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

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Technology Marketing Manager

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Test & Measurement Division

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5G Standardization
3GPP 5G Standardization Schedule

- **Release 14** (2016)
- **Release 15** (2017)
- **ITU IMT-2020 Submission** (2020)

- **3GPP 5G Workshop**
- **5G Scope and Requirements**
- **Channel modeling > 6 GHz**
- **5G Study Items (Evaluation of Solutions)**
- **5G Phase 1 Specification**
- **5G Work Items Phase 1**
- **5G Work Items Phase 2**
- **LTE Advanced Evolution**
IMT 2020 - services

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

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

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

- **Waveforms**
  - 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
today

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

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

UE sends Information about installed applications and behavioural aspects

future
Technology framework: Protocol aspects / targets

- Separation of control + user plane
- Multiple radio connections in parallel
- Mesh networks: multihop and device to device
- Reduce signaling
- Grant free access
- Light MAC and RRM for energy saving modes
Technology framework: Duplex methods

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

The future outlook: Full duplex to obtain higher Capacity (at costs of higher complexity)
Technology framework: Modulation & Coding

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

Filter edges may curtail the constellation of the QAM symbols

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Indoor hotspot</th>
<th>Dense urban</th>
<th>Rural</th>
<th>Urban macro</th>
<th>High speed&lt;sup&gt;6)&lt;/sup&gt; (500 km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency range (aggregated system BW)</td>
<td>4GHz (200MHz) 30GHz&lt;sup&gt;2)&lt;/sup&gt; (1GHz) 70GHz&lt;sup&gt;2)&lt;/sup&gt; (1GHz)</td>
<td>4GHz (200MHz) 30GHz (1GHz)</td>
<td>700MHz 2GHz (20MHz) 4GHz (200MHz)</td>
<td>2GHz (TBD) 4GHz (200MHz) 30GHz (1GHz)</td>
<td>4GHz (200MHz) 30GHz (1GHz) 70GHz (1GHz)</td>
</tr>
<tr>
<td>BS / UE antenna elements&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>256/32</td>
<td>256/32 (30GHz) 256/8 (4GHz)</td>
<td>256/8 (4GHz) 64/4 (700MHz)</td>
<td>256/32 (30GHz) 256/8 (4GHz)</td>
<td>256/32 256/8 (4GHz)</td>
</tr>
<tr>
<td>Coverage range (indoor/outdoor user distribution in %)</td>
<td>20 m 100%/0%</td>
<td>200 m Macro (3 micro TRPs&lt;sup&gt;3)&lt;/sup&gt; per macro 80%/20%</td>
<td>1732 / 5000 m 50%/50%</td>
<td>500 m 80%/20%</td>
<td>1732 m 100% users in train</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Extreme rural&lt;sup&gt;7)&lt;/sup&gt;</th>
<th>Urban overage for mMTC</th>
<th>Highway</th>
<th>Urban grid for connected car&lt;sup&gt;9)&lt;/sup&gt;</th>
<th>Air to Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency range (aggregated system BW)</td>
<td>&lt; 3GHz (40MHz)</td>
<td>700 MHz (TBD) 2.1GHz (TBD)</td>
<td>&lt; 6GHz (200MHz)</td>
<td>&lt; 6GHz (200MHz)</td>
<td>tbd</td>
</tr>
<tr>
<td>BS / UE antenna elements&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>&lt;TBD&gt;</td>
<td>2, 4, 8 (optional) / 1</td>
<td>32/32 (RSU&lt;sup&gt;8)&lt;/sup&gt; 32/8 (in vehicle UE)</td>
<td>32/32 256/8 (4GHz)</td>
<td>40MHz</td>
</tr>
<tr>
<td>Coverage range (indoor/outdoor user distribution in %)</td>
<td>100 km (even up to 300 km)</td>
<td>500 / 1732 m 80%/20%</td>
<td>500 m 100% in vehicles</td>
<td>500 m Vehicles, bicycles, pedestrian</td>
<td>[100km]</td>
</tr>
</tbody>
</table>

- 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.

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

Frequency spectrum considerations for 5G in Europe

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

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

- Channel Bandwidth (Bo)
- Guard Band
- Individual Channels

- Total Symbol Period ($T_S$)
- Useless Symbol Period ($T_U$)
- Data Payload

### Resistance to Interference

- Rx Power (dB)
- Time
- Frequency

### Out of Band Emissions

- LTE system bandwidth
- UE1, UE2, UE3

### Spectral Efficiency

- Normalized Average Spectral Density
- Frequency (Hz)

### Flexibility

- Vehicle or Vehicle
- Vehicle or Thing
-凡本网 or Other single-antenna

### 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)
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

- Sub-band 1 → iFFT 1 e.g. 256 → CP 1 e.g. 1/10 → Filter 1 → Σ
- Sub-band 2 → iFFT 2 e.g. 256 → CP 2 e.g. 1/16 → Filter 2 → Σ
- Sub-band N → iFFT N e.g. 1024 → CP N e.g. 1/32 → Filter N → Σ

- 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

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“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

- **Outdoor**
  - **LA**
  - **D2D**

- **Macro / wide area**
  - **H**igh **prop. delay**
  - **v > ~50km/h**
  - **doubly dispersive channel**

- **Micro / small cell**
  - **H**igh **throughput**
  - **New spectrum**
  - **Higher frequencies / cognitive radio**

- **Outdoor LA**
  - **short block length**
  - **MTC/MMC**
  - **asynchronous access**
  - **coexistence with other systems**

- **Wireless BH (outdoor)**
  - **Multi-site CoMP**

- **D2D**
  - **e.g. out of band emission**
  - **UFMC using different filter types**

**Waveform – summary**

- **Figure 6: Bend edge behavior of OFDM and UFMC (e.g. ~ [30, 40] dB).**
Test Solution for 5G: Waveform candidates

- CP-OFDM
- FBMC
- UFMC
- GFDM
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
Waveform Gains: From Theory to Reality

From: Waveform theory and simulation

To: Real devices with non-linear elements

- **OFDM**: -70 dBm, Δ=20 dB
- **FBMC**: -90 dBm, Δ=20 dB
- **UFMC**: -70 dBm, Δ=20 dB
- **GFDM**: -45 dBm, Δ=2-3 dB

DUT: Power Amplifier

R&S®SMW200

R&S®FSW85
Two use cases: 5G Trial Services, Fixed Wireless Access (FWA)

...mobility required

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

April 21, 2016 | By Monica Alieven

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

<table>
<thead>
<tr>
<th>spec. number</th>
<th>title</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR 38.801</td>
<td>Study on New Radio Access Technology: Radio Access Architecture and Interfaces</td>
</tr>
<tr>
<td>TR 38.802</td>
<td>Study on New Radio Access Technology: Physical Layer Aspects</td>
</tr>
<tr>
<td>TR 38.803</td>
<td>TR for Study on New Radio Access Technology: RF and co-existence aspects</td>
</tr>
<tr>
<td>TR 38.900</td>
<td>Study on channel model for frequency spectrum above 6 GHz</td>
</tr>
<tr>
<td>TR 38.912</td>
<td>Study on New Radio (NR) Access Technology</td>
</tr>
<tr>
<td>TR 38.913</td>
<td>Study on Scenarios and Requirements for Next Generation Access Technologies</td>
</tr>
</tbody>
</table>
Current working assumption (WA) based on 3GPP RAN1#85 is that subcarrier scaling is based on $f_0 \times 2^m$ with $f_0 = 15$ kHz and scaling factor is $2^m$ with $m \{-2, 0, 1, \ldots, 5\}$.

A more detailed look at the relationships between subcarrier spacing, symbol length, component carrier bandwidth, cyclic prefix length, subframe length, and radio frame length:

<table>
<thead>
<tr>
<th>$m$</th>
<th>-2</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>\ldots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcarrier Spacing [kHz]</td>
<td>3.75</td>
<td>15</td>
<td>30</td>
<td>60</td>
<td>120</td>
<td>240</td>
<td>480</td>
<td>\ldots</td>
</tr>
<tr>
<td>Symbol Length [µs]</td>
<td>266.67</td>
<td>66.67</td>
<td>33.33</td>
<td>16.67</td>
<td>8.333</td>
<td>4.17</td>
<td>2.08</td>
<td>\ldots</td>
</tr>
</tbody>
</table>

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)

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

- OFDM Carrier #1
- OFDM Carrier #2
- OFDM Carrier #3
- OFDM Carrier #8

Channel Raster: 99 MHz
Channel BW: 100 MHz

OBW: 90 MHz

Subcarrier spacing 75 kHz

up to 64QAM modulation

Captured and analyzed with R&S®FS-K96 OFDM Analysis Software

Nov 2016  Verizon Wireless 5G and R&S test solutions
Verizon 5G specification
Basic principles: Downlink and Uplink

- PSS, SSS, Extended Synchronization Signal (ESS)
- xPDCCH, xPDSCH
- xPBCH, ePBCH
- xPUCCH, xPUSCH
- Downlink Phase Noise Compensation Reference Signal (DL PNCRS)
- Phase Noise Compensation Reference Signal (PNCRS)
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

The receiver equation becomes more complex:

\[ r = s * H + n \]

The 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

Model 1

Achievable SNR [dB]

6 GHz
39 GHz
70 GHz

Model 1

improving achievable SNR => widening Δf

low
high

3GPP R1-165177
5G scenarios: dual link scenario between LTE and 5G NR
5GTF: mapping of phase noise reference signals, e.g. xPUSCH

\[ r(m) = \frac{1}{\sqrt{2}} (1 - 2 \cdot c(2m)) + j \frac{1}{\sqrt{2}} (1 - 2 \cdot c(2m + 1)). \]

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.
Old and new synchronization signals
PSS/SSS, Extended Synchronization Signal (ESS)
xPBCH, ePBCH – Where are the broadcast channels transmitted?

- 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).

### Table: BRS transmission period and subframe counts

<table>
<thead>
<tr>
<th>BRS transmission period</th>
<th># of subframes</th>
<th>Subframes within radio frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 slot &lt; 5 ms</td>
<td>1</td>
<td>49th</td>
</tr>
<tr>
<td>1 subframe = 5 ms</td>
<td>2</td>
<td>48th, 49th</td>
</tr>
<tr>
<td>2 subframes = 10 ms</td>
<td>4</td>
<td>46th, 47th, 48th, 49th</td>
</tr>
<tr>
<td>4 subframes = 20 ms</td>
<td>8</td>
<td>42nd, 43rd, ..., 48th, 49th</td>
</tr>
</tbody>
</table>
Initial synchronization aspects in 5G NR: LTE reminder

DC subcarrier, or subcarrier 0 = centre of channel bandwidth

20MHz bandwidth

P-SCH

S-SCH

Sent over 62 subcarriers

10 ms radio frame

1 ms subframe

0.5 ms slot

Interleaved concatenation of 2 binary sequences

Identical
5GTF: concept of extended synchronization signal ESS

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)**

- Subframe #0 and #25
- 0.2 ms
- 41 PRB

**Sequence (OCC)** depends on antenna port:

```
+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 +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
```

- Used as Demodulation Reference Signal (DMRS)

---

**ROHDE & SCHWARZ**

Nov 2016  Introduction to 5G  53
5G air interface aspects: beam sweeping for initial access

Traditional approach: omnidirectional Tx of BCCH for cell detection

Friis equation

\[ \frac{P_{Rx}}{P_{Tx}} = G_{antenna} \left( \frac{c}{4\pi fd} \right)^\gamma \]

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

Beam forming reference signal, BRS allows the determination of beams
5G air interface aspects: beam reporting

UE reports the beam status indication BSI

"the received BRS power level BRSRP on BRS_A is -90dBm"
5G air interface aspects: beam status reports

5GNB orders the UE to report BSI via xPDCCH commands.

Event triggered reports: BRSRP of the best beam is higher than beamTriggeringRSRPoff set dB + the BRSRP of serving beam.
5G air interface aspects: beam forming reporting

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

<table>
<thead>
<tr>
<th>Field</th>
<th>Bit width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam index</td>
<td>9*N</td>
</tr>
<tr>
<td>Wide-band BRSRP</td>
<td>7*N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field</th>
<th>Bit width</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRRS-RI</td>
<td>3*N</td>
</tr>
<tr>
<td>Wide-band BRRS-RP</td>
<td>7*N</td>
</tr>
</tbody>
</table>
5G air interface aspects: beam switching procedure

DCI based

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

BSI report. Strongest BSRP will be new beam index

Beam switch to strongest BSRP indicated by UE in previous report

MAC-CE based
Aspects of DoA estimation – motivation for simpler methods

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

Brute force:
- Tx based with feedback
- Rx based w/o feedback

1.) coarse sector level switching
2.) beam refinement

beams / sectors may contain an ID

Multi level beam training
5G air interface aspects: beam reference and refinement

Beam forming reference signals to identify beam and sent feedback

BSI based on BRS

DCI scheduling indicates the transmission of beam refinement signals BRRS. Alternative UE may request BRRS via scheduling requests

BSI based on BRRS
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.

<table>
<thead>
<tr>
<th>BRS transmission period</th>
<th># of subframes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 slot &lt; 5 ms</td>
<td>1</td>
</tr>
<tr>
<td>1 subframe = 5 ms</td>
<td>2</td>
</tr>
<tr>
<td>2 subframes = 10 ms</td>
<td>4</td>
</tr>
<tr>
<td>4 subframes = 20 ms</td>
<td>8</td>
</tr>
</tbody>
</table>
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 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

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

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

NOMA

Signal specific filtering
SIC, successive interference cancellation of user 1 signal
Decoding of user 2 signal
Decoding of user 1 signal

User 1
User 2
Multiple access – Bit division multiple access BDM

broadcast & multicast problem: tradeoff between coverage & throughput

UE with good SNR

Traffic broadcast

UE with bad SNR

Time division multiplexing: adjusted MCS to SNR situation of UEs => not extremely efficient, but higher coverage possible
Multiple access – Bit division multiple access BDM

stream 1 \rightarrow \text{Encoder 1} \rightarrow \text{bits } b_1, b_2 \rightarrow \text{hierarchical QAM} \rightarrow \text{stream 2} \rightarrow \text{Encoder 2} \rightarrow \text{bits } b_3, b_4

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

- Encoding
- Interleaving
- Spreading/scrambling
- S/P
- IFFT
- P/S
- Add CP

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 $E_{\text{bit}}/N_0$.

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

**Question:** scheduling and (a)-synchronous 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

1. Sum signal containing k users, each user scrambled with specific sequence g(t)
2. Matched filter to detect strongest signal
3. Decision + decoding
   - Amplitude estimation
   - Scrambling sequence

   „Regenerate“ signal of user x for subtraction purpose

4. Signal content of user x for further processing
5. Iteration until last signal is decoded
   - $\sum_{k=k-1}$
   - $T_b$

"ROHDE & SCHWARZ"
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.

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

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
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

Basic idea of low density signature

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

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

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

only this part would overlap between these codes
Low density signature codes
example: LDS indicator matrix, one idea how to generate LDS for spreading

$K = 16$ users

$N = 12$ chips

$F_{12 \times 16}$

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

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

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

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

\[ (b_1, b_2) \]

\[ (0,0), (0,1), (1,0), (1,1) \]

1. Step: Binary data pattern, e.g. 010011101011001

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

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

K-N zero elements

N non-zero elements

\[ (0,0), (0,1), (1,0), (1,1) \]
SCMA encoding multiple access by using multiple codebooks

- Codebook 1 = user 1
- Codebook 2 = user 2
- Codebook 3 = user 3
- Codebook 4 = user 4
- Codebook 5 = user 5
- Codebook 6 = user 6

Example:
User 1 sends bits 1,1 which is codeword 4 out of the UE specific codebook.

Σ

Here we have an overload situation: 6 users with codelength = 4

E.g. the combined signal would end up with max 3 symbols overlapping (MAI) -> sparsity of codes
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 independent

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.

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

real axis mother constellation

imaginary axis mother constellation

the first tone would contain this „vector“ / IQ symbol

the second tone contains this „vector“
Higher frequencies: path loss issues

Higher frequencies = higher attenuation
Higher frequencies = smaller antennas

**Friis equation**

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

**EXAMPLE @ 28 GHz:**

<table>
<thead>
<tr>
<th>PathLoss 28 GHz</th>
<th>(\gamma = 2) Free Space</th>
<th>(\gamma = 1.6) to 1.8 Indoor LOS</th>
<th>(\gamma = 2.7) to 3.5 Urban Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>-61.4 dB</td>
<td>-52 dB (k=1.7)</td>
<td>-92.1 dB (k=3)</td>
</tr>
<tr>
<td>10 m</td>
<td>-81.4 dB</td>
<td>-69 dB</td>
<td>-122.1 dB</td>
</tr>
<tr>
<td>100 m</td>
<td>-101.4 dB</td>
<td>-86 dB</td>
<td>-151.1 dB</td>
</tr>
<tr>
<td>1000 m</td>
<td>-121.4 dB</td>
<td>-103 dB</td>
<td>-181.1 dB</td>
</tr>
</tbody>
</table>

\(\gamma = \text{path loss exponent}\)
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

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

Separatibility of MPP components

Identify each MPP component.

\[ \tau_{RES} \approx \frac{1}{B} \]

Minimum measurement duration

Path delay
Path attenuation
Path phase

Delay spread

|h|^2

\( B \)
Channel sounding – 5G request

Each multipath component is characterized by:
- Time $t$
- Angle of arrival $\Delta \phi$
- Doppler shift
- Excess delay $\Delta T$
- Phase shift

In MIMO condition it would end up in a NxM matrix set.

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

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

GBSM
Geometry Based Stochastic Model

Raytracing
Channel sounding measurement aspects - structure

Channel sounding

Time domain (Sig Gen + Anal.)
- Time invariant
  - SISO
  - Angular information
  - MIMO
- Time variant
  - SISO
  - Angular information
  - MIMO

Frequency domain (VNA)
- Time invariant
- Time variant
Channel measurements in mmWave frequency bands
R&S TS-5GCS channel sounding solution

Measurement Setup

- Pulsed Correlation Sequence Generation
  - 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
  - High receiver sensitivity
  - Built-in LNA
  - Large dynamic range
  - Power Angular Profile (Angle of Arrival)

- Realtime data analysis software
  - HHI Synchronomat: absolute propagation time
  - No synchronization: relative propagation time

R&S®SMW200
R&S®FSW85

I/Q Data
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.
There is no golden setup - various aspects to consider

- Dynamic range
- Adjustable attenuator: instantaneous dynamic range decreases when attenuation increases
- Antenna influence: e.g. outdoor setup at 17 GHz using omnidirectional and directional (Vivaldi) antenna
- Amplitude error - calibration required

Source: Characterization of mm-wave Channel sounders (EuCAP2016 paper #1570230959)
Problem: Where does the echo come from?

Transmitter

Receiver

LOS

CIR(τ) Delay spread

CIR(φ) Angular spread

0° 45° 180° 315°
Directional Information: Spatial Filtering

- 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

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

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

MIMO ✓
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
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

- 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)
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

- 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)

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

(✓)
Direction of Arrival DoA Evaluation

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

\[ \phi = \arccos \left( \frac{c \cdot d\tau}{d\tau} \right), \quad 0 \leq \phi \leq \pi. \]

<table>
<thead>
<tr>
<th>distance [m]</th>
<th>\cos(\phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 – 20</td>
<td>-1.00 0.92 -0.52 -0.75 -0.96 1.01 -1.13</td>
</tr>
<tr>
<td>15 – 20</td>
<td>-0.97 -0.78 0.94 -1.03 1.08 1.01 -0.99</td>
</tr>
<tr>
<td>10 – 15</td>
<td>-1.03 -1.08 -0.46 -1.02</td>
</tr>
<tr>
<td>5 – 10</td>
<td>-1.09 1.11 1.21 1.24 -1.25 -1.16 1.15 -1.28</td>
</tr>
<tr>
<td>0 – 5</td>
<td>-0.65 0.86 -0.33 0.92 -0.81 -0.59 0.90</td>
</tr>
</tbody>
</table>
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

**Frequencies:**

- **Pre-5G:** Only 28GHz in focus
- **3GPP 5G + vision:** Various frequencies in focus: 700MHz, 3.5GHz, 5.9GHz, 15GHz, 25GHz, 28GHz, 38GHz, ...

**Application:**

- **Pre-5G:** Only focus on eMBB
- **3GPP 5G + vision:** 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

- **Modulation scheme:**
  - QPSK, 16QAM + 64QAM

- **Subcarrier spacing:**
  - $\Delta f = \text{const} = 75\text{kHz}$

**3GPP 5G + vision**

- **Bandwidth:**
  - 1 channel = 10 or 20MHz | 1 channel ~80MHz | 1 channel ~640MHz
  - Total bandwidth up to 2GHz

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

- **Subcarrier spacing:**
  - $\Delta f = \text{variable} = 3.75\text{kHz} \ldots 240\text{kHz}$
Massive MIMO Theory & Hardware
Energy Efficiency: Why Massive?

Number of Antennas = 1

<table>
<thead>
<tr>
<th>Number of BS Transmit Antennas</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Output Power of Antennas</td>
<td>$P_{\text{unit}} = \frac{1}{M_i} = 1$</td>
</tr>
<tr>
<td>Normalized Output Power of Base Station</td>
<td>$P_{\text{total}} = \sum_{i=1}^{M} P_{\text{unit}}^i = 1$</td>
</tr>
</tbody>
</table>

Number of UEs: 1
120 antennas per UE

$P_{\text{BS}} = 1$

$P_{\text{BS}} = 0.008$

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 $\Theta$
- Phase front reaches antenna elements at different times

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

$$\Delta \varphi = \frac{2\pi}{\lambda} d \sin \Theta$$

Phase front
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
Question: How to get side lobe level down?

Answer: Additional weighting by magnitude!

Phased Array Antenna Principle

weighting phase and magnitude

Triangular weighting function
beamforming with phased array = phase + amplitude modification

ROHDE & SCHWARZ
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

- Phase shift calculated for boresight of 15° @30GHz
- Frequency dependency translates into shift of main lobe: beam squint
- Boresight of 25° @20GHz
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
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: \[ r = sH + n \]
MIMO – work shift to transmitter
MIMO – codebook based precoding

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 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

MIMO Array: $M$ Data Streams

- $x_1(t)$
- $x_2(t)$
- $x_3(t)$
- $x_4(t)$

$M = 4$ Transceivers

Beamforming Array: 1 Data Stream

- $x_1(t)$
- TRx

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

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

<table>
<thead>
<tr>
<th>Passive Antenna</th>
<th>Active Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input/Output:</strong> Radiated Signal</td>
<td><strong>Input/Output:</strong> Radiated Signal</td>
</tr>
<tr>
<td><strong>Outer enclosure:</strong> Radome</td>
<td><strong>Outer enclosure:</strong> Radome</td>
</tr>
<tr>
<td><strong>Antenna + Feeding Network</strong></td>
<td><strong>Antenna + Feeding Network</strong></td>
</tr>
<tr>
<td><strong>RF I/O ports</strong></td>
<td><strong>RF Transceiver Boards + Filters</strong></td>
</tr>
<tr>
<td><strong>Front Radome</strong></td>
<td><strong>CPRI + FPGA Board</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Shielding + Heatsink</strong></td>
</tr>
<tr>
<td><strong>Rear Radome/Heatsink</strong></td>
<td><strong>Outer enclosure</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Input/Output:</strong> Digital IQ Baseband Data</td>
</tr>
</tbody>
</table>

---

*Image source: ROHDE & SCHWARZ*
Massive MIMO Challenges
Massive MIMO Challenges

Data Bottleneck
- CPRI Bottleneck
- Increased Costs

Calibration
- Reduced MU-MIMO

Mutual Coupling
- Reduced Capacity

Irregular Arrays
- Grating Lobes

Complexity
- Increased Costs

RFIC
Digital IQ
FPGA
RX
RFIC
Digital IQ
Limitations of Digital IQ on Fiber: Latency & Capacity

Latency

<table>
<thead>
<tr>
<th>Round Trip Time</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fronthaul RTT</td>
<td>&lt; 1ms</td>
</tr>
<tr>
<td>Sub-frame Processing</td>
<td>400-800 µs</td>
</tr>
<tr>
<td>Optical Fiber RTT</td>
<td>FH_{RTT} - SFP_{RTT} 200-400 µs</td>
</tr>
</tbody>
</table>

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

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

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

Phase/Magnitude/Frequency Tolerances (Static & Dynamic)
Phase Tolerances

MU-MIMO

- Multiple beams
- Places nulls at UEs (Null-steering)

\[ \Delta \phi < \pm 2.5^\circ \]

Comparison between ideal and calibrated

Comparison between ideal and non-calibrated

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

Max = 47A/m

AAS Square Array: 8 Adjacent Antennas

Max = 47A/m

More Capacity = More Spacing = Larger AAS Systems
Measure Mutual Couple & Capacity in Massive MIMO

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

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
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

- Mutual Coupling Isolation
- Beamforming Architecture
- Wideband: PA and Filter Banks
- mmWave = Non-CMOS components
- Fiber Transceivers
- Fiber Multiplexing
- Heat Dissipation
- Clock Synchronization
- Adaptive Self-Calibration
- 128 Element AAS Prototypes: Complexity increased by 8 times
### Fundamental Design Parameters for Active & Passive Antennas

#### Passive Antennas (Conducted)

<table>
<thead>
<tr>
<th>UEs</th>
<th>Basestations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance matching (Smith Chart)</td>
<td></td>
</tr>
<tr>
<td>S-Parameters &amp; Return Loss</td>
<td></td>
</tr>
<tr>
<td>$S_{12}$ &amp; Mutual Coupling</td>
<td></td>
</tr>
</tbody>
</table>

#### Active Antennas (Radiated)

<table>
<thead>
<tr>
<th>User Equipment/Terminals</th>
<th>Basestations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Gain Patterns (2D/3D)</td>
<td></td>
</tr>
<tr>
<td>Active (UE): TRP, TiS</td>
<td>Active (Basestation): EiRP, EiS</td>
</tr>
<tr>
<td>Radiation Efficiency (UE)</td>
<td></td>
</tr>
<tr>
<td>Specific Absorption Ratio (UE)</td>
<td></td>
</tr>
<tr>
<td>Beamsteering &amp; Beamtracking (mmWave)</td>
<td></td>
</tr>
</tbody>
</table>

**5G**
Fundamental Properties: Electromagnetic Fields

Basestation 8 Element Array at 2.7 GHz

Reactive Near Field Region (< 0.6m)

Far Field Magnitude

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

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

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

ROHDE & SCHWARZ
Chamber Size: Far-field or Near-field?

**Basestations: Subarray Measurements (D_{\text{ant}} \ll \text{DUT})**

- D_{\text{ant}} = 8.5 cm

- 28GHz Subarray (\(\lambda = 10.7\) mm, HPBW = 7.2°)
  - Criteria: \(2\lambda/\text{HPBW}^2\)
  - Far-field Distance: 1.35 meters

- 28GHz Entire Base-station (HPBW = 1.2°)
  - Criteria: \(2D^2/\lambda\)
  - Far-field Distance: 46 meters

**UEs: D_{\text{ant}} \sim \text{DUT}**

- D_{\text{ant}} = 4 cm

- 28GHz UE Subarray (HPBW = 15°)
  - Criteria: \(2\lambda/\text{HPBW}^2\)
  - Far-field Distance: 0.30 meters

- 28GHz Entire UE
  - Criteria: \(2D^2/\lambda\)
  - Far-field Distance: 1.86 meters

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

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

HPBW (radians)
Half-power beam width
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.

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

OTA Gain, EiS, EiRP

Multiport Antenna Array Measurements

Element/System OTA EVM, ACLR

Production TRx & Antenna Calibration

Measure mutual coupling S-Parameters
## R&S OTA Product Matrix

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequencies</strong></td>
<td>0.4 to 18 GHz</td>
<td>0.4 to 40 GHz</td>
<td>0.4 to 90 GHz</td>
<td>28-75 GHz</td>
<td>28-90 GHz</td>
</tr>
<tr>
<td><strong>Minimum Size</strong></td>
<td>250x250x220 cm</td>
<td>250x250x220 cm</td>
<td>70x100x140 cm</td>
<td>45x50x48 cm</td>
<td>77x76x70 cm</td>
</tr>
<tr>
<td><strong>Fields</strong></td>
<td>Near &amp; Far</td>
<td>Near &amp; Far</td>
<td>Near &amp; Far</td>
<td>Far Field</td>
<td>Far Field</td>
</tr>
<tr>
<td><strong>Signals</strong></td>
<td>Modulated/CW</td>
<td>Modulated/CW</td>
<td>Modulated/CW</td>
<td>Modulated/CW</td>
<td>Modulated/CW</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>EiRP, EiS, Gain, EVM, ...</td>
<td>EiRP, EiS, Gain, EVM, ...</td>
<td>EiRP, EiS, Gain, EVM, ...</td>
<td>Gain</td>
<td>EiRP, EiS, Gain, EVM</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Available for purchase</td>
<td>Available for purchase</td>
<td>Available for purchase in Q2 2017</td>
<td>Available for Purchase</td>
<td>Available for Purchase</td>
</tr>
</tbody>
</table>
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

Active Antenna Near-field

Active Antenna Far-Field

R&S®ZVA Narrow-Band Signal

Phase Shifter \( \varphi = [0, \pm \pi/2, \pi] \)

Reference Antenna

Measurement Antenna

Active Antenna System DUT

R&S®FSW/FSV (CW/Modulated)

or

R&S®NRP (Magnitude Only)

2

Passive Antenna (Near or Far-Field)

R&S®ZVA

1

3a

3b
**Alternative for far-field TRP measurements**

NRPM OTA Power Sensor: Magnitude Measurements

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

**Magnitude Only**

- mmWave DUTs will not have antenna connectors
- OTA Measurements will be mandatory for production

**Measurement Equipment**
- R&S® NRPM
- R&S® TS7124
- Vivaldi Probe 28-77 GHz

**Measurement Scenarios**
- 2D Beam-Steering
- 3D Beam-Steering

**RF antenna array**
ATS1000 flexible shielded chamber (launched @ MWC2017)

Conical or Spherical

Hemi-spherical: 1.4 m
Spherical: 1.8+ m

Flexible Range Length

≥ 1.4 meters
≥ 1 meter
≥ 0.7 meter

Positioner

Pyramidal absorber shown for illustration only.
Actual product contains flat absorber for space savings.

R&S®ATS1000

R&S®NRPM

OTA Power Sensors

Active or Passive DUT

Pyramidal absorber shown for illustration only.
# R&S Antenna Test Solutions Summary

## Massive MIMO
- **R&S®TS8991**

## mmWave
- **R&S®ATS1000**
- **R&S®SMW200A**

## Multiport Testing
- **R&S®FSW**
- **R&S®ZVA**
- **R&S®ZNBT**
- **R&S®SMW200A**
  - 6x R&S®SGT100

## CTIA Radiation Patterns
- **R&S®TS8991**
- **R&S®FSV**
- **R&S®NRP**

## mmWave Beamsteering
- **DUT**
- **R&S®NRP**
- **R&S®NRPM-A66**

## Production & Benchtop
- **R&S®DST200**
- **R&S®TS7124**
- **R&S®RTO**
- **R&S®FSV/FSP**
- **R&S®ZVC/D**

---

**Phase-coherent RF generation**

**Multi-port VNA for Active Return Loss**

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**ROHDE & SCHWARZ**
### R&S test solutions to investigate, develop and standardize

#### Wideband Signal Testing
- **R&S®SMW200**
  - Signal generator
  - < 40 GHz
  - > 40 GHz
- **R&S®FSW85**
- **Spectrum Analyzer**

- 40 GHz signal generation
- 85 GHz signal analysis
- 2 GHz bandwidth support

#### Channel Sounding Solution
- **R&S®SMW200**
  - Signal generator
- **R&S®FSW85**
  - Spectrum Analyzer
- **R&S®TS-5GCS**

- Fast measurement in time domain
- Support for in- and outdoor sounding
- Very high dynamic range

#### Component Characterization
- **R&S®ZVA**
- **R&S®FS-K196**

- Direct measurements up to 110 GHz

#### New 5G PHY Candidates
- **R&S®SMW200-K114**
- **R&S®FS-K196**

#### Massive MIMO - Beamforming
- **R&S®SMW200+ 6x R&S®SGT100**
- **R&S®ZNBT**
  - Phase-coherent RF generation
  - Multi-port VNA

#### Massive MIMO - Beamforming
- **R&S®CMW500**
  - **R&S®CMW500**

#### E2e Application Testing
- **CONTEST**
  - **CMWrun**

- Analyze application behavior like signaling load, delay, power etc.
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