INTRODUCTION

James Kimery | Director of RF and Communications, NI

NI software defined radio solutions integrate hardware and software to help scientists and engineers rapidly prototype high-performance wireless systems. NI works with researchers worldwide to advance wireless research, and their use cases are fascinating and inspiring. This book includes incredible examples of how researchers transformed their novel wireless research ideas into real working prototypes.

I would like to thank all of our lead users from around the world who continue to inspire us to build and evolve our platforms. You set the bar ever higher and ultimately help the wider research community innovate faster!

For additional information on these use cases and ways to innovate faster, please feel free to contact me and visit ni.com/sdr.

james.kimery@ni.com
About the RF and Communications Team

With a common goal of rapidly moving from theory to prototype, NI established lead user programs to accelerate next-generation research in controls, mechatronics, robotics, and wireless communications. Established in 2010, the wireless communications lead user program includes numerous research institutions examining multiple 5G communications aspects. Many researchers around the world are making significant contributions to 5G research based on the foundational work completed by the lead user program.

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Paul Harris received his BEng (Hons) in electronic engineering from the University of Portsmouth in 2013 and later joined the CSN group at the University of Bristol to pursue a doctorate in communications. He completed two internships at NI in Austin, Texas, most recently in the wireless research group to help develop and test several aspects of the latest massive MIMO reference design in LabVIEW FPGA. Through his experience working on larger scale LabVIEW projects, he became a Certified LabVIEW Architect in 2015. His doctoral research within the CSN focuses pragmatically on massive MIMO. Through ongoing use of the NI testbed, he is investigating the real-world performance and behavior of the technology and subsequently identifying opportunities to implement and test new algorithms.

Mark Beach received his doctorate in 1989 from the University of Bristol for research on the application of smart antenna techniques to GPS. He later became a faculty member at the university, and was promoted to senior lecturer in 1996, reader in 1998, and professor in 2003. He was head of the Department of Electrical and Electronic Engineering from 2006 to 2010, and then spearheaded Bristol’s hosting of the EPSRC Centre for Doctoral Training (CDT) in Communications. He manages the delivery of the CDT in Communications, leads research on enabling technologies for the delivery of 5G and beyond wireless connectivity, and serves as the school research impact director. He conducts his research activities through the Communication Systems and Networks Group, so they form a key component within Bristol’s Smart Internet Lab. He has over 25 years of physical layer wireless research experience during which he has embraced the application of spread spectrum technology for cellular systems, adaptive or smart antenna for capacity and range extension in wireless networks, MIMO-aided connectivity for throughput enhancement, and flexible RF technologies for software defined radio modems.
Massive MIMO Measurements in Real Time Using a 128-Antenna Testbed

Professors: Mark Beach and Andrew Nix; Drs. Angela Doufexi, Simon Armour, and Evangelos Mellios
Research Students: Mr. Paul Harris, Ms. Siming Zhang, Mr. Henry Brice, Mr. Wael Hasan, and Mr. Benny Chitambira
Communication Systems and Networks Group, University of Bristol

Our Goals
- Obtain and process massive MIMO channel metrics in real-time
- Measure real-time performance in dynamic environments
- Develop algorithms that exploit the massive effect to improve the efficiency of future systems

Our System
This is a 128-Antenna Massive MIMO Testbed which operates in real-time at 3.51 GHz (20 MHz bandwidth) using an LTE-like TDD PHY. All hardware is provided through BristolIsOpen (BIO):
- 64 USRP RIO Remote Radio Heads (RRHs) performing OFDM mod/demod
- 4 FlexRIO Kintex 7 FPGAs performing 128x12 MIMO Processing
- Up to 12 UE clients can be supported

BIO also provides fiber-optic links allowing us to deploy the system with a backhaul connection. These links will also enable the exploration of distributed massive MIMO research.

First Experimental Trials on March 10, 2016
Initial measurements conducted in an indoor atrium using 3.5 GHz sleeve dipoles at both the BS and 12 UE clients. The UEs were placed 20m away in a variety of configurations.

Power Delay Profile (PDP) and frequency response can be viewed in real-time for all 128x12 channels. The received signal level of each user across the antenna array can also be visualised along with the eigenvalues ($HH^H$).

Very strong diagonal indicating good spatial orthogonality between users.

1.59 Gbps sum-rate achieved using 256-QAM for all 12 users. On 20 MHz of bandwidth, that’s a staggering 79.4 bits/s/Hz. Received constellations and throughput display shown below.
Peter Bagot

Peter Bagot received his MEng degree in computer science and electronics from the University of Bristol in 2011. In early 2016, he completed his doctorate on adaptive broadcast techniques from the same institution. He is working as a postdoctoral research assistant at the university investigating power amplifier characteristics over wide bandwidths.

Mark Beach

Mark Beach received his doctorate in 1989 from the University of Bristol for research on the application of smart antenna techniques to GPS. He later became a faculty member at the university, and was promoted to senior lecturer in 1996, reader in 1998, and professor in 2003. He was head of the Department of Electrical and Electronic Engineering from 2006 to 2010, and then spearheaded Bristol’s hosting of the EPSRC Centre for Doctoral Training (CDT) in Communications. He manages the delivery of the CDT in Communications, leads research on enabling technologies for the delivery of 5G and beyond wireless connectivity, and serves as the school research impact director. He conducts his research activities through the Communication Systems and Networks Group, so they form a key component within Bristol’s Smart Internet Lab. He has over 25 years of physical layer wireless research experience during which he has embraced the application of spread spectrum technology for cellular systems, adaptive or smart antenna for capacity and range extension in wireless networks, MIMO-aided connectivity for throughput enhancement, and flexible RF technologies for software defined radio modems.
Spatially Adaptive TV Broadcast: Hardware-in-the-Loop Operational Analysis

Supervisors: Professors Mark Beach, Andrew Nix and Joe McGeehan
Research Student: Mr. Peter Bagot
Communication Systems and Networks Group, University of Bristol

Introduction

- Broadcast antennas are installed and run on a ‘one-off’ basis, based on several planning assumptions which can never fully reflect real-world conditions.
- This leads to an over engineering of the network which decreases the energy efficiency.
- How the energy efficiency of a digital broadcast network can be optimised by adapting the coverage in real-time by using beamforming techniques based on user feedback.
- DVB-T Amplifiers are inherently inefficient which adds to the energy efficiency problem.

Hardware-in-the-Loop Experiment: Emulating an Adaptive Broadcast System

Block Diagram of the hardware-in-the-loop experiment

- Multiple USRPs could be utilised to create multiple feedback nodes per antenna segment.
- Channel fluctuations can be compensated per antenna segment.
- Adaptive broadcast shown to reduce broadcast powers and maintain the same level of coverage.
- DVB-T signal generated and fed into a channel emulator.
- Emulator defines broadcast channel and signal fluctuations.
- USRPs define the QoS of the channel.
- Data fed to LabVIEW for signal analysis.
- Signal analysis fed to Control algorithm.
- Control alters the broadcast power to overcome the effects of the channel variations.
- Process is repeated and the adaptive system is fully emulated.

An Adaptive Solution

- Internet enabled user equipment will feedback relevant Quality of Service (QoS) metric data to a central controller.
- Based on this feedback data, the broadcast powers and beam patterns can be altered to optimise the energy efficiency of the broadcast network.
- This system is designed to not require every user in an area to be able to feedback data, limiting infrastructure overheads.

Live TV Signal Analysis

- 72 hour, power in band recording of a live TV Broadcast, taken using a NI-USRP 2920.
- Intensity charts and Spectrum measurements constructed in LabVIEW.
- Enabled the power fluctuations over time to be evaluated and then modelled within a channel emulator for the hardware in the loop experiment.

Predicted Energy Savings to the UK DTT Network

- Through this research it was shown that an adaptive system could reduce the ERP of a broadcast tower by between 20% and 35%.
- Applying the estimated ERP reductions to the largest 49 UK broadcast sites would result in the yearly network savings shown in the table.
- This shows a substantial reduction in the carbon footprint of the UK network, and would result in significant monetary savings.

<table>
<thead>
<tr>
<th>Predicted ERP Reductions</th>
<th>20%</th>
<th>35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Reduction</td>
<td>55,994,880 kWh</td>
<td>97,928,040 kWh</td>
</tr>
<tr>
<td>Emission Reduction</td>
<td>25,863,635 kg CO₂e</td>
<td>45,261,361 kg CO₂e</td>
</tr>
<tr>
<td>Carbon Reduction</td>
<td>7,090,772 kg</td>
<td>12,356,352 kg</td>
</tr>
<tr>
<td>Money Saved</td>
<td>£6,155,547</td>
<td>£10,772,084</td>
</tr>
</tbody>
</table>

Equivalent carbon dioxide, kg CO₂e, is the UK measure for the equivalent greenhouse gases released into the atmosphere; it includes gases other than CO₂, such as methane and nitrous oxide.

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This work is supported by EPSRC (EP/ I028153/1), the University of Bristol, and BBC Research and Development.
Selahattin Gökceli

Selahattin Gökceli received a bachelor’s degree in electronics and communication engineering from Istanbul Technical University (ITU) in Turkey in 2015. He is working on his master’s degree in telecommunication engineering at the same university. He has served as a member of the ITU Wireless Communication Research Laboratory since 2014. He is an NI Certified LabVIEW Associate Developer, and he has used LabVIEW as a programming tool in projects such as software defined radio implementations of OFDMA-based NCC systems, cooperative communication, and 5G techniques like full-duplex communication. His research interests include cooperative communication networks and 5G techniques.

Semiha Tedik Başaran

Semiha Tedik Başaran received bachelor’s and master’s degrees in telecommunication engineering from Istanbul Technical University in 2011 and 2014, respectively. She is working on a doctorate in telecommunication engineering at the university. Her research interests include full-duplex communication, power minimization of relay-aided transmission, network coding, and general communication theories.
OFDMA-Based Network Coded Cooperation Testbed: Implementation and Performance Results

Selahattin Gökceli, Semiha Tedik Başaran, Günes Karabulut Kurt
Electronics and Communication Engineering, Istanbul Technical University

System Model
- Network coding implies combining the received packets at intermediate nodes, and it can improve the transmission reliability or transmission rate, according to the soft forwarding technique [1]. Due to the broadcast nature of wireless networks, cooperative gain is inherently obtained in the network coding system, leading to network coded cooperation (NCC) systems [2].
- Transmission of multiple nodes can be ensured by using time-division multiple access (TDMA) or frequency-division multiple access (FDMA). As an efficient implementation of FDMA, orthogonal frequency-division multiple access (OFDMA) can be used to serve multiple nodes under the condition of frequency-selective channels that may be encountered in both phases.
- We investigated the performance of an NCC-OFDMA system through image transmission by using software defined radio nodes. The implementation details are given in [3]. As indicated with measurements, NCC is a very powerful technique for improving transmission quality. The proposed NCC-OFDMA scheme based on packet transmission significantly improves BER performance, according to direct transmission, and images can be received successfully.

Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>2.45 GHz</td>
</tr>
<tr>
<td>IQ data rate</td>
<td>1 MS/sec</td>
</tr>
<tr>
<td>Number of bits used in one frame</td>
<td>2048 bits</td>
</tr>
<tr>
<td>Number of OFDM symbols</td>
<td>1040 samples</td>
</tr>
<tr>
<td>Number of subcarriers of the one user data portion</td>
<td>128 samples</td>
</tr>
<tr>
<td>Number of reference subcarriers</td>
<td>40 samples</td>
</tr>
<tr>
<td>Number of source/relay/destination node</td>
<td>3/1/1</td>
</tr>
<tr>
<td>Zero-guarding/DFT/CP length</td>
<td>1200/1200/1200 samples</td>
</tr>
<tr>
<td>Distance between source and destination</td>
<td>50 cm</td>
</tr>
</tbody>
</table>

OFDMA Frame Structure

<table>
<thead>
<tr>
<th>Subcarrier Index</th>
<th>0</th>
<th>50</th>
<th>101</th>
<th>151</th>
<th>201</th>
<th>251</th>
<th>301</th>
<th>351</th>
<th>401</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>110 Samples</td>
<td>300 Samples</td>
<td>1 Sample</td>
<td>180 Samples</td>
<td>300 Samples</td>
<td>1 Sample</td>
<td>180 Samples</td>
<td>300 Samples</td>
<td>1 Sample</td>
</tr>
<tr>
<td>SC0</td>
<td>60 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
<td>90 Samples</td>
</tr>
<tr>
<td>SC1</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
</tr>
<tr>
<td>SC2</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
<td>0 Sequence</td>
</tr>
</tbody>
</table>

Testbed and Implementation

Results

Figure 1. Implemented NCC-OFDMA Testbed
Figure 2. Received Images at Direct Link
Figure 3. Received Images at Network Decoder
Figure 4. Link Performance Comparison for Source Nodes

References

Acknowledgements
The authors would like to thank COST Action 1104 and The Scientific and Technological Research Council of Turkey-TUBITAK for funding this project (Grant ID: 113E294).
Simon Yau

Simon Yau received his bachelor’s degree in electrical engineering from Texas A&M University in College Station, Texas, and is pursuing his doctorate at the same institution. His research interests include prototyping Medium Access Control (MAC) protocols for wireless networks, with a focus on protocols involving real-time and QoS constraints, and cross-layer designs between the networking layer and the MAC layer.

Ping-Chun Hsieh

Ping-Chun Hsieh received his bachelor’s and master’s degrees in electronics engineering from National Taiwan University in 2011 and 2013, respectively. He is a doctoral candidate in the Department of ECE at Texas A&M University. His research interests focus on wireless communication networks, with an emphasis on MAC for wireless networks, wireless video streaming, and queueing theory. In addition to theoretical research, he is interested in the experimentation of wireless MAC protocols, especially for IEEE 802.11 WLANs.
WiMAC: Rapid Implementation Platform for User-Definable MAC Protocols Through Separation

Simon Yau, Liang Ge, Ping-Chun Hsieh, I-Hong Hou, Shuguang Cui, P. R. Kumar
Electrical and Computer Engineering Department, Texas A&M University

Abstract
This demo presents WiMAC, a general-purpose wireless testbed for researchers to quickly prototype a wide variety of real-time Medium Access Control (MAC) protocols for wireless networks. As the interface between the link layer and the physical layer, MAC protocols are often tightly coupled with the underlying physical layer, and need to have extremely small latencies. Very few MACs have ever been implemented even though dozens of new MAC protocols have been proposed. To enable quick prototyping, we employ the Mechanism versus Policy separation to decompose the functionality in the MAC layer and the PHY layer. Built on the separation framework, WiMAC achieves the independence of the software from the hardware, to offer a high degree of function reuse and design flexibility.

Motivation
- In most of today’s 802.11 implementation, the MAC and PHY layers are very tightly coupled
- New protocols have to be redeveloped from the ground up, which presents two problems:
  - Long development time
  - MAC developers have to implement PHY layer features (which lie outside their area of expertise)
- As a result, most protocols do not get tested beyond simulations
- Without testing protocols with over-the-air transmissions, we do not know how well these protocols actually work
- Our goal is to develop a platform that:
  - Reflects 802.11 performance realistically
  - Reduces protocol prototyping time
  - Is capable of supporting a large class of MAC protocols
  - Is upgradeable for future MAC designs (for example multichannel, directional antenna support)

WiMAC
- Uses a Mechanism vs. Policy separation framework
- Mechanism: Low-level operations that handle the real packet transmissions over the network
- Policy: High-level schemes for channel contention and packet scheduling
- Features of WiMAC:
  - Independence of software from hardware
  - Enable protocol changes on-the-fly
  - Supports cross-layer design
  - Quick prototyping

What Protocols Have We Implemented?
- We have implemented 3 different protocols on our testbed as a starting point:
  - CSMA\cite{1}: most widely used protocol
  - CHAIN\cite{2}: improves uplink efficiency
  - Weighted Transmission\cite{3}: takes into account delay constraints/QoS
- This has given us valuable insights on some of the common mechanisms used in most MACs

Implementation Details
- Based on LabVIEW Communications System Design Suite 802.11 Application Framework
- Used USRP-2953R for development

Future Work
- Examine other mechanisms that could be used in MAC protocols
- Implement more MAC protocols using the separation framework
- Enable all mechanisms to be controlled in software

Acknowledgements
This material is based on work partially supported by AFOSR Contract FA9550-13-1-0008, NSF under Contract Nos. CNS-1302182, Science Technology Center Grant CCF-0939370, CNS-1343155, ECCS-1305979, CNS-1265227 DoD with grant HDTRA1-13-1-0029, and by grant NSFC-61328102.

References
Wenda Li
Wenda Li received his master’s degree in electrical engineering from the University of Bristol in 2013. He is a doctoral student in the Department of Electrical Engineering at the same university. His research interests include signal processing, indoor localization, and e-healthcare applications.

Mark Beach
Mark Beach received his doctorate in 1989 from the University of Bristol for research on the application of smart antenna techniques to GPS. He later became a faculty member at the university, and was promoted to senior lecturer in 1996, reader in 1998, and professor in 2003. He was head of the Department of Electrical and Electronic Engineering from 2006 to 2010, and then spearheaded Bristol’s hosting of the EPSRC Centre for Doctoral Training (CDT) in Communications. He manages the delivery of the CDT in Communications, leads research on enabling technologies for the delivery of 5G and beyond wireless connectivity, and serves as the school research impact director. He conducts his research activities through the Communication Systems and Networks Group, so they form a key component within Bristol’s Smart Internet Lab. He has over 25 years of physical layer wireless research experience during which he has embraced the application of spread spectrum technology for cellular systems, adaptive or smart antenna for capacity and range extension in wireless networks, MIMO-aided connectivity for throughput enhancement, and flexible RF technologies for software defined radio modems.
Non-Contact Breathing Detection Using Passive Radar

Motivation
- Non-contact breathing detection is valuable in intensive care monitoring, long term monitoring as well as in other non clinical fields such as the case of workers health monitoring (i.e. airplane pilots, firefighters, etc.)
- The passive radar enables the detection system to be both device-free and source-free

Passive Radar System Model
- **Source**
  - Energy harvesting transmitter
- **Receiver**
  - Data acquired from two USRP-2921 devices

Advantages
- Low-cost, no dedicated transmitter
- No dedicated frequency allocation
- Fast update
- Flexible deployment

CAF Mapping With Batch Processing
- CAF mapping is used for searching the target's range and Doppler information
- Batch processing can reduce the computational power
- Formula: $CAF(f_r, f_d) = \sum_{n=0}^{N-1} S_n(t)S_n^*(t+\frac{2\pi}{f_d})e^{j2\pi f_r n}$
  - $t$ – delay
  - $f_d$ – Doppler shift
  - $S_n(t), S_n^*(t)$ is the surveillance and reference signal received from USRP

Micro Doppler Extraction
- The traditional CAF spectrogram is unable to display the breathing signal
- The micro Doppler extraction compares the shape difference of each pulse in CAF mapping
- Traditional CAF Spectrogram: $\rho(f_r, f_d) = \sum_{n=0}^{N-1} |S_n(t)|^2$
- Micro Doppler Extraction: $\rho(x) = \sum_{n=0}^{N-1} |S_n(t)|^2$ for $f_d = \frac{x}{J}$
  - $J$ - the size of column length
  - $-1$ - output the sign of value

Real System

Measured Result
We exam the performance of different distance between chest to surveillance antenna. Then compare with chest belt signal and calculate the mean square error and correlation coefficient.

<table>
<thead>
<tr>
<th>Distance</th>
<th>MSE</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm</td>
<td>0.1378</td>
<td>0.8532</td>
</tr>
<tr>
<td>40 cm</td>
<td>0.1358</td>
<td>0.8583</td>
</tr>
<tr>
<td>60 cm</td>
<td>0.1670</td>
<td>0.7935</td>
</tr>
<tr>
<td>80 cm</td>
<td>0.2178</td>
<td>0.6432</td>
</tr>
<tr>
<td>100 cm</td>
<td>0.2034</td>
<td>0.6022</td>
</tr>
</tbody>
</table>

Experiment Layout

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This work is supported by SPHERE IRC funded by the UK Engineering and Physical Sciences Research Council (EPSRC).
Yi-Pin Lu

Yi-Pin Lu received his bachelor’s degree in ESS from National Tsing Hua University in Hsinchu in 2002 and his master’s degree in electrical engineering from National Taiwan University (NTU) in Taipei in 2005. He has worked at Himax and Retronix (subsidiary of Renesas Electronics) for five years as a digital circuit design engineer for digital TV SOC solutions. From 2012 to 2013, he was an intern at Broadcom Inc. His research interests include MIMO detection algorithms and architectures, signal processing for digital communications, wireless multimedia streaming systems design, and digital integrated circuit design. In 2016, he received his doctorate degree from the NTU Graduate Institute of Electronics Engineering under the guidance of Tzi-Dar Chiueh for his research on next-generation wireless video streaming and prototyping using the FlexRIO SDR platform.
An Implementation of a Fountain Code-Based MIMO-OFDM Receiver for Real-Time Wireless Video Streaming

Professor: Tzi-Dar Chiueh, MicroSystem Research Lab., Department of Electrical Engineering, National Taiwan University
Student: Yi-Pin Lu, Yi-Feng Cheng, and Wei Lan

Objective
Providing a prototype for how a real-time wireless video streaming system that includes low-latency RaptorQ code will function.

Wireless Video Streaming System Using Fountain Code
Multimedia streaming is the major application for next-generation wireless transmission.
Real-time streaming cannot be realized because of the inefficient wireless network methodology.
Fountain code can exclude the retransmission; it only gathers sufficient packets to decode, which is suitable for multimedia streaming.
RaptorQ code, the most advanced solution for fountain code, is used by the wireless video streaming system.
An FPGA implementation of both a RaptorQ decoder and a MIMO-OFDM receiver is realized using NI FPGAs.
In addition to an RF front end via a USRP-2943 device and a progressive video codec implemented via software, we developed the prototype for a high-performance real-time wireless video streaming system.
The resulting PSNR gain for the proposed scheme compared to the conventional ARQ scheme was more than 6 dB higher using the “Lena” pattern.

Design and Implementation of the Wireless Video Streaming System

System Overview
Encoder Architecture
RaptorQ Codec Block Diagram
Streaming Receiver Architecture

Real-Time Wireless Video Streaming Prototype Powered by NI Products

System Specification (WiFi-based)

Specification for RaptorQ Code Decoder

PSNR vs. SNR Performance

Demonstration link: http://dodger.ee.ntu.edu.tw/video.htm
Avishek Patra
Avishek Patra received his M.Sc. degree in communications engineering from RWTH Aachen University in Germany and his B.Tech. degree in electronics and communication engineering from Heritage Institute of Technology in India. He is pursuing an engineering doctorate degree at RWTH Aachen University, where he is working as a research assistant. His research interests are mmWave communication systems, future network architectures, and network management.

Andreas Achtzehn
Andreas Achtzehn received his engineering doctorate degree from RWTH Aachen University. He holds a diploma degree in computer engineering and a diploma degree in business administration and engineering from the same university. He is a study coordinator and senior researcher at the Institute for Networked Systems. His extended research interest is the system-wide design and optimization of next-generation communication networks, with a focus on radio-environment modeling, techno-economic assessments, and scalability issues in ultradense network deployments.

Marina Petrova
Marina Petrova is an assistant professor of electrical engineering and information technology at RWTH Aachen University. She is also a chief research scientist at the Institute for Networked Systems. Her research interests focus on cognitive radios and cognitive wireless networks, adaptive wireless systems technologies, and resource optimization problems in wireless networks. She has actively participated in several EU-funded international cooperative projects and industry projects in the field of wireless communications and cognitive radios. Moreover, she is involved in research on prototyping the implementation of resource management solutions for cognitive radios. She holds a degree in electrical engineering and telecommunications from Ss. Cyril and Methodius University in Skopje, Macedonia, and an engineering doctorate degree from RWTH Aachen University.
ULLA-X: A Programmatic Middleware Enabling Large-Scale and Distributed Wireless Experimentation

Avishek Patra, Andreas Achtzehn, and Marina Petrova
Institute for Networked Systems RWTH Aachen University Aachen, Germany

Motivation
The control and automation of wireless experimentation can be tedious. It often slows down researchers and practitioners aiming to evaluate new algorithms and RF designs in distributed and large-scale setups. Wireless systems research in particular often requires pervasive reconfiguration capabilities, but is hampered by heterogeneous control facilities and domain-specific control tools. We aim to bridge this pertinent gap with a new middleware that enables network-based control through easily accessible, generic, and powerful interfaces.

Our Proposal
We propose ULLA-X, a middleware that:
- Resides in between custom user applications and technology-dependent radio implementations
- Provides easy, generic, and centralized access to lower layer configurations for higher layer research applications
- Enables the automation of recurring configuration and logging tasks with automatic event handling
- Offers a domain-specific declarative programming language that allows users to specify tasks in a unified and simple manner

Architecture
The ULLA-X core interacts with user applications through a standard network protocol. It schedules monitoring tasks, collects device statistics, and reacts to state changes based on trigger events. The core connects to the different radio systems through vendor-specific connector modules that transform read and write statements into the respective query and configuration commands. For integrating reference design specifics, simple description and configuration files are employed.

ULLA-X offers advanced management capabilities, or example auto discovery and distributed control schemes.

ULLA-X and NI Products
Through connectors for the NPSV subsystem of LabVIEW, ULLA-X integrates seamlessly into the NI products ecosystem.

Controls for new and existing reference designs can be easily made accessible through exposure in the LabVIEW design software. This allows for rapid prototyping with custom radio reference designs.

In recent demonstrations, we have shown the wide application space of ULLA-X, for example by simultaneously monitoring and reconfiguring USRP-2952R devices acting as IEEE 802.11 transceivers and FlexRIO-controlled NI 5791 RF front ends emulating LTE.
Enoch Yeh

Enoch Yeh is a doctoral student in the Electrical and Computer Engineering Department at The University of Texas at Austin under the supervision of Robert W. Heath Jr. He received his bachelor’s in electrical engineering from UT-Austin in 2014. His research interests include wireless communications, communications and radar in vehicular networks, and wireless networking. He is working on improving a prototype of a joint radar and communications framework for 802.11p (DSRC) that is designed specifically for forward collision warning and avoidance in automotive radar.

Robert W. Heath Jr.

Robert W. Heath Jr. received his doctorate in electrical engineering from Stanford University in 2002. From 1998 to 2001, he was a senior member of the technical staff and then a senior consultant at Iospan Wireless Inc. in San Jose, California. There he worked on the design and implementation of the physical and link layers of the first commercial MIMO-OFDM communication system.

Since January 2002, he has been with the Department of Electrical and Computer Engineering at The University of Texas at Austin where he is a Cullen Trust for Higher Education endowed professor and a member of the Wireless Networking and Communications Group. He is also president and CEO of MIMO Wireless Inc., chief innovation officer at Kuma Signals LLC, and a member of the executive team at PHAZR Inc. His research interests include several aspects of wireless communication and signal processing: limited feedback techniques, multihop networking, multuser and multicell MIMO, interference alignment, adaptive video transmission, manifold signal processing, and millimeter wave communication techniques. He is a coauthor of the book Millimeter Wave Wireless Communications published by Prentice Hall in 2014.
Forward Collision Vehicular Radar With IEEE 802.11: Feasibility Demonstration Through Measurements

Enoch R. Yeh, Robert C. Daniels, and Robert W. Heath, Jr. | Wireless Networking and Communications Group | The University of Texas at Austin

Motivation

- NTSB mandate requiring frontal collision detection and avoidance on all new vehicles [NTSB15]
- mmWave RADARs are expensive, susceptible to spoofing, and do not accompany a communication network [CB87]
- IEEE 802.11 devices are widely available and compatible with IEEE 802.11p [JD08]
- Implementation possible with low-bandwidth requirement: 20 MHz at 5 GHz band

Range Estimation Algorithm

- Predefined set of frequency and phase offset candidates
- Brute force minimization matches received channel estimate to the cosine signal model
- Returns range arguments associated with the best fit cosine with the least residuals
- Demonstrated meter-level accuracy up to 50 m in simulated environment
- Figure 2. RMS Range Error Using IEEE 802.11 Packets in a 20 MHz Channel With a Single Target With Variable Range (5–50 m) in a Simulated Environment

Two-Path Link Model

- Complex-Baseband Link Model
- OFDM Channel Estimate
- Mean-Normalized Channel Energy

Platform

NI Hardware: USRP RIO (2953R)
NI Software: LabVIEW FPGA 2014

Measurements and Results

Table 1. Implementation Parameters

Future Work

Optimization Performance via Design, Multitarget Localization, Extensions for Pedestrian Targets, Compact Vehicular Implementation and Design

References:


Acknowledgements:

This research was partially supported by the U.S. Department of Transportation through the Data-Supported Transportation Operations and Planning (D-STOP) Tier 1 University Transportation Center and by the Texas Department of Transportation under Project 0-6877 entitled “Communications and Radar-Supported Transportation Operations and Planning (CAR-STOP).” Dr. Daniels is also with Kuma Signals, LLC.

Figure 1. Illustration of Link Model: The IEEE 802.11p PHY is connected to separate transmit (TX) and receive (RX) RF chains. Path 2 is the reflected path from the ranging target.

Table 1. Hardware Specifications for Measurement Platform

Figure 3. Block Diagram Description of RF Components in the Measurements Campaign

Figure 2. RMS Range Error Using IEEE 802.11 Packets in a 20 MHz Channel With a Single Target With Variable Range (5–50 m) in a Simulated Environment

Figure 4. IEEE 802.11 RadCom Link Setup for Measurements: During measurements, the antenna edges were separated by a minimum of 0.5 m.

Table 2. Implementation Parameters

Figure 5. RMS range error on a single target with variable range from 5 to 30m. Post-calibration estimates are presented.

Table 3. Range Estimate Statistics
**USER PROFILE**

**Naofal Al-Dhahir**
Naofal Al-Dhahir is an Erik Jonsson Distinguished Professor at The University of Texas at Dallas. He earned his doctorate degree in electrical engineering from Stanford University. From 1994 to 2003, he was a principal member of the technical staff at GE Research and AT&T Shannon Laboratory. He is co-inventor of 40 issued US patents, co-author of over 300 papers, and corecipient of four IEEE best paper awards. He is editor-in-chief of IEEE Transactions on Communications and an IEEE Fellow.

**Brian L. Evans**
Brian L. Evans is the Engineering Foundation Professor at The University of Texas at Austin. He earned a bachelor’s degree in electrical engineering and computer science from the Rose-Hulman Institute of Technology and master’s and doctorate degrees in electrical engineering from Georgia Tech. From 1993 to 1996, he was a researcher at the University of California, Berkeley. His research and teaching efforts bridge signal processing theory and real-time implementation of digital communications and image/video processing systems. He has published 240 papers and three books, and has graduated 26 doctoral students. Through students, publications, and software releases, his research has had a significant impact on HP, Intel, NI, NXP, Qualcomm, Schlumberger, Texas Instruments, and Xerox, among other companies. An IEEE Fellow, he has won three best paper awards and three teaching awards.

**Mostafa Sayed**
Mostafa Sayed received his bachelor’s and master’s degrees in electrical engineering from Cairo University, Giza, in 2008 and 2013, respectively. He is working on his doctorate degree in electrical engineering at The University of Texas at Dallas. From 2008 to 2013, he was a system design engineer at Varkon (Wasiela) Semiconductors in Cairo, where he worked on the design of hardware-oriented digital signal processing algorithms for wireless communications receivers. As an intern at Texas Instruments in Dallas during summers 2014 and 2015, he worked on PHY layer algorithm design for low-power powerline and wireless smart grid communications. His current research interests include smart grid communications, the design of wireless and powerline communication systems, and the implementation of hardware-efficient signal processing algorithms.

**Ghadi Sebaali**
Ghadi Sebaali received her bachelor’s degree in computer and communication engineering from the American University of Beirut (AUB) in 2014. She is pursuing her master’s and doctorate degrees in electrical and computer engineering at The University of Texas at Austin. Her research interests include interference cancellation and coexistence algorithms for wireless communication systems in Austin, Texas, during summer 2015, she worked with the Microcontrollers Connectivity Team on modeling communication systems and verifying radio board specifications. She is the recipient of several awards: Nikola Tesla Electrical Engineering Scholar Honor (declined), of Columbia University, Mudair Scholar Fund from the Boston University Study Abroad Office, Merit Scholarship, Creative Achievement Award, and a Best Paper Award from AUB.

**Junmo Sung**
Junmo Sung received bachelor’s degrees in electrical engineering from Kyungpook National University and The University of Texas at Dallas in 2010 through a dual-degree program. He received his master’s degree from The University of Texas at Dallas in 2012. From 2012 to 2015, he worked for NI in Seoul, South Korea, where he designed and implemented a real-time frequency division MIMO receiver on an FPGA and conducted research on 5G cellular communications systems. He is pursuing his doctorate degree in electrical and computer engineering at The University of Texas at Austin. His research interests include interference mitigation techniques, heterogeneous wireless networks, and multiuser MIMO systems.
Diversity and Coexistence Within Smart Grid Communications

Prof. Brian L. Evans, Wireless Networking and Communications Group, The University of Texas at Austin
Students: Ms. Ghadi Sebaali and Mr. Junmo Sung
Current Collaborators: Prof. Naofal Al-Dhahir (UT Dallas) and Mr. Mostafa Sayed (UT Dallas)Past Collaborators: Dr. Jing Lin (Qualcomm), Dr. Marcel Nassar (Samsung), Dr. Aditya Chopra (NI)
Sponsors: Semiconductor Research Corporation GRC under Task Id 1836.133 (from Freescale and Texas Instruments)

Objective: Improve reliability of smart grid communications

1. Project Overview

Focus
Neighborhood-area smart utility network between a data concentrator and smart meters along two paths

<table>
<thead>
<tr>
<th>Powerline (PLC) Link</th>
<th>Wireless Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-voltage power lines in 3–500 kHz band</td>
<td>Unlicensed wireless 900–928 MHz band</td>
</tr>
</tbody>
</table>

Goal
Integrating customers in the grid
- Scale voltage with energy demand
- Bill customer using real-time rates
- Analyze customer load profiles
- Improve system reliability

Limitations
Signal attenuation in propagation channel
- Reflections at impedance discontinuities
- Noise or interference
- Frequency selectivity

Project Components
- Interference mitigation
- PLC/wireless diversity
- Coexistence mechanisms
- PLC/wireless testbed

Current Work
- Add simultaneous wireless communication to the PLC testbed
- Evaluate communication performance versus complexity trade-offs for wireless diversity methods

Project Webpage: http://users.ece.utexas.edu/~bevans/projects/plc/index.html

2.1. Wireless/PLC Diversity

- Nonidentical channel, noise, and interference statistics
- Maximal ratio combining is a maximum likelihood optimal technique for AWGN
- OFDM transmission with 256 subchannels and BPSK modulation
- 0.4 MHz sample rate
- Wireless link noise model: Gaussian mixture with two components
- PLC noise model: cyclostationary noise

2.2. Coexistence Mechanisms

- 802.11ah and 802.15.4g standards share the 900 MHz ISM band
- Path loss (PL) model used is outdoor large-zone model
- Interference model is used as follows: d(Rxv, Txv) = dD and d(Rxi, Txi) = dU
- Metric used is desired/undesired signal ratio

2.3. Testbed

- A real-time hardware/software testbed for wired MIMO OFDM communication
- Algorithms evaluated: bit allocation, time equalization, far-end crosstalk cancellation (zero-forcing and successive interference)

Project Components
- Interference mitigation
- PLC/wireless diversity
- Coexistence mechanisms
- PLC/wireless testbed

Software
- Graphical user interface (GUI) runs in LabVIEW
- Real-Time OS running on embedded processors

Hardware
- PXI-1045 chassis
- PXI-5132 for analog-to-digital (A/D) conversion
- PXI-5421 for digital-to-analog (D/A) conversion
George R. MacCartney Jr.

George R. MacCartney Jr. received his bachelor’s and master’s degrees in electrical engineering from Villanova University in 2010 and 2011, respectively. He is pursuing a doctorate degree in electrical engineering at the New York University (NYU) Tandon School of Engineering under the supervision of Theodore Rappaport with the NYU WIRELESS Research Center. He has authored or coauthored over 20 technical papers in the field of millimeter-wave (mmWave) measurements and models. His research interests include mmWave channel sounder prototyping and mmWave measurements, models, and analysis for 5G communications.

Shu Sun

Shu Sun received a bachelor’s degree in applied physics from Shanghai Jiao Tong University in China in 2012 and a master’s degree in electrical engineering from the NYU Tandon School of Engineering in 2014. She is pursuing a doctorate degree in electrical engineering under the supervision of Theodore Rappaport at NYU while conducting research at the NYU WIRELESS Research Center. She has authored or co-authored over 20 technical papers in the field of mmWave wireless communications. Her current research interests include mmWave mobile communications and the analysis of MIMO systems for mmWave channels.

Theodore (Ted) S. Rappaport

Ted Rappaport is the David Lee/Ernst Weber Professor of Electrical and Computer Engineering with the NYU Tandon School of Engineering and the founding director of the NYU WIRELESS Research Center. He also holds professorship positions with the Courant Institute of Mathematical Sciences and the NYU School of Medicine. In addition to the NYU WIRELESS Research Center, he founded major wireless research centers at the Virginia Polytechnic Institute and State University (MPRG) and The University of Texas at Austin (WNCG). He also founded two wireless technology companies that were sold to publicly traded firms. He is a highly sought-after technical consultant who has testified before the US Congress and served the ITU. He has advised more than 100 students. He holds more than 100 patents issued and pending and has authored or coauthored several books, including the best-seller Wireless Communications: Principles and Practice (Second Edition, Prentice Hall, 2002). His latest book, entitled Millimeter Wave Wireless Communications (Pearson/Prentice Hall, 2015), is the first comprehensive text on the subject.
A Flexible Millimeter-Wave Channel Sounder With Absolute Timing

George R. MacCartney Jr., Shu Sun, and Theodore S. Rappaport (Advisor)

I. Channel Sounder Transmitter
- FPGA–generated PN sequence via leap-forward linear feedback shift register state machine with PXIe-7966R FlexRIO FPGA
- 200 Mcps to 500 Mcps → 400 MHz to 1 GHz RF null-to-null bandwidth

II. Gimbal and Track Control
- Full control of gimbal and linear track via PS3 remote through LabVIEW with controls for AGC, signal acquisition, and antenna positioning

III. Channel Sounder Receiver
- IQ baseband acquisition with NI-5771R and PXIe-7966R FlexRIO FPGA for high-speed continuous acquisition into DRAM
- Real-Time undilated power delay profiles (PDPs)
- Option for time-dilated PDPs via traditional sliding correlation method
- Absolute propagation delay PDPs with synchronized Rubidium references via 1 PPS and time-based digital trigger with PXI trigger lines
- Automatic azimuth sweeps and linear track sweeps
- Sliding correlator oscilloscope AGC control and live feedback for acquisitions outside linear range
- Future Work:
  - Control of TX from RX over WiFi
  - Estimate channel Doppler
  - Full AGC control

IV. Dynamic Human Blocking Measurements
- NI-based channel sounder allows for high-speed acquisition of periodic PDPs to understand channel dynamics and human blocking attenuation over short time frames
- Current system can record 41,000 consecutive PDPs in a minimum period of 32.752 µs with a multipath time resolution of 2 ns
- Measurements (41-49) conducted with human blocker walking perpendicular to LOS point-to-point link (5 m T-R separation distance) at 0.5 m increments from 0.5 m to 4.5 m

- Increases in signal strength up to 2 dB on average when entering blockage region (diffraction/constructive interference)
- Portions of small-scale fading when in the shadow/blockage region, with signal attenuated by only 14 to 17 dB for the 2.5 m measurement (halfway between TX and RX) compared to the other cases
- Video: https://www.youtube.com/watch?v=2FIlwyyQKb8
Leo Laughlin

Leo Laughlin received an M.Eng. degree in electronic engineering from the University of York in the UK in 2011. Between 2011 and 2015, he was a doctoral student at the University of Bristol, where his work on novel transceiver architectures for 4G and 5G mobile devices was sponsored by u-blox AG. From 2009 to 2010, he worked at Qualcomm on physical layer DSP for GSM receivers. In 2011, he worked on radio geolocation systems at Omnisense Ltd. He received funding to continue his research activities beyond his doctorate as a senior research associate in the Communications Systems and Networks Laboratory working on self-interference cancellation technologies for in-band full-duplex and tunable frequency-division duplexing applications. He received the York Probe Prize for best M.Eng. graduate in 2011 and won the Technology Everywhere category at the 2015 EPSRC UK ICT Pioneers competition.

Chunqing (Jack) Zhang

Jack Zhang received a master’s degree in telecommunication and information systems from Beijing Jiaotong University in China in 2004. Since 2014, he has pursued a doctorate at the University of Bristol, where he is working on a novel transceiver architecture for 4G and 5G mobile devices under the supervision of Mark Beach and Kevin Morris. He also worked as a research assistant for the Communication Systems and Networks Group in the Department of Electrical and Electronic Engineering. Between 2004 and 2014, he worked in the R&D and testing departments of Datang Mobile Telecommunication Equipment Co. Ltd. in Beijing.

Mark Beach

Mark Beach received his doctorate in 1989 from the University of Bristol for research on the application of smart antenna techniques to GPS. He later became a faculty member at the university, and was promoted to senior lecturer in 1996, reader in 1998, and professor in 2003. He was head of the Department of Electrical and Electronic Engineering from 2006 to 2010, and then spearheaded Bristol’s hosting of the EPSRC Centre for Doctoral Training (CDT) in Communications. He manages the delivery of the CDT in Communications, leads research on enabling technologies for the delivery of 5G and beyond wireless connectivity, and serves as the school research impact director. He conducts his research activities through the Communication Systems and Networks Group, so they form a key component within Bristol’s Smart Internet Lab. He has over 25 years of physical layer wireless research experience during which he has embraced the application of spread spectrum technology for cellular systems, adaptive or smart antenna for capacity and range extension in wireless networks, MIMO-aided connectivity for throughput enhancement, and flexible RF technologies for software defined radio modems.
Motivation
- In-band Full Duplex allows simultaneous Tx and Rx on the same frequency, potentially doubling spectral efficiency, but requires high levels of self-interference cancellation.

Goal
- Implement self-interference cancellation using low cost, small form factor implementation technologies to enable in-band full duplex operation in mobile devices.

Traditionally, co-channel self-interference has been avoided: TDD and FDD avoid self-interference using separate channels for Tx and Rx.

Instead, self-interference can be cancelled to enable In-band Full Duplex

Novel Self-Interference Cancelling Transceiver Architecture
Combines Electrical Balance Duplexing With Active Cancellation

Tunable balancing impedance is adjusted to cause signals to cancel out in a hybrid junction

After the first stage of cancellation in the hybrid junction there is still some residual interference
- Residual self interference reduced by actively injecting a cancellation signal
- Suitable for small form factor multiband mobile devices: requires just one antenna, can be implemented using low cost technologies
- Can be tuned over wide frequency ranges

Hardware Prototype
- Signal processing for cancellation and hardware control implemented in LabView
- Interfaced with 2x Vector Signal Transceivers which implement Tx, Rx, and cancellation signal generation

Achieves >80 dB self-interference cancellation

This work is supported by EPSRC (EP/N028163/1), the University of Bristol, and u-blox.
Gerhard P. Fettweis

Gerhard P. Fettweis earned his doctorate under H. Meyr’s supervision from RWTH Aachen University in 1990. After one year at IBM Research in San Jose, California, he moved to TCSI Inc. in Berkeley. Since 1994, he has served as the Vodafone Chair Professor at TU Dresden, Germany, and has been conducting research on wireless transmission and chip design with the sponsorship of 20 companies from Asia, Europe, and the United States. He coordinates two German Research Foundation (DFG) centers at TU Dresden, cfaed and HAEC. He is an IEEE Fellow, a member of the German academy acatech, and a recipient of the Stuart Meyer Memorial Award from IEEE VTS. In Dresden, he created 11 startups and set up funded projects worth nearly half a billion euros. He has helped organize IEEE conferences, most notably as TPC chair of ICC 2009 and of TTM 2012 and as general chair of VTC Spring 2013 and DATE 2014.

Martin Danneberg

Martin Danneberg received his master’s degree in electrical engineering from Technische Universität Dresden in 2013. From 2008 to 2012, he worked as a student assistant for the Vodafone Chair on the EASYC project. His final thesis focused on the development of a backplane for a phased array. He serves as a member of the Vodafone Chair Mobile Communications Systems department and participates in several research and industry projects, for example, eWINE, SATURN, and the NI Lead User Program. His professional interests include FPGA-based prototyping of communication systems, cognitive radio, and novel applications of flexible waveforms in future 5G networks.

Nicola Michailow

Nicola Michailow received his Dipl.-Ing. degree in electrical engineering with a focus on wireless communications and information theory from Technische Universität Dresden in 2010. From 2008 to 2009, he developed signal processing algorithms for sensor data analysis for the R&D department at Asahi Kasei Corporation in Japan. Since 2010, he has served as a research associate for the Vodafone Chair. He received his Dr.-Ing. degree in 2015, and his professional interests include nonorthogonal waveforms for future 5G cellular systems, new applications like the Internet of Things and the Tactile Internet, and the FPGA-based prototype implementation of flexible multicarrier modulation schemes. He currently focuses on software defined radios for NI.
Motivation

Innovative 5G applications will challenge future cellular systems with new requirements. The OFDM-based 4G standard cannot address all of them. Generalized frequency-division multiplexing is a flexible multicarrier waveform with additional degrees of freedom. This poster presents a strategy toward a flexible FPGA implementation of GFDM [1], which is reconfigurable at run time using the LabVIEW Communications System Design Suite.

Results

- Flexible FPGA design
- Parameters configurable on run time:
  - Subcarriers K
  - Subsymbols M
  - Pulse shaping filter
  - Time window
  - Cyclic prefix
  - Resource map
  - Trainings sequence

Prototype

Hardware and Software Platform

Further Reading

Mingming Cai received a bachelor’s degree in automation engineering from Nanjing University of Aeronautics and Astronautics in China in 2011 and a master’s degree in electrical engineering from the University of Notre Dame in Indiana in 2014. He is pursuing his doctorate in electrical engineering at Notre Dame. His research interests include wireless communication, cognitive radios, software defined radios, and millimeter wave communication.

J. Nicholas Laneman is founding director of the Wireless Institute in the College of Engineering, a professor of electrical engineering, and a fellow of the John J. Reilly Center for Science, Technology, and Values at the University of Notre Dame. He joined the faculty in August 2002 shortly after earning a doctorate in electrical engineering and computer science from the Massachusetts Institute of Technology. His research and teaching interests include communications architecture (a blend of information theory), error-control coding, signal processing for communications, network protocols, and hardware design with an emphasis on wireless systems.
An LTE-Based Wideband Distributed Spectrum Sharing Architecture

Mingming Cai (mcai@nd.edu) and J. Nicholas Laneman (jnl@nd.edu) University of Notre Dame

Abstract
A radio architecture is developed for distributed spectrum sharing among secondary users (SUs) in a localized area and a wide band of frequencies. Based on an OFDM physical layer, the architecture allows multiple pairs of SUs to utilize one or more subchannels within the band without causing harmful interference to each other. A prototype implementation of the architecture has been developed using NI USRP RIO devices and the LabVIEW Communications System Design Suite and LTE Application Framework System tests show that the spectrum sharing efficiency of the implemented distributed spectrum sharing system is close to an upper bound when signal-to-noise ratio (SNR) is high enough.

System Architecture

Flexible Physical Layer

LTE Application Framework Modifications:
- Channelize 100 physical resource blocks (PRBs) into 10 PRB groups (PRBGs) in PHY
- Energy detection for wideband spectrum sensing
- Various multichannel random access protocols, for example, CSMA, MRAH
- Multiple sync loops for immediate rendezvous
- Single demodulation and decoding loop to save FPGA resources
- More details in paper

MAC: Multichannel CSMA

- Spectrum sharing efficiency increases as $N$ increases
- System has better performance when $N \geq M$

References
USER PROFILE

MinKeun Chung
MinKeun Chung received his bachelor’s degree in electrical and electronic engineering from Yonsei University in Korea in 2010. He is a doctoral candidate in the Mobile Communication Laboratory and the Convergence Communications Networking Laboratory at Yonsei University under the joint supervision of Dong Ku Kim and Chan-Byoung Chae. He was a research intern with the Advanced Wireless Research Team at NI in Austin, Texas, in summers 2013 and 2015. His main research interests are future wireless communication systems design and FPGA-based physical layer real-time prototyping. He was a corecipient of the Samsung Humantech Paper Award in 2016. From 2004 to 2009, he also received a scholarship for engineering students from the Korea Student Aid Foundation (KOSAF). From 2010 to 2015, he was awarded a full scholarship from the Samsung Electronics academic-industrial collaboration program.

Chan-Byoung Chae
Chan-Byoung Chae is an Associate Professor in the School of Integrated Technology, College of Engineering, Yonsei University, Korea. He was a Member of Technical Staff (Research Scientist) at Bell Laboratories, Alcatel-Lucent, Murray Hill, NJ, USA from June 2009 to Feb 2011. Before joining Bell Laboratories, he was with the School of Engineering and Applied Sciences at Harvard University, Cambridge, MA, USA as a Post-Doctoral Research Fellow under the supervision of Vahid Tarokh. He received the Ph.D. degree in Electrical and Computer Engineering from The University of Texas (UT), Austin, TX, USA in 2008 under the supervision of Robert W. Heath, Jr., where he was a member of the Wireless Networking and Communications Group (WNCG). Prior to joining UT, he was a Research Engineer at the Advanced Research Lab., the Telecommunications R&D Center, Samsung Electronics, Suwon, Korea, from 2001 to 2005. He was a Visiting Scholar at the WING Lab, Aalborg University, Denmark in 2004 and at University of Minnesota, MN, USA in August 2007 to work with Nihar Jindal. While having worked at Samsung, he participated in the IEEE 802.16e standardization, where he made several contributions and filed a number of related patents from 2004 to 2005. His current research interests include capacity analysis and interference management in energy-efficient wireless mobile networks and nano (molecular) communications.
**Introduction**

**Motivation**
- A candidate for creating a new breakthrough to alleviate the spectrum crunch
- Theoretical throughput doubling

**Objective**
- Prototyping a real-time full duplex SISO / MIMO radio system for 5G wireless networks
- Practical throughput doubling achievement

**Proposed Full Duplex SISO/MIMO Architectures**

**PHY Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>2.52 GHz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>30.72 Ms/s</td>
</tr>
<tr>
<td>Subcarrier Spacing</td>
<td>15 kHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK / 16QAM / 64 QAM</td>
</tr>
<tr>
<td>FFT Size</td>
<td>2048</td>
</tr>
<tr>
<td>CP Length</td>
<td>512 (Extended CP)</td>
</tr>
<tr>
<td>MIMO Receiver</td>
<td>Zero-Forcing</td>
</tr>
</tbody>
</table>

**Prototype Setup**

**Analog Self-Interference Canceler**
- Dual-Polarization Based Full Duplex Antenna

**Digital Self-Interference Canceler**
- NI PXIe-1092 Chassis
- NI PXIe-9135 Real-Time Controller
- NI 5791R RF Transceiver
- NI PXIe-7975 FlexRIO FPGA Module

**Demo Results**

* Full duplex MIMO: Partially collaborated with LG Electronics

Swapnil Mhaske

Swapnil Mhaske received his bachelor’s degree in electrical engineering from the University of Pune in India and his master’s degree from Rutgers University in Piscataway, New Jersey. He is a graduate assistant in the Wireless Information and Networking Laboratory (WINLAB) at Rutgers, where he is working on his doctorate under the guidance of Predrag Spasojevic. His area of research is design and implementation of efficient channel-coding schemes for wireless systems. He has interned with the Advanced Wireless Research and the Software R&D groups at NI, where he worked on the development of channel-coding systems on the FPGA.

Predrag Spasojevic

Predrag Spasojevic received his Diploma of Engineering degree from the University of Sarajevo School of Electrical Engineering in 1990 and his master’s and doctorate degrees in electrical engineering from Texas A&M University in College Station, Texas, in 1992 and 1999, respectively. From 2000 to 2001, he worked as a Lucent postdoctoral fellow at WINLAB in the Electrical and Computer Engineering Department at Rutgers University. He is an associate professor in the same department, and his research interests include communication and information theory and signal processing. He was an associate editor of the IEEE Communications Letters from 2002 to 2004 and served as a cochair of the DIMACS Princeton-Rutgers Seminar Series in Information Sciences and Systems from 2003 to 2004. He served as a technical program cochair for the IEEE Radio and Wireless Symposium in 2010. From 2008 to 2011, he was publications editor of IEEE Transactions of Information Theory.
Impact of 5G Requirements

- 1000X capacity over current cellular (LTE)
- 10 Gbps peak throughput user experience
- < 1 ms Latency
- High-throughput PHY processing
- Spectrum and power efficient hardware architectures
- Overall reduction in cost per bit
- Potential for design change
- Hardware platform must be reconfigurable
- Shorter development cycles necessary for iterative design
- Potential for several GHz of spectrum
- Relatively unstable channel needs significantly more processing
- Reliable channel codes necessary
- PHY processing budget for channel coding further reduced

Low-Density Parity-Check Codes

- Code length: High (-S2: 16 k-64 kb)
- Code rate: 1/2, 2/3, 3/4, 5/6 Code
- Digital Video Broadcasting (DVB) [1]: scalable solutions for evolving requirements
- Wi-Fi 802.11n, WiMAX 802.16e [2]: scalable solutions for evolving requirements
- Structure simplifies decoder architecture
- Wide standard acceptance

Resource Utilization [3]

- Throughput
- 1x: 3.17 Gb/s
- 2x: 6.34 Gb/s
- BER: 9.3 x 10^-3
- E_b/N_0 (dB): 5.5
- LFAM (dB): 6.7
- LFAM (dB): 6.2
- LDPC: Decoding of LDPC resource utilization and throughput in the Kintex-7 FPGA in this non-parallelized version and 2x in the parallelized version [5]

2.5 Gb/s LDPC Decoder

Algorithmic Description Schematic [4, 5]

Design Choices

- QC-LDPC Codes
- Parallelistsm offered by LDPC codes
- Structure simplifies decoder architecture
- Wide standard acceptance

Error-Rate Performance [4]

Throughput (Gb/s) | 1 | 2 | 4 | 8 | 16
--- | --- | --- | --- | --- | ---
BER (x10^-3) | 10.0 | 5.0 | 2.5 | 1.0 | 0.5

design choices for low power design

High-Throughput Architecture

- Strategies for Channel Coding
  - Develop code structures that result in low encoding and decoding latency
  - Algorithmic Optimization
  - Identify algorithmic dependencies and parallelize
  - Develop algorithmic approximations to reduce complexity
  - Develop efficient methods for rate adaptation to implement rate-compatible architecture

Traditional Decoding

- Reduced complexity check-node processing
- z-fold parallelization of node processing
- Compact representation of PCM
- Multi level pipelining on account of modification for reduced complexity check-node processing

Standard Acceptance

- 10 Gigabit Ethernet (10GBASE-T)
  - Code rate: High
  - Code length: High (G: 16 k-64 kb)
  - Throughput: 6.4 Gb/s
- Digital Video Broadcasting
  - Code rate: 11 different rates
  - Code length: 84, 128, 1944 bits
  - Throughput: ~350 Mb/s
- Wi-Fi 802.11n, WiMAX 802.16e
  - Code rate: 1/2, 2/3, 3/4, 5/6 Code
  - Code length: 648, 1296, 1944 bits
- Throughput
  - 135 Mb/s

High-Throughput FPGA Architectures for Channel Coding

Swapnil Mhaske, Predrag Spasojevic, Rutgers University
Hojin Kee, Tai Ly, Ahsan Aziz, National Instruments

Strategies for High Throughput [2]

- Throughput
  - 10 Gb/s peak throughput user experience
- High-Throughput FPGA Architectures
- Overall reduction in cost per bit

Proprietary Methods

- Relatively unstable channel needs significantly more processing
- Reliable channel codes necessary
- PHY processing budget for channel coding further reduced

Prototyping in LabVIEW Communications

- FPGA: Xilinx Kintex-7 on PXIe-7975R
  - High-rate iterative LDPC decoder [2]
  - Time-critical algorithmic processing
- HLS provides SCTL implementation
- USRP-2953R used for real-world verification of wireless systems
- FPGA: Xilinx Kintex-7 on PXIe-7975R
  - 2.5 Gb/s LDPC Decoder
  - Resource Utilization [4]
  - Error-Rate Performance [4]

Main References

Dr. Li Li
Li Li received his doctorate degree in communications from the University of Bristol in 2013, and is working as a postdoctoral researcher in the CSN group at the university. His main research interests include software-defined networking (SDN), wireless network virtualization, and self-organization and self-configuration in wireless communication networks. He is using NI equipment to build a real-world SDN wireless testbed to investigate the convergence of different and heterogeneous wireless network domains.

Imad Al-Samman
Imad Al-Samman received his MSc (Hons) in mobile broadband communications from Lancaster University in 2012 and joined the CDT program at the University of Bristol in 2013 to obtain a doctorate degree in communications. In 2012, he completed an LTE test engineer internship at Aeroflex-Stevenage, where he tested the TMS500 network tester and developed validation scenarios. His research focuses on SDN, Cloud-RAN, and network virtualization. For the TOUCAN project, he is helping to build a testbed of NI equipment for real-world SDN measurements and the integration of different wireless technologies in one architecture.
TOUCAN Vision and Objectives

- To achieve ultimate network convergence enabled by a radically new technology agnostic architecture targeting a wide range of applications and end users services.
- To facilitate optimal interconnection of network technology domains, networked devices and data sets with high flexibility in data through-put, high adaptability, resource and energy efficiency.
- To break conventional barriers between hardware infrastructure and services by including network infrastructure and its control as part of the end-to-end service delivery chain.
- To Seamlessly converge heterogeneous technology domains.
- To Support very high bandwidth granularity range and capacity.

TOUCAN Wireless SDN Testbed

- Part of TOUCAN LAB, a unique, largescale multi-technology experimental platform, to validate, refine and showcase the novel solutions developed in TOUCAN technical challenges.
- A converged wireless, optical, and IT experimental platform that is integrated at both Hardware and Software level.
- A multi-technology emulation facility able to support various TOUCAN technologies at scale and at real-time.
- An experimental platform which is open for experimentation across all layers and domains offering researchers full control and programmability in order to create a feature-rich unique research environment.

Real System

- Enhanced legacy interface (programmability + agility)
- Optical Interface
- IP/L2
- ATM
- PON
- Data Centre Network
- Flexible User of Time Spectrum and Space
- Seamless multi-technology Mobility
- Wi-Fi
- mm-Wave
- LTE

Future Work

- Design wireless resource description model, resource abstraction & virtualization
- Integration with mmWave and LiFi test-beds
- Implement SDN applications: wireless resource management, roaming in multi-domain, traffic offloading
Yue Tian
Yue Tian received his bachelor’s degree from the Beijing University of Posts and Telecommunications in 2007 and his master’s degree in wireless communication and signal processing from the University of Bristol in 2011. He is pursuing a doctorate in electrical engineering at the University of Bristol. His research focuses on 5G communication system techniques such as interference alignment, massive MIMO, and nonorthogonal multiple access.

Vaia Kalokidou
Vaia Kalokidou graduated from the University of Reading in 2005 with a master’s degree in electronic engineering. Her final-year project was based on WPANs (“Development of high level functions in a UWB system”). In 2011, she started the four-year program at the Centre for Doctoral Training in Communications at the University of Bristol. In 2015, she completed her doctorate on interference management techniques for 5G networks. It focuses on blind interference alignment, topological interference management, and nonorthogonal multiple access. She works as a research associate for the H2020 5G-Xhaul project, which includes mmWave beamforming, channel estimation, and C-RAN architectures.

Mark Beach
Mark Beach received his doctorate in 1989 from the University of Bristol for research on the application of smart antenna techniques to GPS. He later became a faculty member at the university, and was promoted to senior lecturer in 1996, reader in 1998, and professor in 2003. He was head of the Department of Electrical and Electronic Engineering from 2006 to 2010, and then spearheaded Bristol’s hosting of the EPSRC Centre for Doctoral Training (CDT) in Communications. He manages the delivery of the CDT in Communications, leads research on enabling technologies for the delivery of 5G and beyond wireless connectivity, and serves as the school research impact director. He conducts his research activities through the Communication Systems and Networks Group, so they form a key component within Bristol’s Smart Internet Lab. He has over 25 years of physical layer wireless research experience during which he has embraced the application of spread spectrum technology for cellular systems, adaptive or smart antenna for capacity and range extension in wireless networks, MIMO-aided connectivity for throughput enhancement, and flexible RF technologies for software defined radio modems.
Interference Management in LTE-Based NI Testbed

Supervisors: Professors Mark Beach and Andrew Nix, Dr. Robert Piechocki
Researchers. Mr. Yue Tian and Dr. Vaia Kalokidou
Communication Systems and Networks Group, University of Bristol

Introduction

- Interference management is one of the main challenges of wireless communication networks.
- Interference alignment (IA), as a revolutionary technique, can improve the capacity of MU-MIMO.
- We propose and evaluate a relay-aided IA (RIA) scheme over a low-complexity LTE-based multiuser interference testbed featuring NI USRP devices.

Interference Alignment

- IA exploits the availability of multiple antennas/frequency block/time slots.
- Our goal is to align interfering signals at each Rx into a low-dimensional subspace by linearly encoding signals in multiple dimensions.
- At each Rx, three interferers collapse to appear as two, which enables interference-free decoding in a desired signal subspace.

Relay-Aided Interference Alignment

- RIA can overcome outdated channel state information at the transmitter (CSIT) in source-to-destination channels.
- The base station (BS) designs include beamforming to the relay system, and the relay designs include beamforming to users.
- All Rxs have the same linear combination for interference signals by exploiting current and outdated CSI.

IA From Theory to Practice

- We have built an LTE MU testbed with LabVIEW and USRP-2920 devices and implemented IA algorithms on it.
- We can switch each USRP device, which uses ADC/DAC/RF front ends and drives two antennas (one rx and one tx), between rx’ing and tx’ing mode.
- Different USRP devices can be connected via a MIMO cable to build MIMO/MISO Txs and Rxs.
- A two-antenna BS (laptop) is connected through a TCP/IP Ethernet link to the corresponding USRP device.

MIMO Relay Testbed and LabVIEW Structure

- To realize RIA, we designed a two-user (two antennas each) system with two multiple antenna relays.
- The BS and its desired mobile station (MS) are separately connected to two PCs.
- The CSI of the interfering MS is fed back to the BS, through the Ethernet line, so that the BS can perform interference avoidance precoding.

Interference Mitigation Schemes in the NI Testbed

- We implemented zero forcing (ZF), singular value decomposition (SVD), and signal-to-leakage-and-noise ratio (SLNR) in the testbed.
- All three interference mitigation techniques reduce the impact of interference.
- We computed SLNR, a prior probability that is not always completely accurate, for a precoding matrix. SLNR works optimally when CSI can be easily predicted, such as in a reliable communication environment, and it works poorly in an environment with large CSI fluctuations, such as a busy city or a high-mobility user (car).
- ZF and SVD (block diagonalization) drive the interference power closer to zero.

Conclusions/Future Work

- Build DL distributed cooperative relay testbed.
- Model delayed feedback scenarios (for source-to-destination, source-to-relay, relay-to-destination channels) in RIA communication networks.
- Evaluate performance of RIA in this environment.
- Implement opportunistic IA and topological interference management with NI USRP devices’ multiuser testbed.

References


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