MIMO OFDM PHY for the MINUTEMAN

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Overview

- Introduction & Background
- Accomplishments
  - System
  - ASIC
  - Testbed
- Testbed Evolution
- Next Frontier, Cognitive Wireless Communicaitons

Physical Layer to Enable Network Centric Warfare

PHY to Deliver Life-line Communications in ALL Scenarios

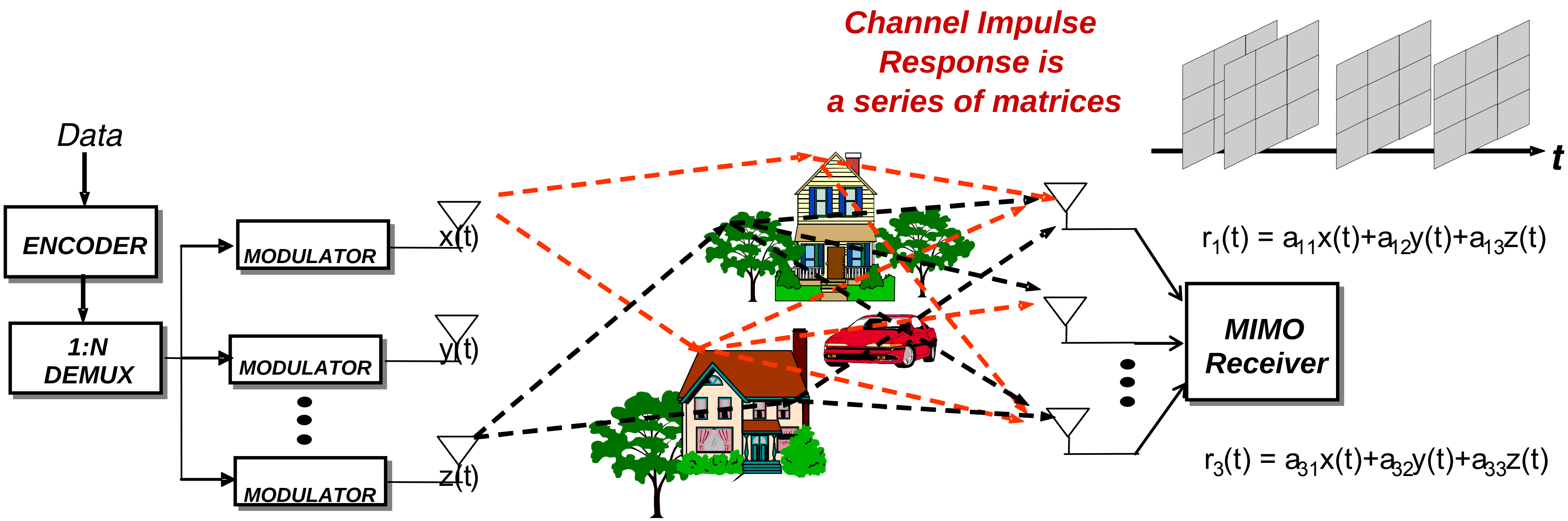
-Same underlying MIMO OFDM technology for all communications

- Simplified logistics

Potential impact to military communications

- Powerful technology can deliver reliable communications in diverse environments

Multi Input Multi Output (MIMO) Wireless Comms.

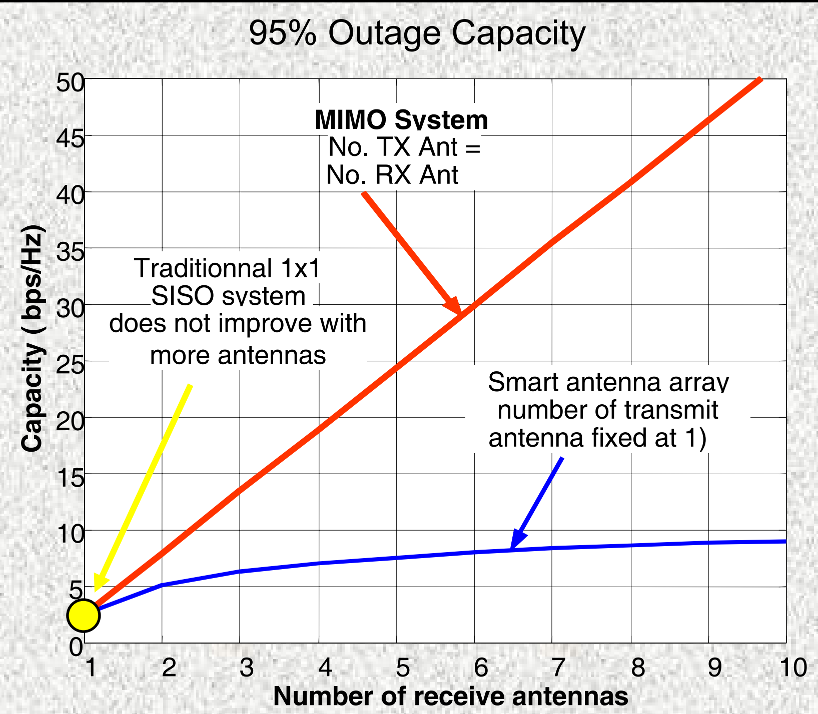


MIMO Antenna Processing

- Different data sent on different transmit antennas
- The signal from each transmit antenna is received at ALL receive antennas
- Channel impulse response is a matrix
  - NxN matrix; where N is the number of TX and RX antennas

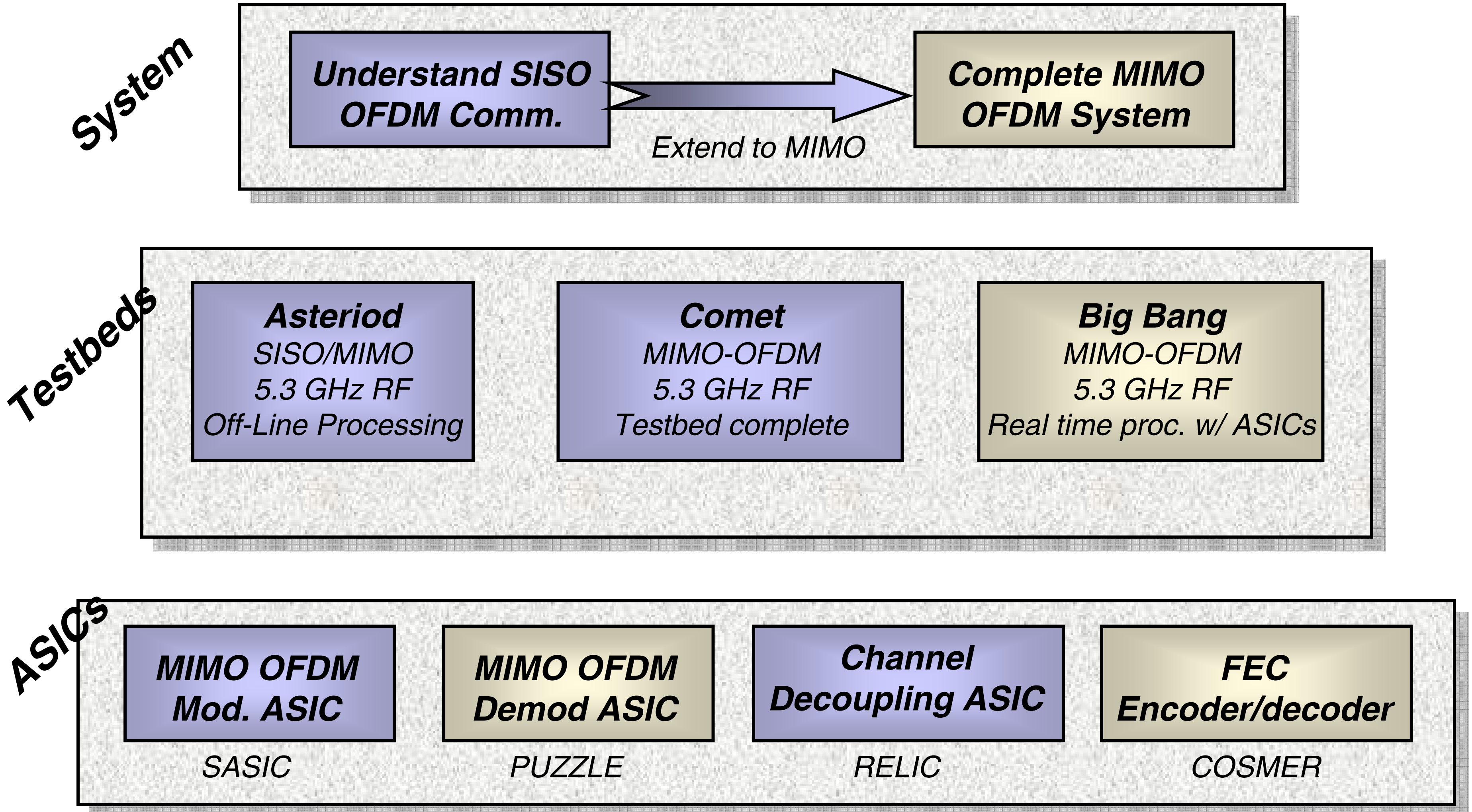
MIMO Delivers 10x+ Capacity Improvement

MIMO Config.	95 % Capacity at 20 dB SNR	Required SNR to achieve capacity of 1 bit/sec/Hz
1x1	2.6 bits/sec/Hz	12.8 dB
2x2	8.0 bits/sec/Hz	1.2 dB
4x4	19.0 bits/sec/Hz	-4.9 dB
8x8	40.8 bits/sec/Hz	-9.3 dB



- 10x to 20x capacity increase with same total TX power
- 23 dB (200x) improvement in LPD/AJ properties
  - This is additive to improvements achieved with conventional Spread Spectrum techniques (i.e. DSSS, FHSS, …)

Three Pronged Approach

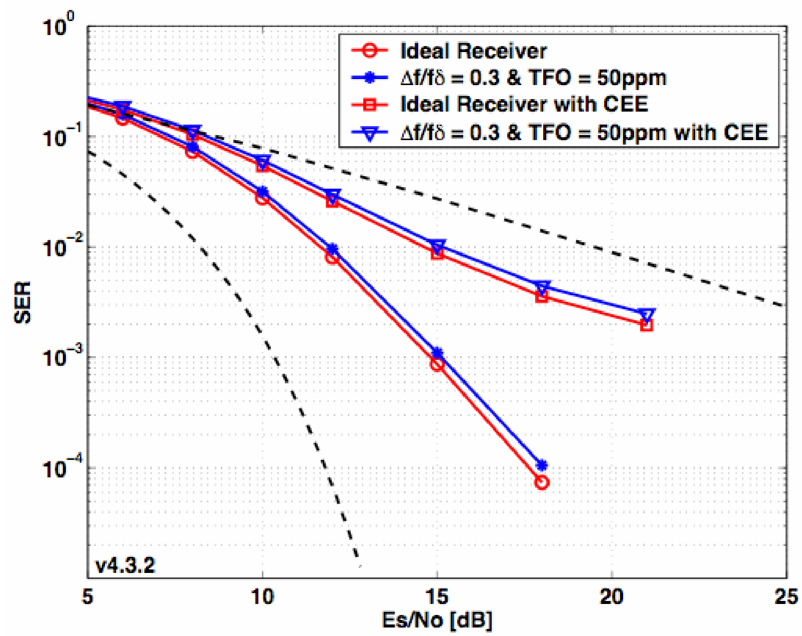


Accomplishments

- System
  - ML carrier and timing recovery for MIMO (ICC 2004)
  - Channel Estimation (PIMRC 2004)
  - Linear interpolation based MIMO decoding (WCNC 2004)
  - Scalable OFDM transceiver (VTC 2004)
  - Minimum wordlength requirement for MIMO OFDM (Globecom '03)
  - OFDM modeling and simulation, with Rajive Bagrodia (PADs 2004)
- VLSI
  - MIMO OFDM modulator
  - 8x8 MIMO decoder ASIC
  - Gbps LDPC decoder ASIC in design
  - MIMO OFDM demod accelerator ASIC in design
- Testbed
  - SISO OFDM testbed (Comm. Mag. June 2004)
  - MIMO OFDM testbed (Comm. Mag. Dec. 2004)
  - IQ mismatch cancellation (PIMRC 2004)
  - MIMO OFDM overhead optimization (VTC 2004)
  - Field measurements (Globecom 2004)

Maximum Likelihood Tracking Algorithm for MIMO OFDM

- We derived the joint ML-optimum estimators of CFO and TFO for MIMO-OFDM
  - Estimators use pilot information at the output of the receiver FFTs
- No particular MIMO decoding engine is required
- Simulation results show that larger MIMO configurations allow for
  - Reduced number of pilot subcarriers
  - Improved estimator reliability when tracking at lower SNR
- SER simulations show that tracking performance is not sensitive to poor channel estimates



Performance Evaluation

- Performance was evaluated by means of simulation
- Main simulation parameters mimic IEEE 802.11a setting
  - 64 subcarriers (48 data + 4 pilot + 2 × 6 unused)
  - 20 MHz bandwidth
  - 16 samples for cyclic prefix
- Channel model
  - Quasi-static
  - Exponentially decaying Rayleigh fading paths
  - $\tau_{RMS} = 50$ ns (⇔ 1 sample period)
- Uncoded transmissions
- Maximum Likelihood MIMO decoding engine

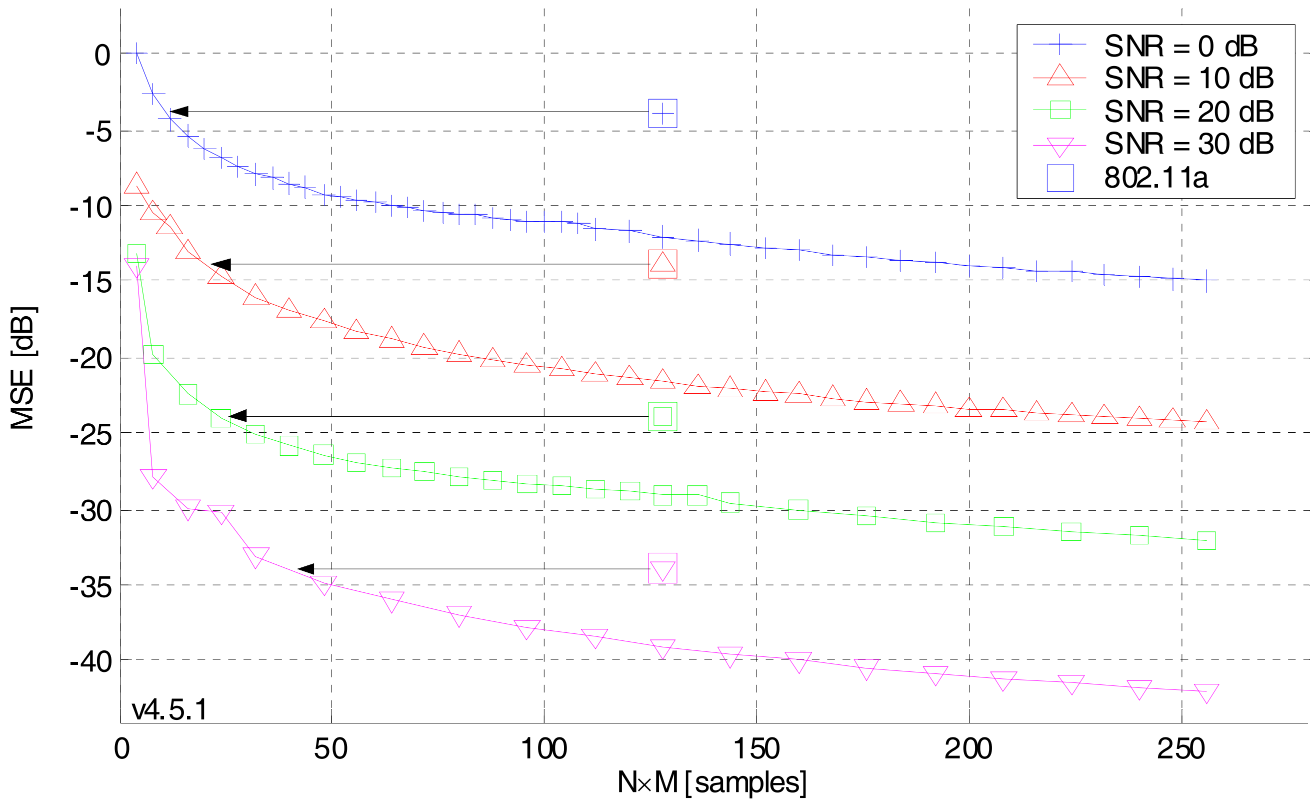
$$\hat{\mathbf{X}}(k) = \min_{\mathbf{X}(k)} \left\{ \left\| \mathbf{Y}(k) - \mathbf{H}(k) \cdot \mathbf{X}(k) \right\|^2 \right\}$$

Low-Overhead Channel Estimation & Acquisition

- The goal of this research is to develop acquisition techniques for MIMO-OFDM with low training overhead
  - Overall acquisition preamble length must be minimal
- Main challenges:
  - <u>Fast MIMO channel estimation</u>
  - Fast acquisition of OFDM symbol timing
  - Fast estimation of carrier frequency offset for coarse adjustment
- Current focus is on channel estimation
  - Approach:
    - Sub-sample frequency responses of individual SISO channels in order to trade off training time with estimation accuracy
    - Derive maximum likelihood estimators for received signals

Channel Estimator Performance – MSE

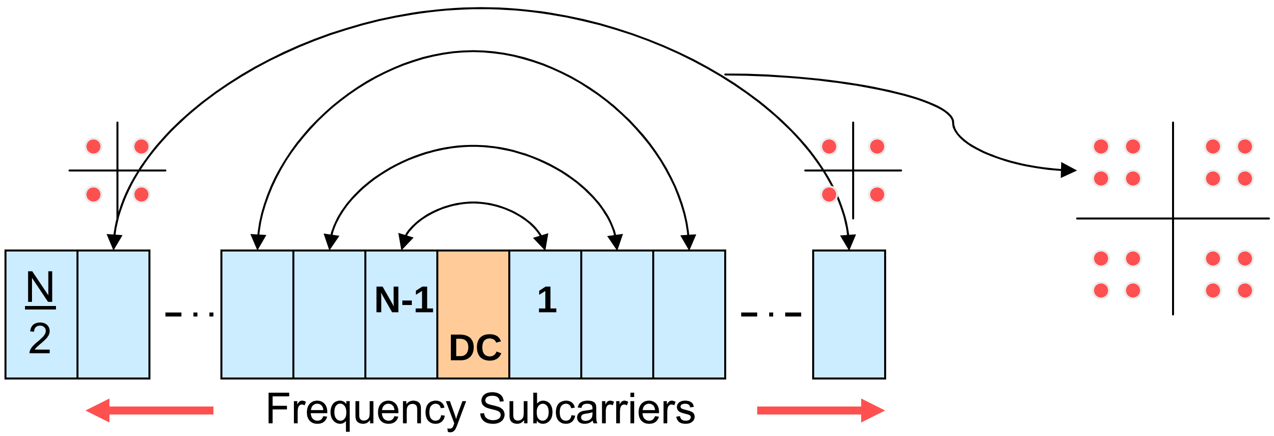
- Mean Square Error of channel estimator shows significant overhead reduction in comparison to techniques used in IEEE 802.11a standard



Channel Estimation – Conclusions

- Proposed channel estimation method allows for fine and explicit trade-off between training overhead and estimation accuracy
- Compared to 802.11a, proposed method requires 6-8 times less training data
- Low complexity implementation by virtue of FFT hardware reuse
- Advantages in UAV applications
  - Fast channel estimation and tracking for scenarios with high mobility
  - Low overhead leads to efficient use of spectrum
  - Algorithm is reusable without modification in a large variety of MIMO-OFDM configurations

Effect of I/Q mismatch in an OFDM system



$$Y(k) = \left[\frac{A(k)+B(k)}{2}\right]X(k) + \left[\frac{A(k)-B(k)}{2}\right]X^*(N-k)$$
$$Y(N-k) = \left[\frac{A(k)-B(k)}{2}\right]X^*(k) + \left[\frac{A(k)+B(k)}{2}\right]X(N-k)$$

→

$$\begin{bmatrix} Y(k) \\ Y^*(N-k) \end{bmatrix} = \begin{bmatrix} \frac{A+B}{2} & \frac{A-B}{2} \\ \frac{A-B}{2} & \frac{A+B}{2} \end{bmatrix} \begin{bmatrix} X(k) \\ X^*(N-k) \end{bmatrix} + \begin{bmatrix} V_1(k) \\ V_2(k) \end{bmatrix}$$

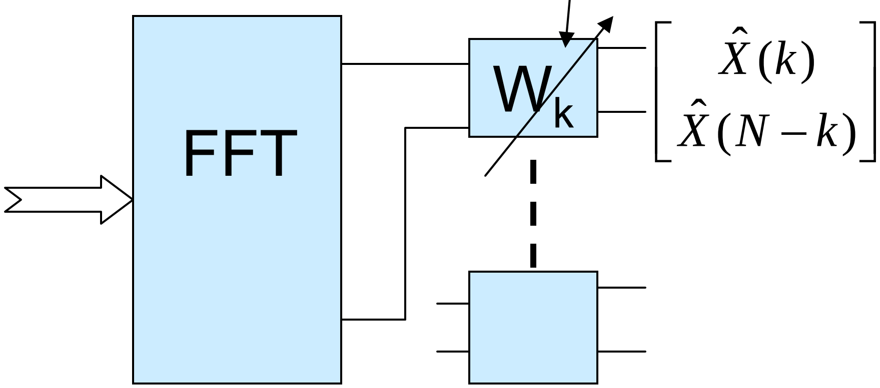
I/Q mismatch cancellation – MMSE solution

$$\begin{bmatrix} Y(k) \\ Y^*(N-k) \end{bmatrix} = \begin{bmatrix} \frac{A+B}{2} & \frac{A-B}{2} \\ \frac{A-B}{2} & \frac{A+B}{2} \end{bmatrix} \begin{bmatrix} X(k) \\ X^*(N-k) \end{bmatrix} + \begin{bmatrix} V_1(k) \\ V_2(k) \end{bmatrix}$$

MMSE solution

$$\hat{X} = R_{xy} R_y^{-1} Y = WY$$

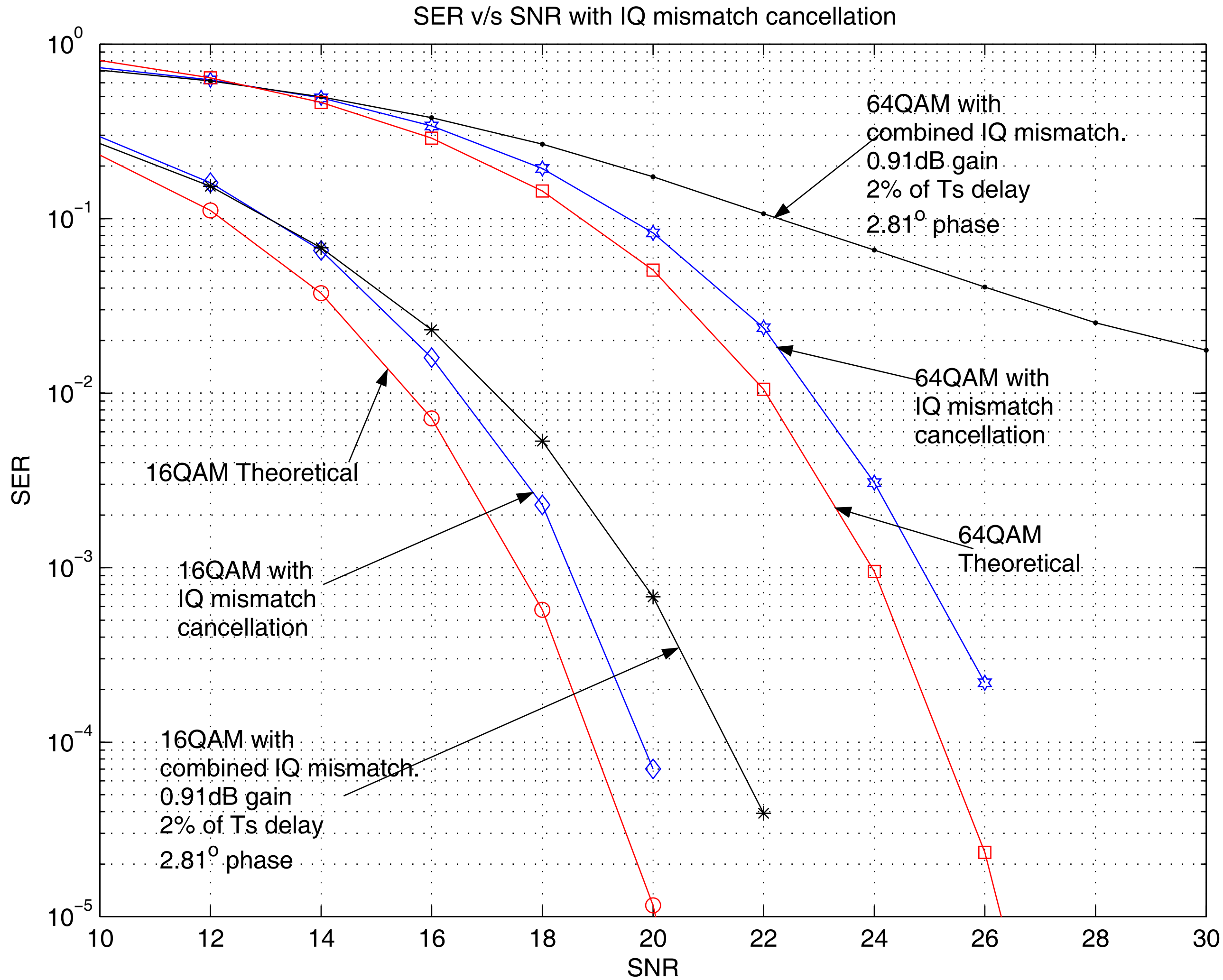
$$\begin{bmatrix} \hat{X}(k) \\ \hat{X}(N-k) \end{bmatrix} = \begin{bmatrix} W_{k1} & W_{k2} \\ W_{(N-1)1} & W_{(N-1)2} \end{bmatrix} \begin{bmatrix} Y(k) \\ Y(N-k) \end{bmatrix}$$



W_k is the weight matrix

- -Trained adaptively
- -Works in frequency selective channels
- -Works with receive antenna diversity.
- -Can correct I/Q mismatch in the presence of other impairments like CFO, phase noise, etc.
- -Corrects all forms of I/Q mismatch

SER curves with cancellation

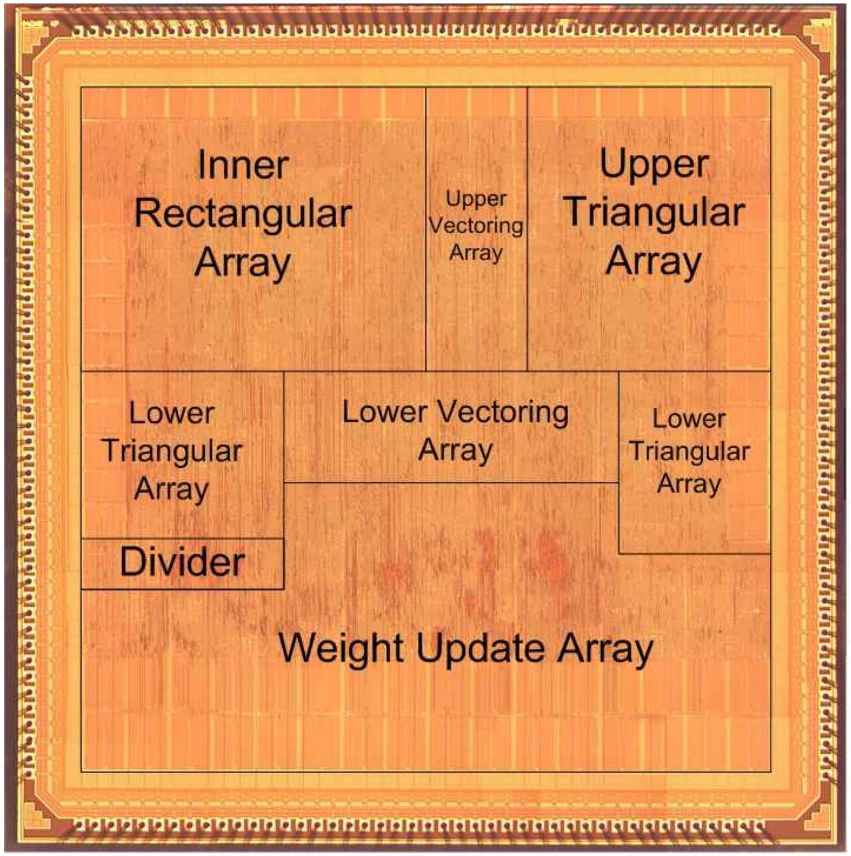


RELIC Specifications

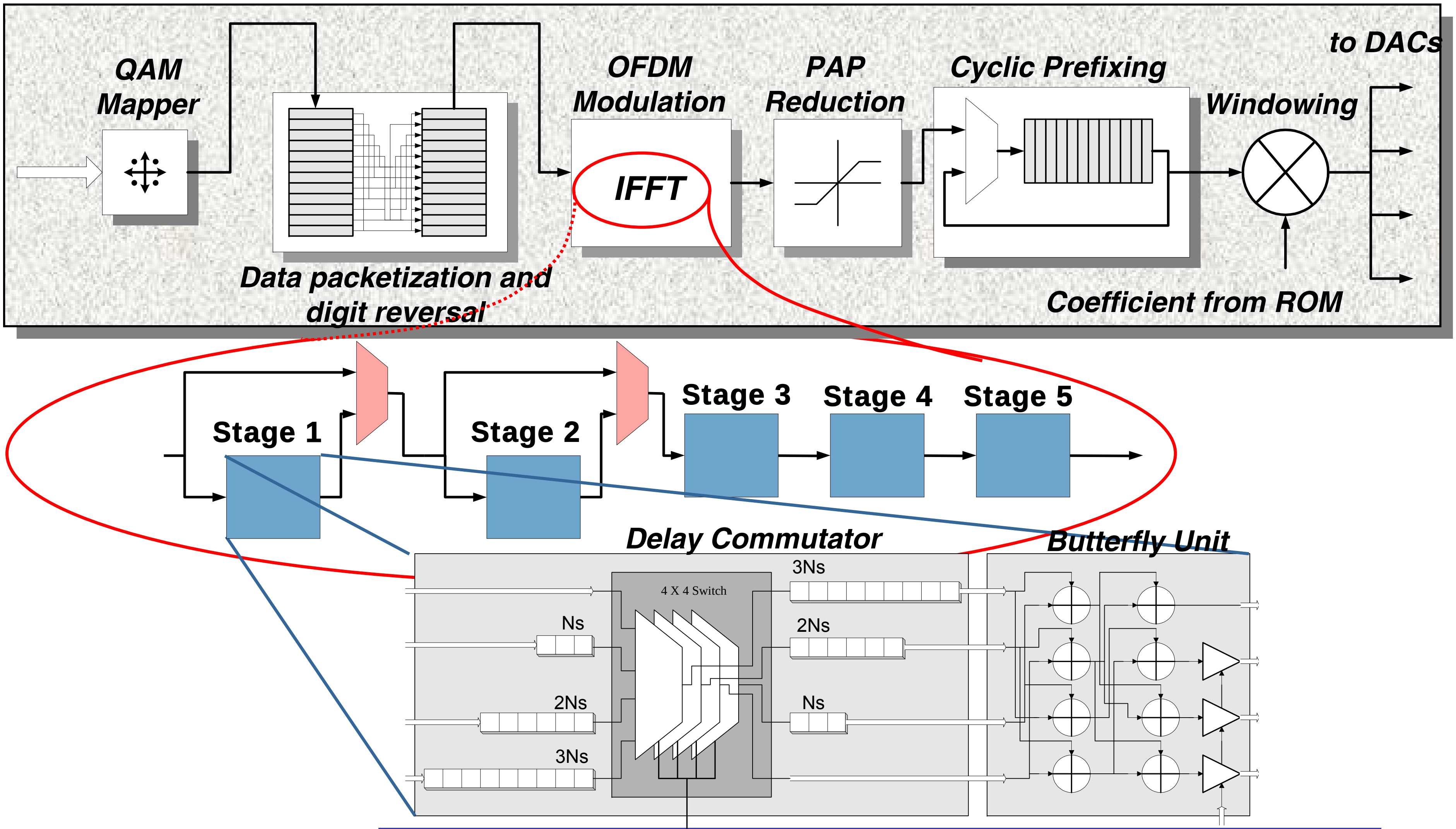
- Maximum clock frequency: 50 MHz
- Supported antenna setup: any valid combination of antennas ($N_t \leq N_r$) up to 8x8
- Dual modes
  - Full band (25MHz): up to 4x4 with 1024 subcarriers
  - Half band (12.5MHz): up to 8x8 with 512 subcarriers and expandable to full band with two RELIC chips
- Real-time (packet-wise reconfigurable) receive antenna selection (soft switching)
- Extremely flexible architecture that can be easily adapted to different OFDM packet structures

V: RELIC Implementation

- Process
  - TSMC 0.18μm CMOS
- Die Size
  - 39.4mm^2 (core: 29.2mm^2)
- Gate Count
  - 2.3M (SRAM: 819Kb)
- Packaging
  - 181-lead PGA (77 inputs, 68 outputs)
- Power
  - 360mW (@58MHz, 2x2 full band mode)
- Clock Frequency
  - 50MHz (max: 58MHz)

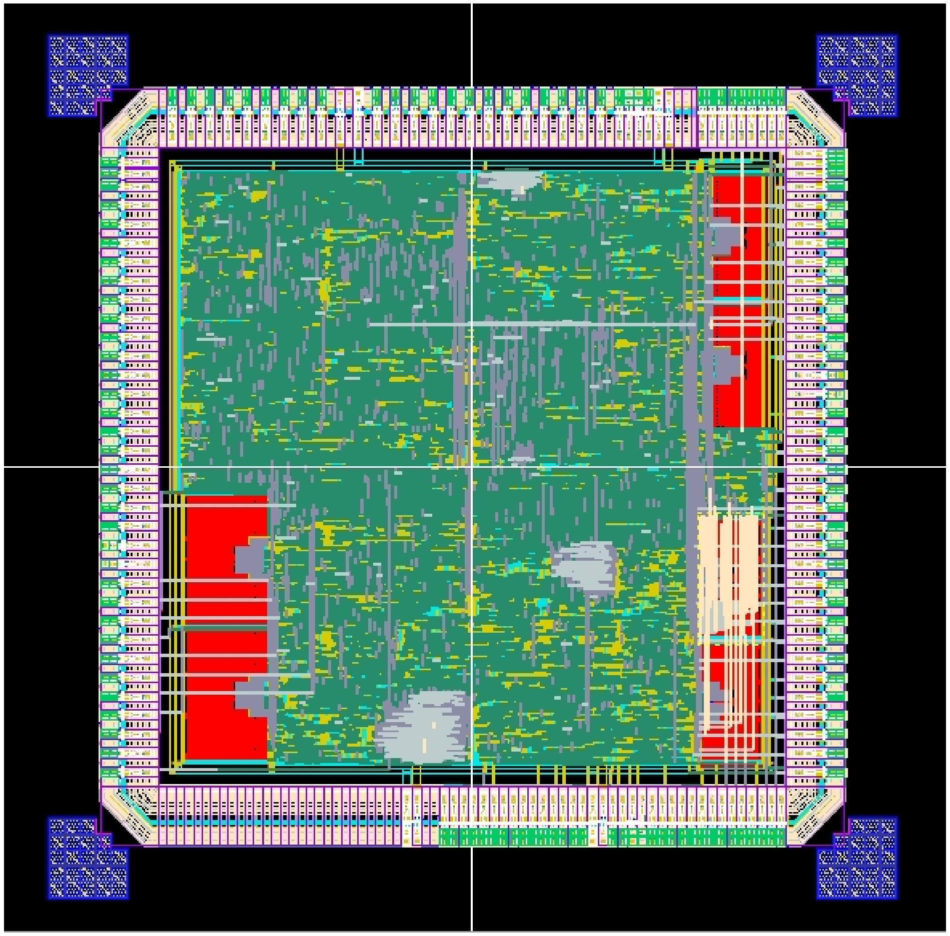


MIMO OFDM Modulator ASIC

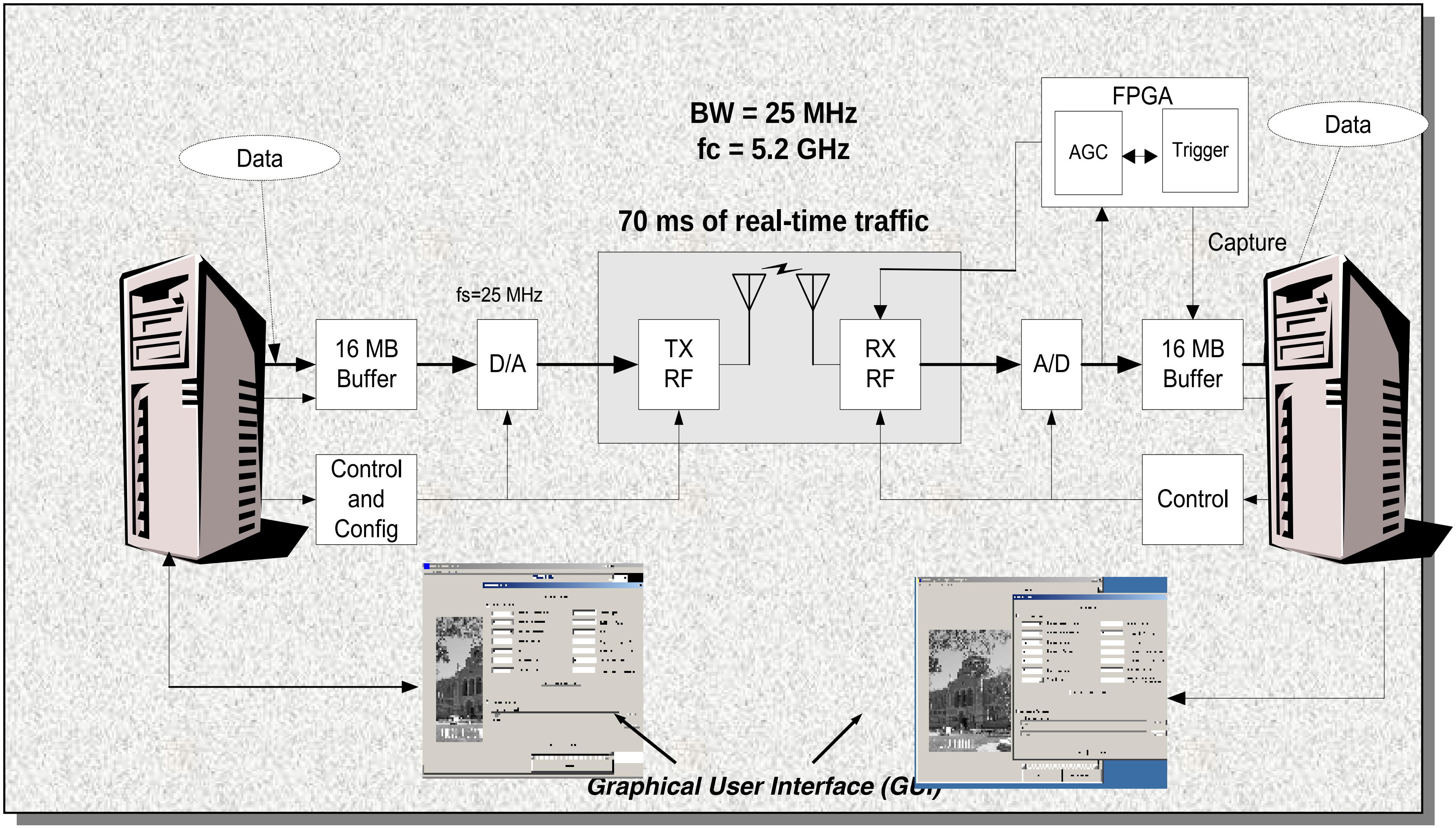


MIMO OFDM Transmitter ASIC

- 25 mm^2 chip, 0.18u CMOS technology
- 1.6 million transistors
- The first ever fully integrated MIMO OFDM transmitter operating
- Implements UCLA MOBSTER packet structure
- Support for 64 to 1024 pt FFT
- Extreme programmability makes SASIC ideal for testbed purposes,



Phase-1 Testbed



Testbed Components

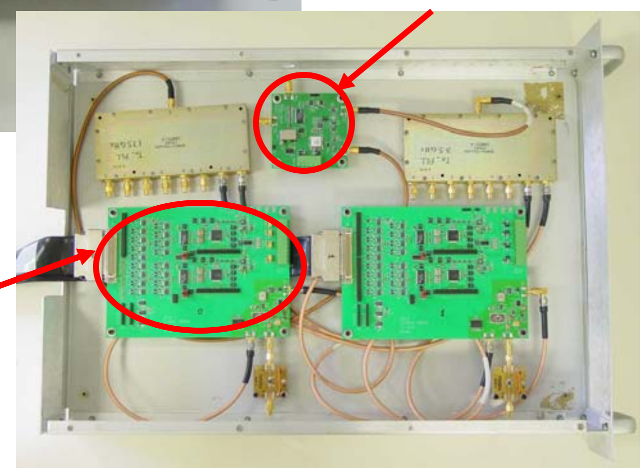
UCLA Phase-2 2x2 MIMO Testbed

Memory Buffer
I/O Boards

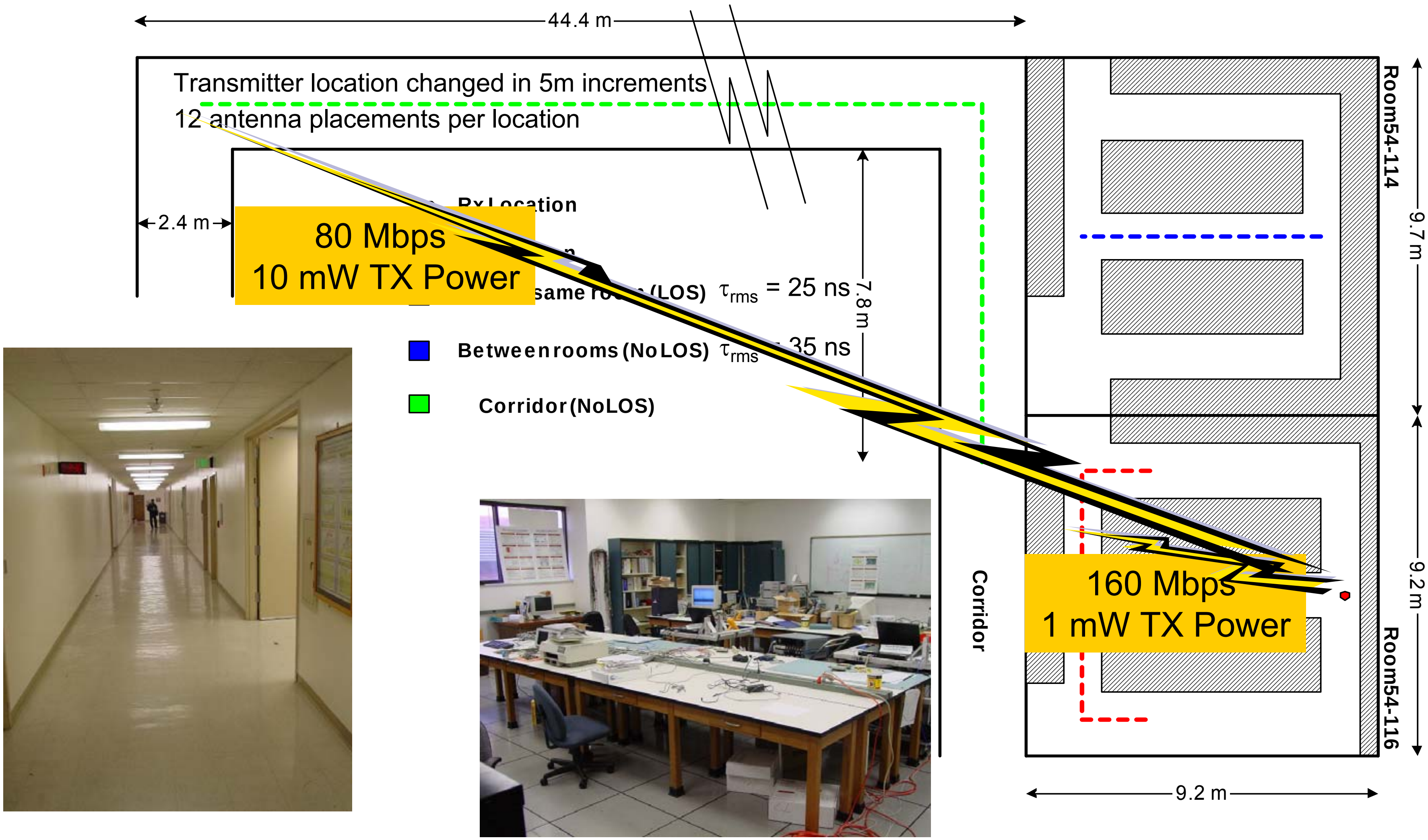
PLX Control
Board

Phase Locked
Loop Circuit

Radio Freq.
Circuit



Controlled Field Trials



2x2 MIMO vs. 802.11a & 802.11b

	Effective User throughput (Mbps)		
Distance between TX and RX (feet)	2x2 MIMO with 10mW TX power	802.11a with 45 mW TX power (source Atheros)	802.11b (source Atheros)
10’	85 Mbps	54 Mbps	11 Mbps
50’	49 Mbps	37 Mbps	11 Mbps
100’	49 Mbps	18 Mbps	11 Mbps
150’	42 Mbps	12 Mbps	6 Mbps
200’	30 Mbps	6 Mbps	2 Mbps

Testbed Evolution

Current Testbed → ***Proposed Prototype***

Form Factor

Table Top

→

Swarm enabled

Processing Speed

Non-real-time PC

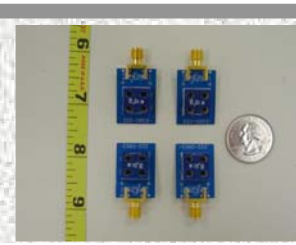
→

Real-Time ASIC + FPGA

MIMO Configuration

1x1, 1x2, 2x2

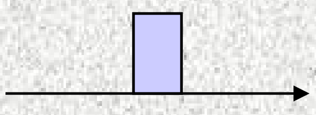
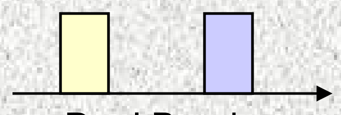
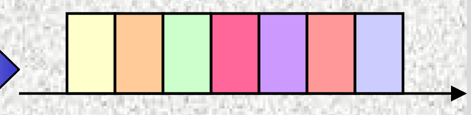
→



1x1 1x2
1x3 1x4
2x2 2x3
2x4 4x4

Testbed Evolution

Current Testbed → Proposed Prototype

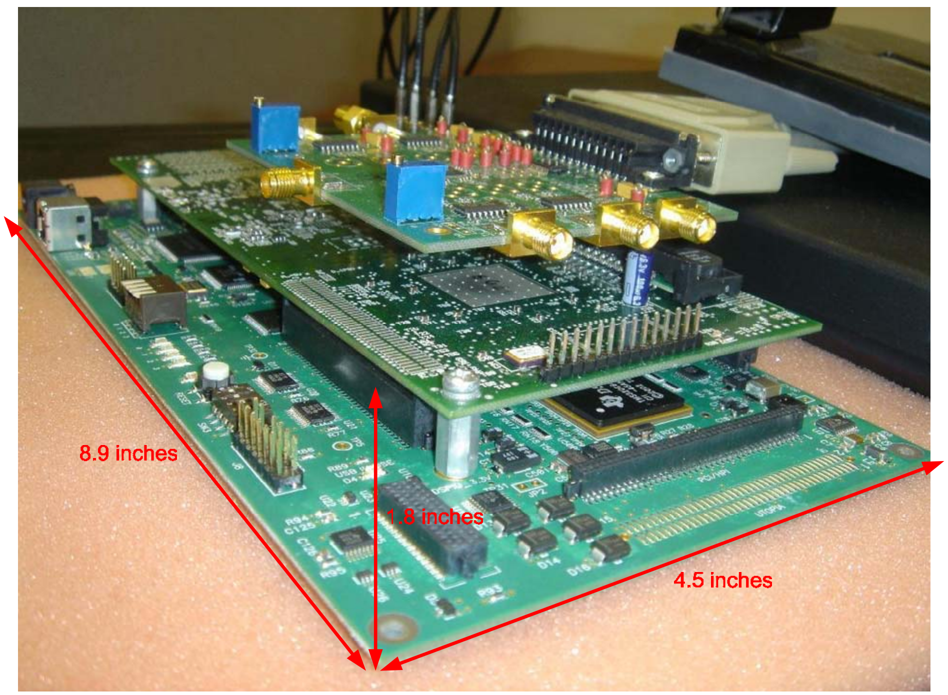
	Current Testbed		Proposed Prototype
Multi-Band Operation	 Single Band, 5.2 GHz	 Dual Band, 2.4 GHz + 5.2 GHz	 Any Band, 400 MHz to 5.2 GHz
Bandwidth	 Fixed at 20 MHz		 Variable from 500 KHz to 25 MHz
Operating Environment	Controlled Indoor		Outdoor/Indoor/Sea Harsh military communication
Networking	Single Link		Networked Nodes

Two Step Transition Path

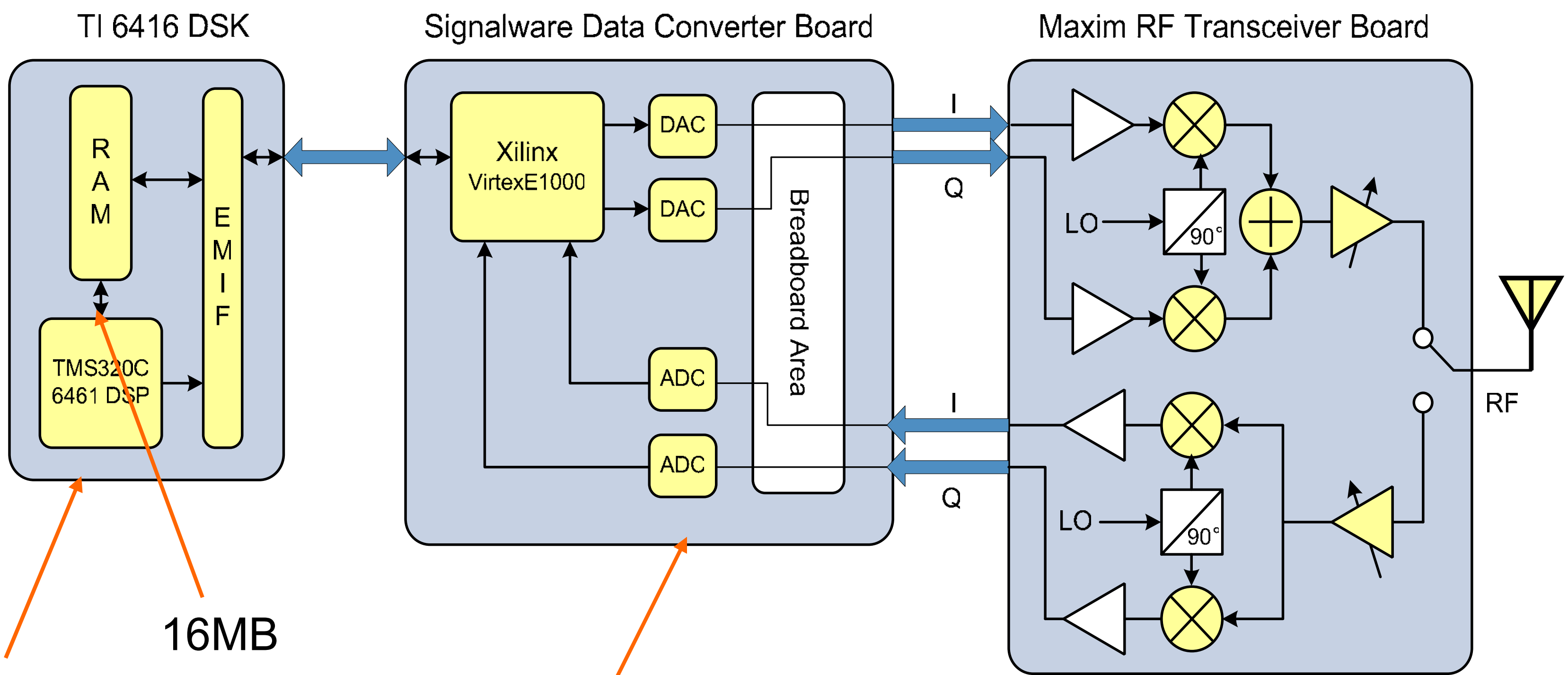
- Mini-Me Testbed
- FOM Testbed

Mini-Me Testbed

- Compact!
  - Gives same performance as mobster at 1/100 the volume.
- Faster,
  - at least twice as fast.
- Cheaper,
  - with off the shelf components
- Expandable.
  - Components are stackable (MXM MIMO)



System



720MHz

16MB

16Msps, 12-bit

2.4GHz; LNA gain, PA bias, Tx power, Rx bandwidth, etc.. User configurable

Current status

- Current Status
  - All Mobster FOM transceiver code ported successfully to DSP.
  - Baseband transceiver, data converters, and RF blocks tested independently with success.
  - Transmitter-DAC-RF chain completed.
  - RF-ADC link completed.
  - RF wireless link tested over the air (independently).
  - All steps so far are SISO.

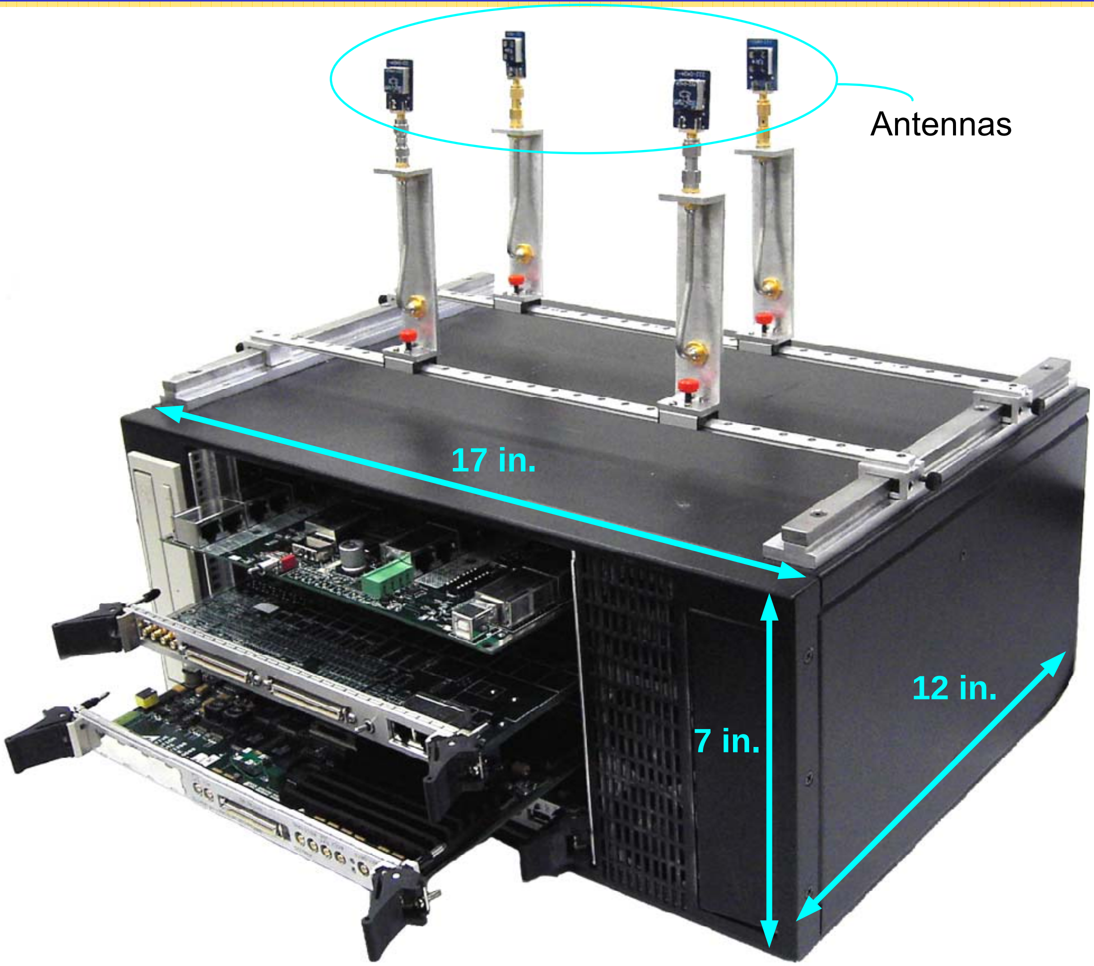
- Pending Work
  - Complete ADC-baseband receiver link to close the loop.
  - Extend to MIMO (baseband is ready).
  - Migrating critical functions (e.g. block boundary detection) to signalware's Xilinx FPGA.
  - Hardware packaging.
  - Software packaging (leave TI code composer?).
  - Testing modularity by (e.g.) including LDPC or STC in a new rev.

Overview of the UCLA FOM Testbed

Stephan Lang

University of California, Los Angeles

FOM: Small Form-Factor

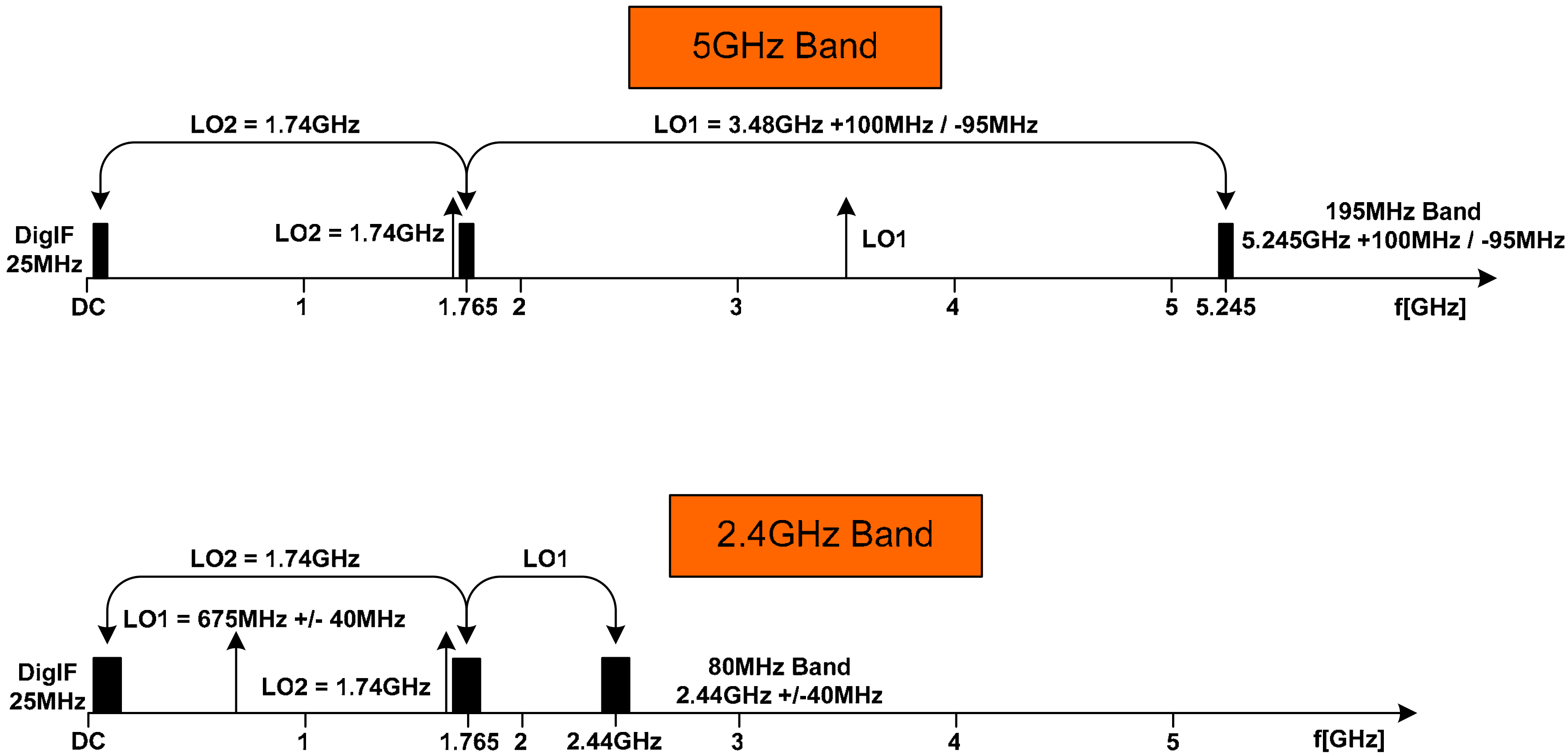


- **4x4 MIMO system fits into 6u CPCI chassis**

FOM: Motivation

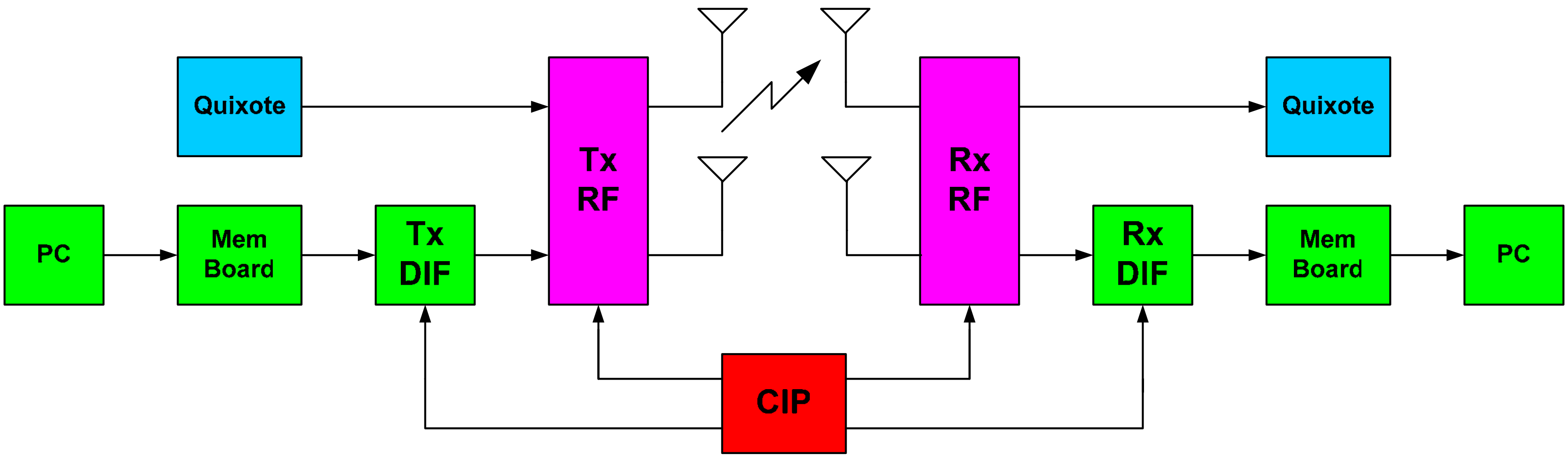
- Dual-band architecture (5.245GHz / 2.44GHz)
- Flexible Band-selection
- Flexible Bandwidth
- Realtime and non-realtime operation
- Increase Tx power for outdoor measurements
- Mitigate I/Q mismatch with Digital IF
- Reduce phase noise (place PLL on RF board)
- Emergency (high input power) shutdown of the LNAs
- Implement RSSI and Tx power control
- Full control over all parameters of the FOM testbed through a highly flexible GUI
- Reliable and repeatable testbed operation

FOM: Frequency-plan



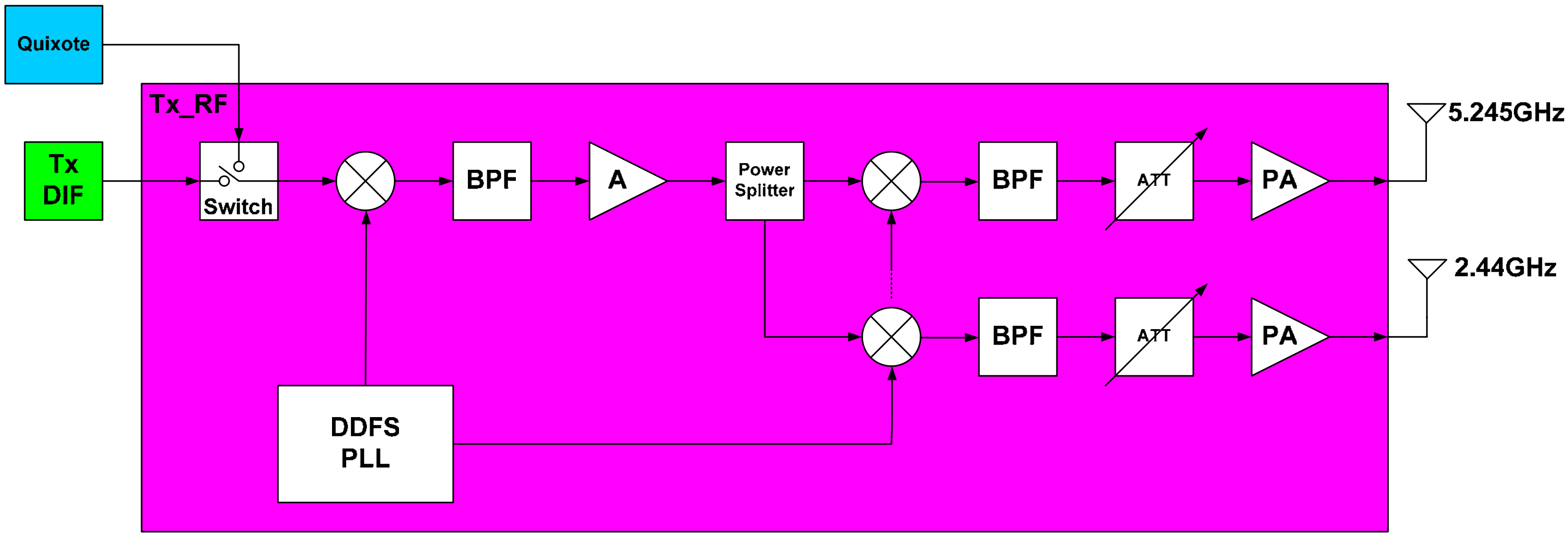
- **Dual-band architecture (5.245GHz / 2.44GHz)**

FOM: High-level architecture



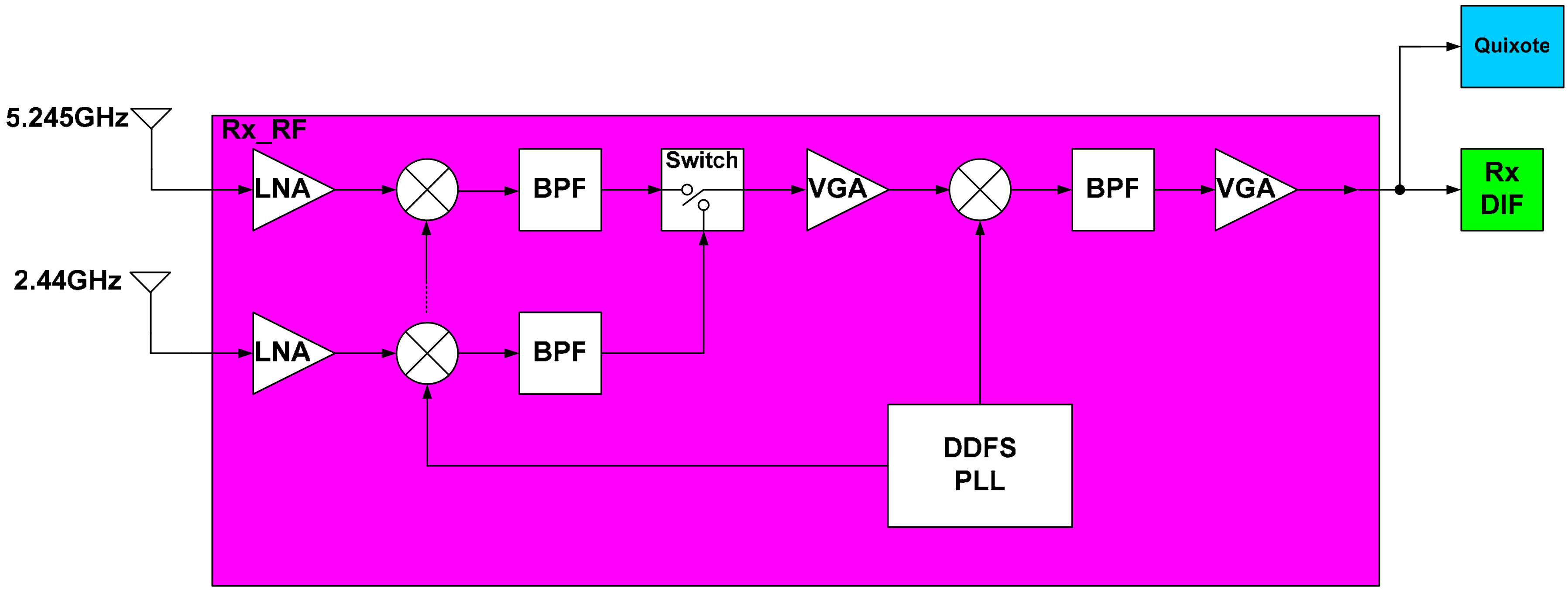
- **Real-time testbed with Quixote (FPGA, DSP platform)**
- **Non-real-time testbed with Memory boards**
- **Controlling through CIP board**

FOM: Tx_RF (Radio Frequency)



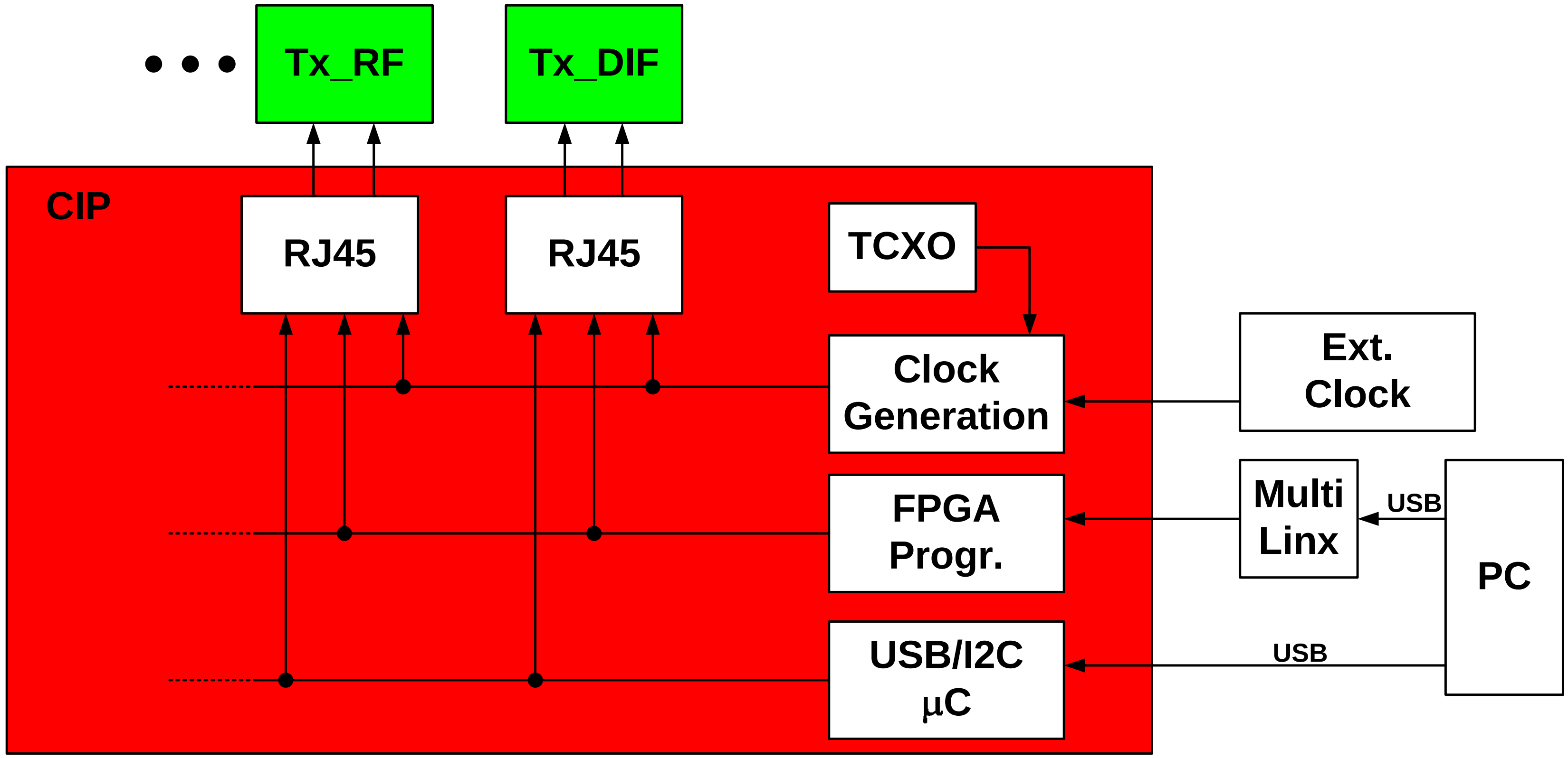
- **Data from Quixote or Tx_DIF**
- **Dual band (5.245GHz / 2.44GHz)**
- **Transmit power: -24.5dBm…31.5dBm in 0.5dBm steps**
- **Turn ON/OFF individual RF chains**

FOM: Rx_RF (Radio Frequency)



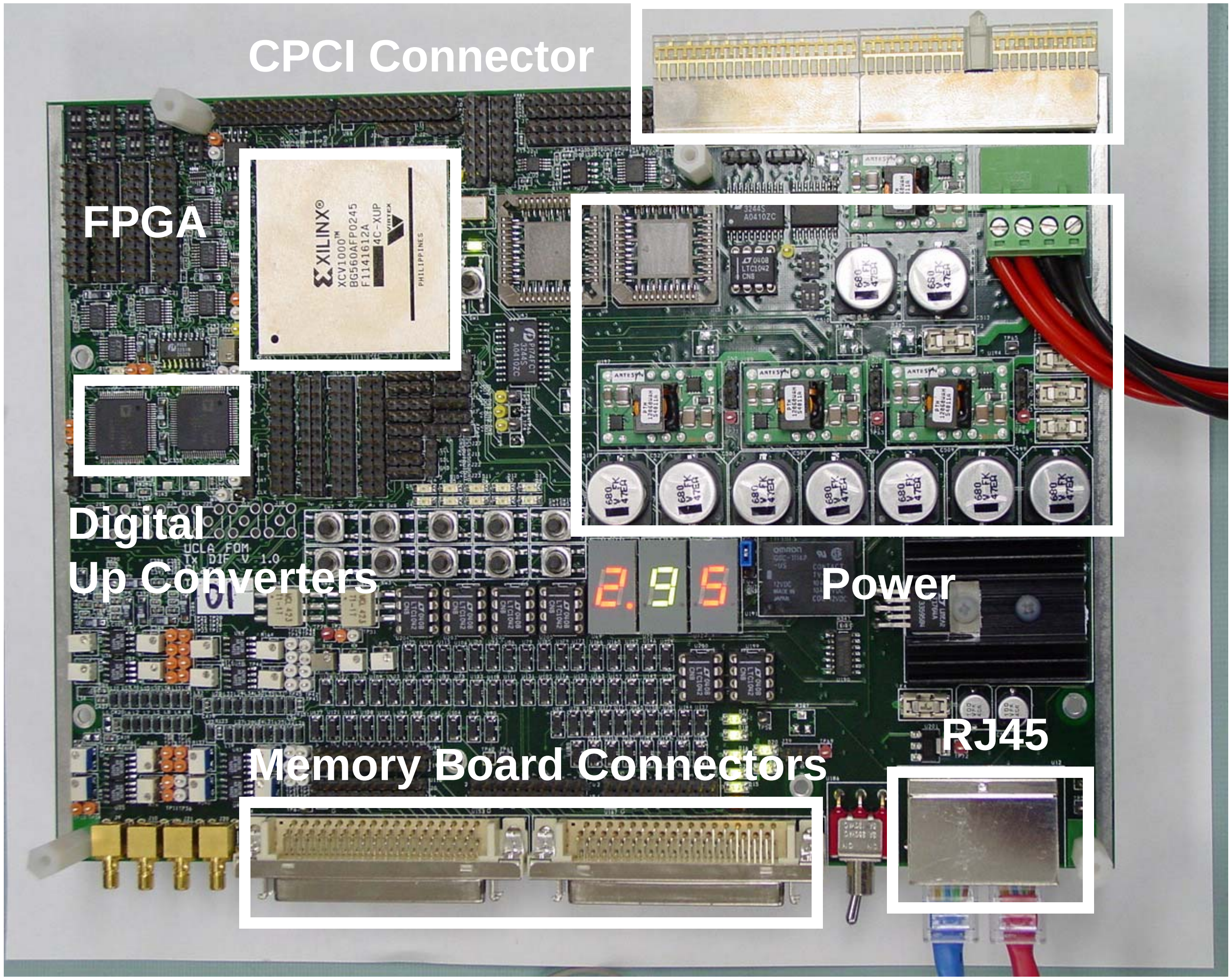
- **Dual band (5.245GHz / 2.44GHz)**
- **VGA at IF and Digital IF**
- **Dynamic range: 181.6dB (5.245GHz), 190.1dB(2.44GHz)**
- **Noise Figure: 7.9dB(5.245GHz), 5.8dB(2.44GHz)**

FOM: CIP (Clock, I2C, Programming)

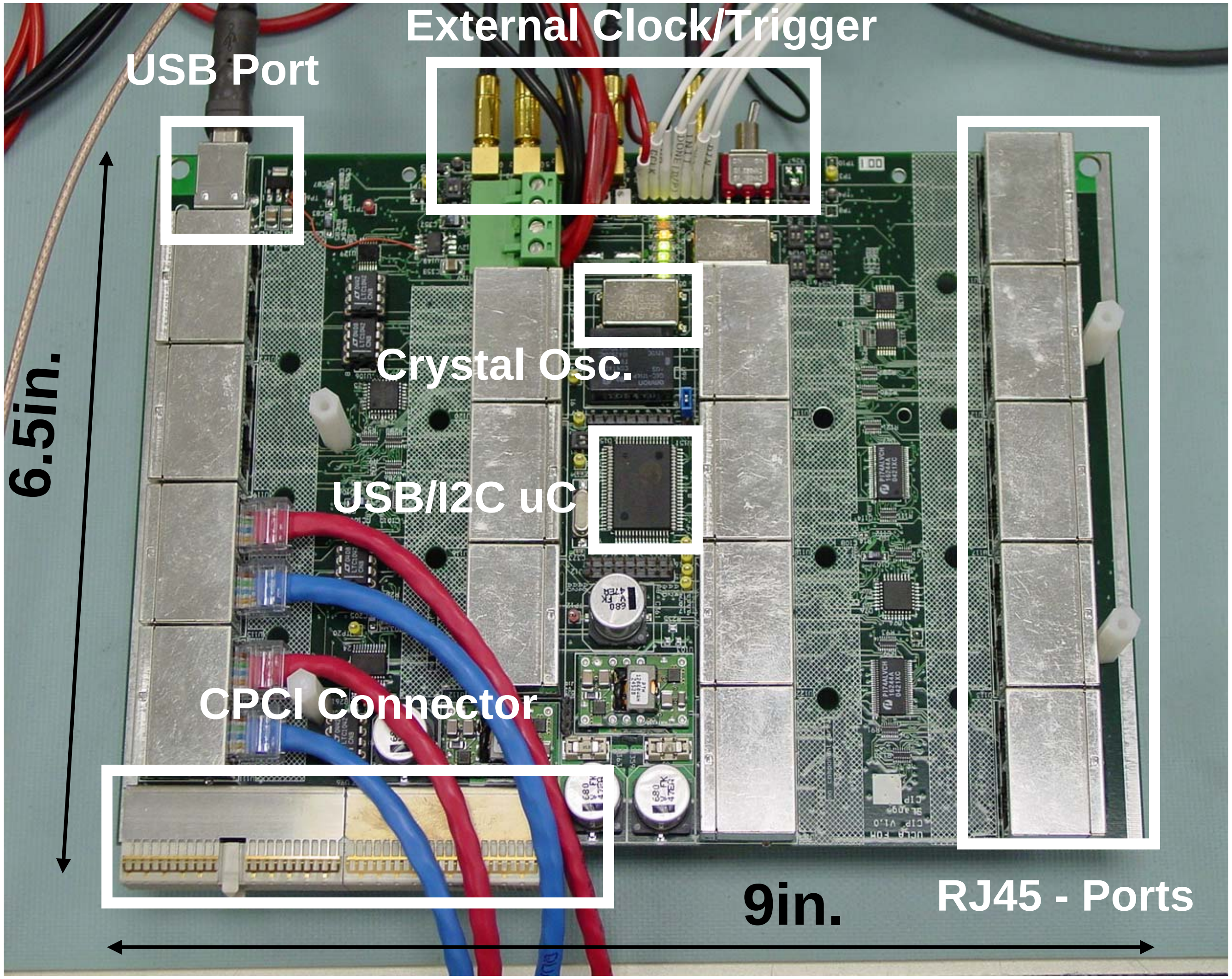


- **CIP: "Heart" of the FOM testbed**
- **Controls up to an 8x8 system**

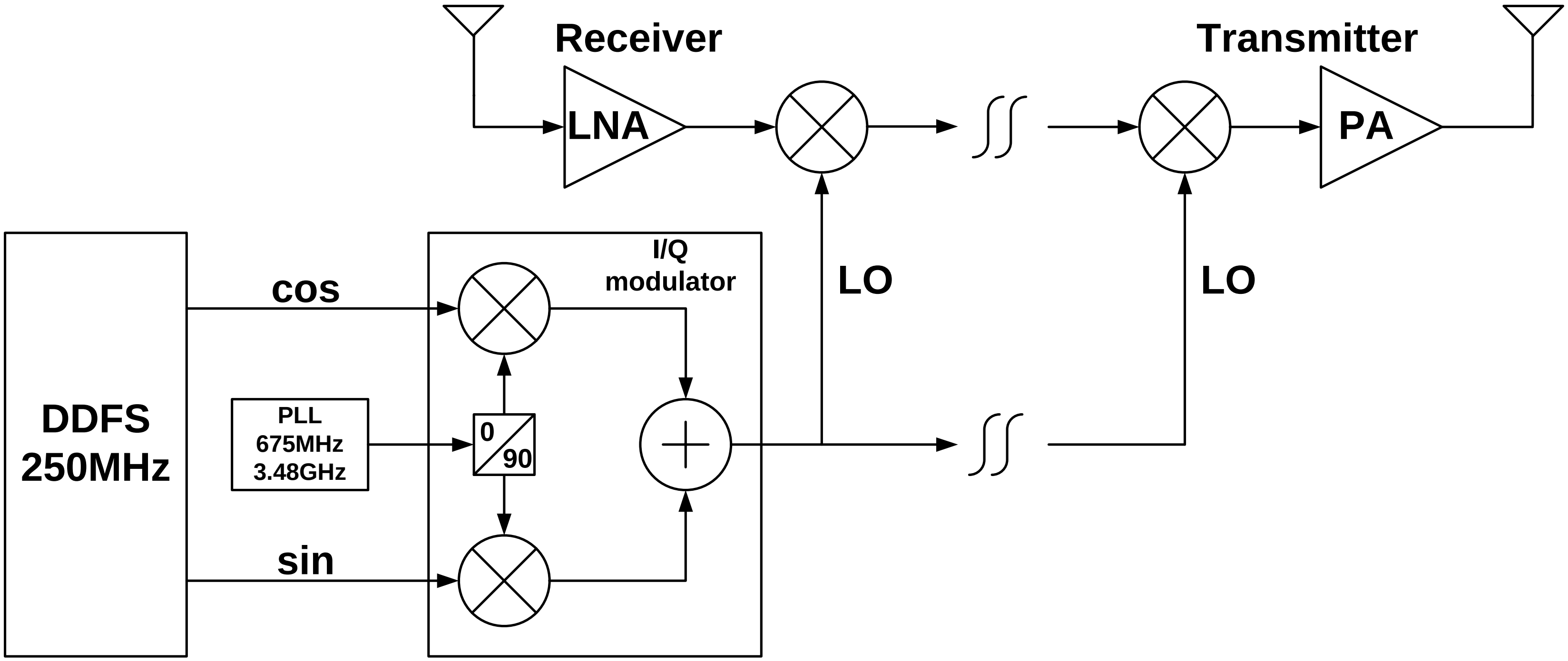
FOM: Tx_DIF cont'd



FOM: CIP cont'd

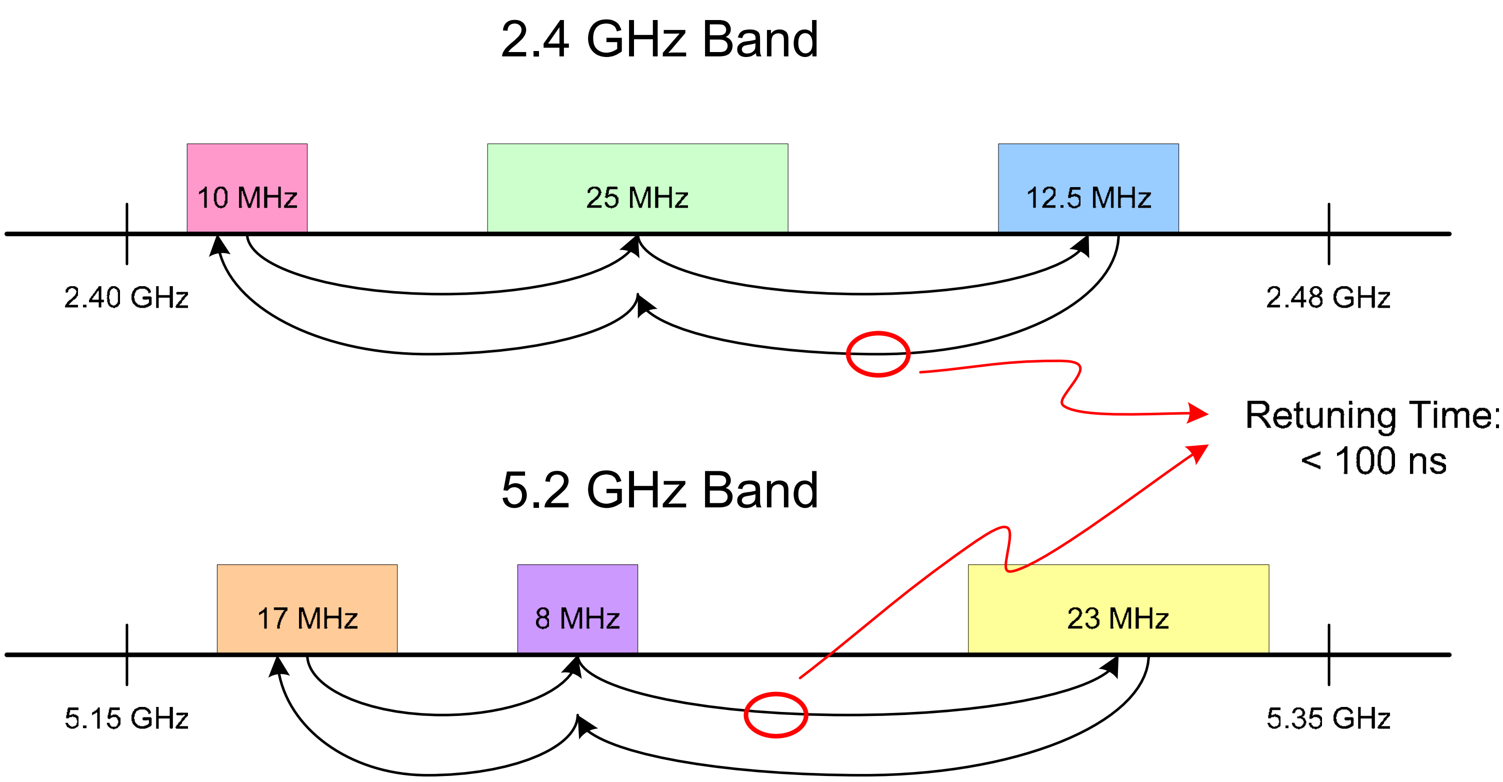


FOM: LO generation with DDFS and PLL



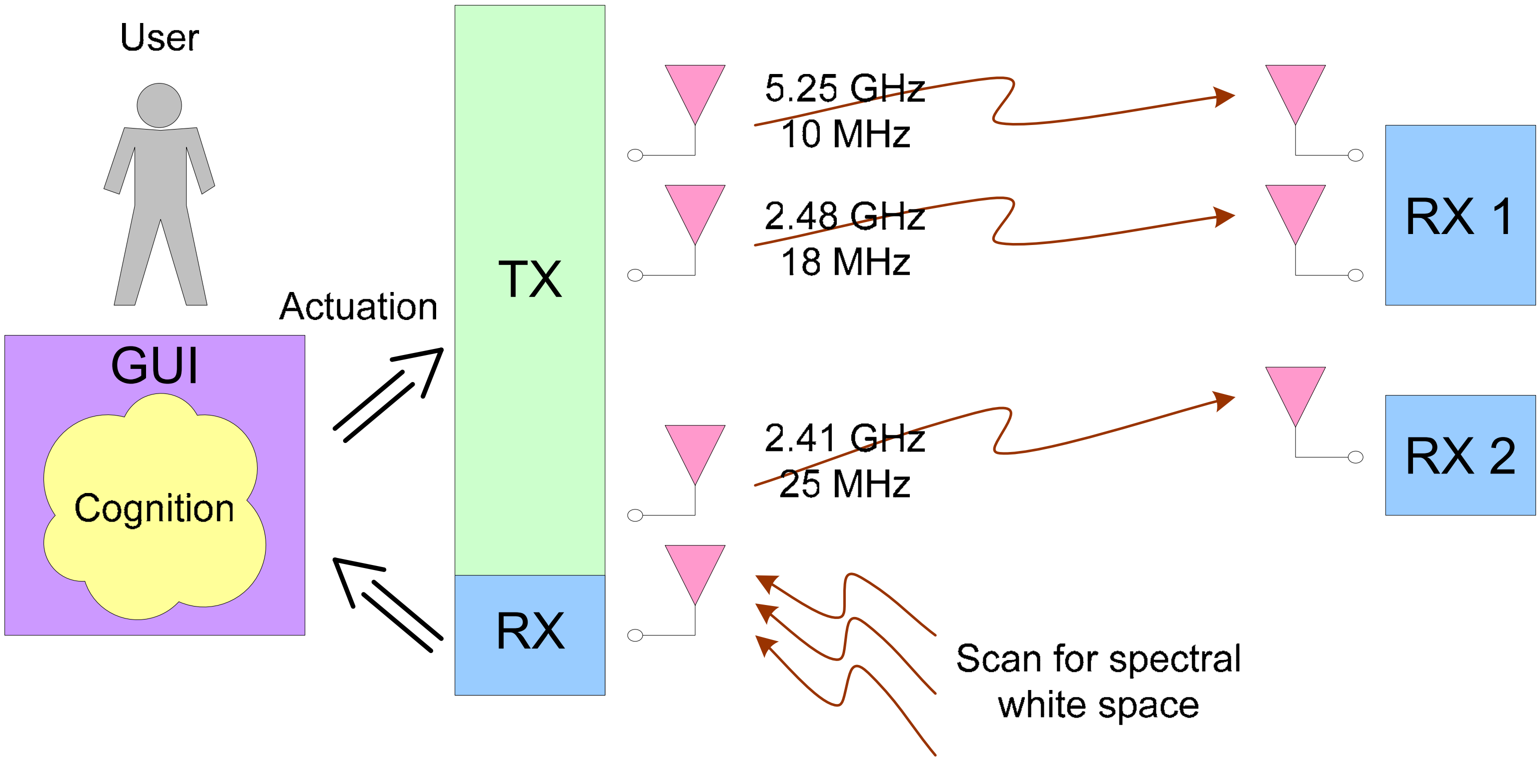
- **Combination of tunable DDFS and fixed PLL for LO generation allows fast channel hopping**

FOM: Channel / Bandwidth Selection



- **Re-tuning time <100ns (10us for conventional PLL)**
- **Variable Bandwidth using Digital re-sampling**
- **Random channel selection with DDFS**

FOM: Flexible Testbed configuration



- **User can specify any of 8 Transceivers to operate in Tx or Rx mode**
- **Tx and Rx units can operate simultaneously in different bands / channels.**

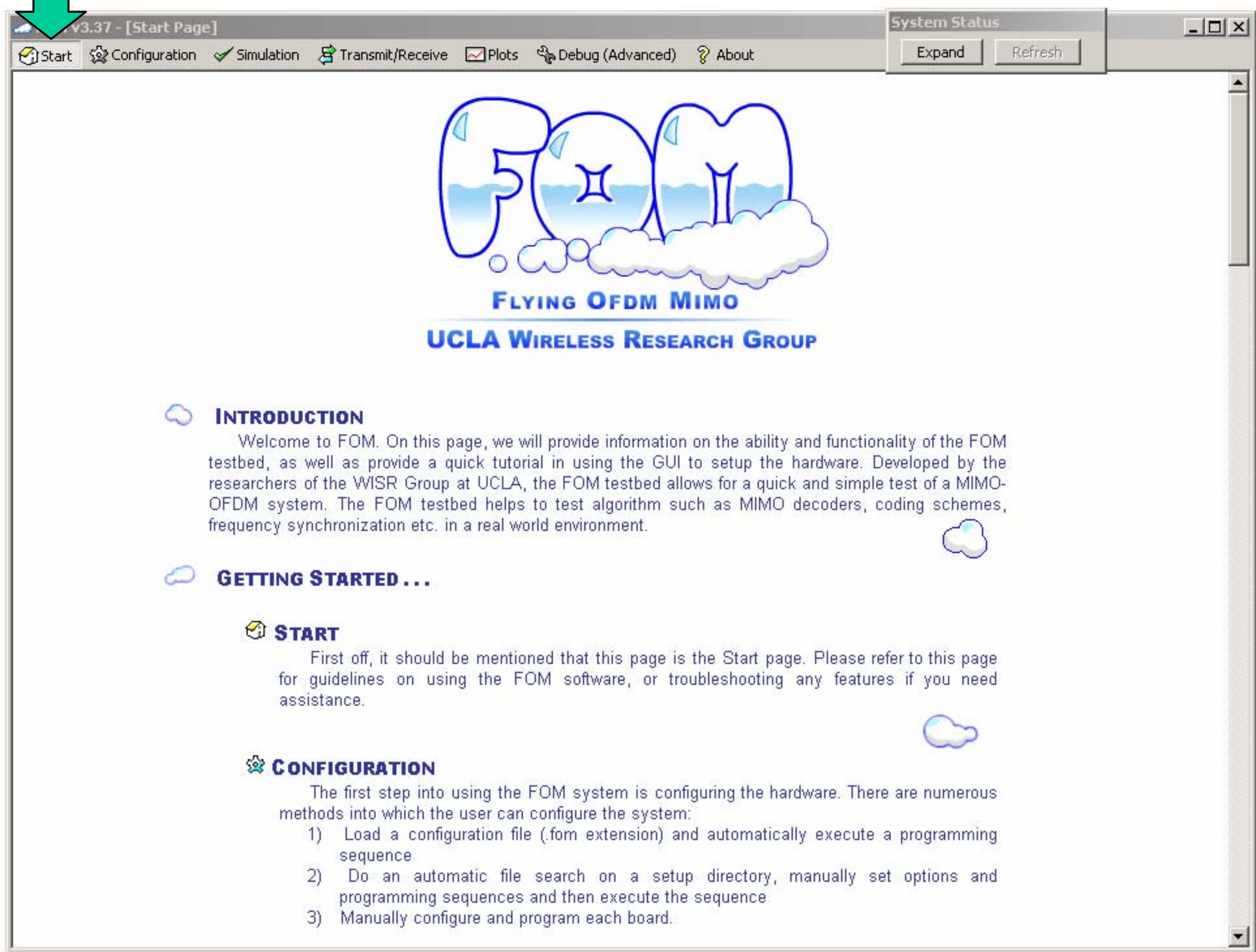
FOM: GUI Navigation Overview

Start [illegible] **Transmit/Receive** **Debug** **About**

- Brief Intr[illegible]

Navigation Bar

- Intuitive setup & execution



FOM: GUI Configuration Overview

Mini-window to check the hardware status of system.

Click on Configuration to display hardware configuration features:

First time configuration can be done with other boards:

Similar to USB connection

Save and load configuration

To avoid tediousness, program sequence allows fast setup:

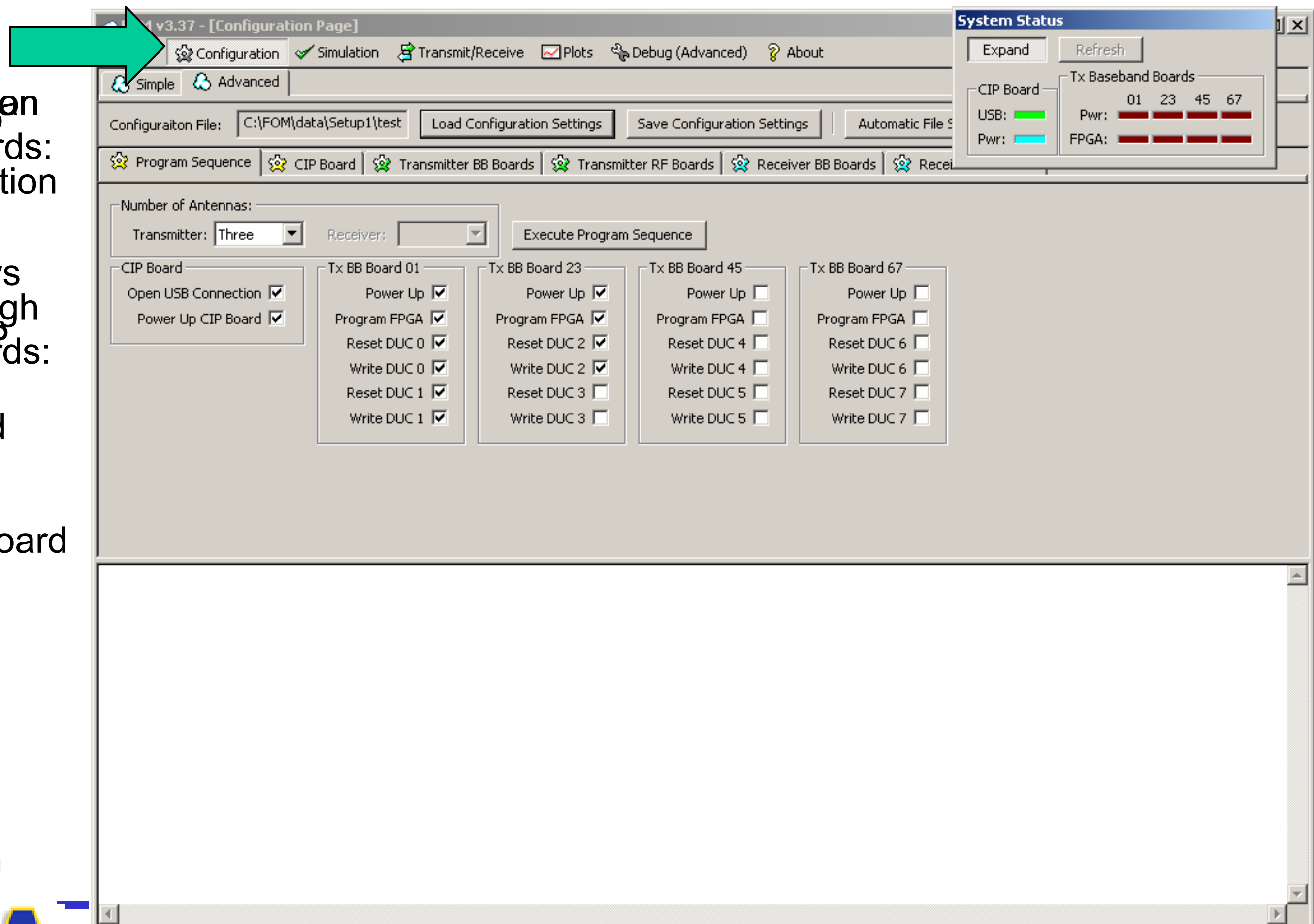
Tabs allow flipping through the 5 hardware boards:

1. CIP
2. Tx Baseband
3. Tx RF
4. Rx Baseband
5. Rx RF

Settings to power up CIP board and assign I2C addresses to each board

Choose board to port connection on the CIP board

Clock / Trigger Selection

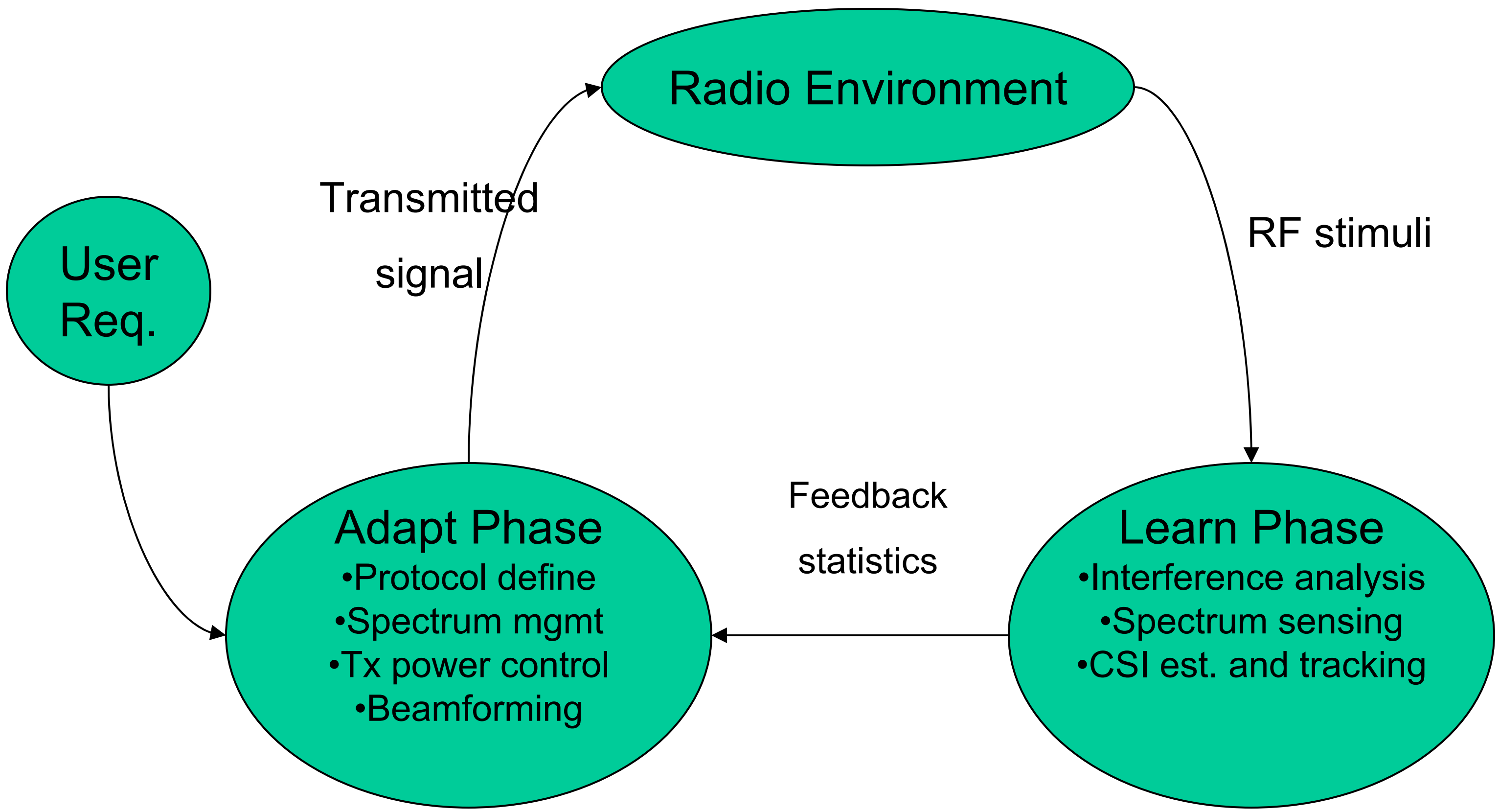


Cognitive radio – research overview

Cognitive radio

- "*Smart radios*" – self-adaptive radio, ***learns*** its environment and ***adapts*** by adjusting radio parameters to improve spectrum utilization
- Phases of a cognitive radio
  - Learning phase at receiver
    - Estimation and modeling of in-band RF interference profile
    - Detection/sensing of spectrum holes
    - Channel estimation and tracking
  - Feedback statistics
    - Feedback rate determines performance
  - Adaptation phase
    - Dynamic spectrum management – optimize utilization of spectrum
    - Adaptive modulation – optimize throughput
    - Adaptive beamforming – minimize interference

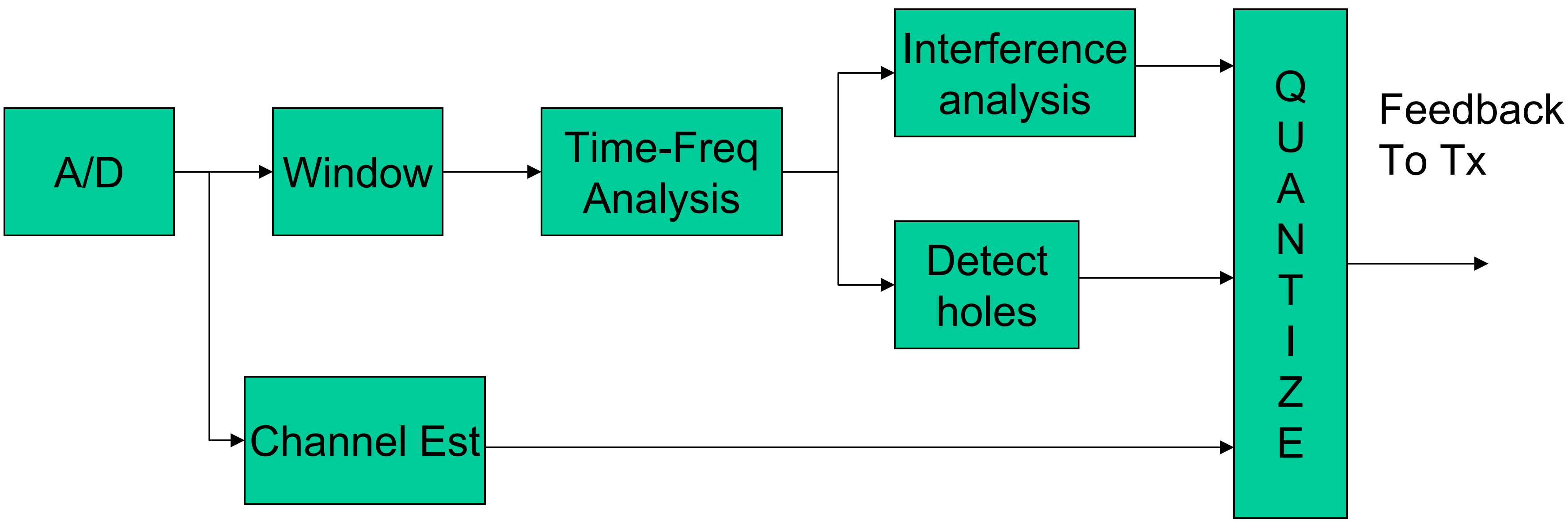
Cognitive radio phases



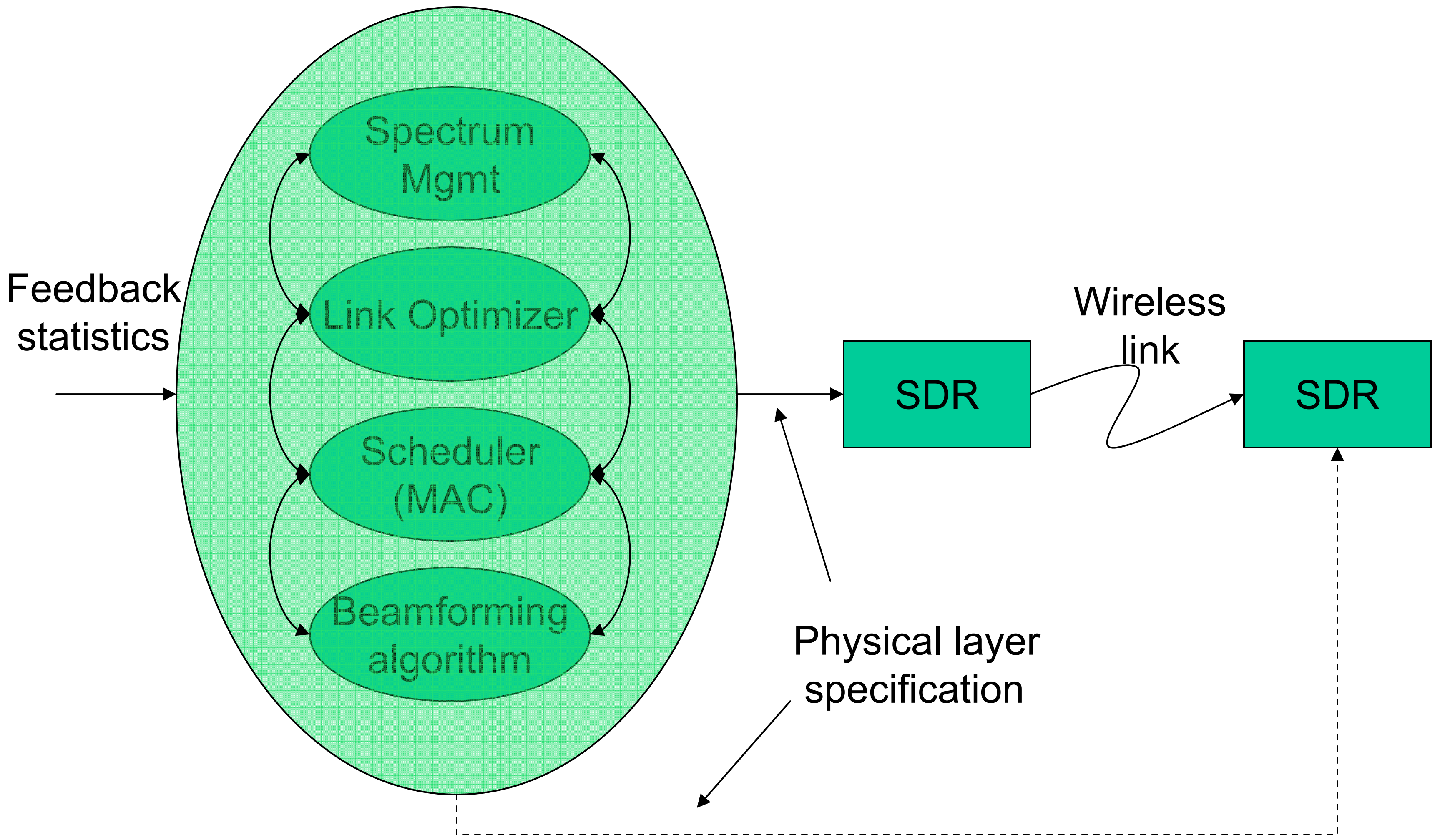
Implementation challenges

- SDR is an enabling technology for cognitive radio
  - Mixed HW/SW to meet algorithm complexity and flexibility requirements. (ASIC/FPGA/DSP)
- Wideband antennas
- Agile, multi-band, digitally controlled RF transceiver
  - Highly sensitive radio (multiple antennas help)
  - RF signal gain linearization (pre-distortion, feed-back or feed-forward control)
  - Dynamic calibration / compensation
  - Reduction of analog filtering for area & cost saving

Learning Phase



Adaptation Phase



Potential research directions

- Radio and prototype work
  - RF transceiver hardware design
  - SDR architecture and design flow tools (FPGA/DSP and ASIC)
- Communication Systems work
  - Framework for maximization of spectral efficiency given all the tunable parameters
  - Design of radio detectors for radio policy violations
  - Design of optimal (co-operative) multi-user policy given location of users and traffic patterns