Overcoming 5G Design and Simulation Challenges with SystemVue

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SystemVue
Agenda

– Motivation: What are the challenges in 5G simulation?
– Massive MIMO & Beamforming
– Physical Layer
– Channel
## Technology Challenge in 5G Simulation

### Massive MIMO & Beamforming

**Beamforming Architectures**
- RF beamforming
- Digital beamforming
- Hybrid beamforming

**RF System Architectures**
- Nonlinearities
- Frequency response
- ADC / DAC quantization

**Antenna Array**
- 3D configuration
- 3D EM element patterns
- Distribution manifolds

### Physical Layer

**Waveform Design Principles**
- Flexibility
- Spectral efficiency
- Uniform design for DL, UL

**5G Waveform**
- CP-OFDM (Cyclic Prefix OFDM)
- Universal-Filtered (UF-OFDM)
- F-OFDM (Filtered OFDM)
- FBMC (filter bank multi-carrier)
- GFDM (Generalized frequency division multiplexing)

### Channel

**New Channel Model**
- 3D channel model
- Difference between channel models in frequency range
- 3GPP 6G-100G channel model

**Channel Model Simulation**
- Channel sounding
- Parameter extraction
Suggested approach: System-level flow for 5G Simulation

Application/Scenario Layer (Dataflow)

System / PHY Layer (Dataflow)

RF Architecture Layer (Spectrasys)

5G/Comms Mod, Coding Control

Radar Multiple TX RX

Satellite NewSpace

WLAN WPAN 3\textsuperscript{rd} Party environments

Inertial position, velocity, attitude

T&M Connect to test

Multi-Channel RF\_LINK (Dataflow)

N paths

Inertial position, velocity, attitude

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Agenda

– Motivation: What are the challenges in 5G simulation?

– Massive MIMO & Beamforming
  • Beamforming Architecture
  • Antenna Configuration
  • RF Impairment

– Physical Layer

– Channel

– Performance & Implementation
Conventional Architecture (Take Source as Example)

Digital MIMO Architecture

Analog RF Beamforming Architecture

Baseband

Precoder \( F_{BB} \)

\[
\begin{bmatrix}
    F_{11} & F_{12} & \cdots & F_{1N} \\
    F_{21} & F_{22} & \cdots & F_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    F_{N1} & F_{N2} & \cdots & F_{NN}
\end{bmatrix}
\]

Combiner \( W_{BB} \)

\[
\begin{bmatrix}
    W_{11} & W_{12} & \cdots & W_{1N} \\
    W_{21} & W_{22} & \cdots & W_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    W_{N1} & W_{N2} & \cdots & W_{NN}
\end{bmatrix}
\]

RF Chains

\( \cdots \)

Baseband

RF precoder : \( F_{RF} \)

RF combiner : \( W_{RF} \)
Hybrid Beamforming Architecture

- Reduced hardware complexity
- Similar performance with DBF architecture
Hybrid Beamforming in 5G Library

BB MIMO Source precoder

Tx RF Chains Antennas

MIMO Channel

Rx RF Chains Antennas

BB MIMO Receiver deprecoder

Imported Real Ant Element Pattern

HBF Algorithm

BER

Imported Real Ant Element Pattern
Antenna array in Dataflow
unique “Timed Envelope Matrix” datatype

“I can do a couple channels.”

“But how do I even draw 1000 channels?”

“The new Envelope Matrix stuff is fantastic. I have modeled our 16x16 phased array and I love the speed and snappiness. I’m really impressed by what it can do.”
Hybrid Beamforming in 5G Library

Features of Interest

- Narrowband and Broadband (OFDM-based) system design
- RF/IF Impairments introduction (behavior/RF circuit)
  - PA non-linear distortion
  - Mixed signal components effect (ADC/DAC)
  - Antenna array coupling, Antenna array calibration error
  - Antenna element failure, Antenna element position perturbation
  - Configurable antenna elements’ pattern (Omni/3-Sector/Custom)
- Visualization
  - 2D/3D graph to illustrate whatever we want to view
    - Tx/Rx Signal angular domain beam plotting
    - Antenna element pattern plotting
  - Compare/analyze graph with different configurations/settings

Imported Real Ant Element Pattern
Beam Training Performance in OFDM-based HBF System

Channel Estimation in Wideband HBF System

– Deployment
  • 64 Tx/Rx Antennas, 4 Tx/Rx RF Chains
  • 4 paths’ direction in degree in Tx: (320,-30),(320,30),(40,-30),(40,30)
  • 4 paths’ direction in degree in Rx: (330,-20),(330,20),(30,-20),(30,20)

– Estimated optimal Tx and Rx beams
  • The estimated beams’ optimal directions coincide with the configured channel parameters
Beam Training Performance in OFDM-based HBF System

Departure Direction of Channel: (320,-30),(320,30),(40,-30),(40,30)

Est. Tx Beam 1

m75 (Peak):
az. 320°
el. 30°
mag. 18.06

Est. Tx Beam 2

m76 (Peak):
av. 40°
el. 30°
mag. 18.06

Est. Tx Beam 3

m77 (Peak):
az. 320°
el. -30°
mag. 18.06

Est. Tx Beam 4

m78 (Peak):
av. 40°
el. -30°
mag. 18.06
Beam Training Performance in OFDM-based HBF System

Arrival Direction of Channel: (330, -20), (330, 20), (30, -20), (30, 20)

- Est. Rx Beam 1: m79 (Peak): az. 330°, el. 20°, mag. 18.06
- Est. Rx Beam 2: m80 (Peak): az. 30°, el. 20°, mag. 18.06
- Est. Rx Beam 3: m81 (Peak): az. 330°, el. -20°, mag. 18.06
- Est. Rx Beam 4: m82 (Peak): az. 30°, el. -20°, mag. 18.06
BER Performance in OFDM-based HBF System (QPSK)

1 RF Chain@Tx, 1 RF Chain@Rx

The gap between ideal performance and the simulation one is around 0.2 dB.

The gap between ideal performance and the simulation one is around 0.5 dB, which is a little bit more than the gap in QPSK.
Visualization: Array configurations

Uniform Linear  Uniform Rect.  Triangular  Circular  3D/Conformal
Hybrid Beamforming in RF Architecture Layer (Spectrasys)
Beamforming_WideBand_Source

RF BEAMFORMING

MIMO SOURCE

COMBINED TX BEAM PLOT

ANGLE CONTROL

INDIVIDUAL BEAM PLOT

SPECTRUM & EVM
Antenna array in Spectrasys
RF_Link_PhasedArray

- Manually drawn
- “M” stages of “N” parallel paths
- Manually post-processed

- Special “Phased Array” analysis mode
- Drawn once
- Abstracted to handle “M” stages, “N” paths
- Pre-defined common array measurements

Advantages
- Easy to draw
- Topology easy to change
- Fast and “tunable”
  - 100x100 RF array is ~2 seconds
  - Monte Carlo and failure analysis in minute(s)
- Can use X-parameters, measured filters, etc
- Line-up remains compatible with regular Spectrasys
Impairments: Gain & Phase/Delay Quantization
Discrete-valued states limit beam accuracy and sidelobe levels

Floating point weights
Gain=4bits, Phase=3bits
Impairments: Active loading, and Element to Element Coupling

Changes loading, beam pattern

Loaded with 8x8 S-parameters from ADS Momentum
Monte Carlo and Element Failures

Phase Shift Variances

Atten/Gain Variances

Element Failures
5G application: OFDM link, using linear TX beamformer

4-layer MIMO signal, 2 GHz bandwidth at 28.5GHz carrier
5G application: OFDM link, using nonlinear TX beamformer (RF_Link)

Power-handling limitations creating system-level effects
5G application: OFDM link, using nonlinear TX beamformer (RF_Link)

Power-handling limitations creating system-level effects

OK to use measured X-parameters and S-parameters at the “array” level
5G application: ACLR of the “New Radio” (NR)
For a given ACLR level, beamforming enables $+40\text{dBm} P_{out}$ instead of $+22\text{dBm}$

3GPP TSG-RAN WG4
Meeting #80
Gothenburg, Aug, 2016

Document R4-166116
“Consideration on ACLR for 5G NR”
Submitted by CMCC

ftp://ftp.3gpp.org/tsg_ran/WG4_Radio/
........./TSGR4_80/Docs/R4-166116.zip
Verizon 5G Physical Layer Background

Work in Processing

Frame Structure

- Each radio frame is 10ms long
  - consists of 100 slots of 0.1ms long.
  - Consists of 50 subframes of 0.2ms long, which consists of two consecutive slots

- Four subframe types
  - DL control channel is mandatory
  - Four optional associating to four subframe types
    - DL data channel
    - DL data channel and UL control channel
    - UL data channel
    - UL data channel and UL control channel

Subframe type can change on a subframe basis

OFDM  Hybrid Beamforming  Half Duplex TDD

75 kHz Subcarrier Spacing  100 MHz bandwidth

7 OFDM symbols per slot

DL up to 8 streams  UE up to 2 streams (DL and UL)

Beam can change on a OFDM symbol basis

Up to 8 serving cells
Agenda

– Motivation: What are the challenges in 5G simulation?
– Massive MIMO & Beamforming

– Physical Layer
  • Various Waveforms
  • Waveforms Performance

– Channel
### New Waveforms Key Facts

#### Compared to OFDM

<table>
<thead>
<tr>
<th></th>
<th>FBMC</th>
<th>GFDM</th>
<th>UF-OFDM</th>
<th>F-OFDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out of band radiation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BER</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Throughput</td>
<td>✓</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>PAPR</td>
<td>=</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Complexity</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Sensitivity to time/freq offsets</td>
<td>✓</td>
<td>✓</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>

- ✓ Better than OFDM
- ✗ Worse than OFDM
- = Same as OFDM
OFDM vs. FBMC (Filter Bank Multi-Carrier)
Simulation Example for FBMC Systems

Simulation parameters

**Parameters Table**

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SignalPower</td>
<td>Signal power of FBMC signal</td>
<td>0.1 W</td>
<td></td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
<td>20 (1)</td>
<td></td>
</tr>
<tr>
<td>SampleRate</td>
<td>Basic sample rate without oversampling</td>
<td>192 (1) Hz</td>
<td></td>
</tr>
<tr>
<td>OverSampleRatio</td>
<td>Over sampling ratio</td>
<td>1 (1)</td>
<td></td>
</tr>
<tr>
<td>BitInterval</td>
<td>Bit time at the beginning of each frame</td>
<td>0 (s)</td>
<td></td>
</tr>
<tr>
<td>NumFrameLengths</td>
<td>Number of preamble symbols in one frame</td>
<td>6 (1)</td>
<td></td>
</tr>
<tr>
<td>NumDataLengths</td>
<td>Number of data symbols in one frame</td>
<td>20 (1)</td>
<td></td>
</tr>
<tr>
<td>NumSubCarriers</td>
<td>Number of total subcarriers in one symbol</td>
<td>120 (1)</td>
<td></td>
</tr>
<tr>
<td>ActiveSubCarriers</td>
<td>Allocation of active subcarriers</td>
<td>[0-64(64)]</td>
<td></td>
</tr>
<tr>
<td>Modifiable</td>
<td>Whether plot is inserted into data points</td>
<td>1 (YES)</td>
<td></td>
</tr>
<tr>
<td>ModSequence</td>
<td>Modulation data sequence</td>
<td>[1, 1, 1, 1, 1, 1, 1]</td>
<td></td>
</tr>
<tr>
<td>ModIndex</td>
<td>Subcarrier index associated to plot</td>
<td>[44(44)]</td>
<td></td>
</tr>
<tr>
<td>FilterOverlapFactor</td>
<td>Filter overlap factor</td>
<td>4 (1)</td>
<td></td>
</tr>
<tr>
<td>FilterCoeff</td>
<td>Filter Coefficient</td>
<td>[1, -0.795, 0.5, 0.2]</td>
<td></td>
</tr>
<tr>
<td>FiltBandStructure</td>
<td>Filter band structure</td>
<td>Extended FFT</td>
<td></td>
</tr>
<tr>
<td>ZC_RootIndex1</td>
<td>Root index of ZC sequence 1 in preamble</td>
<td>7 (1)</td>
<td></td>
</tr>
<tr>
<td>ZC_RootIndex2</td>
<td>Root index of ZC sequence 2 in preamble</td>
<td>3 (1)</td>
<td></td>
</tr>
<tr>
<td>ModulationType</td>
<td>Modulation type</td>
<td>QPSK (1)</td>
<td></td>
</tr>
<tr>
<td>NumPream</td>
<td>Number of frames for simulation</td>
<td>10000(1)</td>
<td></td>
</tr>
<tr>
<td>ChannelEnable</td>
<td>Channel enable</td>
<td>Fading Channel</td>
<td></td>
</tr>
<tr>
<td>TimeInterval</td>
<td>Time interval of the largest nullpath</td>
<td>2x10^-3 s</td>
<td></td>
</tr>
</tbody>
</table>
SystemVue UF-OFDM reference transmitter

UF_OFDM Source

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaseSampleRate</td>
<td>Basic sample rate without oversampling</td>
<td>10e-8</td>
</tr>
<tr>
<td>OversampleOption</td>
<td>Over sampling option</td>
<td>0:Ratio 1</td>
</tr>
<tr>
<td>NumSubcarriers</td>
<td>Number of total subcarriers in one symbol</td>
<td>125</td>
</tr>
<tr>
<td>NumSubbands</td>
<td>Number of total subbands</td>
<td>1</td>
</tr>
<tr>
<td>NumSubcarriersPerSub</td>
<td>Number of total subcarriers in one subband</td>
<td>6</td>
</tr>
<tr>
<td>SubbandStartLocation</td>
<td>The location index of first active subcarrier in a</td>
<td>[-6]</td>
</tr>
<tr>
<td>PilotsEnable</td>
<td>Pilots enable or not</td>
<td>0: NO</td>
</tr>
<tr>
<td>PilotsLocation</td>
<td>Relative location index of pilots inside each sub</td>
<td>0.5</td>
</tr>
<tr>
<td>PilotsSeq</td>
<td>Pilots value sequence</td>
<td>[-1,-1]</td>
</tr>
<tr>
<td>FilterLength</td>
<td>Length of filter for each subband</td>
<td>16</td>
</tr>
<tr>
<td>FilterCoeff</td>
<td>Coefficients of filter for each subband</td>
<td>[0.1135,0.1964,0.3319,]</td>
</tr>
<tr>
<td>AddCP</td>
<td>Add cycle prefix or not</td>
<td>0: NO</td>
</tr>
<tr>
<td>CP_NumSymbols</td>
<td>Number of symbols without oversampling in cy</td>
<td>15</td>
</tr>
<tr>
<td>CompensateFilterResp</td>
<td>Compensate filter response in active subcarrier</td>
<td>0: NO</td>
</tr>
</tbody>
</table>
Simulation Example for F-OFDM Systems
Waveform Performance Comparison

FBMC using different filter overlap factor $K = 3, 4$

UF-OFDM using Dolph-Chebyshev filter with side lobe level $-40\text{dB}, -120\text{dB}$

GFDM using RRC filter with/without cyclic prefix
Waveform Performance Comparison

102MHz@6GHz, AWGN channel

- **Uncoded BER**
  - CP-OFDM: no HW impair
  - F-OFDM: no HW impair
  - FBMC: no HW impair
  - UF-OFDM: no HW impair
  - CP-OFDM: PN
  - F-OFDM: PN
  - FBMC: PN
  - UF-OFDM: PN
  - CP-OFDM: PN + nonlinear PA
  - F-OFDM: PN + nonlinear PA
  - FBMC: PN + nonlinear PA
  - UF-OFDM: PN + nonlinear PA

- **EVM (dB)**
  - With phase noise and nonlinear PA
  - With low phase noise

- **SNR (dB)**
  - 10, 12, 14, 16, 18, 20, 22

- **EVM (dB)**
  - -22, -20, -18, -16, -14, -12, -10, -8, -6, -4

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– Motivation: What are the challenges in 5G simulation?
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– Channel
– Performance & Implementation
Channel Model in Communications Theory

• Traditional multipath fading channel is modeled as a linear finite impulse-response (FIR) filter

\[ y_i = \sum_{n=N_1}^{N_2} x_{i-n} g_n \]

• But, real channel is much more complex to represent

• Need to consider four different domains
4 categories of Channel Model parameters

- Mean excess delay ($\tau$)
- RMS delay spread ($\sigma_r$)
- Noise threshold
- Excess delay (ns)

[ Power Delay Profile ]

- Delay spread
  - Frequency selectivity
  - Coherence bandwidth
- Doppler spread
  - Time selectivity
  - Coherence time

[ Spreading in Multi-Domain]

- Angular spread
  - Spatial selectivity
  - Coherence distance
  - MIMO/BF
  - Scheduling

[ Angular Spread ]

Per path angular spread

* Tx antenna element $s$ to Rx element $u$ for cluster $n$

Antenna field patterns

$$H_{s,u}(t) = \sqrt{P_s/M} \sum_{n=0}^{M-1} \left( \frac{F_{s,t,0} \phi_{t,u,0,0,0}}{F_{s,t,0} \phi_{t,u,0,0,0}} \right) \left[ \exp(j2\pi \theta_{t,u,0,0,0}) \right]$$

Polarization matrix

$$\begin{bmatrix} \exp(j\Phi_{t,u,0,0,0}) \\ \exp(j\Phi_{t,u,0,0,0}) \end{bmatrix}$$

[ Channel Matrix]

Doppler term

$$\begin{bmatrix} \exp(j2\pi \lambda \phi_{t,u,0,0,0}) \\ \exp(j2\pi \lambda \phi_{t,u,0,0,0}) \end{bmatrix}$$

Polarization matrix

$$\begin{bmatrix} \exp(j\Phi_{t,u,0,0,0}) \\ \exp(j\Phi_{t,u,0,0,0}) \end{bmatrix}$$

[ Channel Matrix]

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Channel Research Work Flow

Reference transmit signal (chirp/pn)

\[ t[k] \]

\[ z[k] \]

Channel sounding

Channel impulse response

\[ H[z] \]

Correlation

Channel sounding

Estimation algorithms

Channel parameters

Parameters estimation

Statistics & modeling

- Scenario selection
- Network layout
- Antenna parameters
- 3GPP model
- NYU model

Large/Small scale parameters generation

Fading coefficient generation

SystemVue Simulation

Input signal

\[ x[k] \]

Faded signal

\[ y[k] \]

Realistic antenna branch signals

Far field data

SystemVue Simulation

Array antenna design

Antenna mutual coupling changes
- The input impedance
- And distorts the radiation pattern

Far field data generation

Implicitly include
- Antenna radiation efficiency
- Loading of the antenna ports

EMPro/HFSS Antenna Design

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5G Channel Sounding in SystemVue

- Support 1x1 up to 8x8 antennas
- Support System Response Calibration
- Output CIR, PDP
- Output Path Delay
- Output Path Loss
- Output AoA, AoD
- Output Doppler Frequency
Simulation Example for MIMO Channel Sounding
Modify LTE-A PHY, Use Custom Channel Model

H matrix from external channel modeling software

Modification to support mmWave frequency band

[MIMO_FastFadingEngine@5G Advanced Modern Models]

[MIMO_3DChannel@5G Advanced Modern Models]
Throughput Analysis

System Parameters

- $F_c = 3.5$ GHz
- Modulation: 64QAM
- Downlink FDD mode
- Closed loop HARQ enable
- 8x8 MIMO (Spatial Multiplexing, 2 Codewords and 8 Layers)
- Channel model: Custom-XX channel
- Antenna pattern type: Omni directional
- # path: 12
- Interpolation algorithm for channel estimation: Linear/MMSE
3GPP New Channel Model (3GPP TR 38.900 V14.0.0)

Working in Processing

– Primary Design objectives

• Support frequency range above 6GHz up to 100 GHz
• Support large channel bandwidths (up to 10% of carrier frequency)
• Take care of mmW propagation aspects such as blocking and atmosphere attenuation
• Be consistent in space, time and frequency
• Cover a range of coupling loss considering current typical cell sizes
• Mobile speed up to 500 km/h
• Support large antenna arrays
Thanks