MATLAB EXPO 2018

# What’s Behind 5G Wireless Communications?

Graham Freeland

# Agenda

- 5G goals and requirements

- Modeling and simulating key 5G technologies
  - Release 15: Enhanced Mobile Broadband
  - IoT and V2X

- 5G development workflow

**3GPP Standardization Timeline**

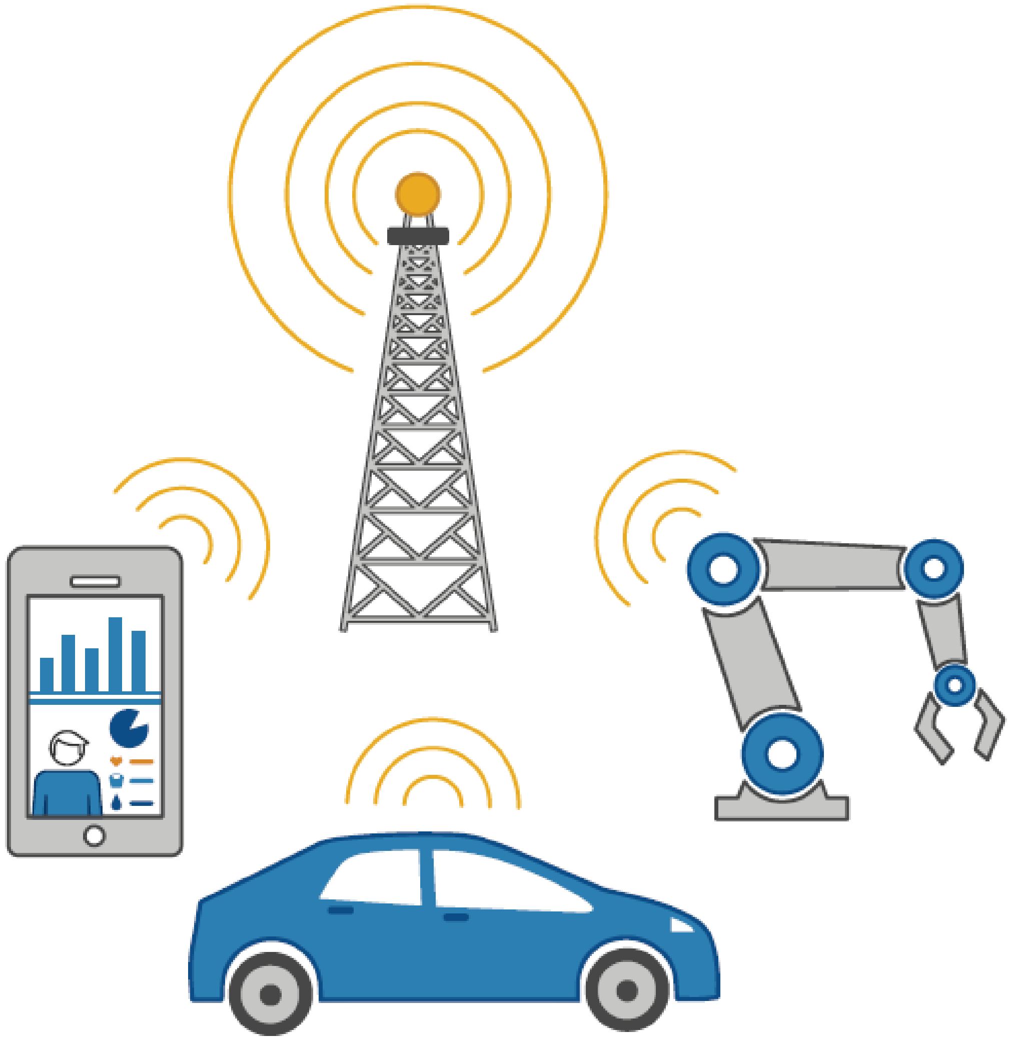

***Jun-18***

**3GPP Release 15**
- **Initial 5G NR specification**

***Dec-2019***

**Release 16**
- **5G Phase 2**

# 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 low latency (<1 ms)

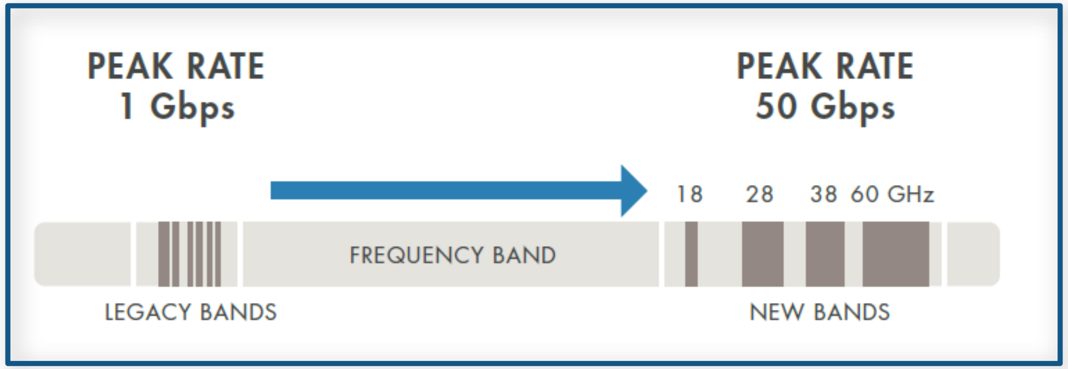
Massive machine-type communication (>1e5 devices)

# Achieving Higher 5G Broadband Data Rates

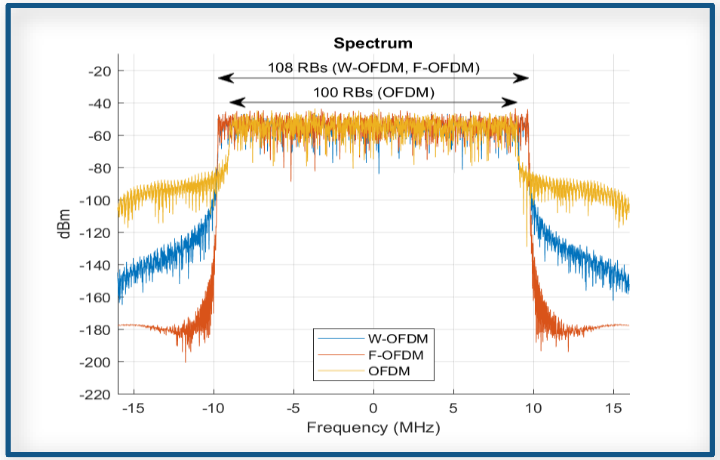
**Technical Solutions**

Increased bandwidth
Better spectral efficiency
Flexible air interface
Densification

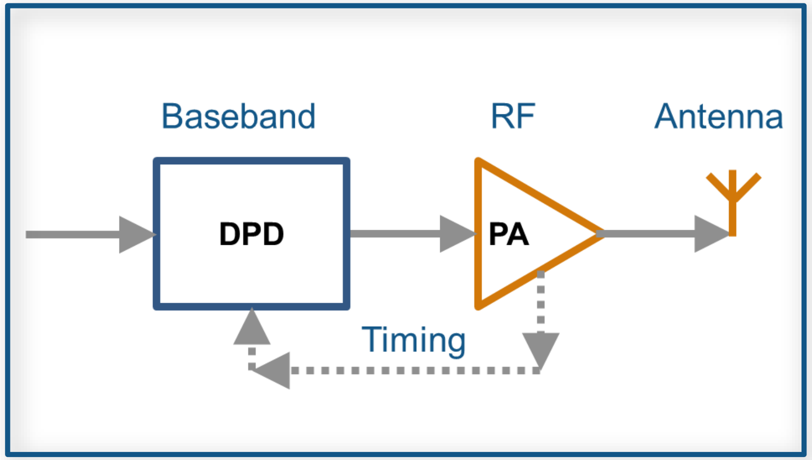
## Higher Frequency Bands




## New Physical Layer




## New RF Architectures

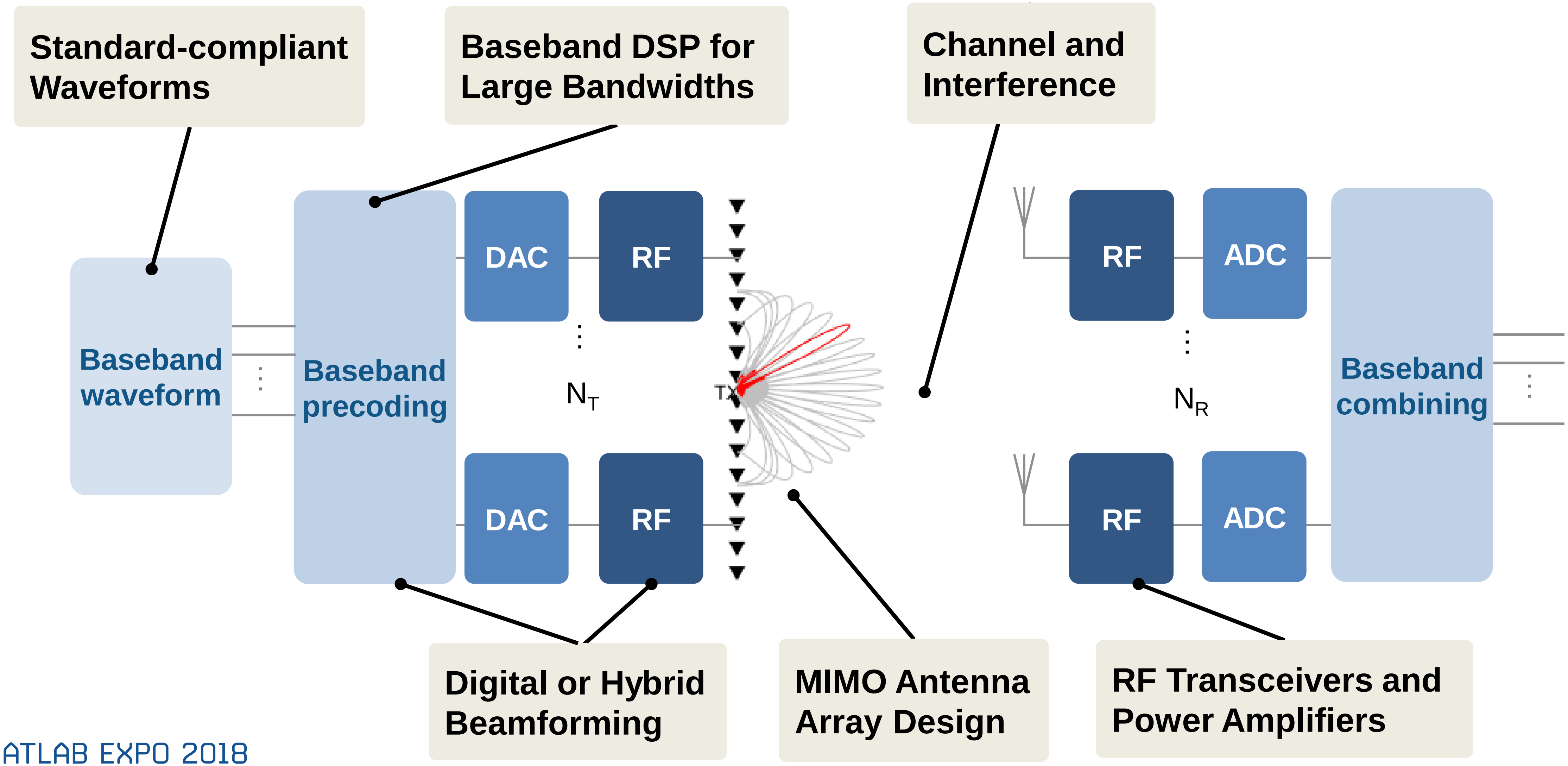



## Massive MIMO

*Massive MIMO antenna array for a Huawei 5G field trial.*

# Multi-Domain Engineering for 5G

## *Subsystems must be designed and tested together*



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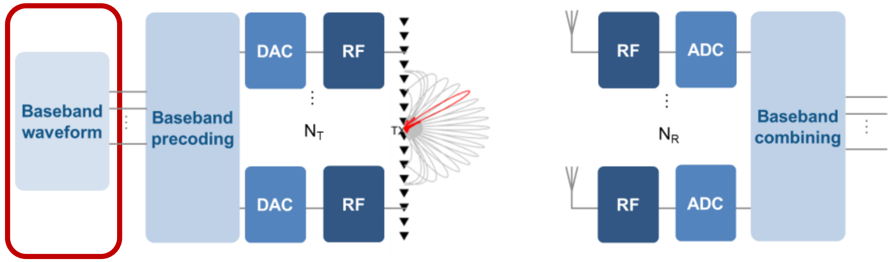
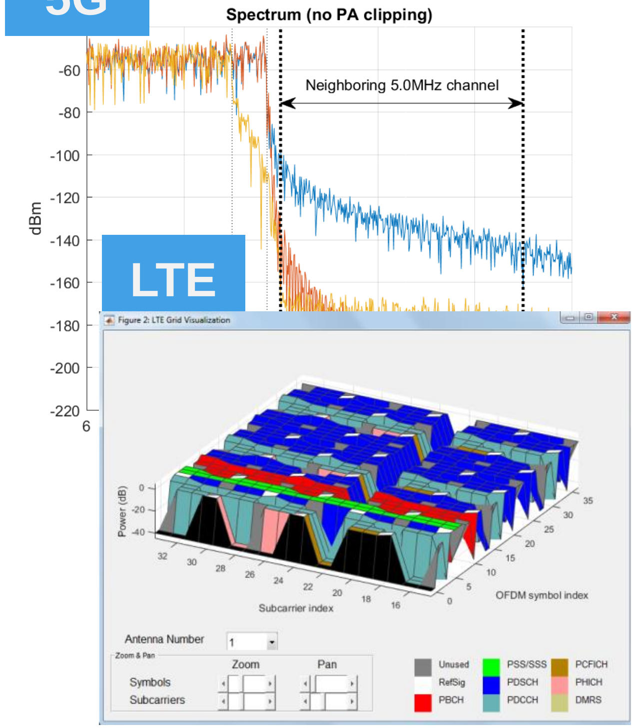
# Waveform Generation

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

## Standard compliance

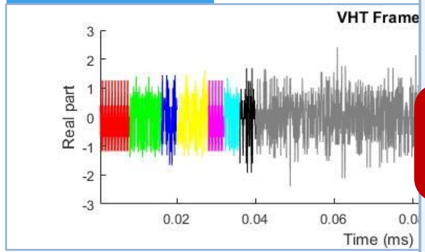



5G




| 3GPP |
|---|
| ✓ LTE & LTE-Advanced |
| ✓ NB-IoT |
| ✓ D2D Sidelink |
| ✓ V2X Sidelink |
| ✓ *5G New Radio* R2018b |

WLAN

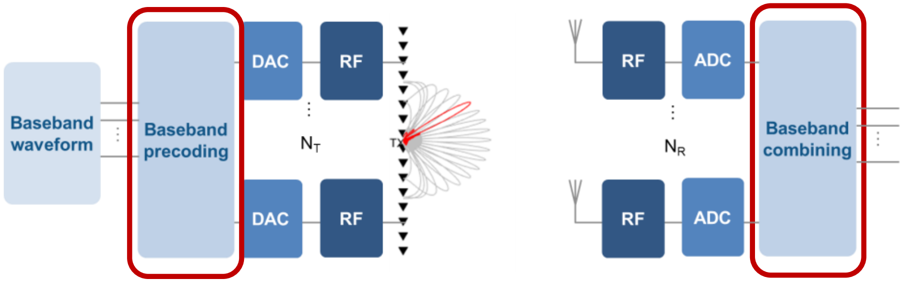



| IEEE 802.11 |
|---|
| ✓ *802.11ax (draft)* |
| ✓ 802.11ad R2018b |
| ✓ 802.11ah |
| ✓ 802.11ac |
| ✓ 802.11a/b/g/n |
| ✓ 802.11p/j |

# New Physical Layer in Release 15

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

**5G Baseband Processing**
- Increased bandwidth
- Greater spectral efficiency




- PHY techniques used to achieve goals
  - Flexible frame structure and carrier spacing
    - Shorter slot durations for lower latency
    - Variable bandwidth
  - Higher capacity coding schemes
  - Spatial channel models: sub-6GHz to mmWave

# Baseband DSP for Large Bandwidths

- 5G waveform same as LTE: Cyclic-Prefix OFDM (CP-OFDM)
- Flexible NR subcarrier spacing and frame numerologies

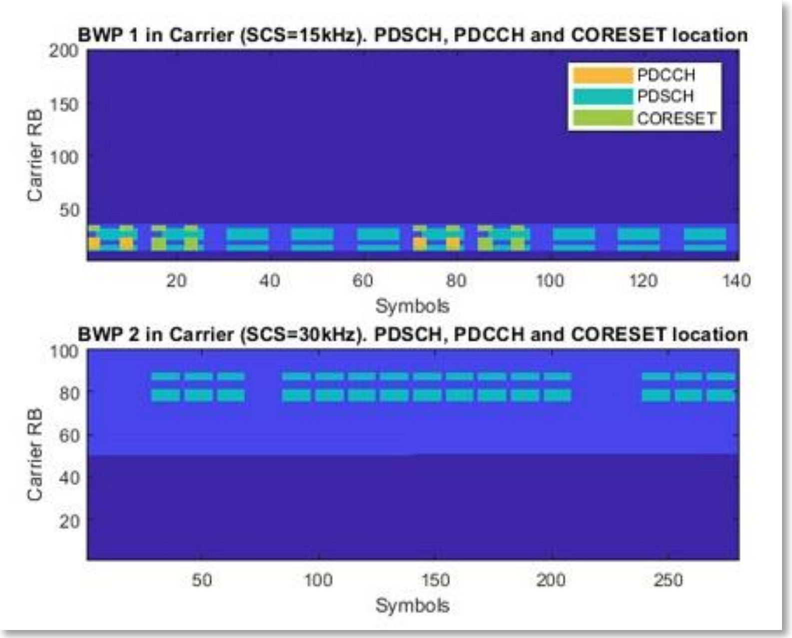
5G Toolbox

NEW PRODUCT

R2018b

| μ | Subcarrier Spacing $\Delta f = 2^{\mu} * 15\text{kHz}$ | Bandwidth (MHz) |
|---|---|---|
| **0** | 15 | 49.50 |
| **1** | 30 | 99 |
| **2** | 60 | 198 |
| **3** | 120 | 396 |
| **4** | 240 | 397.44 |
| **5** | 480 | 397.44 |

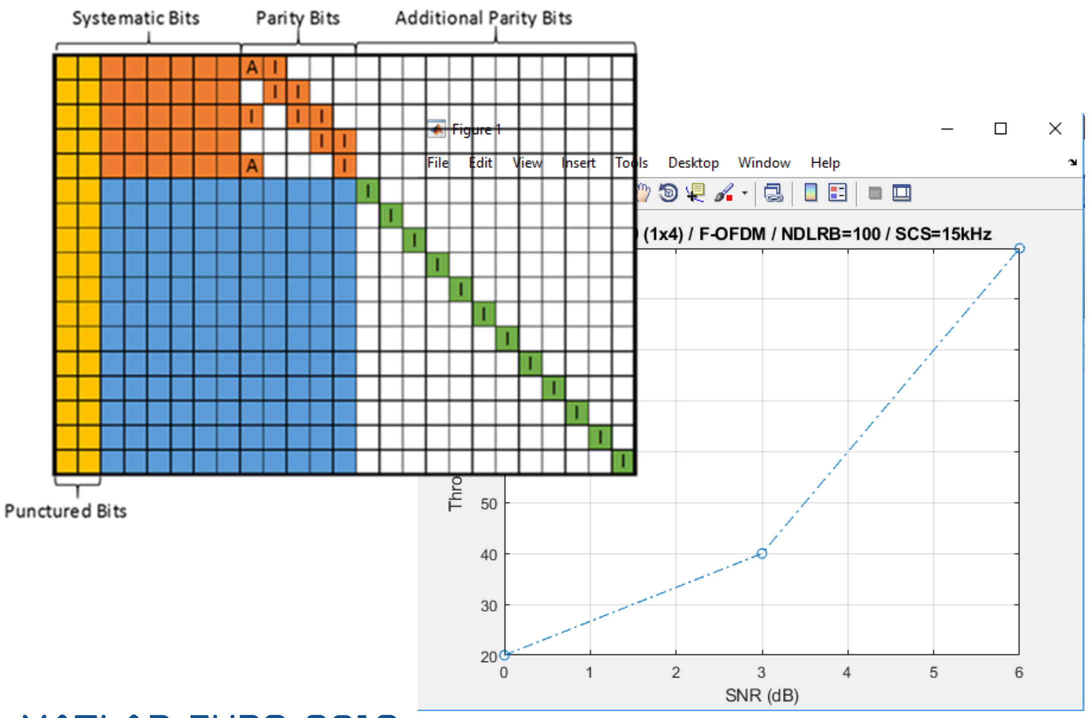
**Flexible bandwidth latency in 5G NR**



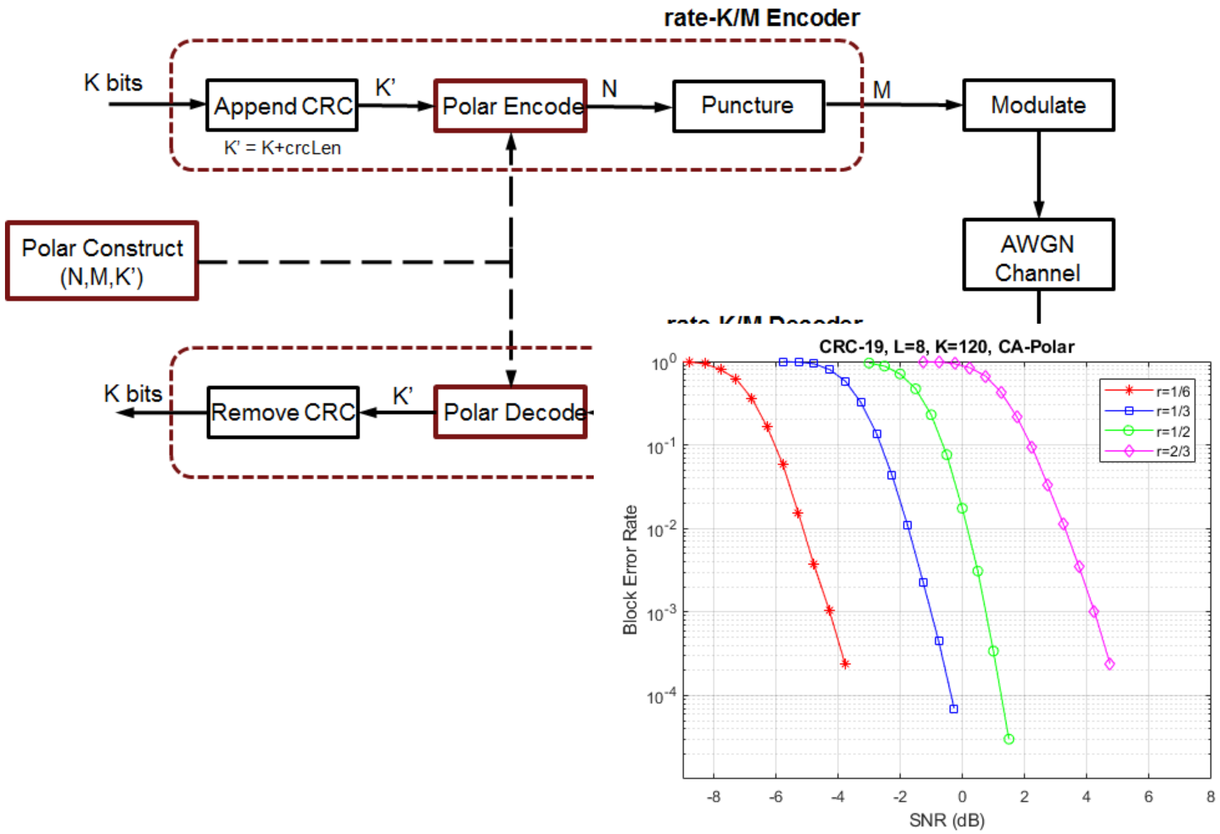

**Downlink waveform generation with carrier bandwidth parts**

# Efficient Channel Coding Methods

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




- Polar Codes for control channel: achieve channel capacity

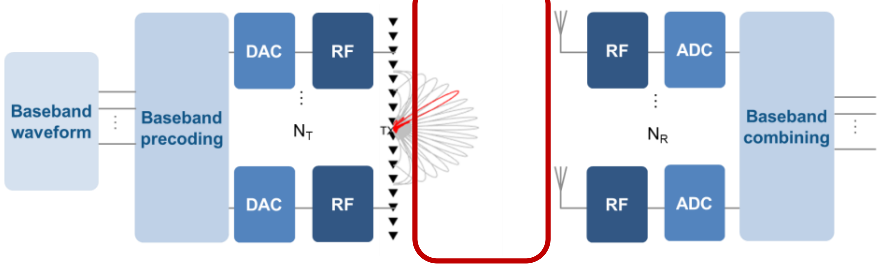


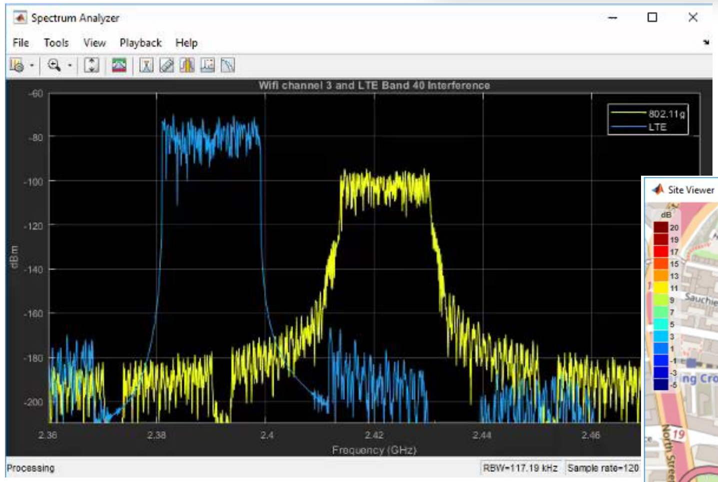
# Model Channel and Interference

- Interference
  - Multiple standards: 5G/LTE/WLAN
- 3D propagation channels
  - 5G, LTE, 802.11, Custom
- Visualize propagation on maps
  - Rx/Tx location
  - Signal strength and coverage
  - Signal-to-interference-plus-noise (SINR)

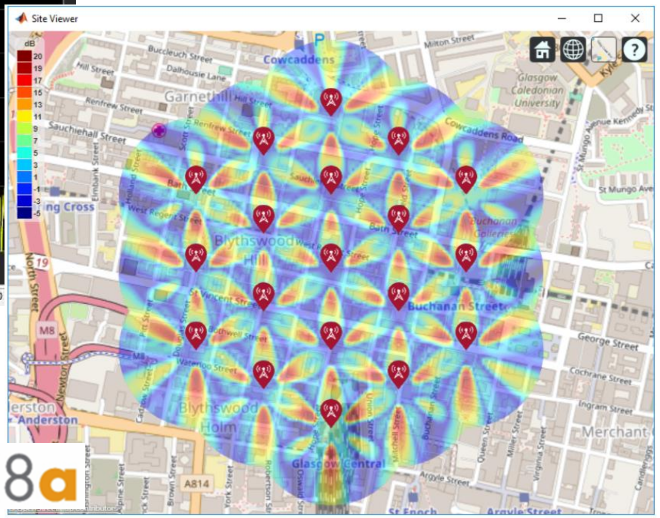
**Channel and Interference**

- Multiple UEs/Base Stations
- Signal propagation




**LTE-WLAN interference**

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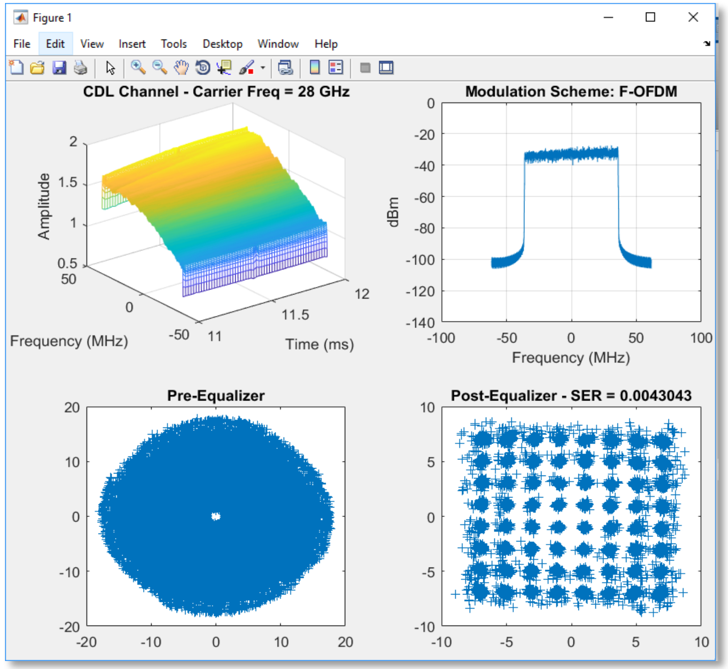
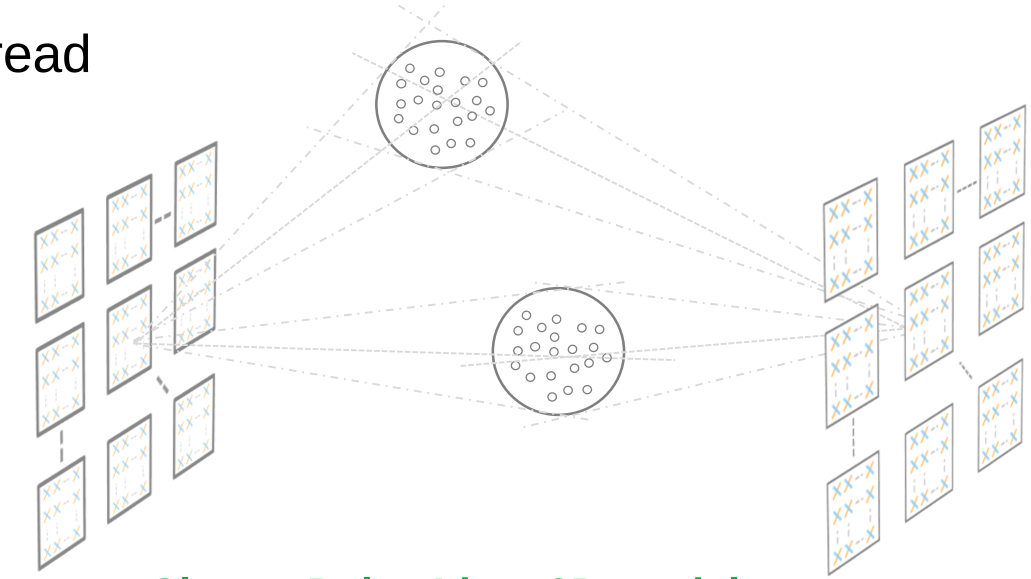
**SINR for 5G urban macro-cell**

# 5G Channel Model

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

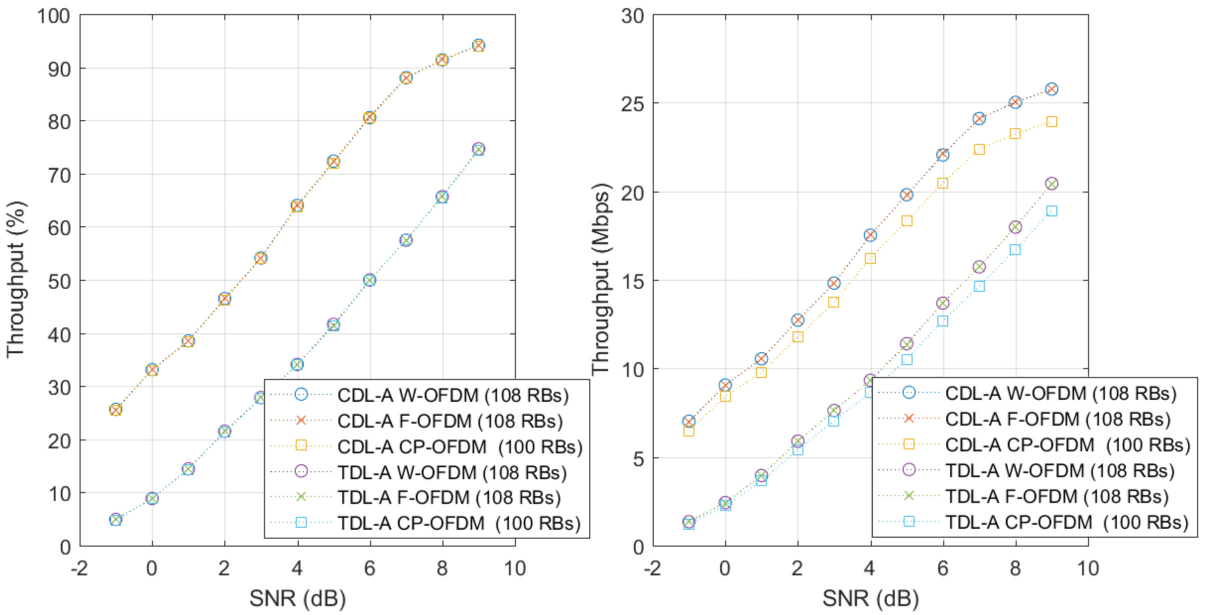


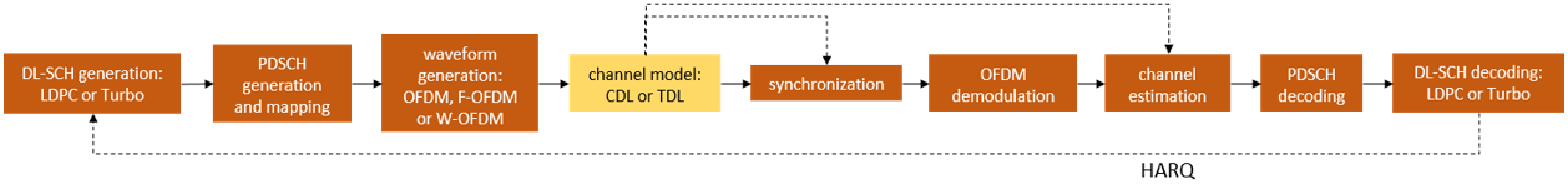



Cluster Delay Line: 3D model

# 5G Link Level Simulation

- End-to-end physical layer reference model
- Verify implementation
- Evaluate impact of algorithm designs on link performance



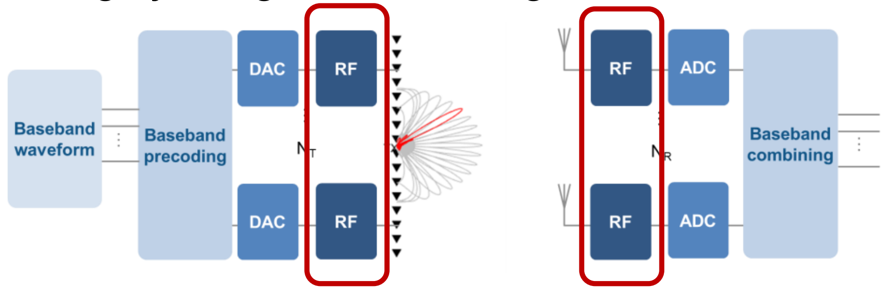



# RF Power Amplifier (PA) Linearization

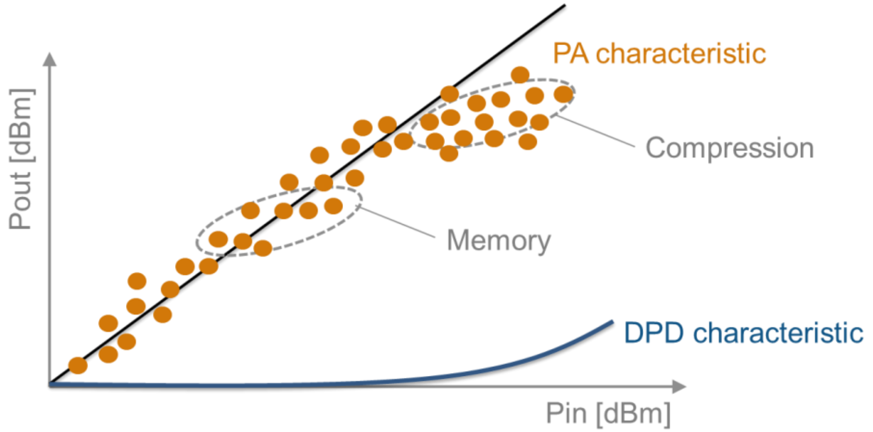
- 5G frequencies and bandwidth put greater requirements on RF transmitter efficiency

**RF challenges in 5G**

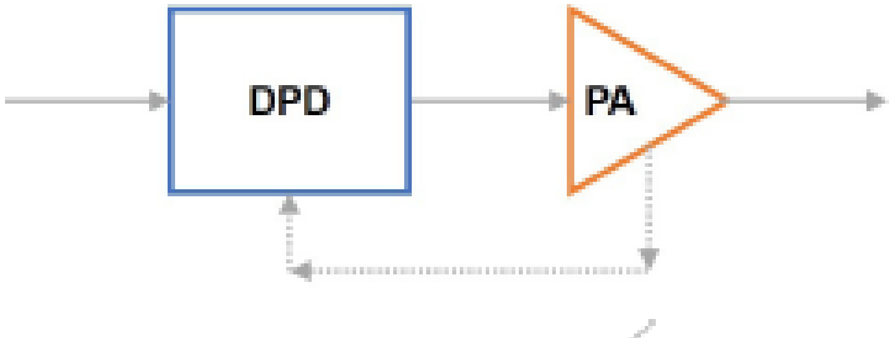
- Frequency dependent behavior
- Highly integrated RF + digital devices




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

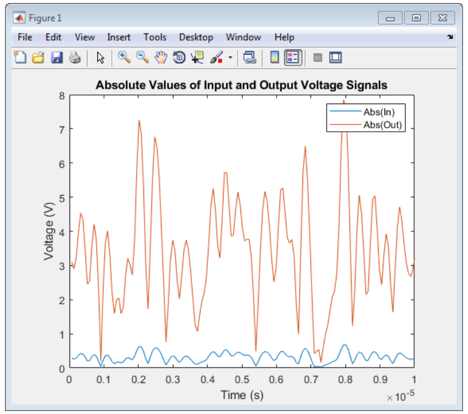



- Solution: Linearization using adaptive digital pre-distortion (DPD)



# Characterize PA Model Using Measured Data

## PA Data




## MATLAB fitting procedure (White box)

```
function a_coef = fit_memory_poly_model(x,y,memLen,degLen,modType)
% FIT_MEMORY_POLY_MODEL
%   Procedure to compute a coefficient matrix given input and output
%   signals, memory length, nonlinearity degree, and model type.
%
%   Copyright 2017 MathWorks, Inc.

x = x(:);
y = y(:);
xLen = length(x);

switch modType
  case 'memPoly'  % Memory polynomial
    xrow = reshape((memLen:-1:1)' + (0:xLen:xLen*(degLen-1)),1,[]);
    xVec = (0:xLen-memLen)' + xrow;
    xPow = x.*(abs(x).^(0:degLen-1));
    xVec = xPow(xVec);
  case 'ctMemPoly'  % Cross-term memory polynomial
    absPow = (abs(x).^(1:degLen-1));
    partTop1 = reshape((memLen:-1:1)'+(0:xLen:xLen*(degLen-2)),1,[]);
    topPlane = reshape(                                              ...
        [ones(xLen-memLen+1,1),absPow((0:xLen-memLen)' + partTop1)].', ...
        1,memLen*(degLen-1)+1,xLen-memLen+1);
    sidePlane = reshape(x((0:xLen-memLen)' + (memLen:-1:1)).',       ...
        memLen,1,xLen-memLen+1);
    cube = sidePlane.*topPlane;
    xVec = reshape(cube,memLen*(memLen*(degLen-1)+1),xLen-memLen+1).';
end

coef = xVec\y(memLen:xLen);
a_coef = reshape(coef,memLen,numel(coef)/memLen);
```

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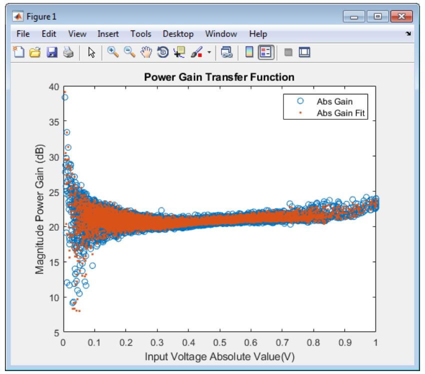
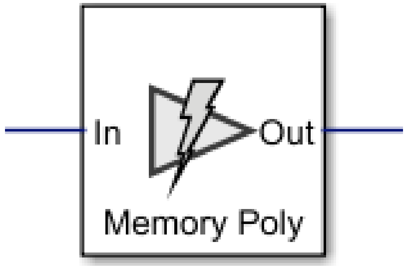
## MATLAB PA model

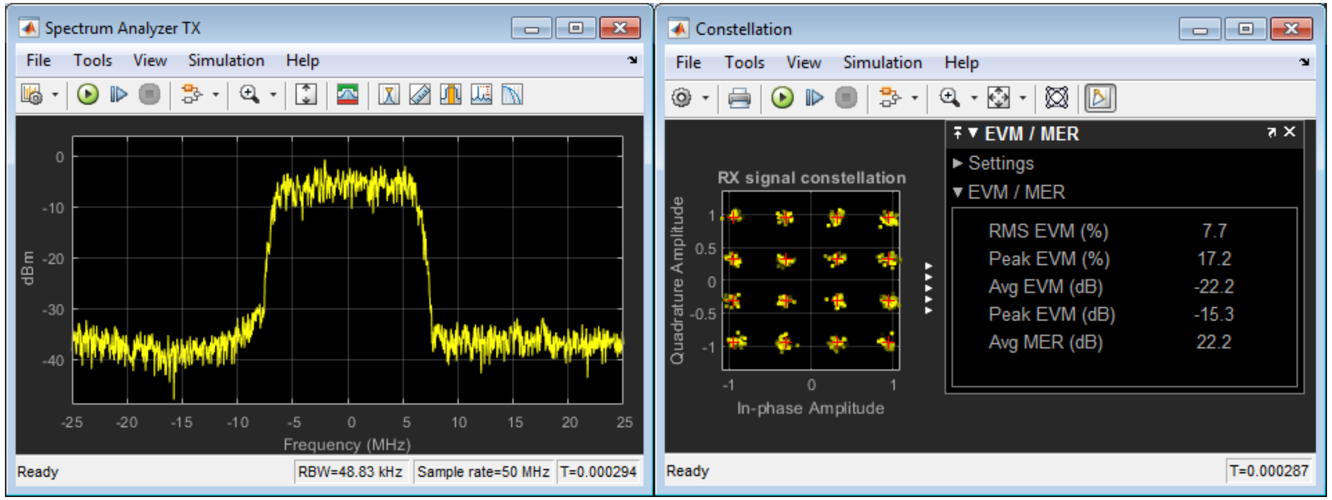


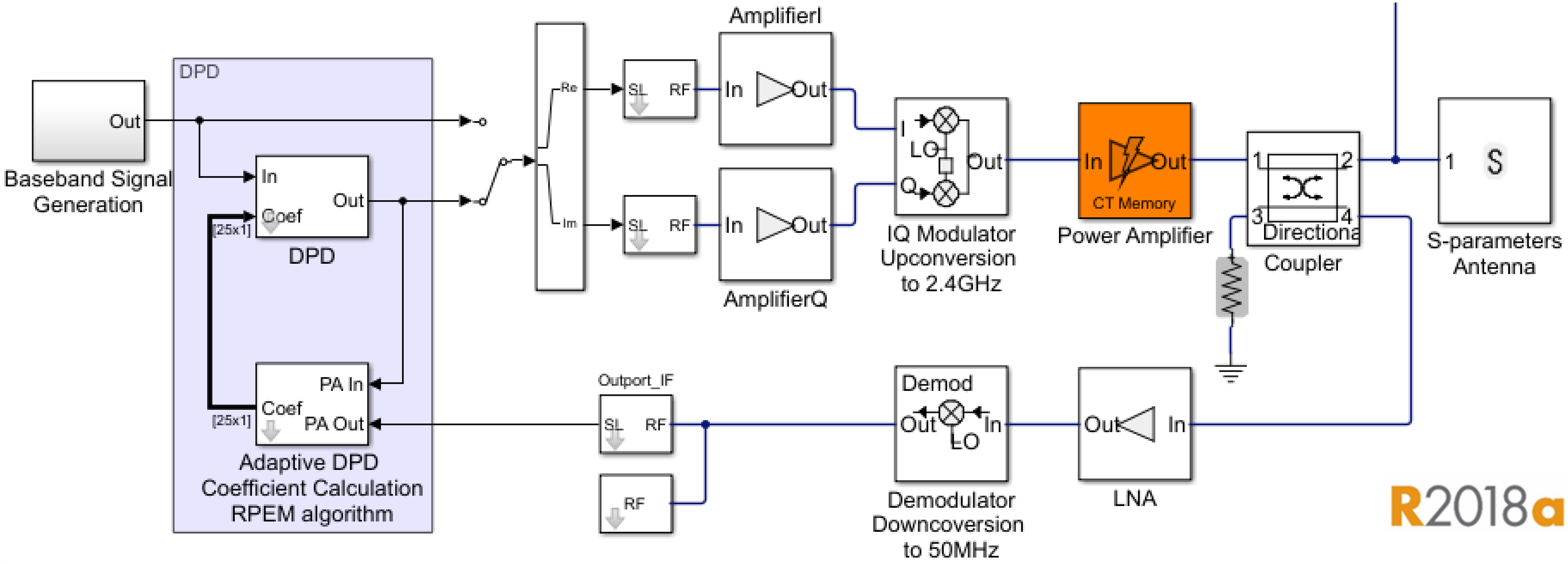




PA model for circuit envelope simulation

# PA + DPD Simulation

- Closed loop multi-domain simulation
  - Circuit Envelope for fast RF simulation
  - Low-power RF and analog components
  - DPD signal processing algorithm (behavioral or hardware-accurate)

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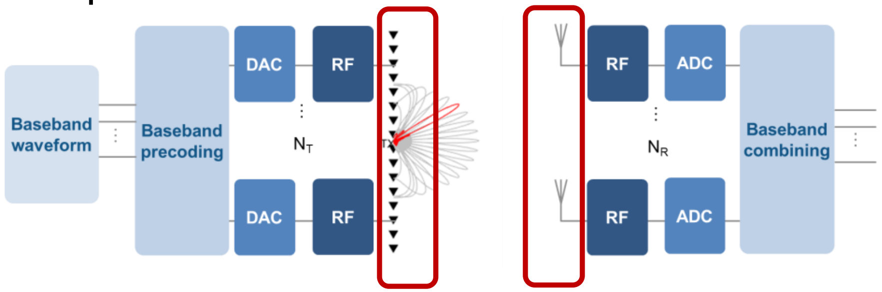
# Massive MIMO Antenna Arrays

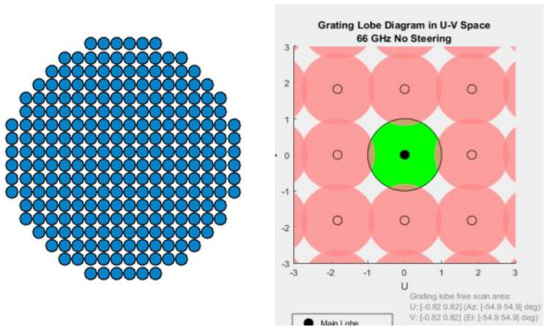
- Model antenna and array beam patterns
- Model antenna element failures
- Optimize tradeoffs between antenna gain and channel capacity
- Simulate with 3D channel model

**Antenna array design considerations**

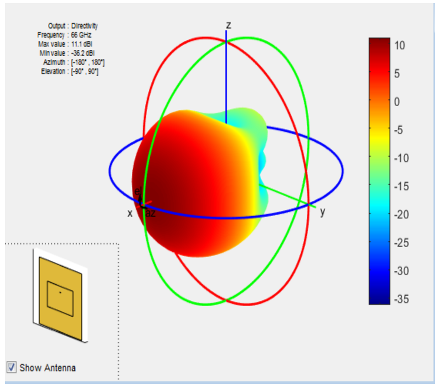
- Element coupling
- Imperfections



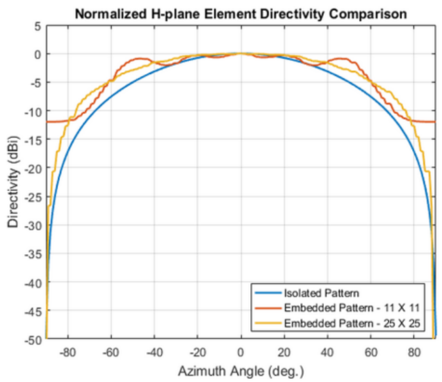

Design an array



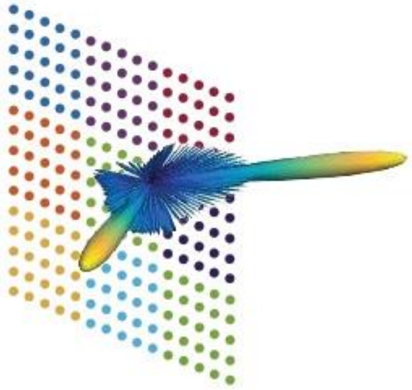

Import antenna patterns




Model mutual coupling




Array beam pattern

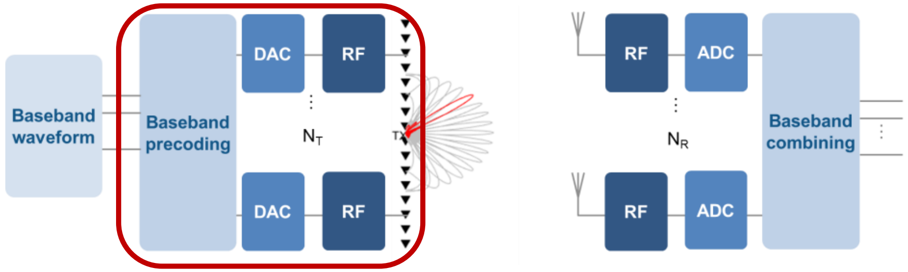


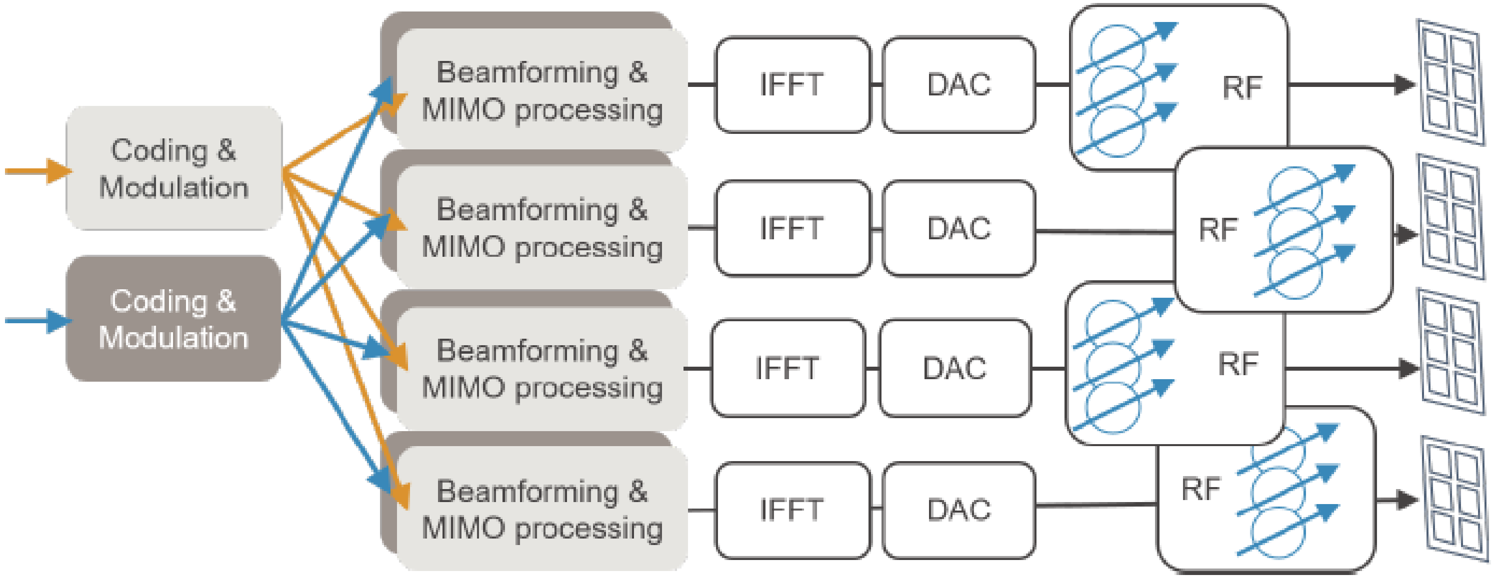
# Hybrid Beamforming for Massive MIMO

- Beamforming partitioned between digital and RF
  - Each Tx and Rx element has phase control
  - Subarrays handle amplitude and additional phase
  - Number of transmit antennas can be >> $N_S$ ($N_{RF}$)
- Model and optimize beamforming architecture
- Model imperfections in the signal chain

**Why Hybrid Beamforming?**

- Massive MIMO reduces mmWave propagation loss
- Hybrid beamforming reduces implementation cost




Different realizations have different complexity tradeoffs

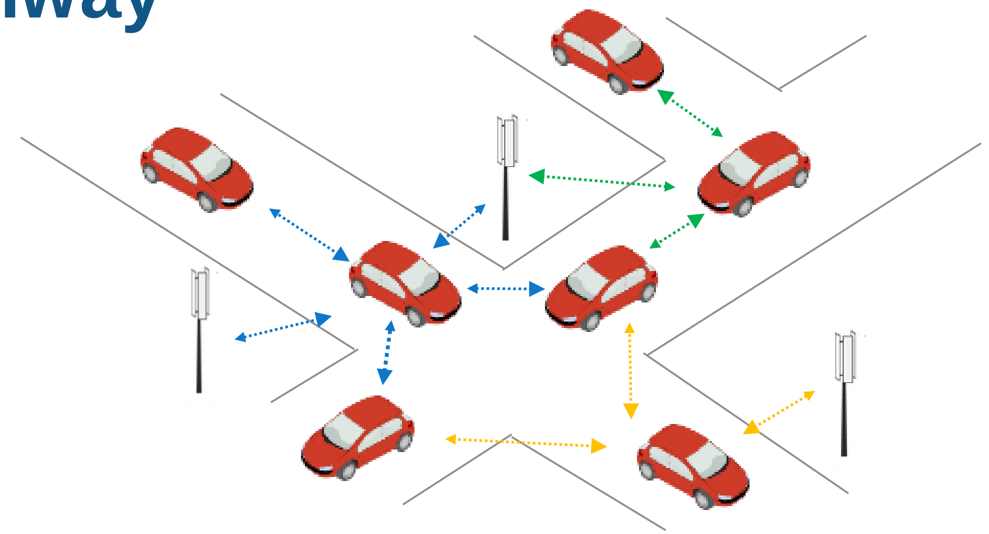
# Agenda

- 5G goals and requirements

- Modeling and simulating key 5G technologies
  - Release 15: Enhanced Mobile Broadband
  - Connecting Vehicles and IoT Devices

- 5G development workflow

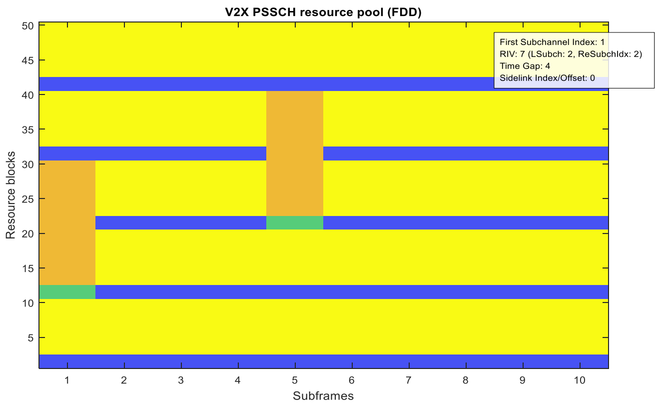
# V2X: Building the Connected Car Highway



## Standards for V2X

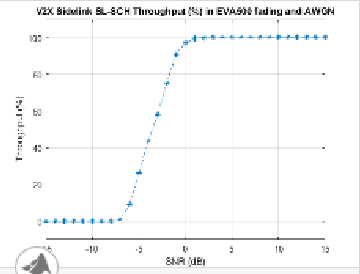
- 5G: Reserved for future release
- Cellular V2X (C-V2X)
  - Release 14 LTE Sidelink
  - **LTE Toolbox**
- DSRC
  - IEEE 802.11p
  - **WLAN Toolbox**

## PHY Waveform Generation




## Throughput Simulation

R2017b

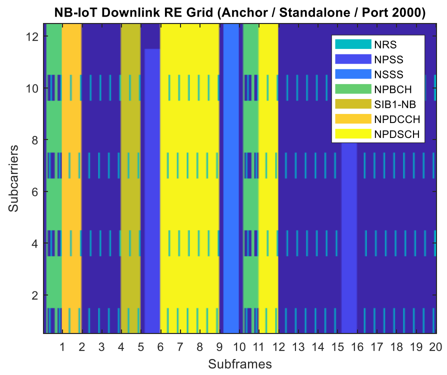



**Release 14 V2X Sidelink PSCCH and PSSCH Throughput**

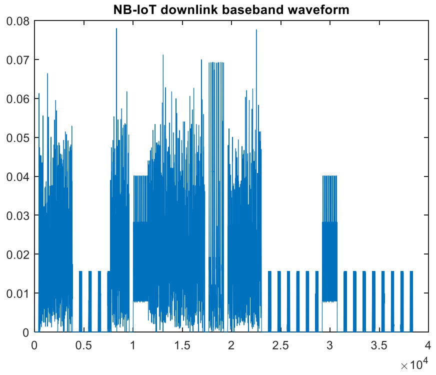
Demonstrates how to measure the Physical Sidelink Shared Channel (PSSCH) and Physical Sidelink Control Channel (PSCCH)

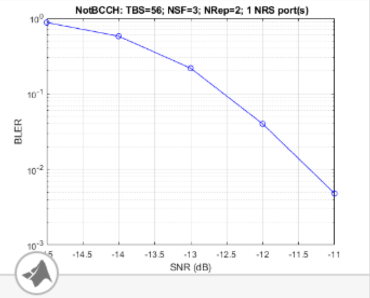
# Future 5G Use Case: IoT Connectivity

- 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)




## Waveform Generation




**NB-IoT NPDSCH Block Error Rate Simulation**

How LTE System Toolbox™ can be used to create a NB-IoT Narrowband Physical Downlink Shared Channel (NPDSCH) Block

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## BLER Simulation

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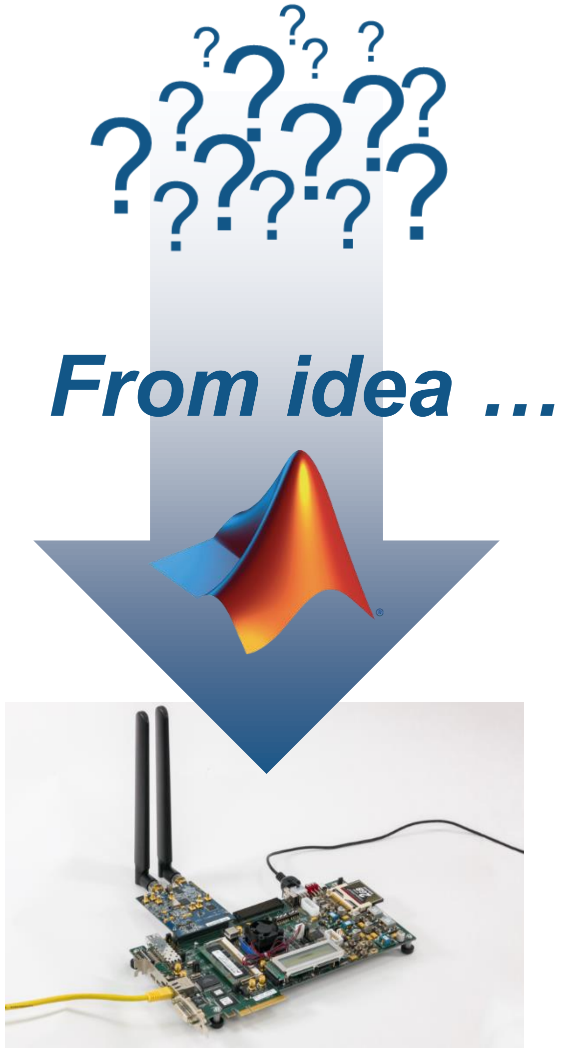



… to implementation

# 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**

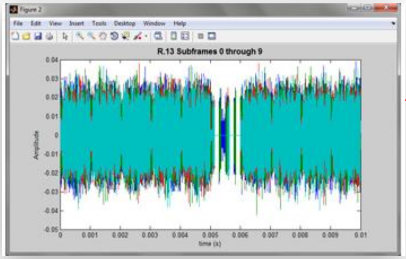
- Communications Toolbox
- 5G Toolbox
- LTE Toolbox
- WLAN System Toolbox

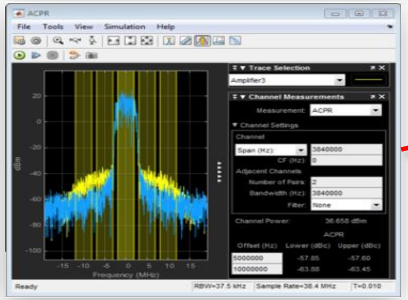
**RF Front End**

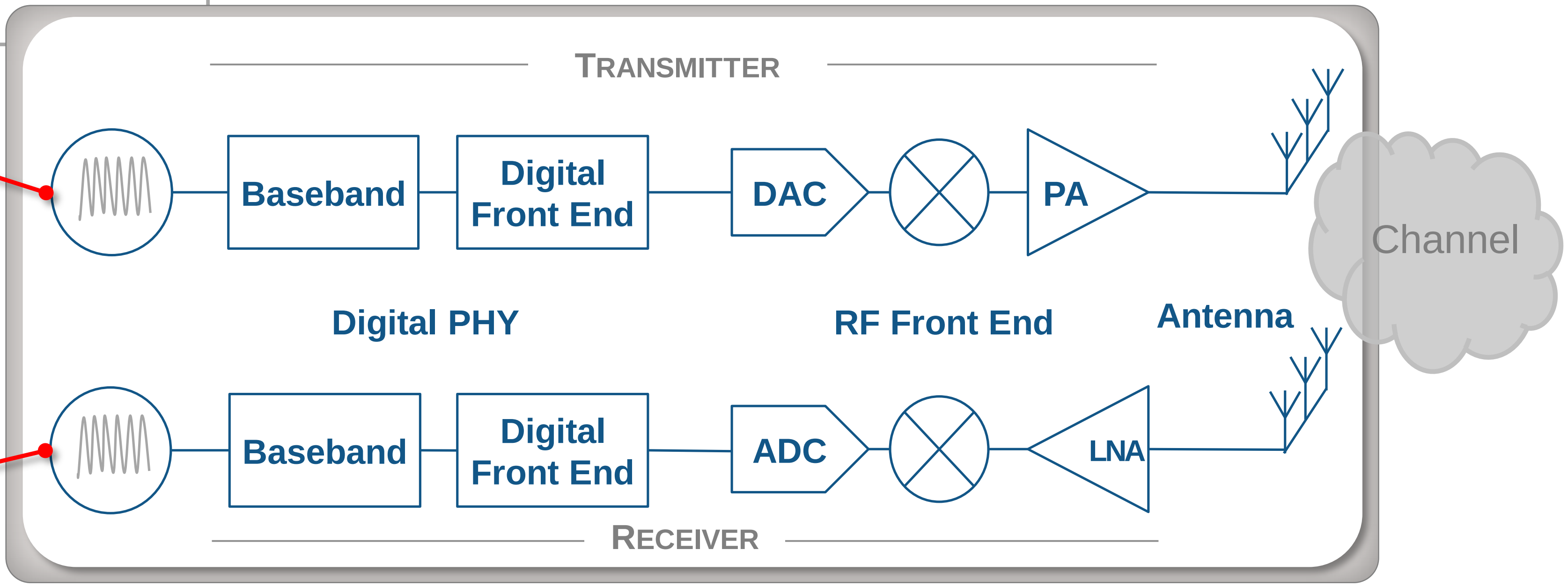
- RF Toolbox
- RF Blockset

**Antennas, Beamforming**

- Antenna Toolbox
- Phased Array System Toolbox







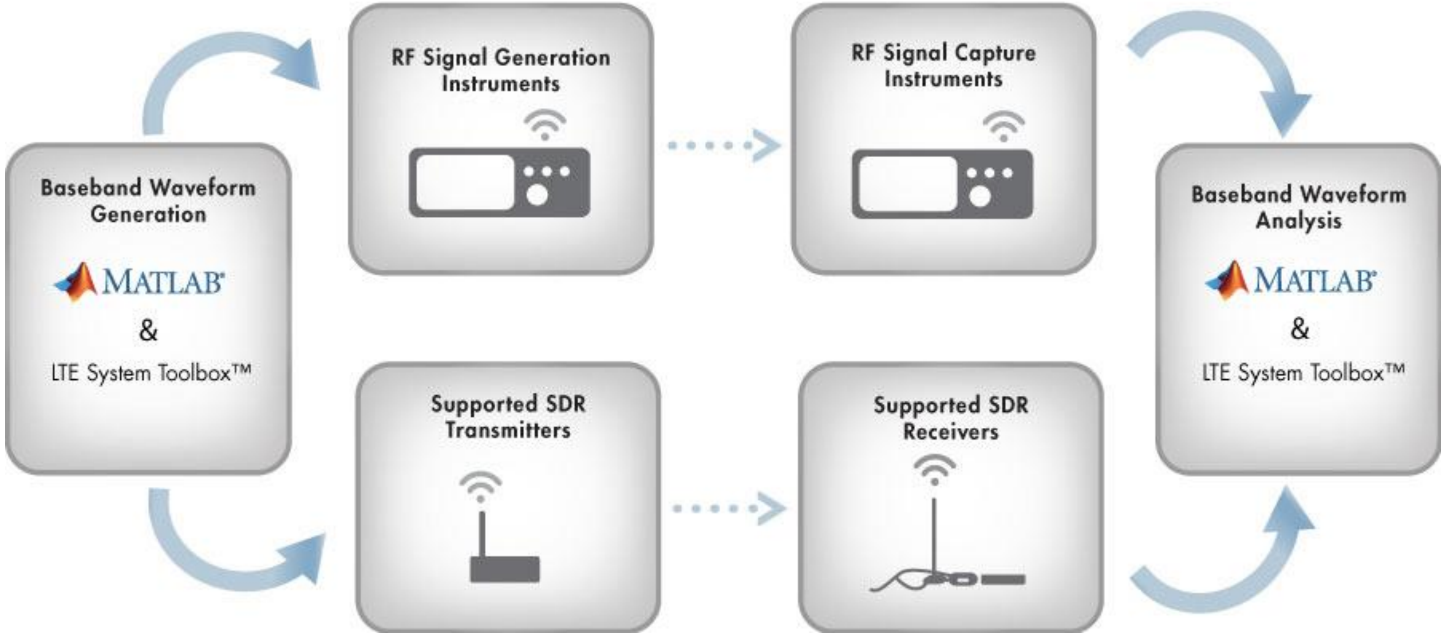

- Simulink
- DSP System Toolbox
- Control System Toolbox

**Mixed-signal**

- Communications Toolbox
- Antenna Toolbox
- 5G, LTE, WLAN Toolboxes

**Channel and Propagation**

# Over-the-Air Testing with SDR and RF Instruments





Ettus USRP SDR

RTL-SDR

Pluto SDR

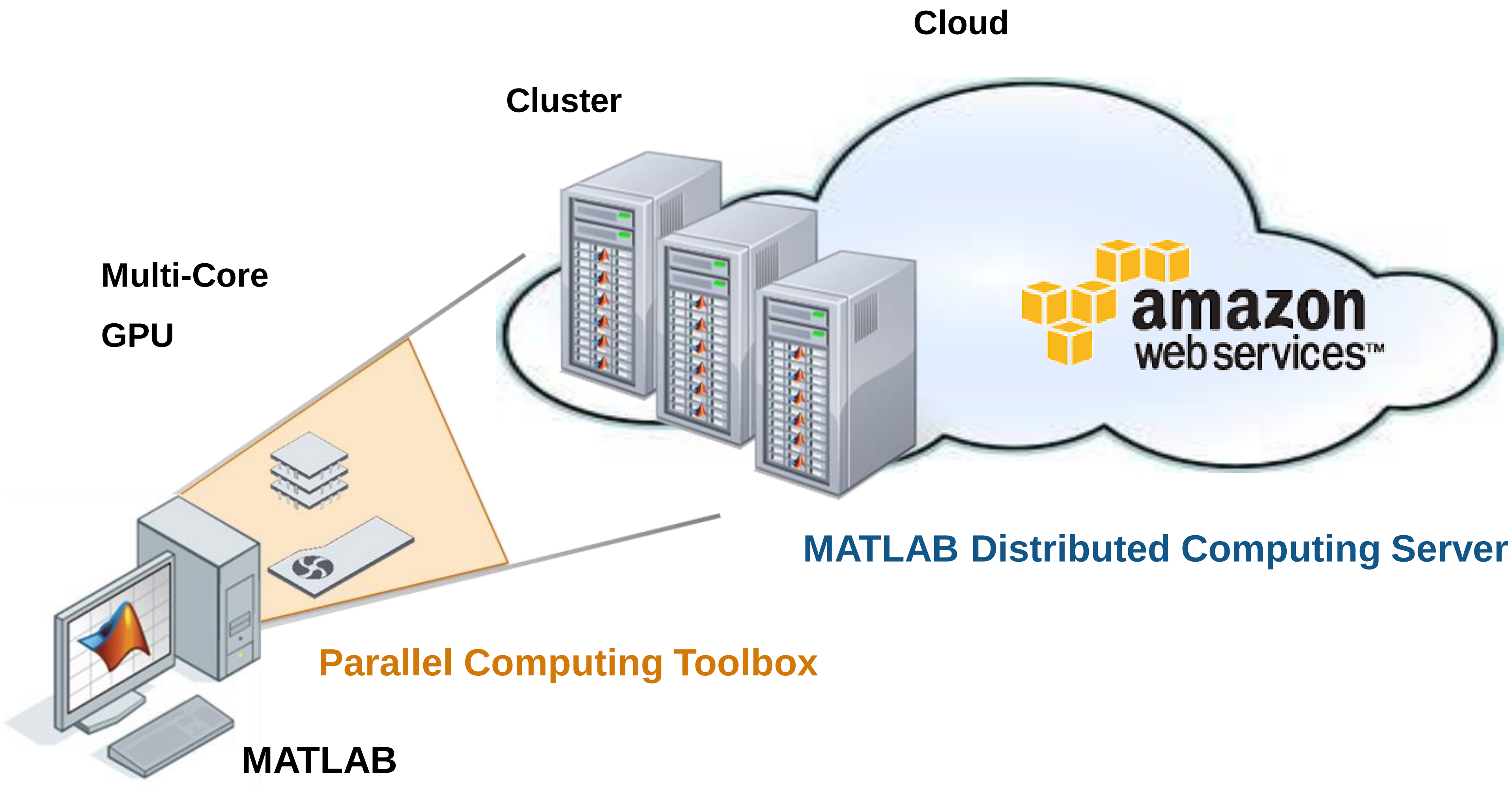
Zynq SDR

RF Signal Generator

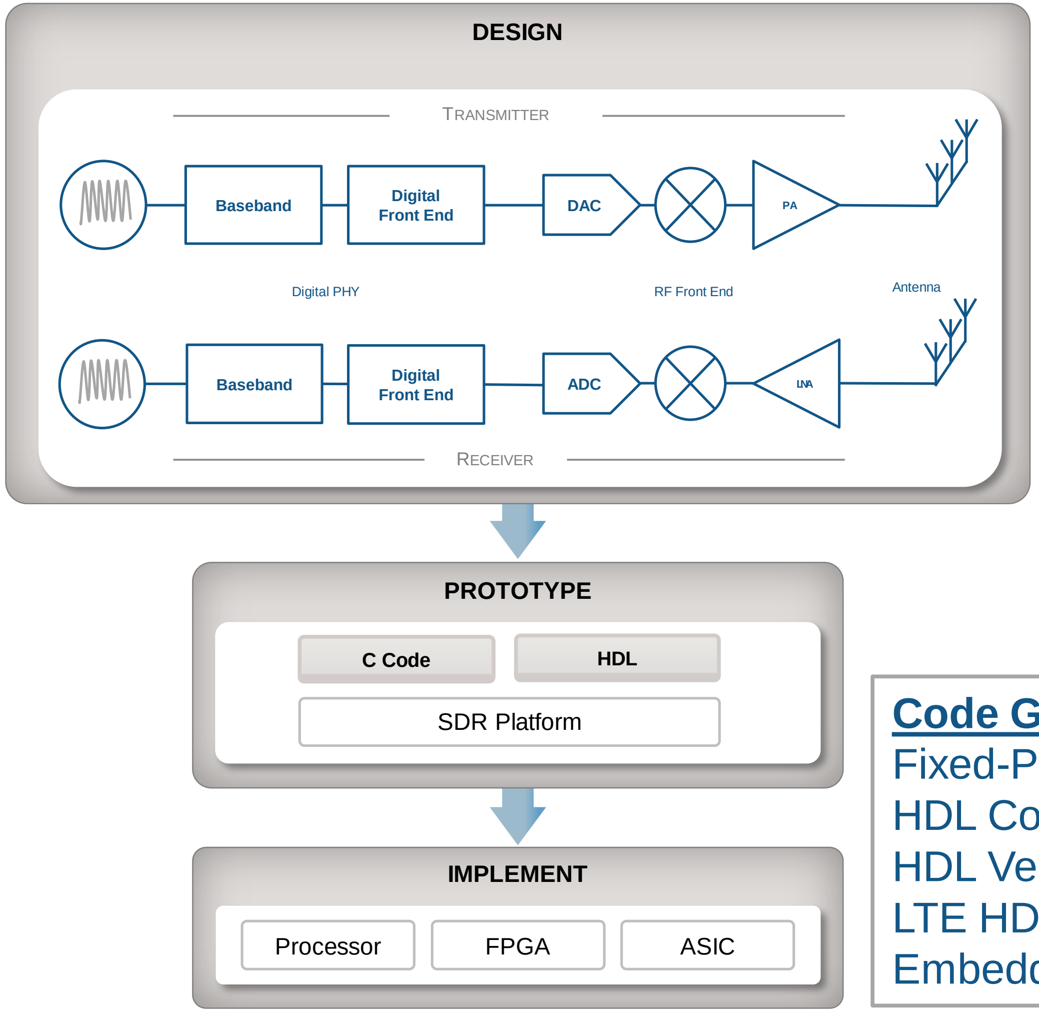
Spectrum Analyzer

**Over-the-air Testing**
Instrument Control Toolbox
SDR Support Packages
*Communications Toolbox*

# Accelerate Simulations with Scalable Computing



# Common Platform for Wireless Development




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

**Code Generation and Verification**
Fixed-Point Designer
HDL Coder
HDL Verifier
LTE HDL Toolbox R2017b
Embedded Coder

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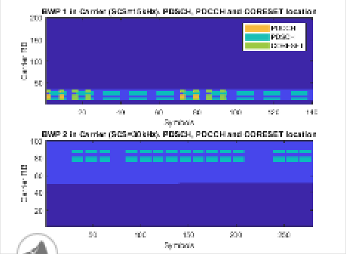
- **Modeling and simulating key 5G technologies**
  - Release 15: Enhanced Mobile Broadband
  - Connecting Vehicles and IoT Devices
- **5G development workflow**
- **Learn more…**

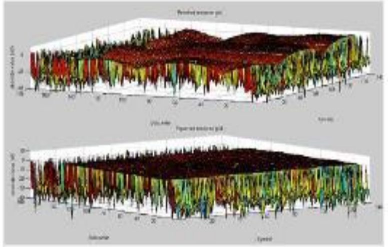
# Resources to Help You Get Started – Links in PDF Document



**Downlink Carrier Waveform Generation**

Implements a 5G NR downlink carrier waveform generator using 5G Toolbox™.

R2018b

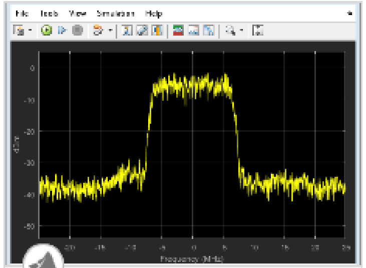


**Conformance Testing**

Ensure your designs comply with the supported 3GPP LTE standard releases.

» Learn more

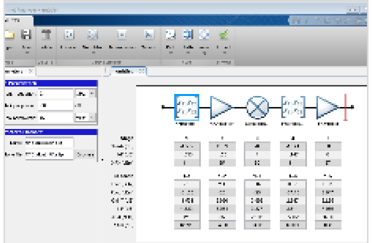
R2018a



**Power Amplifier Characterization with DPD for Reduced Signal**

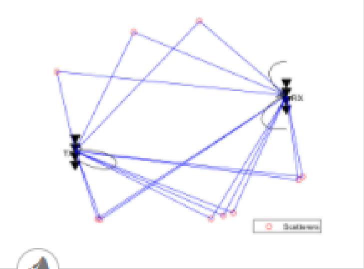
Provides a methodology for characterizing a nonlinear RF Blockset™ power amplifier (PA) with memory and an adaptive DPD

R2018a



**Visualizing RF Budget Analysis Over Bandwidth**

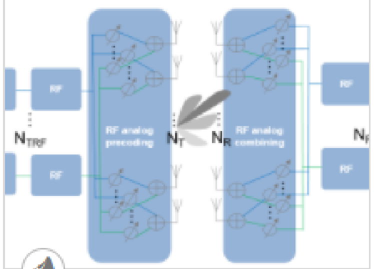
Programmatically perform an RF budget analysis of an RF receiver system and visualize computed budget results across the bandwidth



**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

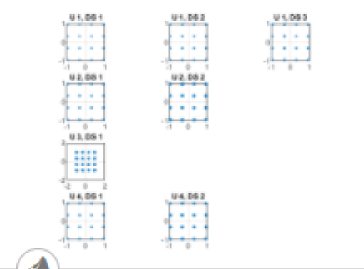
Open Script



**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 end of a massive MIMO communications system, using techniques for both

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**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

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# Resources – Links in PDF Document

## 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