Ultra-wideband System Simulation using SystemC AMS in Industrial Environment

COSEDA UG Meeting 2025

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Introduction

Ultra-wideband SystemC/-AMS Model

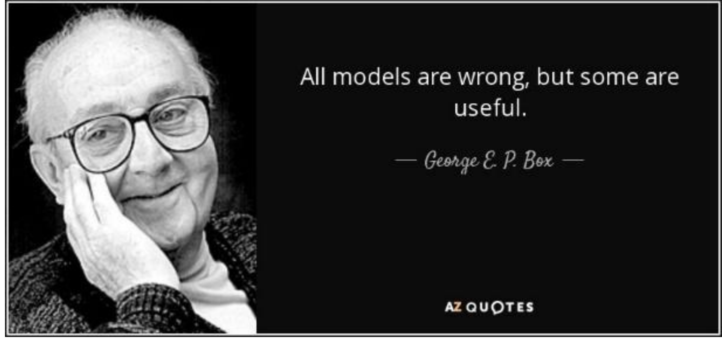
- Implementation
- Verification setup

Simulation vs. measurements results

Statistical simulation results

Conclusion

Introduction



- Shift-left approach: Moving verification in the early-stage together with software development & testing

- Virtual models play a crucial role

- Benefits:
  - Earlier detection of bugs
  - Reduced costs
  - Improved Quality
  - Faster time to market

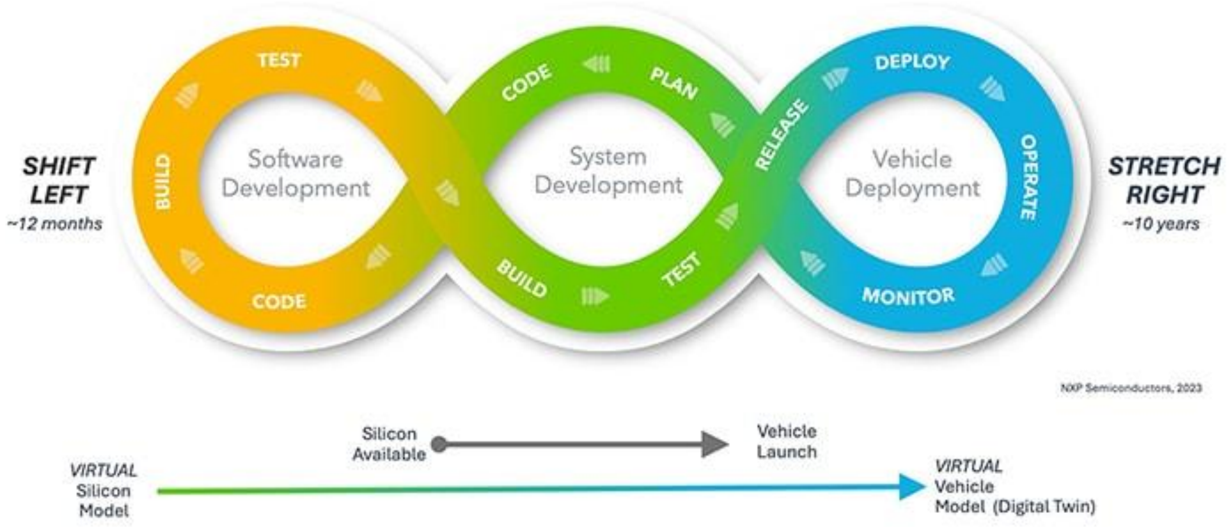
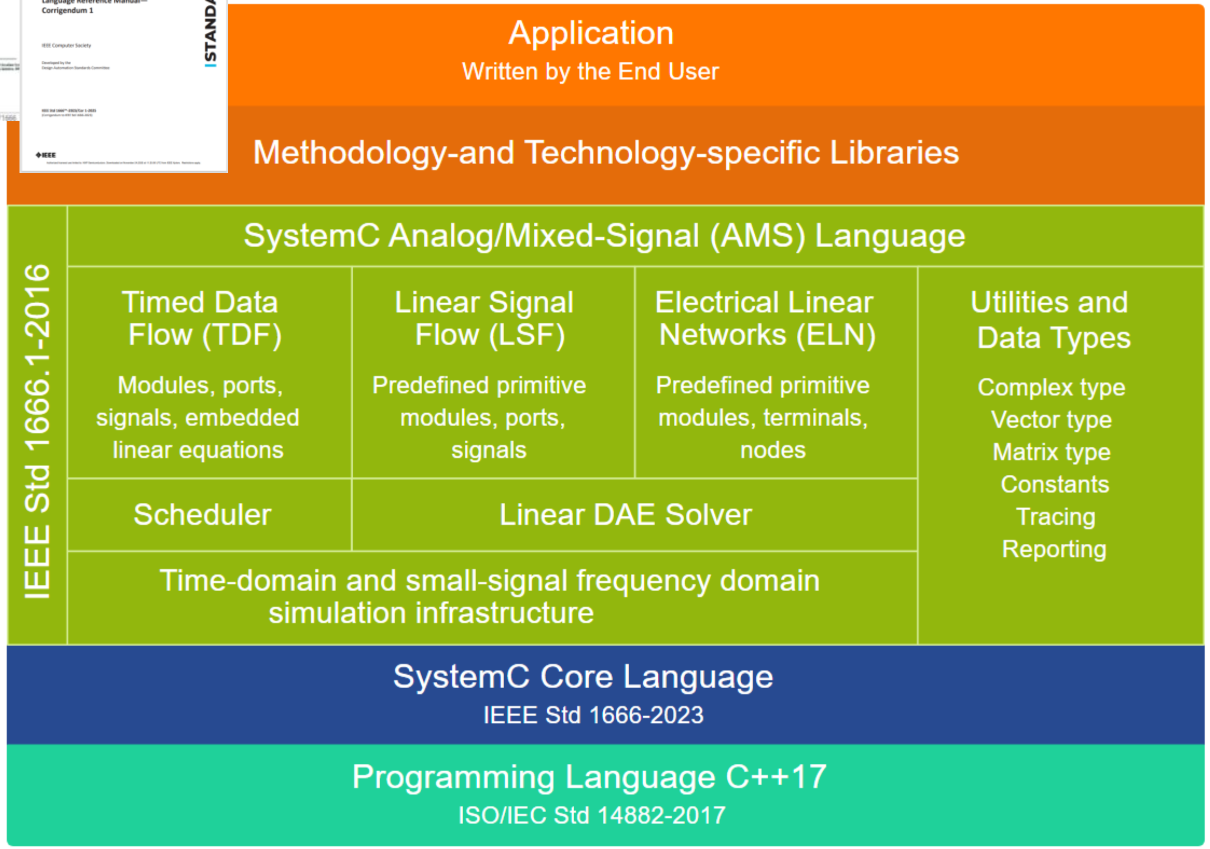


Fig. source: [The Future of SDVs | NXP Semiconductors]

Why SystemC/-AMS?

Open and well-established IEEE & IEC standard



RF Modelling Modes (offered by COSIDE)

- Passband, baseband & envelope simulations

Multi-domain support

- Analog (TDF, ELN, LSF)
- Digital
- SW Components

C++ foundation

- Fast model execution
- Easy integration across tools
- Firmware in the loop capability

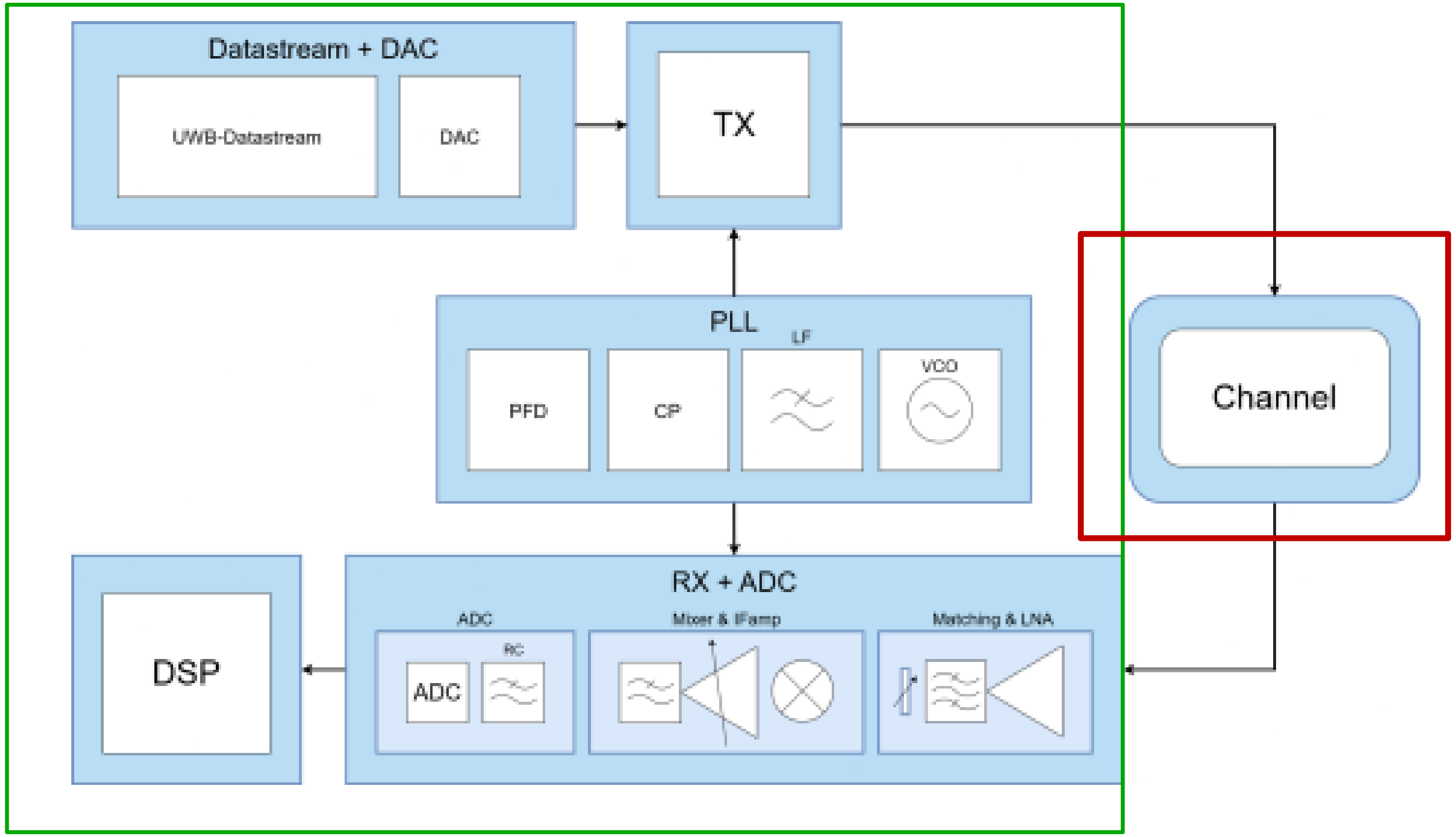
Fig. source: systemc.org

Ultra-wideband System Modelling in SystemC/-AMS

Ultra-wideband (UWB) System

- UWB system is composed of:
  - Transceiver
  - Channel

- The transceiver building blocks:
  - A datastream + DAC input generator
  - Transmitter Tx
  - Receiver Rx
  - ADC
  - Simplified DSP to quantify the PER
  - PLL to provide the RF clocks for Tx and Rx



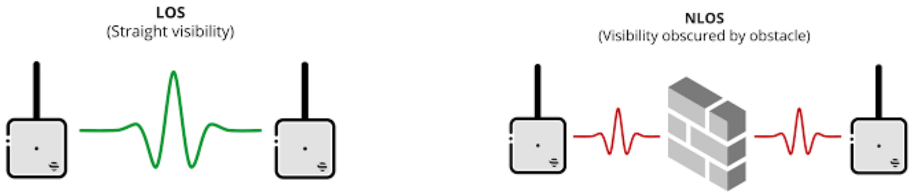
Block diagram of the UWB system in a loop-back configuration

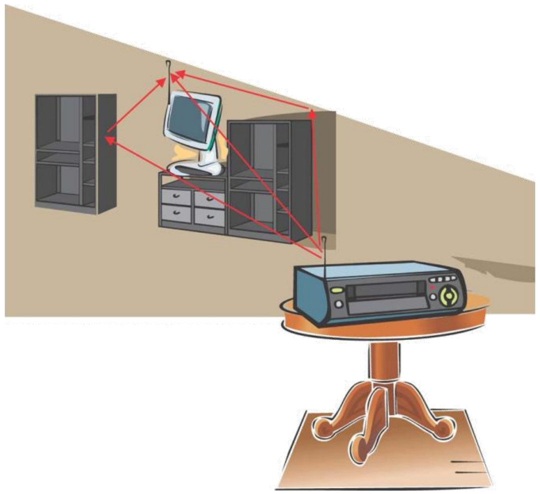
PER – Packet Error Rate

Note: The figure is for demonstration purpose only. The real setup includes an inter-chip communication between two UWB transceivers (in the upcoming slides).

UWB channel

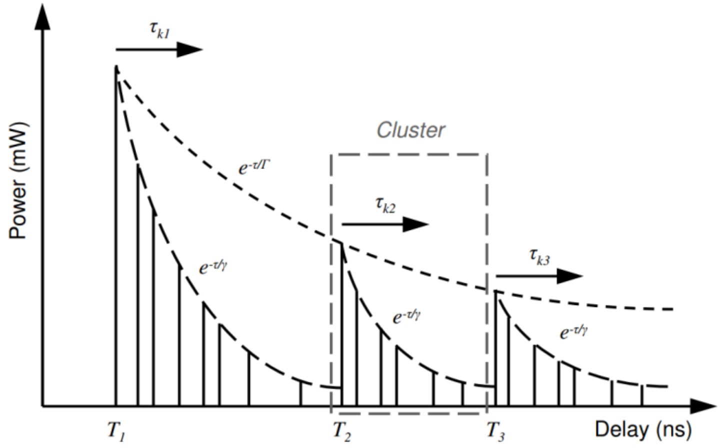
- The channel modelled in SystemC following the standard IEEE 802.15.4a
- The standard differentiates between Line of Sight (LoS) & non-Line of Sight (NLOS) scenarios





Signal reaches receiver through different paths and interactions; Signal components called multipath components (MPCs)

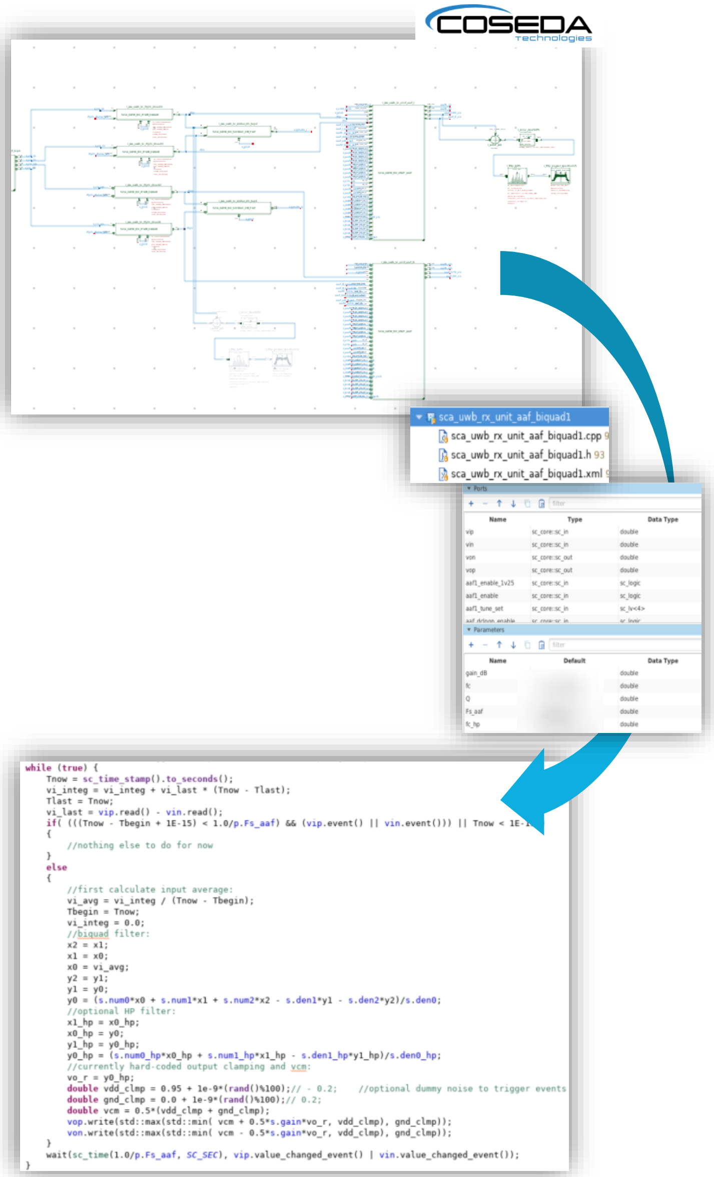
- Different effects captured by the SystemC model:
  - Pathloss over distance and frequency
  - Multipath propagation
  - Shadowing



Transceiver modelling in SystemC/-AMS

- SystemC DE - Discrete Event:
  - Used for the majority of the UWB system blocks
  - Control paths with rare events
- SystemC-AMS:
  - TDF – Timed Data Flow with fixed sampling rate
  - Modeling subparts (e.g. LNA+mixer), improved speed when used for datapath and longer chains of TDF blocks
- RF modelling techniques in COSIDE:
  - Passband with full RF frequencies → **our focus here**
  - Baseband and Envelope modelling, currently under investigation

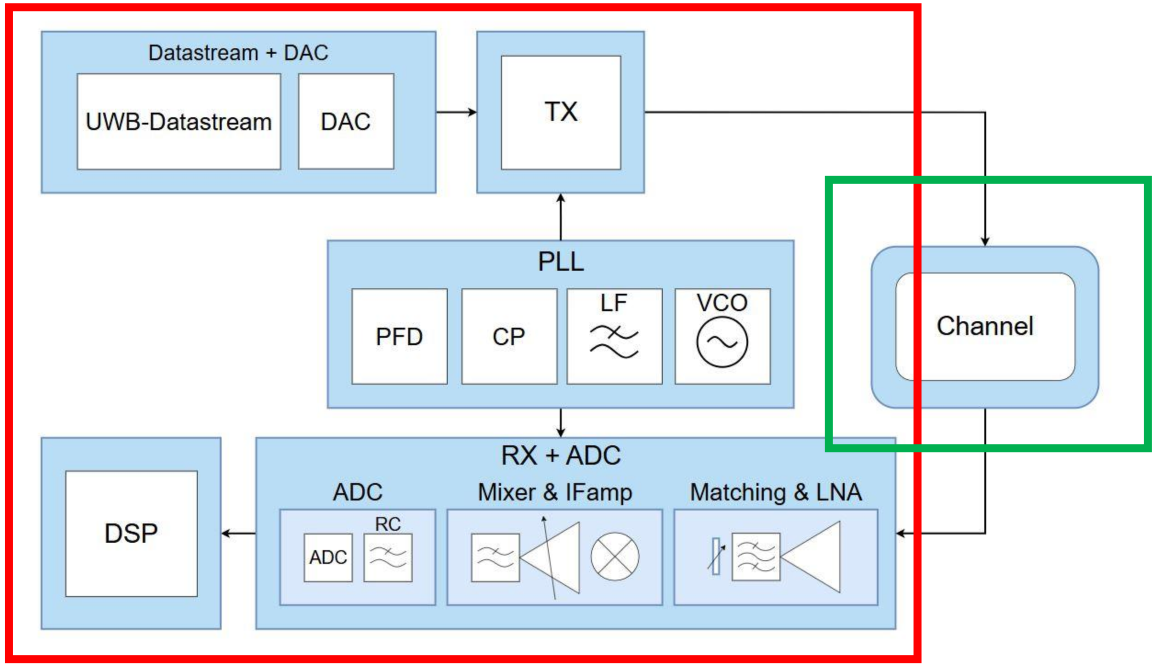
Coside GUI automatic model creation



Verification of SystemC/-AMS implemententaions

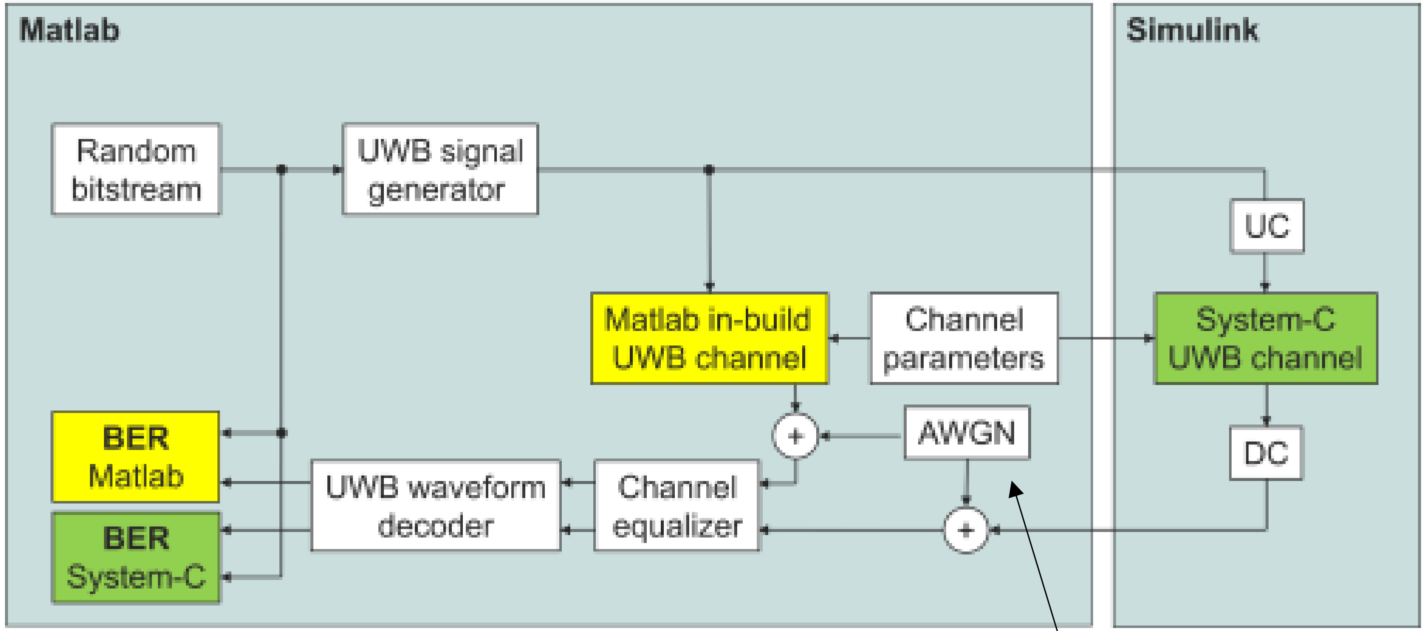
Verification of SystemC AMS implementations

- Transceiver implementation verified through comparison with measurements
- Anechoic chamber used as environment
- Channel implementation compared to the existing MATLAB implementation



Channel Verification Setup

- Direct conversion SystemC -> Matlab/Simulink using COSIDE
- Passband channel implementation
- Random bitstream encoded in the payload of an UWB waveform according to the IEEE 802.15.4a
- At the receiver side the payload get decoded and its BER is calculated



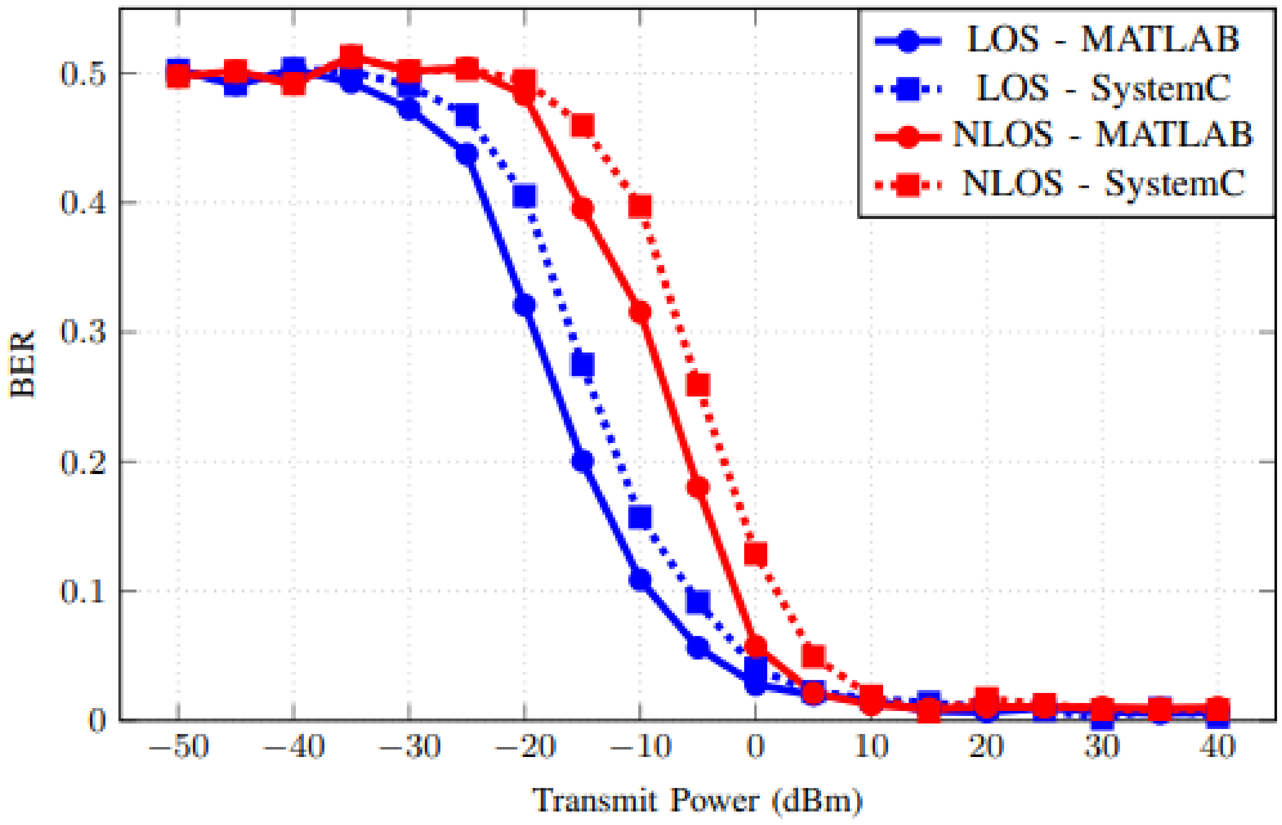
Receiver noise at -75dBm added before equalizer

UC – Up conversion
DC- Down conversion

BER – Bit Error Rate

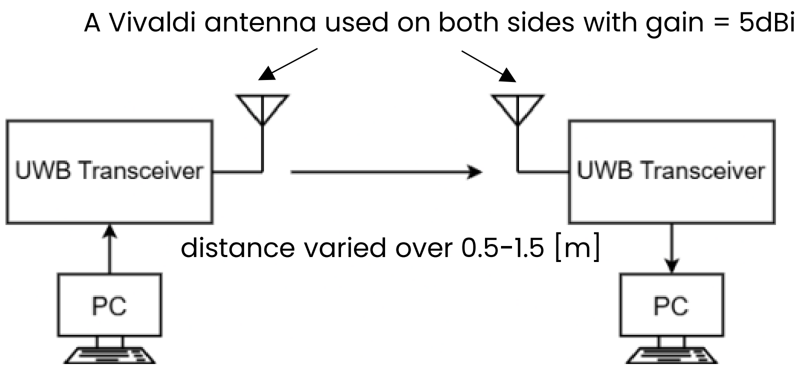
Channel verification results

- Good agreement of the Bit Error Rate (BER) from MATLAB and SystemC
- The results averaged over 200 realisations of the industrial environment
- Beside a constant 4-5 dB power difference the BER curves of both models match in the LOS and NLOS scenario
- Deeper analysis shows that shift is caused by the differences in the Power Delay Profile

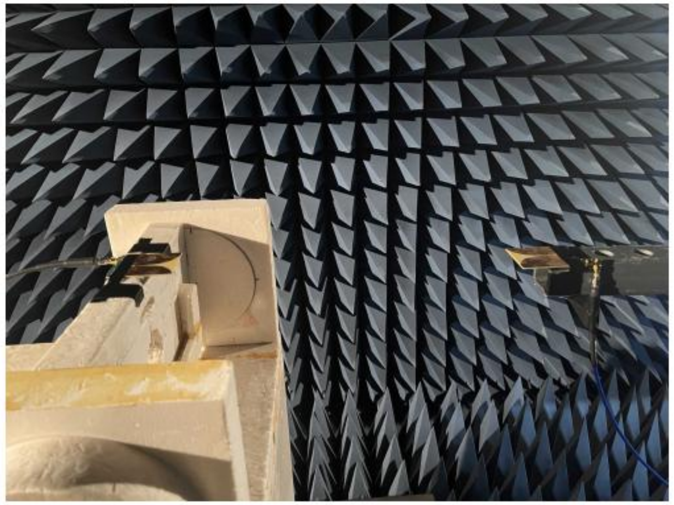


UWB Transceiver Verification

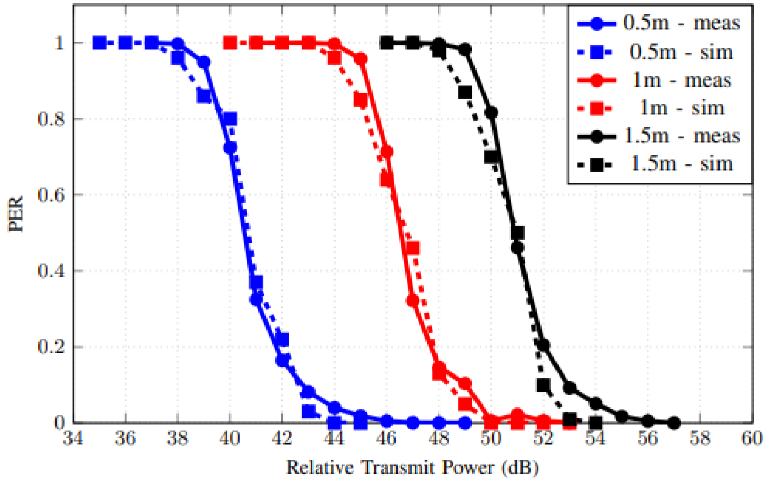
- Measurements:
  - Sent by transmitter: 32 preamble symbols from IEEE code index 25 + 10 bytes payload
  - The packet is erroneous if one or more payload bytes incorrectly received
- SystemC Simulations:
  - On the receiver side, the ADC signal correlated with the preamble signal
  - Correlation > threshold => the frame received correctly



Block diagram of the UWB Measurement Setup



Placement of the antennas connected to the UWB transmitter and receiver in the anechoic chamber



Comparison of PER between simulation and measurements

PER as figure of merit for TRx:

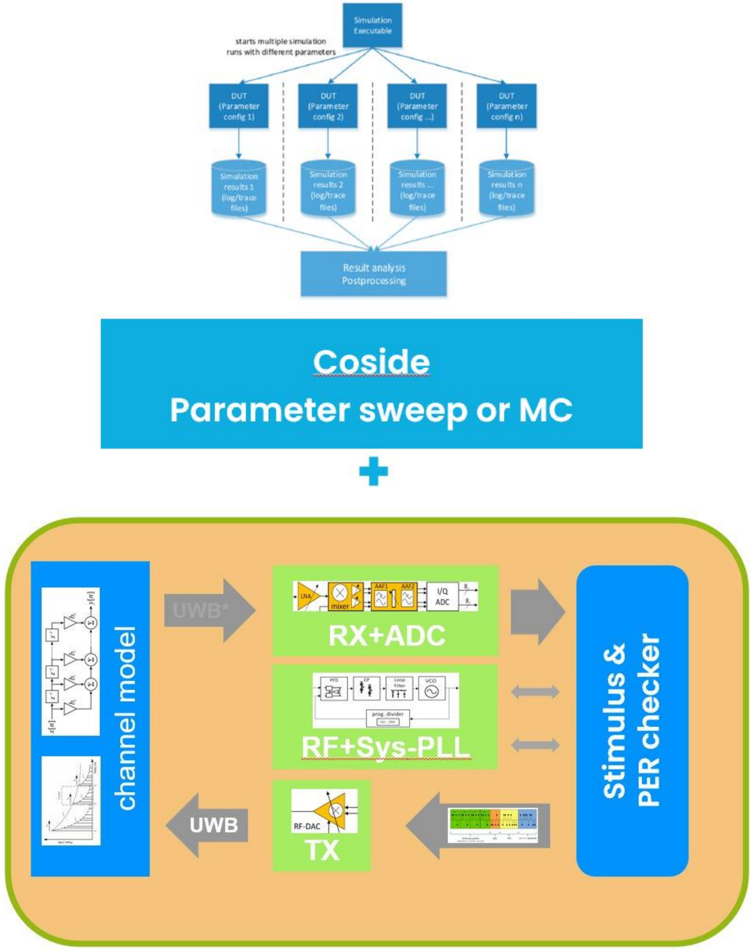
$$PER = \frac{\#erroneous}{\#total\ packets}$$

Statistical UWB simulation

COSIDE SWEEP ENGINE

- Sweep engine offered by the COSIDE statistics library
- Easy setup via generic testbench & setting up simulation type
  - `simulation_type::PARAMETER_SWEEP`
  - `simulation_type::MONTE_CARLO` (statistical)

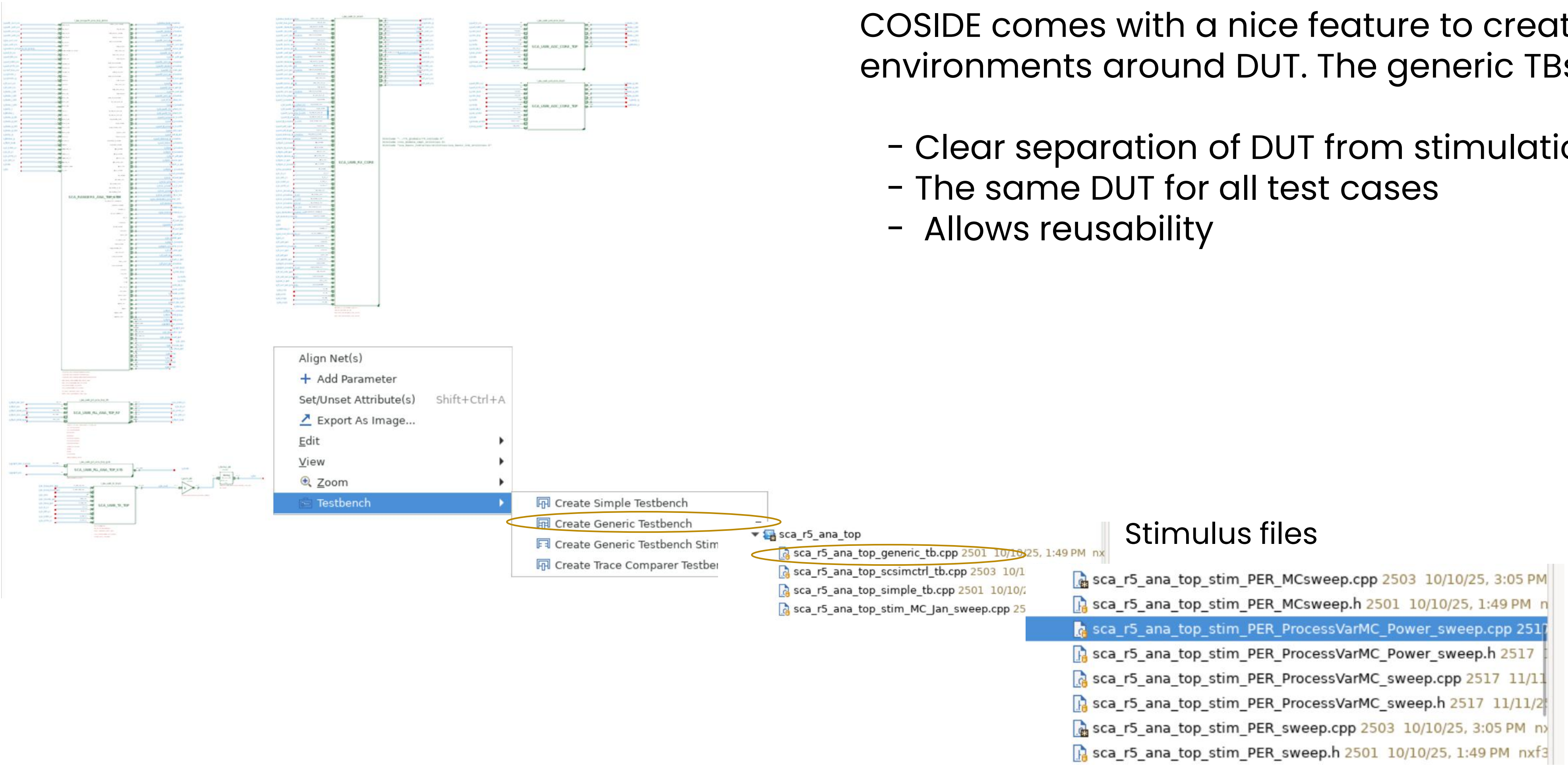
- Analyse the impact of variations on PER



UWB TRx GENERIC TESTBENCH in COSIDE

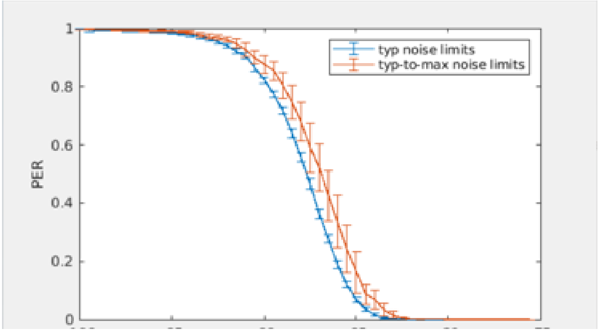
COSIDE comes with a nice feature to create generic TB environments around DUT. The generic TBs advantages:

- Clear separation of DUT from stimulation
- The same DUT for all test cases
- Allows reusability

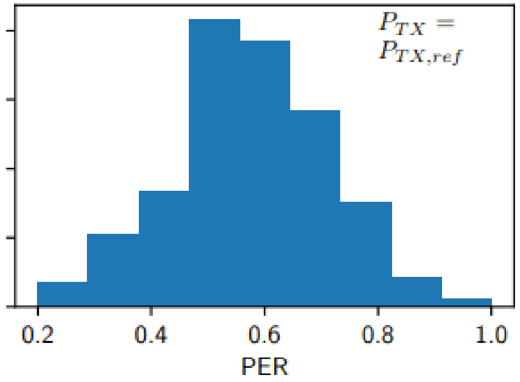


Statistical Simulation results

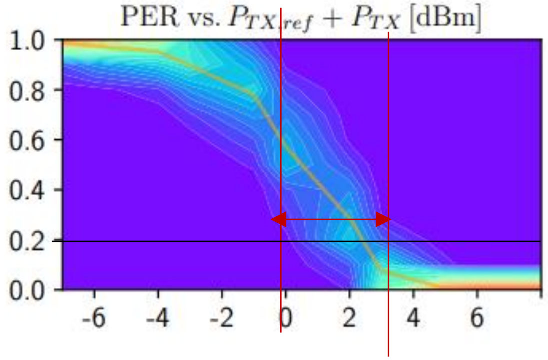
- Stimulus 1 (PER_MCsweep.cpp)
- Noise sources for Rx chain blocks
- Top-down: Equal value probabilities over the specification range ~ U[typical, max]



- Stimulus 2 (PER_ProcessVarMC_sweep.cpp)
- Gain & Noise sources for Rx chain blocks
- Bottom-up: Gain & Noise models as functions of process variations from PDK
- Analyse the impact of process spread on PER at reference Tx power



- Stimulus 3 (PER_ProcessVarMC_Power_sweep.cpp)
- Stimulus 2 + sweep over input Tx power
- Analyse the impact of process spread on Rx sensitivity



Conclusion

- A full UWB system implemented and simulated completely in COSIDE with the channel model according to the IEEE 802.15.4a standard
- The SystemC/-AMS implementation of each component verified either through measurements in anechoic chamber or MATLAB simulations
- Simulations of the full UWB compared with measurements in an industrial environment showed also a good match
- SystemC & its AMS extension is an invaluable tool for early verification of RF systems for the general as well as specific applications & scenarios

This presentation is mainly based on the work published in the paper under the same title.

Get in touch

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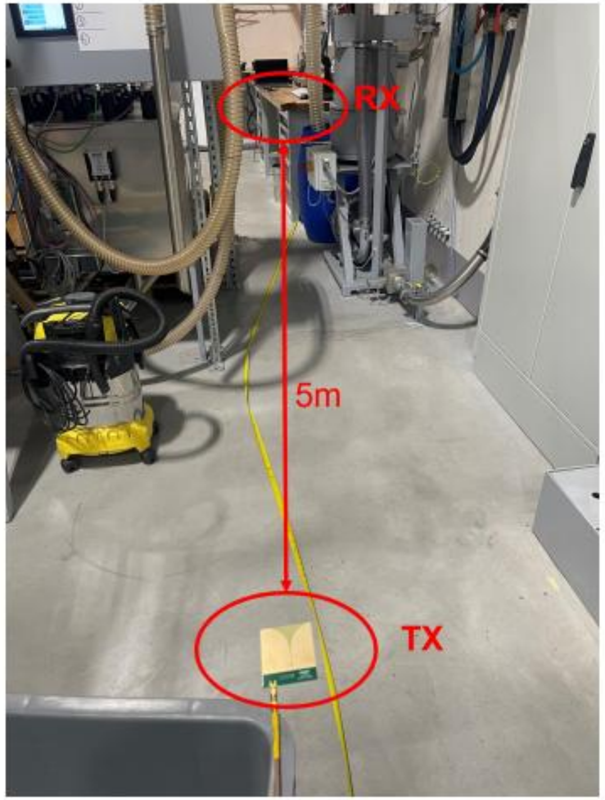
BACKUP SLIDES

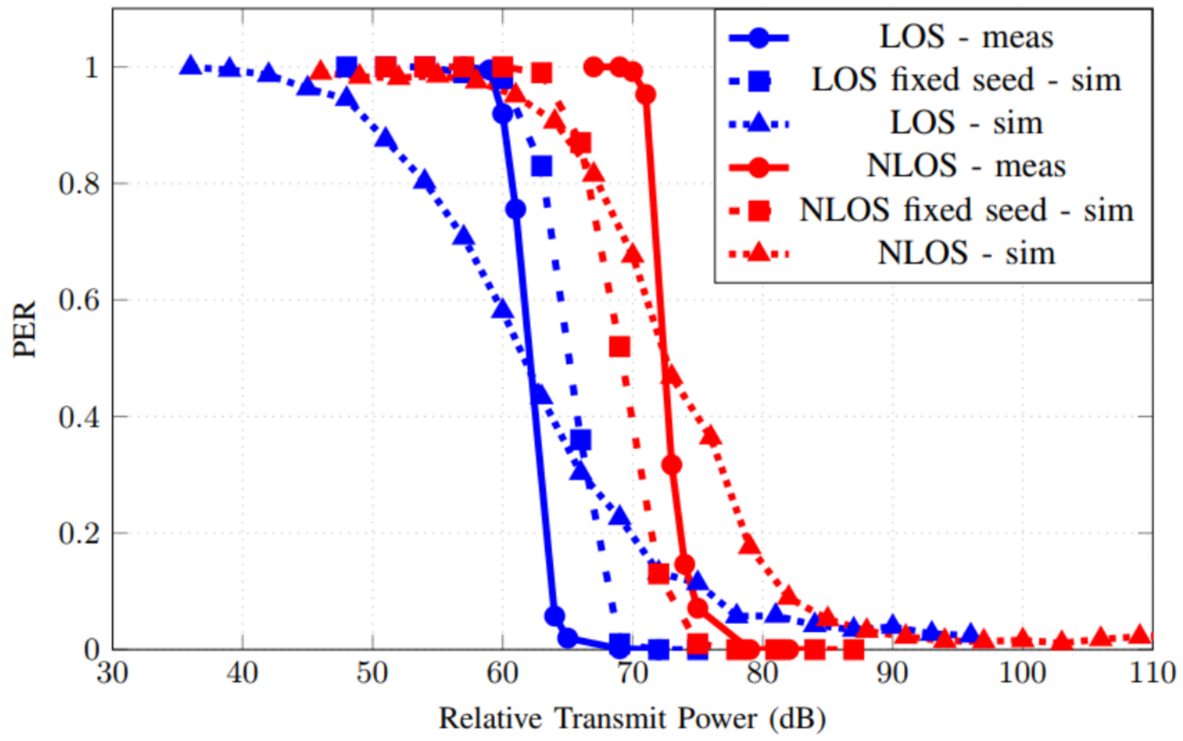
Measurement setup in an Industrial Environment

- Factory floor at Linz Institute of Technology (LIT), Austria
- Vivaldi antenna used as in the anechoic chamber
- 5m distance between Tx and Rx operating at 6.9888 GHz
- LOS and NLOS scenarios



SystemC-based simulations vs. measurements

- Simulation's slope is flatter than measurement
- Stochastic channel model averages over many instances of the same environment as defined by the standard
- Fixing seed of all random variables to simulate a single instance of the channel (squared marked curve)
- Results in a sharper slope closer to measurements
- The choice of the seed value affects the receiver sensitivity; the curve shifted to the right or left



Channel model in SystemC (Approximation of the anechoic chamber behaviour)

- Modelled a simple free space pathloss
- Pathloss is both frequency and distance dependent

Distance dependency:

$$PL\,(d) = PL_0 + 10\log_{10}(\frac{d}{d_0})^n$$

d – Tx-Rx distance
d_0 - reference distance
n - exponent

Frequency dependency:

$$PL(f) \propto \left(\frac{f_c}{f}\right)^{2k+2}$$

f_c – carrier frequency
k – frequency exponent

- In the model
  - Pathloss Exponent n=2
  - Frequency exponent k=0.12
  - The frequency exponent value defined by the standard for the outdoor environment
  - The closest approximation to the anechoic chamber behaviour since in outdoor there are much less reflections

UWB Transceiver Verification Setup

- Tx and Rx operate at 6.9888 GHz
- PER utilized to evaluate the performa of the UWB system

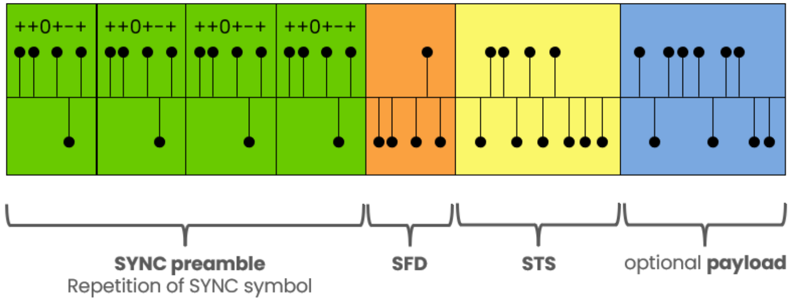
$$PER = \frac{\#erroneous}{\#total\ packets}$$

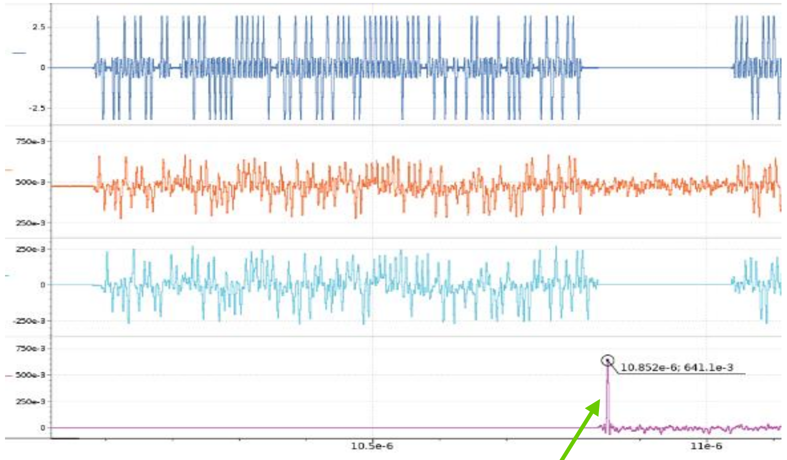
- Measurements:
  - 32-symbol preamble signal + a short payload of 10 bytes sent by the transmitter
  - The packet is erroneous if one or more payload bytes incorrectly received
- Simulations:
  - On the receiver side, the ADC signal correlated with the 32-symbol preamble
  - Correlation > threshold => the frame received correctly

From IEEE code index 25

Table 15-7a—Length 91 ternary codes for the HRP-ERDEV

Code index	Code sequence
25	–0++++––+––+–++++–+–––++––++++++–++–+00+––+0––+0+++++––+ ++––0––0+–+––––0–+–+–+0+––++–+–+++0
26	++0+–+–––+++++–+–++––+––++–––+–0 ++++––+–++00+++––0+–––––+–0+–+–+
27	+++––+++–––+–+–0–+––0++–+–+0–+++ ––+––+++–––0–+++–0+00–––++–+––0–+
28	+++++––+++–++–––+–+––0++–––+–+0+ ++0–0–++00+–+++–++–+0–+0––+–––++
29	+–0––+–++––0++00++–++–––––++++++ +–+++0+–+–0–0–++–––+0–––++0–+–+–+
30	–++0––0++–00––++–++–+––+++++–––+ +–+0––––––++–++–+0––––+–+–0+0+–++
31	–+–++0+++––++–0++00––++––+++–+––– –+–––+–+0–+––0+0+–++–++0+–+––0++
32	–++++++++++++–––+–++––++00–+–+0–+ –0–––++–0––––++++–+–0+0–+–++–++––





Tx in

ADC out

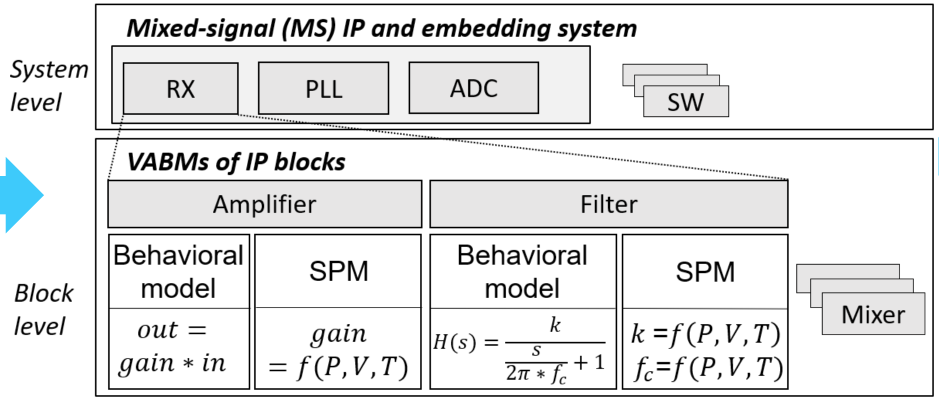
~65% correlation

Statistical Performance Models Bring Variations From Spice to Behavioral Models

Behavioral/System level

Functional description of system behavior $f_{beh}: Inputs \rightarrow Outputs$ in arbitrary modeling language

Variation-Aware Behavioral Model (VABM)



Statistical System Simulation with PVT

SPICE/Circuit level

SPICE netlists
Process design kits (PDK)
Manageable complexity

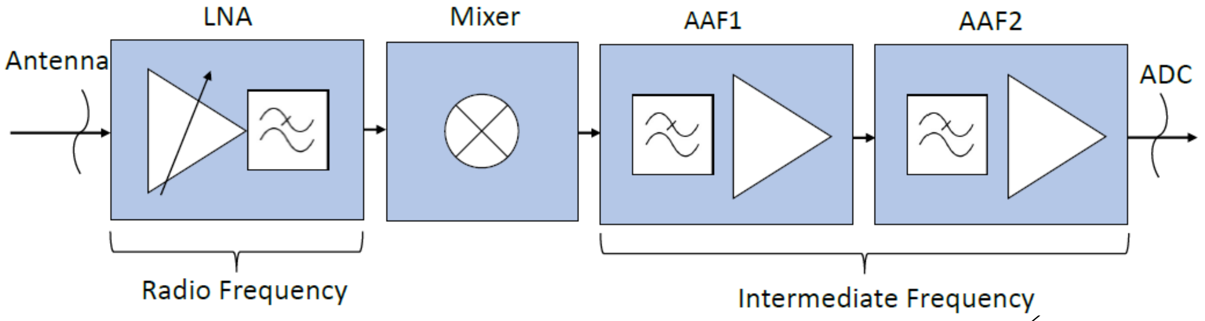
Statistical Performance Models (SPMs):

Model performance metrics as functions of PVT variations:

$$y = f(PVT) \sim \mathrm{SPM}(PVT)$$

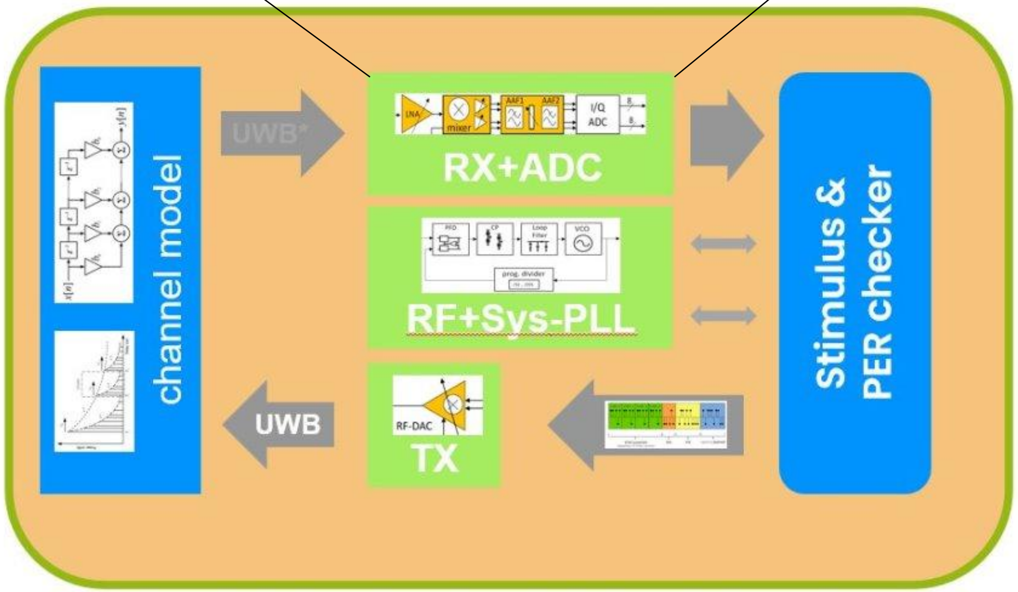
Notes and sources

Bringing variations in UWB Rx chain blocks from Circuit- to System- Level



Circuit level:

- Modeled in SPICE
- seperate testbenches for LNA and AAF chain
- Variations from PDK
- <u>Performances:</u>
  Amplifier Gains, Noise sources



System level:

- Modeled in SystemC/-AMS
- Model contains TX, channel emulation and RX
- <u>Performance:</u> Packet error rate

$$PER = \frac{\#\text{erroneous packets}}{\#\text{total packets}}, \quad 0 \leq PER \leq 1$$

Receiver sensitivity ($P_{TX,\,min}$ [dBm])

Minimum input power $P_{TX,min}$ to achieve a target PER ($PER < thr$)

Thanks to the SCA Team in Gratkorn for their support!