Future Directions in Wireless
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D. Raychaudhuri
WINLAB, Rutgers University
ray@winlab.rutgers.edu

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Introduction
Next-Gen Wireless: System Vision

- Next-gen mobile network with significantly increased capacity and performance for emerging applications:
  
  - Mobile Data (cellular, hetnet)
  - Vehicular Networks
  - Content Delivery
  - Cloud Services
  - Emergency Networks
  - Internet-of-Things
  - Faster Cellular Radio ~1-10 Gbps, ~1000x Capacity
  - Low-Latency/ Low-Power Access Network For Real-Time IoT
  - New Frequencies & Dynamic Spectrum Access
  - Next-Gen Mobile Network & Cloud
  
  Enabling Technologies

WINLAB
Next-Gen Wireless: Architectural Trends

New possibilities in networking enabled by changing technology platforms & architectural concepts

- Cellular
  - 3GPP mobile network
  - Ad Hoc Mesh
- IP
  - IP inter-network
  - WiFi Radio
  - Click Software Router
  - Router/Switch Hardware
  - 100M/1G Ethernet
  - WCDMA & LTE Radio Access
- Mobile-Centric Internet
  - SDN Mobile/Cloud RAN
  - Veh Net, Ad Hoc, etc.
  - Open LTE Base Station
  - Software-Defined Radio (SDR)
  - Programmable Router
- Content-Centric Network
  - Customizable Wide-Area Networks (e.g. CDN, cloud)
  - SDN Enterprise: Ethernet + WiFi
  - Virtual Machine (VM)
- 5G
  - OpenFlow (SDN) Switch
  - 10G/100G Ethernet

Circa 2010

Circa 2020

Circa 2030
Next-Gen Wireless: System Architecture
Concept based on SDN, Cloud, ..

- Architecture driven by innovations in network & cloud technologies:
  - Fundamentally new approaches to radio access and core network design (clean slate Internet, SDN, CRAN, SDR, NFV, …)
  - Potential to preempt top-down linear/compatible evolution from 4G to 5G..
**Next-Gen Wireless: Technical Challenges**

- **Faster Cellular Radios Access**
  - ~1-10 Gbps
  - ~1000x capacity

- **Low-Latency/ Low-Power Access Network**
  - For Real-Time IoT

- **New Spectrum & Dynamic Spectrum Access**
  - 60 Ghz & other new bands
  - New unlicensed/shared spectrum

- **Next-Gen Mobile Network**
  - Mobile network redesign
  - Clean-slate Mobile Internet
  - Software Defined Networks
  - Open wireless network APIs
  - Mobile edge computing
  - Virtualization, NFV

**Key Technologies**

- Wideband PHY
- Massive MIMO
- Cloud RAN arch
- mmWave (60 Ghz)
- Multi-Radio access
- HetNet (+WiFi, etc.)
- Custom PHY for IoT
- New MAC protocols
- RAN redesign
- Light-weight control
- Control/data separation
- Network protocol redesign
- Dynamic spectrum access
- Spectrum sharing techniques
- Non-contiguous spectrum
- Network/DB coordination methods
Network-Assisted Dynamic Spectrum Access
Dynamic Spectrum: Dense deployment of small cells with multiple technologies

Potentially destructive interference between multiple independent networks in a given area
Dynamic Spectrum: Alternative Approaches for Coordination

- Agile/cognitive radio autonomous sensing at radio devices to avoid interference
- Spectrum assignment server (SAS) – visibility via centralized DB for potentially interfering networks and/or global assignment
- Distributed inter-network collaboration – peering protocols for decentralized spectrum assignment algorithms
Dynamic Spectrum: Distributed Inter-Network Coordination Architecture (SAVANT)

- Autonomous networks exchange control info over common control plan
- BGP like distributed control model with an option for local policy
- Can also work with more centralized cloud services such as spectrum broker

Cloud-based regional aggregator level

WD controller level

Radio device level

Joint work with Prof. J. Rexford, Princeton U
Dynamic Spectrum: Fully Distributed Algorithms

Distributed Bellman-Ford based algorithm avoids centralized control
- Maintains state vector of degrees of visibility of 1-hop neighbors at each controller
- Determines relative order of the controller based on state vector

WD Controller Connectivity: Graph $G(V, E)$
- Vertex $V$: Controller
- Edge $E$: overlapping radio coverage
Dynamic Spectrum: Logically centralized coordination model using cloud aggregator

Input from radio devices: Location, channel gain, frequency

Objective: Maximize sum throughput
Network policy: non-zero throughput at each link

Wireless Domain Controller: Coordinated Channel Assignment, Power Control, Channel Access Time Division

Output: Optimized channel, power, access time assignment at both Wi-Fi and LTE networks

Input from neighboring controllers: radio MAP and channel assignment for networks in overlapping radio coverage

Cloud aggregator – WD Controller interaction

Radio devices – WD Controller interaction

WD Controller – neighboring WD Controllers interaction
Dynamic Spectrum: Logically Centralized Optimization

Objective: Downlink power control optimization using Geometric Programming

\[
\text{maximize } \prod_{i \in W} (1 + \beta_w S_i)^{a_w a_i} \prod_{j \in L} (1 + \beta_l S_j)^{a_l}
\]

subject to \(\alpha_w (1 + \log_2 \beta_w S_i) \geq r_{i,\text{min}}, \ i \in W,\)
\(\alpha_l (1 + \log_2 \beta_l S_j) \geq r_{j,\text{min}}, \ j \in L,\)
\[\sum_{k \in M_i^b} P_k G_{ik} + \sum_{j \in L} P_j G_{ij} + N_0 \leq \lambda_C, \ i \in W,\]
\(0 \leq P_i \leq P_{\text{max}}, \ i \in W, L\)

Controlling variables: \(P_i, \ i \in W, L\)

where
\(S_i : \text{SINR at link } i\)
\(a_i = \frac{1}{(1 + |M_i^a|)}, \ M_i^a : \text{Set of Wi-Fi APs in the CSMA range of AP}\)
\(b_i = \frac{1}{(1 + \varsigma |M_i^b|)}, \ M_i^b : \text{Set of Wi-Fi APs in the interference range of AP}\)

Maximize sum-throughput across Wi-Fi and LTE

Minimum SINR requirement for data rate transmission

CCA threshold requirement at Wi-Fi

Range of Tx power

Tx power
Dynamic Spectrum: Logically Centralized Coordination of WiFi and LTE-U

Wireless SDN
SDN Wireless: Future Cellular/5G Arch

- Radio Resources (LTE BS, WiFi AP, etc.)
- also, general purpose Adaptive SDR devices
- Mobility RRM
- Virtual Net Service Mgmt
- Service Applications on Cloud or Operator Machines
- Distributed Control Plane (resource discovery, Bootstrapping, topology control, routing)
- Wired + ad hoc wireless connectivity

Joint work with Ivan Seskar, Rutgers U
SDN Wireless: **Control Plane Concept**

- 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

![Diagram of Network OS with wireless abstractions](image)
SDN Wireless: LTE Open BTS
SDN Wireless: Basic Design

- Interpret wireless control messages as flows
- BS/AP uses Match/Action rules to forward incoming and outgoing control-flows
- Control traffic can be forwarded to/from other BSs or central controller
- Local SDN based controller for low latency actions
SDN Wireless: Application to Dynamic Spectrum Coordination

Inter-network cooperation between autonomous OpenFlow controllers

- enhanced SDN control plane for radio MAP and parameters
- ISCP type protocol for controller-controller negotiation
- logically centralized algorithm via delegation
SDN Wireless: Experimental Validation of Inter-Network Spectrum Coordination

GENI/ORBIT for wide area experimentation

Wide Area Network deeply programmable datapath: Click and/or OVS

bsControl: provides controller implementation with REST API to control all exposable parameters.

dpControl: provides a REST API for datapath control (by interfacing to existing EPC/ASN-GW/AP)

Open Air Interface open-source SDR implementation of a LTE BS.

bsControl
- REST API
- Network OS
- Control API

dpControl
- REST API
- Network OS
- Control API

Hostapd software access point with a supported wifi card.
Benchmark experiment setup for distributed channel assignment algorithm

No cooperation between WD controllers: LTE BS1 causes interference to Wi-Fi AP3 when operating on the same channel

Inter-network coordination between WDs: interference avoidance between LTE and Wi-Fi

Joint work with Parishad Karimi and Ivan Seskar
Rutgers U
SDN Wireless: Experimental Validation of Inter-Network Spectrum Coord (cont.)

Fairness is achieved through Inter-Network Coordination

<table>
<thead>
<tr>
<th></th>
<th>Avg. Thru</th>
<th>JFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Coord</td>
<td>9 Mbps</td>
<td>0.47</td>
</tr>
<tr>
<td>With Coord</td>
<td>8.13Mbps</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Throughput of Wi-Fi/LTE averaged over 5 experiment runs

Avoids Starvation
Next-Gen Mobile Network Protocols
Next-Gen Mobile Network: Clean-Slate Redesign

- Design aims for a “flat” mobile network based on uniform routing protocol (no gateways!)
- 5G/B5G core networks also require several new capabilities based on named-objects:
  - Multi-homing
  - Multicast
  - In-network storage
  - Late Binding
  - ...also ad-hoc modes & disconnection

![Diagram of network architecture]

**TODAY**

**Future Clean Slate Mobile Network**

Wireless Edge Network with Integrated Mobility Support

Custom Access Protocols

Internet Protocol

Radio access specific
Next-Gen Mobile Network: Identifier Based Protocols

- Various proposals for identifier based networking for mobility, IoT, ..
- New “IDEAS” BoF at IETF
Next-Gen Mobile Network: ID-based network as “flat mobile core”

- Self certifiable names (GUIDs)
- Distributed mobility management (GNRS)
- No gateway bottlenecks

Prototype development with OAI and Click software routers for Flat MF core
Next-Gen Mobile Network: Mobility Support Comparison

MobilityFirst

Host Identity Protocol (1)

LISP (2)

Next-Gen Mobile Network: Multi-Homing Results

HetNets (WiFi + LTE)

Multi-Cellular Network

Simulation of spatially correlated signal strengths for LTE NAMH
Next-Gen Mobile Network: Host & Network Mobility Results

Host mobility

- Vehicular mobility (50mph)
- Opportunistic Wi-Fi + disconnection
- Web requests of size: U(10KB-5MB)

Network mobility

- Bus mobility modeled as a moving inter-domain entity
- Data delivery with *late-binding*

5 second improvement in median completion time

**Inter-domain update interval, \( t = f(A) \)**
Next-Gen Mobile Network: Ad Hoc Clustering & Routing for Vehicular

- Identifier based networking also enables dynamic ad hoc clustering and network mobility
- Enables opportunistic communication, both V2V and V2I
Next-Gen Mobile Network: Vehicular Clustering Results

- V2V clustering with cooperative V2I achieves ~2-3x improvement in Internet connectivity (25% to 75% for a highway scenario)

<table>
<thead>
<tr>
<th>Mobility Model</th>
<th>Gauss-Markov &amp; car following</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of access points</td>
<td>12</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>200</td>
</tr>
</tbody>
</table>

Improved connectivity

Enhanced Reachability

Joint work with Prof. R. Yates & Mehrnaz Tavan, Rutgers U
Mobile Edge Cloud
Mobile Edge Cloud: System Architecture

From centralized
To distributed

Routing with
Cloud awareness

Cross layer support

Current Technology

Wide Area Internet

Mobile Edge Cloud Module

Mobile Edge Network Module

Radio Access Network (RAN)

Edge Networks with Cloud Servers

Intra-Domain Router

TCP/IP Connection

TCP/IP client

Mobile Edge Cloud: System Architecture

MEC Technology

Current Technology

http cloud server software

Joint work with Prof. P. Shenoy U Mass
Mobile Edge Cloud: Central Control

- Distributed assignment of cloud requests to servers can be achieved via cross-layer routing which accounts for both network & cloud state.
- For example, “anycast routing” can be used to route cloud requests to the best server.
- Handles both load balancing and mobility.

Evaluation Results
(“SEGUE, 2016”)
Mobile Edge Cloud: Distributed Control

- Distributed assignment of cloud requests to servers can be achieved via cross-layer routing which accounts for both network & cloud state.
- For example, “anycast routing” can be used to route cloud requests to the best server.
- Handles both load balancing and mobility.

Implemented in MobilityFirst as “Application Level Routing” (ASR) Using Virtual Network (VN) capability.
Mobile Edge Cloud: Distributed Control Experiment on ORBIT

<table>
<thead>
<tr>
<th>vBS</th>
<th>MF-VN</th>
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<tbody>
<tr>
<td>- Mode: 802.11n/a</td>
<td>- Routing: ASR</td>
</tr>
<tr>
<td>- Band: 5GHz</td>
<td>- Reporting interval: 2s</td>
</tr>
<tr>
<td>- Tx Rate: 65Mbps</td>
<td>- Transport: hop-by-hop</td>
</tr>
<tr>
<td>- Rx Rate: 65Mbps</td>
<td>- reliability</td>
</tr>
<tr>
<td>- # of BS: 2 (Ch 36,48)</td>
<td>- Retrans. limit: unlimited</td>
</tr>
</tbody>
</table>

- Retrans. timeout: 200ms

APP-level Query & Response (mfping)

**Response Time**

- Query: $T = t_0$
- Response: $T = t_1$

**90%ile Response Time**

- CDF: $90\%$
- vBS&MF
- vBS only
- w/o vBS&MF

Joint work with Francesco Bronzino, INRIA and K. Nakauichi, NICT, Japan
Mobile Edge Cloud: Distributed Control Experiment on ORBIT (cont.)

Significant improvement in 90% latency relative to nearest server baseline

300 data units with 25KB size are generated in this experiment
Cloud Assisted Driving and Self-Driving will soon become feasible due to advances in wireless network ("5G") and edge cloud technology.

Joint work with Prof. S. Dey, UCSD
Concluding Remarks
Concluding Remarks: Next Steps – PAWR Advanced Wireless Testbed

- New US National Science Foundation initiative aimed at realizing advanced wireless vision via city-scale testbed
- PAWR testbed will focus on future wireless scenarios involving high bandwidth/low latency and integrated edge computing
- Rutgers/Columbia/NYU working on proposal for city-scale deployment in NYC with focus on ultra high BW/low latency + edge computing
- Technologies include:
  - mmWave
  - Gbps SDR
  - Open API base stations
  - Next-gen mobile network
  - Low latency optical x-haul
  - Edge cloud