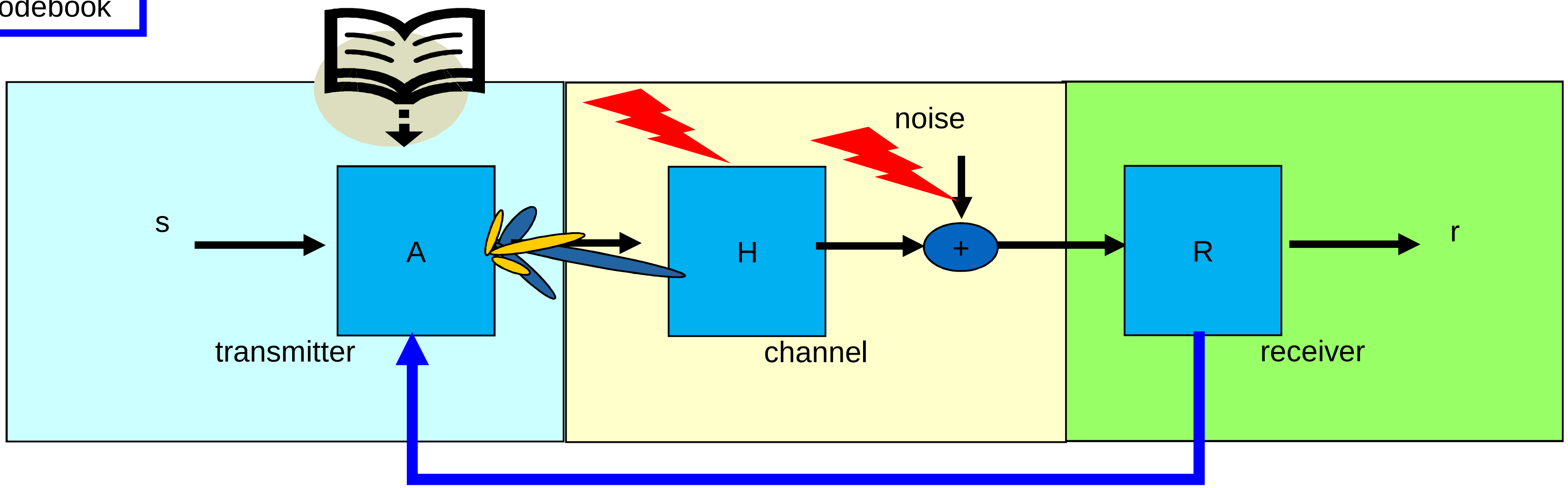
Transmitter

Channel

Receiver

MIMO – codebook based precoding

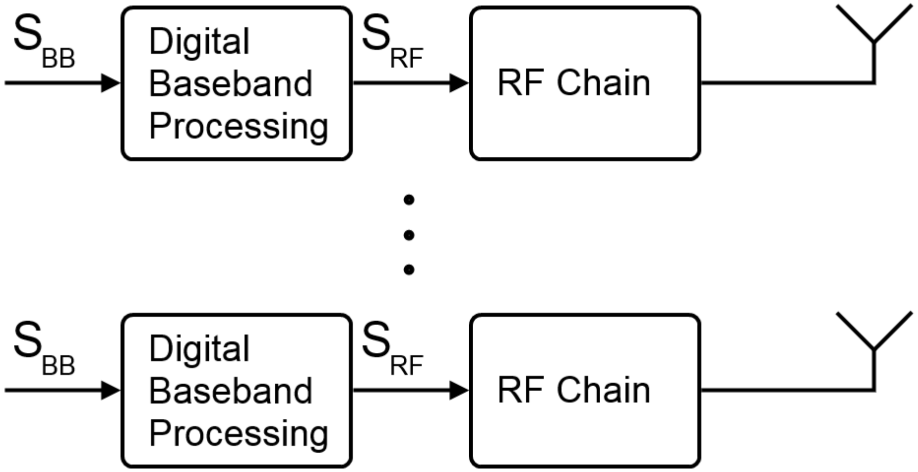
Precoding codebook



Precoding Matrix Identifier, PMI

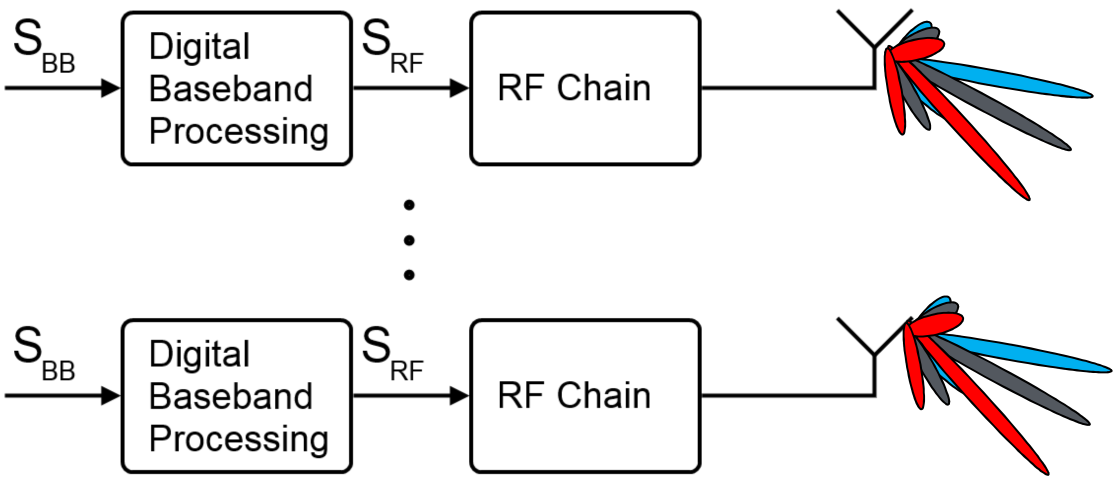
Codebook based precoding creates some kind of „beamforming lite“

Digital beamforming concept



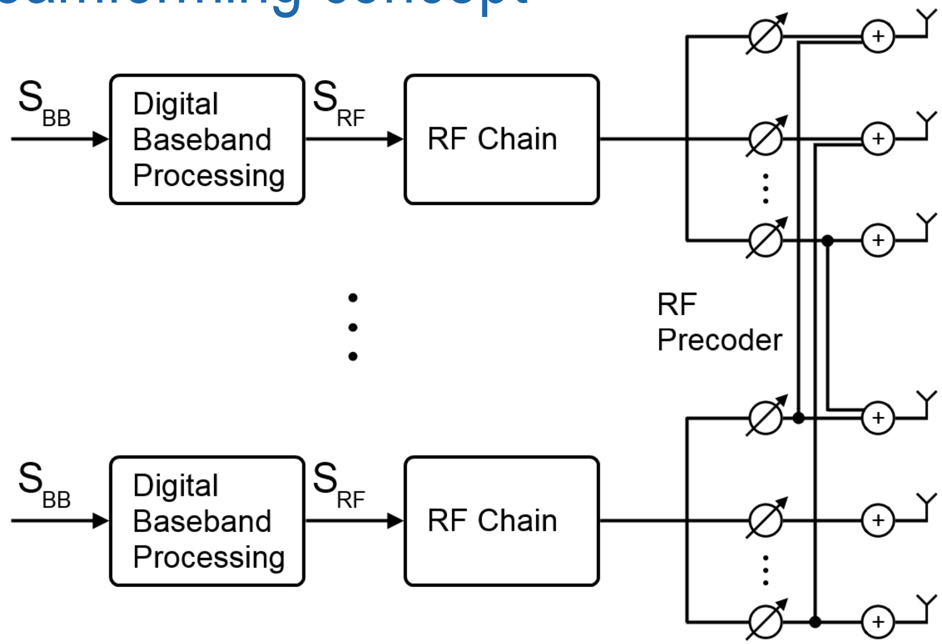
- digital beamforming in theory supports as many RF chains as there are antenna elements
- suitable precoding is done in the digital baseband, this yields higher flexibility regarding transmission and reception
- additional degree of freedom can be leveraged to perform advanced techniques like multi-beam MIMO
- Digital beamforming can accommodate multi-stream transmission and serve multiple users simultaneously
- Digital control of the RF chain enables optimization of the phases according to the frequency over a large band
- very high complexity and requirements regarding the hardware may significantly increase cost, energy consumption and complicate integration in mobile devices

Digital beamforming concept



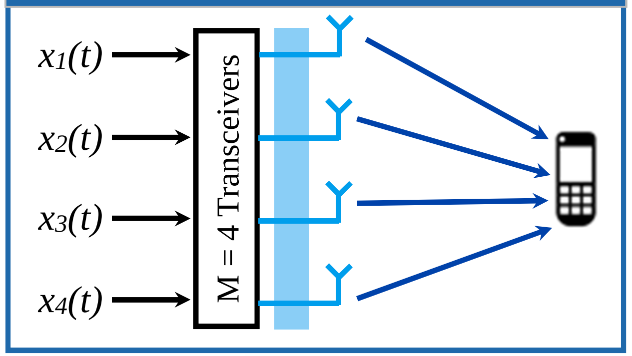
digital beamforming allows to simultaneously generate multiple beams by using the same hardware antenna elements.
-> at the price of higher complexity, i.e. number of RF chains

Hybrid beamforming concept

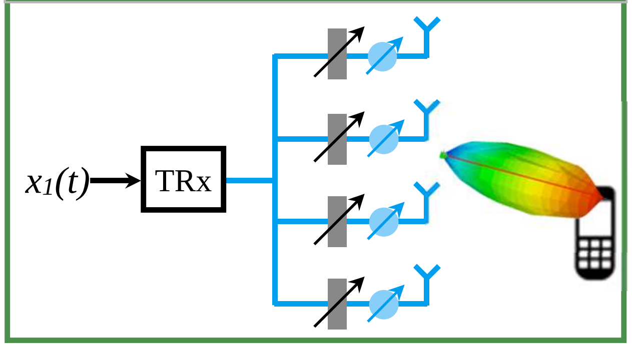


- trial to combine the advantages of both analog and digital beamforming architectures
- reducing the number of complete RF chains
- number of simultaneously supported streams is reduced compared to full blown digital beamforming

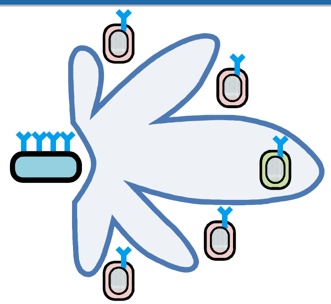
Hardware Perspective: Massive MIMO = Beamforming + MIMO



+



Massive MIMO: Combine Beamforming + MIMO = MU-MIMO with M antennas >> # of UEs



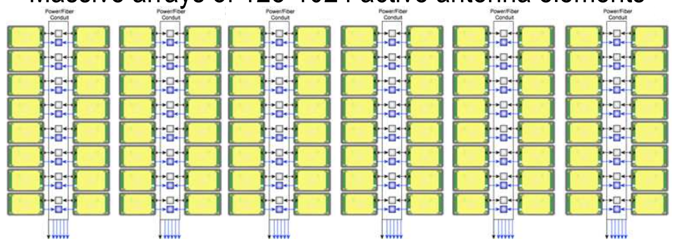
Multi User-MIMO

Increase SINR and capacity for each user

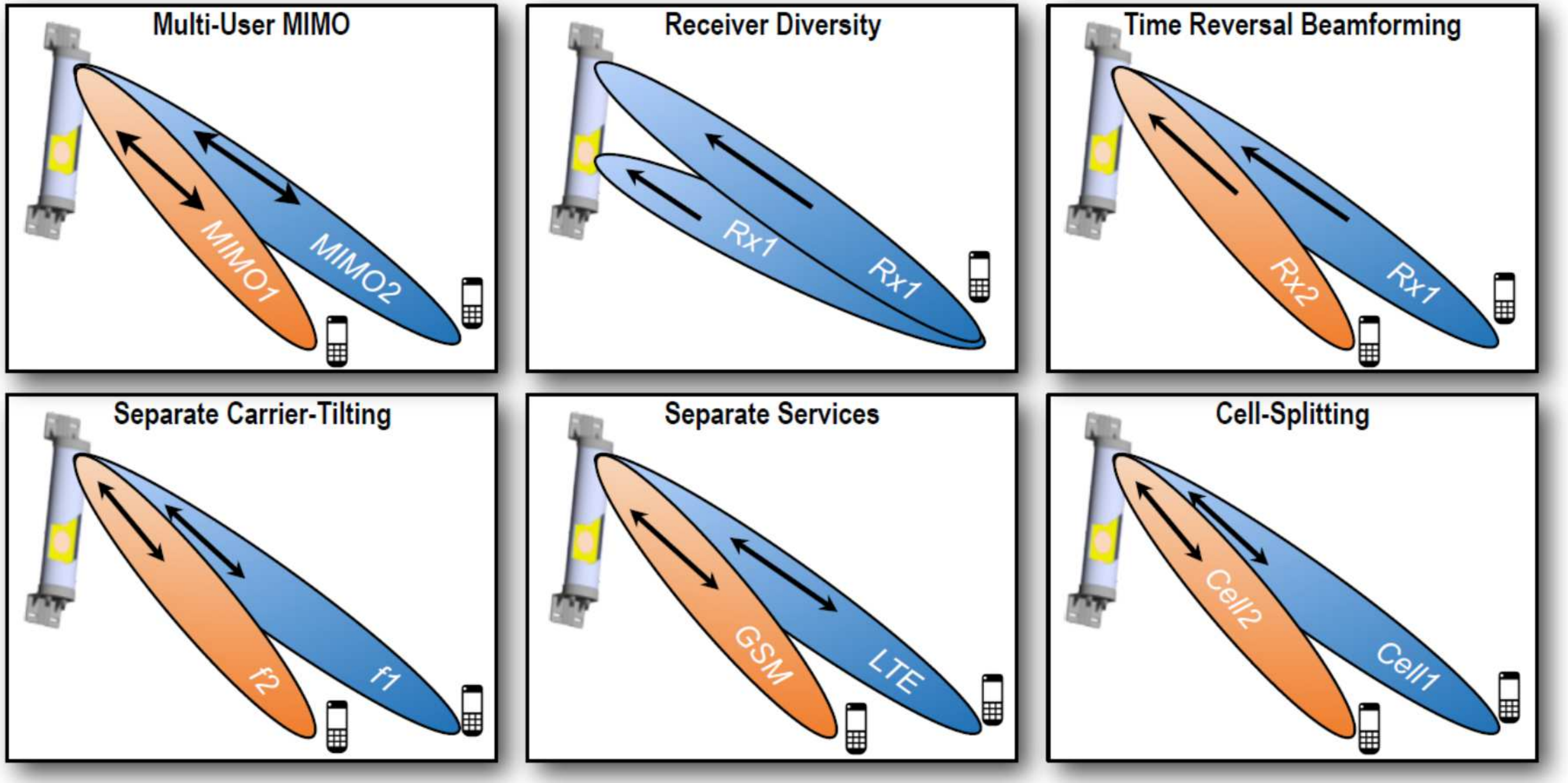
i.e. UE1: 32 ant BF with 16x2 MIMO

UE2: 16 ant BF with 8x2 MIMO

Massive arrays of 128-1024 active antenna elements



Applications of Massive MIMO from the networks perspective



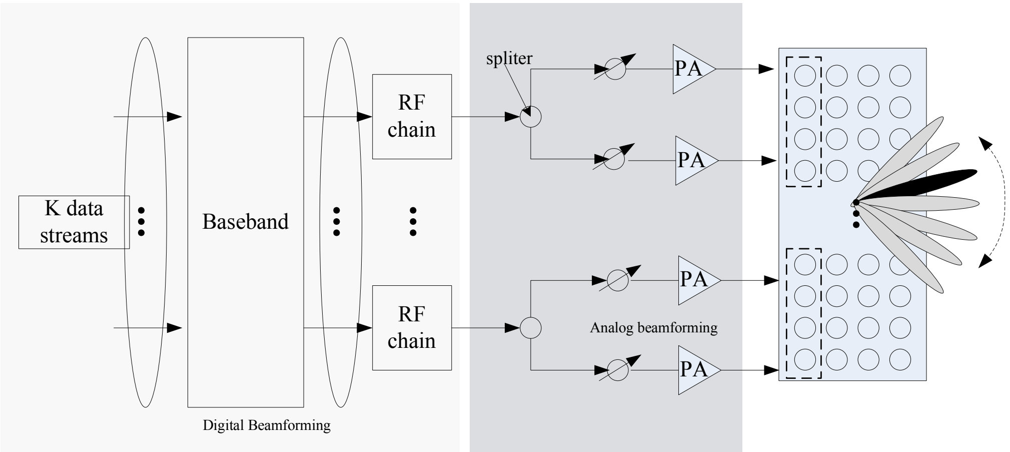
3GPP RAN1#85 mMIMO transceiver architectures

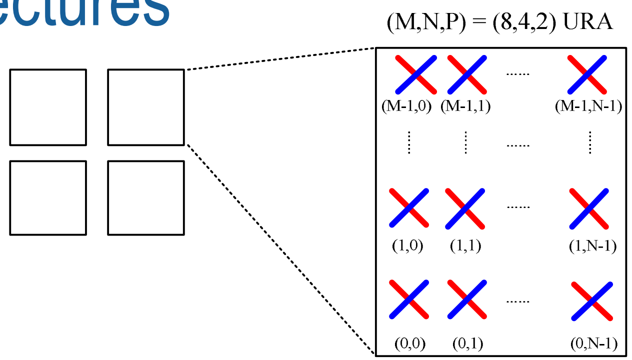
(sources: Tdoc R1-164018, Tdoc R1-164038, Tdoc R1-164334)

Option 1: Digital beamforming

Option 2: Analog beamforming

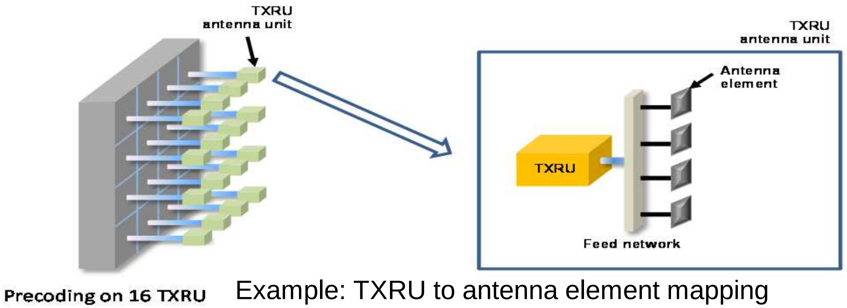
Option 3: Hybrid beamforming





Example: URPA with 2x2 panels

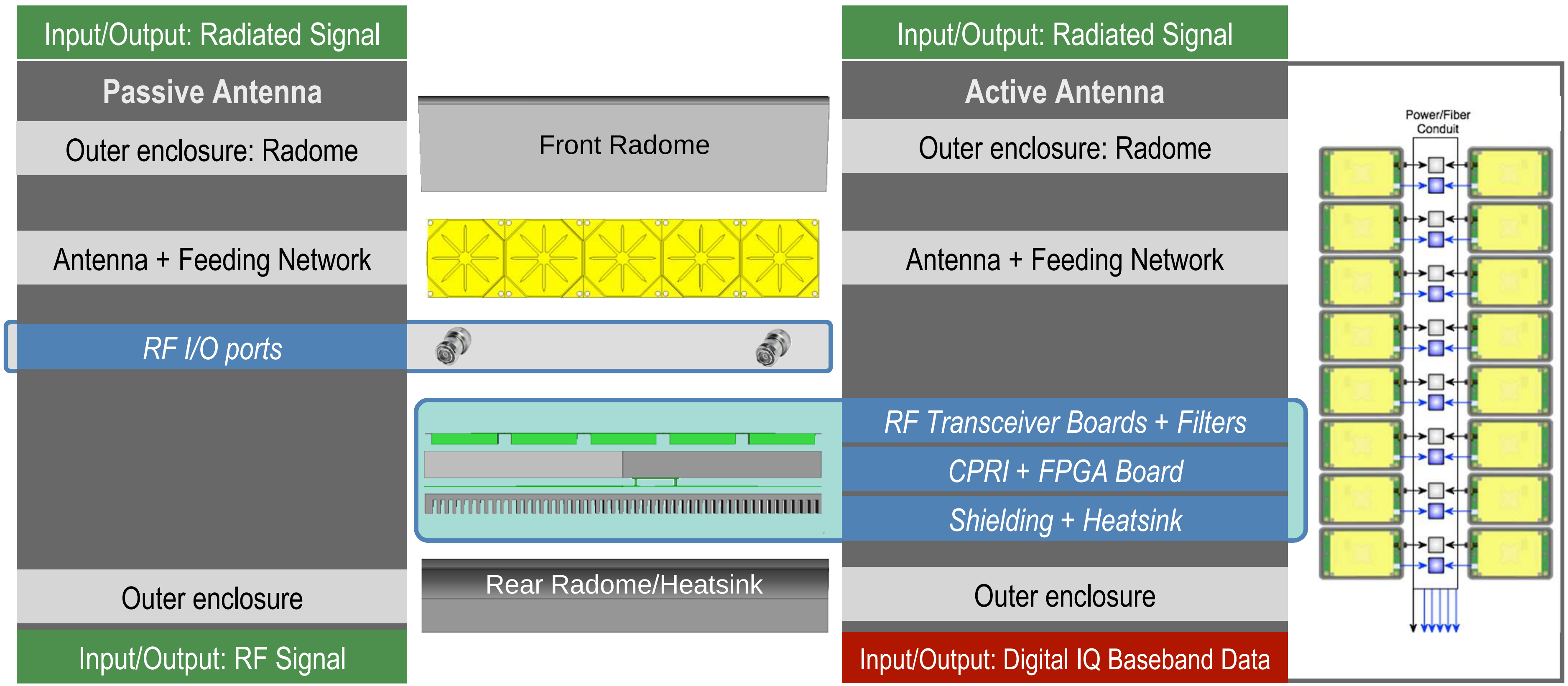
URPA = uniform rectangular panel array



Example: TXRU to antenna element mapping

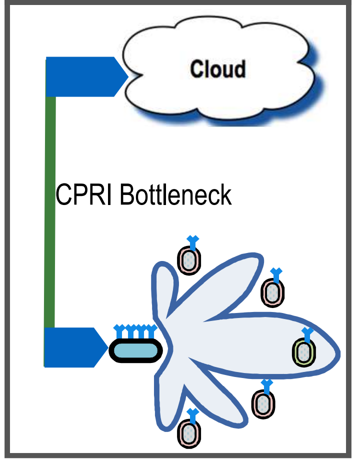
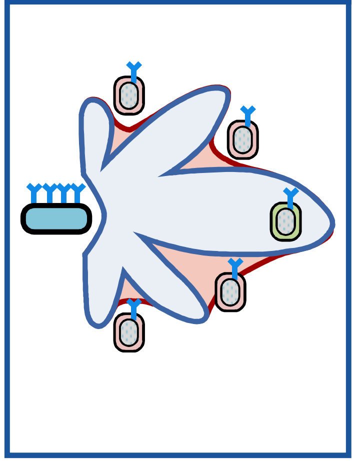
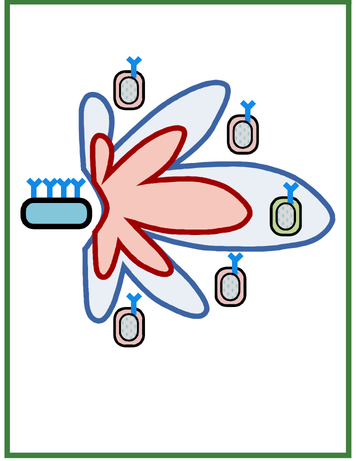
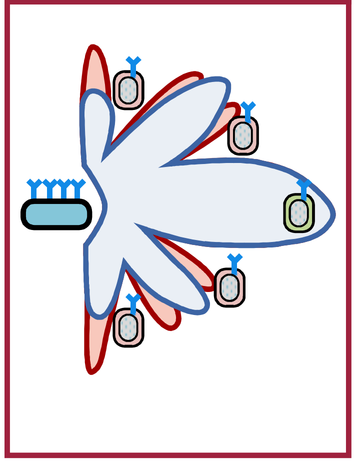
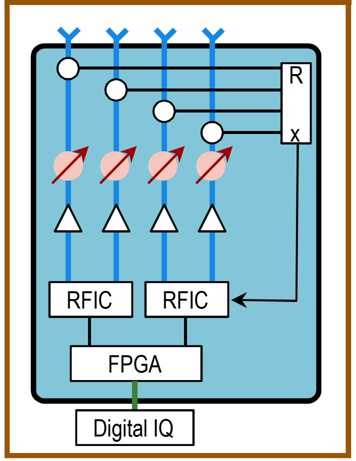
Tdoc R1-164334: "Hybrid beamforming seems the most promising beam steering strategy for massive MIMO systems, and should be supported."

Passive vs. Active Antennas



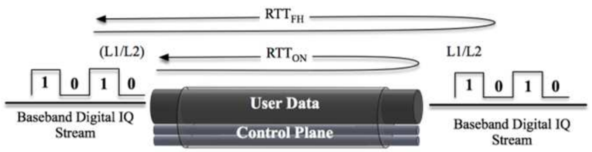
Massive MIMO Challenges

Massive MIMO Challenges

Data Bottleneck	Calibration	Mutual Coupling	Irregular Arrays	Complexity
				
Increased Costs	Reduced MU-MIMO	Reduced Capacity	Grating Lobes	Increased Costs

Limitations of Digital IQ on Fiber: Latency & Capacity

Latency



Round Trip Time	Value
Fronthaul RTT	< 1ms
Sub-frame Processing	400-800 µs
Optical Fiber RTT	FH_{RTT} - SFP_{RTT}
	200-400 µs

$$v_{fiber} = 2 \cdot 10^8 \text{ m/s}$$

Therefore Maximum Radius = 20-40 km

Lower Latencies will further reduce fiber radius

CPRI Data Bottleneck

Digital I/Q is constant bit-rate (always operates at full capacity)

$$BW_{CPRI} = S \cdot A \cdot f_s \cdot b_s \cdot 2 \cdot O \cdot LC$$

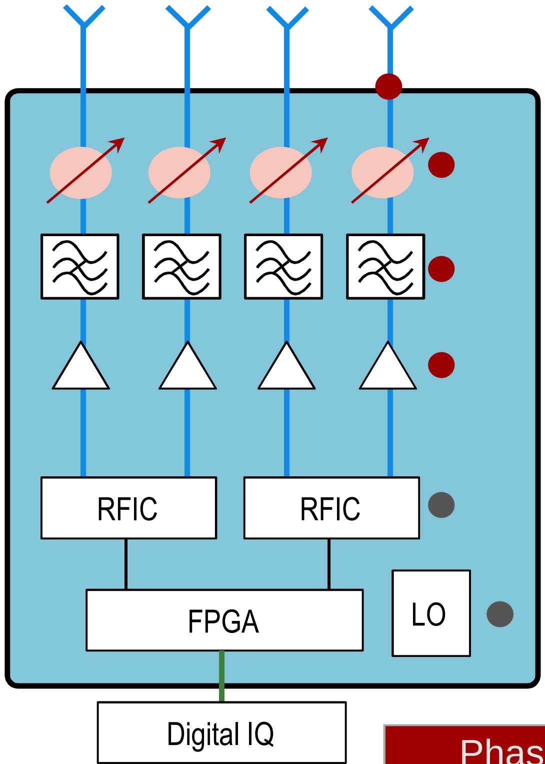
S: Sectors | O: Overhead | b_S: bits/samples | LC: Line Coding

f_S: Sample Rate | A: Antennas

Bandwidth requirement scales linearly with antennas and signal bandwidth (15 MS/s per 10 MHz radio bandwidth)

System	IP Data Rate	CPRI Data Rate
2G: GSM with 3 sectors	114 kbps	1.44 Gbps
4G: LTE with 1 antenna	150 Mbps	3.70 Gbps
5G: 32 antennas	10 Gbps	786 Gbps

Active Antenna Arrays: The Calibration Problem



RF Feeding Network

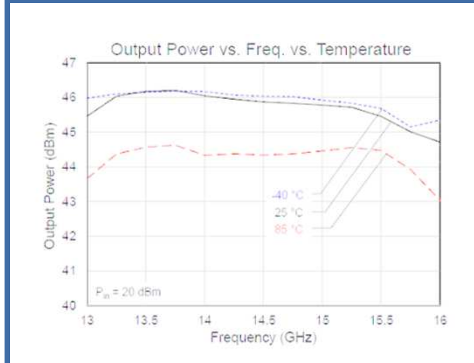
Phase Shifter Tolerances

Group Delay Variations

Dynamic Thermal Effects in PAs

Timing Errors in ADCs

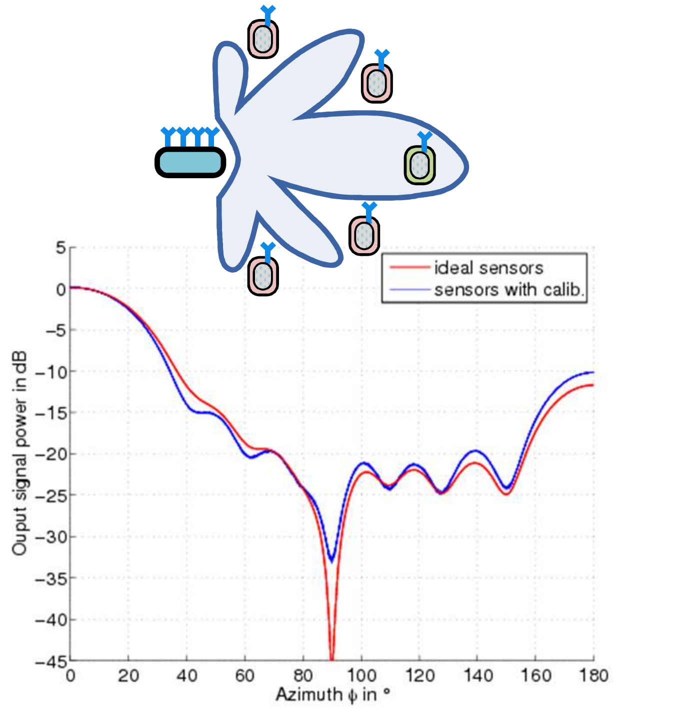
Frequency Drift Between Modules



General
Manufacturing Tolerances of Components & Thermal Effects

Phase/Magnitude/Frequency Tolerances (Static & Dynamic)

Phase Tolerances

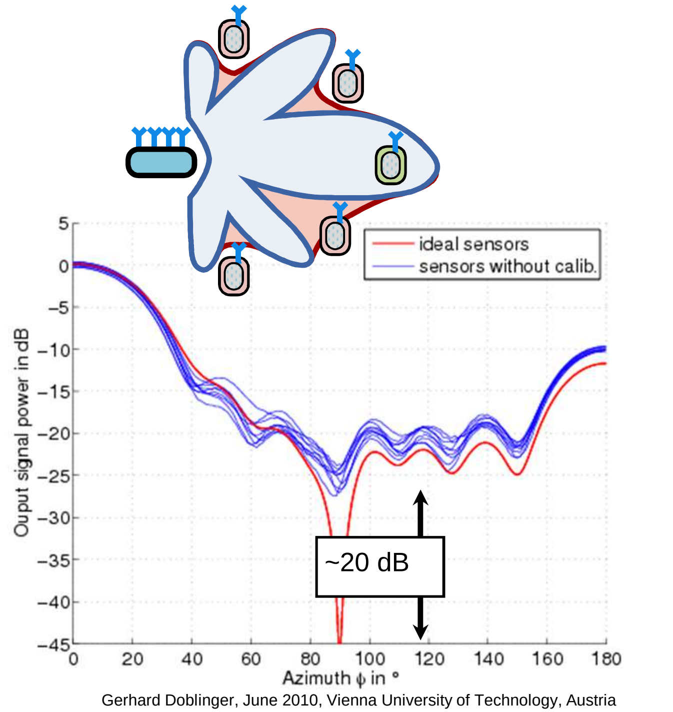


Comparison between ideal and calibrated

MU-MIMO

Multiple beams
Places nulls at UEs
(Null-steering)

$\Delta\phi < \pm 2.5°$

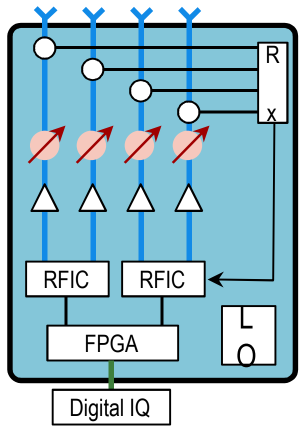


Comparison between ideal and non-calibrated

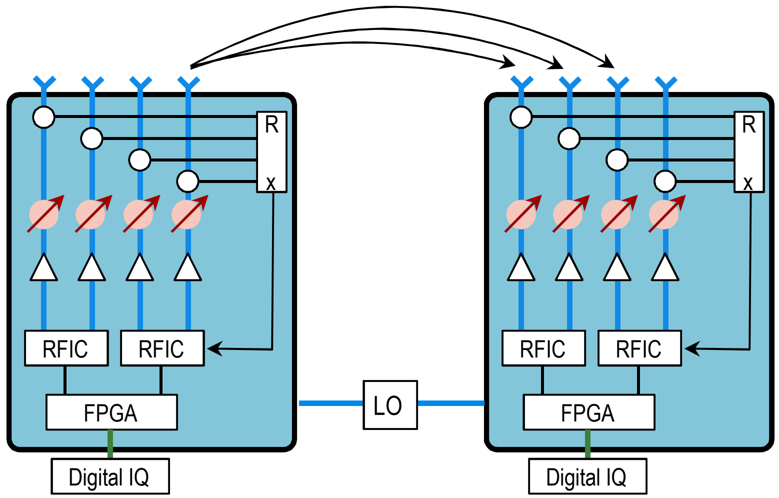
ROHDE&SCHWARZ

Requires adaptive self-calibration in operation

Antenna Self-Calibration



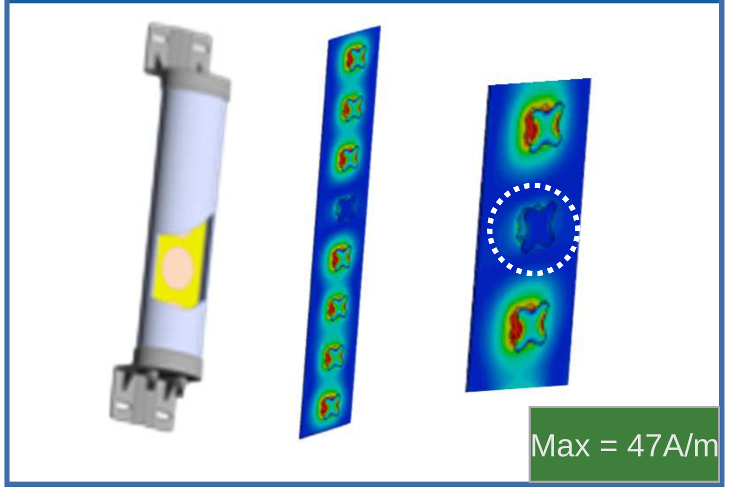
Module Calibration
Directional Couplers



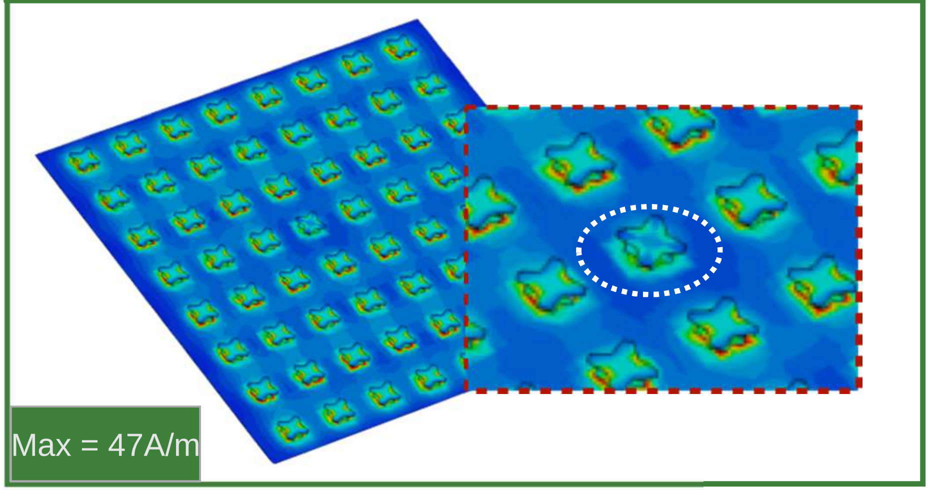
Array Calibration
Directional Couplers + External LO + OTA?

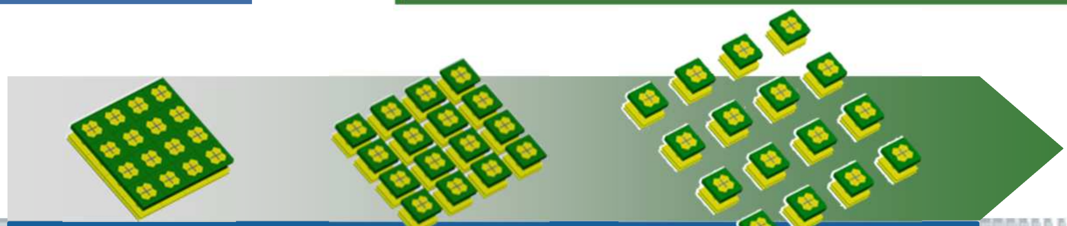
Antenna Mutual Coupling

Basestation Linear Array: 2 Adjacent Antennas



AAS Square Array: 8 Adjacent Antennas

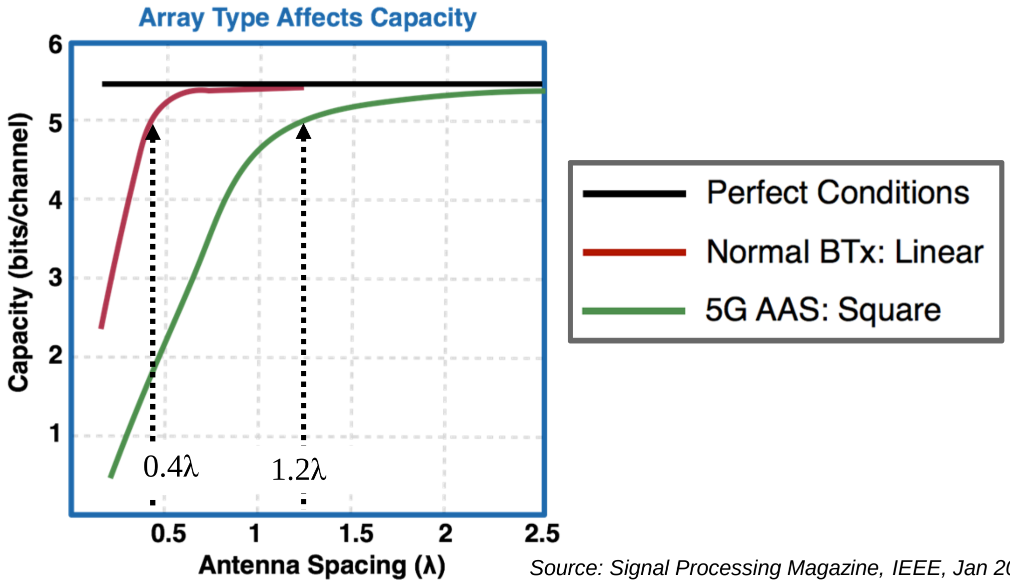




More Capacity = More Spacing = Larger AAS Systems

Measure Mutual Couple & Capacity in Massive MIMO

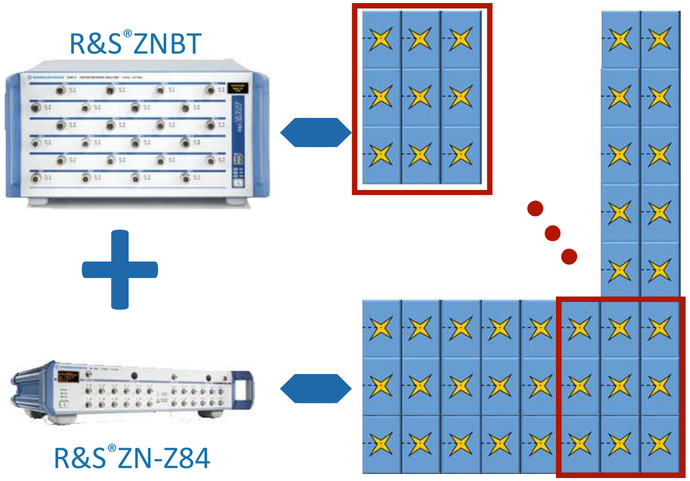
Problem: Antenna mutual coupling reduces capacity



Source: Signal Processing Magazine, IEEE, Jan 2013

In order to maintain capacity, square antenna arrays require more spacing to reduce antenna mutual coupling

Solution: Measurement with Multi-Port VNA



- 0-8.5 GHz
- All S-parameters
- Up to 288 elements

True simultaneous 24-port measurement

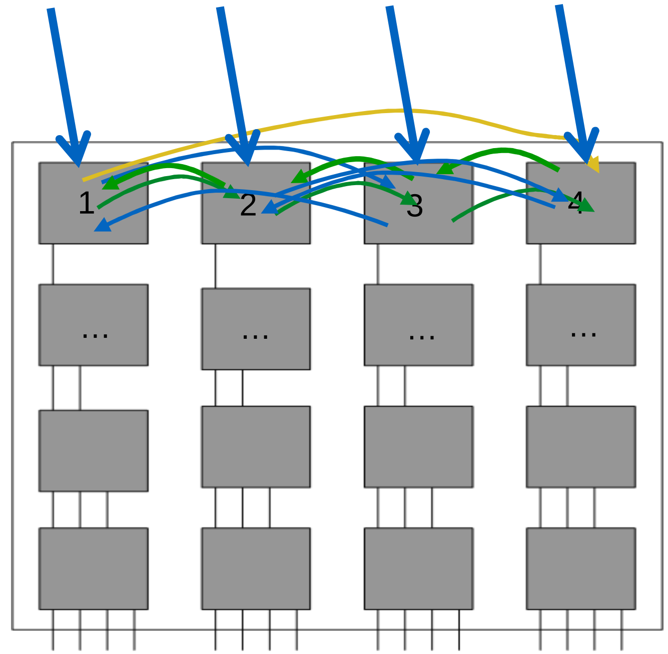
ROHDE&SCHWARZ

The ZNBT is the only VNA capable of measuring mutual coupling in Massive MIMO antenna arrays

Measurements of S-Parameters of Antenna Arrays

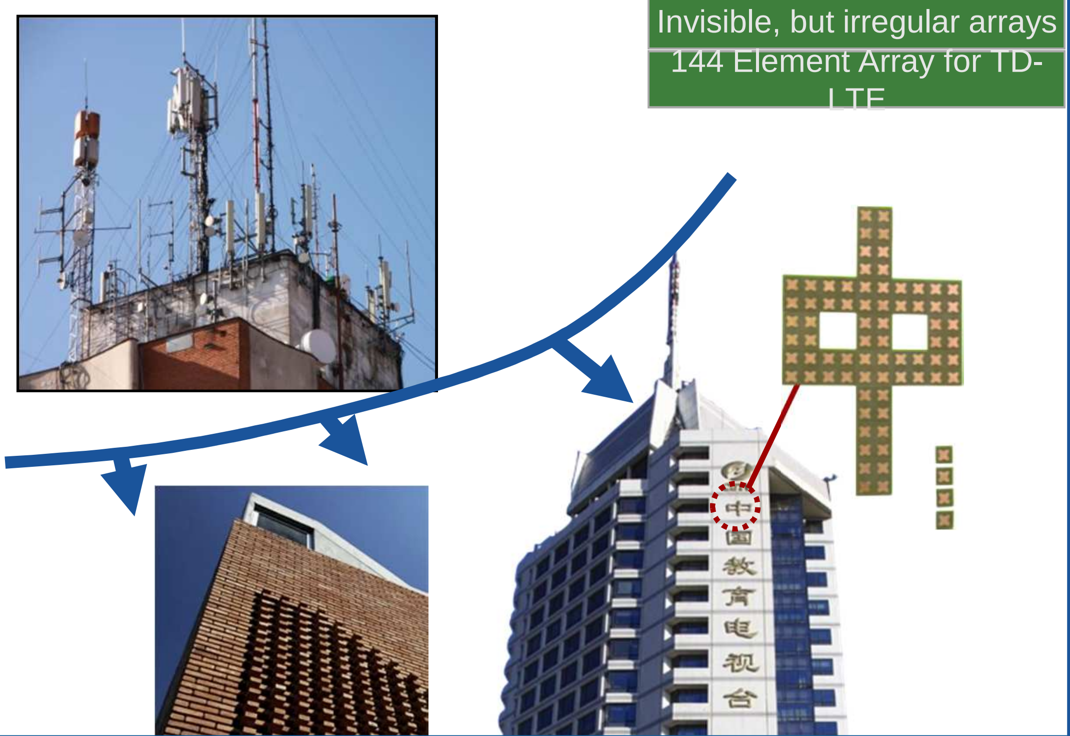
Active testing: excite all antenna elements simultaneously
and measure the coupling to other elements.
-> this is much faster

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

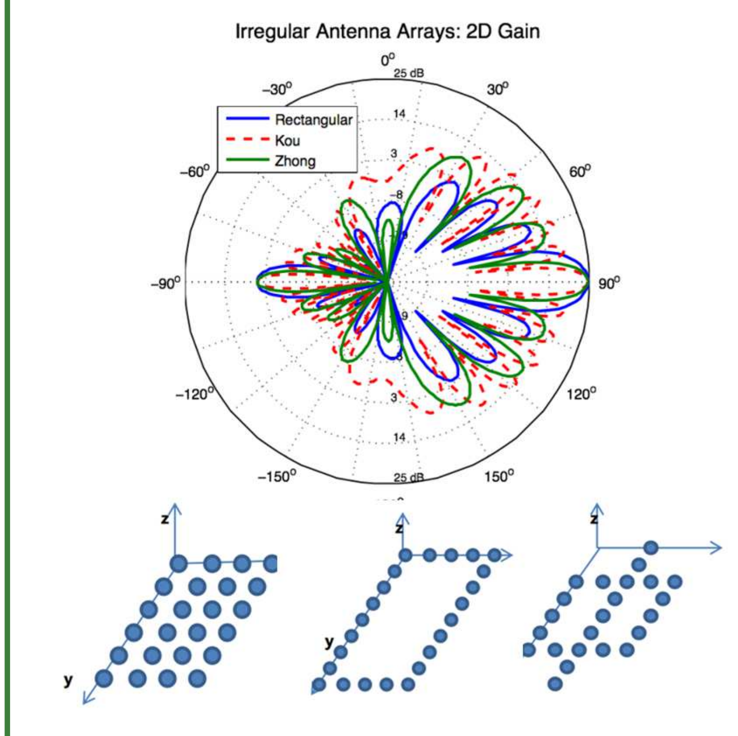


Irregular Arrays

Invisible, but irregular arrays
144 Element Array for TD-LTE

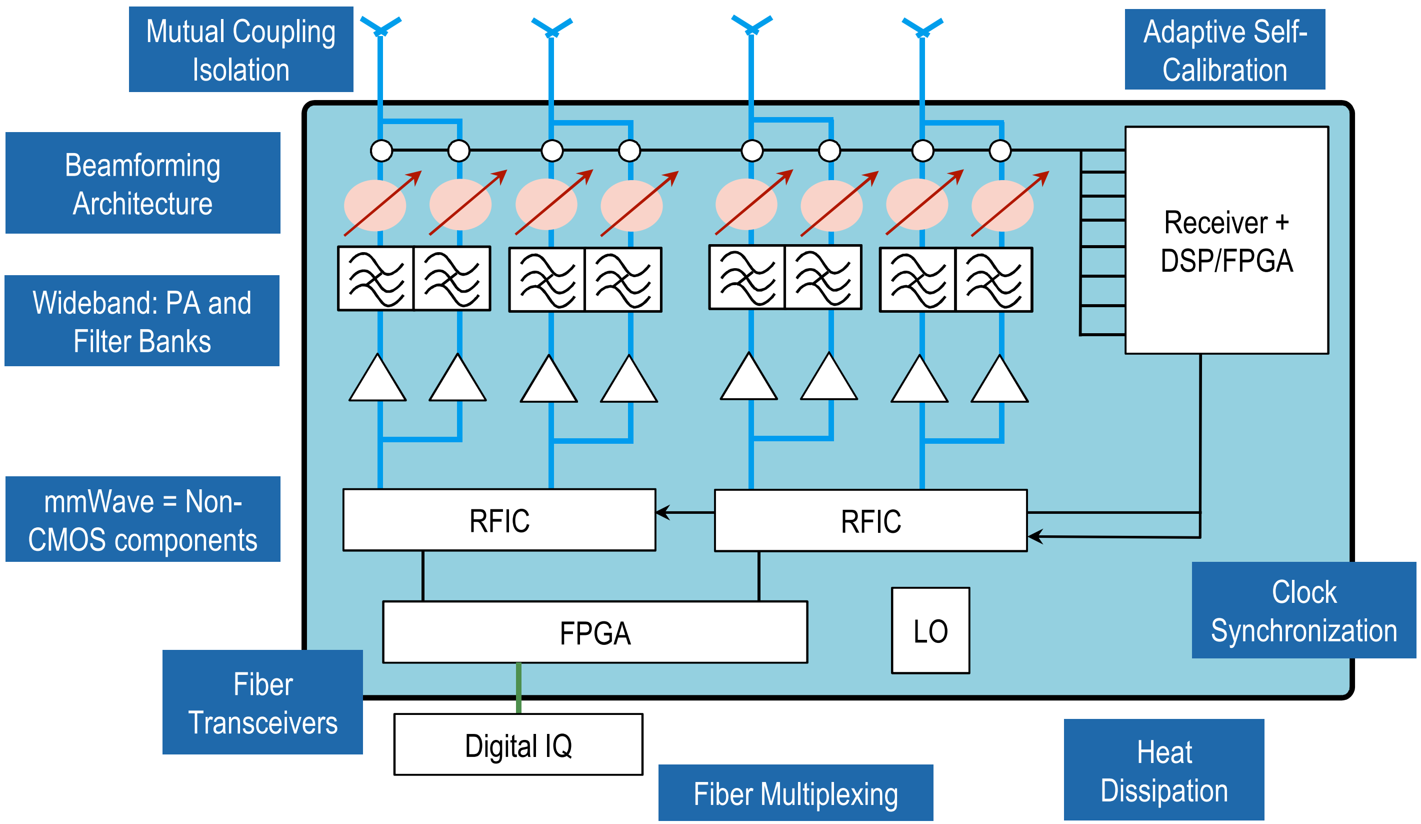


Absorbed into the Environment



More Sidelobes and Lower Mutual Coupling

Massive MIMO = Complex Basestations



128 Element AAS Prototypes: Complexity increased by 8 times

Fundamental Design Parameters for Active & Passive Antennas 5G

Passive Antennas (Conducted)

UEs | *Basestations*

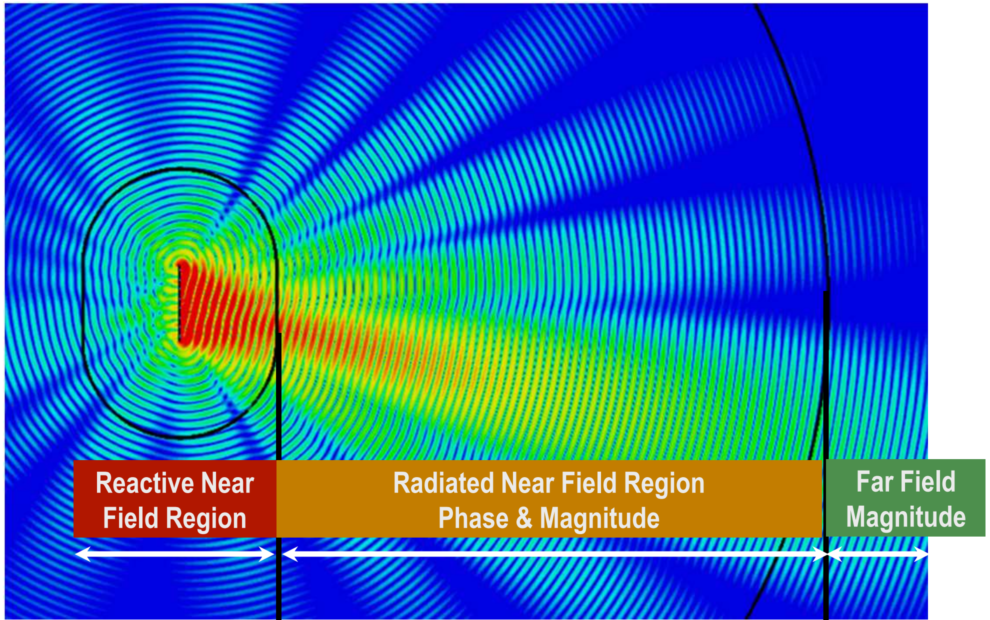
- Impedance matching (Smith Chart)
- S-Parameters & Return Loss
- S_{12} & Mutual Coupling

Active Antennas (Radiated)

User Equipment/Terminals	*Basestations*
Radiation Gain Patterns (2D/3D)	
Active (UE): TRP, TiS	Active (Basestation): EiRP, EiS
Radiation Efficiency (UE)	5 Point Beam Specification (3GPP)
Specific Absorption Ratio (UE)	Multiple Beam Specification (3GPP)
Beamsteering & Beamtracking (mmWave)	

Fundamental Properties: Electromagnetic Fields

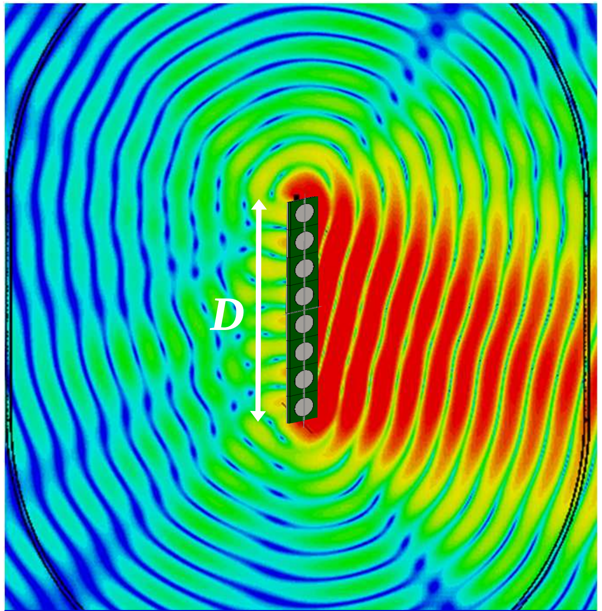
Basestation 8 Element Array at 2.7 GHz



$0.62\sqrt{\frac{D^3}{\lambda}} = 0.6$ m

$\frac{2D^2}{\lambda} = 4.5\ m$

Reactive Near Field Region ($< 0.6m$)



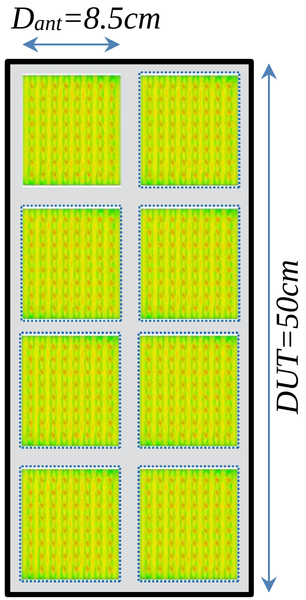
Any object in this region becomes part of antenna system & interferes with the measurements

Chamber Size: Far-field or Near-field?

$$R_{FF} = \left(\frac{2D^2}{\lambda} \ or \ \frac{2\lambda}{HPBW}\right)$$

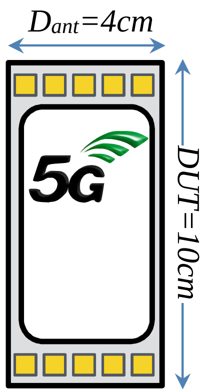
HPBW (radians)
Half-power beam width

Basestations: Subarray Measurements (D_{ant} << DUT)



28GHz Subarray (λ = 10.7mm, HPBW=7.2°)	
Criteria	**Far-field Distance**
$2\lambda/HPBW^2$	**1.35 meters**
28GHz Entire Base-station (HPBW=1.2°)	
$2D^2/\lambda$	**46 meters**

UEs: D_{ant} ~ DUT

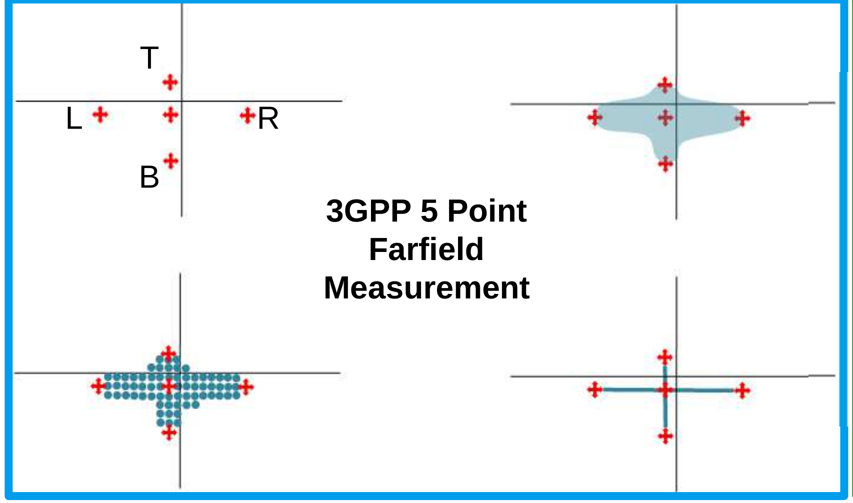


28GHz UE Subarray (HPBW=15°)	
Criteria	**Far-field Distance**
$2\lambda/HPBW^2$	**0.30 meters**
28GHz Entire UE	
$2D^2/\lambda$	**1.86 meters**

Far-field criteria is met for UE & Base-station Subarrays for R&S Chambers

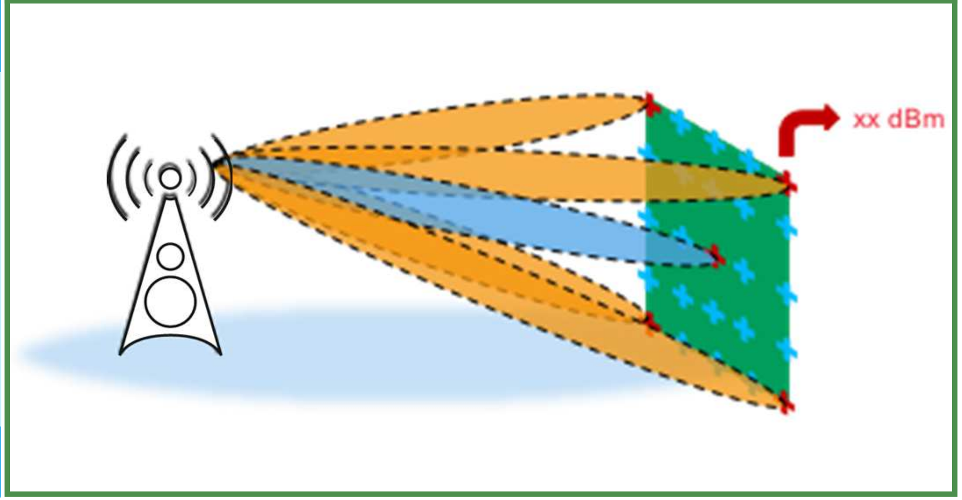
3GPP Active Base-station Beam Requirements (2016)

Individual Beam Specification



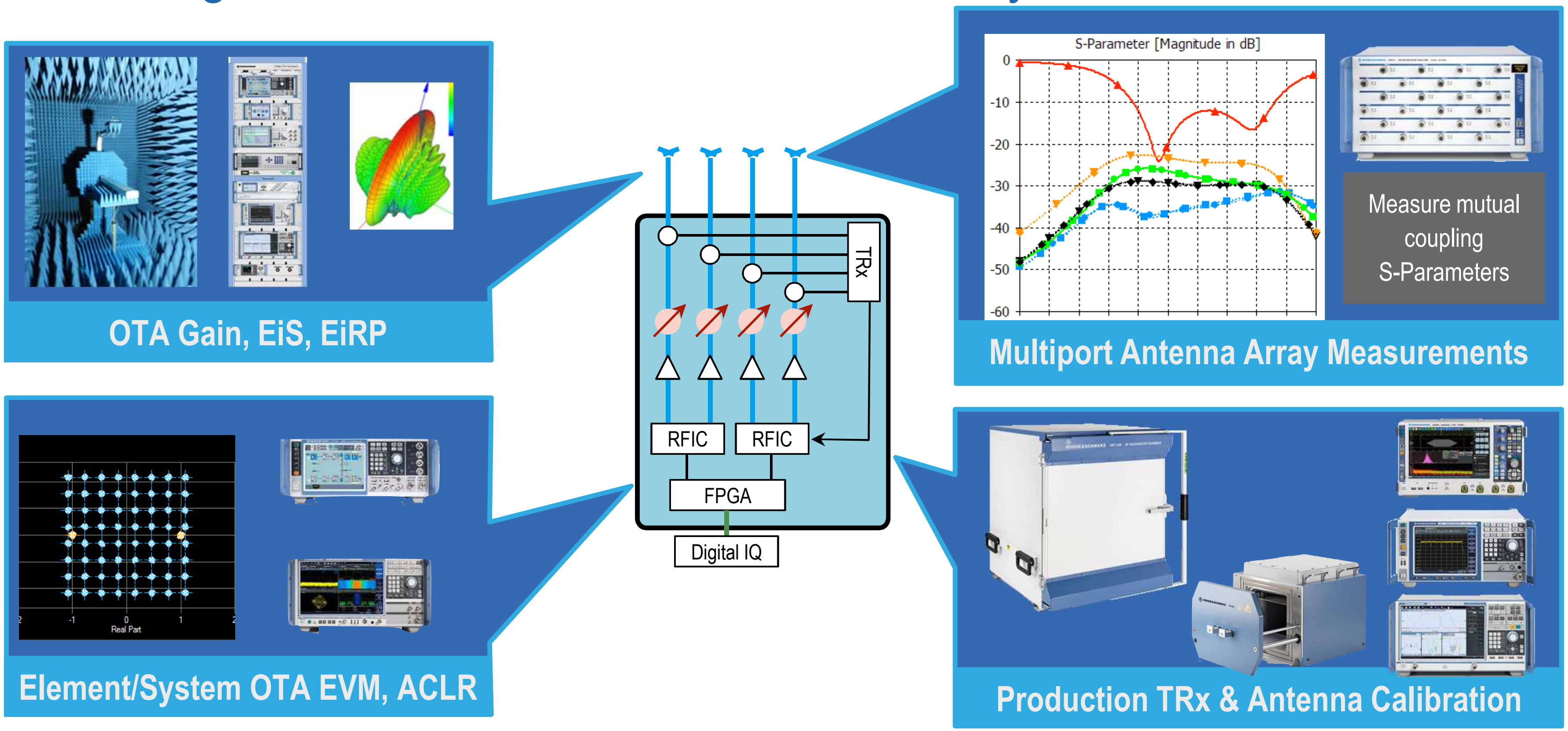
The manufacturer of the AAS will declare both the beam direction and a threshold comprised of four points for each AAS beam. The maximum radiated EIRP of the declared AAS beam is the mean power level measured in the boundary formed by the four points. The four points are defined as B (bottom), T (top) L(left), and R(right); together with the beam peak, this is known as the five point beam test.

Multiple Beams

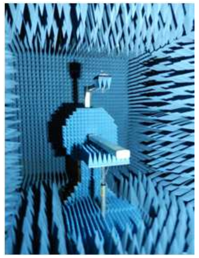


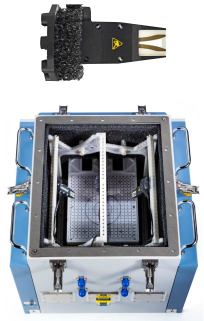
The number of beams supported by the AAS is left to the manufacturer to declare where both continuous and non-continuous beam declarations are possible. Radiated transmit power is defined as the EIRP level for a declared beam at a specific beam peak direction. Although the claimed EIRP level (blue and red crosses) has to be achieved for all claimed beam peak directions, however, for compliance only the declaration of the center and the extreme directions are sufficient to be measured (marked with red crosses)

Measuring 5G mmWave & Massive MIMO Systems



R&S OTA Product Matrix

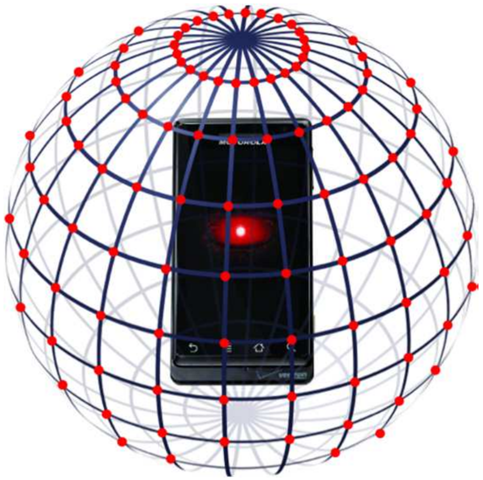




	CTIA OTA: TS8991/WPTC	OTA R&D: Massive MIMO Spiral Scanner	OTA Production: ATS1000	OTA Production: OTA Power Sensors	Benchtop Systems: DST200 & TS7124
Frequencies	0.4 to 18 GHz	0.4 to 40 GHz	0.4 to 90 GHz	28-75 GHz	28-90 GHz
Minimum Size	250x250x220 cm	250x250x220 cm	70x100x140 cm	45x50x48 cm	77x76x70 cm
Fields	Near & Far	Near & Far	Near & Far	Far Field	Far Field
Signals	Modulated/CW	Modulated/CW	Modulated/CW	Modulated/CW	Modulated/CW
Parameters	EiRP, EiS, Gain, EVM, …	EiRP, EiS, Gain, EVM, …	EiRP, EiS, Gain, EVM, …	Gain	EiRP, EiS, Gain, EVM
Availability	Available for purchase	Available for purchase	Available for purchase in Q2 2017	Available for Purchase	Available for Purchase

TS8991: Total Radiated Power Sampling Methods

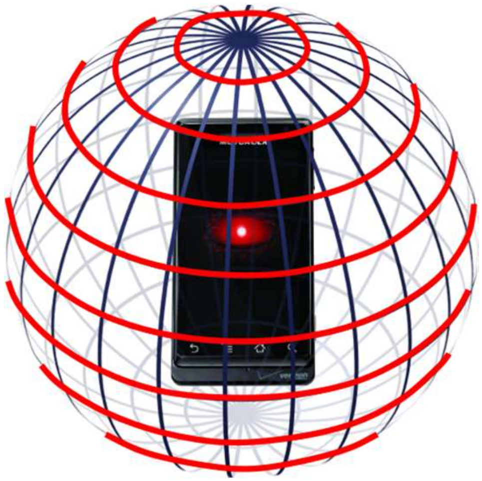
Stepped Sampling
6 minutes per channel



Elevation(θ): Stepped

Azimuth(φ): Stepped

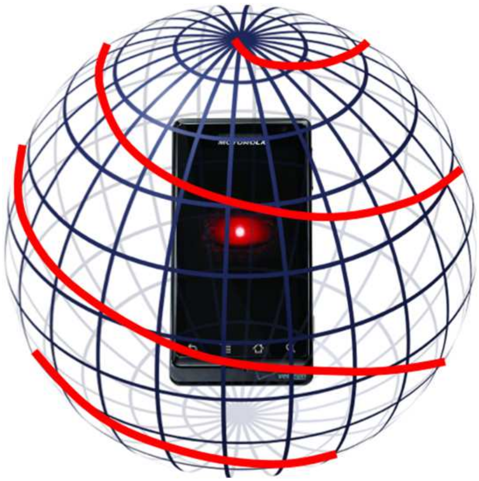
Step-Swept Sampling
2-3 minutes per channel



Elevation(θ): Swept

Azimuth(φ): Stepped

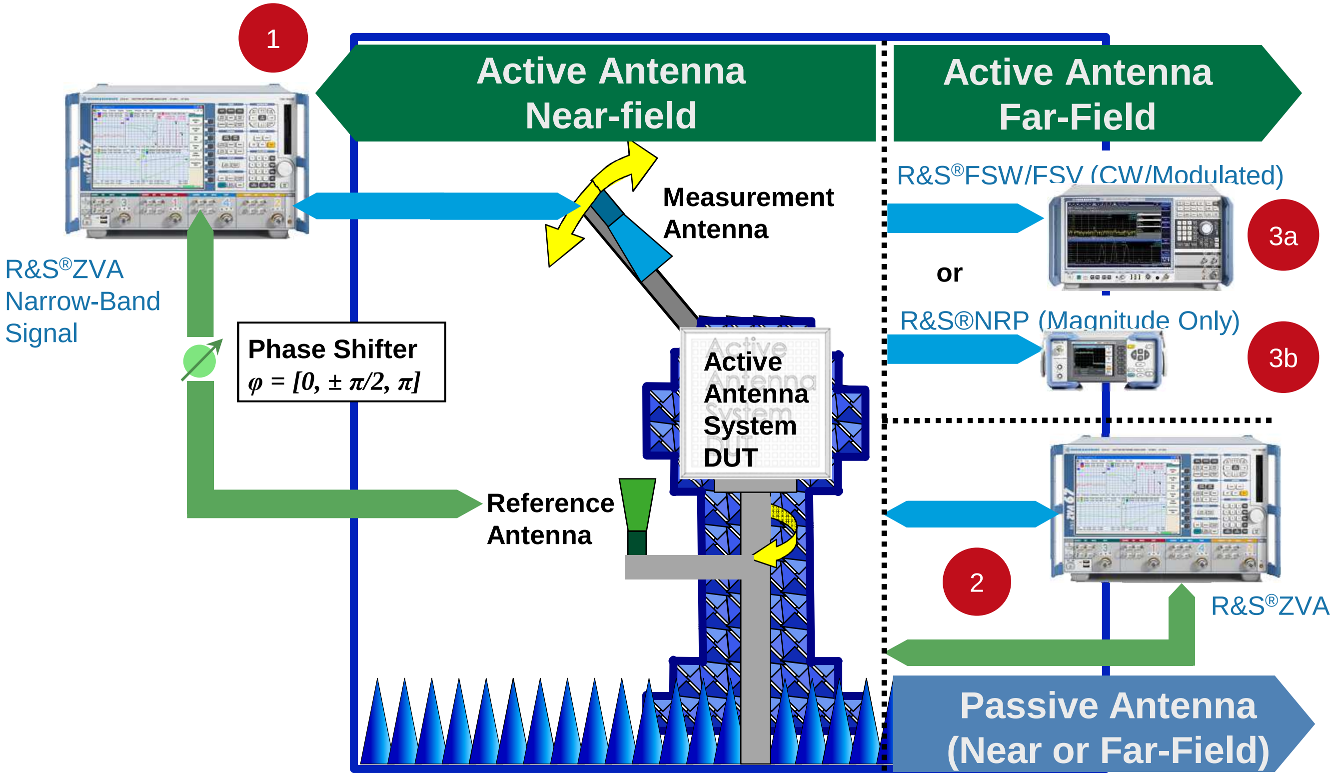
Spiral Scan Sampling
30-60 seconds per channel

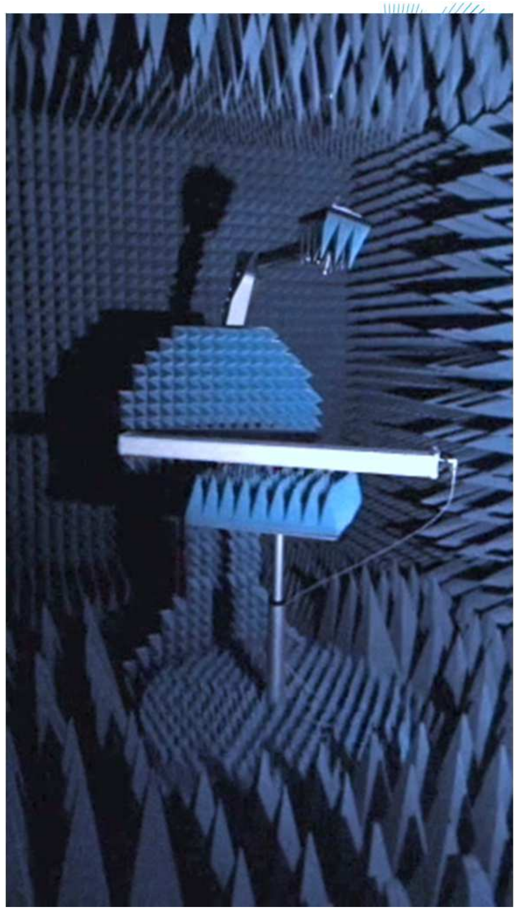


Elevation(θ): Swept

Azimuth(φ): Swept

Spiral Scanner Reference Antenna OTA System





Alternative for far-field TRP measurements

NRPM OTA Power Sensor: Magnitude Measurements

R&S®NRPM OTA Power Sensor
Combination of power sensor and Vivaldi antenna on one module
Integrated level detector diode – no cable losses
Frequency range: 27.5 GHz to 75 GHz
Level range: -75 dB to -25 dBm (continuous) -62 dBm to -25 dBm (trace)
Low radar cross section: < -20 dBsm (typical)
Accuracy for relative power measurements @28 GHz and 39 GHz: Levels ≤ -35 dBm: < 0.1 dB Levels > 35 dBm: < 0.2 dB

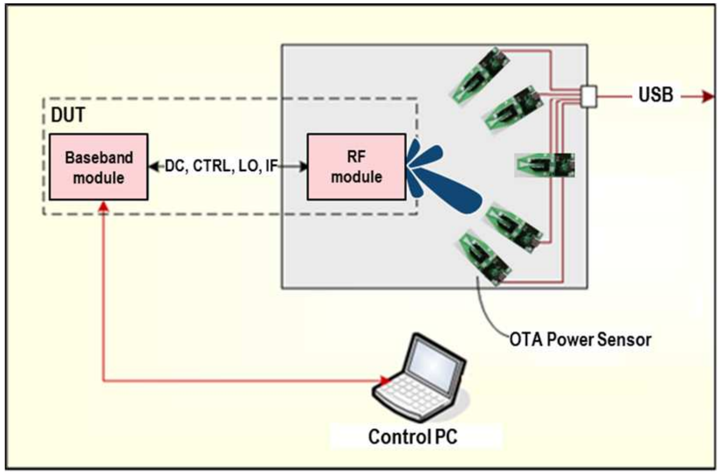
NRPM OTA Power Sensor Antenna Module

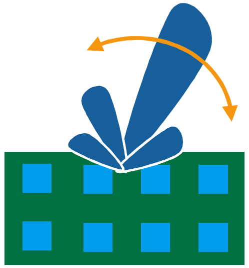
3 Channel NRPM OTA Power Sensor

Antenna Array Beamsteering
Magnitude Only

mmWave DUTs will not have antenna connectors

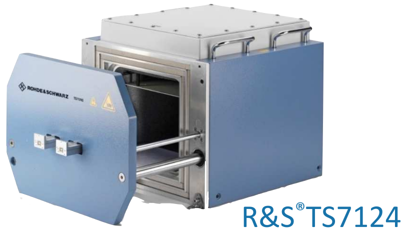
OTA Measurements will be mandatory for production





RF antenna array

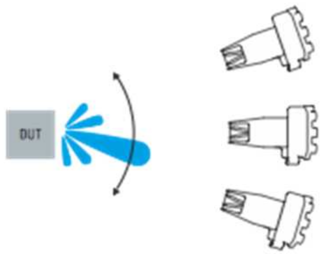
Measurement Equipment

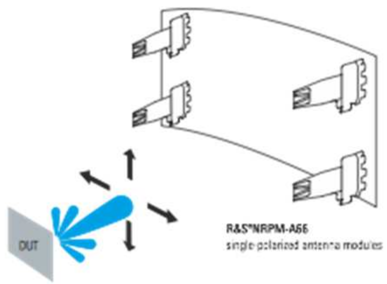


Shielded chamber (TS7124)

Vivaldi Probe 28-77 GHz

Measurement Scenarios

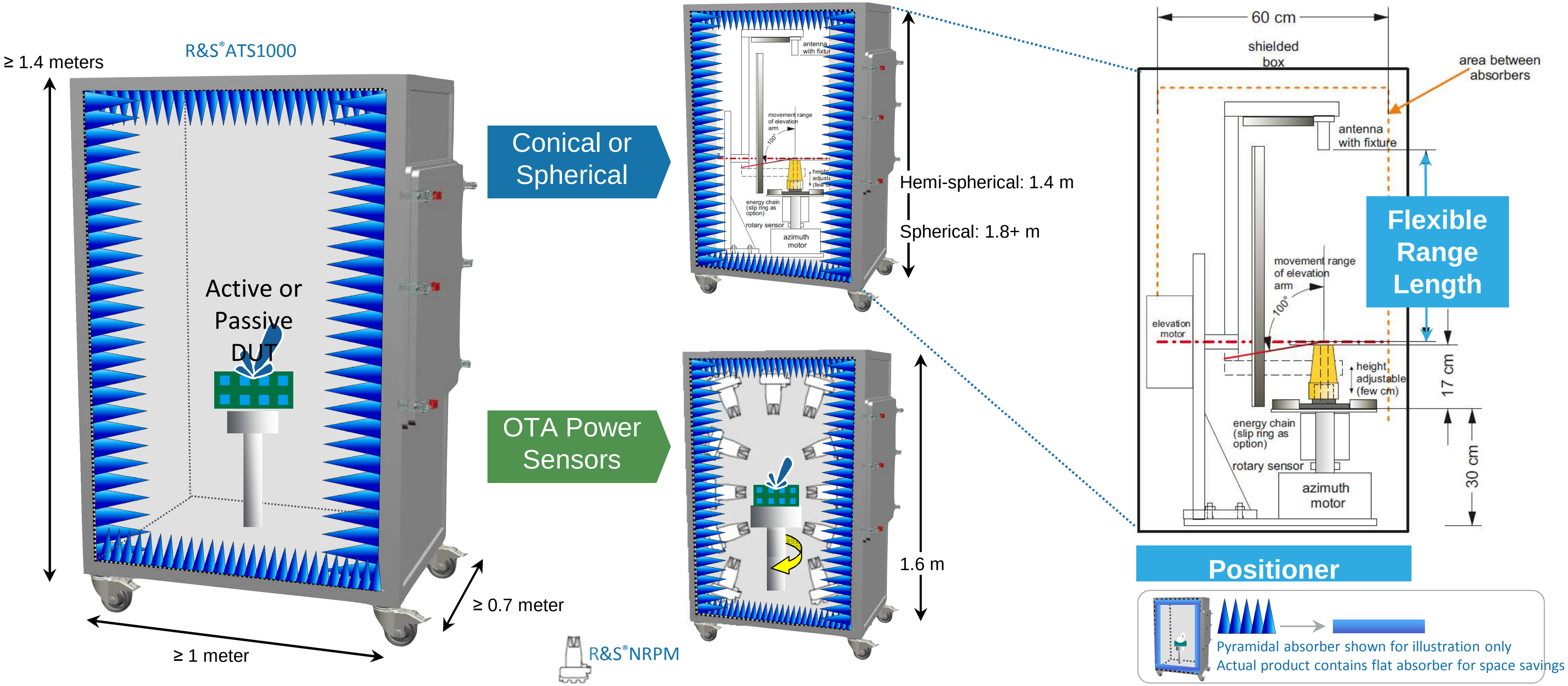




2D Beam-Steering

3D Beam-Steering

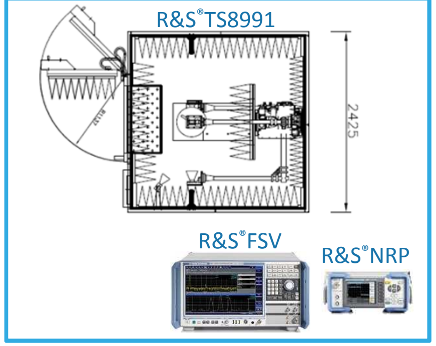
ATS1000 flexible shielded chamber (launched @ MWC2017)



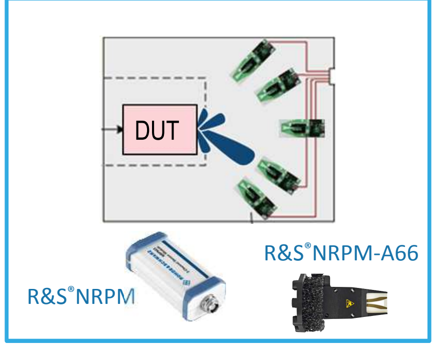
R&S Antenna Test Solutions Summary

Massive MIMO

CTIA Radiation Patterns

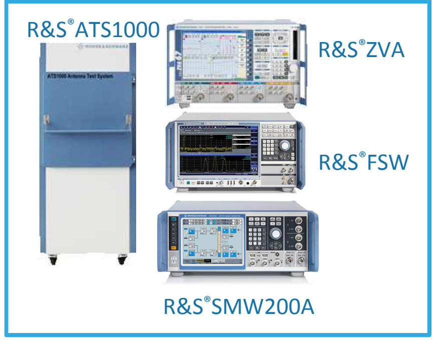


mmWave Beamsteering

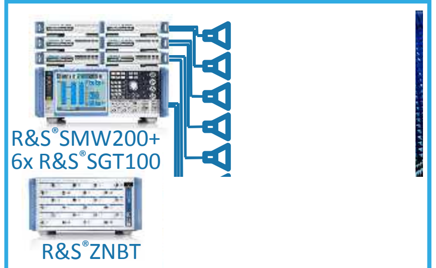


RF Conformance

mmWave



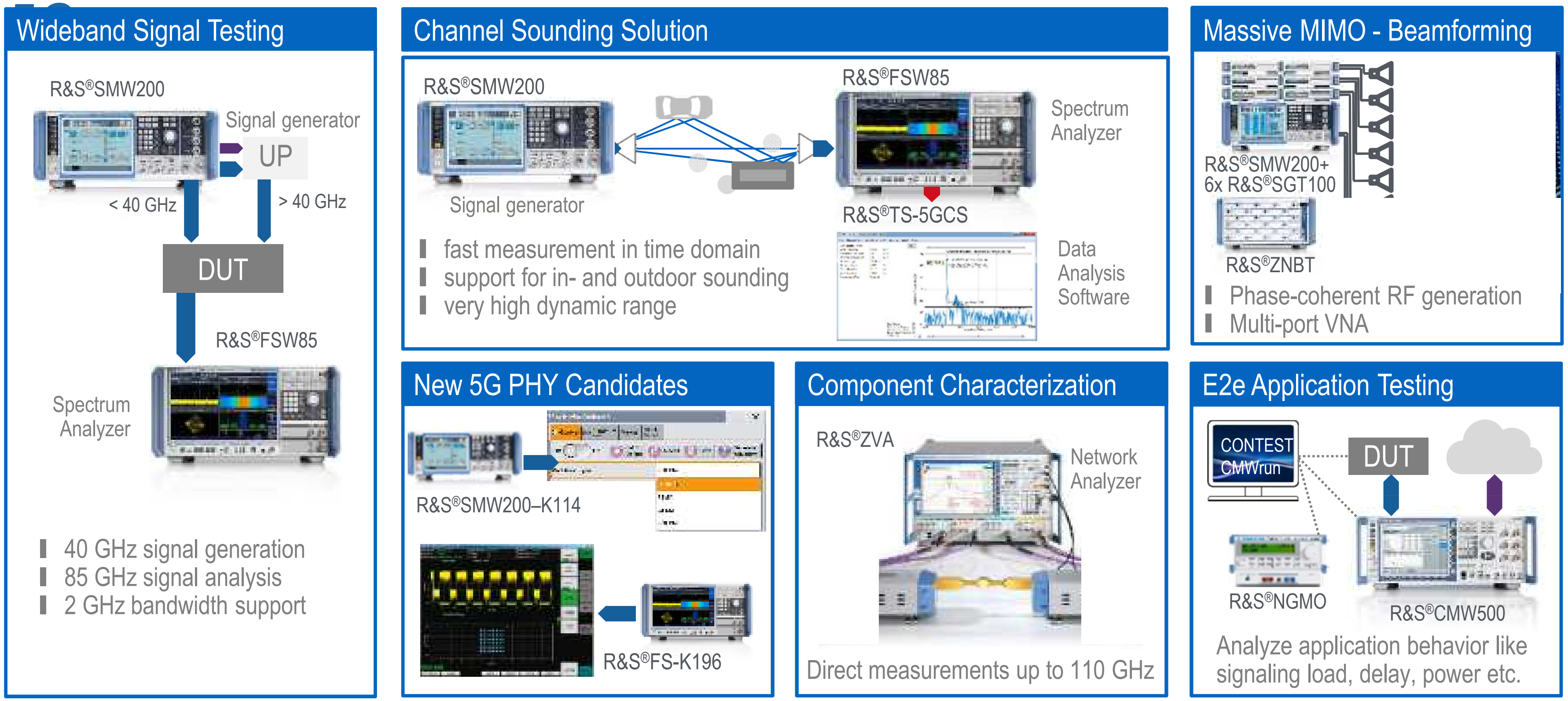
Multiport Testing



- Phase-coherent RF generation
- Multi-port VNA for Active Return Loss

Production & Benchtop

R&S test solutions to investigate, develop and standardize



Conclusion

Is 5G just the next generation? No: It is a paradigm shift!

- Approach in industry:
  - UMTS: 1: define a technology for data transmission, 2: for what? / "*what is the killer app?*"
  - LTE (3GPP: e-UTRA): 1: define a better technology than UMTS, 2: use case (mobile web)
  - 5G: 1: define use cases, 2: requirements, 3: elaborate technologies / solutions
- From cell-centric (2G - 4G) to user-centric / application-centric in 5G (beamforming)
- From link efficiency (2G - 4G) to system efficiency in 5G (RAT defined per app)
- From antenna connectors (2G - 4G) to Over-the-Air testing in 5G (antenna arrays, beamforming)
- Increasing demand for security / high reliability in 5G (up to mission- and safety-critical use cases)

Rohde & Schwarz offers all essential capabilities to support the wireless communications industry with solutions needed to investigate, standardize, develop and rollout 5G

"If you want to go fast, go alone.
If you want to go far, go together!"

African proverb