UK China Bridges Beyond 4G Test Bed

From Concept, Implementation and Initial Results

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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

MIMO hardware
NI Testbed

SMod
PHY-layer Simulator

Real Urban MIMO Channels

MIMO hardware
NI Testbed

SMod
PHY-layer Simulator

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

Pat Chambers, Zengmao Chen & Cheng-Xiang Wang

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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

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- 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

- Local PC
- Local PC
- Local Server
- Hub
- 4 Channel Tx
- 2 Channel Rx & RAID

LAN
Transmitter Hardware Architecture

- FPGA (Flexrio)
- Embedded PC
- 4-Channel RFSG
- Antennas
Receiver Hardware Architecture
Offline Testbed Configuration

- Embedded PC
- FPGA
- Antennas

4-Channel RFSG

2-Channel RFSA

Wireless Channel
Real-Time Testbed Configuration

Embedded PC

FPGA

4-Channel RF

Antennas

Embedded PC

FPGA

2-Channel RF

Antennas

Disk Array

Wireless Channel
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

4 x 2 LTE MIMO, 16 QAM Modulation, 20 MHz bandwidth

- BER vs. Rx SNR [dB]
- Multplexing (Testbed)
- Diversity (Testbed)
- Multiplexing (Rayleigh)
- Diversity (Rayleigh)
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:
National instruments (NI) based channel emulator:
Demo 3: Channel Emulator – Schematic

Current solution for the channel emulator:

- Binary file for baseband Tx data (Imag. & Quad parts)
- Binary file of baseband data passed Channel
- Binary file for CIR Coeff. (I. & Q)
- Buffer for Baseband Transmit data stream
- Buffer for CIR coefficients in time domain
- System Timing
- Multiple TDL Channel Conv.
- FSM Controller

NI PXIe-8133 Embedded Controller

NI FlexRIO PXIe-7965R
Demo 3: Channel Emulator – Convolution

462 delays 16 taps 8 adders 4 adders 2 adders 1 adder

WINNER II: scenario C4
Demo 3: Channel Emulator – Evaluation

Frequency Response of Channel Input

Amplitude

Frequency Response of Channel Output

Amplitude

Channel Frequency Response

Channel Emulator

Reference Channel

Amplitude

Frequency (MHz)
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

<table>
<thead>
<tr>
<th></th>
<th>Channel Simulator</th>
<th>Channel Emulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 M samples</td>
<td>180.608 s</td>
<td>14.682 s</td>
</tr>
<tr>
<td>130 M samples</td>
<td>886.053 s</td>
<td>66.258 s</td>
</tr>
</tbody>
</table>

>13 times faster
Spatial Modulation: Latest Research Findings & Outlook

Professor Harald Haas

The University of Edinburgh
h.haas@ed.ac.uk
• 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**
Signal Constellation Diagram

Spatial Constellation

100111000110

Spatial symbol

QPSK symbol

t₁  t₂  t₃

01  11  00  01  10

Spatial symbol

QPSK symbol

Spatial symbol

QPSK symbol

10 (Tx0)

Im

Re

00 (Tx0)

01 (Tx1)

10 (Tx2)

11 (Tx3)

01(10)

10(10)

00(10)

11(10)
Spatial Constellation

Signal Constellation Diagram

100111000110

Spatial symbol
QPSK symbol
Spatial symbol
QPSK symbol
Spatial symbol
QPSK symbol

$\begin{align*}
t_1 & : 10 \\
t_2 & : 01 \\
t_3 & : 11 \\
\end{align*}$

$\begin{align*}
10 & : (Tx0) \\
01 & : (Tx1) \\
11 & : (Tx2) \\
10 & : (Tx3) \\
\end{align*}$
Spatial Constellation

Signal Constellation Diagram

10 01 11 00 01 10
Spatial symbol QPSK symbol Spatial symbol QPSK symbol Spatial symbol

$t_1$ $t_2$ $t_3$

00 (Tx0)

01 (Tx1)

10 (Tx2)

11 (Tx3)

100111000110

QPSK symbol QPSK symbol QPSK symbol QPSK symbol
Computational Complexity

![Graph showing the comparison between Spatial Modulation and Spatial Multiplexing](image)

- Spatial Modulation
- Spatial Multiplexing

Number of mathematical operations vs. Signal-to-noise ratio (dB)

- Red line: Spatial Modulation
- Blue line: Spatial Multiplexing

Signal-to-noise ratio is decreasing from 0 to 20 dB.

Note: The graph indicates a significant difference in computational complexity between the two methods, with Spatial Modulation requiring fewer operations.
Energy-efficient assessment and optimization of SM-MIMO against state-of-the-art MIMO

<table>
<thead>
<tr>
<th>$N_r = 2$</th>
<th>Rate / $\Delta^{(X/Y)}_{\text{SNR}}$</th>
<th>2 bps</th>
<th>3 bps</th>
<th>4 bps</th>
<th>5 bps</th>
<th>6 bps</th>
</tr>
</thead>
<tbody>
<tr>
<td>(PSK, SM–PSK)</td>
<td>$-1.0543$</td>
<td>1.9011</td>
<td>4.5154</td>
<td>5.6931</td>
<td>5.9642</td>
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<tr>
<td></td>
<td>N.A.</td>
<td>1.6453</td>
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<td>11.1650</td>
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<td>N.A.</td>
<td>5.2585</td>
<td>9.2429</td>
<td>13.1632</td>
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<tr>
<td>(QAM, SM–QAM)</td>
<td>$-1.0543$</td>
<td>1.7709</td>
<td>0.1040</td>
<td>2.3751</td>
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<td>2.0064</td>
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<td>2.6976</td>
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<td>N.A.</td>
<td>1.9177</td>
<td>4.2581</td>
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$N_t = 2, 4, 8$

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<tr>
<th>$N_r = 3$</th>
<th>Rate / $\Delta^{(X/Y)}_{\text{SNR}}$</th>
<th>2 bps</th>
<th>3 bps</th>
<th>4 bps</th>
<th>5 bps</th>
<th>6 bps</th>
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</thead>
<tbody>
<tr>
<td>(PSK, SM–PSK)</td>
<td>$-0.6461$</td>
<td>3.0103</td>
<td>5.5248</td>
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<td>N.A.</td>
<td>2.8560</td>
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<tr>
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<td>N.A.</td>
<td>N.A.</td>
<td>7.2144</td>
<td>11.8624</td>
<td>16.1295</td>
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<tr>
<td>(QAM, SM–QAM)</td>
<td>$-0.6461$</td>
<td>2.7651</td>
<td>0.9978</td>
<td>3.3520</td>
<td>1.6807</td>
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<tr>
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<td>N.A.</td>
<td>2.6108</td>
<td>3.6577</td>
<td>3.8842</td>
<td>4.4339</td>
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<tr>
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<td>N.A.</td>
<td>N.A.</td>
<td>3.6044</td>
<td>6.5402</td>
<td>4.7666</td>
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</tbody>
</table>

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


SM-PSK
6 bpcu

www.ukchinab4g.ac.uk
Energy-efficient and low-complexity encoding and decoding for SM-MIMO – The case of “massive MIMO”

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

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

Multiple Access Spatial Modulation

$N_t = 4, \ N_r = 3$ and spectral efficiency of $4 \text{bits/s/Hz}$

$\alpha_{(2)}^2 = 10^{-1}$

$\alpha_{(2)}^2 = 10^{-2}$

Single-user detector

Interference-aware detector

Outlook
Testbed Extension: SM Relaying

<table>
<thead>
<tr>
<th>Relay #1</th>
<th>0</th>
<th>0</th>
<th>→</th>
<th>0</th>
</tr>
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<tbody>
<tr>
<td>Relay #2</td>
<td>0</td>
<td>1</td>
<td>→</td>
<td>1</td>
</tr>
<tr>
<td>Relay #2</td>
<td>1</td>
<td>0</td>
<td>→</td>
<td>0</td>
</tr>
<tr>
<td>Relay #2</td>
<td>1</td>
<td>1</td>
<td>→</td>
<td>1</td>
</tr>
</tbody>
</table>

X: means no transmission
SM Massive MIMO for Downlink and Cooperative Relaying for Uplink
Use of Real Channel Date to Evaluate Spatial Modulation:

Initial Results

Mark Beach¹, Pat Chambers³, Zengmao Chen³, Peter Grant², Harald Haas², Joe McGeehan¹, William Thompson¹, Cheng-Xiang Wang³, Abdelhamid Younis²,

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

Area 1: Broadmead
Area 2: Victoria Street & Knights Templar
Area 3: Queens Square, Waterfront & City Centre
Area 4: Eye Hospital & Bus Station
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

Correlation Coefficient:

<table>
<thead>
<tr>
<th>Modified Channel Sample</th>
<th>Corr Coef</th>
<th>CDF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.19</td>
<td>19.5</td>
</tr>
<tr>
<td>2</td>
<td>0.30</td>
<td>76</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
<td>86.7</td>
</tr>
<tr>
<td>4</td>
<td>0.59</td>
<td>95.6</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

BER vs SNR (dB)

- Laptop Walking Chan1
- Laptop Walking Chan2
- Laptop Walking Chan3
- Laptop Walking Chan4
- Laptop Walking Chan5
- Laptop Walking Chan6
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/
$N_t = 2, \ N_r = 2 \ and \ spec. \ eff. = 2 \ bits/s/Hz$
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?