Towards Software-Defined Wireless Networks

Network Infrastructures

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Based on Slides from Ian Akyildiz, Sachin Katti, Jennifer Rexford and Li Erran Li

Outline

- CellSDN: Towards Software Defined Cellular Networks
- OpenRadio: Taking Control of Wireless
- SoftRAN: Software Defined Radio Access Networks

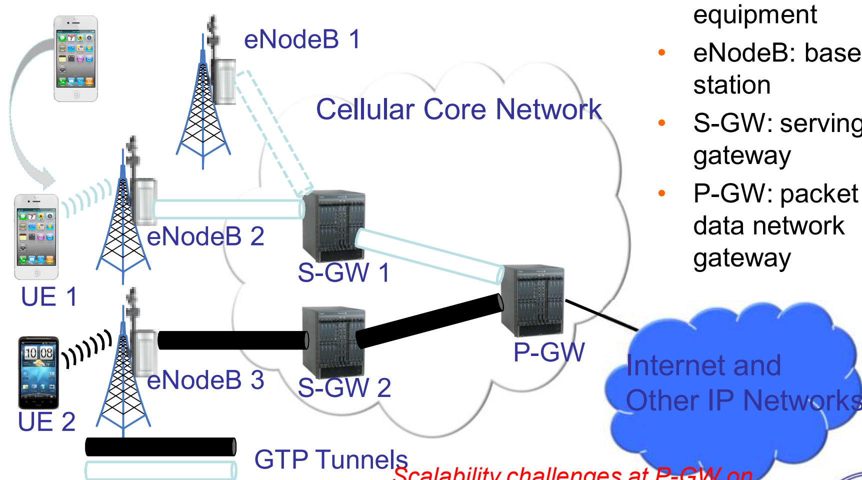
Towards Software Defined Cellular Networks

Outline

- Critiques of LTE Architecture
- CellSDN Use Cases
- CellSDN Architecture
- Related Work
- Conclusion and Future Work

LTE Data plane is too centralized

- Data plane is too centralized

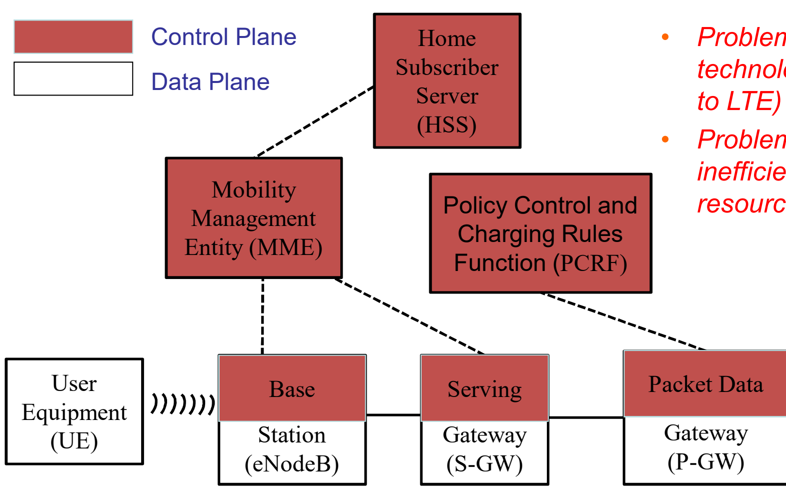


- UE: user equipment
- eNodeB: base station
- S-GW: serving gateway
- P-GW: packet data network gateway

Scalability challenges at P-GW on charging and policy enforcement!

LTE Control plane is too distributed

- No clear separation of control plane and data plane



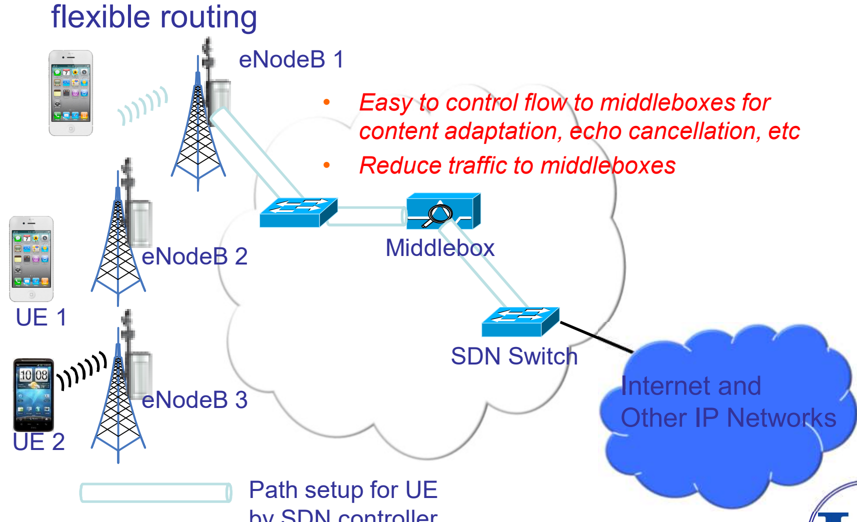
- *Problem with Inter-technology (e.g. 3G to LTE) handoff*
- *Problem of inefficient radio resource allocation*

Advantages of SDN for Cellular Networks

- Advantage of logically centralized control plane
  - Flexible support of middleboxes
  - Better inter-cell interference management
  - Scalable distributed enforcement of QoS and firewall policies in data plane
  - Flexible support of virtual operators by partitioning flow space
- Advantage of common control protocol
  - Seamless subscriber mobility across technologies
- Advantage of SDN switch
  - Traffic counters enable easy monitoring for network control and billing

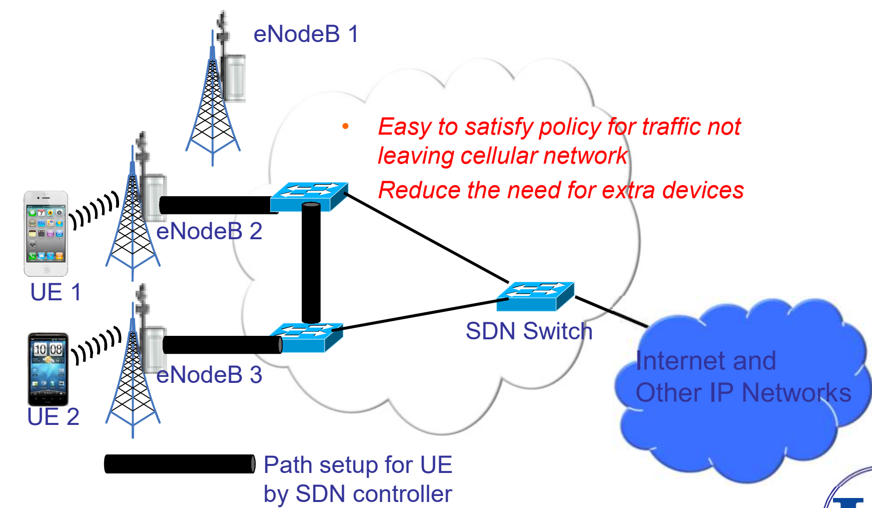
Flexible Middlebox Support

- SDN provides fine grained packet classification and flexible routing



Flexible Middlebox Support (Cont'd)

- SDN switch can support some middlebox functionality



Monitoring for Network Control & Billing

- Packet handling rules in SDN switches can efficiently monitor traffic at different level of granularity
  - Enable real time control and billing

Rule	Action	Stats

Packet + byte counters

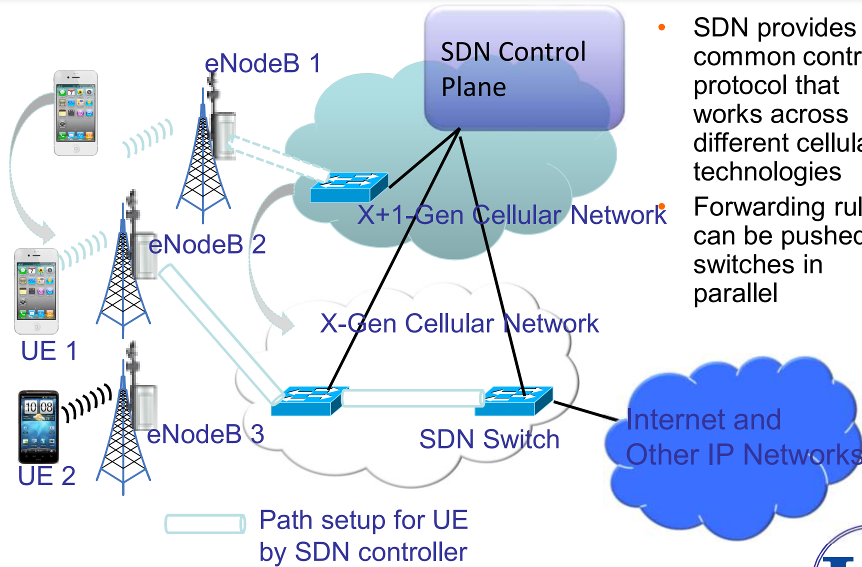
1. Forward packet to port(s)
2. Encapsulate and forward to controller
3. Drop packet
4. Send to normal processing pipeline

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport

10

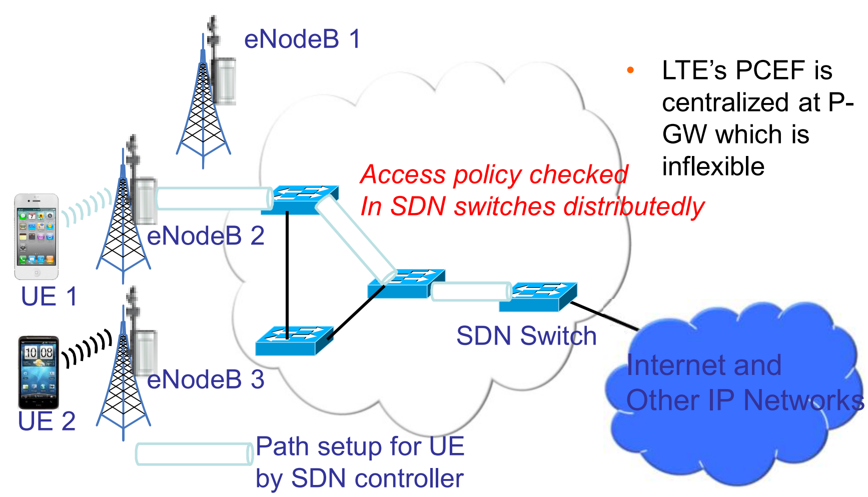
+ mask

Seamless Subscriber Mobility



- SDN provides a common control protocol that works across different cellular technologies
- Forwarding rules can be pushed to switches in parallel

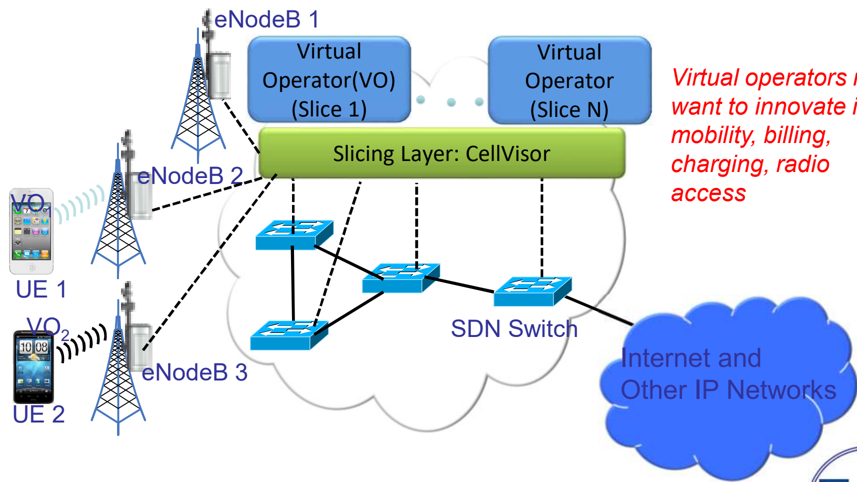
Distributed QoS and ACL Enforcement



- LTE's PCEF is centralized at P-GW which is inflexible

Virtual Operators

- Flexible network virtualization by slicing flow space

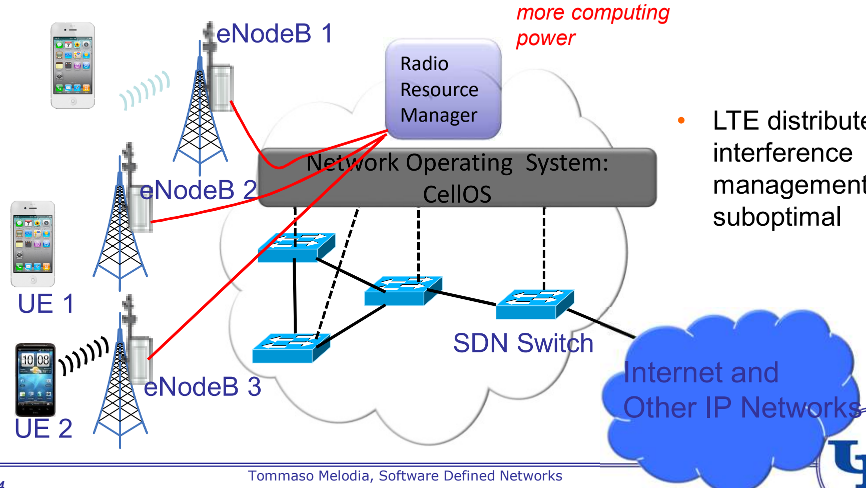


Virtual operators may want to innovate in mobility, billing, charging, radio access

Inter-Cell Interference Management

- Central base station control: better interference management

Global view and more computing power

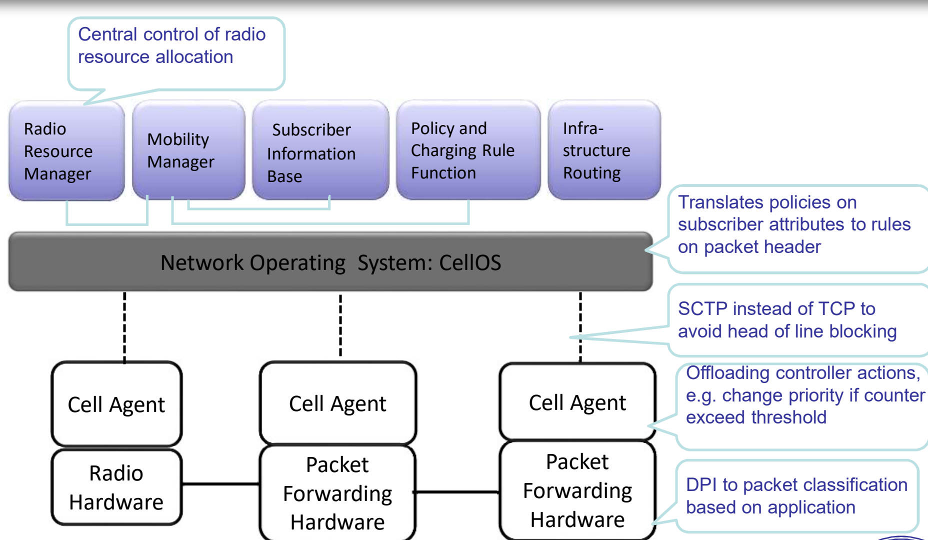


- LTE distributed interference management is suboptimal

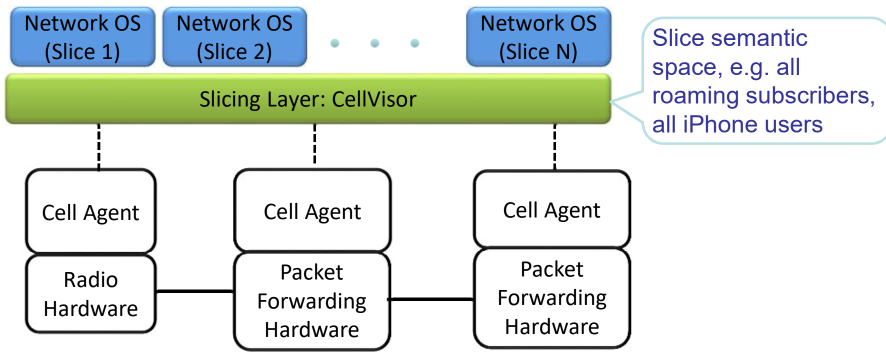
CellSDN Architecture

- CellSDN provides scalable, fine-grain real time control with extensions:
  - Controller: *fine-grain* policies on subscriber attributes
  - Switch software: local control agents to improve control plane *scalability*
  - Switch hardware: *fine-grain* packet processing to support DPI
  - Base stations: remote control and virtualization to enable flexible *real time* radio resource management

CellSDN Architecture (Cont'd)



CellSDN Virtualization



Related Work

- Stanford OpenRoad
  - Introduced openflow, FlowVisor, SNMPVisor to wireless networks
- Stanford OpenRadio
  - Programmable cellular data plane
- NEC base station virtualization
  - Slicing radio resources at the MAC layer
- Ericsson CloudEPC
  - Modify LTE control plane to control openflow switches

Conclusions

- CellSDN advantages:
  - Simple and easy to manage
  - Simple and easy to introduce new services
  - Easy to inter-operate with other wireless technologies

- Future work: detailed CellSDN design

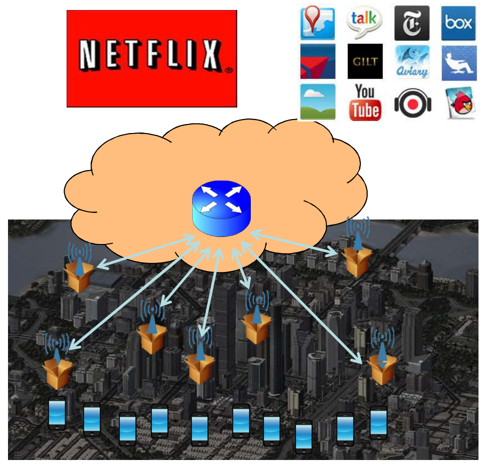
OpenRadio: Taking Control of Wireless

Three Dissatisfied Parties

Applications

Carriers

Users



Frustrated Users

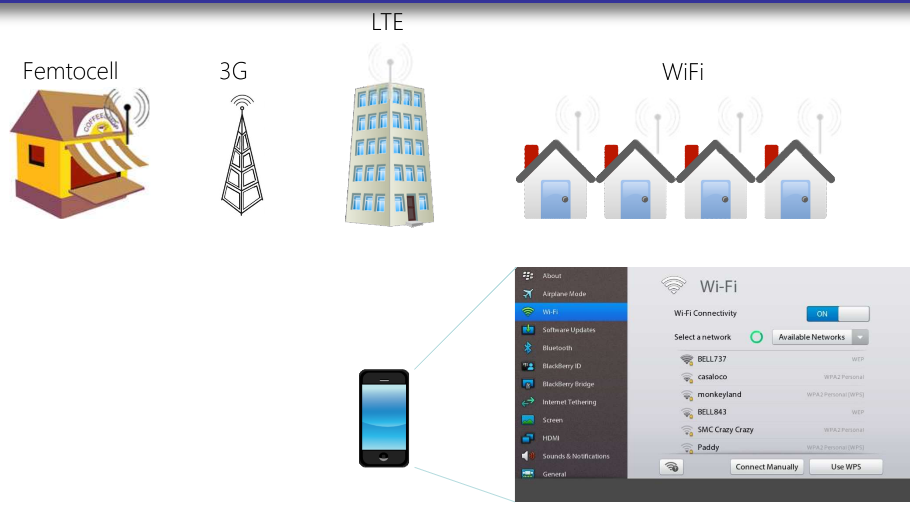
Smartphone owners confront challenging mobile problems

% in each group who have encountered mobile phone problems AT LEAST WEEKLY...

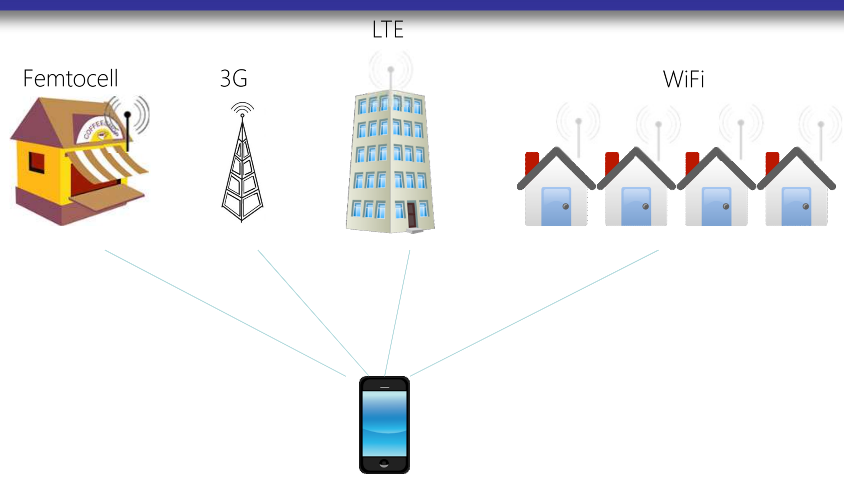
	Smartphone owners	Other cell owners
Dropped calls (among cell owners)	35%*	28%
Unwanted sales, marketing calls (among cell owners)	26%	23%
Spam, unwanted texts (among texters)	29%*	20%
Slow download speeds (among mobile internet / email / apps users)	49%*	31%

* Denotes statistically significant difference

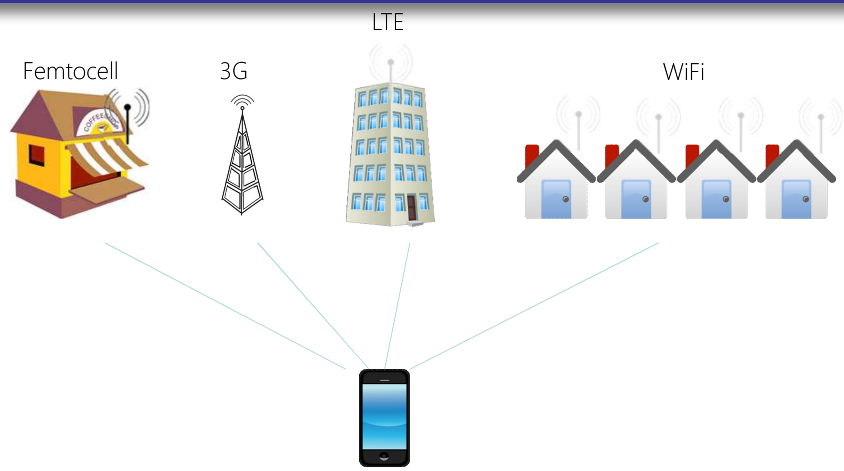
Source: Pew Research Center's Internet & American Life Project Spring Tracking Survey, March 15-April 3, 2012. N for cell owners=1,954. N for cell owners who text message=1,395. N for cell owners who use the internet or email on their cell phones or download apps to their cell phone=953. Interviews conducted in English and Spanish and on landline phones and cell phones.



Paradoxically, surrounded by wireless APs (WiFi, 3G, 4G, picocells, femtocells, whitespace ….)

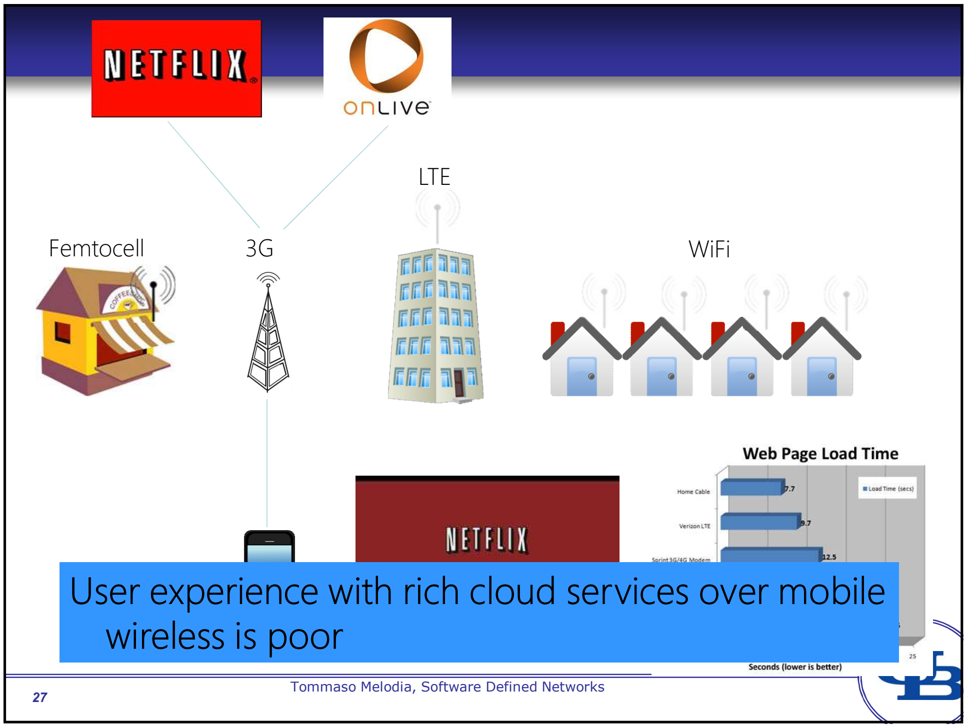


Why can’t I seamlessly connect to the best AP available?



Why can't I seamlessly connect to multiple APs if I want more speed?

Applications' Perspective


NETFLIX
onLive
LTE
Femtocell
3G
WiFi
Web Page Load Time
NETFLIX
User experience with rich cloud services over mobile wireless is poor
Seconds (lower is better)
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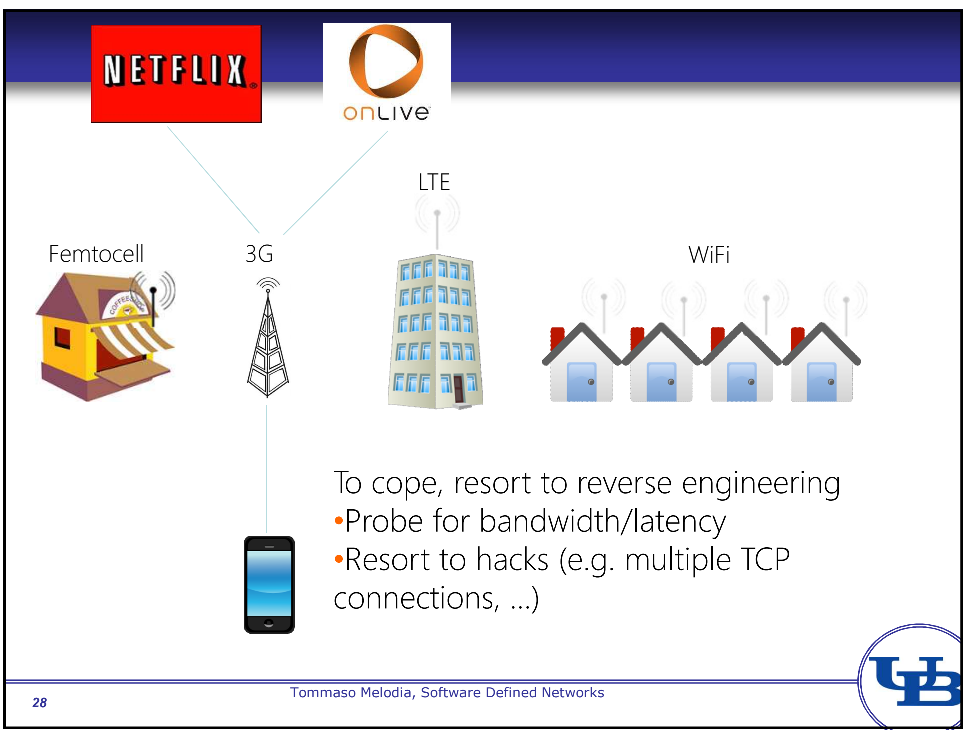
NETFLIX
onLive
LTE
Femtocell
3G
WiFi
To cope, resort to reverse engineering
•Probe for bandwidth/latency
•Resort to hacks (e.g. multiple TCP connections, …)
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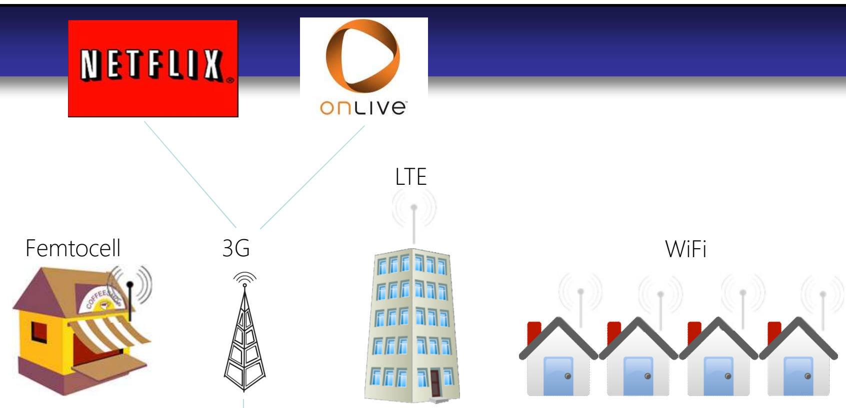


Why can't applications directly ask the network its current state, or directly request the connectivity they need?

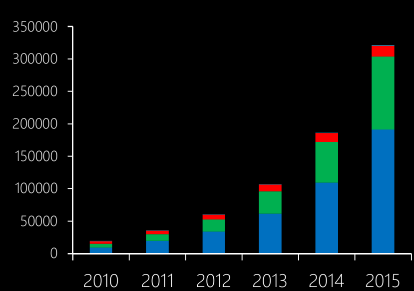
More generally, why isn't the network a partners for apps rather than an opaque bit pipe?

- Network knows user location, connectivity, billing ….
- Well positioned to host & enhance applications

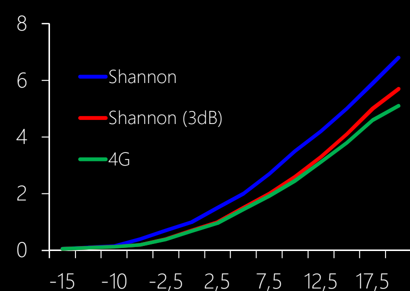
Carrier's Perspective

Carrier's Dilemma

Exponential Traffic Growth

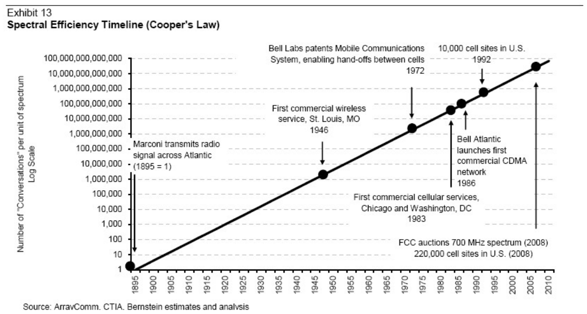


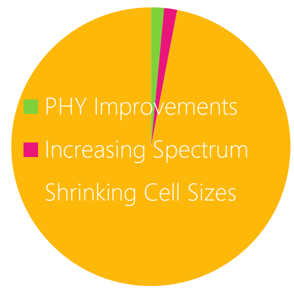
Limited Capacity Gains



Exponential growth + Limited spectrum/capacity gains
→ Poor wireless connectivity

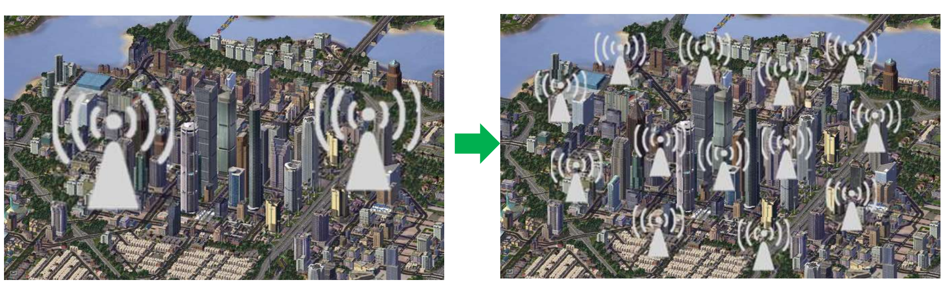
Cooper's Law





Capacity Improvements come from increasing cell density

Capacity → Dense/Chaotic Deployments



Dense → Higher SNR/user → Higher Capacity

- Femtocells, dense Wi-Fi deployments, etc.

Dense & Chaotic → Hard to Manage

- Limited spectrum + Dense → **Intercell Interference**
- Many, chaotic cells → **Variable Load & Backhaul**
- **Operators need to dynamically manage how their traffic is routed, scheduled and encoded on a per packet level to manage inter-cell interference & variable load in a chaotic infrastructure** → Hard to build at scale

Everyone is Dissatisfied!

Underlying Cause: <u>Lack of control</u>

Infrastructure does not scalably expose state

- Hard or infeasible to find available APs, their speeds, user locations, fine-grained network/load information etc

Infrastructure does not provide granular control

- Hard or infeasible to granularly control traffic E2E across all layers and network infrastructure

Open the wireless infrastructure to provide users, applications and carriers control over their traffic across all layers end to end across the entire infrastructure?

OpenRadio: Taking Control of Wireless

Wireless network architecture that provides unified software interfaces to:

1. Query wireless networks about availability, quality, location, spectrum, interference …

2. Control granularly how individual user or application traffic is handled by the network across the entire stack

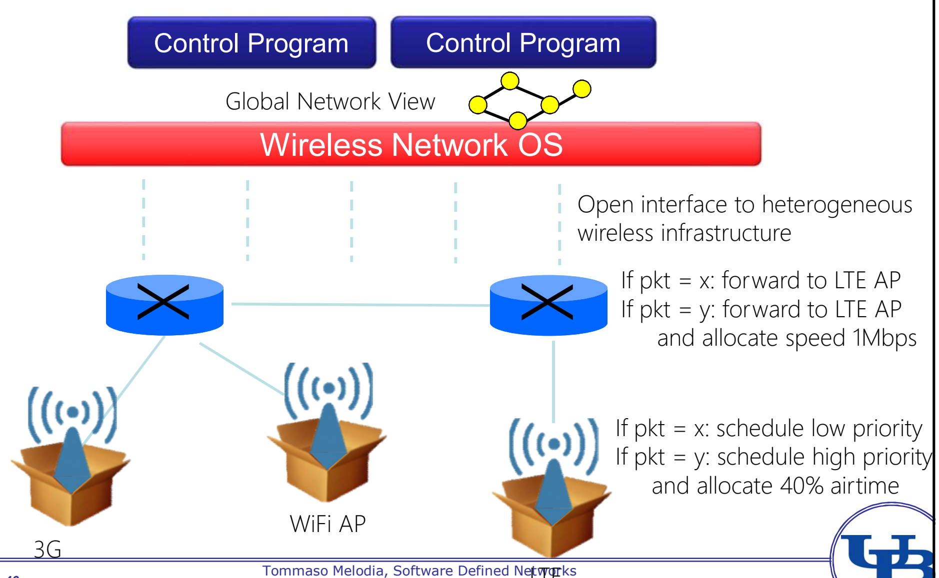
OpenRadio: Control Interface

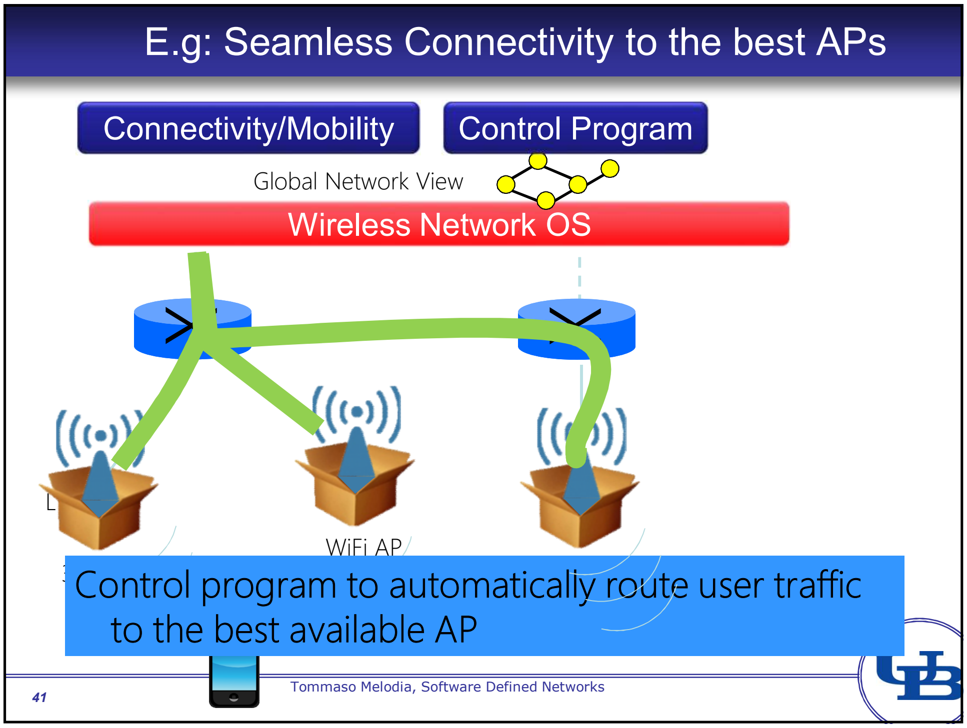
Match/Action interface for the entire stack

Match: Identify and tag flows of individual users and/or applications

Action: Control how packets are routed, what speeds & priorities they get, and how they are scheduled/encoded at the AP

OpenRadio: Architecture




E.g: Seamless Connectivity to the best APs
Connectivity/Mobility
Control Program
Global Network View
Wireless Network OS
WiFi AP
Control program to automatically route user traffic to the best available AP
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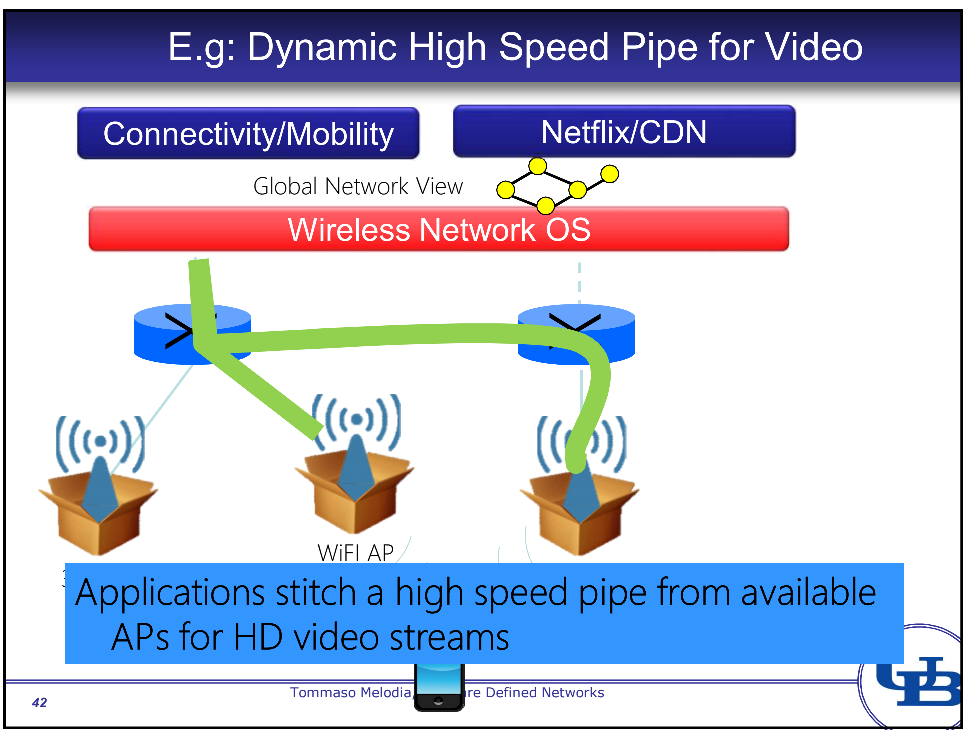
E.g: Dynamic High Speed Pipe for Video
Connectivity/Mobility
Netflix/CDN
Global Network View
Wireless Network OS
WiFi AP
Applications stitch a high speed pipe from available APs for HD video streams
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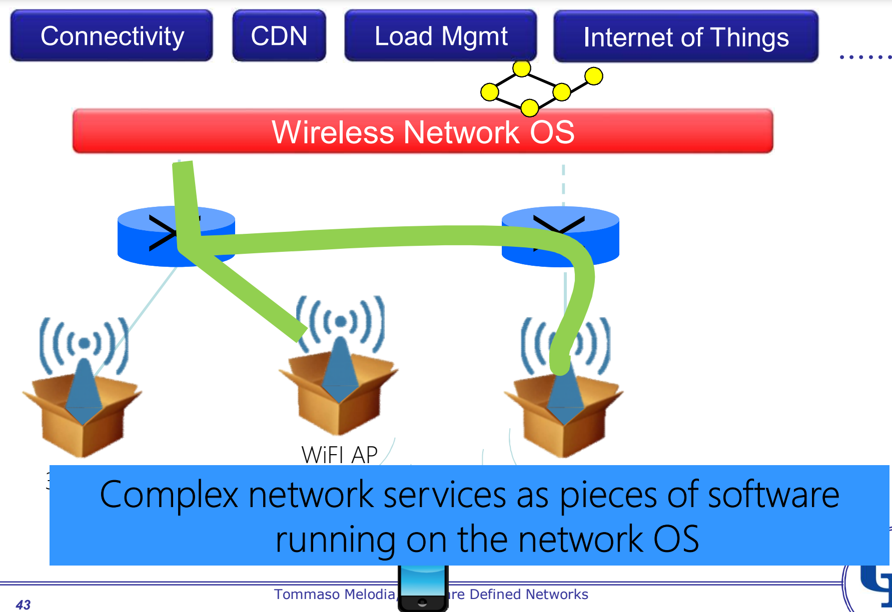


Complex network services as pieces of software running on the network OS

OpenRadio: Design

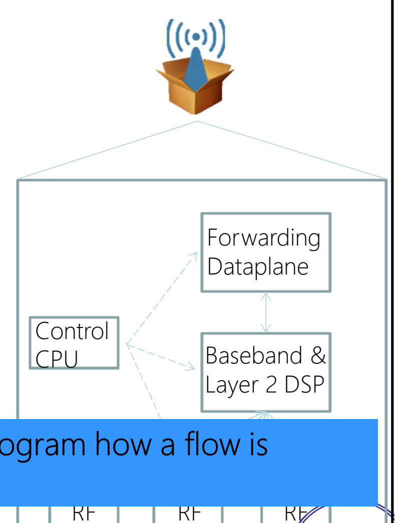
- <u>Data Plane</u>: Access, backhaul & core network
  - Can we build a programmable data plane using merchant silicon?
- <u>Control Plane</u>: Modular software abstractions for building complex network applications
  - What are the right abstractions for wireless?

OpenRadio: Radio Access Dataplane

OpenRadio: Access Dataplane

OpenRadio APs built with merchant DSP & ARM silicon

- Single platform capable of **LTE, 3G, WiMax, WiFi**
- OpenFlow for Layer 3
- Inexpensive ($300-500)



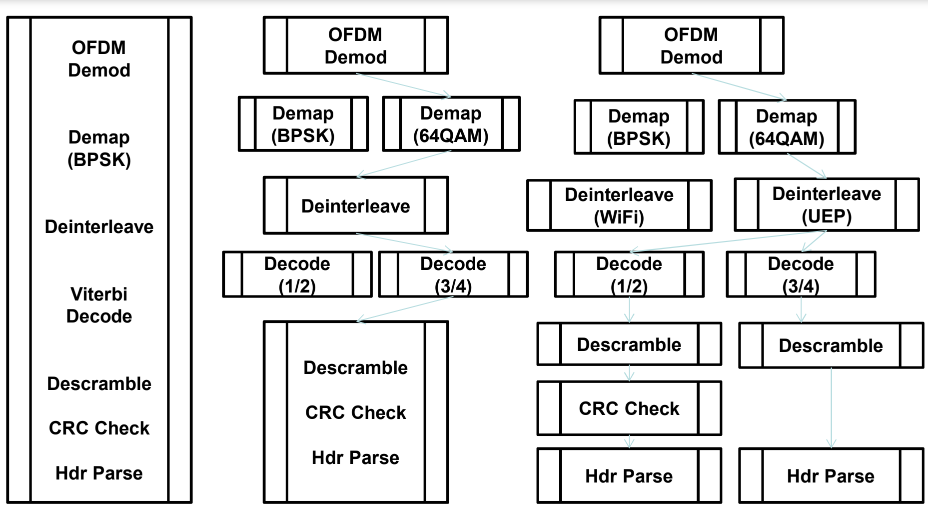
Exposes a match/action interface to program how a flow is forwarded, scheduled & encoded

Design Goals and Challenges

Programmable wireless dataplane using off-the-shelf components

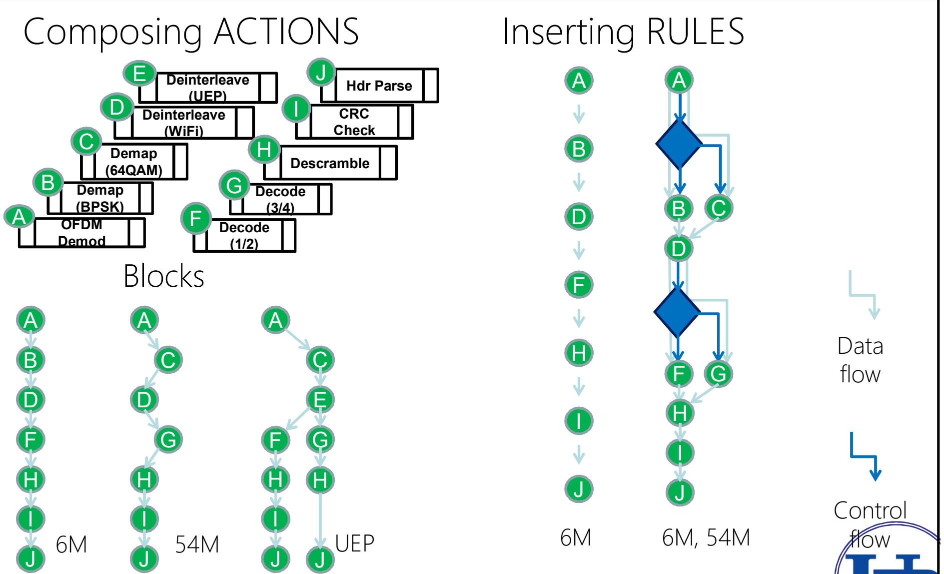
- At least 40MHz OFDM-complexity performance
  - More than 200 GLOPS computation
  - Strict processing deadlines, eg. 25us ACK in WiFi
- Modularity to provide ease of programmability
  - Only modify affected components, reuse the rest
  - Hide hardware details and stitching of modules

Wireless Basebands



WiFi 6mbps WiFi 6, 54mbps WiFi 6, 18mbps and UEP

Modular declarative interface

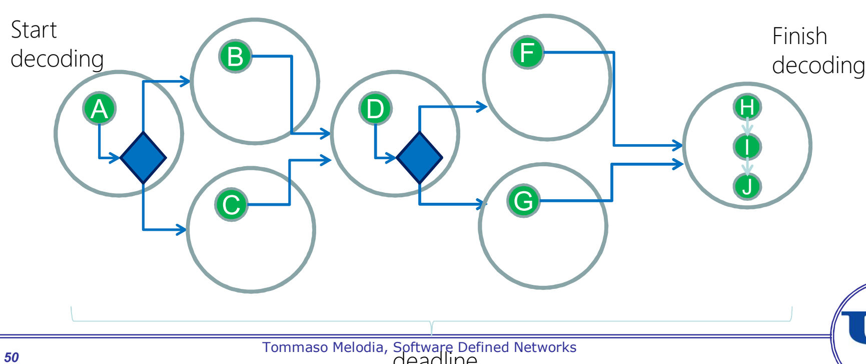


 Actions: DAGs of blocks

Rules: Branching logic

State machines and deadlines

- Rules and actions encode the protocol state machine
  - Rules define state transitions
  - Each state has an associated action
- Deadlines are expressed on state sequences



Design principle I – Judiciously scoping flexibility

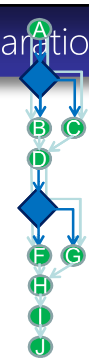
- Provide just enough flexibility
- Keep blocks coarse

- Higher level of abstraction
- High performance through hardware acceleration
  - Viterbi co-processor
  - FFT co-processor
- Off-the-shelf heterogeneous multicore DSPs
  - TI, CEVA, Freescale etc.

Algorithm	WiFi	LTE	3G	DVB-T
FIR / IIR	√	√	√	√
Correlation	√	√	√	√
Spreading			√	
FFT	√	√		√
Channel Estimation	√	√	√	√
QAM Mapping	√	√	√	√
Interleaving	√	√	√	√
Convolution Coding	√	√	√	√
Turbo Coding		√	√	
Randomi-zation	√	√	√	√
CRC	√	√	√	

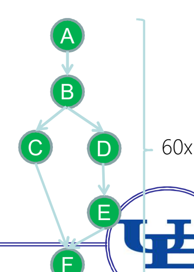
Design principle II - Processing-Decision Separation

- Logic pulled out to decision plane
- Blocks and actions are branch-free
  - Deterministic execution times
  - Efficient pipelining, algorithmic scheduling
  - Hardware is abstracted out

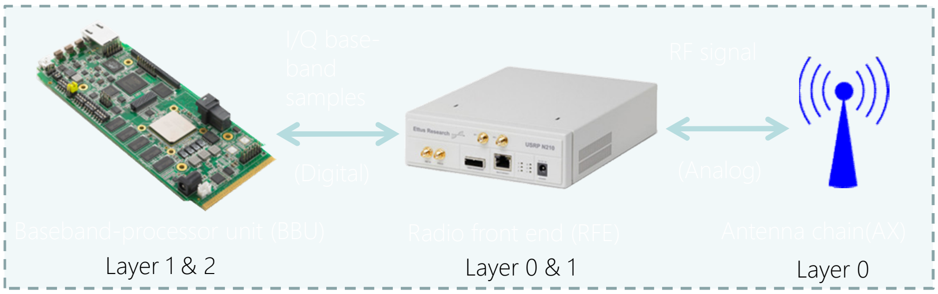


6M, 54M

Regular compilation	OpenRadio scheduling
Instructions	Atomic processing blocks
Heterogeneous functional units	Heterogeneous cores
Known cycle counts	Predictable cycle counts
Argument data dependency	FIFO queue data dependency

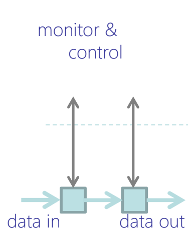


Prototype



- COTS TI KeyStone multicore DSP platform (EVM6618, two chips with 4 cores each at 1.2GHz, configurable hardware accelerators for FFT, Viterbi, Turbo)
- Prototype can process 40MHz, 108Mbps 802.11g on one chip using 3 of 4 cores

Software architecture



OR Wireless Decision Plane
protocol state machine, flowgraph composition, block configurations, knowledge plane, RFE control logic

OR Wireless Processing Plane
deterministic signal processing blocks, header parsing, channel resource scheduling, multicore fifo queues, sample I/O blocks

OR Runtime System
compute resource scheduling, deterministic execution ensuring protocol deadlines are met

Bare-metal with drivers

OpenRadio: Current Status

- OpenRadio APs with full WiFi/LTE software on **TI** C66x DSP silicon
- OpenRadio commodity WiFi APs with a firmware upgrade
- Network OS under development

To Conclude…

OpenRadio: Taking control of wireless through SDN

Provides programmatic interfaces to monitor and program wireless networks

- High performance substrate using merchant silicon

Complex network services as software apps

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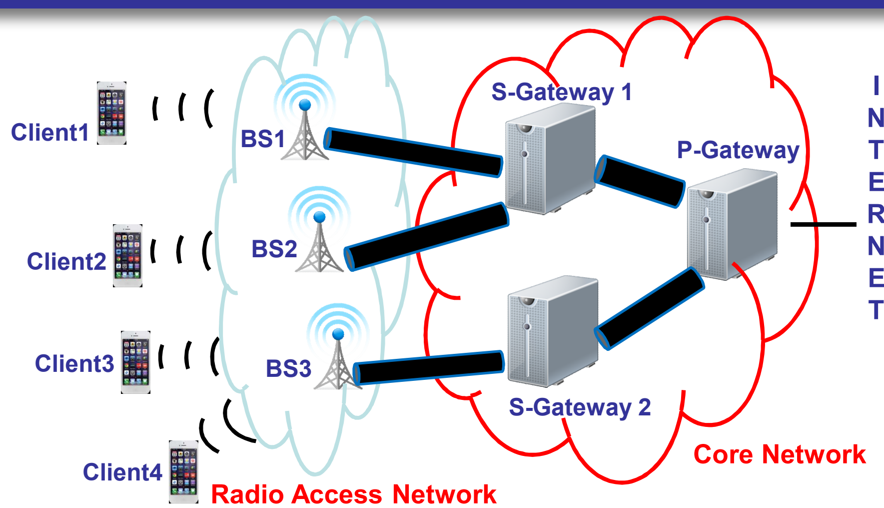
SoftRAN : Software Defined RAN

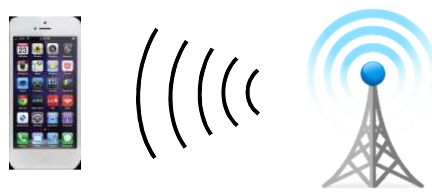
Aditya Gudipati†, Daniel Perry†,
Li Erran Li*, Sachin Katti †

LTE - Radio Access Network

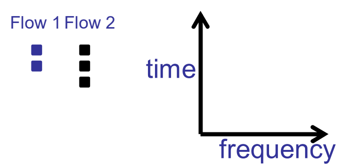


High Capacity, Uniform Coverage Wide-Area Wireless Network

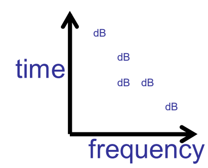
RAN Actions: Radio Resource Management



1. Assign each client to a base station



2. Assign resource blocks (time-frequency slots) to each flow



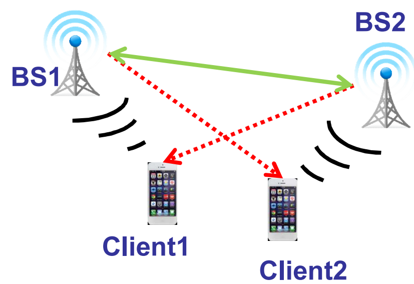
3. Assign transmit powers to be used for each resource block

RAN Challenges

- Increasing demand on wireless resources
  - Dense deployments of small cells

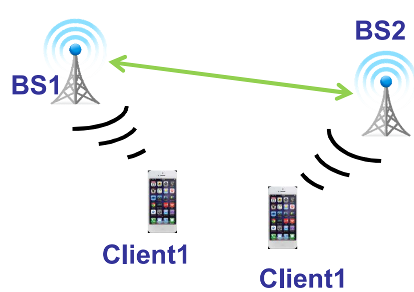
Coupled Radio Resource Management: Interference

- Power used by BS1 affects interference at Client 2
- Interference at Client 2 affects power reqd. at BS2



Coupled Radio Resource Management: Mobility

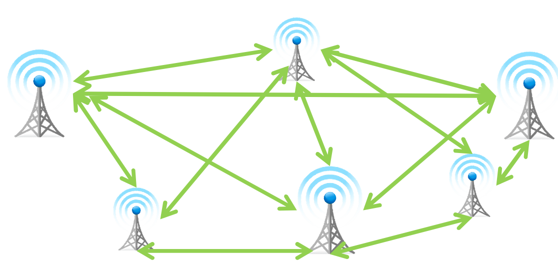
- Dense deployments
  - Higher frequency of handovers
  - More candidate base stations
  - Coordinating handovers critical

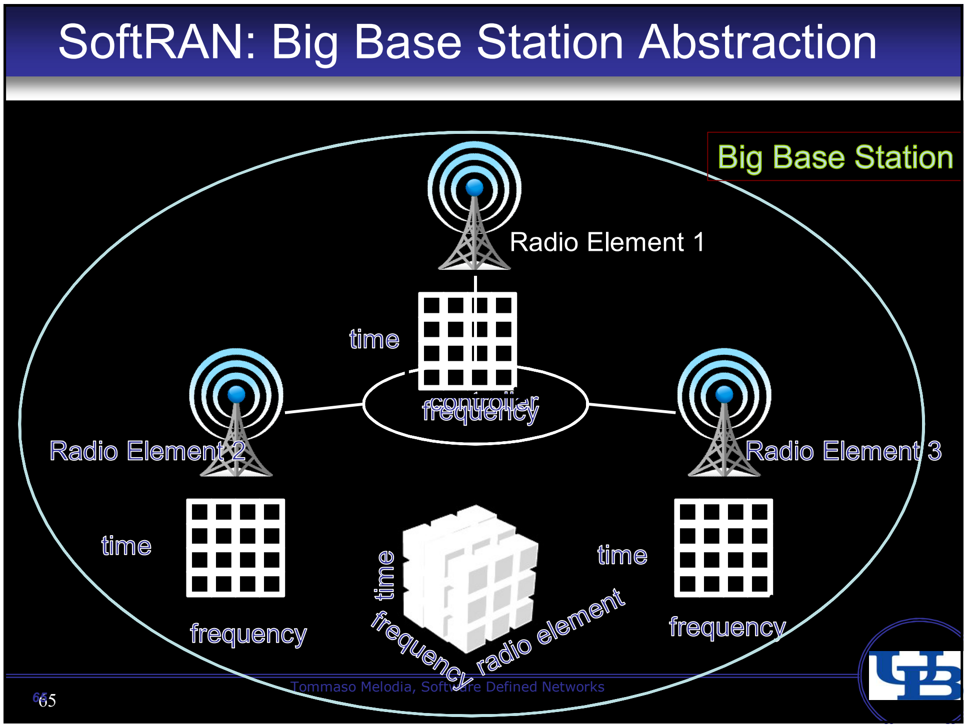


In dense deployments, Radio Resource Management needs to be ***tightly coordinated***

LTE-RAN: Current Architecture

- Distributed control plane
  - Tight coordination becomes infeasible with density
    - Huge demands on the backhaul network
  - Inefficient radio resource management
  - Hard to manage in a dense network




SoftRAN: Big Base Station Abstraction
Big Base Station
Radio Element 1
time
controller
frequency
Radio Element 2
Radio Element 3
time
frequency
time
frequency
radio element
time
frequency
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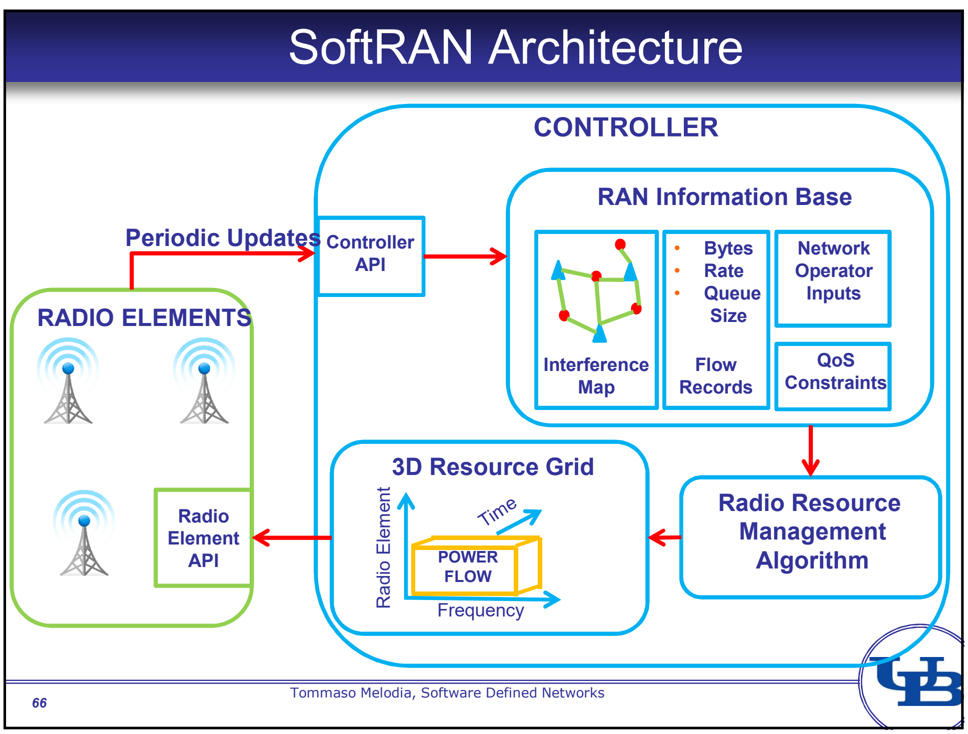
SoftRAN Architecture
CONTROLLER
RAN Information Base
Periodic Updates
Controller API
RADIO ELEMENTS
Interference Map
Bytes
Rate
Queue Size
Flow Records
Network Operator Inputs
QoS Constraints
3D Resource Grid
Time
Radio Element
POWER FLOW
Frequency
Radio Element API
Radio Resource Management Algorithm
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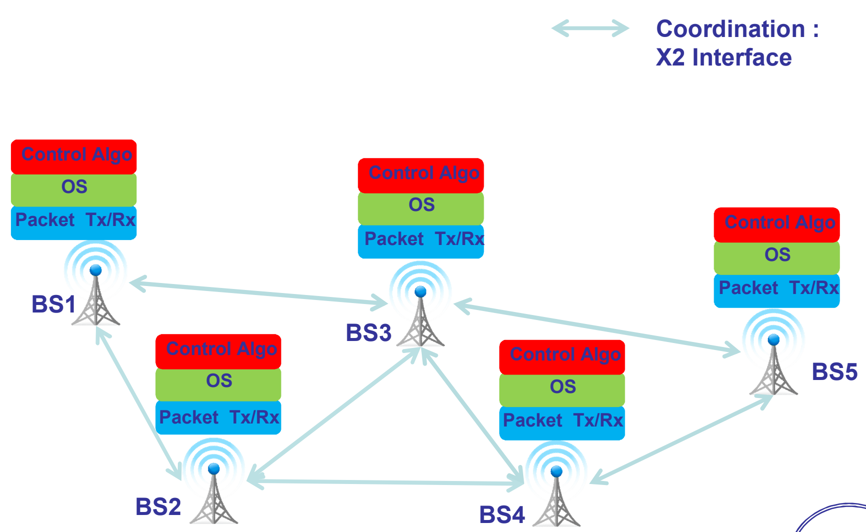
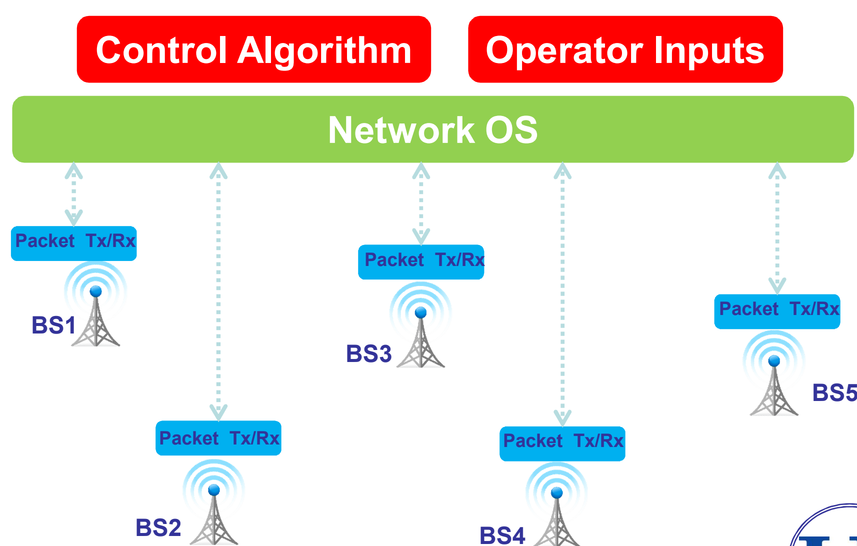
SoftRAN: SDN Approach to RAN



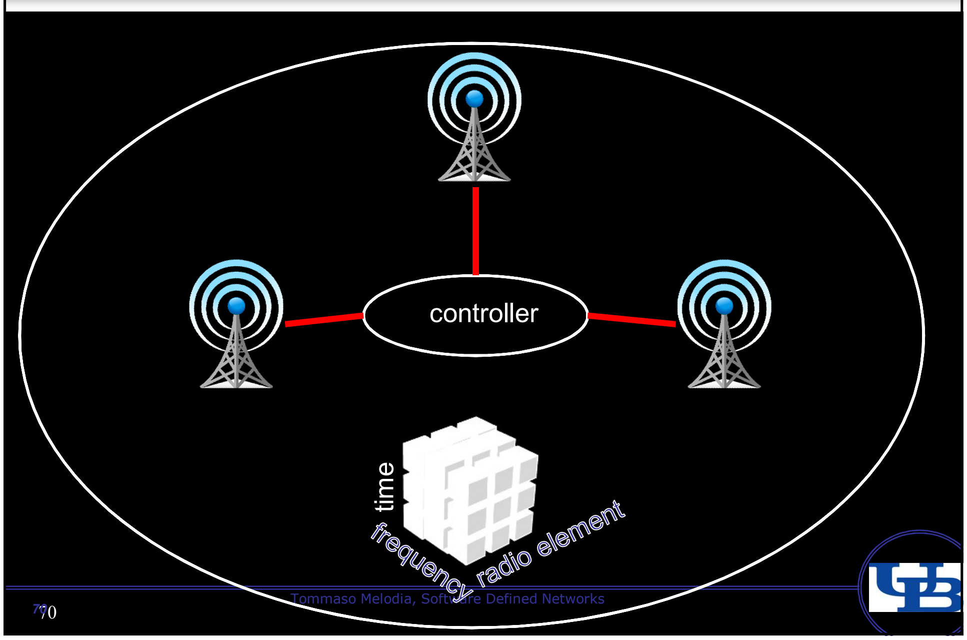
SoftRAN: SDN Approach to RAN



SoftRAN: SDN Approach to RAN

- Efficient use of wireless resources
  - Global view on interference and load
- Simplified network management
  - Plug-and-play control algorithms

Challenges: Backhaul Latency



Challenges: Backhaul Latency

- Refactor control plane based on latency
  - Low latency (< 1 ms) => No refactoring
- Principles for refactoring:
  - Controller manages global network state
  - Radio Elements leverage frequently varying local network state

Implementation

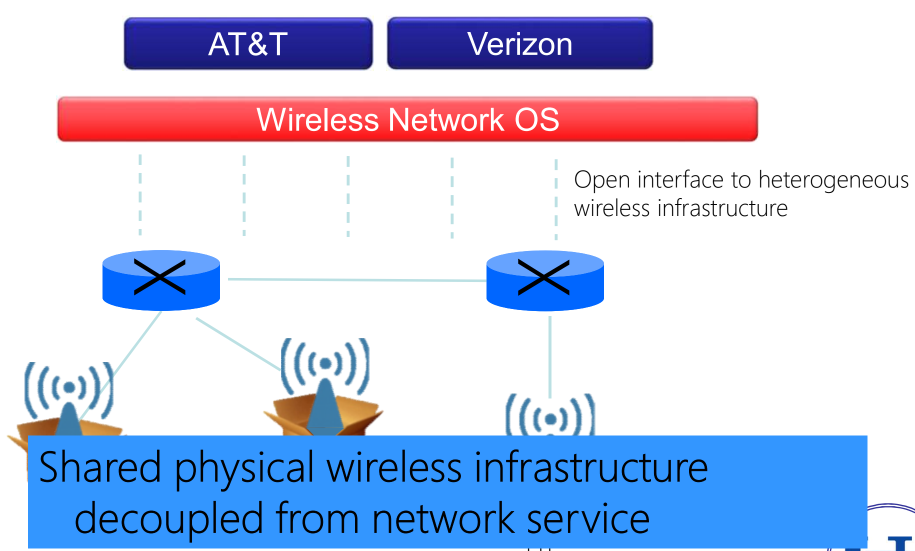
- Incrementally deployable on current infrastructure
  - No modification to Base Station – client interface
  - New API definitions for Base Station
    - Femto API: Standardized interface between scheduler and L1 *

*http://www.smallcellforum.org/resources-technical-papers

Future Vision

- Expand SoftRAN to include 3G and Wifi networks
- Coordinated management of all available radio resources

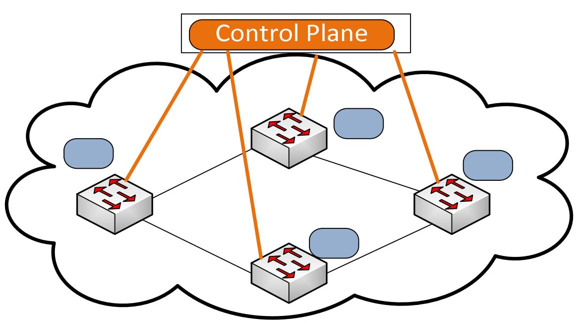
Virtualized Wireless Networks



Future Work: FASET

SOFTWARE DEFINED Networks

- Concept
  - Improve resource management by including optimized and fine-grained application-awareness
- How?
  - Separate the control plane from the data plane
  - Optimize the control plane decisions from a global network perspective



SDN: BENEFITS

- All control plane resides in the SDN Controller
- Data plane (i.e., forwarding) resides in the SDN switches
- SDN controller propagates forwarding rules to SDN switches
  - Avoids conflicting configuration among NW devices
  - Reduces the number of human configuration of NW elements;
  → reducing errors and network downtime

SDN: Benefits

- SDN Controller contains all SW, functionality, & features needed by the NW:
  - Single point of configuration
  - Simplifies deployment, maintenance and reconfiguration
  - SW can be developed without vendor involvement
  (i.e., faster innovation)

SDN FOR CELLULAR NETWORKS

- Major scalability and cost limitations of current cellular networks arise from:
  - Centralized data-plane functionalities implemented at the gateways
  - Vendor-specific configuration interfaces that communicate through
  - complex control-plane protocols and
  - Inefficient and non-flexible network architecture

FASET: Enabling Self-Evolving Wireless Networks via Software-defined Architecture

Objective:

study fundamental principles underlying a new generation of software-defined wireless network architectures and algorithms, to lay a foundation for future self-evolving wireless systems that will be far more evolvable and flexible than current ones.