Initial radio models and analysis towards ultra-high data rate links in 6G

31.12.2021
Outlines

• Introduction
• RF system level analyses and simulations of initial 6G radio
• Waveform candidates for 6G: impact of hardware impairments and complexity-performance trade-offs
• Hybrid beam forming analyses
• D-MIMO radio architecture studies
• Understanding the above-100 GHz wave-material interaction and wave propagation through measurements
• Proof-of-concepts for communications
Introduction

- New insights on the upcoming 6G radio implementations by providing initial simulation models and frameworks which will be utilized during the Hexa-X project
- D2.2 is to deepen insights on
  - Hardware
  - Waveforms
  - Beamforming
  - Distributed MIMO
  - Channel models

WP2 is focused on exploring the upper mmW frequencies:

Main requirements for D2.2 studies:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial release of 6G radio</th>
<th>Long-term vision for 6G radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>100 Gbps</td>
<td>1 Tbps</td>
</tr>
<tr>
<td>Operational/carrier frequency (fc)</td>
<td>100 – 200 GHz</td>
<td>Up to 300 GHz</td>
</tr>
<tr>
<td>Radio link range</td>
<td>100 – 200 meters</td>
<td>10 – 100 meters</td>
</tr>
<tr>
<td>Duplex method</td>
<td>Time Division Duplexing (TDD)</td>
<td>TDD</td>
</tr>
<tr>
<td>Initial device class targets</td>
<td>Device to infrastructure, mobile backhaul/fronthaul</td>
<td>Infrastructure backhaul/front haul, local fixed links, and interfaces (data centres, robots, sensors, etc.)</td>
</tr>
</tbody>
</table>
RF system level analyses and simulations of initial 6G radio

<table>
<thead>
<tr>
<th>Abstraction level</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical signal model</td>
<td>$P_{out}(dB) = P_s + P_{int}(dB)$</td>
<td>$y[n] = h[x][n] + z[n] \ast r[n]$</td>
<td>$y[n] = f[x][n] \ast r[n]$</td>
</tr>
<tr>
<td>Typical FOMs</td>
<td>power, link range, SNR, coverage</td>
<td>Capacity, bit error rate (BER), block error rate (BLER), outage probability</td>
<td>EVM, ACLR, SNR, Robustness against RF non-linearities (e.g. fading, phase noise, nonlinearity), Ambiguity function</td>
</tr>
<tr>
<td>Typical research problems</td>
<td>Link budget, component specifications, chain power and SNR calculations, chain nonlinearity analysis</td>
<td>Beamforming techniques, Algorithms, statistical simulations, Monte-Carlo simulations, equalization</td>
<td>Waveform design, link performance analysis, compensation of RF non-linearities, equalization</td>
</tr>
<tr>
<td>Special note</td>
<td>Impact of non-linearities on EVM/SNR, power dependent EVM/SNR models</td>
<td>Non-linearities abstracted to the effective channel model, signal and non-linearities separated, non-linearities additive.</td>
<td>Non-linearities modeled with behavioral models from sample to sample.</td>
</tr>
<tr>
<td>Simulation time/cnt</td>
<td>Fast, Reference cases</td>
<td>Slow, Large number of realizations</td>
<td>Moderate, Depends on research problem</td>
</tr>
</tbody>
</table>

Digital-RF-digital simulation models:

- **Digital Transmitter**
  - QAM symbols
  - Oversample
  - Pulse shaping
- **Digital Receiver**
  - Equalize
  - Time synch
  - Down sample
  - Pulse shaping

100 Gbps 6G receiver ADC power consumption model:

ADC model approaches:

**Model 1:** signal scaling + quantization

$x(n) \rightarrow g(x(n)) \rightarrow$ quantize $\rightarrow y(n)$

$z_q(n) = \cdots$

$Z_n \sim CN(0,1)$

**Model 2:** signal scaling + add noise

$x(n) \rightarrow g(x(n)) \rightarrow + y(n)$
RF system level analyses and simulations of initial 6G radio

LNA noise figure frequency dependency models:

- GaAs, p & mHEMT
- InP, HEMT & HBT
- SiGe, Measured
- SiGe, Simulated
- CMOS
- Best NF, SiGe
- Best NF, InP
- Best NF, GaAs
- Best NF, CMOS

Phase noise model:
- RMS phase jitter approximation, white noise (model1)
- Colored phase noise generation (model2), below

\[ \Phi_W(n) \sim N(0,1) \]

\[ H(f) = \frac{1}{\sqrt{2}} \sqrt{5(f)} \]

LO phase simulation results and effects to EVM:

- 3GPP phase noise model:
  - Scaled up to 120 GHz
  - Gaussian white noise
Focus of waveform studies:

- Increased impact of HW impairments and reduced HW capabilities at mmWave frequencies (phase noise, reduced max PA power)
  - Needed: higher robustness to phase noise, smaller envelope variations
- Increased power consumption due to high signalling rates
  - Needed: low-complexity processing

Iterative equalization and decoding performance for measurement-based channel at 140 GHz

Performance gain with 4 iterations compared with no iterations = 1-3 dB, depending on channel

Impact of phase noise on CP-OFDM, DFTS-OFDM and SC-FDE at 120 GHz

DFTS-OFDM and SC-FDE more robust to PN than CP-OFDM at higher order modulations

Joint impact of phase noise and PA nonlinearity on DFTS-OFDM at 70 GHz
Waveform candidates for 6G: impact of hardware impairments and complexity-performance trade-offs

Performance of zero-crossing modulation under phase noise at 70 GHz for different faster-than-Nyquist signalling factors $M$

Link budget improvement of DFTS-OFDM compared with OFDM under the influence of PA nonlinearity at 60 GHz

PA efficiency vs. PAPR/RCM for various waveforms
Hybrid beam forming analyses

System Model

- Signal model for link-level simulation
- Evaluation of theoretical limits
  - Bandwidth impact
  - MIMO spatial multiplexing
  - Beamforming architecture
- Design constraints
  - Array geometry and size
- Models for the waveform
  - SNR, digital channel response

Ideal assumptions

- Ideal DAC/ADC
- Ideal filtering
- Linear phase and gain control
- Ideal mixers
- Linear PA, LNA
- Narrow band assumption
- Static channel within the observation time

Next steps

- Integration of the HW models

Ideal assumptions table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Dependency</th>
<th>Further consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>$\sum_l H_l \delta(t - \tau_l)$</td>
<td>Radio environment, carrier frequency, Antenna array: geometry, number of TX elements ($P$) and RX elements ($Q$), and TX and RX antenna element gain</td>
<td>Time variation, antenna coupling, phase noise</td>
</tr>
<tr>
<td>$\tilde{H}(f)$</td>
<td>$\sum_l H_l e^{-j2\pi f \tau_l}$</td>
<td>Hybrid TX beamforming matrix, Digital precoding $W_D$ ($M \times M$), Analogue gain and phase $W_A$ ($M \times P$)</td>
<td>Non-linearity of gain and phase, DAC resolution</td>
</tr>
<tr>
<td>$W$</td>
<td>$W_A W_D$</td>
<td>Hybrid TX beamforming matrix</td>
<td>Digital decoding $F_D$ ($N \times N$), Analogue gain and phase $F_A$ ($N \times Q$)</td>
</tr>
<tr>
<td>$F$</td>
<td>$F_A F_D$</td>
<td>Hybrid TX beamforming matrix</td>
<td>Filters, PA and Mixer nonlinearities, IQ imbalance, Quantization noise</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>TX- baseband signals</td>
<td>Number of TX-RF chains ($M$)</td>
<td></td>
</tr>
<tr>
<td>$y(t)$</td>
<td>RX- baseband signals</td>
<td>Number of TX-RF chains ($N$)</td>
<td>Filters, LNA and Mixer nonlinearities, IQ imbalance, Quantization noise</td>
</tr>
</tbody>
</table>
Study cases

- Impact of HW limitations on beam training strategies and initial access
  - Analog beamforming → full-channel information per antenna is not available
  - High beamforming gain in the upper mm Wave band → Narrow beams
  - Initial beam training needs to probe many beams → long training time

- Approach: beam shape to wider beams
  - Requirements of variable gain

- Beam tracking under mobility
  - Line-of-sight model

  Illustration of the transition of devices at positions P1 at x1, y1 to P3 x3, y3 from the region covered by one beam to other regions, given a movement radius defined by the maximum speed and beam training time interval.

Illustration of the area in which the one beam is optimal including two device positions (P1 and P2) and the respective areas for staying inside the area of this beam or transitioning to another one.

Absolute values of beam weights for widened beams

- Spatial Coherence Based Model

  Probability of devices leaving a given coherence area given different beam training intervals τB ∈ (10 ms, 20 ms, 50 ms, 100 ms, 200 ms, 500 ms, 1 s) and number of beams (a) N_b = 8 and (b) N_b = 16 for cell radius r_B = 50 m

- Beam coherence model
  - Device position
  - Device movement
  - Area inside current beam
  - Area outside current beam

Probability P_f of devices leaving a given coherence area given different beam training intervals τ_f ∈ (10 ms, 20 ms, 50 ms, 100 ms, 200 ms, 500 ms, 1 s) and coherence radii (a) r_c = 5 m, and (b) r_c = 2.5 m.
D-MIMO radio architecture studies

Motivation:

- D-MIMO offers great potential to help and mitigate both, unreliable links due to blockage as well as increased path-loss.
- D-MIMO offers robustness against blockade at mm-wave frequencies by macro diversity.
- D-MIMO also allows for further densification of Aps for further robustness, and area capacity.
- An increased density of cooperating APS is also important for sufficient link margin due to output power limitations and increased pathloss at upper mmW and (sub-)THz frequencies.
- Low power APs, allows for lowering the EIRP, which simplifies deployment.

Recent results on key technical components in D2.2:

- Analog centralized beamforming
- Distributed digital beamforming
- Integrated access and backhauling
D-MIMO radio architecture studies

D2.2 Contributions on D-MIMO:
- Challenges and opportunities with D-MIMO and its potential role in 6G
- The different challenges at lower and upper mmW/THz bands were highlighted, calling for a scalable approach from digital to analog approaches.
- Emphasized the need for efficient backhaul fronthaul solutions by integrating fibre and in-band wireless solutions.

A wide bandwidth D-MIMO system can be implemented using AROF and WDM.

Spectral efficiency for collocated ($L=1$), partially ($L=4, 16$), and fully distributed ($L=64$) interference aware distributed zero-forcing for different operating frequencies for $N_t = \{1, 4, 64\}$.

Comparison of power efficiency of optimized fully digital, and fully/partly connected hybrid beamforming (FDP/FHP/PHP), with/without silence mode activated vs node density.

Conclusions
- Densification is the key enabler to meet coverage and reliability targets at the higher frequency bands and there seems to be sufficient spectrum available.
- Thus, low-cost solutions are more important than spectral efficiency, at least in the early roll-out phases. In the lower mmW bands the need for higher spectral efficiency calls for digital less distributed approaches.
Understanding the above-100 GHz wave-material interaction and wave propagation through measurements

How many beam does sub-THz channel support?

Motivation:

- Is line of sight (LOS) the only path that has enough gain to conduct communication or positioning signals?
- Are there spare beam directions available if the LOS path is temporally blocked?
- Do antenna arrays and related phase control circuits need capability to control multiple simultaneous beams or is only one sufficient?
- Is spatial multiplexing a viable option at sub-THz?
- Can one rely with a positioning system to have only the LOS path present?

→ These questions affect research and design of antennas, RF circuits, algorithms, and systems

Three proposed methods:

M1: Number of local maxima
M2: Number of uncorrelated beams
M3: The minimum number of beams for 90% power

Data:

1. Measured Power Angular Delay Profile (PAPD) \[ P_q(\Omega, \tau) = \sum_{l=1}^{L_q} P_{l,q} \delta(\Omega - \Omega_{l,q}) \delta(\tau - \tau_{l,q}) \]
2. Choose beam shape (here synthetic 3GPP antenna gain pattern with 10° HPBW)
3. Apply methods

Results:

Channels support one beam in 11-42%, two in 23-29%, three in 13-23%, and four or more beams in 14-40% of cases, depending on the selected evaluation method.
Understanding the above-100 GHz wave-material interaction and wave propagation through measurements

Material transmission losses from 2 GHz to 170 GHz

Motivation:
• Do we have any physical reasons to think that channels above 100 GHz will be significantly different from those below 100 GHz?
• Focus on transmission losses of different materials

Measurement:
• VNA-based measurement on frequency bands [2 GHz,12 GHz],[12 GHz,30 GHz],[30 GHz,50 GHz], [50 GHz,75 GHz],[75 GHz,110 GHz],[110 GHz,170 GHz]
• Data processing based on raw measurement time-gating and normalization by free space measurement

Results:
• Material transmission losses increase with frequency in accordance with EM theory
• Organic glasses, thermal or sound insulation materials, plasterboard exhibit relatively low losses compared to wood or its derivates and mortar
• More material results included in D2.2. The analysis will be continued with reflection losses
Three different Proof-of-Concept demonstrations are going to be prepared focusing on different aspects:

- Digital implementation aspects for high bandwidth
- High bandwidth communication above 100 GHz with different waveforms
- Joint communication and sensing
Thank you!

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