MATLAB EXPO 2018

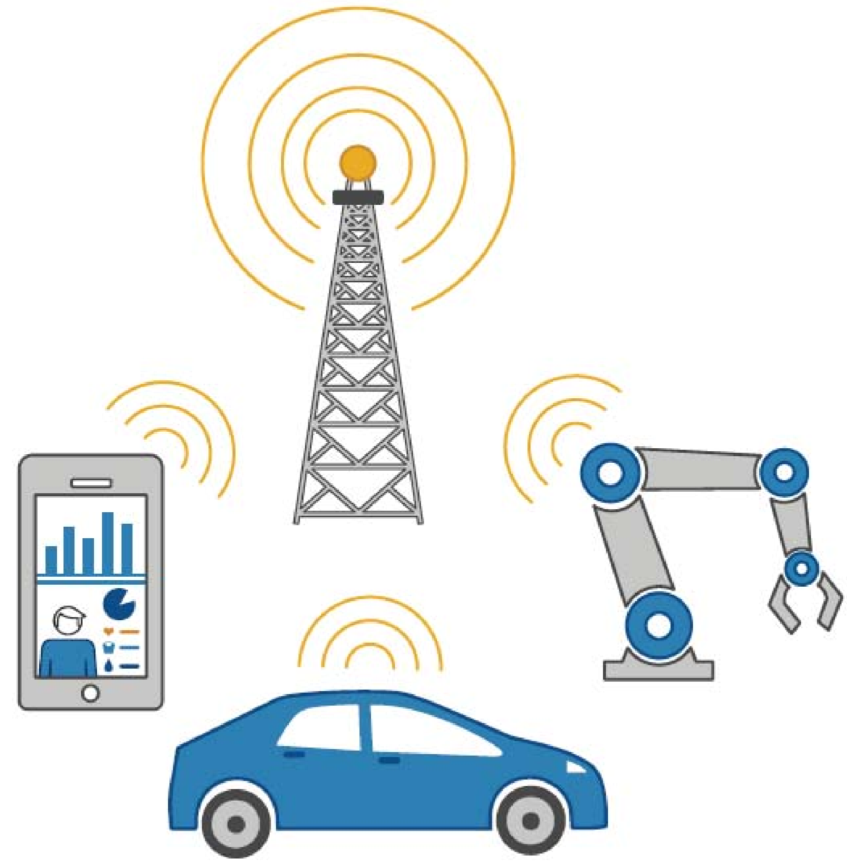
What's Behind 5G Wireless Communications?

Marc Barberis

Agenda

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

5G Applications and Requirements



New Applications

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

5G Requirements / Use Cases

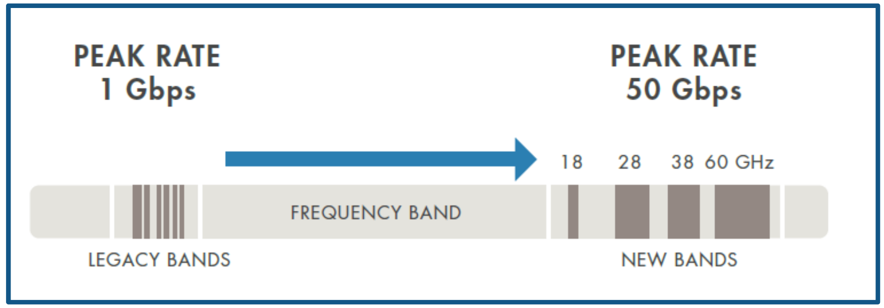
Enhanced mobile broadband (>10 Gbps)
Ultra low latency (<1 ms)
Massive machine-type communication (>1e5 devices)

Achieving Higher 5G Broadband Data Rates

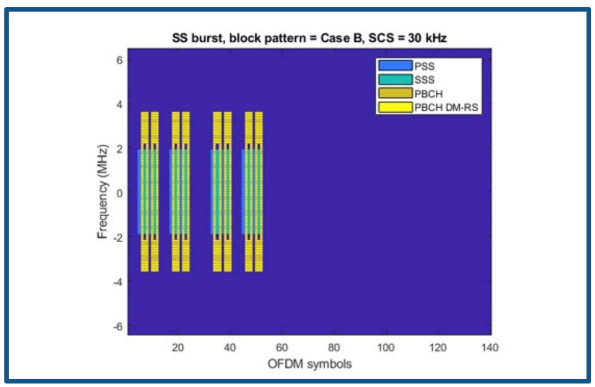
Technical Solutions

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

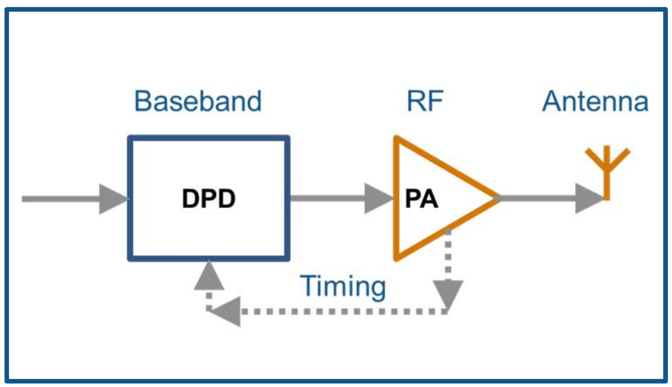
Higher Frequency Bands



New Physical Layer



New RF Architectures

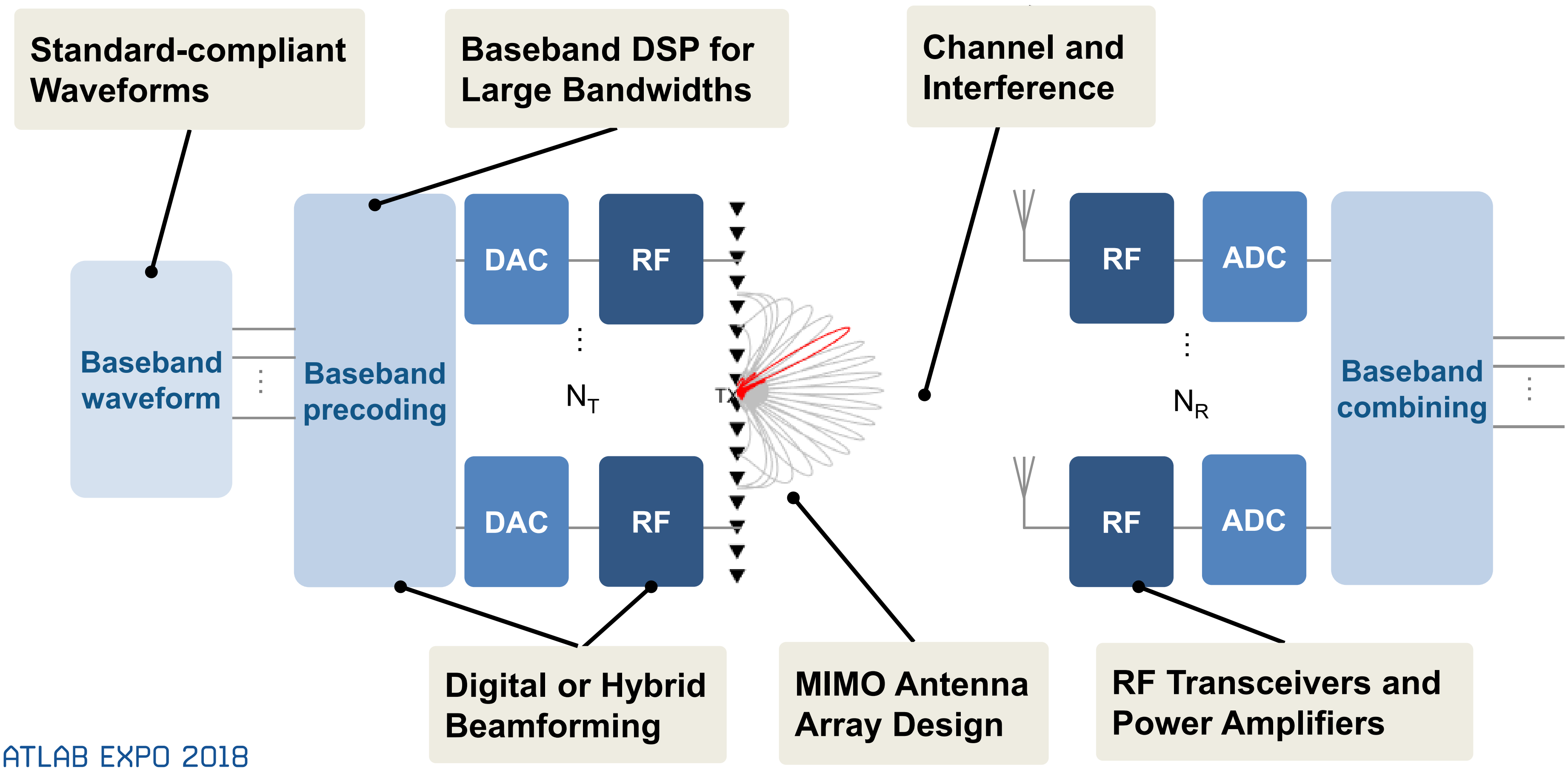


Massive MIMO

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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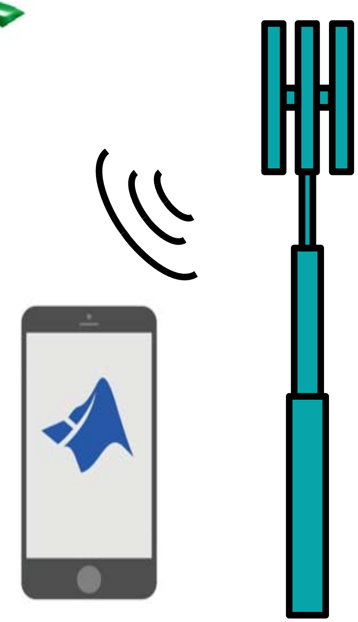
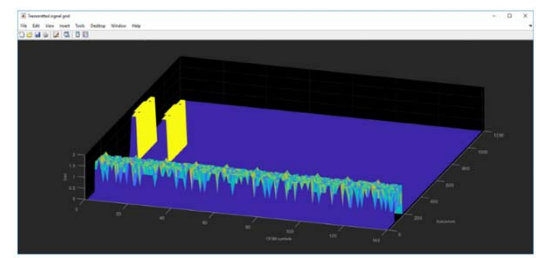
MathWorks

Introducing 5G Toolbox

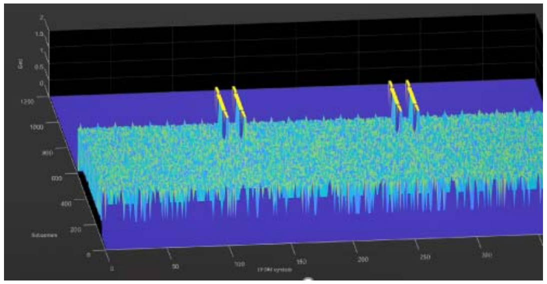
R2018b 5G



- Supports 3GPP Release 15.2.0 (June 2018)
- Key features
  - Waveform generation
  - Downlink processing - Transmit and receive
  - TDL and CDL channel models
  - Physical channels and signals
  - Link-level simulation & throughput measurements
  - Synchronization Bursts
  - Cell search procedures
  - Reference designs as detailed examples

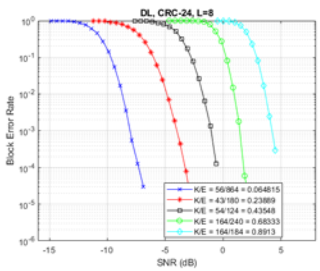


5G Toolbox applications & use-cases



Waveform Generation and Analysis

- New Radio (NR) subcarrier spacings and frame numerologies



End-to-End Link-Level Simulation

- Transmitter, channel model, and receiver
- Analyze bit error rate (BER), and throughput

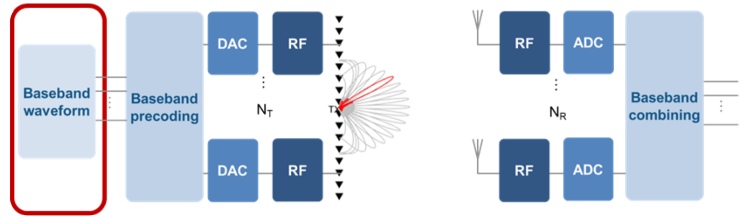
Golden Reference Design Verification

- Customizable and editable algorithms as golden reference for implementation

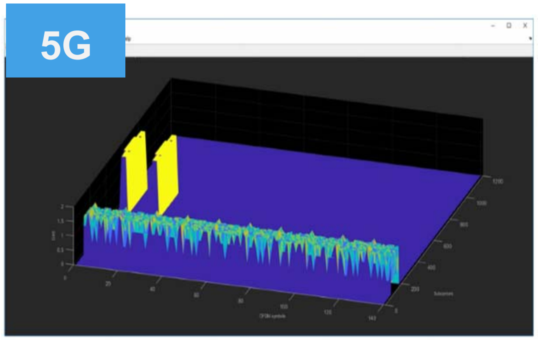
Waveform Generation

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

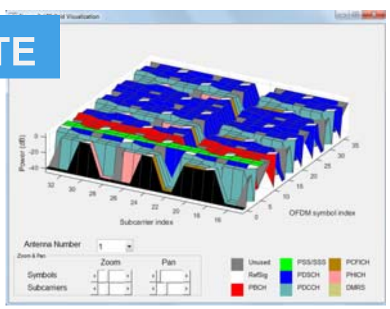
Standard compliance



5G

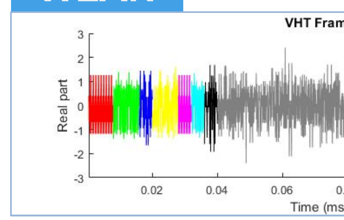


LTE



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

WLAN

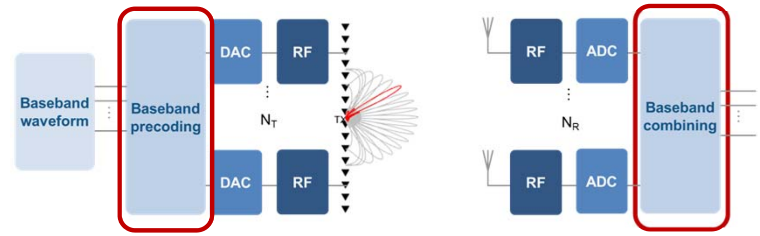


IEEE 802.11
✓ *802.11ax (draft)* R2018b
✓ 802.11ad
✓ 802.11ah
✓ 802.11ac
✓ 802.11a/b/g/n
✓ 802.11p/j

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

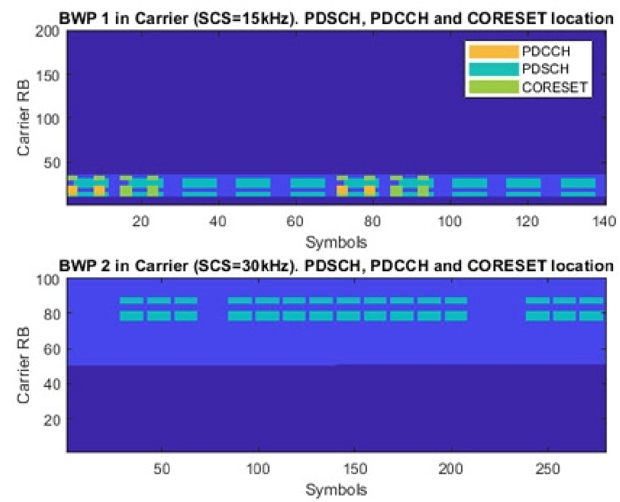
5G Toolbox

NEW PRODUCT

R2018b

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

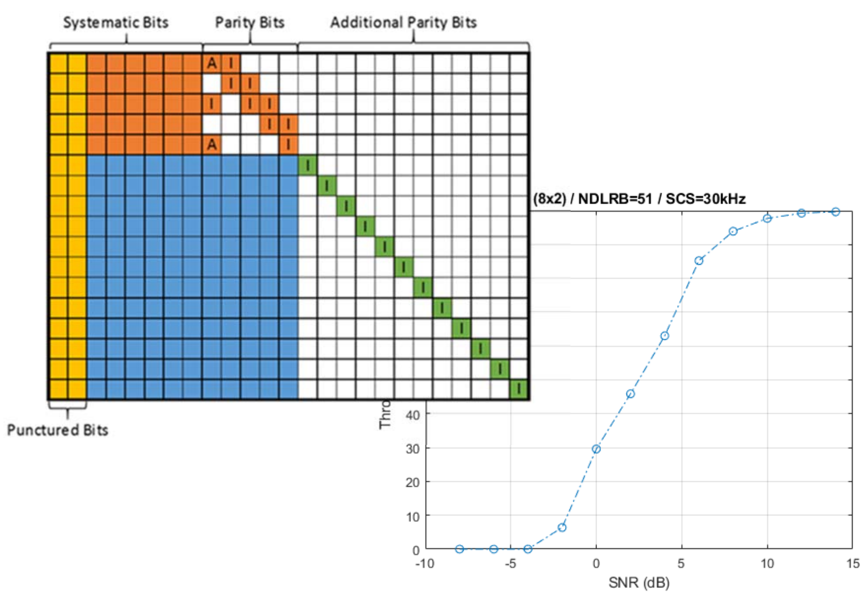
Flexible bandwidth in 5G NR



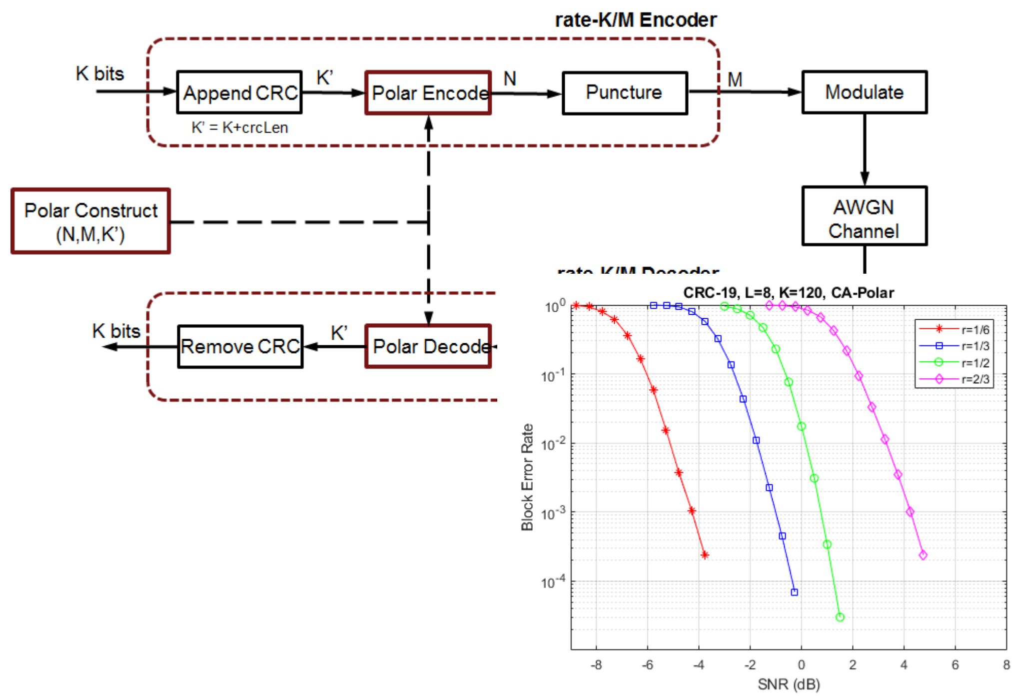
Downlink waveform generation with carrier bandwidth parts

Efficient Channel Coding Methods

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



- Polar Codes for control channel: achieve channel capacity

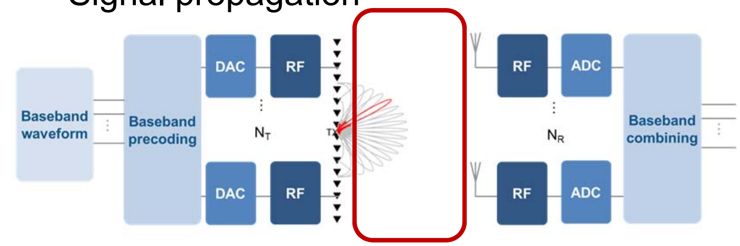


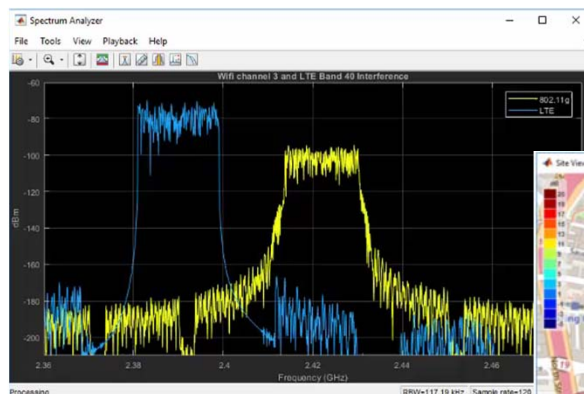
Model Channel and Interference

- 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





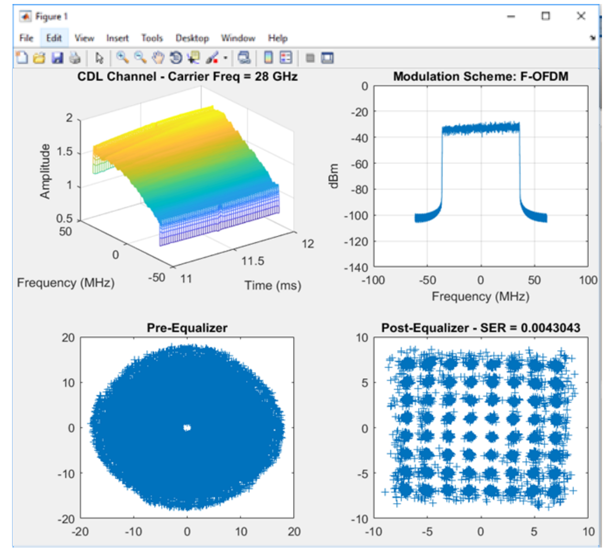
LTE-WLAN interference

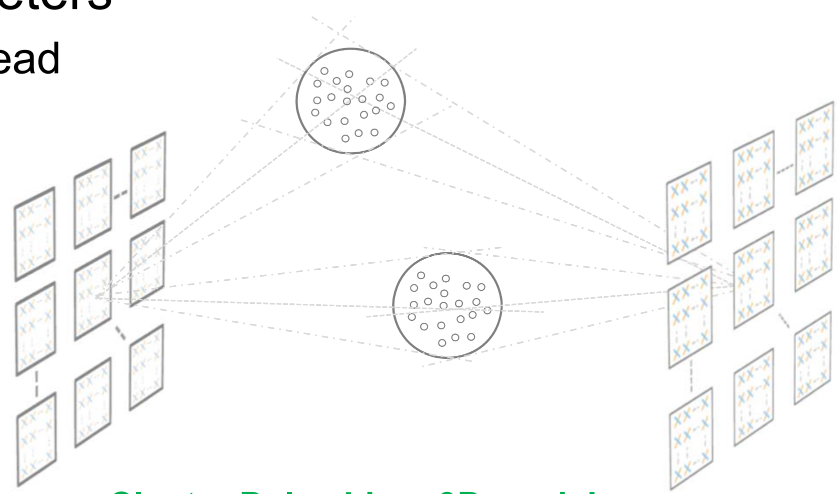
R2018a

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

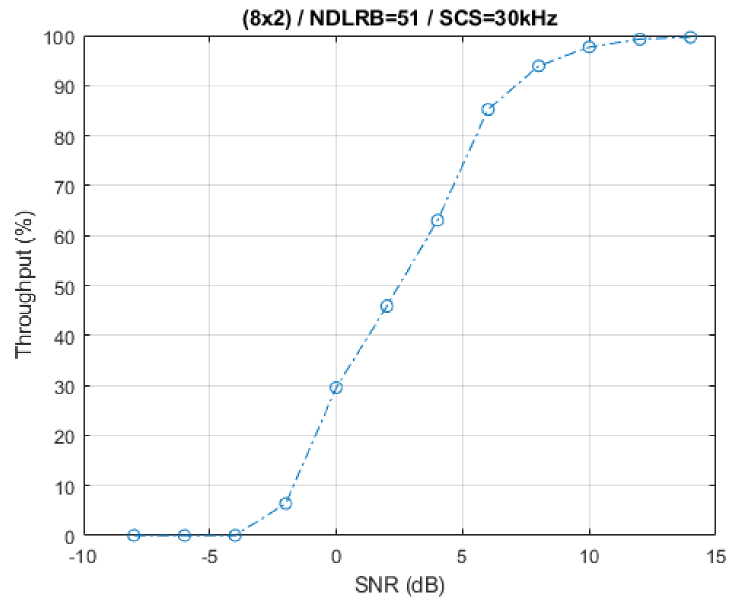


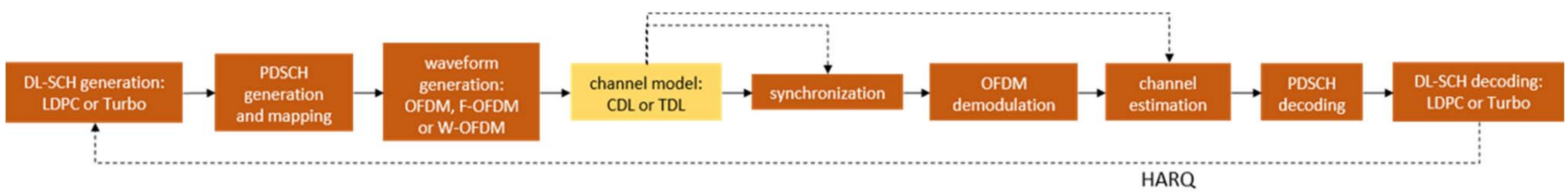


Cluster Delay Line: 3D model

5G Link Level Simulation

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

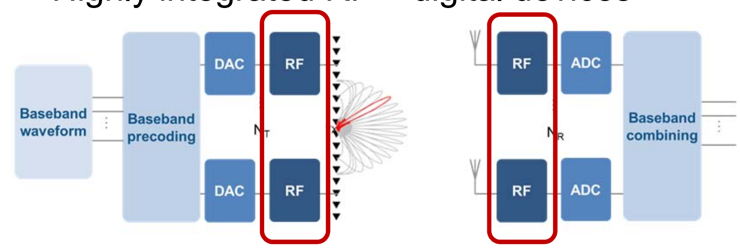


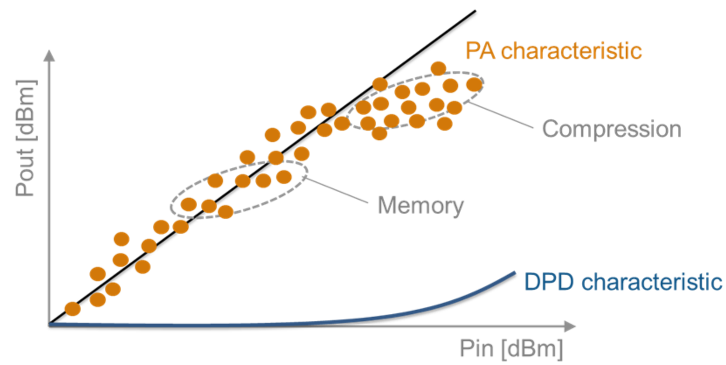


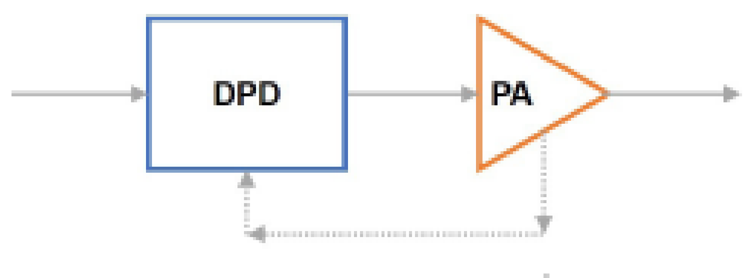
RF Power Amplifier (PA) Linearization

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

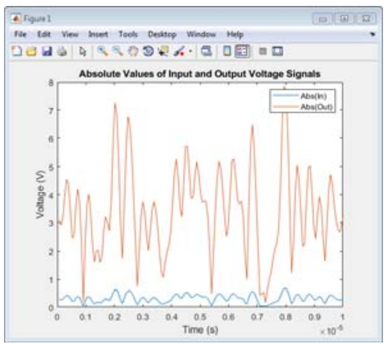






Characterize PA Model Using Measured Data

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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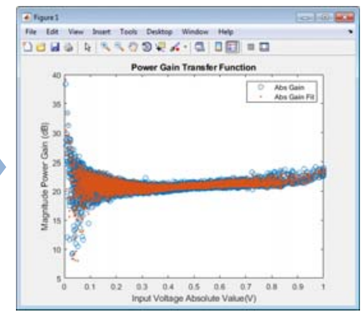
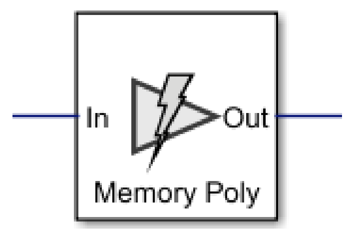
MATLAB PA model

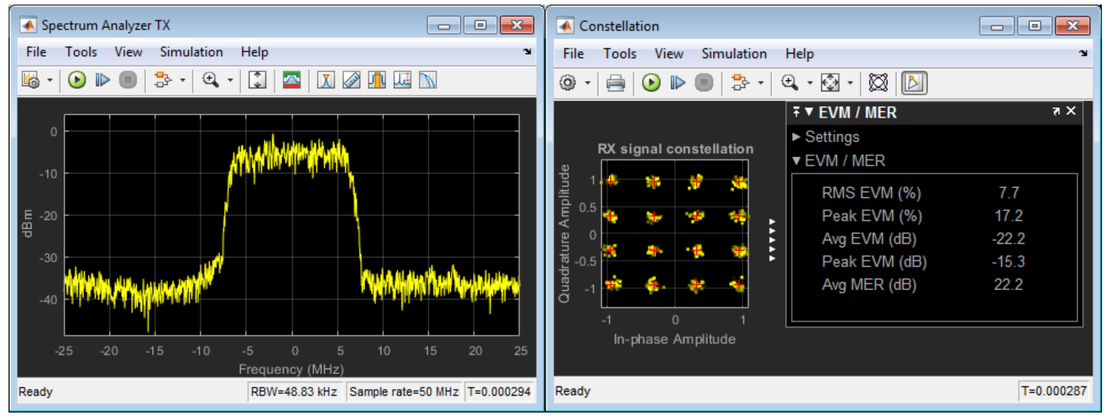


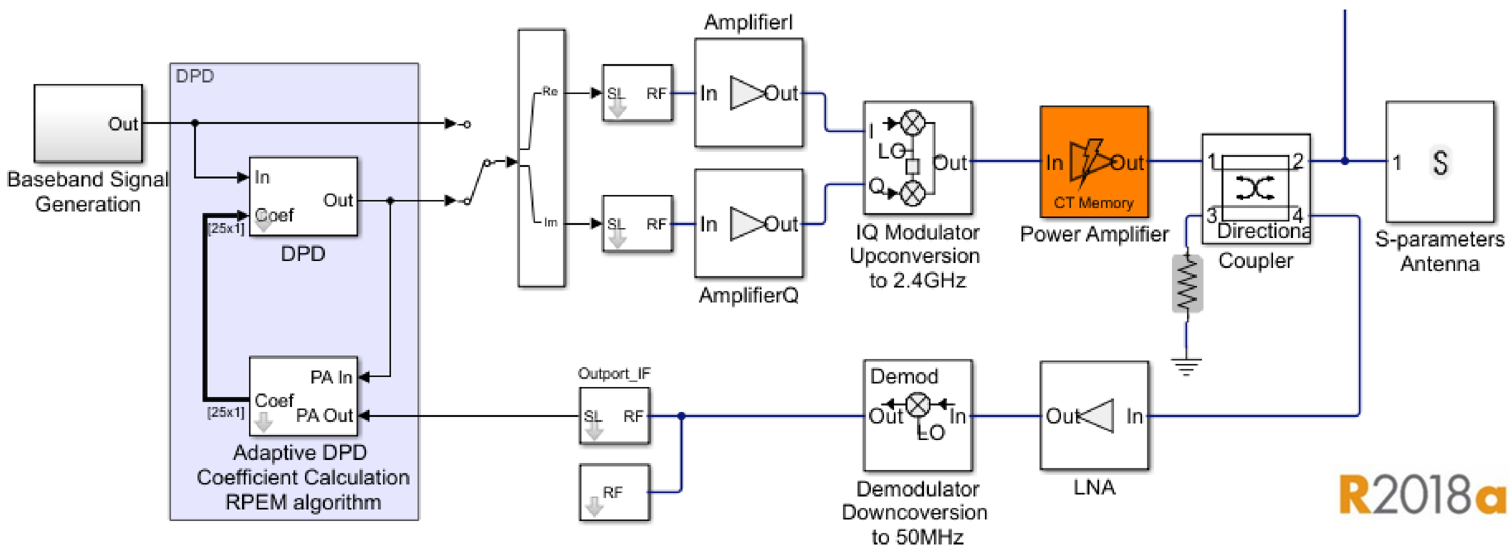


PA model for circuit envelope simulation

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)



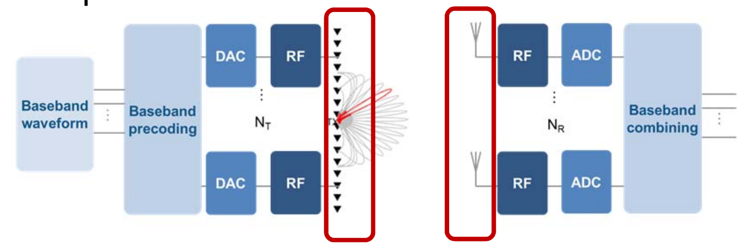


R2018a

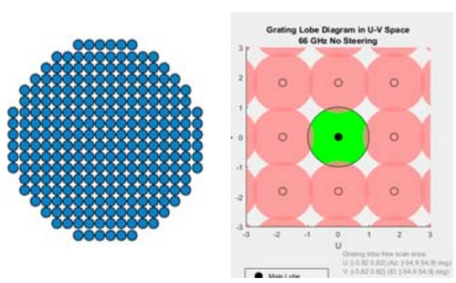
Massive MIMO Antenna Arrays

- Model antenna and array beam patterns
- Model antenna element failures
- Optimize tradeoffs between antenna gain and channel capacity

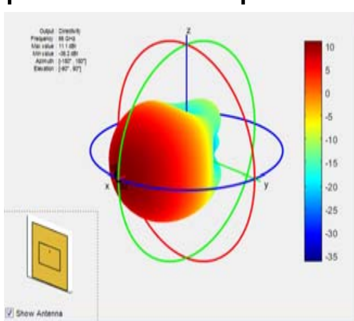
Antenna array design considerations
- Element coupling
- Imperfections



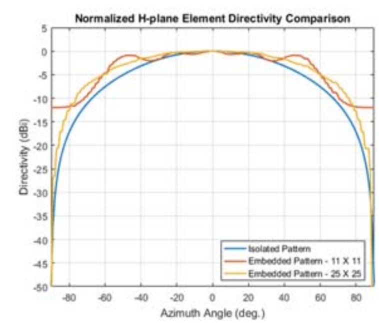
Design an array



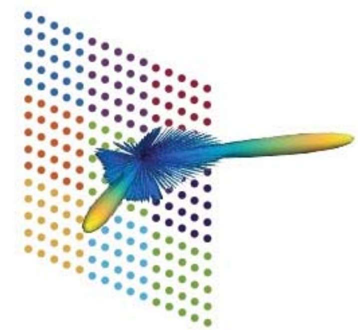
Import antenna patterns



Model mutual coupling



Array beam pattern

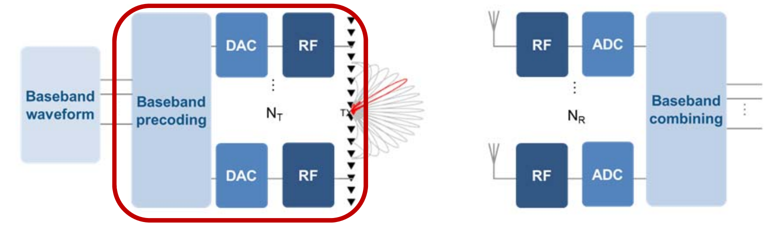


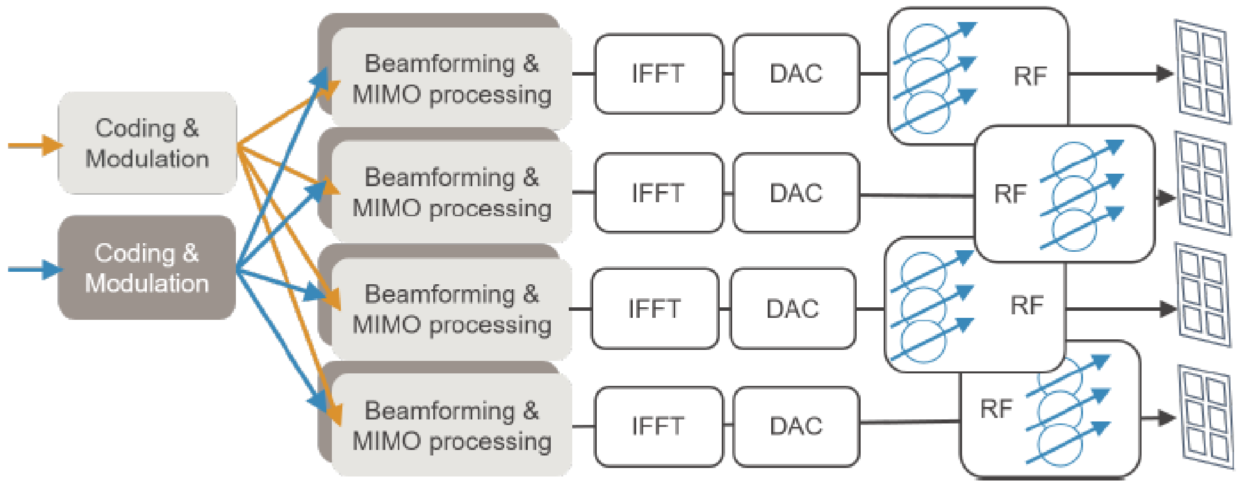
Hybrid Beamforming for Massive MIMO

- 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

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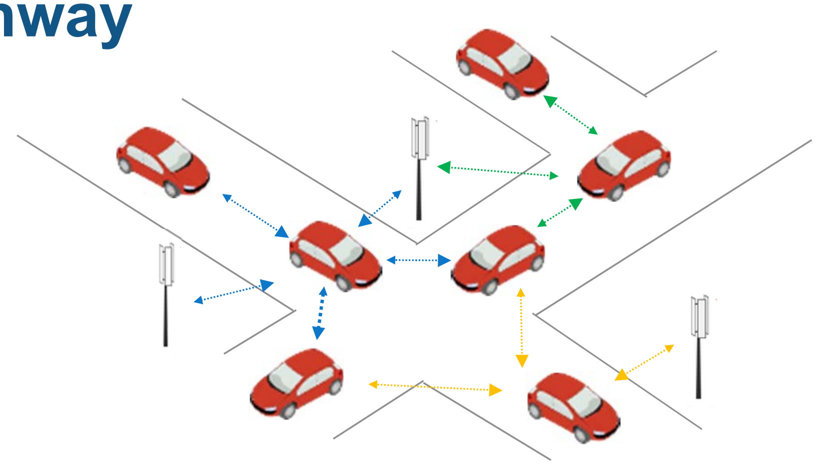
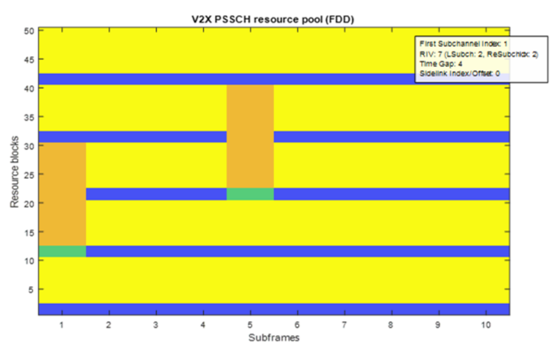
V2X: Building the Connected Car Highway



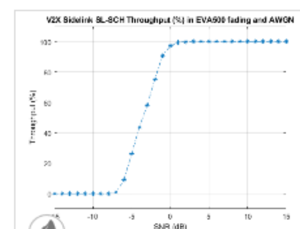
Standards for V2X

- 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



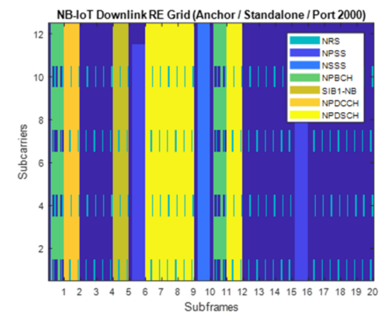
Release 14 V2X Sidelink PSCCH and PSSCH Throughput

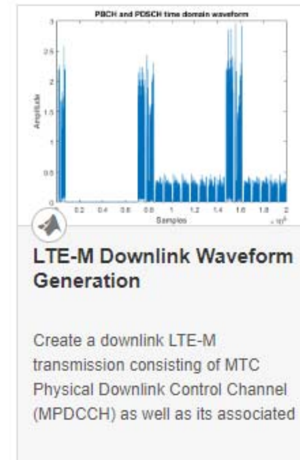
Demonstrates how to measure the Physical Sidelink Shared Channel (PSSCH) and Physical Sidelink Control Channel (PSCCH)

Future 5G Use Case: IoT Connectivity

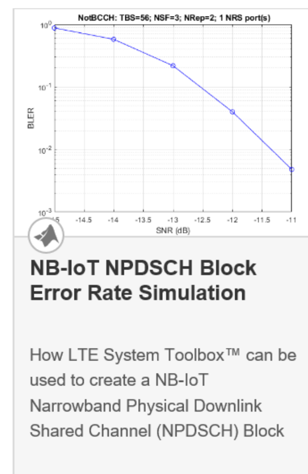
- IoT use case reserved for future 5G release
- Two LTE standards: LTE-M and NB-IoT

Specifications	LTE-M	NB-IoT
Maximum bandwidth	1.4 MHz	200 kHz
Peak rate	1 Mbps	~200 kbps
Duplex	Half duplex	Half duplex
Number of antennas	1	1
Transmit power	20 dBm	23 dBm
Other features	Power saving (eDRx)	Extended coverage
Spectrum	Existing LTE network	Licensed spectrum





Waveform Generation



BLER Simulation

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- **5G goals and requirements**
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Customer Perspective

"MATLAB made it easy for us to prototype 5G features because we could start with validated transmitter functions, customize them with our own enhancements, and rapidly produce a prototype for simulation."

- Allan Yingming Tsai, Convida Wireless

https://www.mathworks.com/content/dam/mathworks/white-paper/convida-interdigital-qa.pdf

"MATLAB and Simulink provide a unified and efficient system development platform to bridge between analog and digital; software and hardware; and algorithm, implementation, and verification."

- Erni Zhu, Huwaei

https://www.mathworks.com/content/dam/mathworks/case-study/huawei-customer-case-study-landscape.pdf

MATLAB & Simulink Wireless Design Environment

for baseband, RF, and antenna modeling and simulation

Algorithms, Waveforms, Measurements

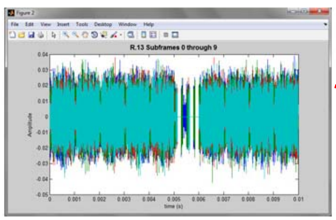
- Communications Toolbox
- 5G Toolbox
- LTE Toolbox
- WLAN System Toolbox

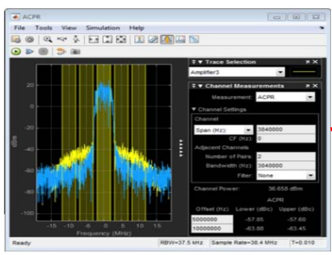
RF Front End

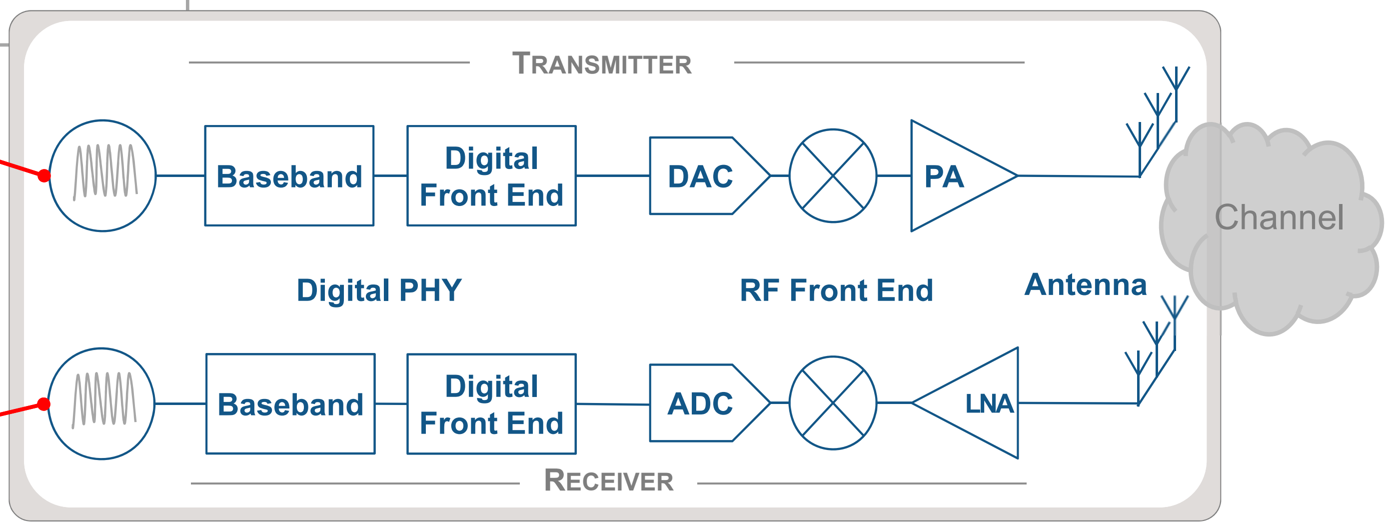
- RF Toolbox
- RF Blockset

Antennas, Beamforming

- Antenna Toolbox
- Phased Array System Toolbox







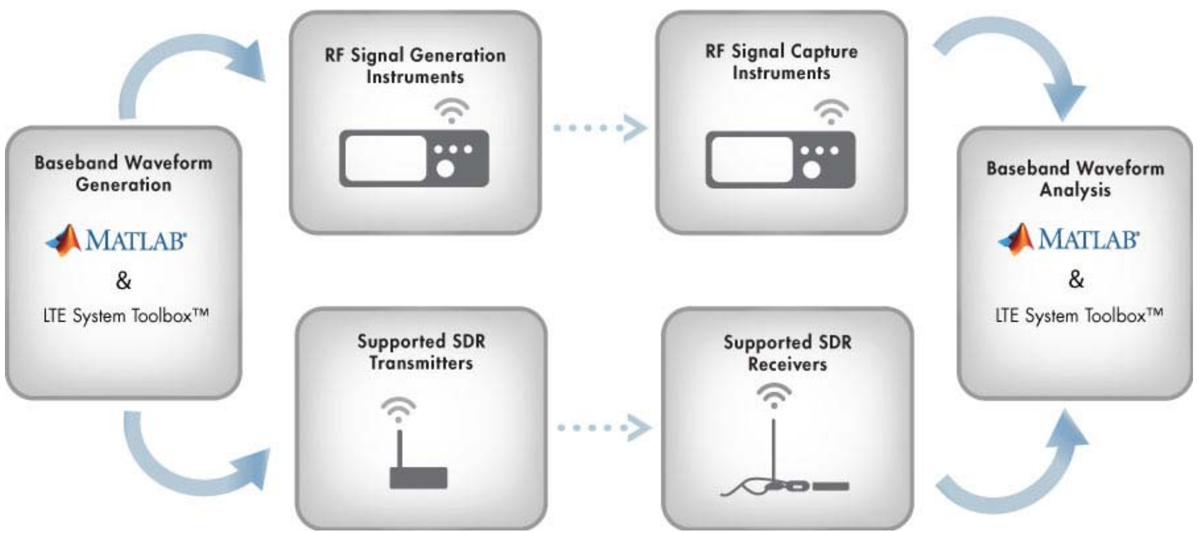
- Simulink
- DSP System Toolbox
- Control System Toolbox

Mixed-signal

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

Channel and Propagation

Over-the-Air Testing with SDR and RF Instruments



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

Ettus USRP SDR

RTL-SDR

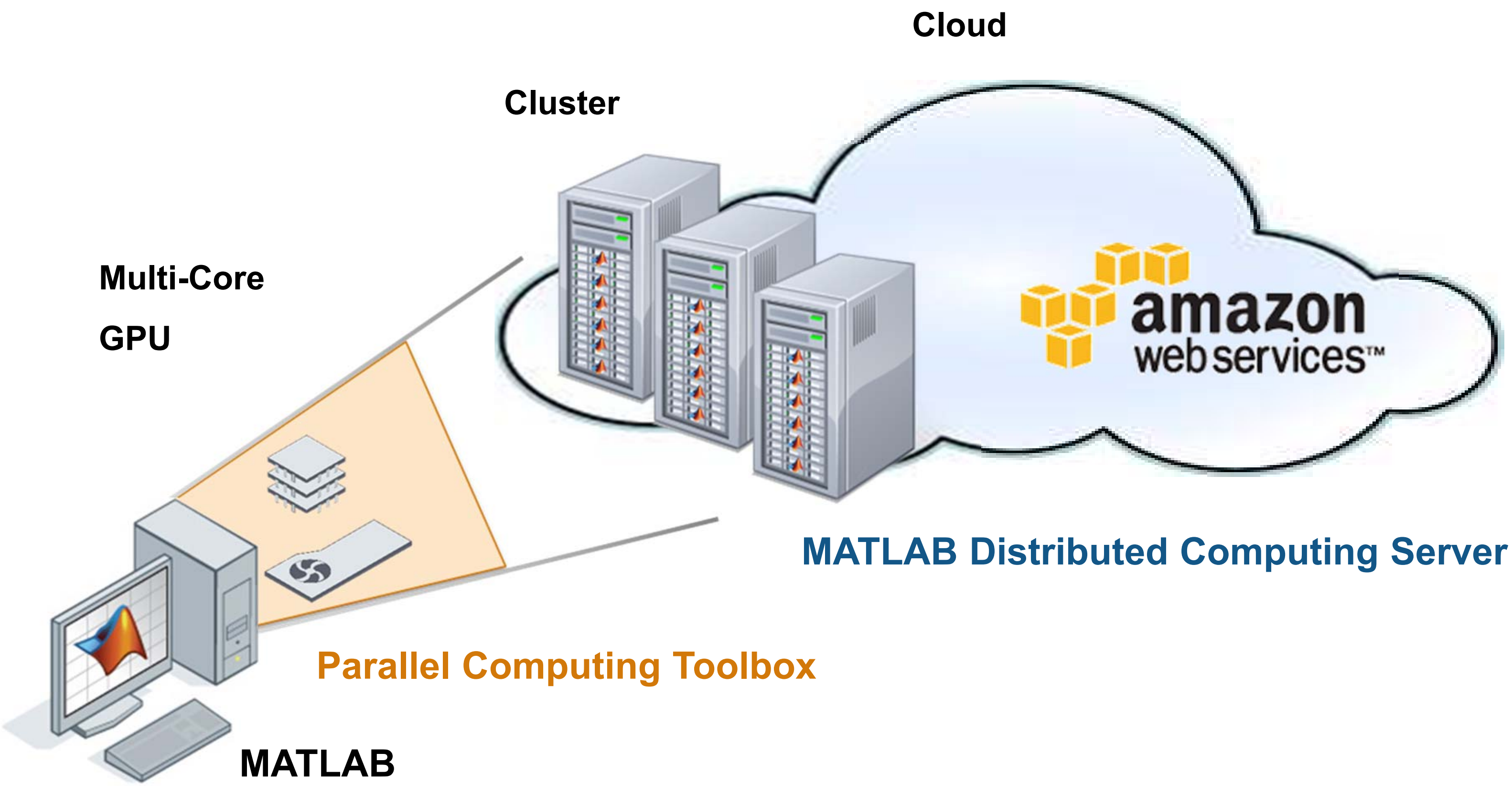
Pluto SDR

Zynq SDR

RF Signal Generator

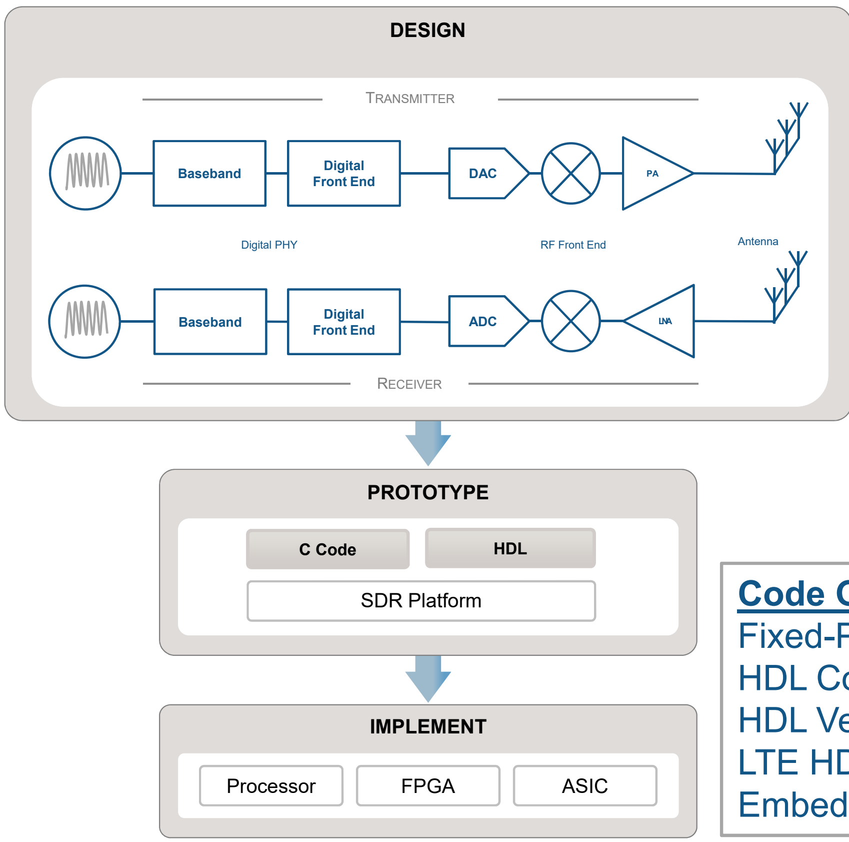
Spectrum Analyzer

Accelerate Simulations with Scalable Computing



Common Platform for Wireless Development

MATLAB® & SIMULINK®



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

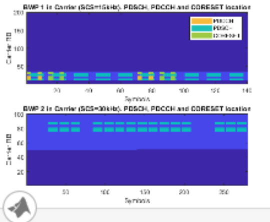
Code Generation and Verification

Fixed-Point Designer
HDL Coder
HDL Verifier
LTE HDL Toolbox
Embedded Coder

Agenda

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

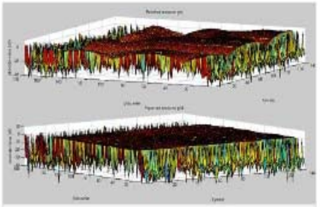
Resources to Help You Get Started – Links in PDF Document



Downlink Carrier Waveform Generation

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

R2018b

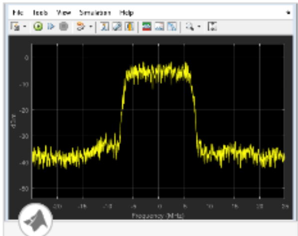


Conformance Testing

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

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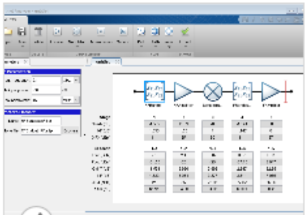
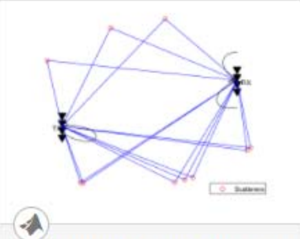


Visualizing RF Budget Analysis Over Bandwidth

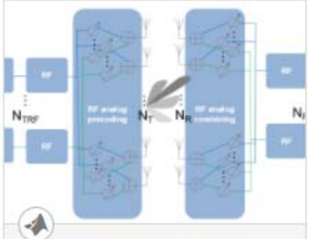
Programmatically perform an RF budget analysis of an RF receiver system and visualize computed budget results across the bandwidth



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

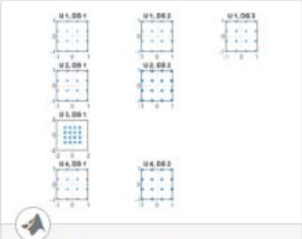
Open Script



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