UK China Bridges Beyond 4G Test Bed

From Concept, Implementation and Initial Results

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[3]Heriot-Watt University, Edinburgh, UK

Overview of Presentation

- Overview of the HWU-UoB-UoE collaboration
  - Mark Beach, University of Bristol
- UC4G Testbed and its capabilities
  - Pat Chambers and Zengmao Chen, Heriot Watt University
- Spatial modulation (SM)
  - Harald Haas, University of Edinburgh
- Evaluations based on Real channel measurements
  - Will Thompson, University of Bristol
- SM Implementation, initial results
  - Abdelhamid Younis, University of Edinburgh
- Our Next Steps

WP4 Prototype development and testing of "beyond 4G" wireless technologies

- **Objective:** To develop prototypes and test/verify findings using wireless testbed(s) and to facilitate proof of concept, technology transfer, and commercialisation.

- **Methodology:** UK/Chinese academic partners will coordinate with each other and relevant industry partners to develop prototypes and verify leading-edge 4G wireless technologies using a professional wireless testbed.
  - Enhancements to OFDM-MIMO technologies to be pursued.

Jan/Feb 2011: Test bed & Air Interface Selection

- Test Bed Selection
  - National Instruments (NI) Vs Lyrtech platforms
  - NI selected for further evaluation
- Comprehensive Evaluation of NI PXI MIMO System
  - Hosted by Toshiba TREL in Bristol
  - Supported by 4 NI staff in Bristol & Multiple Staff by conference bridge (GoToMeeting)
  - Academic teams from Bristol, Edinburgh & Heriot Watt Universities, plus others via conference bridge
- Outcome
  - Procurement of PXI platform
  - Selection of Spatial Modulation as candidate air interface

Re-Shaping the Budget

- Effort re-appraisal
  - Establishment of NI PXI advanced wireless prototyping
  - Further development of Spatial Modulation concept
  - Framework for evaluation
- Outcome
  - Shift of resource from Travel and IP protection to ‘RAs’
    - Pat Chambers (HWU)
    - Abdelhamid Younis (Edinburgh)
    - Will Thompson (Bristol)

Project collaborators

Spatial modulation
concept and
theoretical proof

THE UNIVERSITY OF EDINBURGH

SMod
PHY-layer
Simulator

MATLAB
SIMULINK

Real Urban
MIMO Channels

University of BRISTOL

MIMO
hardware
NI Testbed

HERIOT WATT UNIVERSITY

UK-China (B)4G Wireless MIMO Testbed: Architecture and Functionality

Pat Chambers, Zengmao Chen & Cheng-Xiang Wang

Heriot-Watt University, Edinburgh, UK
School of Engineering & Physical Sciences
Electrical, Electronic and Computer Engineering

The Edinburgh Research Partnership in Engineering and Mathematics (ERPem)
Joint Research Institute for Signal and Image Processing (JRI-SIP)

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Outline

I. Motivation

II. Testbed Specifications

III. Testbed Architecture & Functionality

IV. Testbed Demos

- Demo 1: Offline MIMO LTE
- Demo 2: Real-Time SISO WLAN
- Demo 3: Channel Emulator

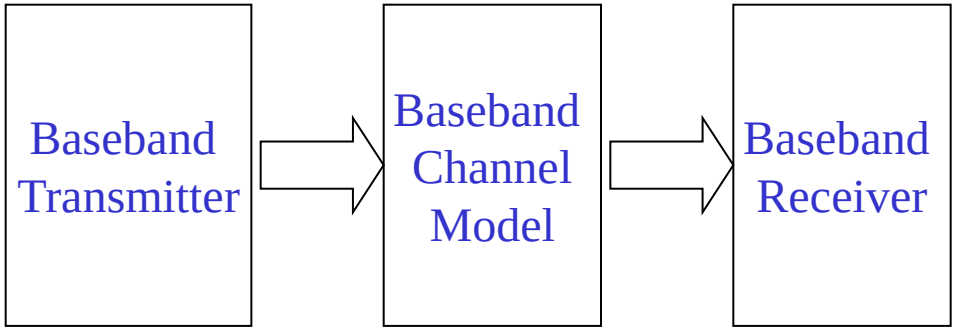
Acknowledgements

In alphabetatical order, the contributions of the following individuals are gratefully recognised:

- Dr. Xeumin Hong.
- Dr. Raed Mesleh.
- Nikola Serafimovski.
- Dr. Jian Sun.
- Dr. Xiangyang Wang.
- Abdelhamid Younis.
- Wuxiong Zhang.

I. Motivation

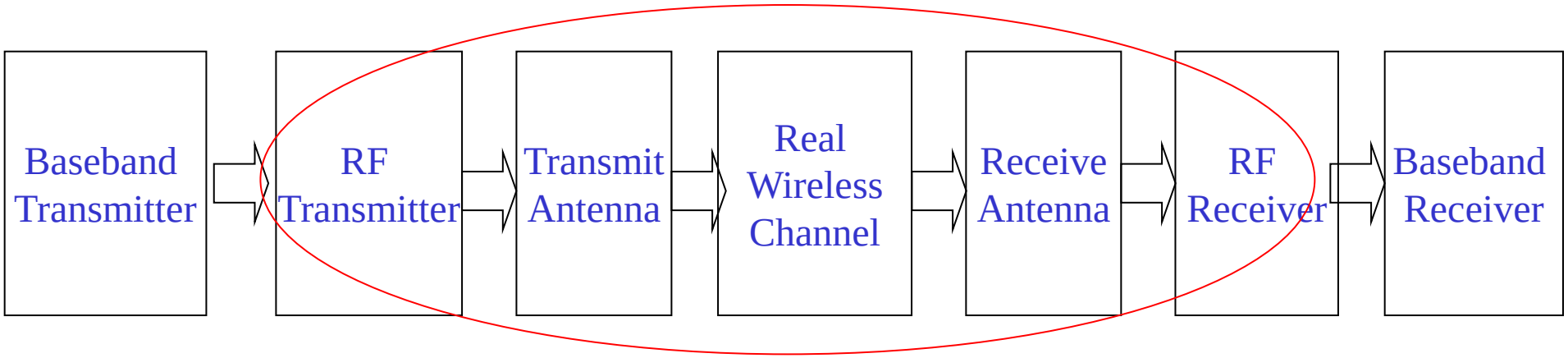
- **Drawbacks of software wireless communication system simulators:**
  - Simulators provide limited fidelity to real-world wireless systems.
    - Simplified channel models
    - Unrealistic interfering conditions
  - Simulators usually fall short of addressing important practical issues.
    - Synchronisation
    - Implementation impairments
    - Real-time requirements
    - Hardware complexity



- **Only Baseband, No RF**
- **Not Accurate**

Benefits of Testbed

- **There is an increasing need for a wireless testbed to**
  - Test new concepts in reality (proof of concept)
  - Showcase advanced technologies
  - Calibrate simulation results
  - Identify practical problems and steer R&D efforts



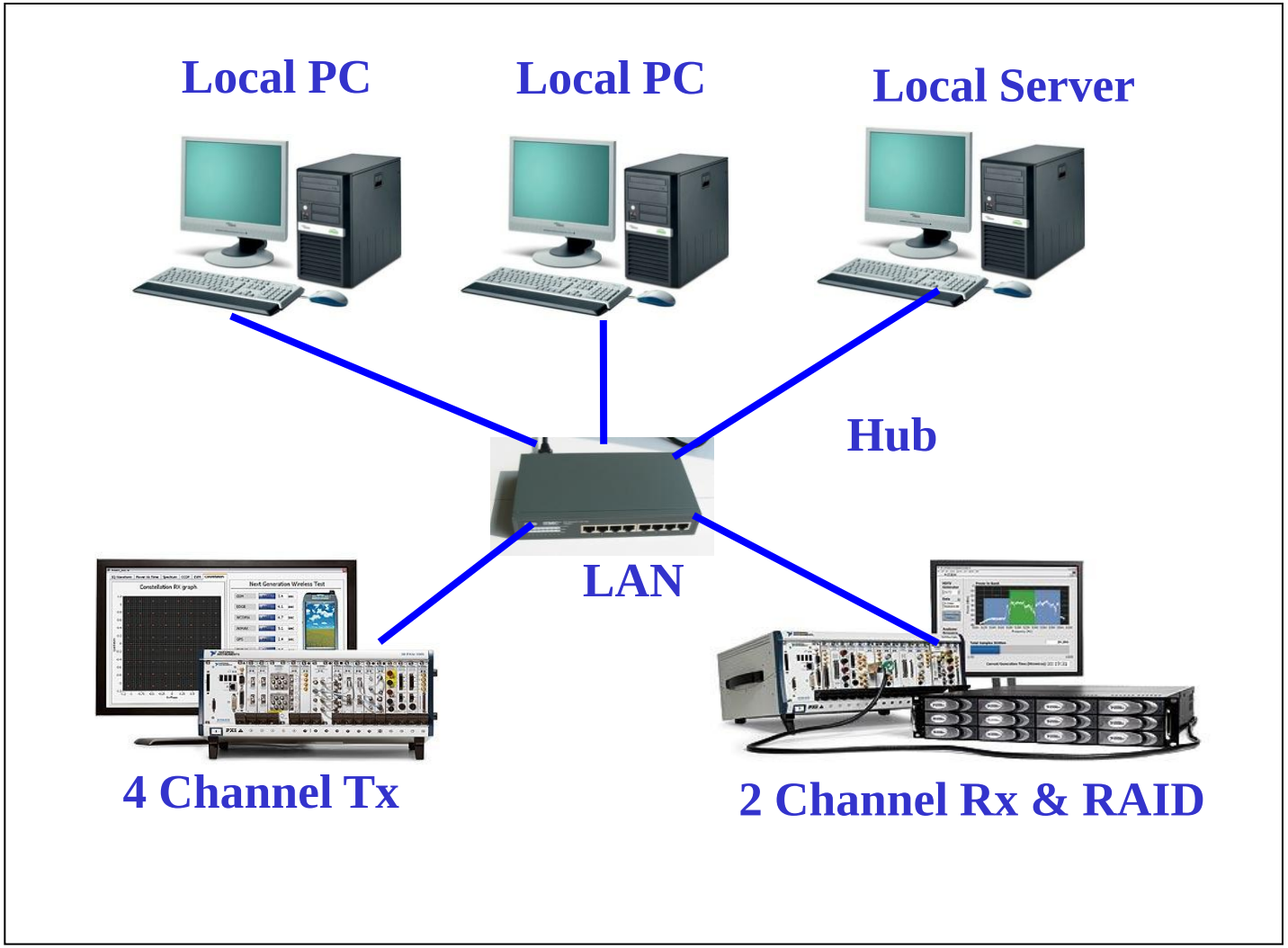
Both Baseband and RF are included; More Practical

Specifications of Testbed

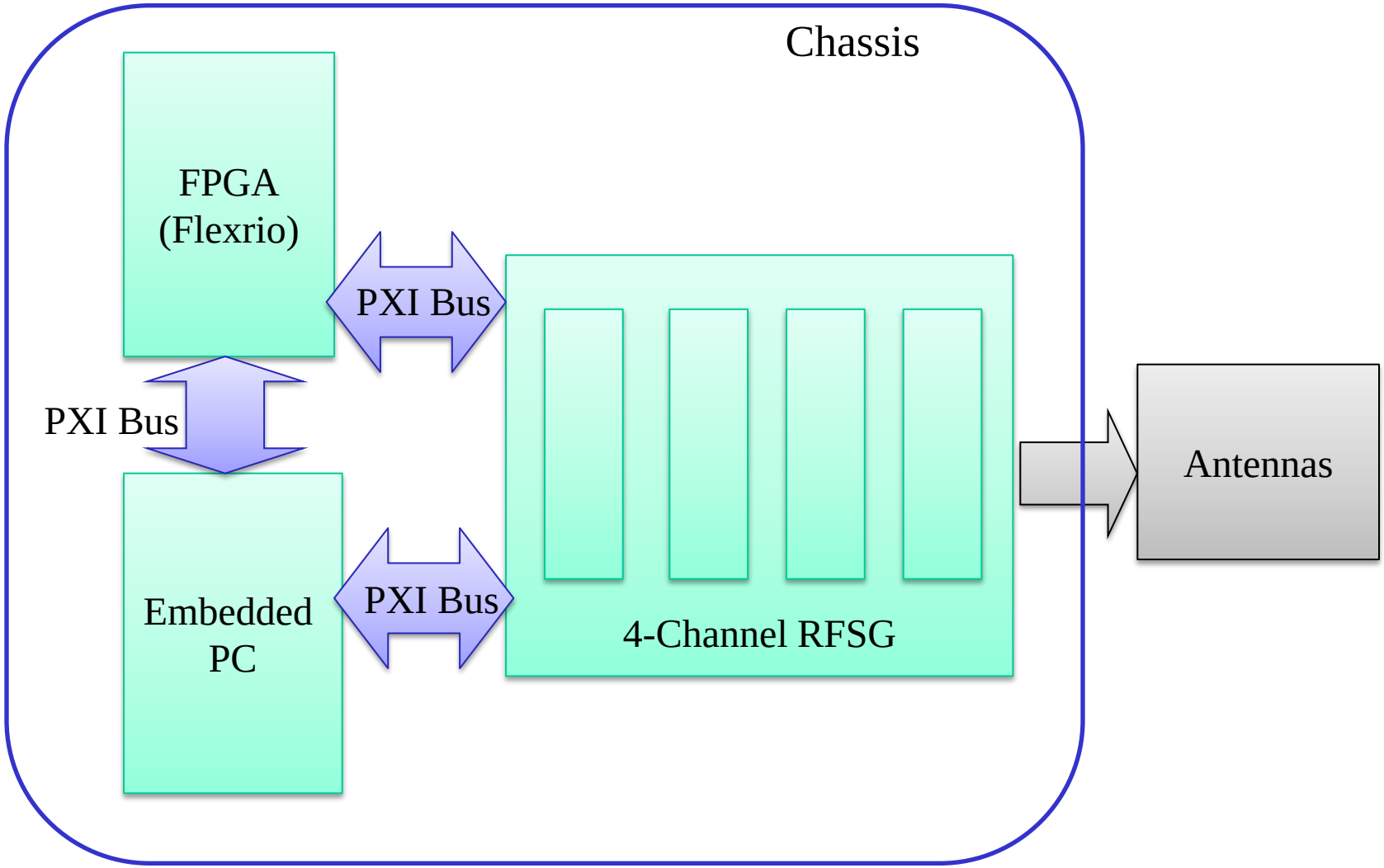
- **Hardware specifics (NI PXI products):**
- Rx → Left-hand side – 2 RF chains
- Tx → Right-hand side – 4 RF chains
- Hard-drive array (RAID)→ Extreme left-hand side: 6 TBs memory
- Tx frequency range (85 MHz – 6.6 GHz)
- Rx frequency range (10 MHz – 6.6 GHz)
- Tx RF bandwidth: 100 MHz
- Rx bandwidth (3dB): 50 MHz
- Embedded FPGA (Xilinx Virtex 5) at the Tx & Rx for real-time signal processing
- Embedded PCs at the Tx & Rx with Windows 7, LabView , Matlab, & NI software

- **Current capabilities/demos:**
- Real-time simplex SISO-WLAN system
- Offline Spatial Modulation (later presentation)
- Offline MIMO LTE
- Channel Emulator
- **Currently developing:**
- Open access interface

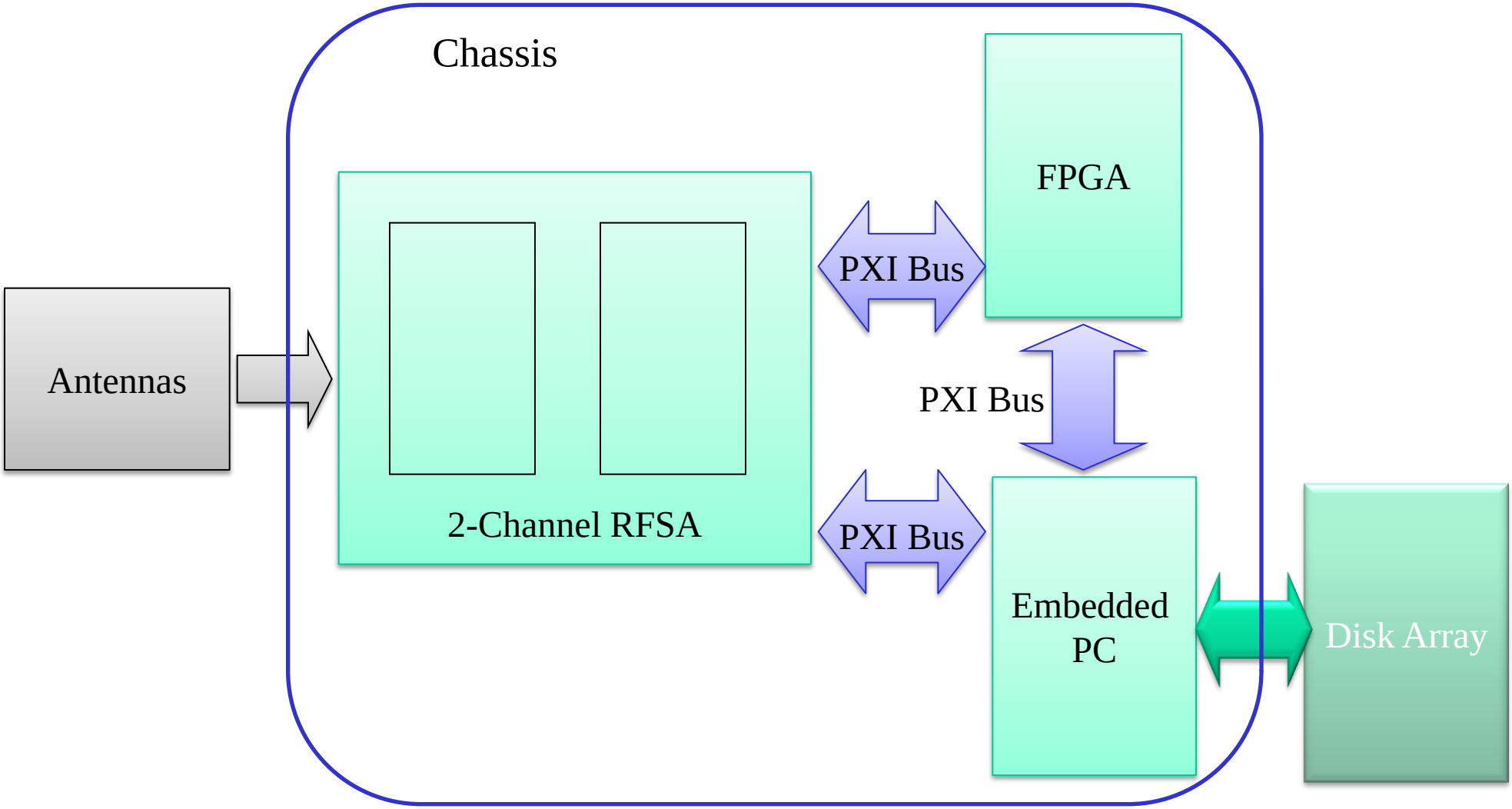
III. Testbed Architecture and Functionality



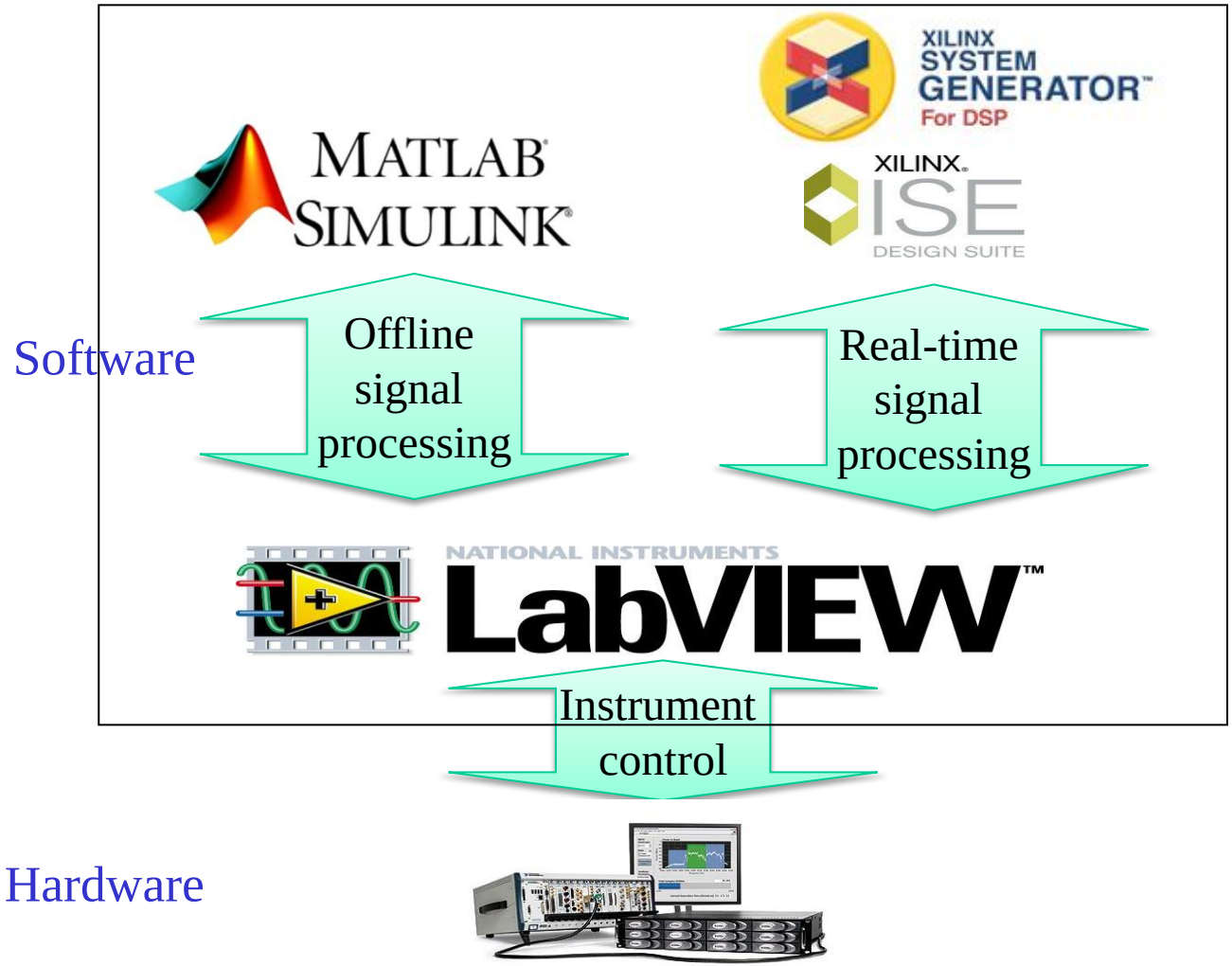
Transmitter Hardware Architecture



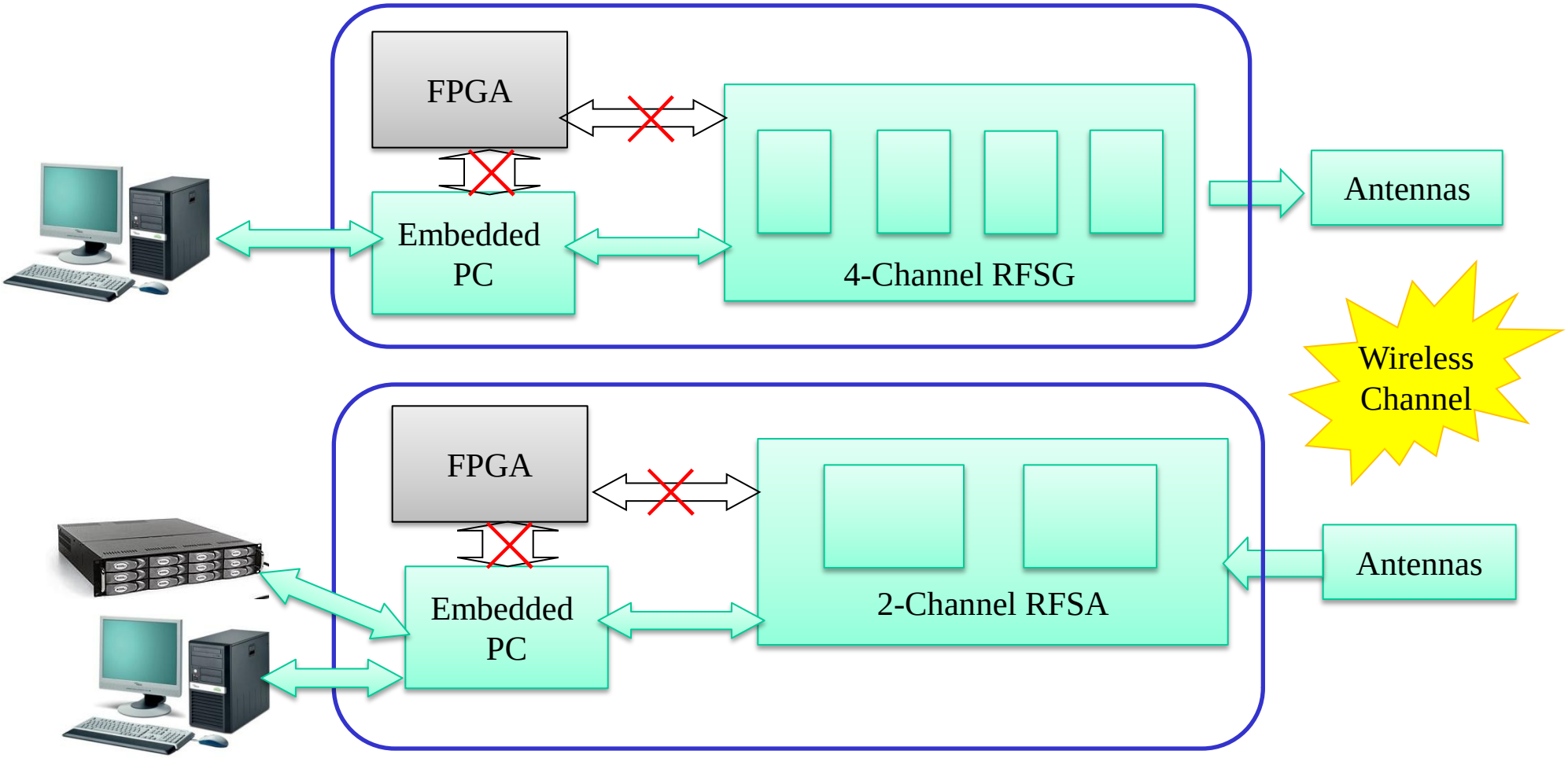
Receiver Hardware Architecture



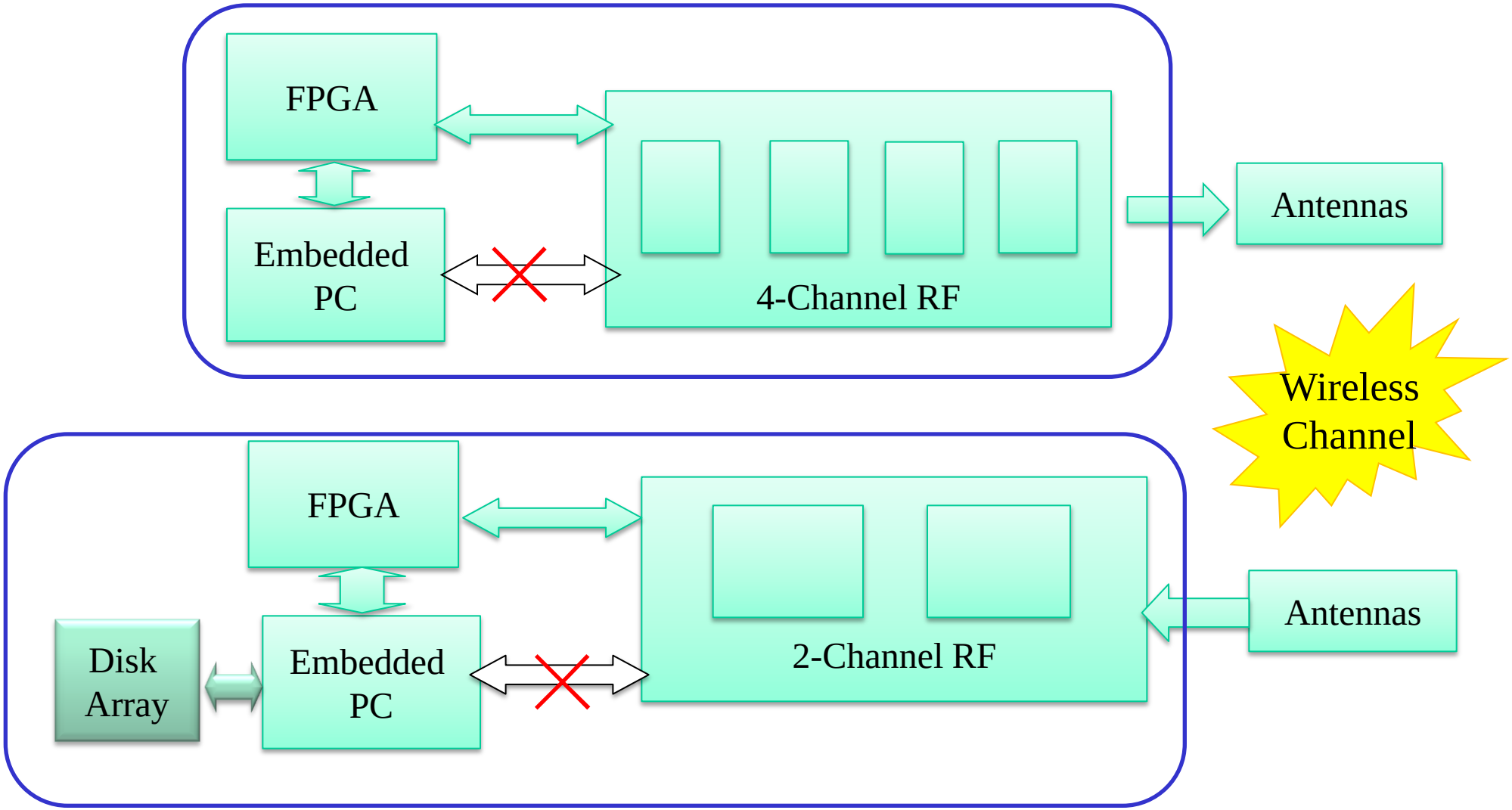
Software Architecture



Offline Testbed Configuration



Real-Time Testbed Configuration

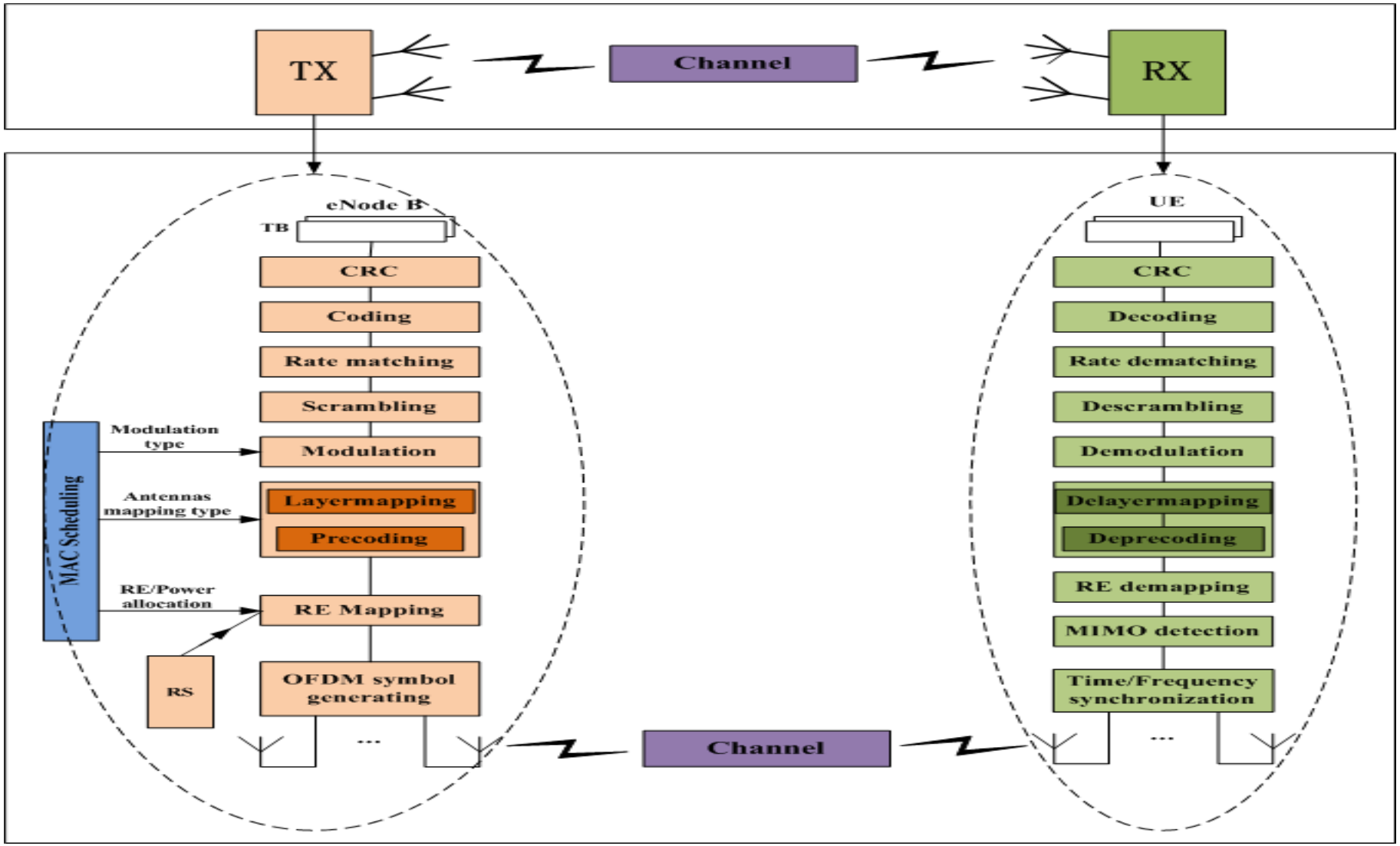


IV. Testbed Demos

Demo 1: Offline MIMO LTE

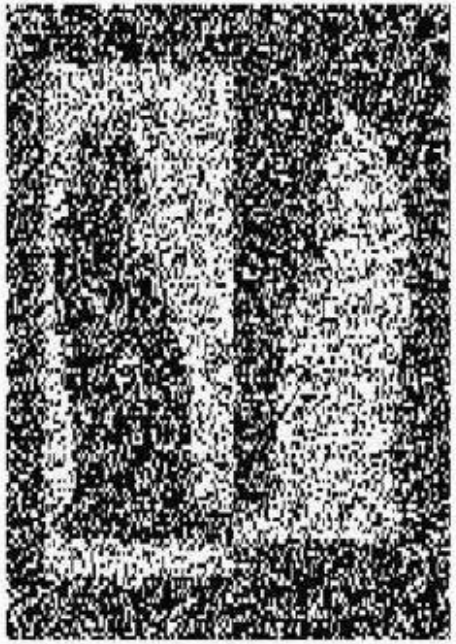
- LTE: Long-term evolution (3.9G)
- System model: 4x2 MIMO diversity & multiplexing
- Diversity -> Space-frequency block codes
- Multiplexing (Open Loop) -> Cyclic delay diversity (CDD)
- Testing parameters (20MHz bandwidth, 2.3GHz centre frequency)
- Results: Transmitted Images, Constellation, BER

Demo 1: Offline MIMO LTE – Schematic

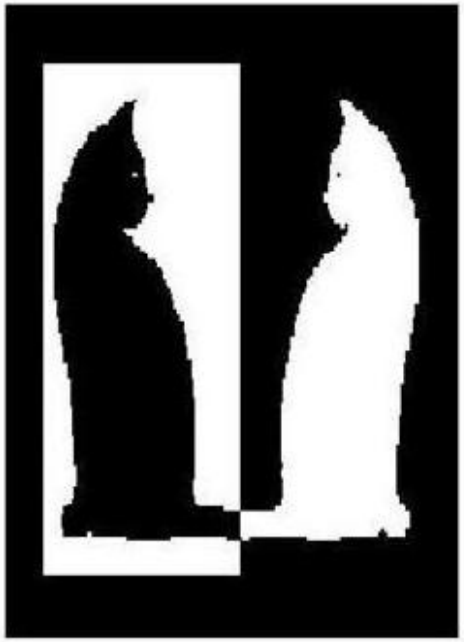


Demo 1: Offline MIMO LTE – Image Transmission Results

- Tx Power: -15 dBm;
- Received SNR: 7.7 dB
- Turbo coding

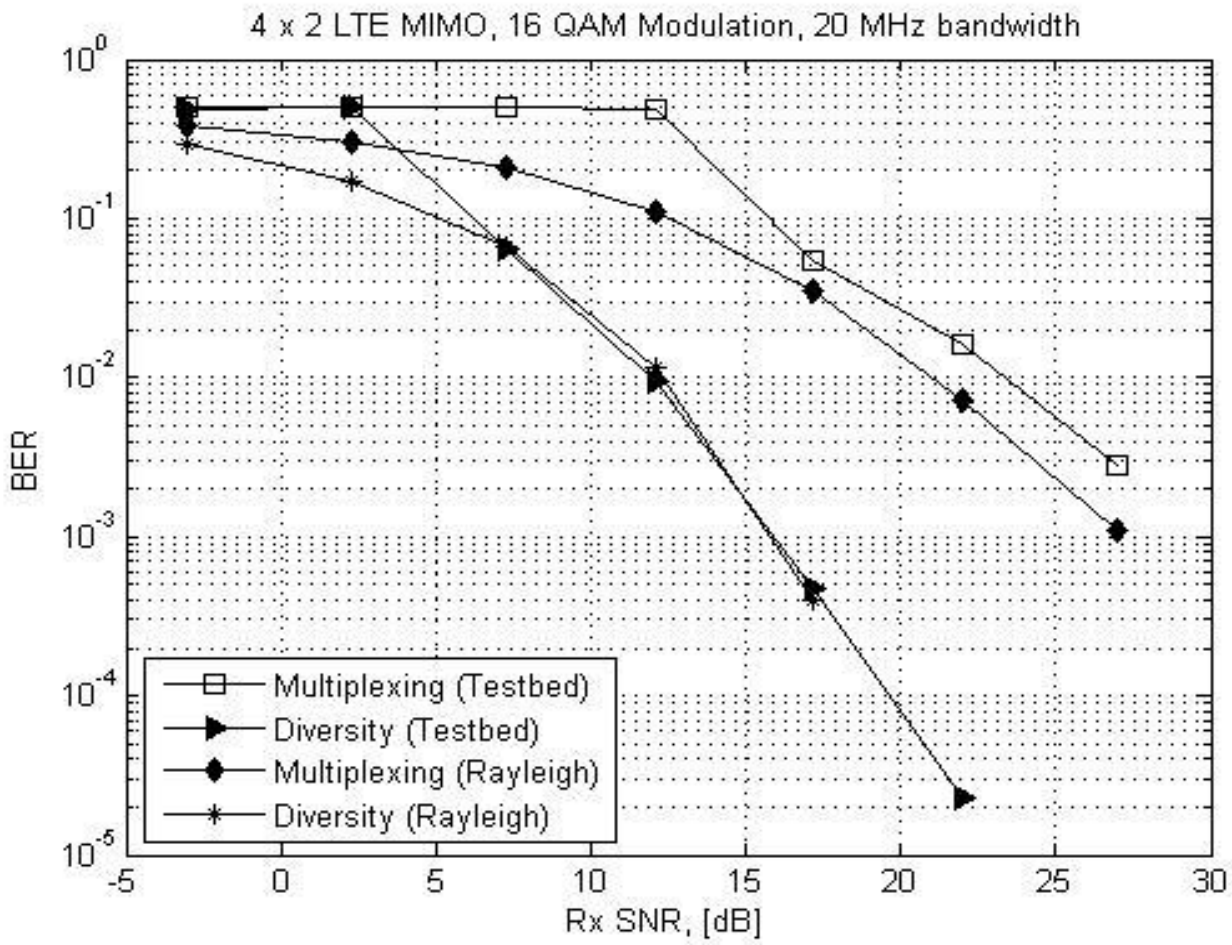


Multiplexing



Diversity

Demo 1: Offline MIMO LTE – BER Curves

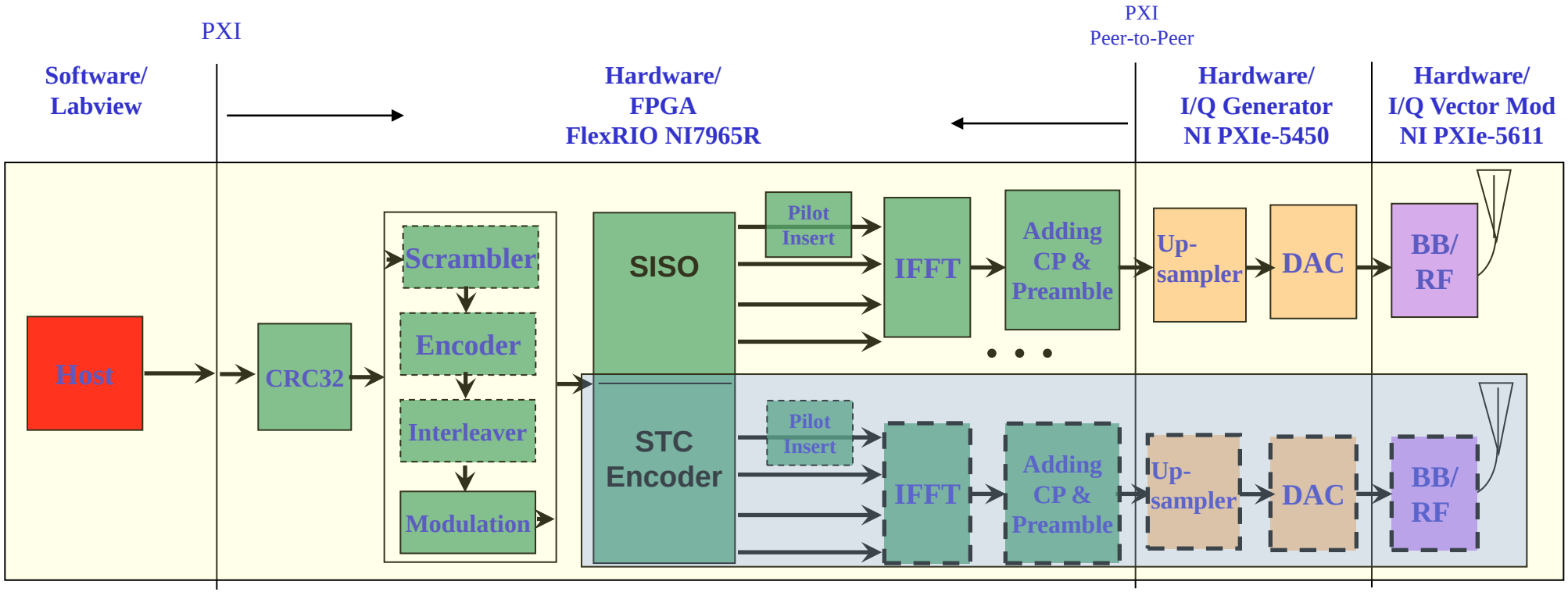


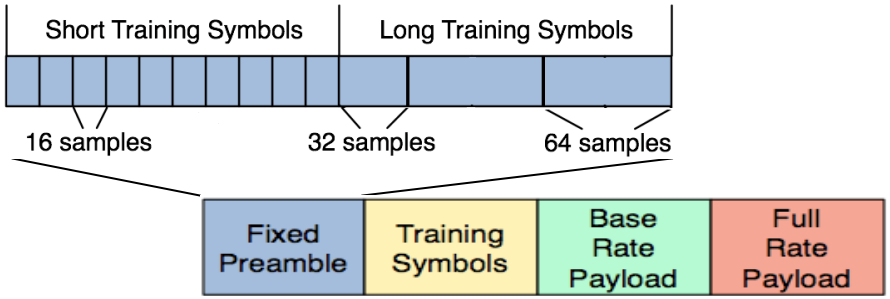
Demo 2: Real-Time SISO WLAN

- **Testing parameters**:
  - System bandwidth: 20 MHz
  - Centre frequency: 2.3GHz
  - 64 point FFT
  - Base Rate modulation: QPSK
  - Full Rate modulation: QPSK/16QAM/64QAM/256QAM
  - No channel coding

- **Results**: Constellation diagram, Channel estimation

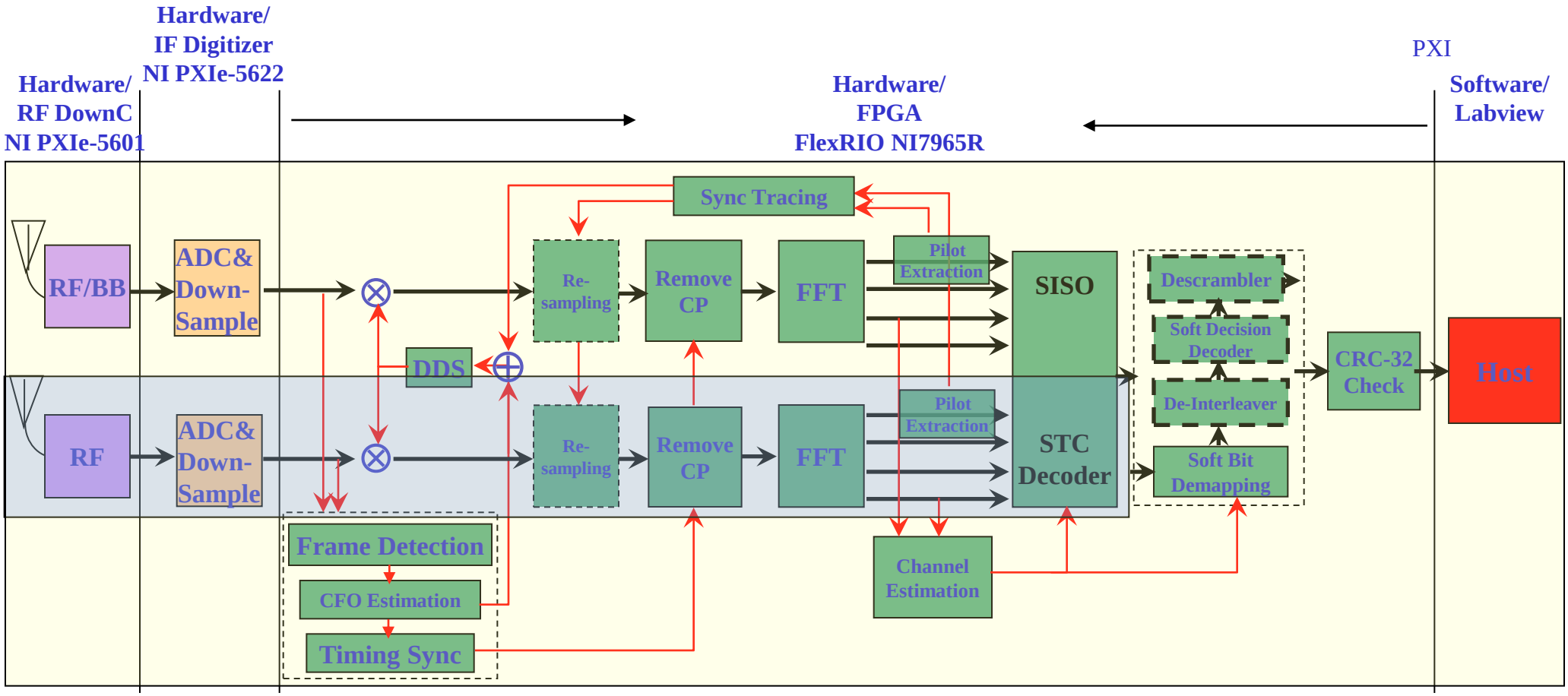
Demo 2: Real-Time SISO WLAN – Transmitter





SISO-OFDM Frame Structure

Demo 2: Real-Time SISO WLAN – Receiver



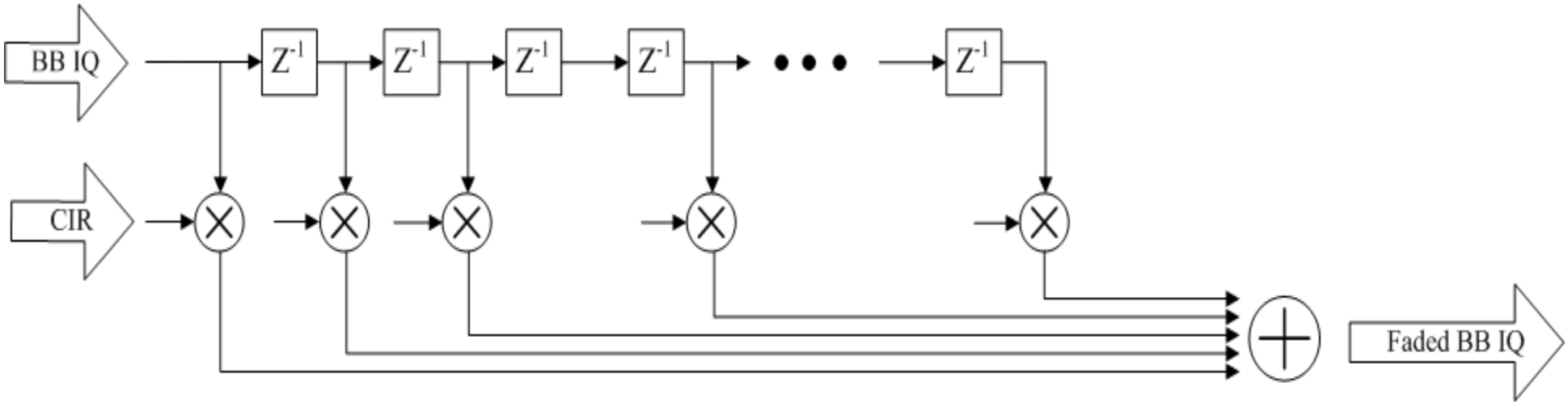
Key Techniques: Frame detection and time Sync, Coarse/fine Carrier Sync and tracing, Soft De-mapping and decision

Demo 3: Channel Emulator

- **What is channel emulator?**
  - It replaces the real-world radio channel between a Tx and a Rx by providing a faded representation of a transmitted signal to the Rx inputs.
  - Applications: anywhere needing a channel, e.g., receiver algorithms evaluation.
- **Advantages of a channel emulator:**
  - Compared with using a real-world channel (e.g., RF testbed):
    - Scenario creation
    - Repeatability
  - Compared with a software channel simulator
    - Higher speed
- **Our contributions:**
  - A time-domain (tapped-delay-line), SISO channel emulator

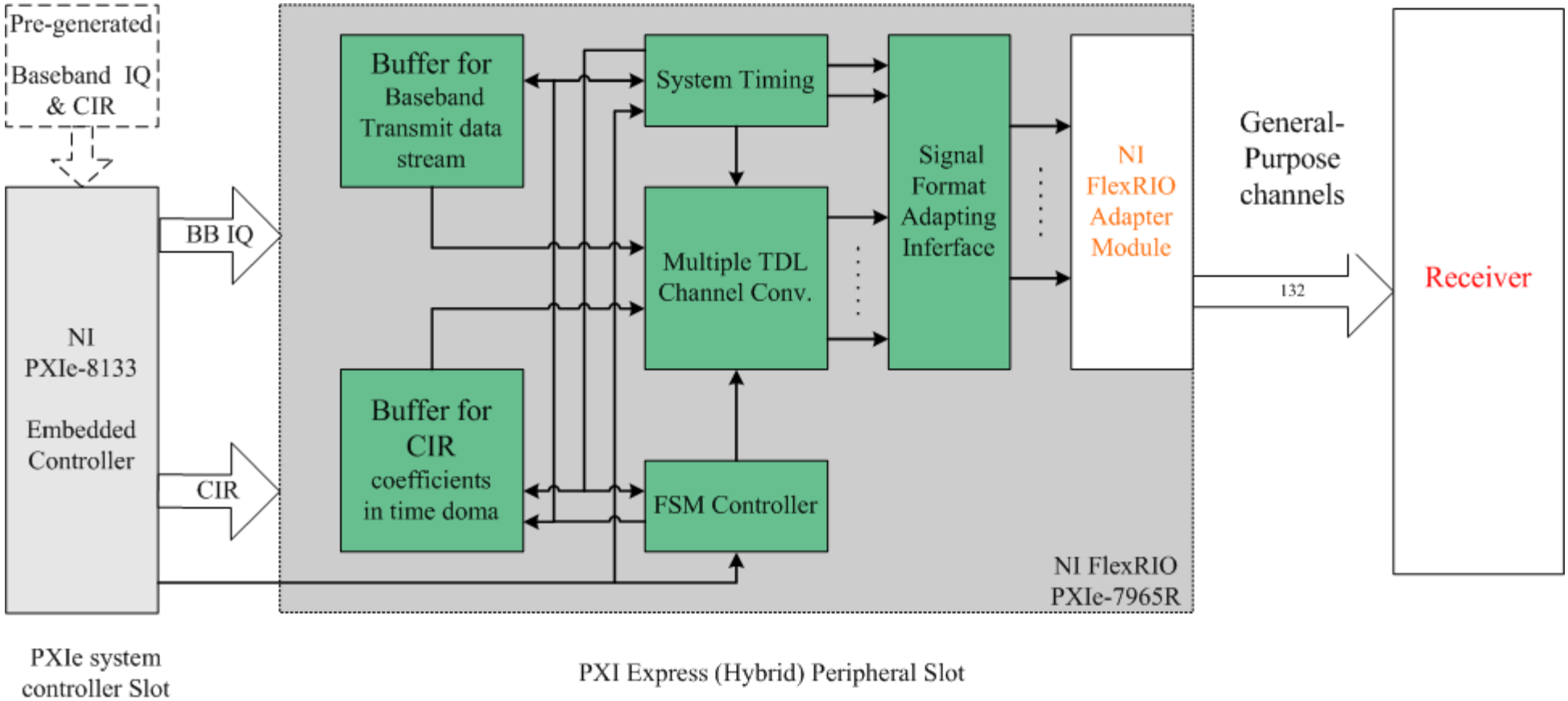
Demo 3: Channel Emulator – Channel Representation

- **Time-domain (Tapped-delay-line) channel representation:**



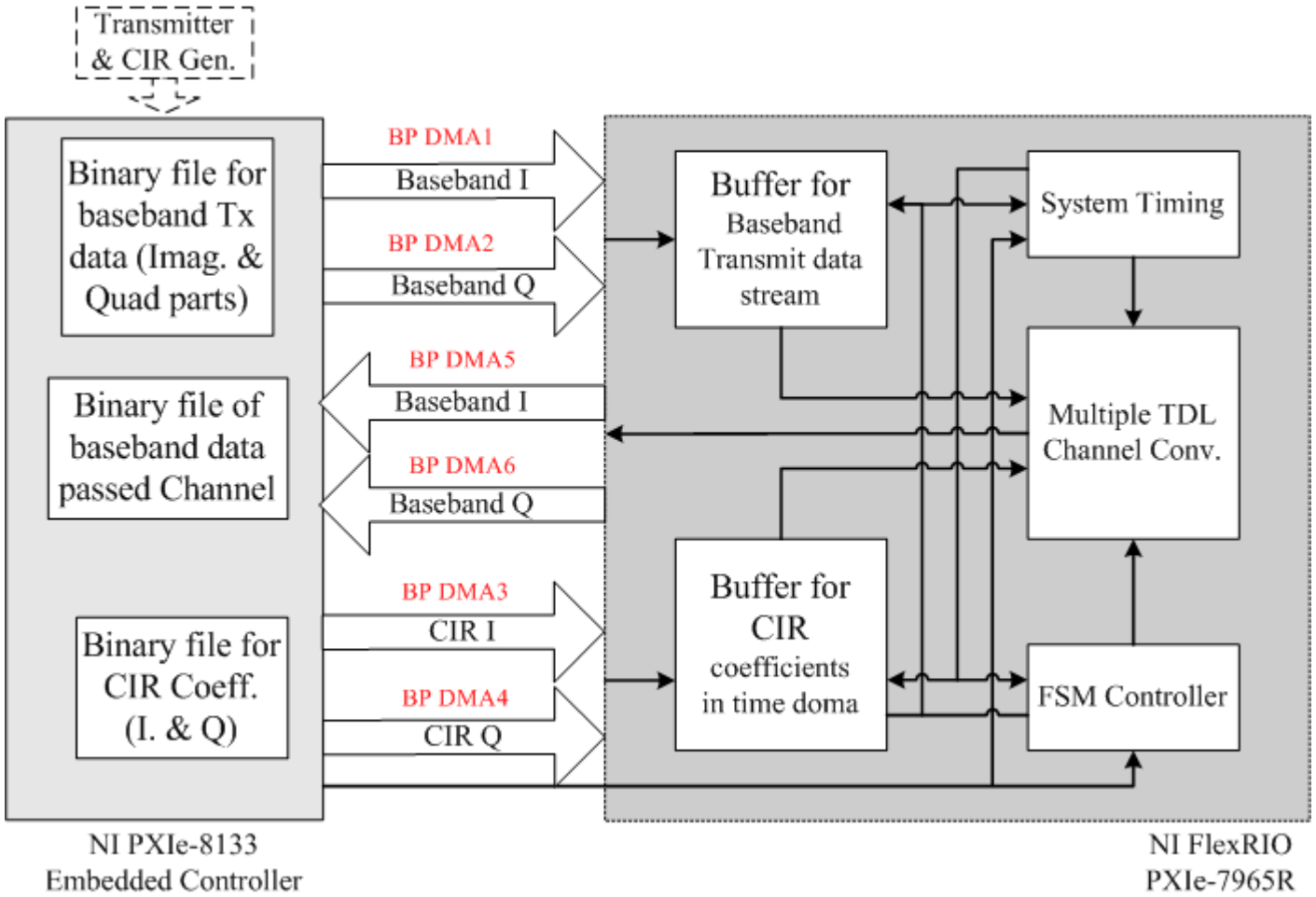
Demo 3: Channel Emulator – NI System

- **National instruments (NI) based channel emulator:**

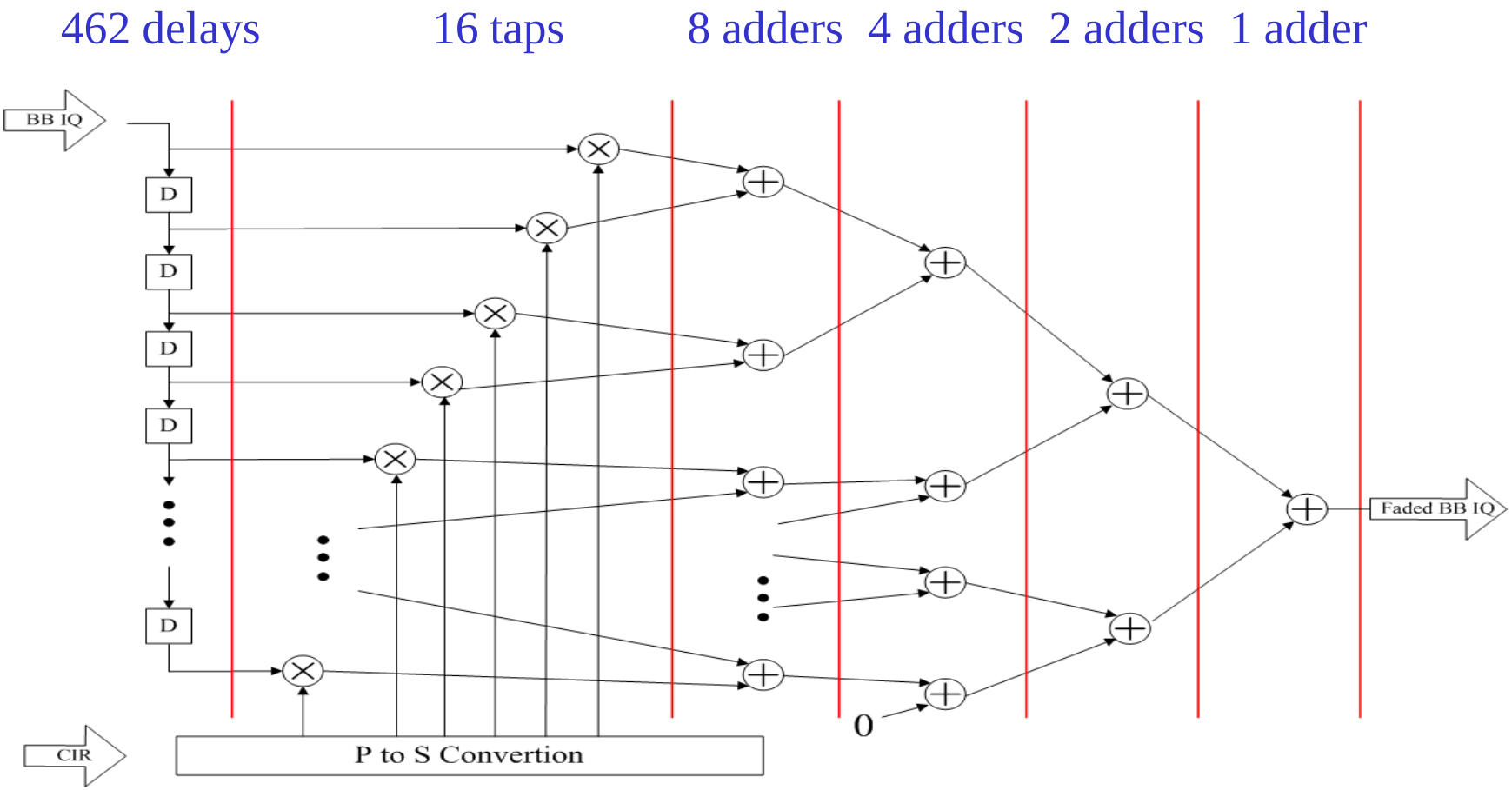


Demo 3: Channel Emulator – Schematic

- **Current solution for the channel emulator:**

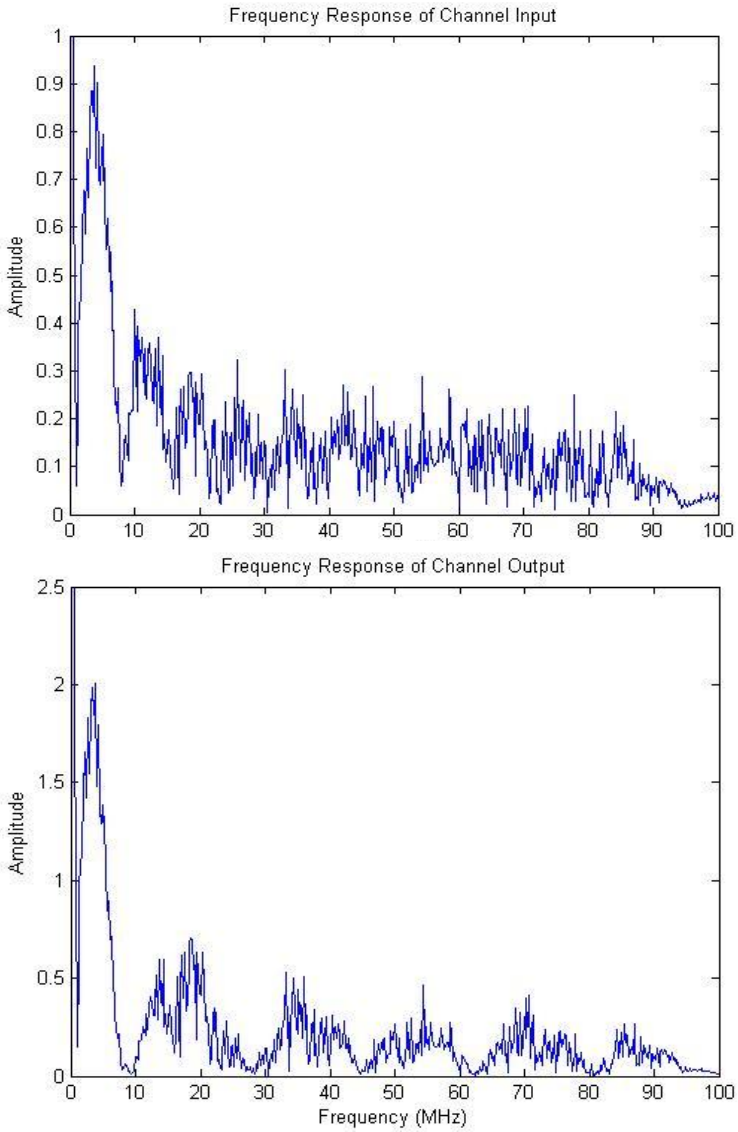


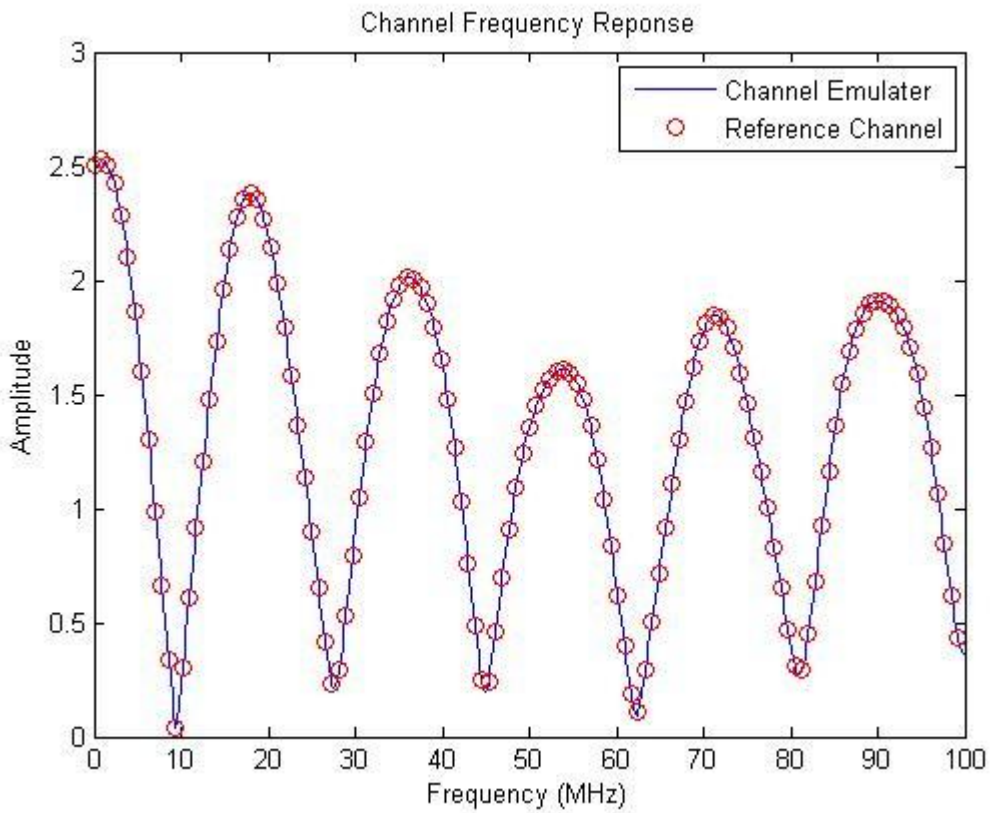
Demo 3: Channel Emulator – Convolution



WINNER II: scenario C4

Demo 3: Channel Emulator – Evaluation





Demo 3: Channel Emulator – Performance

- **FPGA system clock:** 100 MHz
- **FPGA utilisation :** 56.6% (Winner II Scenario C4 in a Xilinx Vertex 5-ST95)
- **Speed comparison:**
  - Winner II Scenario C4 :
    462 effective delays, 16 taps
  - Compare with Matlab-based channel simulator :
    Matlab 2011 @ Windows 7 64bit, Intel Core i7 CPU 1.73 GHz, 4GB RAM

	Channel Simulator	Channel Emulator
26 M samples	180.608 s	**14.682 s**
130 M samples	886.053 s	**66.258 s**

>13 times faster

Spatial Modulation:
Latest Research Findings & Outlook

Professor Harald Haas

The University of Edinburgh
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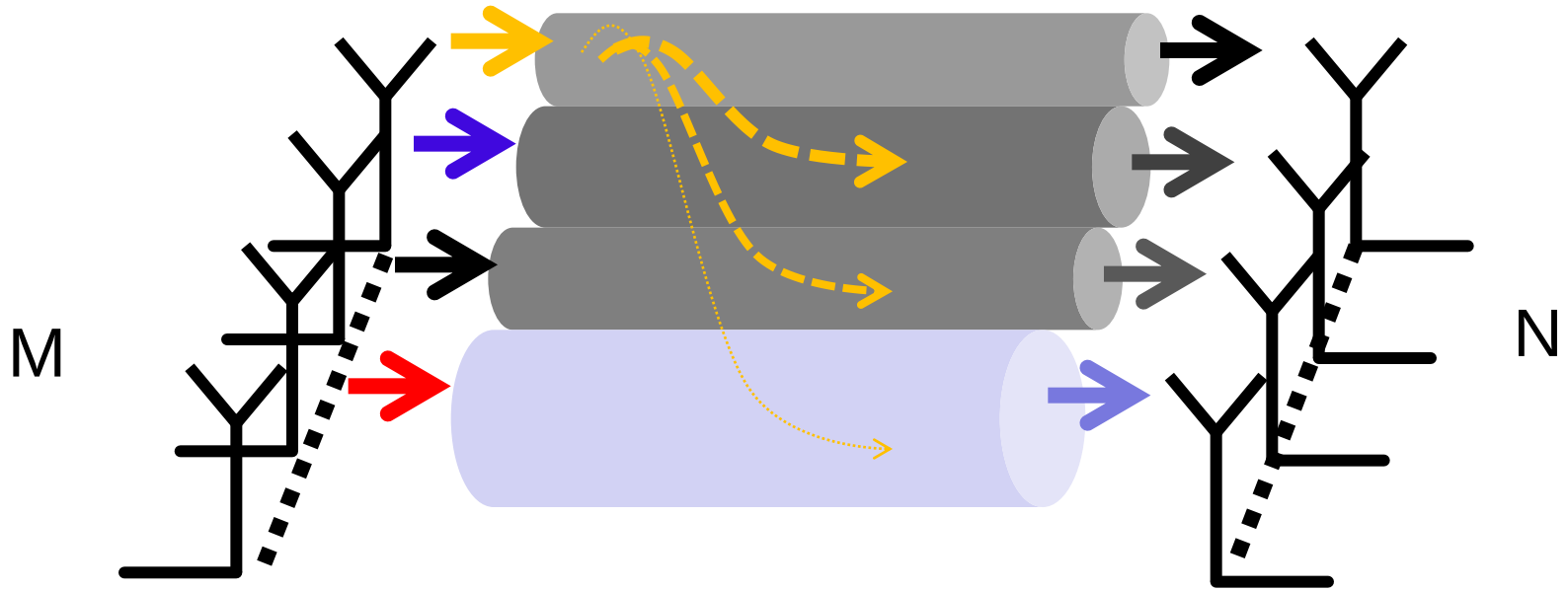
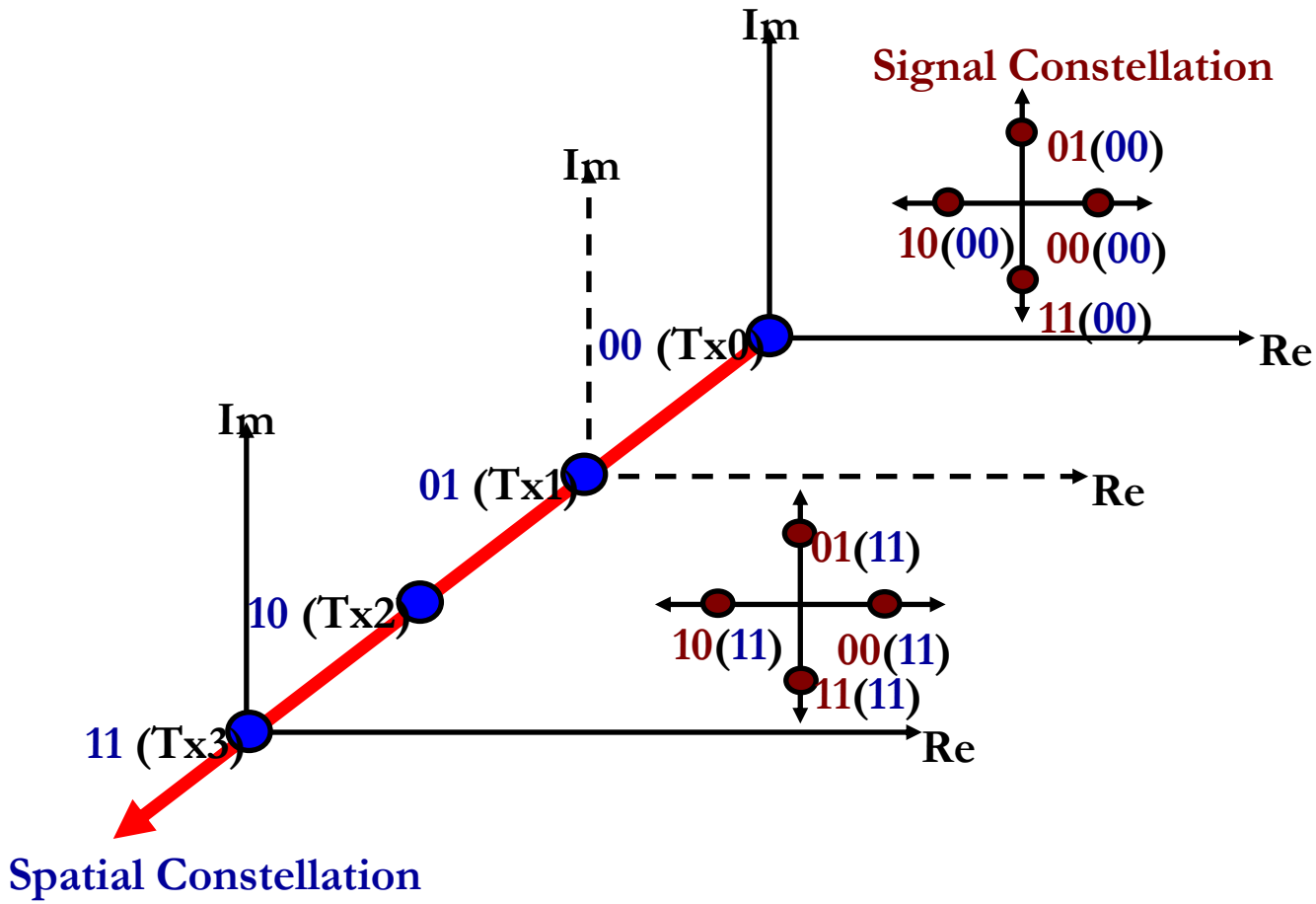
- multiple-input multiple-output (MIMO)

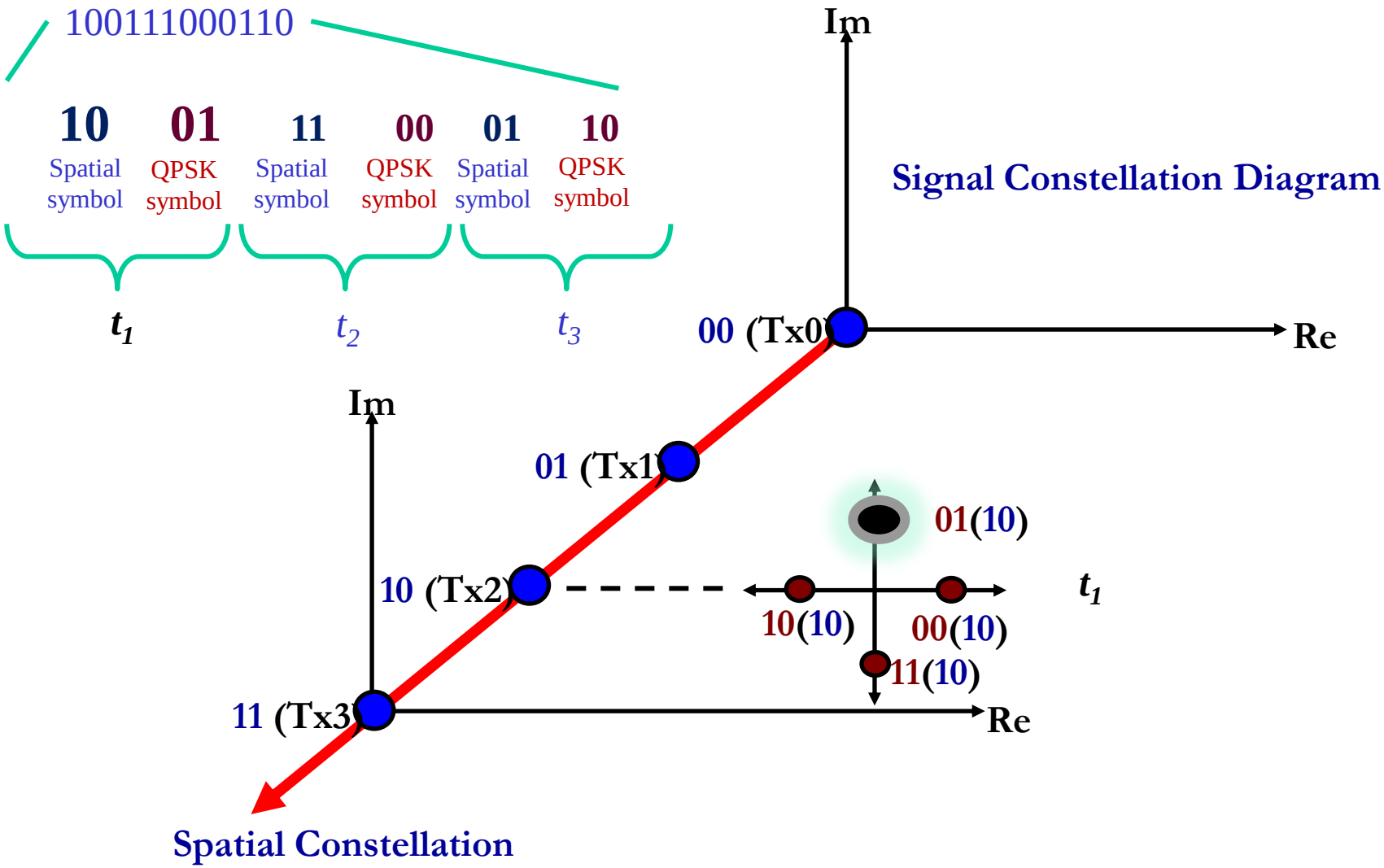


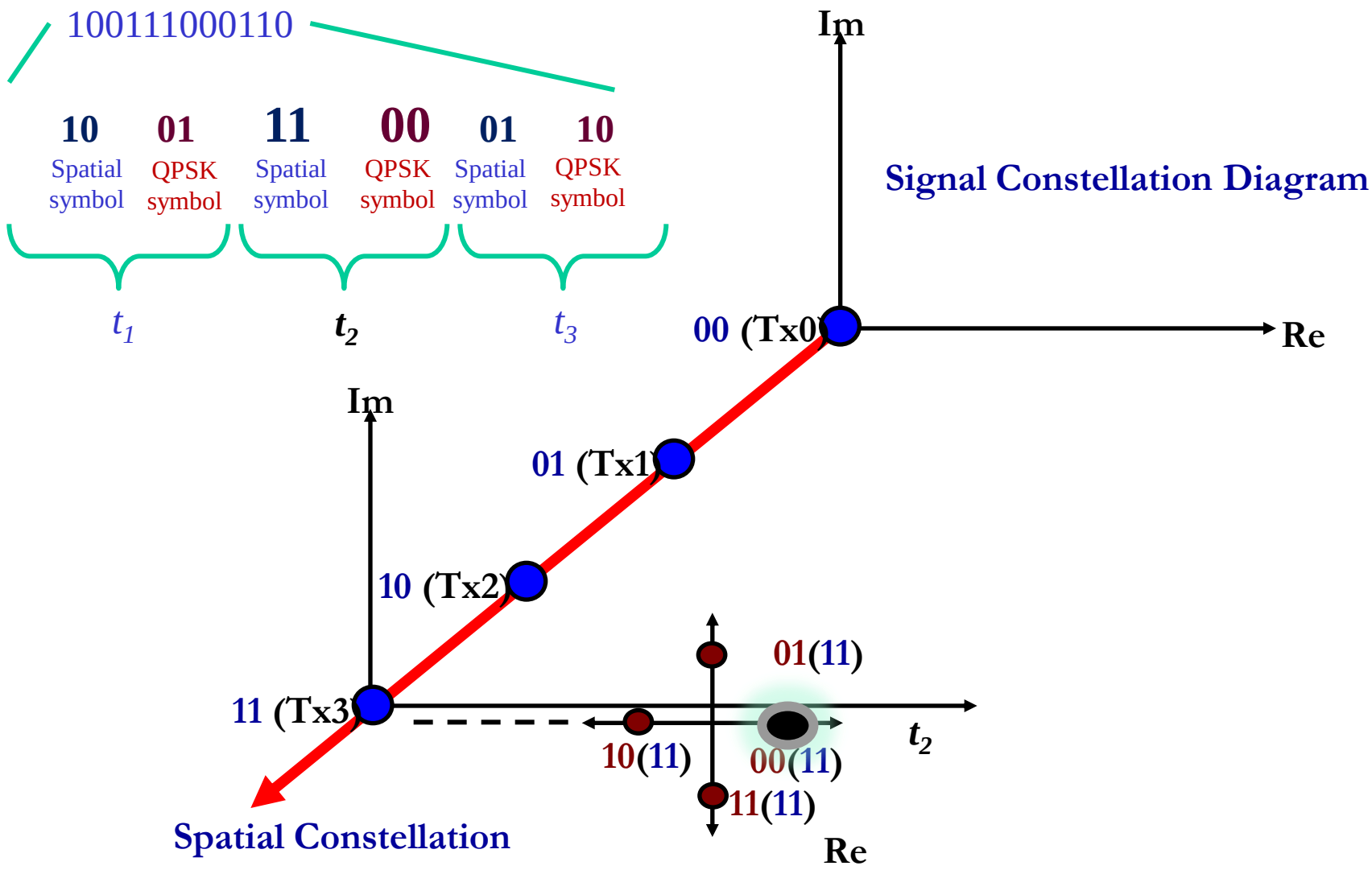
Key issues of spatial multiplexing MIMO

- Spatial multiplexing MIMO significantly improves spectral efficiency, but:
  - Suffers from **inter-channel interference** resulting in **high computational complex** algorithms (*e.g.*, Vertical – Bell Labs Layered Space Time (V-BLAST) algorithm)
  - Requires **inter-antenna synchronisation** (IAS)
  - Requires **multiple RF-chains** (→ expensive)
  - Suffers from **error propagation**



M. Di Renzo, H. Haas, and P. M. Grant "Spatial Modulation for Multiple-Antenna Wireless Systems – A Survey", *IEEE Communications Magazine*, December 2012


100111000110
10
Spatial symbol
01
QPSK symbol
11
Spatial symbol
00
QPSK symbol
01
Spatial symbol
10
QPSK symbol
t_1
t_2
t_3
Im
Signal Constellation Diagram
00 (Tx0)
Re
Im
01 (Tx1)
01(10)
10 (Tx2)
t_1
10(10)
00(10)
11(10)
11 (Tx3)
Re
Spatial Constellation


100111000110
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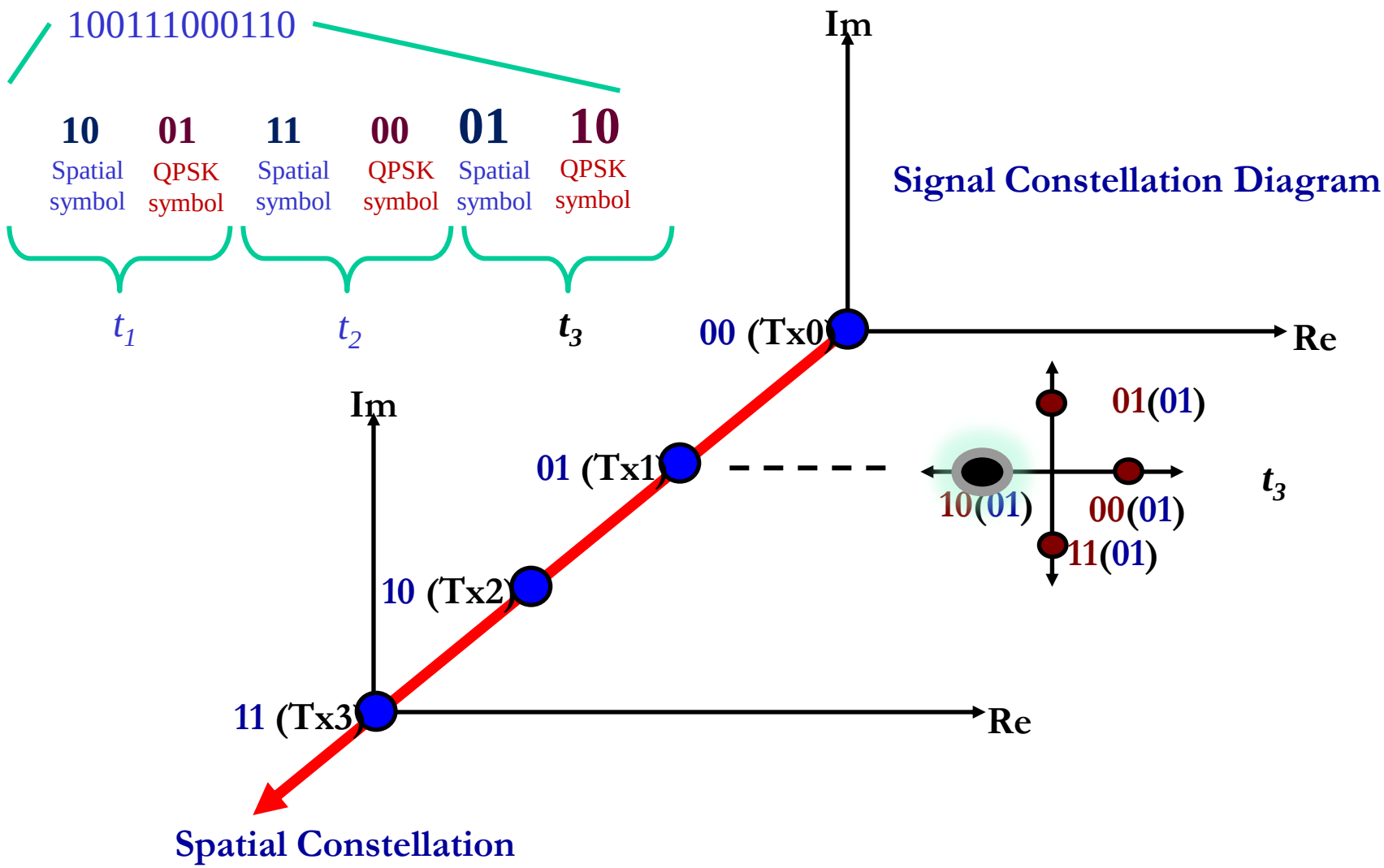
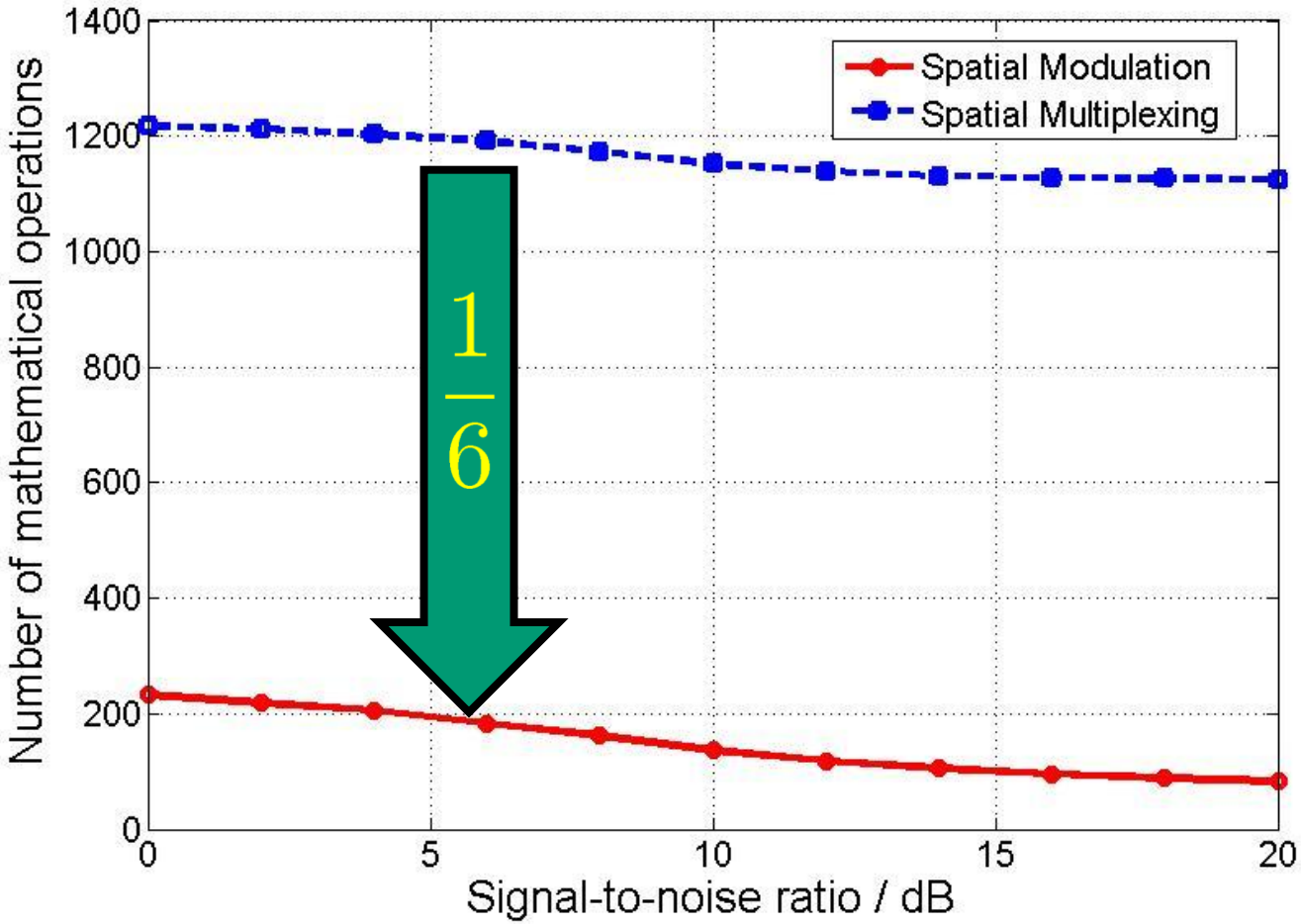
Spatial symbol
01
QPSK symbol
11
Spatial symbol
00
QPSK symbol
01
Spatial symbol
10
QPSK symbol
t_1
t_2
t_3
Im
Re
Signal Constellation Diagram
00 (Tx0)
01 (Tx1)
10 (Tx2)
11 (Tx3)
Im
01(11)
10(11)
00(11)
11(11)
t_2
Re
Spatial Constellation


100111000110
10
Spatial symbol
01
QPSK symbol
11
Spatial symbol
00
QPSK symbol
01
Spatial symbol
10
QPSK symbol
t_1
t_2
t_3
Im
Signal Constellation Diagram
00 (Tx0)
Re
Im
01 (Tx1)
10 (Tx2)
11 (Tx3)
Re
Spatial Constellation
01(01)
10(01)
00(01)
11(01)
t_3

Computational Complexity



Energy-efficient assessment and optimization of SM-MIMO against state-of-the-art MIMO

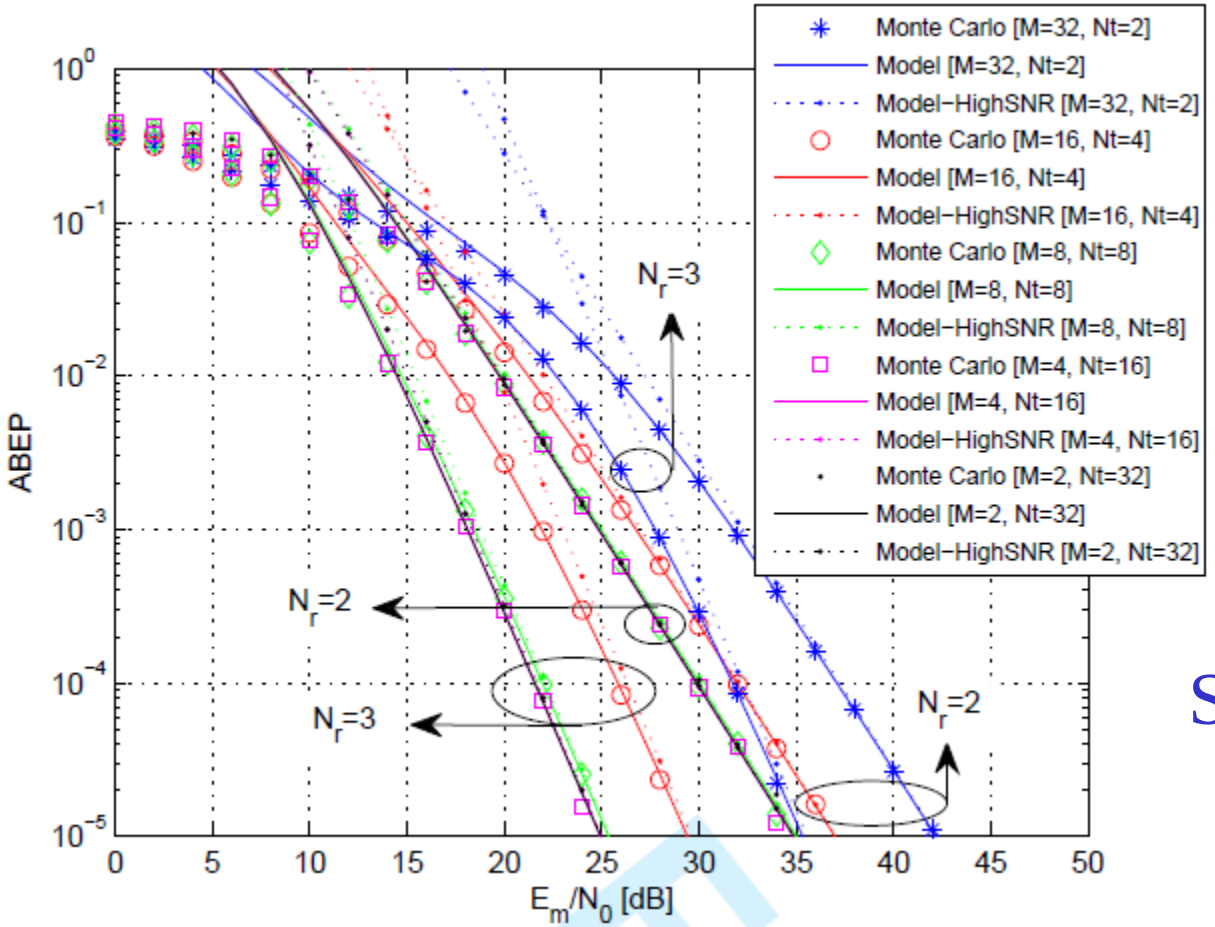
$N_r = 2$					
Rate / $\Delta_{\text{SNR}}^{(X/Y)}$	2 bps	3 bps	4 bps	5 bps	6 bps
(PSK, SM–PSK)	−1.0543	1.9011	4.5154	5.6931	5.9642
	N.A.	1.6453	5.3471	8.8845	11.1650
	N.A.	N.A.	5.2585	9.2429	13.1632
(QAM, SM–QAM)	−1.0543	1.7709	0.1040	2.3751	0.9242
	N.A.	1.5152	2.0064	2.2836	2.6976
	N.A.	N.A.	1.9177	4.2581	2.5484

$N_t = 2, 4, 8$

$N_r = 3$					
Rate / $\Delta_{\text{SNR}}^{(X/Y)}$	2 bps	3 bps	4 bps	5 bps	6 bps
(PSK, SM–PSK)	−0.6461	3.0103	5.5248	5.9627	6.0094
	N.A.	2.8560	7.2677	10.9352	11.9378
	N.A.	N.A.	7.2144	11.8624	16.1295
(QAM, SM–QAM)	−0.6461	2.7651	0.9978	3.3520	1.6807
	N.A.	2.6108	3.6577	3.8842	4.4339
	N.A.	N.A.	3.6044	6.5402	4.7666

M. Di Renzo and H. Haas, "Bit Error Probability of Spatial Modulation (SM-) MIMO over Generalized Fading Channels", *IEEE Transactions on Vehicular Technology*, (minor revision).

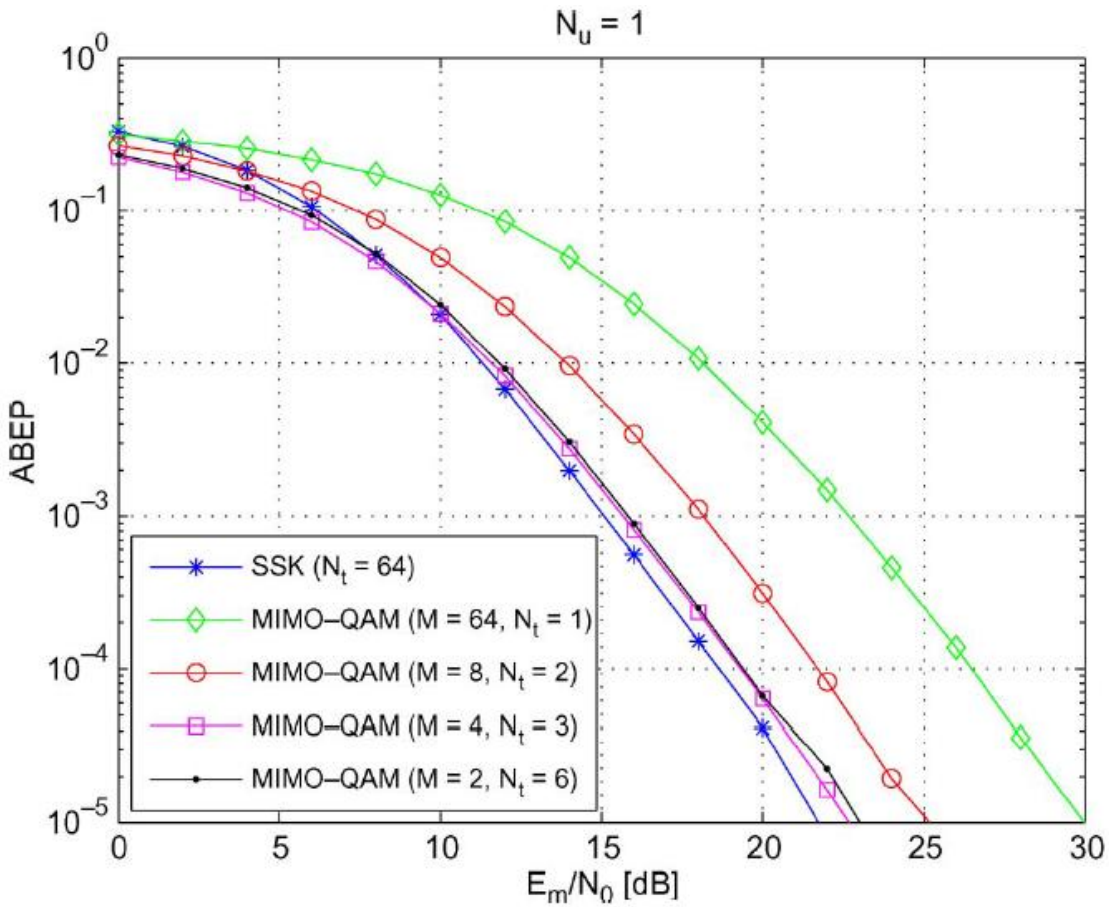
Energy-efficient assessment and optimization of SM-MIMO against state-of-the-art MIMO



SM-PSK
6 bpcu

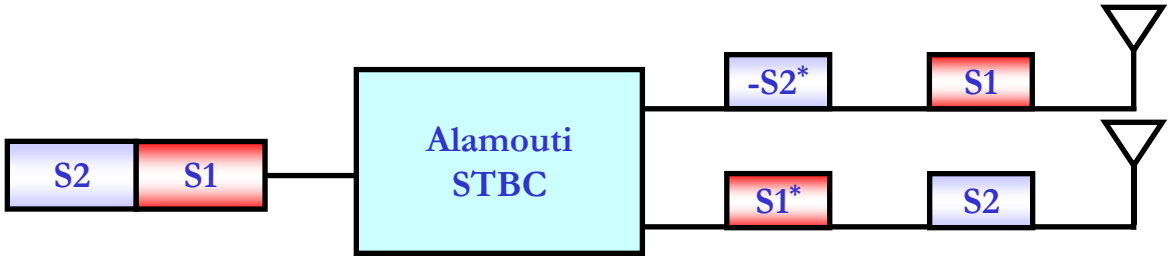
M. Di Renzo and H. Haas, "Bit Error Probability of Spatial Modulation (SM-) MIMO over Generalized Fading Channels", *IEEE Transactions on Vehicular Technology*, (minor revision).

Energy-efficient and low-complexity encoding and decoding for SM-MIMO – The case of "massive MIMO"



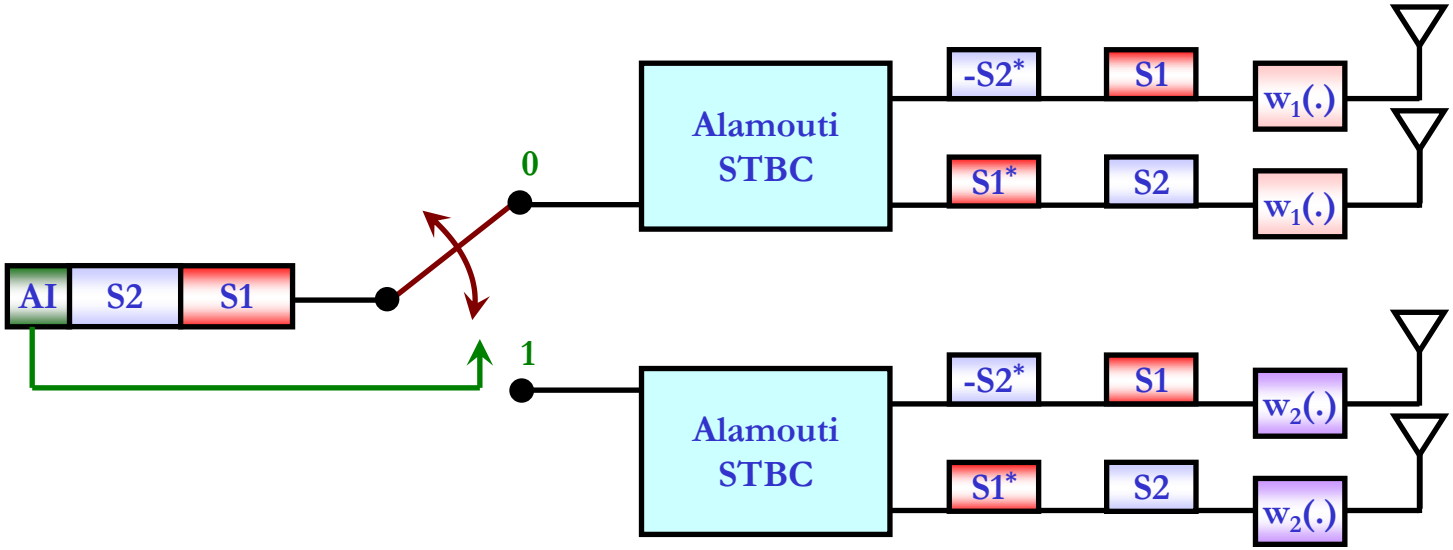
M. Di Renzo and H. Haas, "Bit Error Probability of Space Shift Keying MIMO over Multiple-Access Independent Fading Channels", *IEEE Trans. Vehicular Technology*, Vol. 60, No. 8, pp. 3694-3711, October 2011.

Energy-efficient and low-complexity encoding and decoding for SM-MIMO – The case of transmit-diversity



SOTA

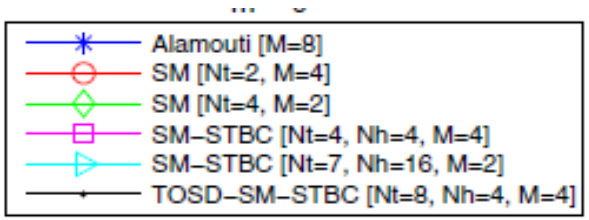
New



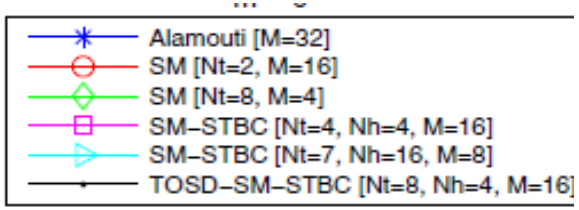
M. Di Renzo and H. Haas, "Transmit-Diversity for Spatial Modulation (SM): Towards the Design of High-Rate Spatially-Modulated Space-Time Block Codes", *IEEE Int. Conf. Commun.*, June 5-9, 2011, Kyoto, Japan.

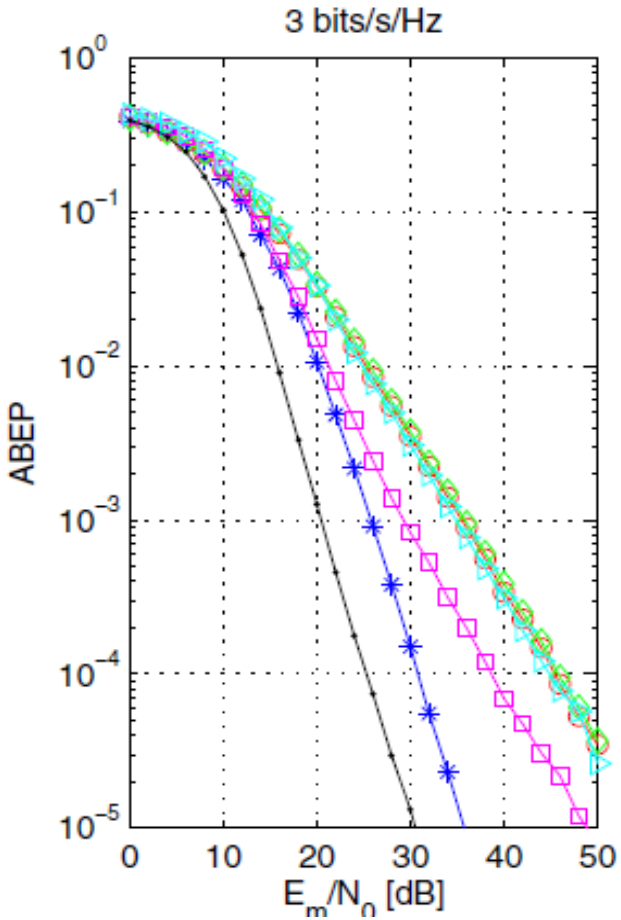
Energy-efficient and low-complexity encoding and decoding for SM-MIMO – The case of transmit-diversity

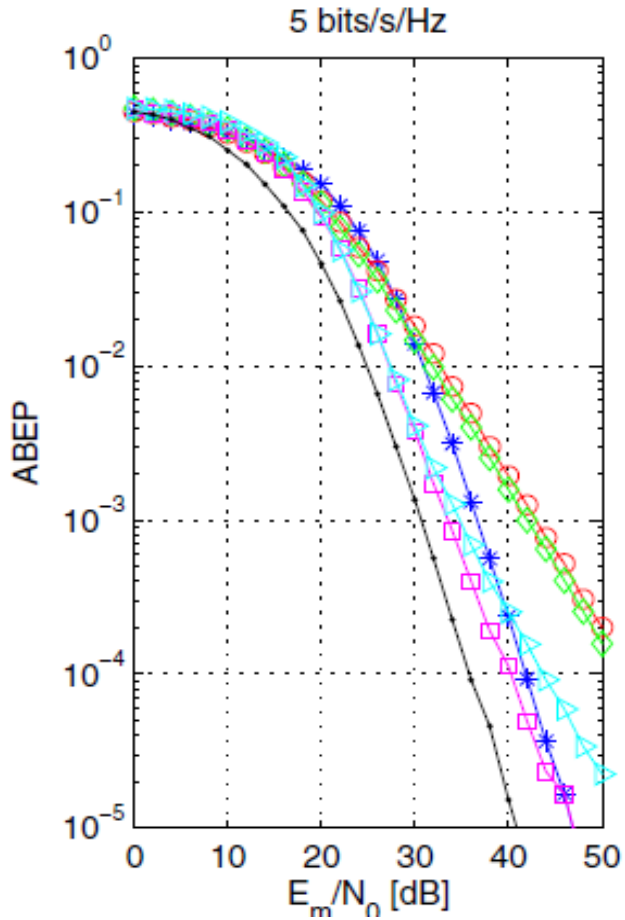
3 bits/s/Hz



5 bits/s/Hz

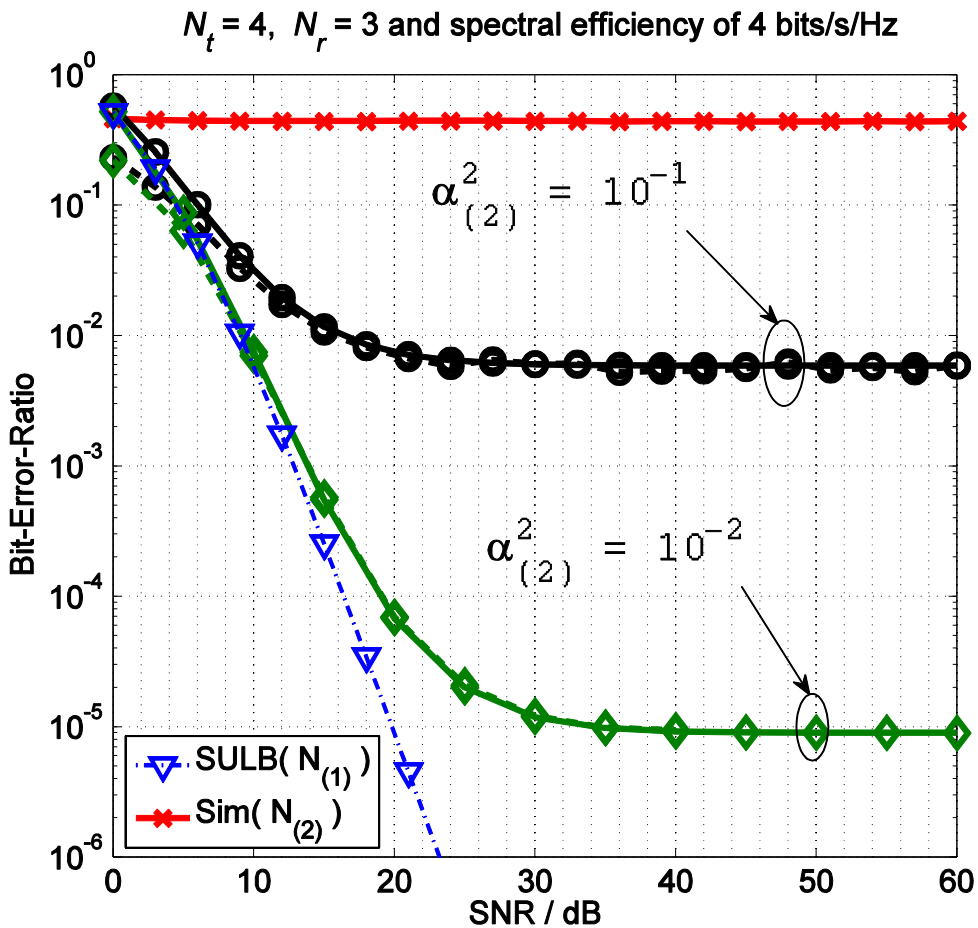


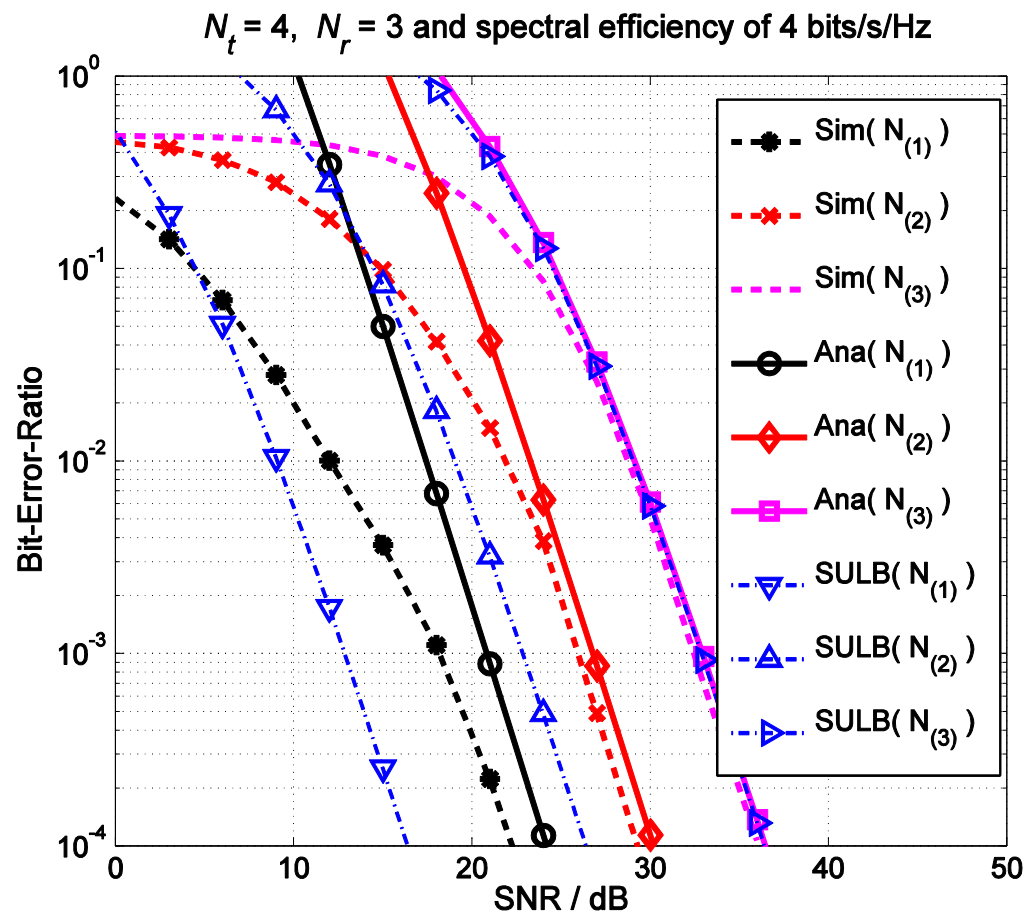




M. Di Renzo and H. Haas, "Transmit-Diversity for Spatial Modulation (SM): Towards the Design of High-Rate Spatially-Modulated Space-Time Block Codes", *IEEE Int. Conf. Commun.*, June 5-9, 2011, Kyoto, Japan.

Multiple Access Spatial Modulation





$\alpha^2_{(1)} = 1$, node 2 with $\alpha^2_{(2)} = 0.1$ and node 3 with $\alpha^2_{(3)} = 0.01$

Single-user detector

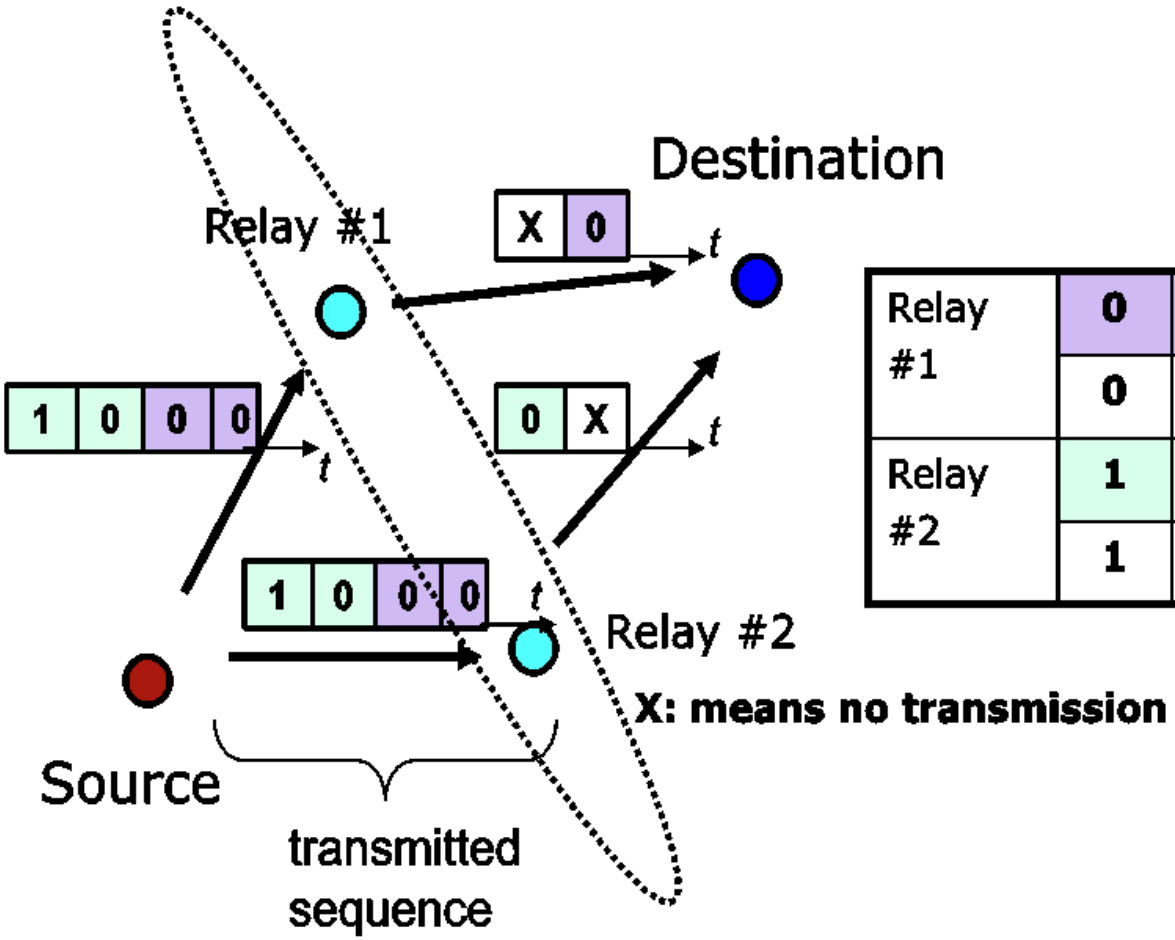
Interference-aware detector

N. Serafimovski, S. Sinanovic, M. Di Renzo and H. Haas, "Multiple Access Spatial Modulation", *IEEE Trans. Veh. Technol.* (under review)

www.ukchinab4g.ac.uk

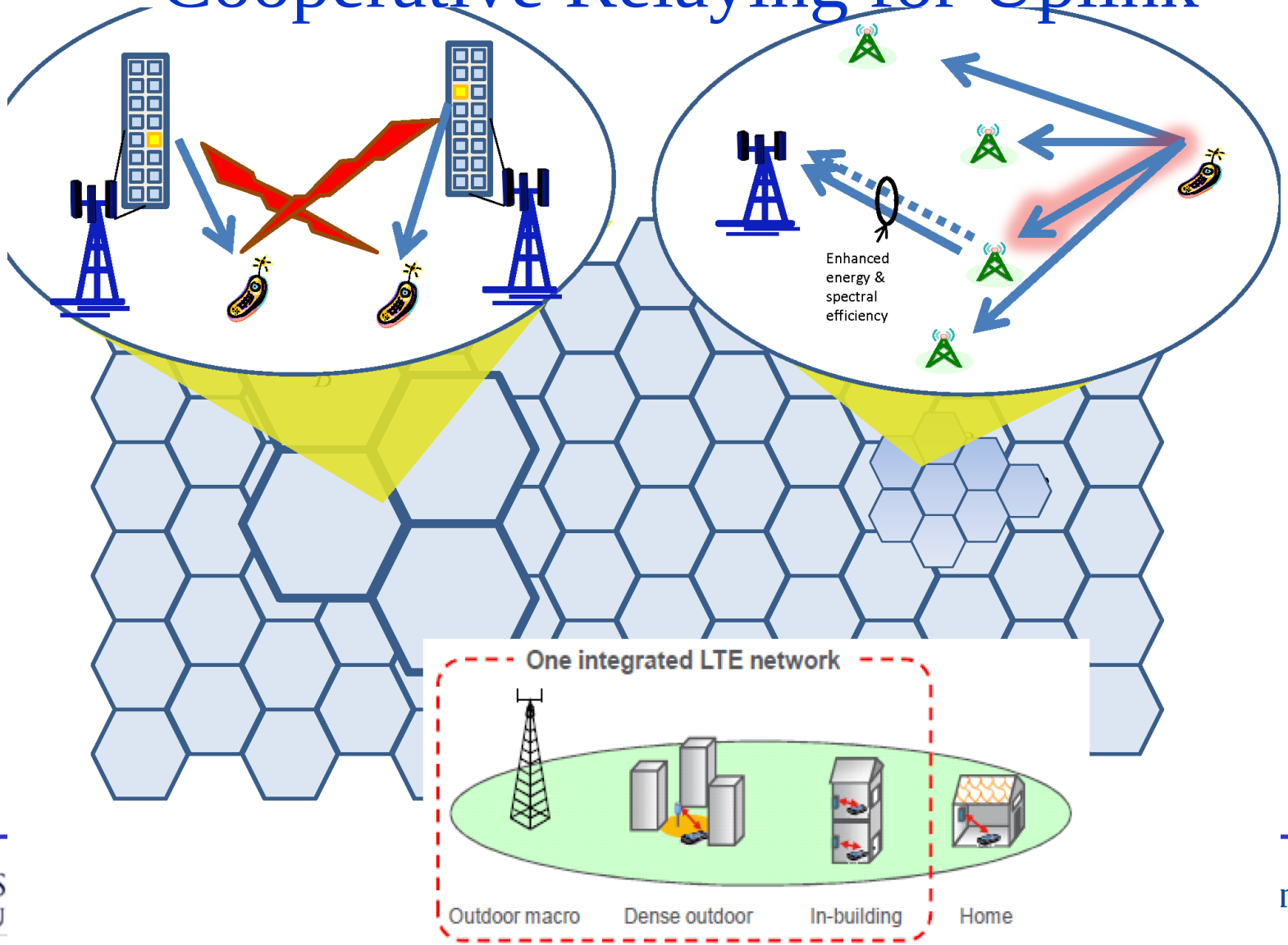
Outlook

Testbed Extension: SM Relaying



Relay #1	0	0	→	0
	0	1	→	1
Relay #2	1	0	→	0
	1	1	→	1

SM Massive MIMO for Downlink and Cooperative Relaying for Uplink



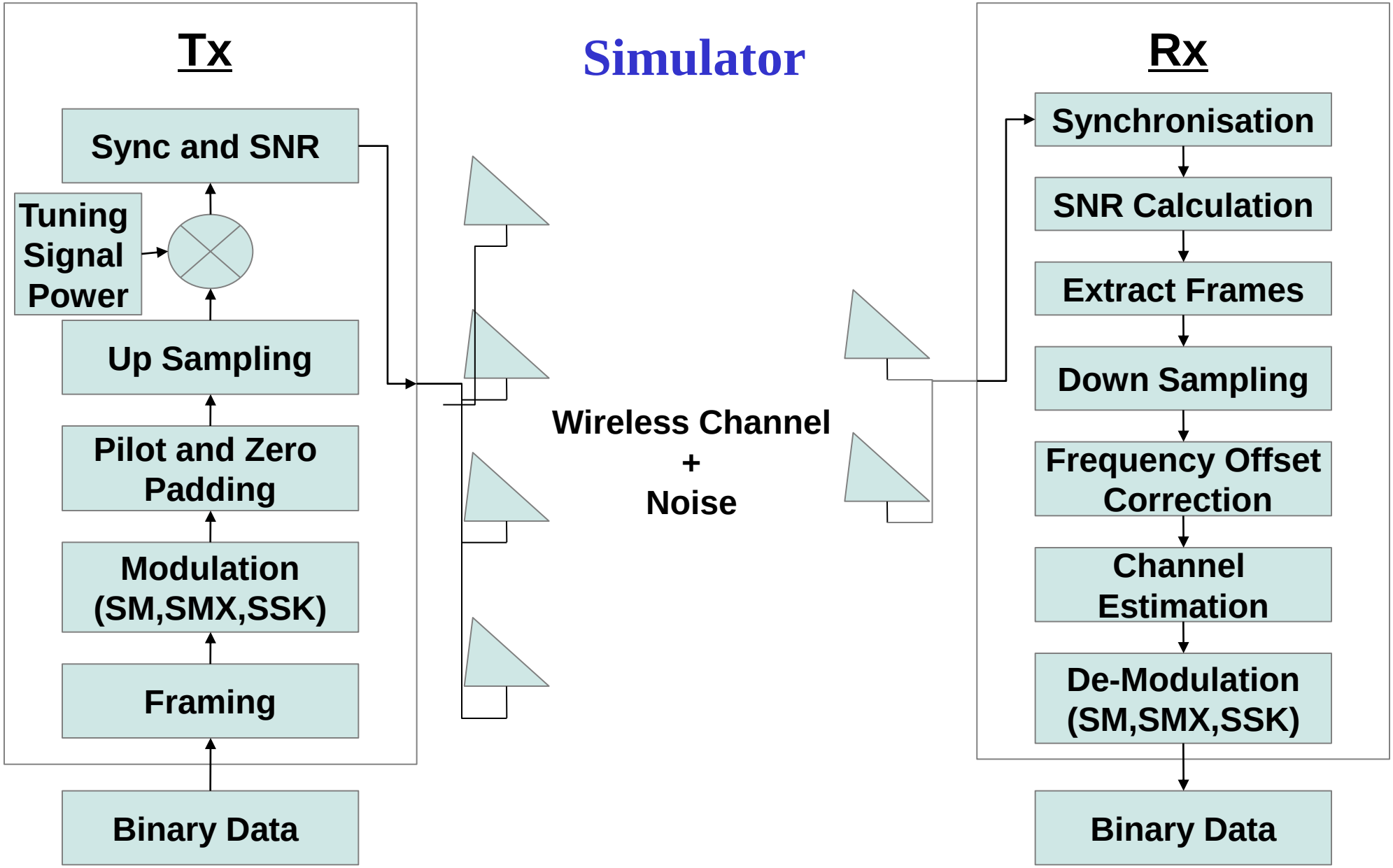
Use of Real Channel Date to Evaluate Spatial Modulation:

Initial Results

Mark Beach[1], Pat Chambers[3], Zengmao Chen[3], Peter Grant[2], Harald Haas[2], Joe McGeehan[1], William Thompson[1], Cheng-Xiang Wang[3], Abdelhamid Younis[2],

[1]University of Bristol, Bristol, UK
[2]University of Edinburgh, Edinburgh, UK
[3]Heriot-Watt University, Edinburgh, UK

Simulator

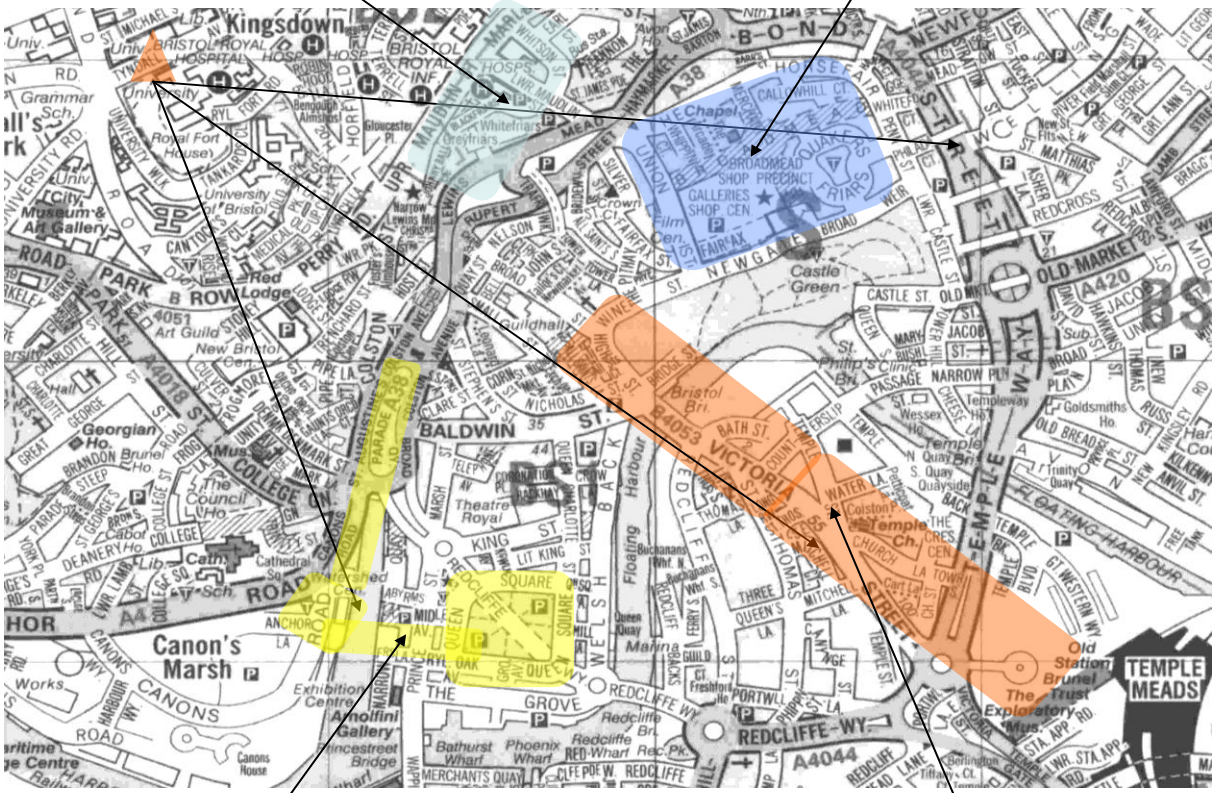

Tx
Sync and SNR
Tuning Signal Power
Up Sampling
Pilot and Zero Padding
Modulation (SM,SMX,SSK)
Framing
Binary Data
Wireless Channel
+
Noise
Rx
Synchronisation
SNR Calculation
Extract Frames
Down Sampling
Frequency Offset Correction
Channel Estimation
De-Modulation (SM,SMX,SSK)
Binary Data

Objectives

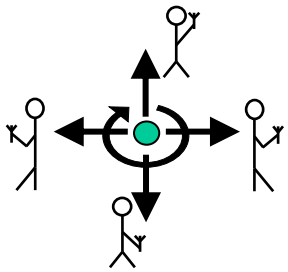
- Collection of channel measurements
- Categorisation of channel data
- PHY-layer simulations using measured channel data

Outdoor MIMO (2GHz Carrier)

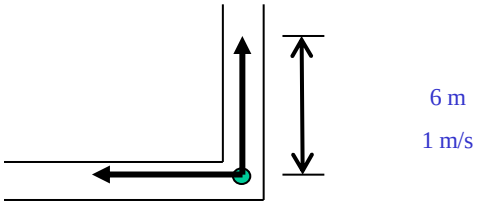
Measurement Campaign



- 58 locations
- Standing (6s) with 4 different orientations



- Walking spanning 6m, 2 routes per location



- Drive 'tests'

10 routes, 30mph

Example Walking Test

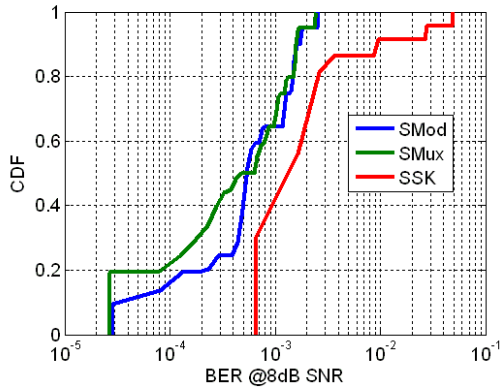
Example Drive Test

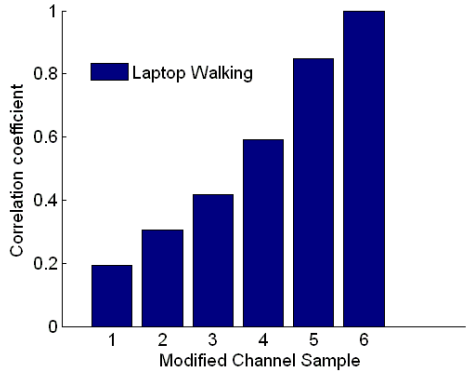
Channel selection

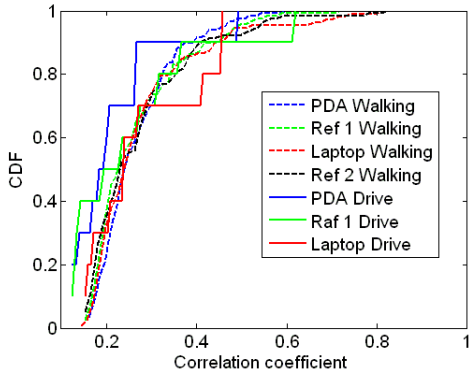
- >1000 channels measured
- Chosen channel parameters:
  - K-factor
  - Spatial correlation
  - Channel power imbalances
  - Transmitter order
  - Theoretical capacity
- Other channel variables
  - Device
  - Movement
- Channel properties
  - 4x4 MIMO channel
  - Narrowband ~ 150 KHz
  - 2GHz centre frequency
  - 1024 or 2048 samples lasting 6.2s
- Average pathloss removed for simulation

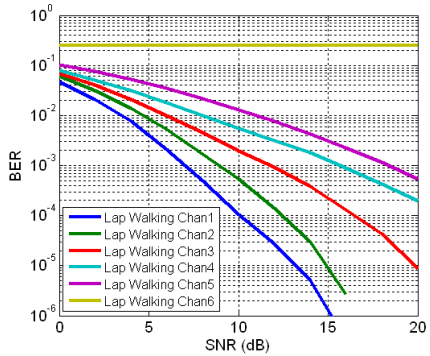
Spatial Modulation Simulation

- Tested Techniques
  - 4x4 Space Shift Keying (SSK) - 2 bit/sym
  - 2x4 Spatial modulation (SMod) BPSK - 2bit/sym
  - 2x4 Spatial multiplexing (SMux) BPSK - 2bit/sym



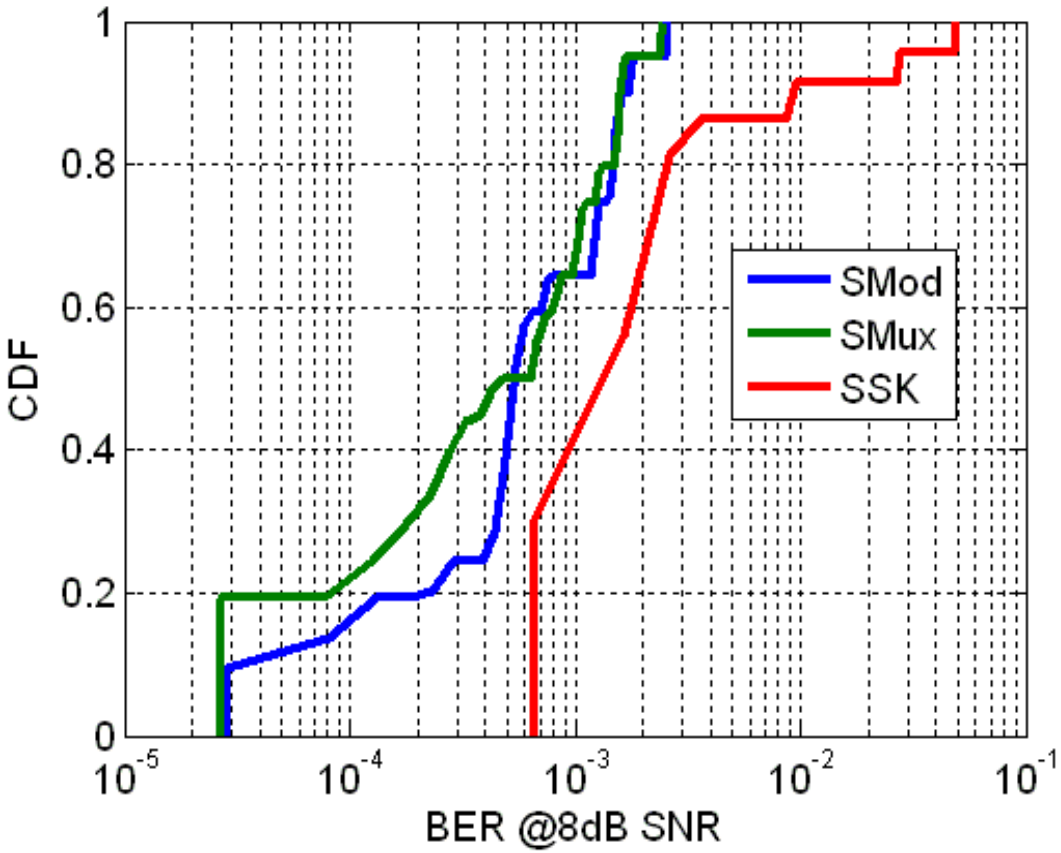






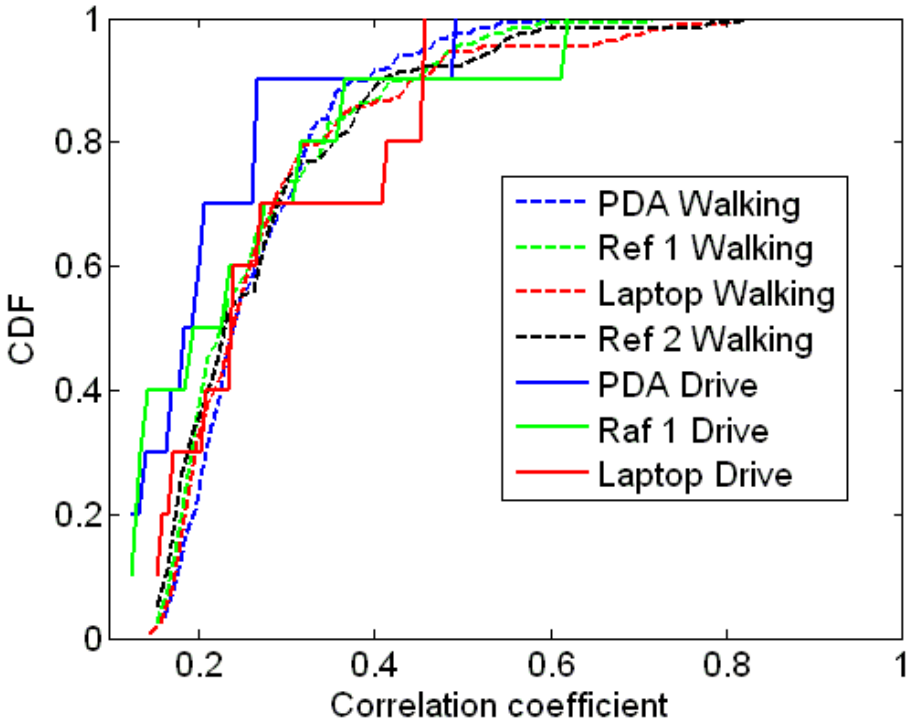
Technique Comparison

- Results for all the devices and movements
  - using ~ 40 different channels
  - Channels selected based on theoretical capacity CDF and location
- Uncoded BER at an SNR of 8dB

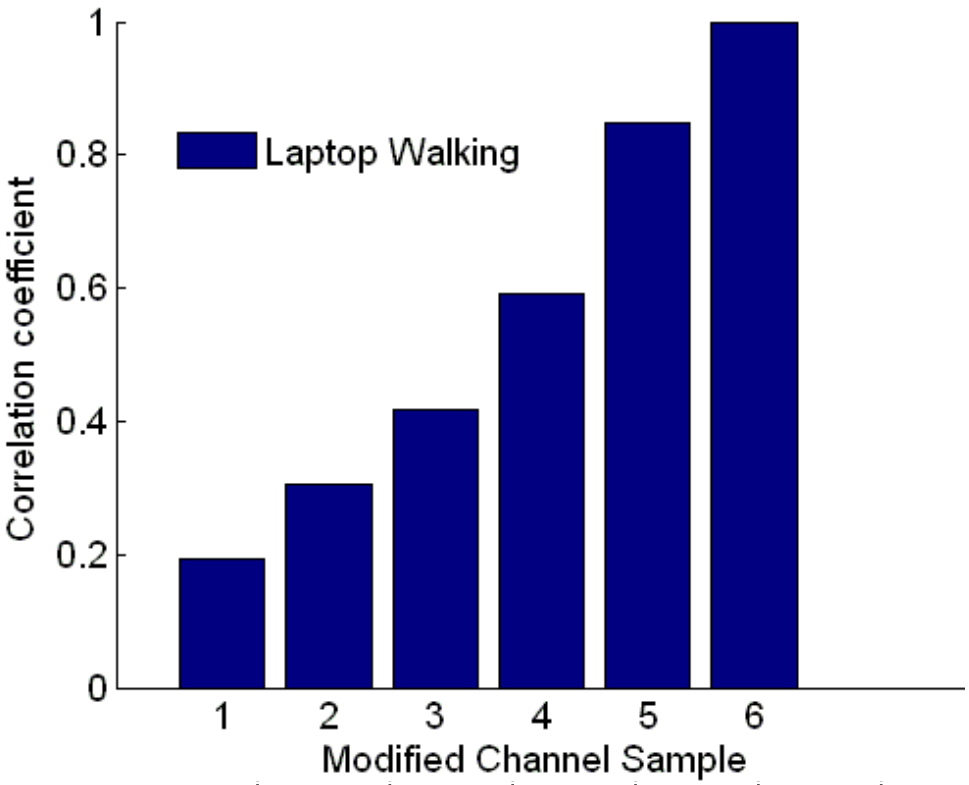


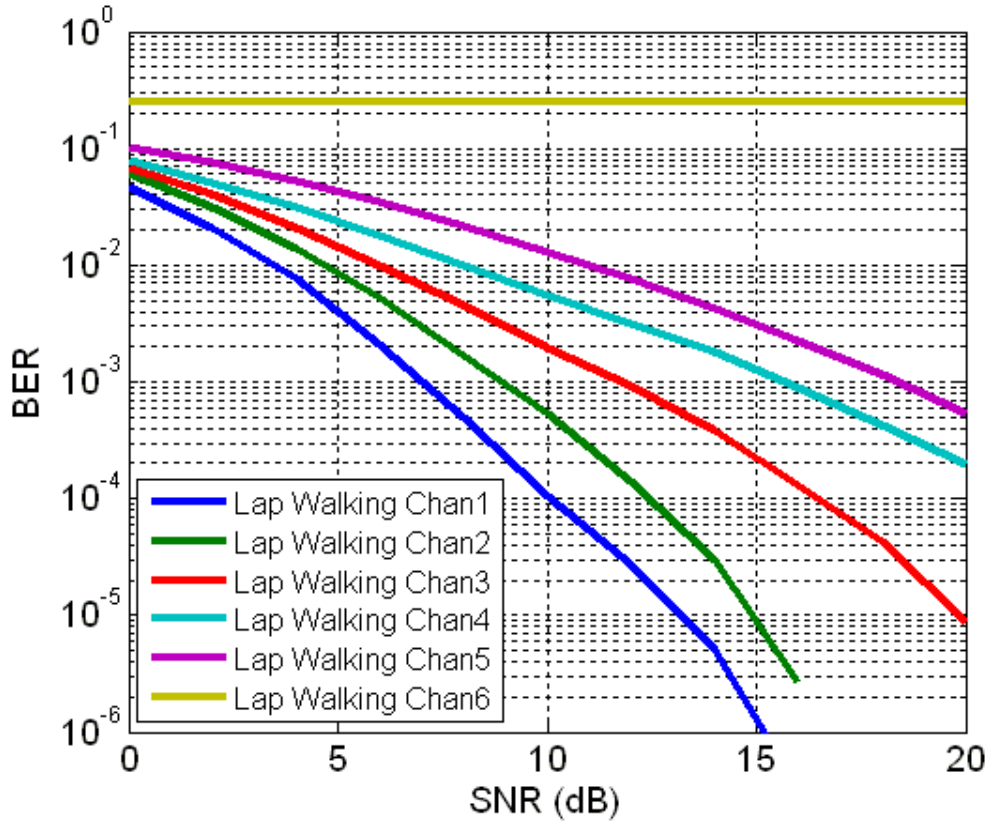
Initial Investigations: Channel Parameters

- System sensitivity to:
  - Spatial channel correlation
  - K-factor
  - Channel power imbalances
  - Antenna utilised
  - Movement
  - Device



Spatial Channel Correlation

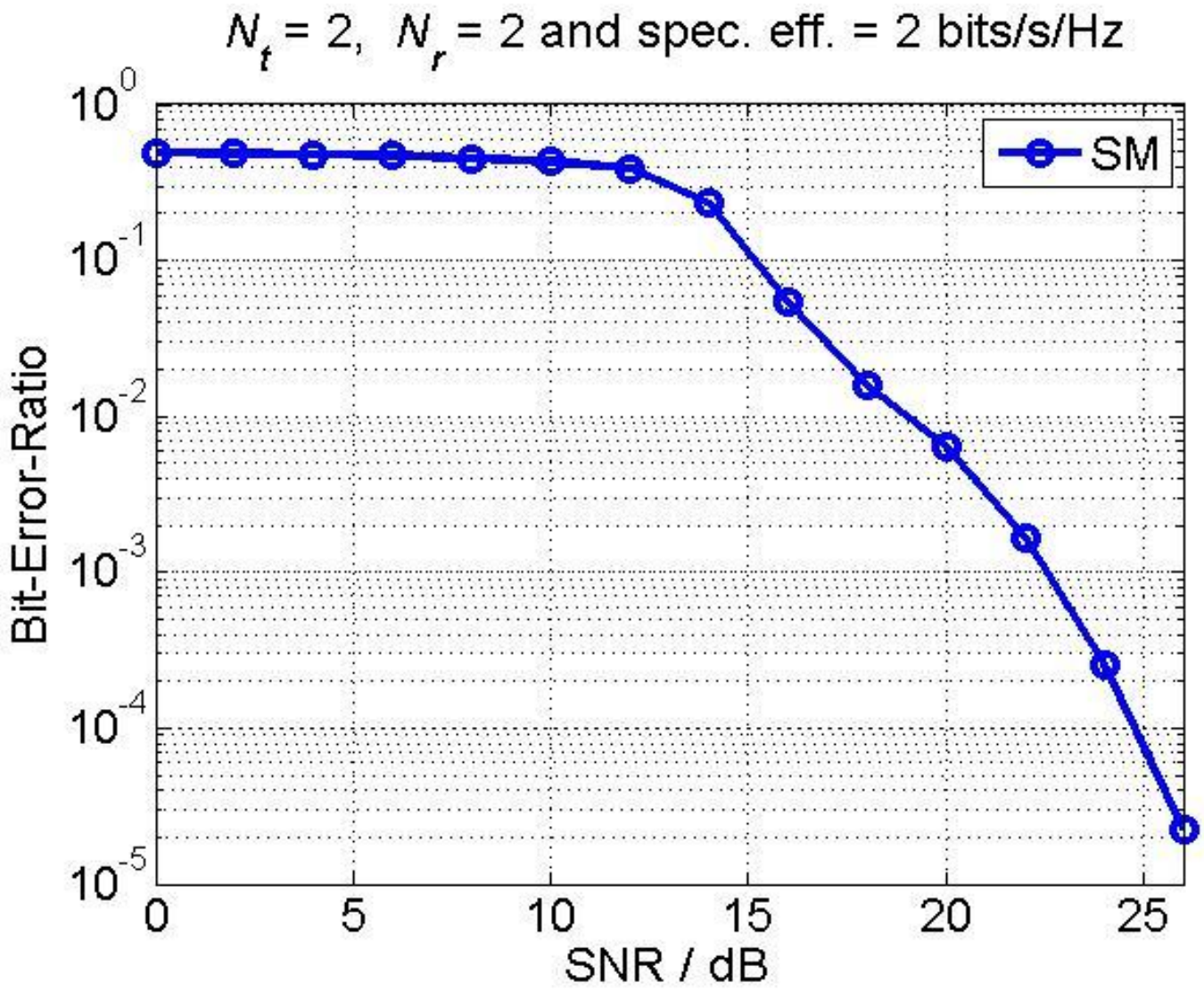




Corr Coef	0.19	0.30	0.42	0.59	0.85	1
CDF (%)	19.5	76	86.7	95.6	100	100

Next Steps

- Detailed sensitivity analysis of other channel properties, including:
  - Branch power variations
  - Transmitter combinations
- COST IC1004 paper
  - 8-10 Feb 2012
  - http://www.ic1004.org/


N_t = 2, N_r = 2 and spec. eff. = 2 bits/s/Hz
SM
Bit-Error-Ratio
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
20
25
SNR / dB

Future Development of Testbed

- **Testbed & Outdoor Channel via C8:** Comparison of spatial modulation results from testbed using emulated (measured) outdoor channels.
- **'LTE' spatial modulation:** Development of spatial modulation in conjunction with OFDM and compare performance with MIMO long term evolution (LTE).
- **Open access testbed:** Development of a web-based interface:
  - Enable third party access to testbed so that project partners can test signal processing ideas.
  - Establish a network of testbeds that can work together in order to establish a wide variety of results efficiently.
- **Other options (Beyond current project)**
  - Extension of the testbed to showcase the advantages of SM in a relaying scenario
  - Extension of the testbed to *massive MIMO* to demonstrate the energy-spectral efficiency trade-off of SM when applied to massive MIMO

Any Questions?