Implementation of an ASIP based SDR platform for MIMO OFDM transceivers

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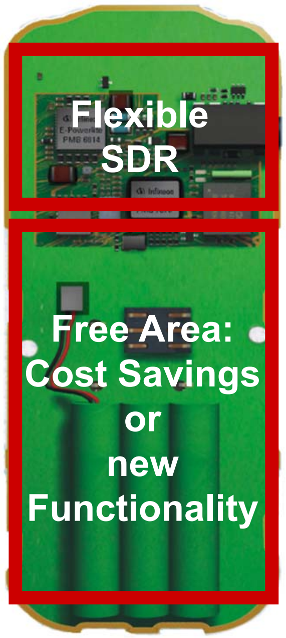
Outline

Software Defined Radio Challenges

- **Nucleus Methodology**
  - Efficient HW/SW Development
  - Case Study: PHY MIMO OFDM Transceiver
- **ASIP based SDR platform**
  - ASIP Design Approach
  - ASIP for MIMO Processing
  - SDR Platform Design
- **Summary**

Software Defined Radio Vision

Source:
Infineon Technologies



Source:
Infineon Technologies

Today‘s Mobile Phone

Future SDR Mobile Phone

The three key properties:

- **Portability**
  - Software is portable onto different platforms
    Standard.exe → Device_1, ..., Device_n
- **Interoperability**
  - Different devices configured for the same standard interoperate
    Standard_1/Device_1 ↔ Standard_1/Device_2
- **Loadability**
  - Platform is capable of running different standards
    Device ← Standard_1.exe, ..., Standard_n.exe

But we <u>must not</u> forget:

- **Efficiency**
  - Power consumption of flexible SDR must be close
    to power consumption of dedicated device (*battery driven!*)

The three key properties:

- **Portability**
  - Software is portable onto different platforms
    Standard.exe → Device_1, ..., Device_n
- **Inte**
  - erate
- **Loa**
  - *Device ← Standard_1.exe, ..., Standard_n.exe*

Contradicting Requirements!

Flexibility (programmability) vs. Energy Efficiency

But we must not forget:

- **Efficiency**
  - Power consumption of flexible SDR must be close to power consumption of dedicated device (*battery driven!*)

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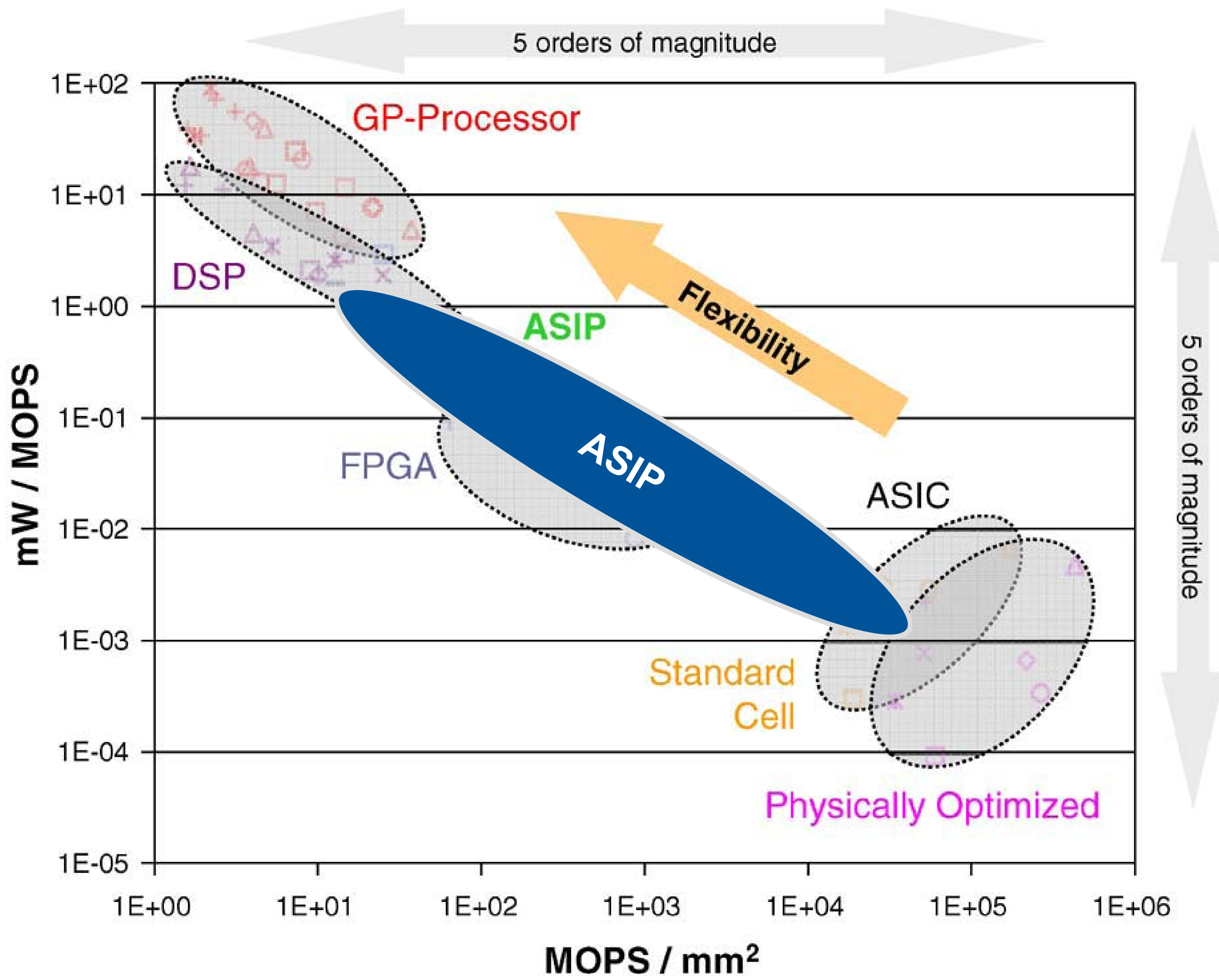
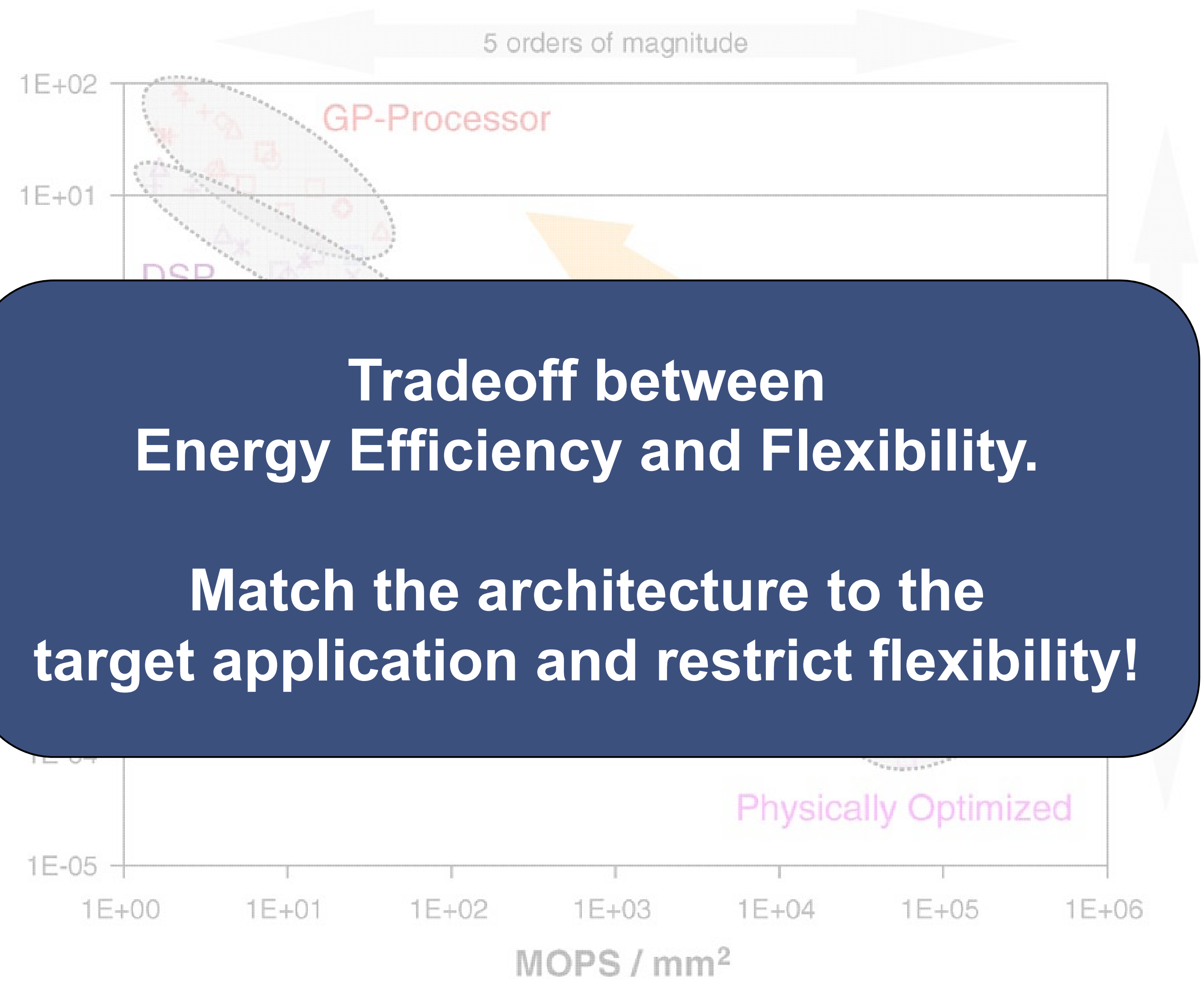
Computational Effiency vs. Flexibility



Source : T.Noll, H. Blume



Tradeoff between
Energy Efficiency and Flexibility.

Match the architecture to the
target application and restrict flexibility!

Source : T.Noll, H. Blume

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Nucleus Methodology: Efficient HW/SW Development

- **Analysis of Communications Applications**
  - Applications are based on a small number of computational kernels (Nuclei)
  - Nuclei represent the major share of computational complexity (90..95%)
  - *Communications applications can be represented as a composition of Nuclei*

- **Impact on ASIP design and software development**
  - Design ASIPs to optimally match a set of Nuclei
  - Design highly optimized Nuclei-implementations (Flavors) for target ASIPs
  - Compose communications application using Flavors

References:

- UC Berkeley, Seven Dwarves, EECS TR, June 15, 2006
- Ienne, Leupers: Customizable Embedded Processors, August 2006

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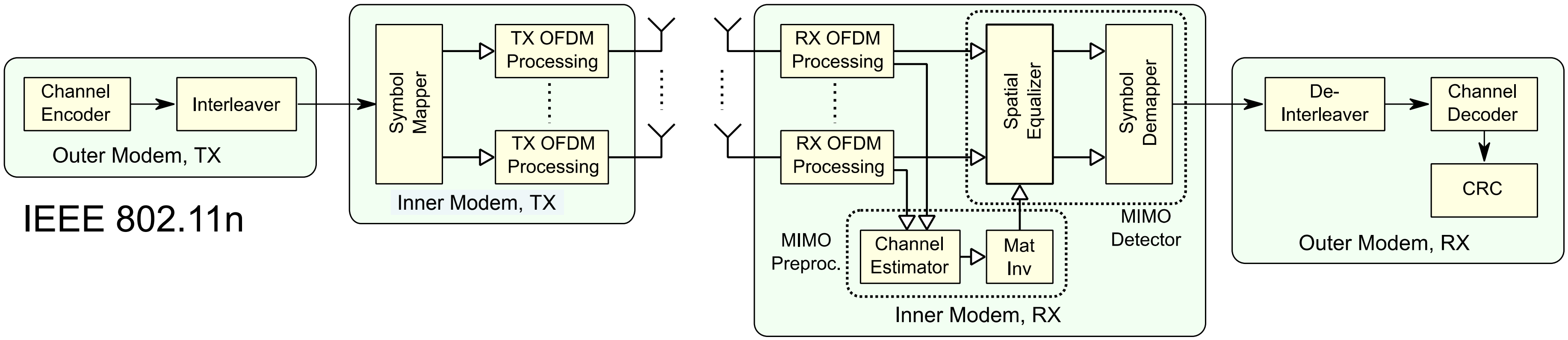
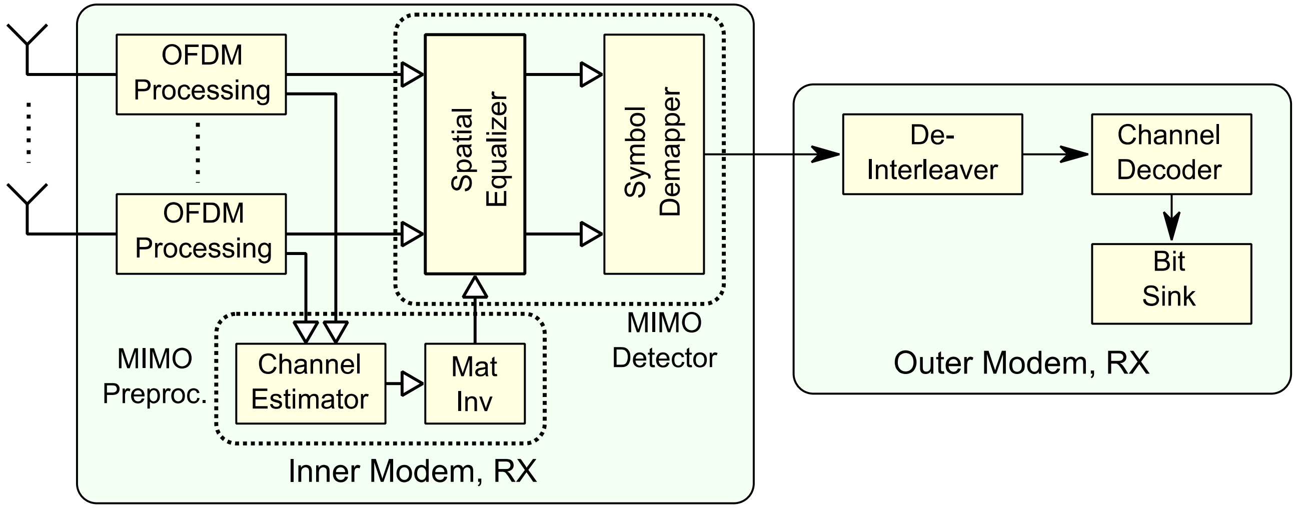
Case Study: PHY MIMO OFDM Transceiver



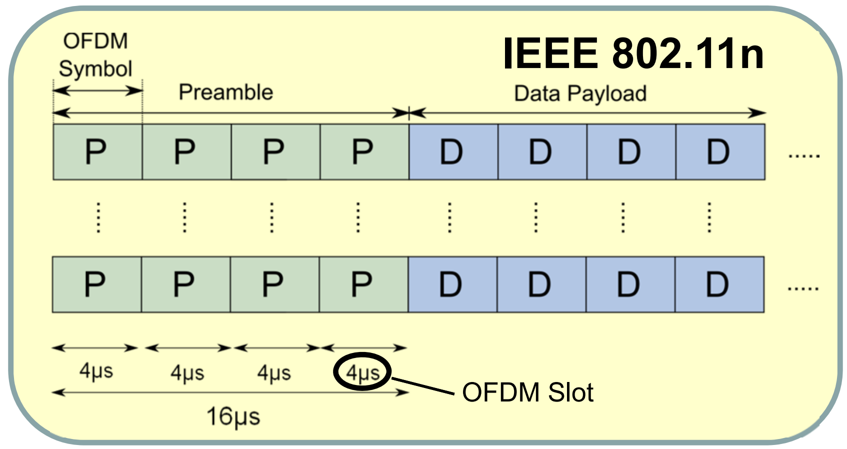
- **MIMO**
  - Multiple-input multiple-output (multi-antenna system)
  - Exploit spatial diversity
- **OFDM**
  - Orthogonal Frequency-Division Multiplexing
  - Robust against frequency selective fading

- **Included in most modern communication standards, e.g. LTE, IEEE 802.11n and WIMAX**

Case Study: PHY MIMO OFDM Transceiver



- **Outer Modem**
  - Channel (De-)coding
  - (De-)Interleaving
- **Inner Modem** (RX)
  - RX OFDM Processing
  - Channel Estimation
  - Spatial Equalizing: Mitigate channel impact on payload
  - Soft Demapping: Calculate soft bits (LLRs)
    BPSK, 4QAM, 16QAM, 64QAM



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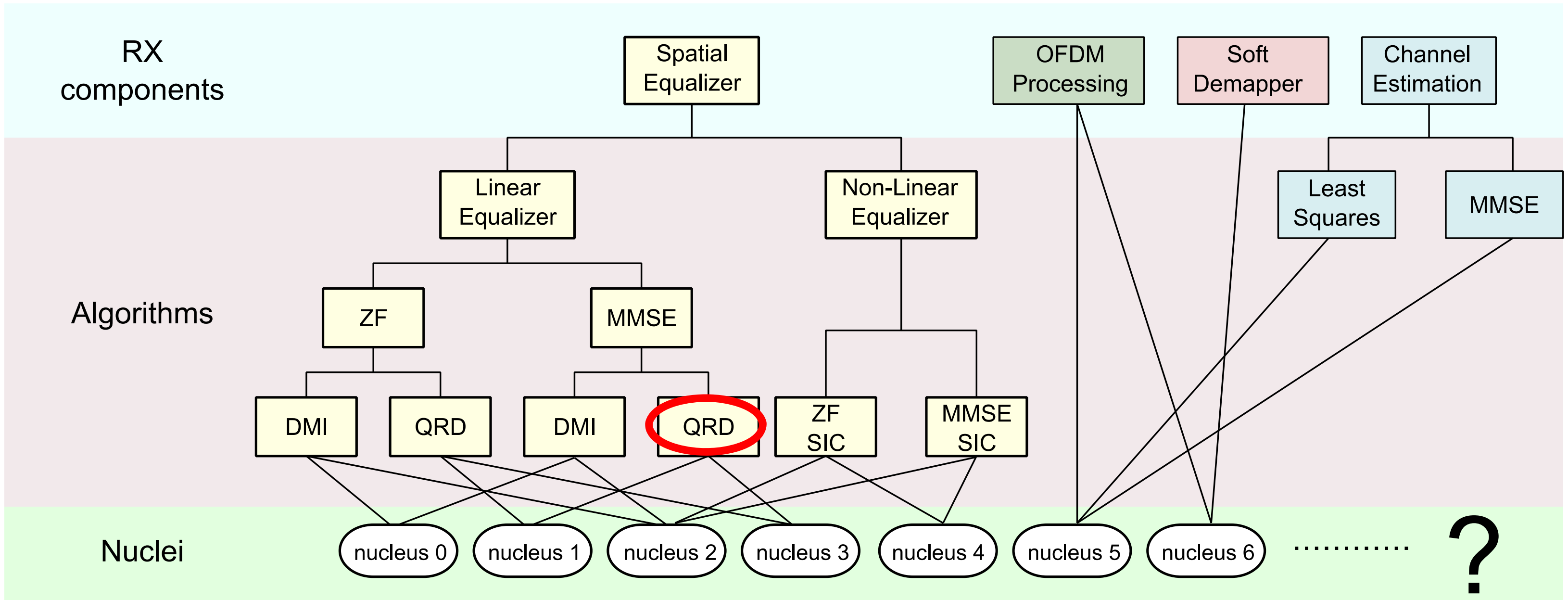
Case Study: PHY MIMO OFDM Transceiver



- **Analyze different algorithmic choices within RX blocks**
  - Identify Nuclei as …
    - … recurring computational operations
    - … operating on data with certain alignment
- **Represent application as composition of Nuclei**

- **LMMSE MIMO Equalizer** with QRD
  - Basic transmission equation

    $$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

  - Linear MMSE equalization

    $$\hat{\mathbf{x}} = \mathbf{G}\mathbf{y}, \quad \mathbf{G} = \left(\hat{\mathbf{H}}^{\mathbf{H}}\hat{\mathbf{H}} + \frac{\sigma_n^2}{E_s}\mathbf{I}\right)^{-1}\hat{\mathbf{H}}^{\mathbf{H}}$$

  - Regularized QRD

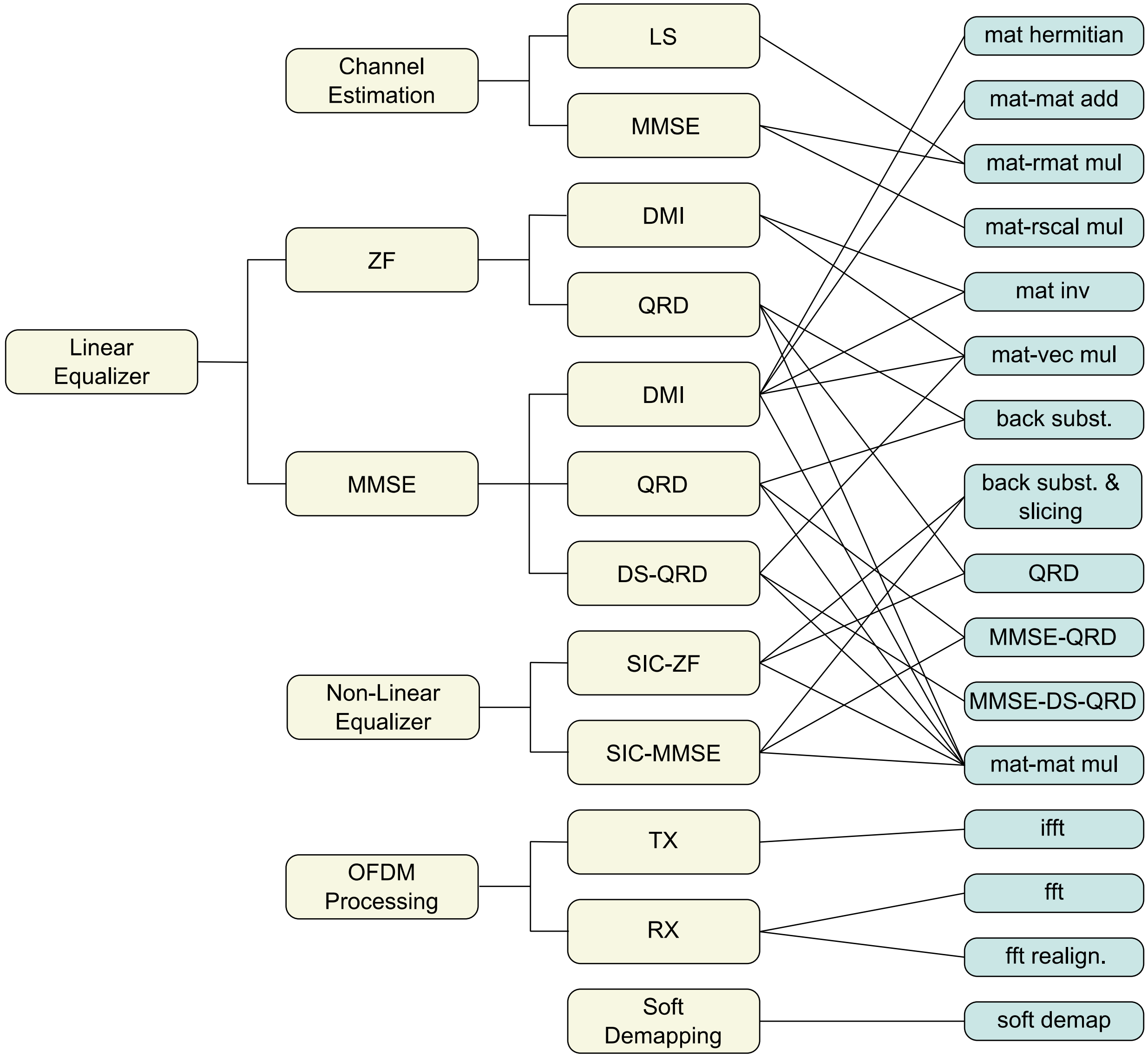
    $$\overline{\mathbf{H}} = \begin{pmatrix} \hat{\mathbf{H}} \\ \frac{\sigma_n}{\sqrt{E_s}}\mathbf{I} \end{pmatrix} = \begin{pmatrix} \mathbf{Q_a} \\ \mathbf{Q_b} \end{pmatrix}\mathbf{R}$$

  - Rewrite **G** using $\mathbf{Q}_a$ and $\mathbf{Q}_b$

    $$\mathbf{G} = \frac{\sqrt{E_s}}{\sigma_n}\mathbf{Q_b}\mathbf{Q_a^H}$$

- **Identified Nuclei**
  - Regularized QR decomposition
  - Matrix-matrix multiplication
  - Matrix-vector multiplication

Case Study: PHY MIMO OFDM Transceiver – Nuclei Identification



- **Application variants consist of a few Nuclei only!**

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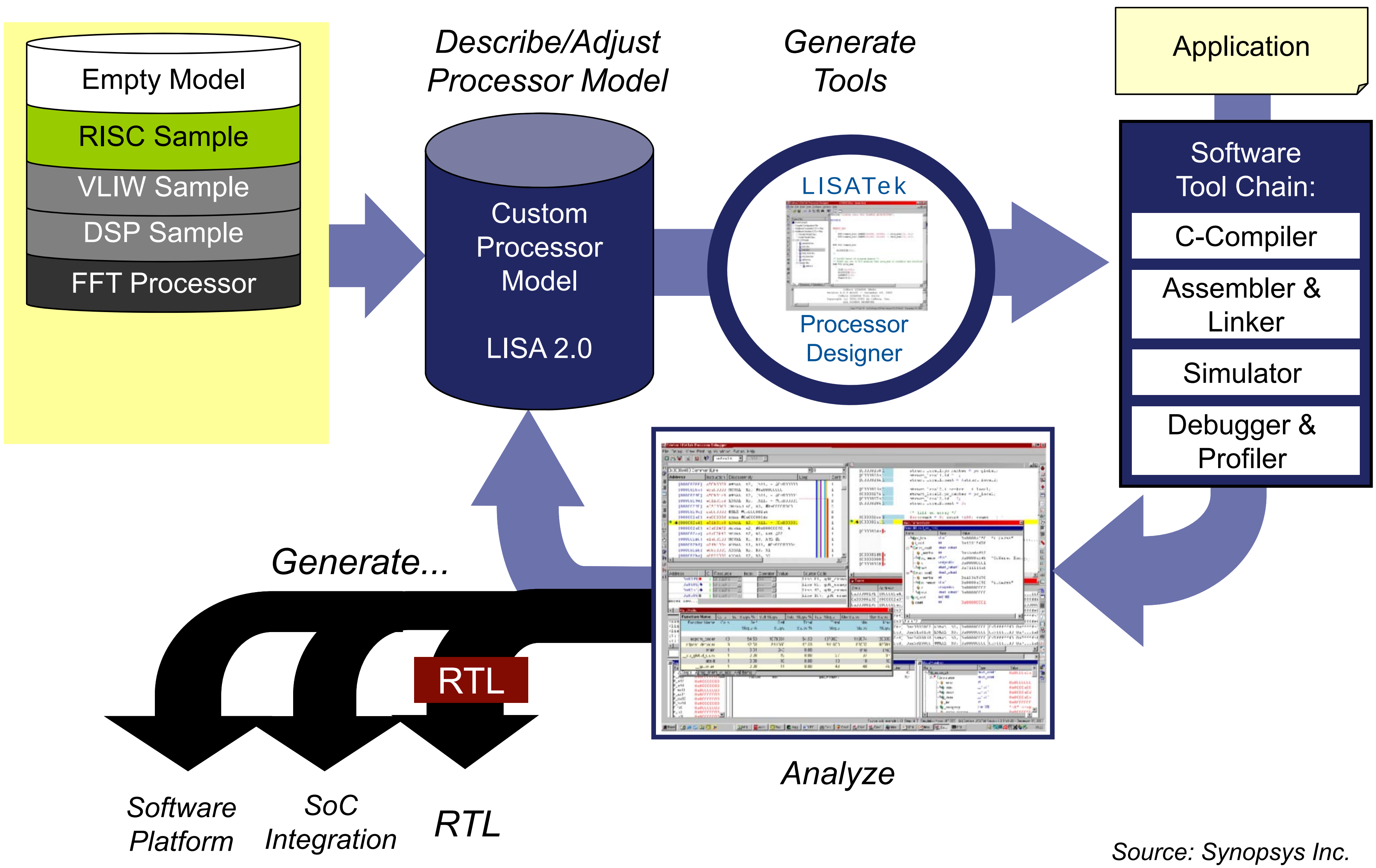
ASIP Design Approach

- **Required ASIP features …**
  - (some) general purpose functionality
    - loops, (conditional) jumps, calls
    - scalar arithmetic
  - application specific “Nuclei-support” functionality

- **Configurable processor cores in industry**
  - Tensilica, e.g. Xtensa LX4 DPU Architecture
  - Synopsys DesignWare ARC Processors, e.g. ARC700 family

- **Architecture Description Language**
  - LISA 2.0 (Synopsys Inc., Processor Designer)
  - nML (Target Compiler Technologies, IP Designer)
  - EXPRESSION (University of California)

ASIP Design Approach: Synopsys Processor Designer™



Source: Synopsys Inc.

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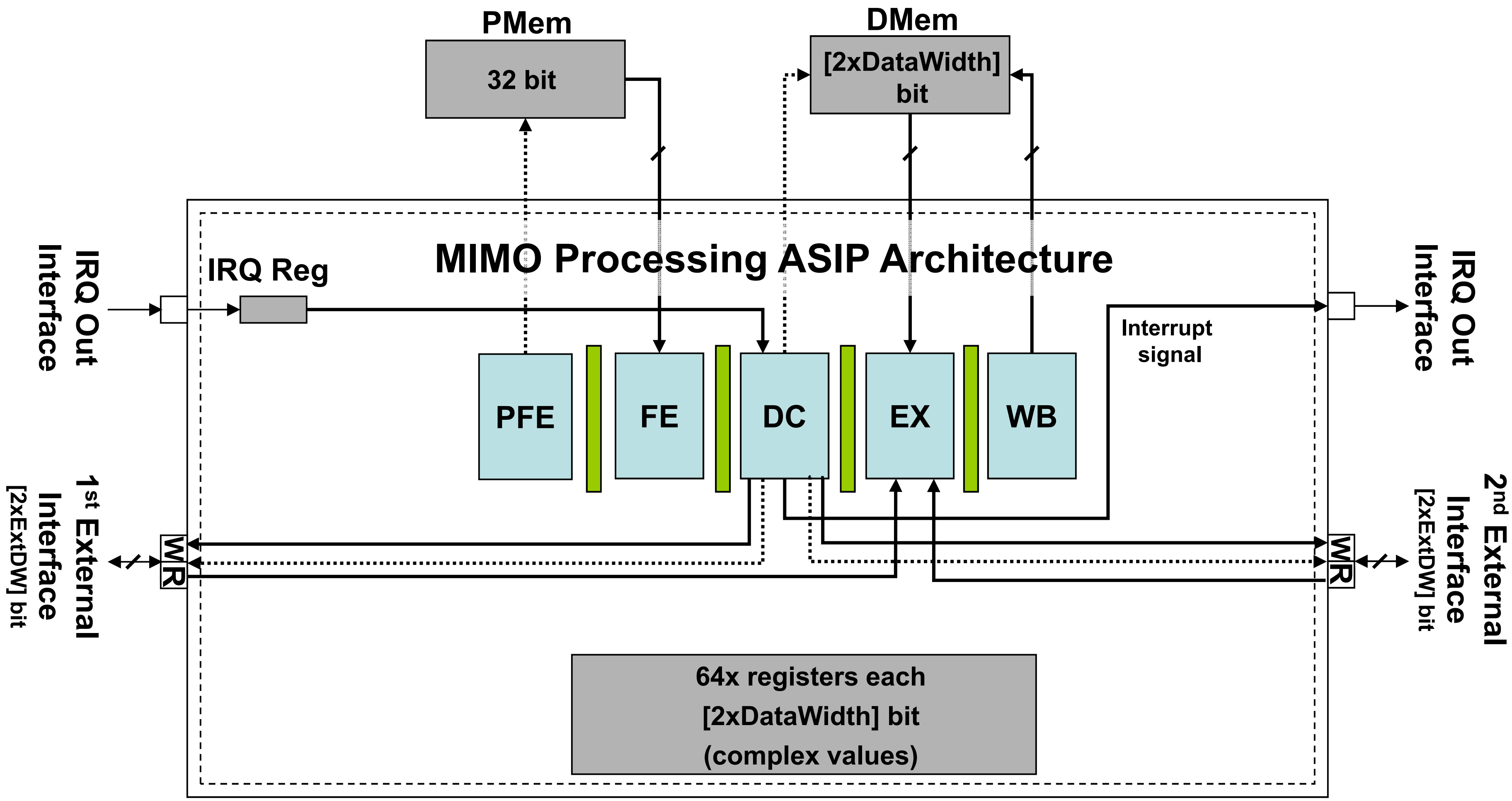
- **Key architectural features**
  - General
    - Register file with 64 registers
    - Short pipeline (PFE, FE, DC, EX, WB)
    - Small data memory to store look-up tables and temporary results
  - Arithmetic
    - Complex values supported as data type
    - Special instructions for inverse square root, reciprocal
    - 2-way SIMD for all complex valued arithmetic operations
  - Communication
    - Fast interfaces for direct IP communication
    - Support for low latency synchronization

ASIP for MIMO Processing



ASIP for MIMO Processing: Synthesis Results

- Synthesis result for 24bit data path (registers, multipliers, etc.)*

Total Core Area	Area Registers	Program Memory	Frequency
~205 kGE	~88 kGE	~28 kGE (1024 instructions)	400 MHz

- Execution times

Flavor (4x4 antenna configuration)	Cycles		Exec. Time (ns)
QRD-DS (augmented matrix) per decomp.		151	377.5
Computation of equalizer matrix G ($G=Q_bQ_a^H$)		19	47.5
SINR computation per symbol vector		36	90.0
Spatial equalization ($x=Gy=(Q_bQ_a^H)y$) per symbol vector		23	57.5
LLR computation per symbol vector	4QAM	13	32.5
	16QAM	19	47.5
	64QAM	25	62.5

Speed up (compared to STM P2012) ≈ 1 order of magnitude

* **Synopsys Design Compiler E2010.12-SP2 Faraday 90nm Library, Standard Performance,Typical case library & conditions, 1.00V, 25°C**

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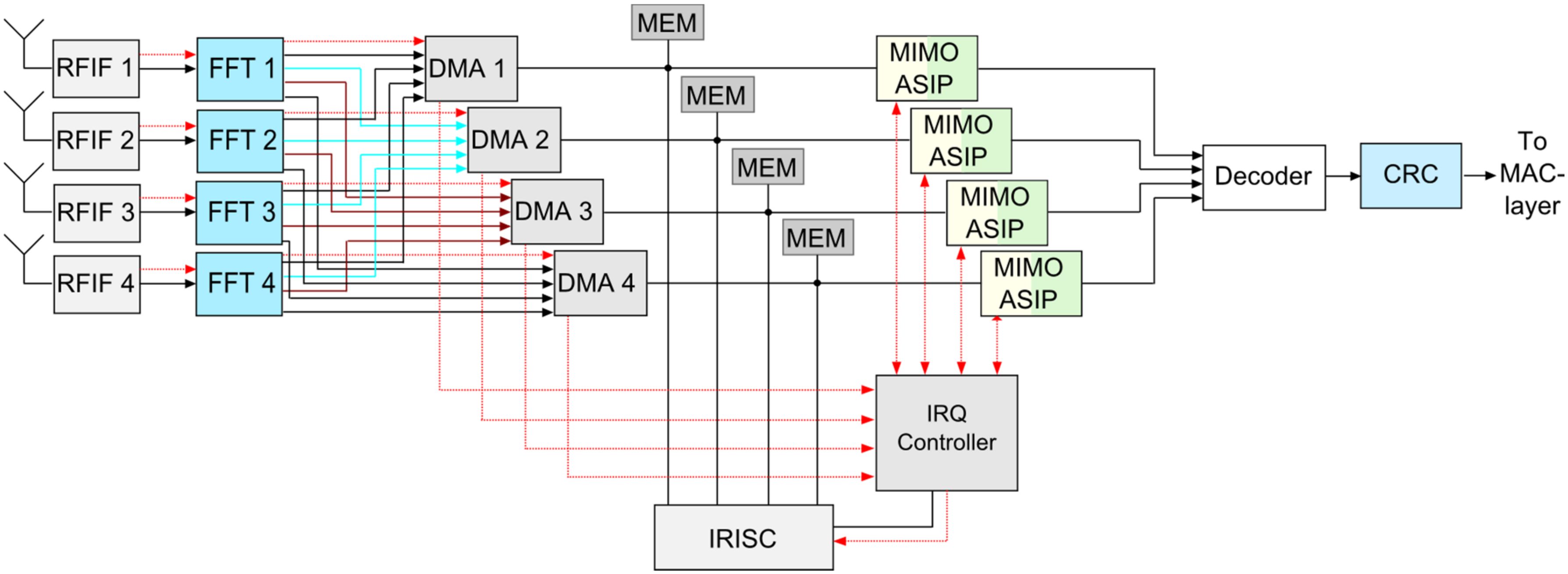
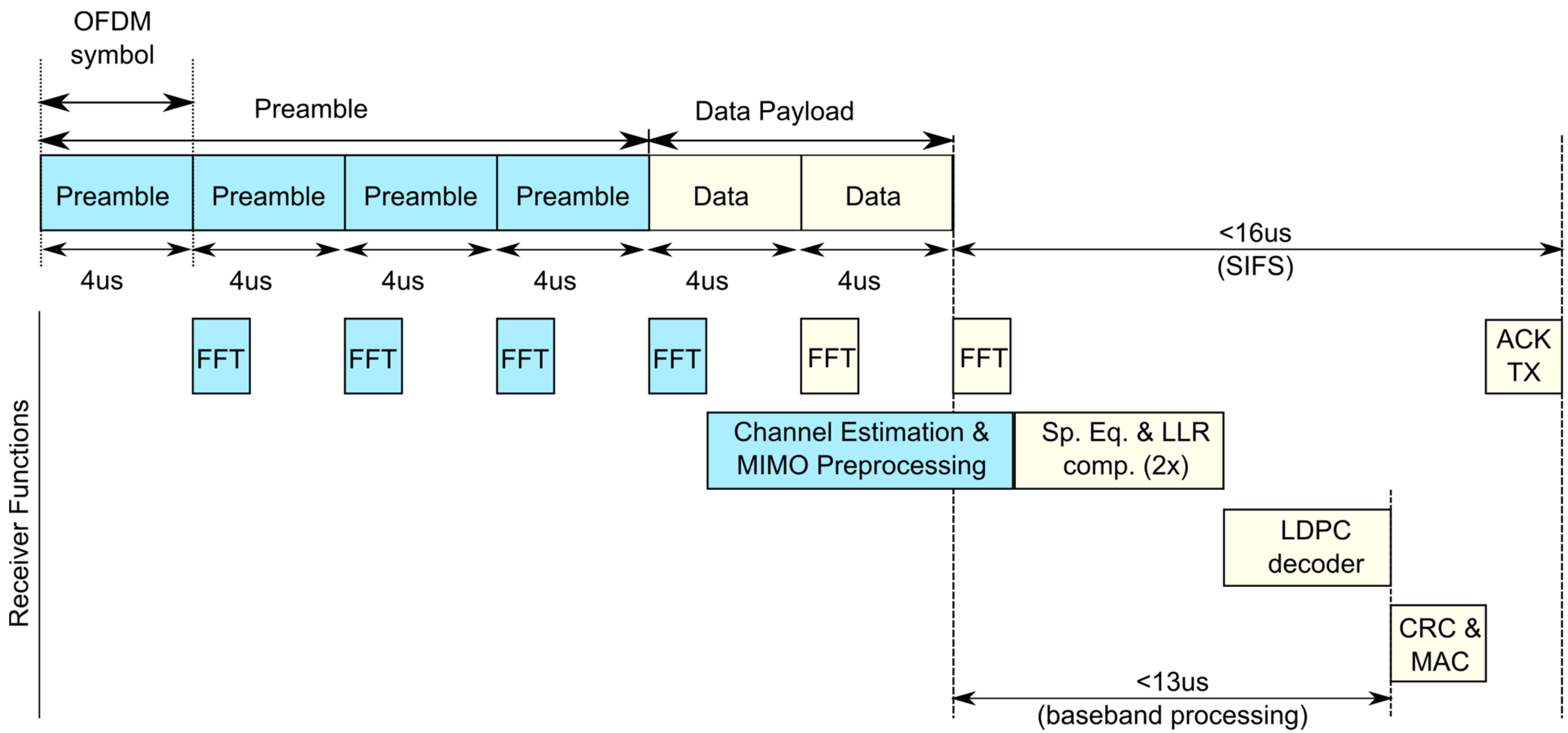
SDR Platform Design: 4x4 MIMO OFDM Transceiver



- **System-level: MIMO OFDM transceiver (up to 4x4 MIMO)**
  - FFT (4x): OFDM demodulation
  - DMA&MEM (4x): Data-forwarding from FFT to ASIP
  - IRQ Ctrl. (1x): ASIP notification
  - ASIP (4x): MIMO Equalizing & Symbol Demapping
  - Dec.&CRC (1x): Channel Decoding
  - Small RISC (1x): Application Control

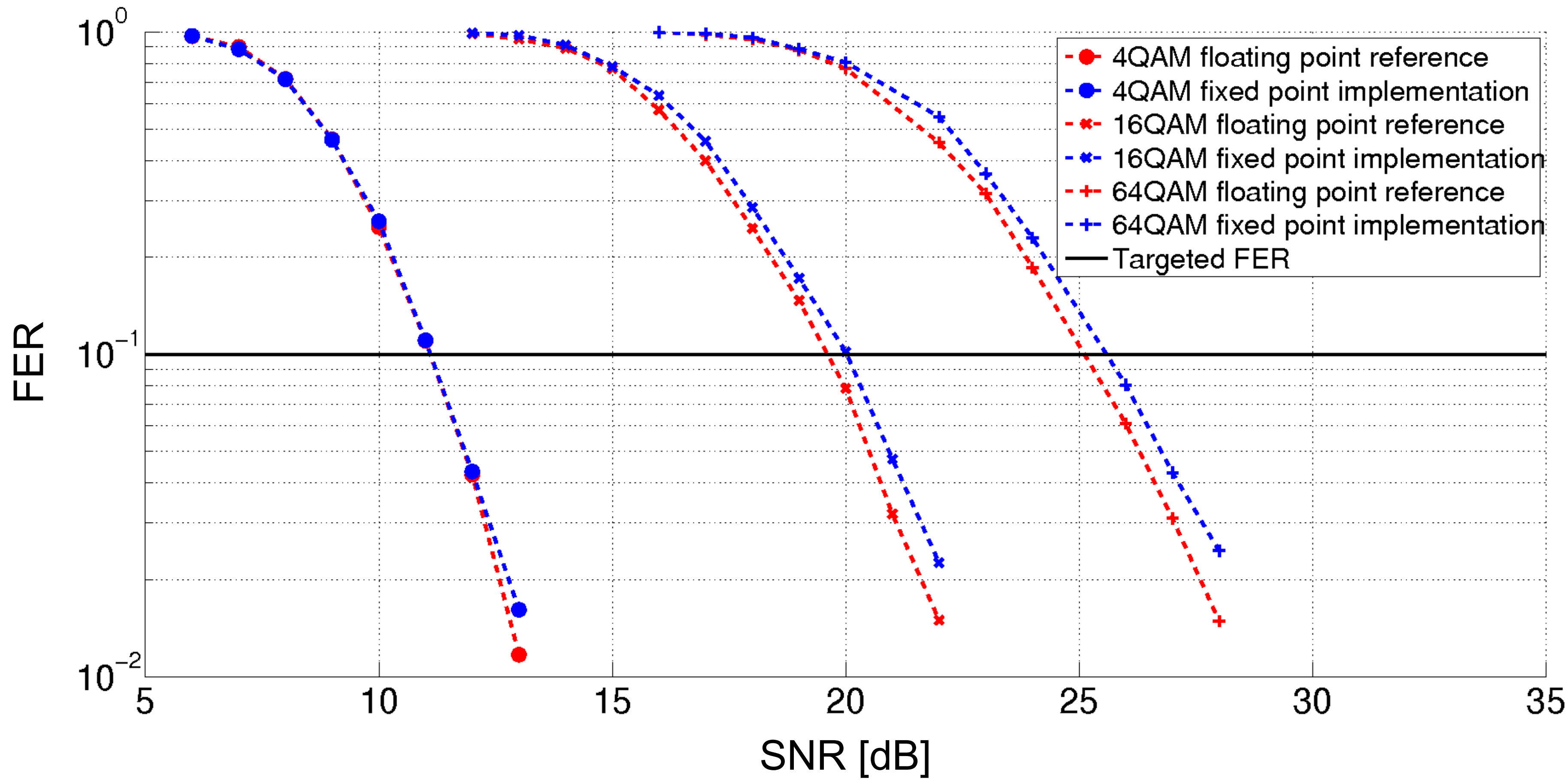
SDR Platform Design: IEEE 802.11n Requirements



Latency and throughput requirements for baseband processing for a frame (2 data symbols) with most demanding timing constraints

✓ Virtual Platform based Simulation: 12.13µs (baseband processing)

SDR Platform Design: Fixed Point Implementation Results



- **Fixed-Point ASIP based SDR platform achieves close to floating-point performance (QoS) at target frame error rate (FER)**

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Summary

- **Communications Application Analysis**
  - Applications consist of a small set of comp. kernels (Nuclei)
  - Nuclei for PHY MIMO OFDM transceiver identified

- **ASIP for MIMO OFDM**
  - Customized functionality for Nuclei-support
  - Highly optimized Nuclei implementations (Flavors) in SW

- **SDR Platform for MIMO OFDM**
  - Heterogeneous platform composed of:
    FFT IPs, ASIPs, ch. decoder, DMAs, MEMs, IRQ Ctrl, GPP
  - Achieves strictest timing constraints as well as QoS constraints of IEEE 802.11n

Thank you!