What’s Behind 5G Wireless Communications?

Tabrez Khan
Application Engineering Group
Agenda

- 5G goals and requirements
  - Modeling and simulating key 5G technologies
- 5G development workflow
- Learn more…
Timeline of 5G standardization

- 3GPP releases

  1. First release of 5G specification: **Sep 2018/Release 15**
5G Applications and Requirements

New Applications
4K, 8K, 360° Video
Virtual Reality
Connected Vehicles
Internet of Things

5G Requirements / Use Cases
Enhanced mobile broadband (>10 Gbps)
Ultra reliable & low latency (<1 ms)
Massive machine-type communication (>1e5 devices)
Achieving Higher 5G Broadband Data Rates

Technical Solutions

- Increased bandwidth
- Better spectral efficiency
- Flexible air interface
- Densification

Higher Frequency Bands

New Physical Layer

New RF Architectures

Massive MIMO

Massive MIMO antenna array for a Huawei 5G field trial.
Multi-Domain Engineering for 5G
Subsystems must be designed and tested together

- Standard-compliant Waveforms
- Baseband DSP for Large Bandwidths
- Channel and Interference

- Baseband waveform
- Baseband precoding
- DAC RF
- N_T
- Digital or Hybrid Beamforming
- MIMO Antenna Array Design
- RF Transceivers and Power Amplifiers
- RF ADC
- N_R

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Waveform Generation

- Test with standard-compliant waveforms
- Generate all physical channels and signals
- Off-the-shelf and full custom waveforms

**5G**

**LTE**

**3GPP**

- ✓ LTE & LTE-Advanced
- ✓ NB-IoT
- ✓ D2D Sidelink
- ✓ V2X Sidelink
- ✓ 5G New Radio

**IEEE 802.11**

- ✓ 802.11ax
- ✓ 802.11ad
- ✓ 802.11ah
- ✓ 802.11ac
- ✓ 802.11a/b/g/n
- ✓ 802.11p/j

**WLAN**

**Standard compliance**

- WLAN
- 3GPP
- LTE & LTE-Advanced
- NB-IoT
- D2D Sidelink
- V2X Sidelink
- 5G New Radio
What’s LTE System Toolbox?

- Over 230 functions for physical layer (PHY) modeling
- LTE, LTE-Advanced, LTE-Advanced Pro (Rel-8 through Rel-14)
- Scope
  - FDD/TDD
  - Uplink/Downlink/Sidelink
  - Transmitter/Receiver

New in R2017b:
- V2X
- NB-IoT
Use Cases

Signal Generation
- RMC, E-TMs

Signal Detection
- eNodeB
- MATLAB: PDCCH search for SI-RNTI...
  Decoding SIB1...
  SIB1 CRC: 0
  Successful SIB1 recovery.

HW & Radio Connectivity
- RF Signal Generator
- Zynq SDR

End-to-End Simulations
- EVM

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Signal Generation and Analysis
Reference Measurement Channels

Standard-compliant signal available in the MATLAB workspace

TS 36.101

>> lteRMCDLTool
Demo: Equalizing the Downlink Grid

Transmitter
- Test Waveform Generation

Channel
- Fading Channel

Receiver
- Synchronisation & OFDM Demodulation
- Channel Estimation & Equalisation

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## LTE System Toolbox Examples

### On this page...
- Downlink LTE Modeling
- Uplink LTE Modeling
- Downlink End to End Simulation
- Uplink End to End Simulation
- Downlink Waveform Generation and Analysis
- Uplink Waveform Generation and Analysis

### Downlink LTE Modeling

- LTE Waveform Modeling Using Downlink Transport and Physical Channels
- PDSCH Transmit Diversity Throughput Simulation
- Release 10 PDSCH Enhanced UE-Specific Beamforming

### Functions in LTE System Toolbox

#### LTE Modeling Basics

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lteResourceGrid</td>
<td>Subframe resource array</td>
</tr>
<tr>
<td>lteResourceGridSize</td>
<td>Size of subframe resource array</td>
</tr>
<tr>
<td>lteDLResourceGrid</td>
<td>Downlink subframe resource array</td>
</tr>
<tr>
<td>lteDLResourceGridSize</td>
<td>Size of downlink subframe resource array</td>
</tr>
<tr>
<td>lteULResourceGrid</td>
<td>Uplink subframe resource array</td>
</tr>
<tr>
<td>lteULResourceGridSize</td>
<td>Size of uplink subframe resource array</td>
</tr>
<tr>
<td>lteDuplexingInfo</td>
<td>Duplexing information</td>
</tr>
</tbody>
</table>

#### Downlink Channels

**Physical Signals**

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ltePSS</td>
<td>Primary synchronization signal</td>
</tr>
<tr>
<td>ltePSSIndices</td>
<td>PSS resource element indices</td>
</tr>
<tr>
<td>lteSSS</td>
<td>Secondary synchronization signal</td>
</tr>
<tr>
<td>lteSSSIndices</td>
<td>SSS resource element indices</td>
</tr>
<tr>
<td>lteCellRS</td>
<td>Cell-specific reference signal</td>
</tr>
<tr>
<td>lteCellRSIndices</td>
<td>CRS resource element indices</td>
</tr>
</tbody>
</table>
5G New Radio and the 5G Library
LTE System Toolbox & 5G Library

- The 5G Library is a free downloadable Add-On for LTE System Toolbox
- It builds on the infrastructure of LTE System Toolbox
- It is based on the January 2018 version of the 38.2xx documents

Download the 5G Library
New Radio (NR) 5G Testbench
New Physical Layer in Release 15

- Enhanced Mobile Broadband (eMBB):
  - Larger bandwidth
  - Greater spectral efficiency

- PHY techniques used to achieve goals
  - Flexible frame structure and carrier spacing
    - Shorter latency
    - Variable bandwidth
  - Higher capacity coding schemes
  - Channel models: sub-6GHz to mmWave

5G Baseband Processing
- Increased bandwidth
- Greater spectral efficiency
Baseband DSP for Large Bandwidths

- 5G waveform same as LTE: Cyclic-Prefix OFDM (CP-OFDM)
- New baseband techniques for higher capacity

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>Subcarrier Spacing $\Delta f = 2^\mu \times 15$kHz</th>
<th>Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>49.50</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>198</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>396</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>397.44</td>
</tr>
<tr>
<td>5</td>
<td>480</td>
<td>397.44</td>
</tr>
</tbody>
</table>

Increase bandwidth and reduce latency with flexible subcarrier spacing

Reduce spectral leakage with filtering or windowing

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Efficient Channel Coding Methods

- Low-Density Parity Check (LDPC) for data channel: memoryless block coding

- Polar Codes for control channel: achieve channel capacity
Model Channel and Interference

- **Interference**
  - Multiple standards: 5G/LTE/WLAN

- **3D propagation channels**
  - 5G, LTE, 802.11, Scattering MIMO, Custom

- **Visualize propagation on maps**
  - Rx/Tx location
  - Signal strength and coverage
  - Signal-to-interference-plus-noise (SINR)

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5G Channel Model

- 3GPP TR 38.901: 500 MHz - 100 GHz (mmWave)
- For massive MIMO arrays (>1024 elements)
- Delay profiles:
  - Control delay line (CDL): Full 3D model
  - Tapped delay line (TDL): Simplified for faster simulation
- Control key parameters
  - Channel delay spread
  - Doppler shift
  - MIMO correlation

Cluster Delay Line: 3D model
5G Link Level Simulation

- End-to-end physical layer reference model
- Verify implementation
- Evaluate impact of algorithm designs on link performance
RF Power Amplifier (PA) Linearization

- 5G frequencies and bandwidth put greater requirements on RF transmitter efficiency

- 5G PA’s are difficult to model
  - Non-linearity
  - Memory effects

- Solution: Linearization using adaptive digital pre-distortion (DPD)

RF challenges in 5G
- Frequency dependent behavior
- Highly integrated RF + digital devices

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Characterize PA Model Using Measured Data

PA Data

MATLAB fitting procedure (White box)

MATLAB PA model

PA model for circuit envelope simulation
PA + DPD Simulation

- Circuit Envelope for fast RF simulation
- Low-power RF and analog components
  - Up-conversion / down-conversion
  - Antenna load
- Digital signal processing algorithm: DPD
Massive MIMO Antenna Arrays

- Model antenna and array beam patterns
- Model antenna element failures
- Optimize tradeoffs between antenna gain and channel capacity
- Simulate with 3D channel model
Call to Action

Designing and Integrating Antenna Arrays with Multi-Function Radar Systems
15:30 – 16:15

In this talk, you will learn how to model antenna and antenna arrays and integrate them with multi-function radar systems. Topics covered include:

- Analyzing the performance of custom printed antennas and fabricating them using Gerber files
- Performing array analysis by computing coupling among antenna elements
- Integrating antenna models with the rest of the system
- Modeling and simulating multi-functional capabilities of radars

Shashank Kulkarni, Ph.D., Principal Developer, MathWorks India
Swathi Balki, Pilot Engineer, MathWorks India
Hybrid Beamforming for Massive MIMO

- Beamforming implemented part in the digital and part in the RF domain
  - Trade-off performance, power dissipation, implementation complexity
- Subarrays contain RF channels with phase shifter
- Digital beamforming performed on signals outside subarrays

Why Hybrid Beamforming?
- Massive MIMO reduces mmWave propagation loss
- Hybrid beamforming reduces implementation cost
V2X: Building the Connected Car Highway

Standards for V2X
- 5G: Reserved for future release
- Cellular V2X (C-V2X)
  - Release 14 LTE V2X Sidelink
  - LTE System Toolbox
- DSRC
  - IEEE 802.11p
  - WLAN System Toolbox

PHY Waveform Generation

Throughput Simulation

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Future 5G Use Case: IoT Connectivity

- IoT use case reserved for future 5G release

- Cellular long-range standard: LTE NB-IoT
  - Compatible with LTE networks
  - Lower cost and power, extended range

- NB-IoT cost and power reduction techniques
  - Reduced peak rate and bandwidth (180 kHz)
  - Reduced maximum transmit power
  - Single antenna
  - No higher-order modulation (BPSK and QPSK)
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From idea …

… to implementation
Customer Perspective

“We need a multidomain platform for simulation, rapid prototyping, and iterative verification from the behavior model to testbed prototyping to the industrial product. MATLAB and Simulink are helping us to achieve these goals.”

- Kevin Law, director of algorithm architecture and design, Huawei

Can you tell us more about how MATLAB and Simulink are helping you?

These two platforms play an important role in our innovation areas like 5G, optical communication, and wireless terminals. The tools give us top-down Model-Based Design, a product ecosystem that covers multiple domains, and code generation and iterative verification.

https://www.mathworks.com/content/dam/mathworks/tag-team/Objects/h/80861v00_Huawei_QA.pdf
MATLAB & Simulink Wireless Design Environment
for baseband, RF, and antenna modeling and simulation

### Algorithms, Waveforms, Measurements
- Communications System Toolbox
- LTE System Toolbox (5G Library)
- WLAN System Toolbox

### RF Front End
- RF Toolbox
- RF Blockset

### Antennas, Beamforming
- Antenna Toolbox
- Phased Array System Toolbox

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**Baseband Digital Front End**
- DAC
- PA
- LNA

**Digital PHY**
- Receiver
- Transmitter

**RF Front End**
- ADC

**Antenna**
- Channel

**Mixed-signal**
- Simulink
- DSP System Toolbox
- Control System Toolbox

**Channel and Propagation**
- Communications System Toolbox
- Antenna Toolbox
- LTE System Toolbox
- WLAN System Toolbox

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Over-the-Air Testing with SDR and RF Instruments

Over-the-air Testing
Instrument Control Toolbox
SDR Support Packages
Communications System Toolbox
Accelerate Simulations with Scalable Computing

Cluster

Cloud

MATLAB Distributed Computing Server

Multi-Core GPU

Parallel Computing Toolbox

MATLAB
Common Platform for Wireless Development

➢ Algorithm Design and Verification
➢ RF, Digital and Antenna Co-Design
➢ System Verification and Testing
➢ Rapid Prototyping and Production

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Resources to Help You Get Started

Conformance Testing
Ensure your designs comply with the supported 3GPP LTE standard releases.
» Learn more

5G Library
Simulate 3GPP 5G new radio technologies.
» Learn more

Power Amplifier Characterization with DPD for Reduced Signal
Provides a methodology for characterizing a nonlinear RF Blockset™ power amplifier (PA) with memory and an adaptive DPD

Visualizing RF Budget Analysis Over Bandwidth
Programmatically perform an RF budget analysis of an RF receiver system and visualize computed budget results across the bandwidth

Improve SNR and Capacity of Wireless Communication Using...
The goal of a wireless communication system is to serve as many users with the highest possible data rate given constraints
Open Script

Introduction to Hybrid Beamforming
Introduces the basic concept of hybrid beamforming and shows how to simulate such a system.
Open Script

Massive MIMO Hybrid Beamforming
How hybrid beamforming is employed at the transmit and of a massive MIMO communications system, using techniques for both

SINR Map for a 5G Urban Macro-Cell Test Environment
This example shows how to construct a 5G urban macro-cell test environment and visualize the signal-to-interference-plus-noise
Call to Action

View web resources
Wireless Communications Design with MATLAB
MATLAB and Simulink for 5G Technology Development

Read eBook and white papers
5G Development with MATLAB (eBook)
Hybrid Beamforming for Massive MIMO Phased Array Systems (white paper)
Four Steps to Building Smarter RF Systems with MATLAB (white paper)
Evaluating 5G Waveforms Over 3D Propagation Channels with the 5G Library (white paper)

Download software
Wireless communications trial package
Download the 5G Library

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- Parallel Computing with MATLAB
- Programming Xilinx Zynq SoCs with MATLAB and Simulink

www.mathworks.in/training
**Updated: Communication Systems Design with MATLAB**

- Advanced communications topics
  - MIMO / OFDM
  - LDPC / Turbo Codes / OSTBCs
  - Examples using IEEE 802.11 (Wi-Fi) & LTE-based system and waveform parameters

- New hands-on content using Software Defined Radios
  - Radio-in-the-loop using RTL-SDR and USRP B210
  - Build end-to-end OFDM system using a USRP
  - Demonstrate a 2x2 OFDM-MIMO over-the-air system using USRPs
Designing LTE and LTE Advanced Physical Layer Systems with MATLAB

Topics include:

- Review of the advanced communications techniques forming the core of an LTE system: OFDMA and SC-FDMA multi-carrier techniques, and MIMO multi-antenna systems
- Descriptions of all of the signals and elements of the processing chain for the uplink and downlink LTE physical channels
- Methods for golden reference verification with the standard
Phased Array System Toolbox Fundamentals

This one-day course provides a comprehensive introduction to the Phased Array System Toolbox™. Themes including radar characterization and analysis, radar design and modeling and radar signal processing are explored throughout the course.

Topics include:

- Review of a Monostatic End-to-End Radar Model
- Characterize and analyze radar components and systems
- Design and model components of a radar system
- Implement a range of radar signal processing algorithms
MathWorks | Training Services

Modeling RF Systems with RF Blockset

**Topics include:**
- Introduction to RF simulation using MathWorks tools
- How do I model my RF system with RF Blockset?
- Importing S-Parameters and modeling linear operation
- Fundamentals of noise simulation
- Modeling non-linear devices
- Developing custom models

New module:
- Testing and Programming the AD9361 with the RF Blockset Model
New: Software Defined Radio with Zynq using Simulink

- Learn the Model-Based Design workflow from simulation of RF chain, testing with Radio I/O to moving design to chip

- Get hands-on experience with PicoZed
  - Setting up and communicating with board
  - Capture over-the-air signal and process in MATLAB
  - AD9361 configuration
  - HW/SW co-design for SDR
**Share your experience with MATLAB & Simulink on Social Media**

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Thanks for your attention

Questions?