WINLAB Research Summary
June 2013

Wireless Information Network Laboratory (WINLAB)
Rutgers, The State University of New Jersey
www.winlab.rutgers.edu
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Introduction: **Mission & Resources**

- WINLAB founded in 1989 as a collaborative industry-university research center with specialized focus on wireless networking
  - Mission is to advance both research and education in the area of wireless technology (… a topic of fast growing importance across the entire information technology field!)
  - Research scope includes information theory, radio technology, wireless networks, mobile computing and pervasive systems
  - Participation in several major federal research initiatives in the wireless and networking fields - cognitive radio/spectrum, future Internet architecture (FIA), GENI
  - Unique SOE resource with local, national and international recognition and impact

- WINLAB resources in brief:
  - ~25 faculty/staff, most from the ECE and CS departments at Rutgers
  - ~40-50 grad students (80% PhD, 20% MS) – ~50 PhD’s graduated since 2005; ~20 UG internships
  - ~$5M/yr research funding (80% federal, 20% industry); ~10 corporate sponsors from all over the world
  - ~20,000 sq-ft facility, mostly at the Rt 1 Technology Center building (see photo)
  - Unique experimental capabilities including ORBIT testbed (see photo) and WiNC2R cognitive radio
WINLAB: Industry Sponsors 12/12

InterDigital

NEC Empowered by Innovation

HUawei

verizonwireless

Alcatel-Lucent

US Army CECOM

ERICSSON TAKING YOU FORWARD

Aruba networks

QUALCOMM

NiCT Cisco Systems

Nokia Connecting People

intel

InPoint

Semandex

*Research Partners
WINLAB Summary: Research Vision

- Radio everywhere → from ~1B wireless devices in 2005 to ~10B in 2010 → 100B in 2020!
  - Fundamental capacity and scale limits
  - Overcoming spectrum scarcity
  - New technology foundation – cognitive radios

- Wireless – Internet convergence into a single global network as mobile terminals replace PC’s
  - Architectural implications of mobility, disconnection, location, …
  - Wireless “network-of-networks” with heterogeneous radios, multi-hop, etc.
  - Clean-slate protocol architecture centered around mobility & context

- From basic voice/data communications → pervasive computing
  - Wireless as the glue for integrating the Internet with the physical world
  - Importance of geographic location as a key attribute
  - Security and privacy
  - Various application domains – transportation, healthcare, security, industrial automation, …
Status Update: WINLAB Research Targets

**Mobile web services**

- Content- and context-aware protocols, M2M
- Programmable networks, cloud services
- Privacy, HCI, mobile social networks

**Static Spectrum Assignment**

- Spectrum sensing, NC-OFDM
- Spectrum server, cognitive algorithms
- Coordination protocols, ..

**Dynamic Spectrum Assignment**

- ~10x efficiency

**Static MAC Protocols**

- Network MIMO, network coding
- Interference alignment, 60 Ghz,

**Single User MIMO/OFDM**

- Cooperative relay, cross-layer, beam switching, software MAC,

**IP Routing + Cellular Mobility**

- Storage-aware routing, global name resolution, location, vehicular nets
- Privacy/security, ad hoc/DTN routing, ...

**Flexible & Adaptive MAC**

- Next-Gen Gigabit PHY

**Mobility-Centric Internet Arch**

- Content- and context-aware pervasive services

**Content- and context-aware protocols, M2M**

- Programmable networks, cloud services
- Privacy, HCI, mobile social networks

**Network MIMO, network coding, interference alignment, 60 Ghz,**
WINLAB Summary: Research Scope

- Dynamic Spectrum Assignment (DSA)
  - Spectrum policy models and coexistence algorithms
  - Spectrum sensing, databases and protocols for coordination
- “Cognitive” Software-Defined Radio (SDR)
  - Core technology for next-generation wireless systems
  - Flexible, high-performance architecture (WiNC2R, GENI SDR)
- Next-generation wireless & the future Internet
  - Clean-slate mobility-centric Internet architecture (MobilityFirst)
  - New protocol concepts: Storage routing, global name service, ..
  - Mobile network privacy and security aspects
- Pervasive computing protocols & applications
  - Active RFID for object tracking and location determination
  - Geographic protocols for vehicular and sensor networks
- Future wireless networking testbeds
  - ORBIT radio grid and outdoor GENI WiMAX (4G cellular)
  - Cognitive radio networking protocols and testbed (CogNet)
Research Highlights
Cognitive Radio: Secondary Coexistence Methods

- Secondary co-existence an important requirement for white space bands
- Various schemes possible depending on system model
  - Completely autonomous, using performance feedback only
  - Common coordination channel
  - Common Internet based spectrum server
Cognitive Radio: LTE Experiment

- Two heterogeneous LTE based secondary links implemented on an NI based embedded platform
- Performance of a particular Secondary link with respect to coexisting secondary link occupying adjacent frequency bins was evaluated
- Effects on performance due to change in bandwidth and guard band separation between two adjacent secondary links was observed

PI: Predrag Spasojevic
Cognitive Radio: LTE Experiment Results

Bit Error rate (BER) of main secondary link as a function of increasing received interfering Secondary SNR

Effect of Increasing Guard band separation between the interfering secondary and the main secondary transmission on the BER of the main secondary link

PI: Predrag Spasojevic
Inter-network Cooperation

Interaction between managed wireless networks over the back-end wired link for making more efficient use of the spectrum

- **Policy/capabilities**
  - Controller type: C2
  - Information sharing enabled
  - Merge RRM enabled

*Aggregate radio map*
Range of operation: \((x_B, y_B, r_B)\)
Technology type: Wi-Fi
Device list: A1 params, B1 params, ...

*Algorithm & policy negotiation*

*Spectrum info exchange*

*Per device parameters*

Radio device A1
- Type: Transmit/Receive (client)
- Location: \((x_{A1}, y_{A1})\)
- Power, BW, frequency, duty cycle

Radio device B1
- Type: Transmit/Receive (client)
- Location: \((x_{B1}, y_{B1})\)
- Power, BW, frequency, duty cycle

PI: D. Raychaudhuri
Random Deployment Results

- 500 x 500m area
- Min. separation of 50m between APs of same network
- No minimum across networks

2x gains in low rate clients, slight gain in median
Realizing inter-network cooperation

- Inter-network cooperation requires more than just a communication link
- We need integration with the way control plane is implemented in wireless networks

**Major Drawbacks**
- **Closed**: Only the vendor can add features
- **Inflexible**: Mix of distributed/centralized not easy
- **Isolation**: Controller-to-controller interaction is not possible
SDN Approach to wireless control plane

- Introducing flexibility in the wireless control plane by leveraging software defined networking techniques
- Inter-network cooperation translates to inter-controller interactions and setting of flow-rules

Through extension of OpenFlow Match/Action Fields
Through the ControlSwitch framework
Example Usage

1. Inter-network Cooperation:
   
   - Accept Msgs of Type: Monitor, Parameter: Channel, From IP: X
   - Local Agent <-> Control Switch
   - Type of Coordination Agreement
   - Other Control msgs
   - Control Switch <-> Local Agent

2. 3rd Party offloading of selected control plane functions:

   - Set Flow Rule: Forward Client Authentication msgs to IP: X
   - Local Agent <-> Control Switch
   - Controller
   - Other Control msgs
   - Authentication msgs
Example Usage

3. Automatic failover to distributed control from central control:

Controller refreshes rule periodically

<table>
<thead>
<tr>
<th>Match Fields</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Msg Type</td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td></td>
</tr>
<tr>
<td>Port</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Discovery</td>
<td>Forward to Central Controller</td>
</tr>
<tr>
<td>Discovery</td>
<td>Forward to neighbors (IP1,IP2)</td>
</tr>
</tbody>
</table>

Higher priority but shorter expiry time

4 AP-4 client topology

Switch between local & centralized channel assignment
Rechargeable Networks: Optimal Retransmission Policies

- Energy replenishment rate is stochastic and environment-constrained
- Rechargeable battery has a long life but its energy should not be abused
- Message transmission carries different rewards

Our goal is to maximize the average reward rate by selective transmission.
Rechargeable Networks: Continuous-Time Markov Model for Battery with Capacity \(N=5\)

Hybrid Energy Replenishment Modeled by Poisson Process

- Characterizing a transmission policy by a set of state-dependent (energy and capacity aware) thresholds \(\{\tau_{N,i}^{*}\}, i=1, 2, \ldots N\)
- Determining “optimal” thresholds by invoking the “termination rule” of Howard’s policy improvement algorithm
Network Coding: DE Framework for Cross-layer Resource Allocation in RNC

- Model RNC as a dynamical system:

\[ \dot{V}_K = \sum_{i \notin K} z_{i,K} (1 - q^{V_K - V_{i \cup K}}), \quad \forall K \subseteq N \text{ and } K \neq \emptyset \]

- Hyperarc capacity of \((i, K)\):

\[ z_{i,K} = \lambda_i P_{i,K} \]

DE framework closely models rank evolution of RNC in terms of PHY and MAC parameters.

Cross-layer Design problems

Solving systems differential of equations

Appropriate boundary conditions
Network Coding Aware Power Control

- Without Power Control (PC), throughput is a constant
- With PC: the instant throughput is improved compared with no PC case
- With PC: throughput converges around $t=60\text{ms}$
- Each node Tx at 1 pkt/ms, min cut between src. and dst. is 1 pkt/ms

RNC with PC achieves optimal throughput!
Bandwidth Exchange: Framework for Enhancing Performance of CR Networks

Technical Significance
- Use of transmission bandwidth as a flexible resource in cooperative forwarding
- Allows dynamic and opportunistic assignment of non-contiguous portions of spectrum to nodes
  - Alternate use in transmission time slot exchange

Approach and Accomplishments
- Proved the convexity/concavity of the optimization problem formulations
- Provided a distributed cooperative pair selection algorithm using graph theory
- Compared the performance of bandwidth exchange with direct transmission scenario
- Implemented time exchange algorithm in software defined radio (USRP2) nodes of the ORBIT testbed.

In Progress:
- Joint resource allocation, scheduling and routing in cognitive radio enabled multi-hop wireless backhaul

Impacts
- Trades off between –
  - Throughput gain
  - Power savings

Office of Naval Research Grant
PI: Narayan Mandayam
Testbed Results of Time Exchange

- Pick 4 USRP nodes of ORBIT
- 1, 2 & 3 are users. Node 0 is the base station.
- Assign 1s orthogonal time slot to each node
- ORBIT is used as the global control plane
- Node 1 & 3 get selected as the optimal cooperative pair through maximum matching
- Node 1 & 3 cooperate and improve goodput through proportional fair objective
- Node 2 transmits with the same goodput
EDMAC: An Enhanced Directional MAC Protocol for 60GHz Networks

- In 60GHz networks, transmitters and receivers employ directional antennas and point their main beams toward each other to overcome high propagation losses and achieve high data rates.

- Problems can be solved if nodes do not employ exponential backoff mechanism and use the same fixed contention window if they send to the same receiver.

- For a network with $n$ senders and one receiver, from analysis we obtain the channel throughput $S$ where $S = \frac{P_s T_{\text{data}}}{P_s (T_{\text{transmit}} - T_{\text{RTS}}) + E[T_c] + \frac{1}{n \lambda}}$.

- $T_{\text{transmit}}$, $T_{\text{RTS}}$, and $T_{\text{data}}$ are constant system parameter and $\lambda$ is the packet arrival rate of each node. The maximum channel throughput is achieved when $S = \max$. Since we only related with $n$, we can find the optimal contention window $W$.

$$E[T_c] = \left( e^{n \lambda T_{\text{RTS}}} - 1 \right) \frac{n}{n \lambda}$$

- CSMA based directional MAC (DMAC) protocols suffer from the “deafness” problem which causes unfairness and low channel utilization.

$$\lambda = \frac{1}{(W + 1) T_{\text{slot}}} \frac{1}{2}$$

$$n \lambda T_{\text{RTS}} = 0.5$$

$$n = \frac{4 T_{\text{RTS}}}{T_{\text{slot}}} \frac{n-1}{n}$$

PI: Roy Yates
EDMAC: An Enhanced Directional MAC Protocol for 60GHz Networks

- Throughput model validation using ns-2

Scenario 1: Two hops scenario: A UDP flow from node S to node D via relay node R.

EDMAC: Receiver calculates $W$ based on number of senders $n$ and inform its sender. Sender store $W$ in its neighbor tables which guarantees nodes send to the same receiver use same contention window size $W$.

Scenario 2: Multi-hops scenario: A TCP or UDP flow from node S to node D via multiple relay nodes.

Performance evaluation using ns-2

PI: Roy Yates

<table>
<thead>
<tr>
<th>ID</th>
<th>Direction</th>
<th>Tx W</th>
<th>Rx activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0</td>
<td>1</td>
<td>Inactive</td>
</tr>
<tr>
<td>C</td>
<td>45</td>
<td>8</td>
<td>Inactive</td>
</tr>
</tbody>
</table>

Example of a neighbor table
Study of Coexistence of Mobile-Fixed AP

Basic Idea
• Study of mobile WLAN hotspot which provides cellular-WiFi tethering services to personal devices.

Objectives of the study
• Heterogeneous traffic condition analysis to model coexisting fixed and mobile WLAN hotspot with saturated-unsaturated traffic conditions due to limited backhaul capacity at mobile WLAN
• Proposal of Adaptive Channel Assignment (ACA) technique to mitigate interference and increase the data throughput at mobile APs.
• Study of effect of mobile speed to further enhance throughput performance due to ACA

Fig. Co-existence scenario of fixed and mobile AP where a user travelling with mobile WLAN from point A to B can be in the range of number of fixed WLAN.
Performance of Mobile AP

**Automatic Channel Assignment (ACA) algorithm**: Mobile AP scans WiFi channels every few seconds and selects the channel which is least crowded in the carrier sense range.

Fig. Throughput at mobile AP as function of number of fixed APs

Note: With application of ACA, maximum gain in throughput is 1.24 Mbps achieving up to 42% of percentage throughput gain.

Fig. Throughput at mobile AP (Mbps) as a function ACA scanning period when no. of fix AP = 50 and assuming channel load is determined in total time 200ms.

Note: Performance is evaluated for mobility speed $s = \{10, 20, 40, 60\}$ mph.
Scenario-based radio channel emulator

- Current RF matrix implementations for emulating channels are not able to support requirements of many tactical waveforms:
  - Dynamics: Many scenarios will involve communicators moving very rapidly (e.g. communications involving jets)
  - Broadband: It is desirable to emulate channels up to 250MHz of bandwidth
  - Multi-party communications: It is desirable to be able to study the performance of an N-to-N communication setting

- WINLAB collaborated with dBm and DSCI on a Navy STTR grant to design an N-to-N broadband RF channel emulator
  - Approach involves implementation using an FPGA architecture
  - WINLAB provided methods to reduce computational complexity while maintaining emulation fidelity
Sensor-assisted anomaly detection for detecting manipulation and exploitation

- **Network Structure for Anomaly Detection**
  - Primary (authorized) transmitter is stationary
  - Distributed detection by a network of sensors that collaborate locally.

- **Significance Testing**
  - Test statistic $T$: a measure of observed data
  - Acceptance Region $\Omega$: we accept the null hypothesis if $T \in \Omega$
  - Significance level $\alpha$: probability of false alarm

- When a channel is dedicated to a single authorized user we can try to distinguish between single and multiple transmissions
  - Formulate a decision statistic that captures the characteristics of the received power in the normal case

$$Y_n = Y_0 - 10\gamma \log_{10}(d_n/d_0) + Y_{R,n}$$
Detecting jamming against the collected system is complicated by normal interference

- Normal Interference in Mobile Networks
  - Experiments have shown that the hidden terminal problem remains in spite of MAC-layer collision-avoidance (e.g. a transmitter outside of the physical carrier sensing range can still cause interference).
  - It is equivalent to a low-power jamming attack.

- Other jamming attacks, such as reactive attacks, require different detection mechanism

- Sender-oriented detection of jamming can utilize network ACKs and signal levels to detect jamming

- AER-RSS signal space consists of three regions
  - Interference-free: no hidden terminal
  - Normal interference: caused by legitimate hidden terminals
  - Intentional interference: malicious jamming
Non-quantum photonic secret key establishment

- Secret key establishment is fundamental to supporting cryptographic services (confidentiality & authentication)
- The photonic layer can be a rich source for establishing keys between two entities
  - Quantum Cryptography is the standard example, but this poses serious engineering challenges
  - Can one optically establish keys without resorting to quantum physics?
- Answer: Yes
  - Prototype design using large-scale Mach Zehnder interferometer

- Result:
  - Alice and Bob create correlated sources, while Eve is uncorrelated
  - Distillation and privacy amplification finalize the process, creating reliable crypto keys!
DARPA: RadioMAP Task 2, Management of RF Network and Tasking Infrastructure (MARTI)

**Proposal Team:** Applied Communication Sciences
WINLAB, Rutgers University
Carnegie Mellon University

**Research Goals:** A distributed system executing on participating RF devices that performs reception, transmission and local processing tasks on behalf of RadioMap applications:

- Without manual intervention
- Subject to available resources and limited impact on the primary mission of the device.

Software that intelligently assigns tasks to RF devices and collects results on behalf of applications.

- Trading off probability of success and overhead
- Provides standardized mechanisms for tasking
- Provides standardized reporting mechanisms and formats

**Modularity and Layering**

Any RF device should be able to perform tasks for any application without customizing MARTI infrastructure
RF Devices, Applications.
EARS: Collaborative Research: Big Bandwidth: Finding Anomalous Needles in the Spectrum Haystack

Proposal Title: EARS: Collaborative Research: Big Bandwidth: Finding Anomalous Needles in the Spectrum Haystack
Proposal Numbers: 1247864 & 1247298
PI Names: Wade Trappe (Rutgers)
Larry Greenstein (Rutgers)
Paul Prucnal (Princeton)

Research Goals: The goal behind the project is to develop a suite of tools that can facilitate the detection of improper usage of radio spectrum. To accomplish this, the project involves the following research goals

*Develop Algorithms and Hardware for a Single-Scanner.* The project explores how a single scanner: Should allocate its scanning strategy to best detect an unknown signal.
Develop sub-Nyquist techniques that allow digital scanning of wide bandwidths
Develop RF photonic scanning that allows for scanning of wide bandwidths

*Develop Algorithms for Multiple-Scanners.* Multiple sensors allows for coordinated scanning. The project will examine how scanning should be allocated across sensors to detect anomalous transmissions.

Potential Payoffs: Spectrum is a valuable resource that, if properly used, will spur economic growth, but if used improperly could hinder economic growth. The proposed project, if successful, will have the following payoffs:

*Provide mechanisms by which the government can ensure spectrum is used properly by those who have negotiated access rights.*
*Provide algorithms for mapping spectral activity across a large time, frequency and spatial domain.*

New algorithms and hardware will advance knowledge in sampling ultra-wide bandwidth, allowing for a comparison between state-of-the-art in sub-Nyquist and RF photonics.

Impact education as the project is inherently multi-disciplinary, and will lead to new curricular efforts between security, wireless and photonics.
TO – comparing wireless sensor boards

Classic

Transmit-Only
TO-PIP(2013)

Antenna
Radio
Micro controller
Battery

Pls: Rich Martin, Rich Howard & Yanyong Zhang
Building a TO MiM receiver from 2 single receivers

• If I see a preamble, tell other radio to start
  – If the second packet is stronger, the other will receive it.

• Tell other radio when I recognized a packet correctly
  – Allows aborts of a bad packet, restart to catch a new one.
TO Channel Utilization at Scale

[Graph showing channel utilization as a function of the number of transmitters for different numbers of receivers and comparison with Low Power Polling and CSMA/CA with max 3 CCA.]
TO Experiment with 500 Transmitters

Bundle of 10 transmitters
MiM Receiver
Theoretical predictions vs. experiment
Connecting TO networks via the Owl Platform

- Sensors connect to an intermediate layer that hides details
- Solvers build higher-level representations from low-level ones
- A uniform model of the world allows sharing
- Applications run in standard environments in the cloud
Development of a V2V Scalability Simulator

- Develops a Dedicated Short Range Communications (DSRC) simulator for the Crash Avoidance Metrics Partnership Vehicle Safety Communications 3 consortium
- Uses field test data from hundreds of DSRC equipped vehicles to develop and calibrate simulation models
- Aims to accurately predict V2V communication performance in very dense, interference-limited scenarios.
Distinguishing Users with Capacitive Communications

- Need for better user identification and authentication techniques on post-pc devices
- Approach: a wearable token can transmit short codes of data through capacitive touch screens

Detection Rate (%)

<table>
<thead>
<tr>
<th>Bits</th>
<th>2 bits/s</th>
<th>3 bits/s</th>
<th>4 bits/s</th>
<th>5 bits/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pl: Marco Gruteser
Smart Meter Privacy and Security

- Analyzed existing meters with USRP software radio
- Meters broadcast every 30s
- Able to spoof readings and eavesdrop on hundreds of meters

PI: Marco Gruteser
Visual MIMO Networks

- Explores MIMO free space optical communications with camera receivers (e.g., download billboard adds by pointing phone camera at it)

PI: Marco Gruteser
User Privacy: Crowdsourcing for Privacy

- Almost nobody reads privacy policies
  - We want to install the app
  - Reading policies not part of main task
  - Complexity of reading these policies (boring!!!!)
  - Clear cost (my time) for unclear benefit

- Crowdsourcing can mitigate these problems

- But what to crowdsource here?
  - Our idea: expectations and misconceptions
Social Networks: Crowdsourcing of Physical-World Tasks with Myrmex

- **Approach:**
  - Opportunistically offering location-constrained tasks to people
  - “Mechanical turk for the real-world”

- **Results in:**
  - Stronger communities
  - Everybody saves
Analysis of Social Networks: Modeling Confusion

- Users seek information from a primary source
- Users receive auxiliary information from several other sources
  - Information from some of the other sources could contradict the one from the primary source
  - Causes confusion for the receiving user
Network switches from highly aggressive to highly passive very quickly (i.e., is unstable) when users place distributed trust.
Cognitive Experiments at Scale

- ORBIT radio grid testbed currently supports ~10 USRP and ~32 USRP2 (GNU) radios, 100 low-cost spectrum sensors, WARP and GENI CR-Kit platforms
- Plan to reach ~64 “cognitive radio” nodes (Q4 2013)

**Radio Mapping Concept for ORBIT Emulator**

- 500 meters
- 300 meters
- Office
- Suburban

**400-node Radio Grid Facility at WINLAB Tech Center**

**Programmable ORBIT radio node**

**Current ORBIT sandbox with GNU radio**

**URSP CR board**

**ORBIT radio grid testbed**

**Pis: Ivan Seskar, D. Raychaudhuri**

**WINLAB**
Why (CRKIT) Framework?

Focus on Creativity, not Engineering Complexity:
Split Baseband in two domain spaces:
- **Dynamic** – Swappable Communication APPs (creative problem)
- **Static** - Open-sourced System-on-Chip (complex engineering problem)

CRKIT = make real-time and wide-tuning radio a viable solution for large scale experiments.

WDR from Radio Technology Solutions

_Pis: Ivan Seskar, D. Raychaudhuri_
What is GENI CRKIT Framework?

**Baseband Processor:**
- FPGA-based off-the-shelf board
- Control up to 4 full-duplex wideband radios
- FPGA-based System-on-Chip (FSoC) implementation

**Wideband Radio (WDR) Module:**
- Wideband: tunable range 300MHz to 7.5GHz
- 25MHz bandwidth
- 50Msps 12-bit ADC, 200Msps 12-bit DAC
- 50us switch between frequencies
Spiral II GENI project: CR kit HW

- Range of baseband FPGA platforms
- 4 (2) configurable radio modules for phased or smart antenna applications with
  - Phase I: Each module allows two 25 MHz bands from 300 to 6000 MHz
  - Phase II: Each module allows two different 300 MHz bands from 100 to 7500 MHz
- Each module supports independent full duplex operation.
- 1 usec RF frequency switching time
- Switched antenna diversity for both TX and RX channels.
CRKIT Programming Model

HOST

Network

CRKIT

Application development

GUI
  - Java, C#
  - System Debugging
  - System Test

Algorithm
  - C

DSA

Comm. APP
  - VHDL/Verilog
  - Mathworks Simulink

CRKIT development

C

Embedded SW

- IP Networking
- HW Configuration
- Host CMD Parsing
  - DHCP/ARP
  - Lookup Tables/RF
  - ETH/VITA

System Test

System Debugging

CR

DSA

Algorithm

Comm. APP

CRKIT development

C
WiSER Baseline Hardware

ZedBoard baseboard (Zynq XC7Z020 device)
- Dual-core ARM® Cortex™-A9
- 256 KB on-chip RAM
- Gigabit Ethernet, 2x SD/SDIO, USB, CAN, SPI, UART, I2C
- 512 MB DDR3, 256 Mb QSPI Flash
- 85K Logic Cells, 106K FF
- 220 Programmable DSP Slices (18x25 MACCs)

Analog Devices FMC RF Front-end
- Software tunable across wide frequency range (400MHz to 4GHz) with 125MHz channel bandwidth (250MSPS ADC, 1GSPS DAC)
- RF section bypass for baseband sampling
- Phase and frequency synchronization on both transmit and receive paths
Future Framework Architecture

1. **Dual-core ARM processors**
   - Linux support
   - Dual AXI bus architecture
   - Independent Data and Control traffic

2. **Independent APP sampling rates**
   - Support Multirate and Multi-APP systems
   - Decoupling of APP clock domains from overall Framework.
   - Permits Spectrum Sensing APP + Communication APP in same architecture

3. **Applications**
   - Reuse previously designed APPs
   - NC-OFDM
   - Spectrum Sensing

4. **RF**
   - 400MHz to 4GHz tuning range
   - 125MHz Channel Bandwidth (250MSPS ADC, 1GSPS DAC)
   - Full-duplex
ZipReel Inc.
Cloud video processing

**INPUT:** High volume, pro-generated video

**OUTPUT:** Fast delivery of high-quality, multi-format processed video

“Processing”
- Transcoding
- Format conversion
- Object search
- Feature insertion

Linear scaling with compute units

Professional-grade quality

Delivery via CDNs

Seeded by an NSF I-Corps grant
- Early stage incubation at WINLAB

Contact: kishore.ramachandran@zipreel.com
Zipreel cloud transcoding applications

Netflix Encodes Every Movie 120 Different Ways...streams to 900 different types of devices... - gizmodo.com

Broadcasters (e.g. ESPN) + Cable/Telco operators (e.g. Comcast) want to replicate tech. but buy-rather-than-build approach

2-3 days to generate 120 formats for one video! - Netflix @ AWS Re-invent

Content owners lose significant ad-revenues for each additional day of processing

Pain point: how to process high video volumes fast?
Zipreel Cloud Video Technology

- **Before**
  - Approach: process videos on commodity clusters in software
  - Challenge: making the cluster interconnection network scale
  - Solution: hierarchical network topology design and/or efficient use of multicasting

- **After**
  - Expected speed
  - Hierarchical-multi-split
  - Multicast-based design
MobilityFirst Update
MobilityFirst Update: Architecture Features

- Named devices, content and context
  - Human-readable name
- End-Point mobility with multi-homing
- Storage-aware Intra-domain routing
- Connectionless Packet Switched Network with hybrid name/address routing
- Network Mobility & Disconnected Mode
- Routers with Integrated Storage & Computing
  - Edge-aware Inter-domain routing
  - Hop-by-hop file transport
- In-network content cache
- Service API with unicast, multi-homing, mcast, anycast, content query, etc.

- Heterogeneous Wireless Access
  - Multi-homing
  - End-to-end content cache
- Network Mobility & Disconnected Mode
- Ad-hoc p2p mode
- Human-readable name
- Strong authentication, privacy
  - 11001101011100100…0011
  - Public Key Based Global Identifier (GUID)
- Storage-aware Intra-domain routing
- Network Mobility & Disconnected Mode
- Ad-hoc p2p mode
- Human-readable name
- Strong authentication, privacy
  - 11001101011100100…0011
  - Public Key Based Global Identifier (GUID)

PI: D. Raychaudhuri
MobilityFirst Update: Protocol Stack

- **NCS**
  - Name Certification & Assignment Service
- **GNRS**
  - Global Name Resolution Service
- **MF Routing Control Protocol**
- **GUID Service Layer**
- **GSTAR Routing**
- **MF Inter-Domain**
- **Hop-by-Hop Block Transfer**
- **Switching Option**

**Control Plane**
- **Link Layer 1 (802.11)**
- **Link Layer 2 (LTE)**
- **Link Layer 3 (Ethernet)**
- **Link Layer 4 (SONET)**
- **Link Layer 5 (etc.)**

**Data Plane**
- **App 1**
- **App 2**
- **App 3**
- **App 4**

**Socket API**

**Optional Compute Layer Plug-In A**

**Network**

**Winlab**
MobilityFirst Update: MF GUID/Storage Router

- Hybrid name-address based routing in MobilityFirst requires a new router design with in-network storage and two lookup tables:
  - “Virtual DHT” table for GUID-to-NA lookup as needed
  - Conventional NA-to-port # forwarding table for “fast path”
  - Also, enhanced routing algorithm for store/forward decisions

GUID –based forwarding
(slow path)

Look up GUID-NA table when:
- no NAs in pkt header
- encapsulated GUID
- delivery failure or expired NA entry

<table>
<thead>
<tr>
<th>GUID</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>11001..11</td>
<td>NA99,32</td>
</tr>
</tbody>
</table>

Network Address Based Forwarding
(fast path)

Look up NA-next hop table when:
- pkt header includes NAs
- valid NA to next hop entry

<table>
<thead>
<tr>
<th>Dest NA</th>
<th>Port #, Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA99</td>
<td>Port 5, NA11</td>
</tr>
<tr>
<td>NA62</td>
<td>Port 5, NA11</td>
</tr>
<tr>
<td>NA32</td>
<td>Port 7, NA51</td>
</tr>
</tbody>
</table>

Store when:
- Poor short-term path quality
- Delivery failure, no NA entry
- GNRS query failure
- etc.
MobilityFirst Update: Dual Homing Example

Multihoming service example

Router bifurcates PDU to NA99 & NA32 (no GUID resolution needed)

GUID
NetAddr = NA99

GUID
NetAddr = NA32

Send data file to “John Smith22’s laptop”, SID= 129 (multihoming – all interfaces)
MobilityFirst Update: Realizing the GNRS

- Fast GNRS implementation based on DHT between routers
  - GNRS entries (GUID <-> NA) stored at Router Addr = hash(GUID)
  - Results in distributed in-network directory with fast access (~100 ms)

Global Prefix Table

<table>
<thead>
<tr>
<th>Prefix</th>
<th>AS #</th>
<th>Next-hop address</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/8</td>
<td>1</td>
<td>8.8.8.8</td>
</tr>
<tr>
<td>67.10/16</td>
<td>55</td>
<td>67.10.1.1</td>
</tr>
<tr>
<td>44/8</td>
<td>101</td>
<td>44.32.1.1</td>
</tr>
</tbody>
</table>

Internet Scale Simulation Results
Using DIMES database

Pls: Yanyong Zhang, Rich Martin, Kiran Nagaraja
Building Mobile Networks with MF

- MobilityFirst enables both tightly and loosely coupled architectures for mobile networks

**Current Mobile Networks**

- Planned Deployment
- Licensed Spectrum
- Fine-grained Managed QoS
- Centralized Mobility Support
- Homogeneous Topology
- Network-wide Authentication

**Loosely Coupled Network-of-Networks**

- Ad-hoc Deployment
- Unlicensed Spectrum
- Coarse-grained Managed
- In-network Mobility Support
- Heterogeneous topology
- Authentication at APs

*Pis: Roy Yates, D. Raychaudhuri*
MobilityFirst Update: GNRS + Storage Routing Performance Evaluation

- Detailed NS3 Simulations to compare MF with TCP/IP
- Hotspot AP Deployment: Includes gaps and overlaps
- Cars move according to realistic traces & request browsing type traffic (req. size: 10KB to 5MB)

Empirical CDF of file transfer time

![File Transfer Time CDF](image)

Single Car: Aggregate Throughput vs. Time

![Throughput Graph](image)
MF Multipath Performance Result

- Multipath service with data striping between LTE and WiFi
- Using backpressure propagation and path quality info

![Diagram showing GNRS Server, data transmission, and Net Addr Path Quality]

![Graph showing Aggregate Throughput (Mb) vs. Time (sec) for MobilityFirst Multihoming, Oracle Application, Using only LTE, and Using only WiFi]
M2M Architecture over MobilityFirst FIA

MobilityFirst Core Network eliminates overlay CDN
  High efficiency: no overlay, DTN transport, in-network multicast
  Security & policy: access control via GNRS
Overlay M2M Server is only used for business operation
  Handle Publish/Subscribe, for sensors and apps, respectively
  Control M2M data delivery via GNRS that has Sensor GUID -> App GUID mapping
Gateway is lightweight and flexible
  Bridge WSN and Internet: fixed or mobile, dedicated or spontaneous
  Perform only one hop forward instead of end-to-end delivery

Pis: Jun Li, D. Raychaudhuri
MobilityFirst M2M Prototype

Use Case: GUID identified sensor data is collected via a mobile gateway and delivered over MobilityFirst FIA, using in-network multicast to multiple subscribing applications

System Components
- 2.4GHz Wireless Sensors (temperature, humidity)
- An android phone used as Mobile Gateway with USB reader
- A web server at public domain runs as the M2M server
- Three mobilityFirst Routers and a GNRS server run on WINLAB Orbit network
- Two android tablets run as subscribing applications

Pics: Jun Li, Kiran Nagaraja, D. Raychaudhuri

2013/12/23
MobilityFirst Proof-of-Concept Prototype

Click-based MF Router
- Storage-aware routing (GSTAR)
- Name resolution server (GNRS)
- Reliable hop-by-hop link transport (Hop)

Android/Linux MF Protocol Stack
- Network API
- Hop
- Dual homing (WiFi/WiMAX)

PI: Kiran Nagaraja
MF Router Architecture and Services Abstraction

PI: Kiran Nagaraja

Forwarding Engine Abstraction

- Message Relay
- Services Registry
- Name Resolution
- Topology Discovery Manager
- Events
- Callback Manager
- Register
- Callback

Forwarding Engine

- Services Table
- Name Resolution Table
- Forwarding Table
- Configurations and Execution State

Other Services
(E.g., Compute, Content Caching)

Name Resolution Request
Forwarding Table Updates
Get/Set Parameter
Exceptions

Register Service
Register Name Res. Callback
Register Topology Callback
Register Exception Callback

MF Pkts To/Fro Services

Interface X
Interface Y
Interface Z
Fast GNRS Implementation

- Redesigned GNRS for modularity and support for multiple networks
- Simplified GNRS engine
  - Picks up requests from network
  - Passes requests to database
  - Returns mappings to requestors
- Mapping Data Access
  - in-memory database for fast updates/lookups,
  - external database for persistency
- Network Access
  - Supports IPV4, IPV6, MF networks, etc.
  - Each network requires different network address hole solution

PI: Yanyong Zhang
MobilityFirst Update: Open-Flow/SDN Implementation

**MF Protocol Stack**
- Protocol stack embedded within controller
- Label switching, NA or GUID-based routing (incl. GNRS lookup)
- Controllers interact with other controllers and network support services such as GNRS

**Logically Centralized Control**

- **PI:** Kiran Nagaraja
MobilityFirst Update: NetFPGA-based High Speed Router

Objective: Explore hardware design challenges for FIA routing platforms

- 160-bit GUID LUT
- Handling large GUID-space: Hierarchical cache-type organization for GUID LUT
- Host-based GNRS lookups
  - Requires packet holding
- Explore design space for combined workloads and custom router fn. (core/access)
  - Manage buffer resources (hold vs transit)
  - Compute resource allocation

Pis: Yanyong Zhang, Ivan Seskar

4 x 1G or 4 x 10G
SRAM (4.5 or 27 MB)
DRAM (64 or 288 MB)
MF Router Prototype on FLARE SDN Platform from U Tokyo (Nakao)

Objectives

- Multi-site deployment of MobilityFirst routing and name resolution services
  - Impact of large RTTs on MobilityFirst network protocols
- High performance evaluation of MobilityFirst delivery services on FLARE - 1Gbps, 10Gbps
  - Augmented Click router elements compiled down to FLARE native
- Evaluation of FLARE platform for design and evaluation of next-generation network protocols
- Demo at GEC-16, March 2013
MF Multi-Site GENI Deployment – Demo at GEC-16, March 2013

- Salt Lake, UT
- Chicago, IL
- Madison, WI
- Ann Arbor, MI
- Cambridge, MA
- N. Brunswick, NJ
- Tokyo, Japan
- Los Angeles, CA
- Palo Alto, CA
- Atlanta, GA
- Clemson, SC

MobilityFirst Routing and Name Resolution Service Sites

- Long-term (non-GENI)
- Short-term
- Wide Area ProtoGENI
- ProtoGENI

Rutgers
WINLAB
FIA-NP Proposal

- Next Phase proposal ($5M) submitted June 7, 2013
- Research Focus on evolving MF architecture to services and trial deployments
  - Content, cloud, context/M2M and mobility services
  - SDN implementation, router platforms, deployment strategies
- Also, three real-world trials (“Network Environments”) for early adopter validation and evaluation
  - Mobile Data Services deployed on 5Nines ISP network in Madison, WI
  - Content & cloud services deployed on PennREN optical network with PBS stations as end users
  - Context-aware emergency warning system (CASA)
- Funding decisions expected by end of 2013
MobilityFirst Update: FIA-NP Trials

NE1: Mobile Data Service Trial with 5Nines (ISP) in Madison, WI
MobilityFirst Update: FIA-NP Trials

NE2: Content Services Trial with PennREN/PBS in PA
MobilityFirst Update: FIA-NP Trials

NE3: Context-Aware Emergency Notification System (CASA)
Web Sites for More Information:

- WINLAB:  www.winlab.rutgers.edu
- ORBIT:  www.orbit-lab.org
- MobilityFirst:  http://mobilityfirst.winlab.rutgers.edu