Wireless Communication and RF System Design Using MATLAB and Simulink

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Outline of Today’s Presentation

- Introduction to RF system-level simulation of wireless transceivers
- MathWorks tools for RF top-down design
- 802.15.4 design example
- Conclusions
Model and Simulate Wireless Systems

- System-level simulation including RF
Model and Simulate Wireless Systems

- System-level simulation including RF
- RF = high frequency analog signals
- RF causes imperfections that cannot be neglected
Why Do We Need RF System Simulators?

Radio Frequency Signals \rightarrow \text{Small simulation time-step} \rightarrow \text{Long Simulation Runs}

Deal with RF complexity with:
- Models at high levels of abstraction
- Solvers that use larger time-step

\sim 10\text{psec}
\sim 5\text{GHz}
Simulink and SimRF

- System-level simulation including RF
- Architectural design of RF transceivers
- Tradeoff simulation time and modeling fidelity
Trade Off Simulation Speed and Modeling Fidelity

- Equivalent Baseband
- Circuit Envelope
- True Pass-Band
Trade Off Simulation Speed and Modeling Fidelity

How do your signals look like?

- Equivalent Baseband
- Circuit Envelope
- True Pass-Band
SimRF Libraries:
Circuit Envelope

Equivalent Baseband
Design of a Wireless Receiver

- 802.15.4 Air interface @2.4GHz
  - 250 kbps
  - 2 Mchps
  - O-QPSK modulation
  - ½ sine pulse shaping
- Robustness to -20dBm UMTS interference
- -100dBm sensitivity @0.00625%BER
- Ultra low cost / power
Wireless Receivers Architectures

Super Heterodyne
- High performance
  - Low power
  - Great sensitivity
- High RF complexity / cost
  - Discrete filters for image rejection and channel selection
  - Multiple LOs
Wireless Receivers Architectures

Low IF
- Moderate performance
- Moderate power
- Good sensitivity
- Moderate RF complexity
- Integrated filters for image rejection
Wireless Receivers Architectures

Direct Conversion

- Moderate performance
  - Moderate power
  - Good sensitivity
- Moderate RF complexity
  - No image rejection
  - Noise mitigation
  - Quality of matching
Typical Direct Conversion Receiver Design

- **broadband direct conversion receiver**
- **high speed ΣΔ data converters**
- **CIC filters and down-samplers**
- **reconfigurable analog filters**
- **analog phase locked loop**
- **baseband DSP**
Top-Down Design of the RF Receiver

- Model the overall communication chain
- Refine the receiver model with a top-down approach
- Verify the specifications at each step
- Trade off model fidelity and simulation speed
Demo: Design of a ZigBee Receiver

- Executable specification of the system
- Architecture exploration and refinement of the RF front-end
ZigBee Specifications

- 802.15.4 Air Interface for 2.4 GHz ISM Band
  - 250 kbps
  - 2 Mchps
  - O-QPSK modulation
  - ½ sine pulse shaping
- Robustness to -20 dBm UMTS interference in IMT-2000 band spanning 2500 MHz to 2690 MHz
- -100 dBm sensitivity @ 0.00625% BER
- Ultra low cost
Step 1: How Much Noise Can Be Tolerated?

- Direct sequence spread spectrum (DSSS)
- Determine minimum allowable SNR to meet specifications
Step 2: Overall RF Receiver Performance

- Determine Receiver Gain / Noise Figure
- ADC dynamic range
Step 3: RF Receiver Noise and Power Budget

- Refine the model of the RF Receiver and determine the link budget
Step 4: Design the RF Architecture

- Specify the architecture of the Receiver: Direct Conversion
Step 5: Add RF Impairments

- Explore the causes and effects of DC offset
Modeling RF Front Ends with SimRF

- Model the entire system including RF
  - Leverage MATLAB and Simulink
- Two libraries supporting two simulation approaches
  - Equivalent Baseband for all digital simulations of 2-port single carrier cascaded systems
  - Circuit Envelope for multi-carrier simulation of arbitrary topologies
- Trade off simulation speed and modeling fidelity
More Technical Details
Equivalent Baseband RF Models
Rapid Single-Carrier Simulation of RF Cascades

- Link budget analysis for super heterodyne transceivers
- In-band odd-order spectral regrowth and mismatches
Equivalent Baseband Library
Discrete-Time Frame-Based RF Simulation

- Frequency defined (linear) elements
  - S-parameters, Lumped components, Transmission lines
  - Equivalent baseband (FIR) descriptions taking into account input / output mismatches

- Nonlinear elements
  - Amplifiers, Mixers
  - Static odd-order characteristics
From Pass-Band to Equivalent Baseband

Pass-band transfer function

Baseband-complex equivalent transfer function

Baseband equivalent time-domain impulse response

... MHz ...GHz ...

Bandwidth = \( 1/T_s \)

Number of sub bands (freq. resolution) equals length of impulse response
Circuit Envelope RF Models
Multi-carrier Simulation of Arbitrary RF Networks

- Interferers and spurs analysis at system-level
- Arbitrary networks
Circuit Envelope Library
A Transient Simulation Superimposed to Harmonic Balance

- Frequency defined (linear) elements
  - Lumped components, Transmission lines
  - S-parameters: frequency domain models for “flat” characteristics
  - S-parameters: rational fitting for broadband components

- Nonlinear elements
  - Amplifiers, Mixers
  - Static even and odd order characteristics

- Author your own model using Simscape
Multi-Carrier Envelope Simulation

Complex envelope of modulated input signals

Circuit-envelope simulation

Complex envelope response around the selected carrier

Carriers

Harmonic tones

Signal envelope
Circuit Envelope 1/2

- Based on multiple Harmonic Balance analysis
- The coefficients of the harmonic tones are time-varying

\[ V_{in} = \text{Re}\{V(t)e^{j\omega_{carrier}t}\} \]

\[ V_{out} = \text{Re}\{\sum_{k=0}^{N} V_k(t)e^{j\omega_{carrier_k}t}\} \]
Circuit Envelope 2/2

- Transient simulation to calculate the time-varying envelopes of the signal around the harmonic tones
SimRF and Simscape
Modeling of the IF Chain for Image Rejection

- Model the RF chain with SimRF and IF chain the electrical domain
Using Simscape Together with SimRF

- Early exploration of the receiver architecture
- Intuitive analog model of the IF chain
- Refine complex architectures:
  - Differential
  - Biasing networks
- Build your own models using the Simscape language
  - Models compatible with SimRF Circuit Envelope
Behavioral Modeling of Analog Electronics

- Simscape: Acausal, implicit, differential algebraic equations
- Very similar to VerilogA

VerilogA

```verilog
module Amplifier(in_port, out_port);

analog begin
  I(in_int) <= cin*1e-9 *ddt(V(in_int));
  I(in_int) <= V(in_port)/rin*(1-s11)/(1+s11);
  I(in_int) <= -a2*s12/(sqrt(rin)*(1+s11));
end
```

Simscape

```simscape
component Amplifier

equations
  in
    
    I_in == cin * Vin.der + ...
    Vin/rin*(1-s11)/(1+s11) + ...
    -a2*s12/(sqrt(rin)*(1+s11));
```

...
Conclusions
Modeling RF Systems with MathWorks

- Combine digital baseband, analog and RF
  - Integrate your design and find errors early

- Progressively refine your design with a top-down methodology
  - The verification effort will be limited

- Trade off accuracy and execution speed by choosing the desired abstraction level
  - You don’t have to become a modeling guru
Next Steps

- For more information please contact me: giorgia.zucchelli@mathworks.com
- For an evaluation or trial please contact your account manager
- Thank you for your interest