Distributed Spectrum Management using Inter-network Cooperation

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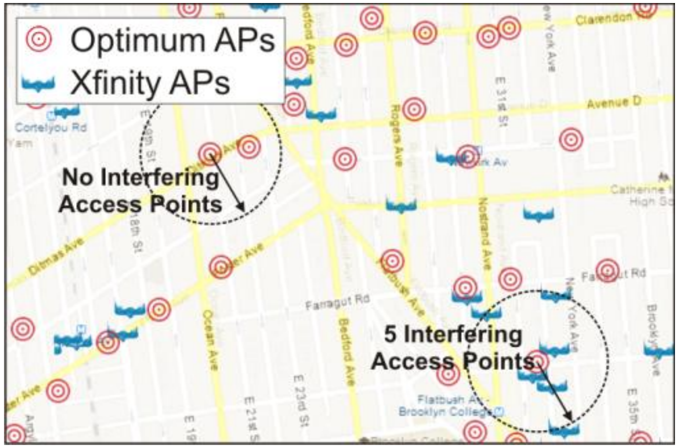
Introduction

- Rise of large-scale, managed, unlicensed-band wireless networks
- Overlapping deployments – time, freq, space

Location of APs of two Wi-Fi deployments in Brooklyn, NY

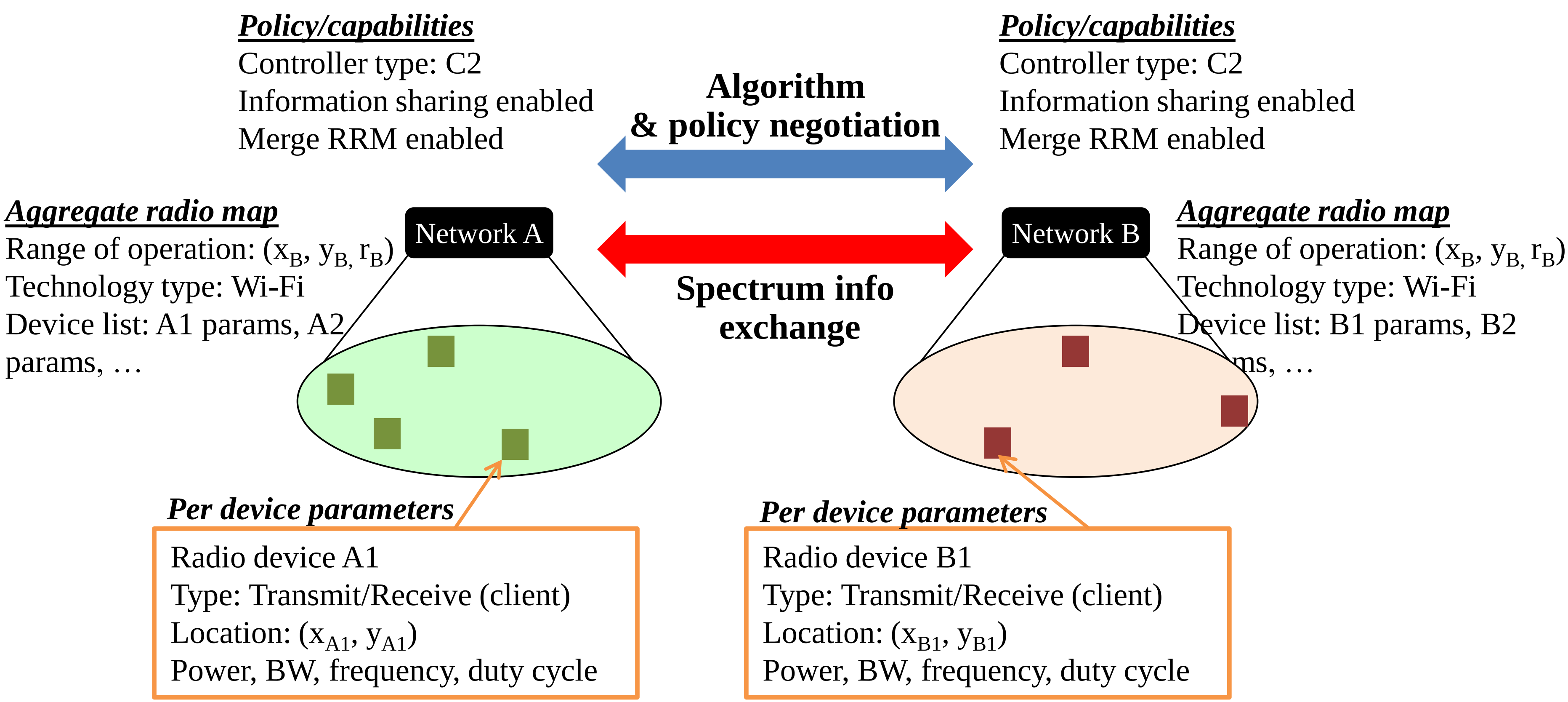


This work explores:

1. **Can networks cooperate on an aggregated manner?**
2. **How can such cooperation be practically realized?**

Inter-network Cooperation

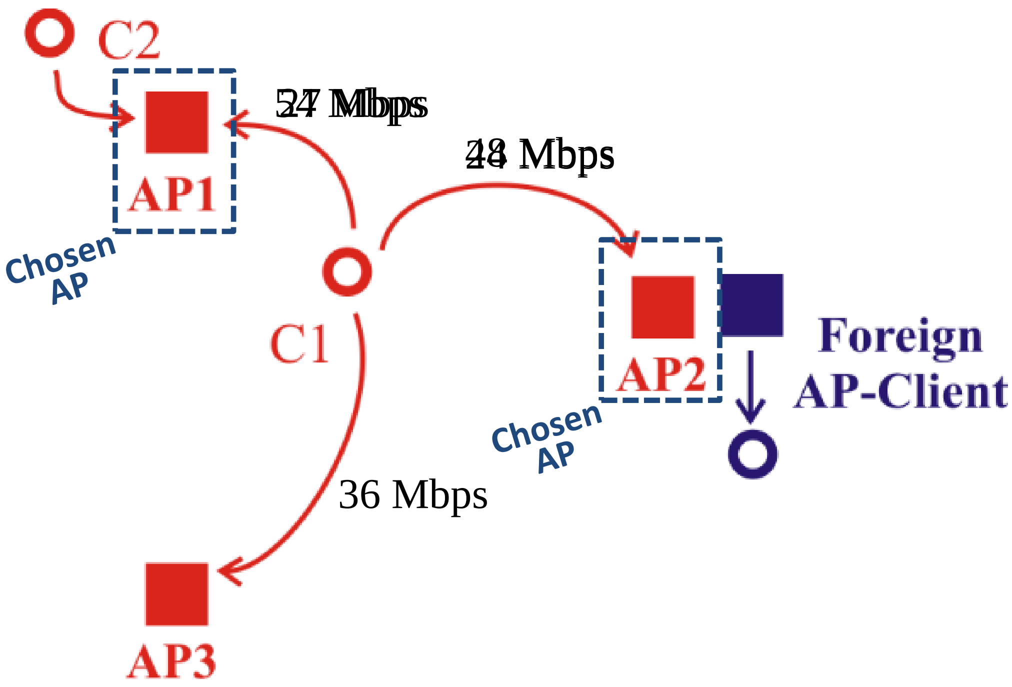
- Interaction between managed wireless networks over the back-end wired link for making more efficient use of the spectrum



Outline

- Potential gains from cooperation
  - Client-association optimization problem
  - Non-linear integer program and its solution
  - Simulation results
- Realizing inter-network cooperation
  - A SDN framework for the wireless control plane
  - ControlSwitch: Flexible switching of control msgs
  - Example use-cases

Client-AP association optimization



Default Selection:
Connect to closest (AP1)

Intra-network optimization:
Take AP load into account (AP2)

Inter-network optimization:
Take effect of foreign APs into account (AP3)

Intra-network optimization of client-AP associations can lead to inefficient results in presence of foreign networks

Study of potential gains

- Comparison of least distance, intra-network, and inter-network optimization

- System Model:
  - N independent WiFi networks: indexed by i
  - A_i Access Points; U_i Clients in the i^{th} network

$x_{ij}(\mathrm{k})$	connection state between the j^{th} client and k^{th} AP of the i^{th} network
$p_{ij}(\mathrm{k})$	fraction of time provided by the AP to the client
$r_{ij}(\mathrm{k})$	effective bit rate
B_{ik}	set of co-channel foreign APs within carrier sense range
C_{ik}	set of co-channel foreign APs outside carrier sense but within interference range (potential hidden nodes)

Optimization Problem

Intra-network Optimization:

$$\text{Maximize:} \quad \sum_{j \in U_i} \log \left(\sum_{k \in A_i} r_{ij}(k) x_{ij}(k) p_{ij}(k) \right)$$

$$\text{subject to:} \quad p_{ij}(k) = \frac{1}{\sum_{j' \in U_i} x_{ij'}(k)} \qquad \forall k \in A_i, j \in U_i$$

$$\sum_{k \in A_i} x_{ij}(k) = 1 \qquad \forall j \in U_i$$

$$x_{ij}(k) \in \{0, 1\} \qquad \forall k \in A_i, j \in U_i$$

Cooperative inter-network Optimization:

$$\text{Maximize:} \quad \sum_{i=1}^{N} \sum_{j \in U_i} \log \left(\sum_{k \in A_i} r_{ij}(k) x_{ij}(k) p_{ij}(k) \right)$$

$$\text{subject to:} \quad p_{ij}(k) = \frac{1}{\sum_{j' \in U_i} x_{ij'}(k)} \cdot \frac{1}{(1 + |B_{ik}|)(1 + \alpha |C_{ik}|)}$$

$$\forall k \in A_i, j \in U_i, i \in [1, N]$$

$$\sum_{k \in A_i} x_{ij}(k) = 1 \qquad \forall j \in U_i, i \in [1, N]$$

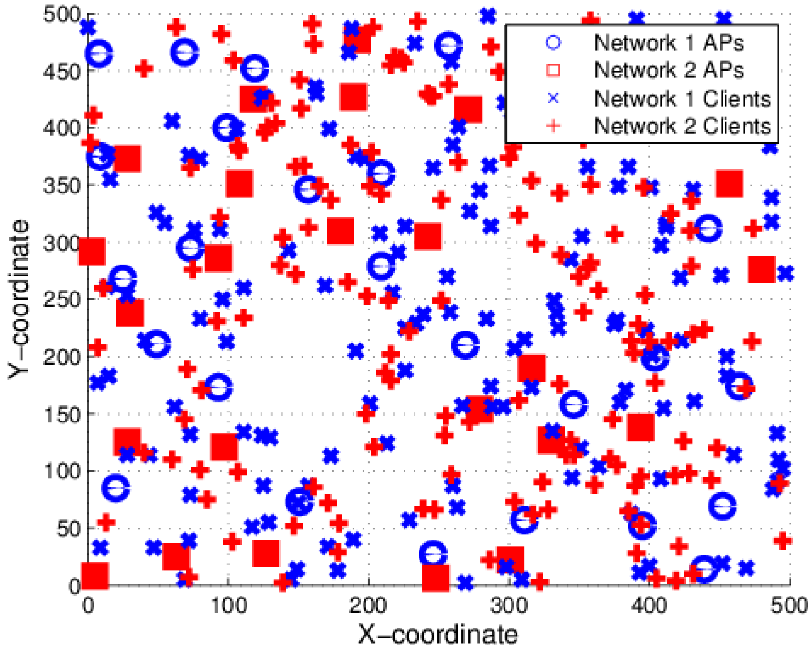
$$x_{ij}(k) \in \{0, 1\} \qquad \forall k \in A_i, j \in U_i, i \in [1, N]$$

This information is through info-sharing between networks

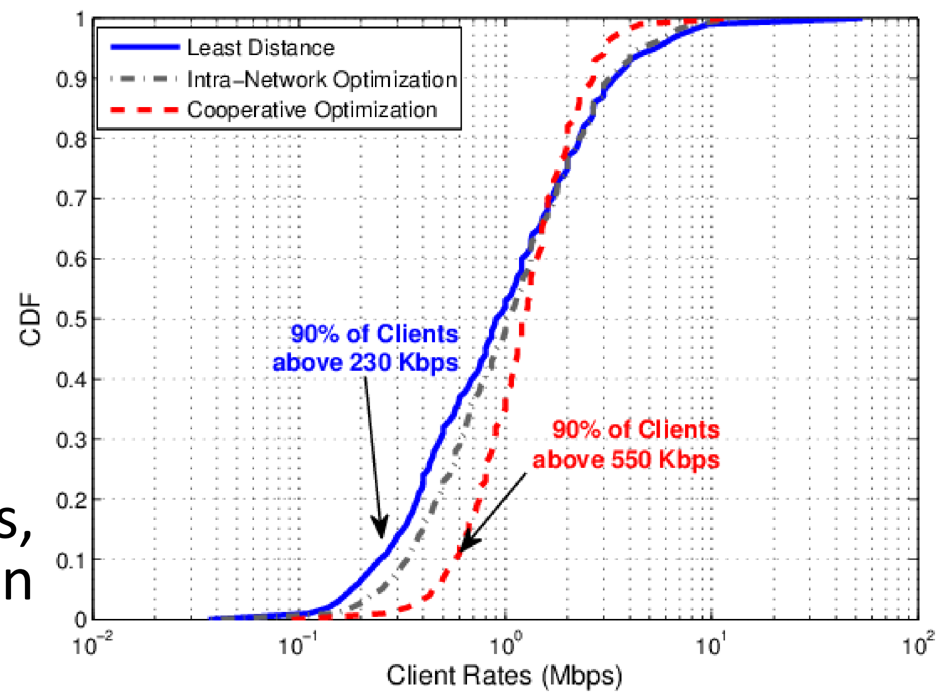
Simulation Details

- Both are non-linear integer programs:
  - $(2 + \in)$ approximate solution in polynomial time
  - For cooperative, problem decomposes into parts which each network can solve on its own
- Settings:
  - 2-6 overlapping networks, 15-35 APs/network, 50-250 clients/network
  - Two types of deployments: Uniform-random, Clustered
- Assumptions:
  - Downlink only, full-buffer traffic
  - Proportional fair scheduling at each AP
  - No priority between clients

Random Deployment Results



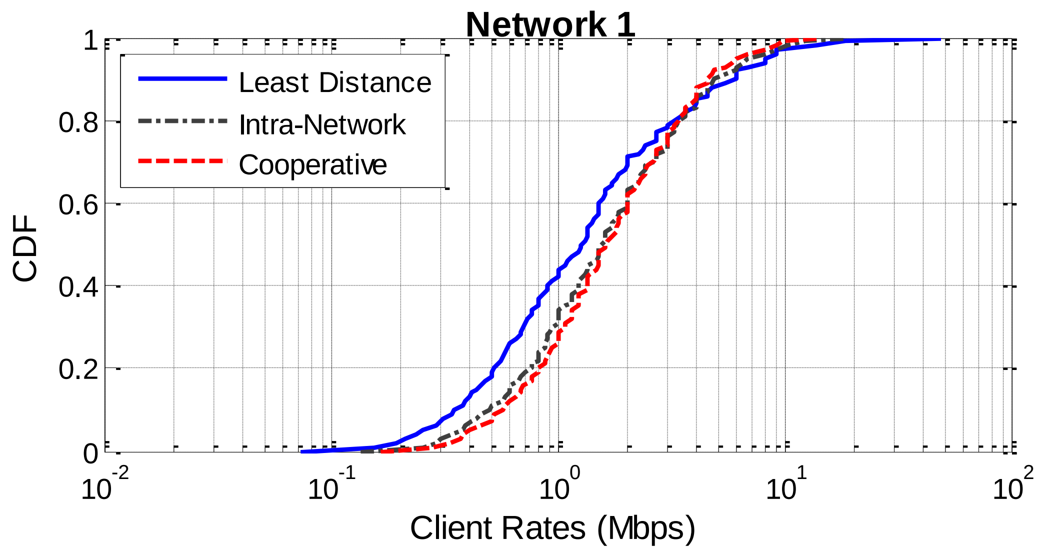
- 500 x 500m area
- Min. separation of 50m between APs of same network
- No minimum across networks



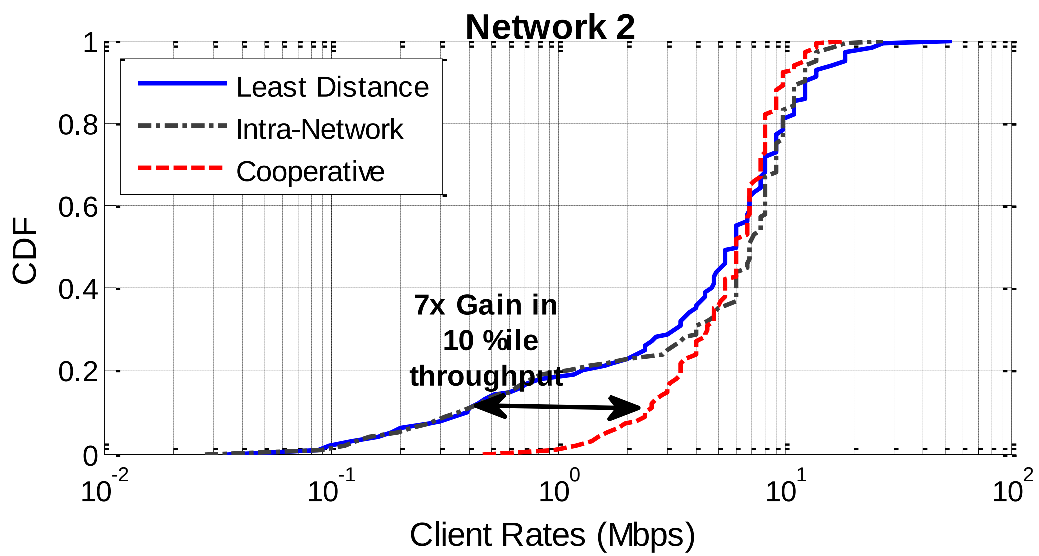
2x gains in low rate clients, slight gain in median

Clustered Deployment Results

- APs of Network 1 clustered in three 200x200m square regions



Net 1 APs are clustered
⇓
Effect of Net 2 APs is less
⇓
Info from Net 2 not very useful



Net 1 APs are clustered
⇓
Effect of the cluster of Net 1 APs on Net 2 is high
⇓
Info from Net 1 helps a lot

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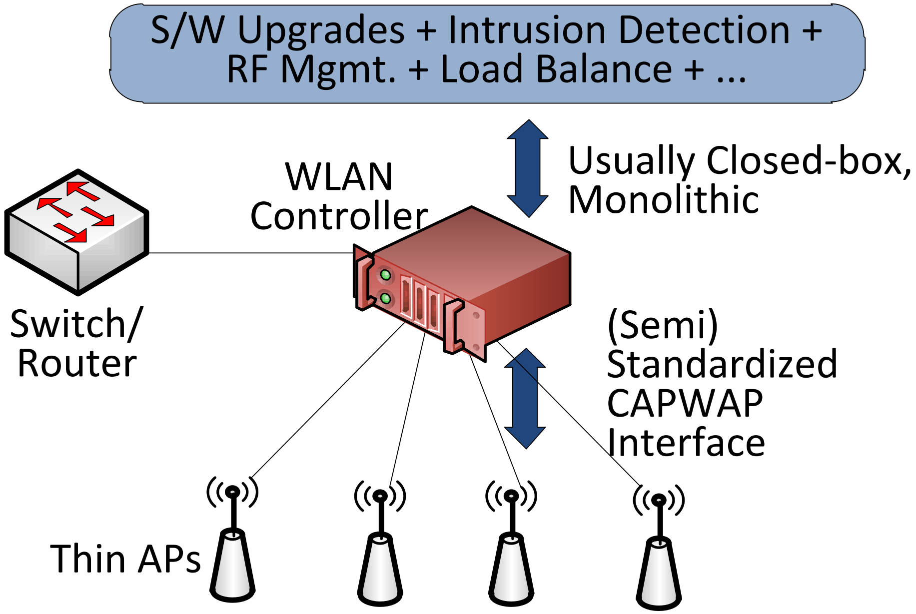
- ➢ Realizing inter-network cooperation
  - A SDN framework for the wireless control plane
  - Flexible switching of control messages
  - Example use-cases

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



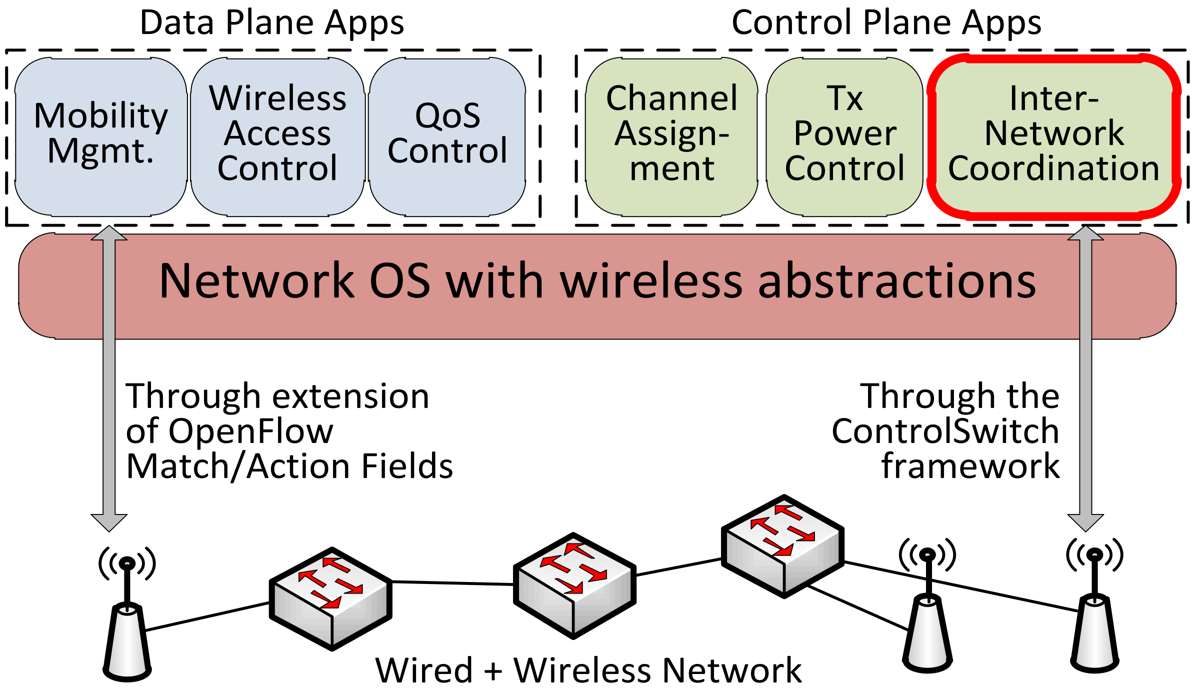
Typical architecture of the WLAN control plane

Major Drawbacks

- Closed: Only the vendor can add features
- Inflexible: Mix of distributed/centralized not easy
- Isolation: Controller-to-controller interaction is not possible

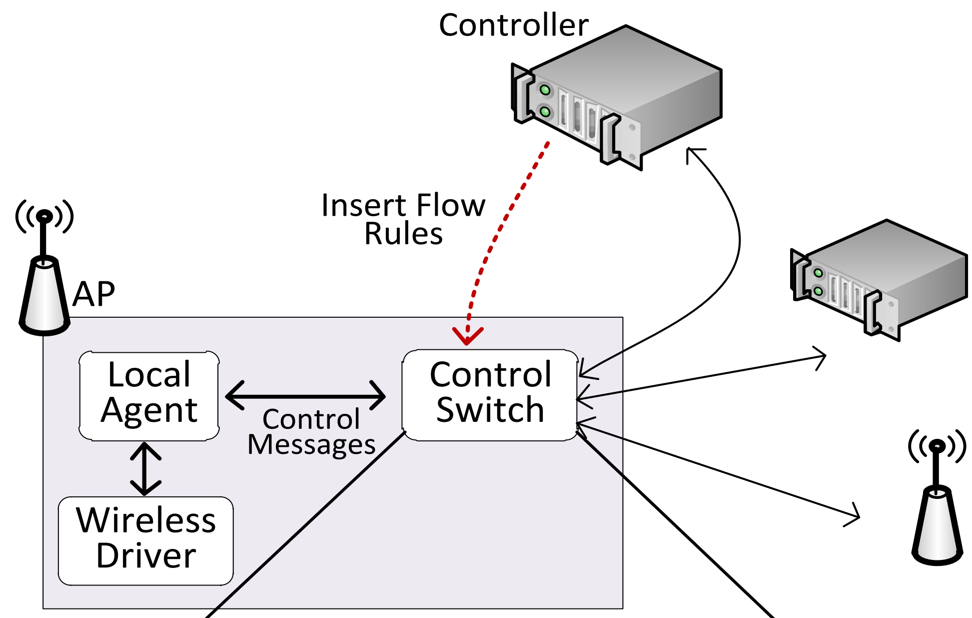
SDN Approach to wireless control plane

- 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



ControlSwitch

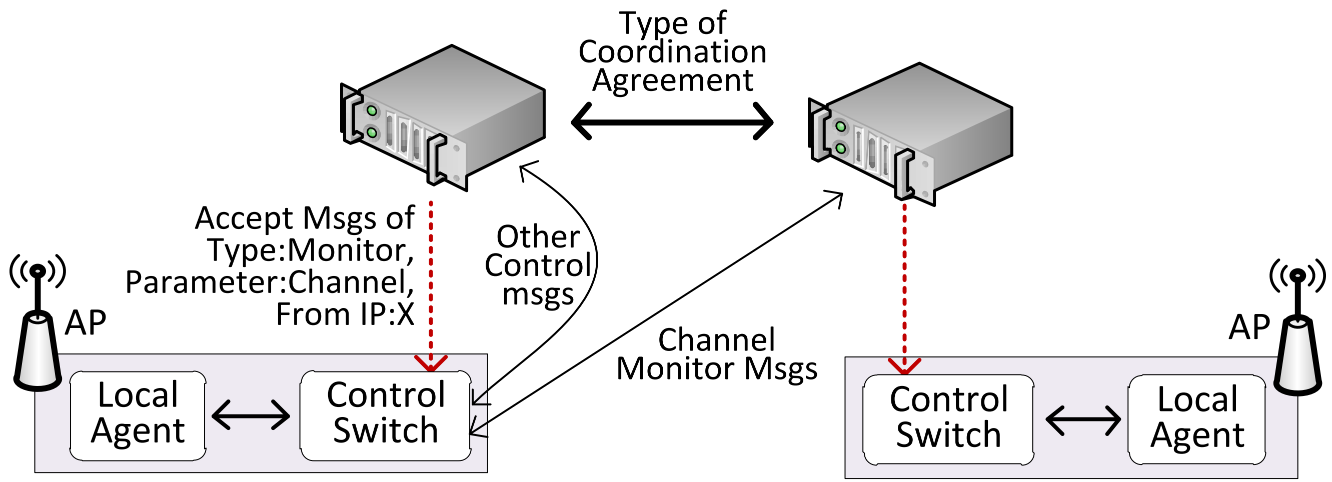
- Interpret wireless control messages as flows
- Software switch inside AP uses Match/Action rules to forward incoming and outgoing control-flows
- Control traffic can be forwarded to/from other APs or other controllers



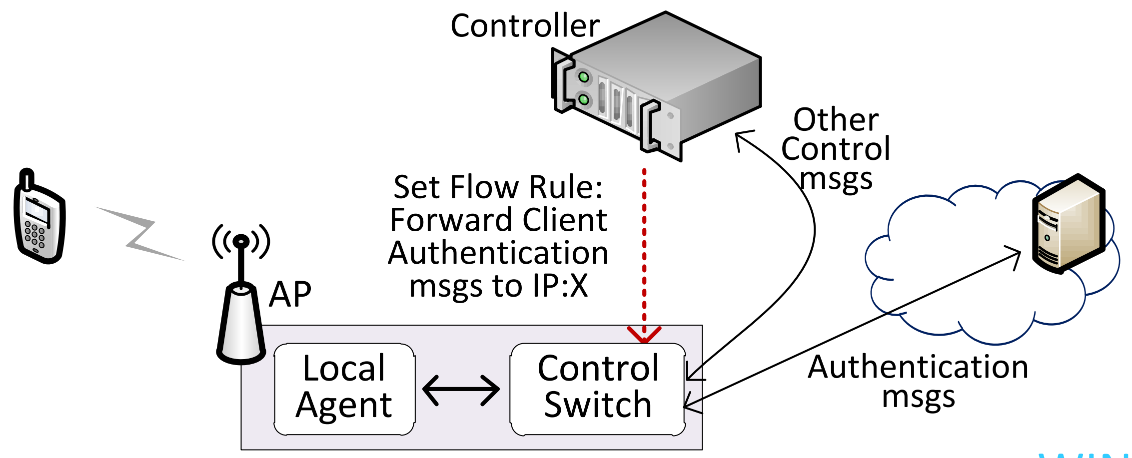
Match Fields					Action
Msg Type	Parameters	IP	Port	...	
Set	Channel				Forward to Port 1
Report	Beacons				Forward to IP1,IP2

Example Usage

1. Inter-network Cooperation:



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



Example Usage

3. Automatic failover to distributed control from central control:

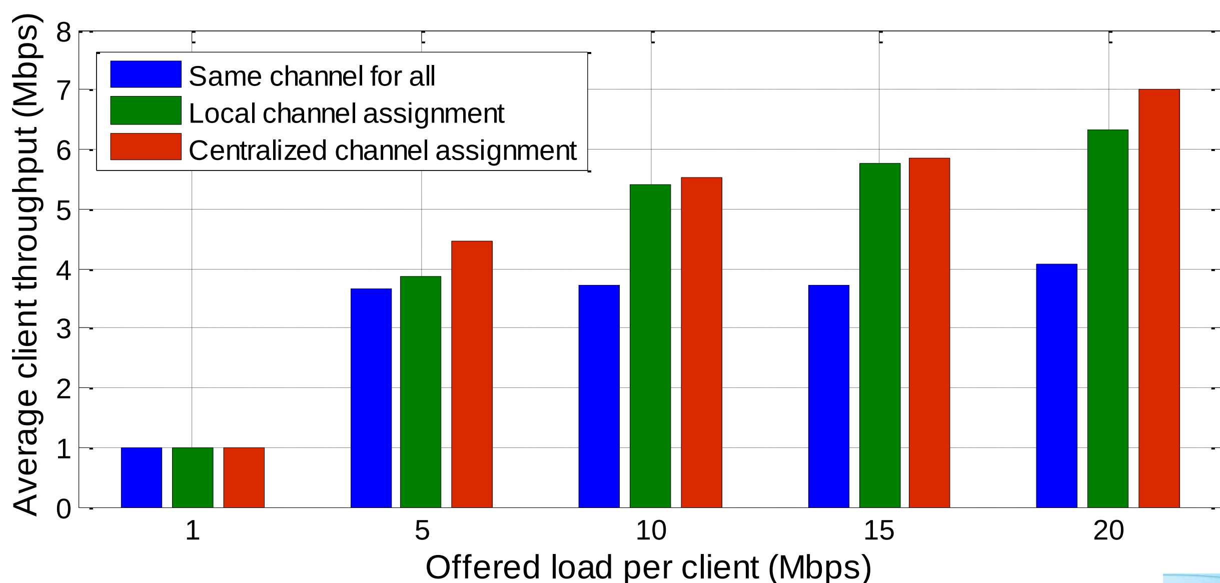
Controller refreshes rule periodically

Match Fields					Action
Msg Type	Parameters	IP	Port	…	
Discovery					Forward to Central Controller
Discovery					Forward to neighbors (IP1,IP2)

Higher priority but shorter expiry time

4 AP-4 client topology

Switch between local & centralized channel assignment



Ongoing Work

- Defined a wireless controller-to-controller API as an extension of the OpenFlow API
- Exploring technology-agnostic, practical techniques of aggregated 'radio-map' sharing between networks

Per-Transceiver Information	
Frequency Domain	Power Spectral Density Mask: Start-stop frequencies & corresponding Tx power level
Time Domain	Avg. Duty Cycle | Scheduled/Random Access
Physical Characteristics	X, Y, Z Coordinates | Outdoor/Indoor | Antenna Height | No. of Antennas | Antenna Directionality
Receiver Characteristics	Rx Sensitivity in dB |
Adaptation Logic	Freq. Change Algorithm | Rate Control Algorithm
Aggregate Information	
Estimated aggregate interference power map: dBm v/s location & frequency table	
Estimated spectrum occupancy ranking: Ordered list of most-free frequencies	

Conclusions

- Interactions between overlapping managed wireless networks are not clearly understood
- Simple cooperative schemes can help each network in its performance optimizations
- A general wireless control plane framework is required to facilitate inter-network cooperation
- Ideas from and the framework of SDN look promising for building a flexible, generic wireless control plane

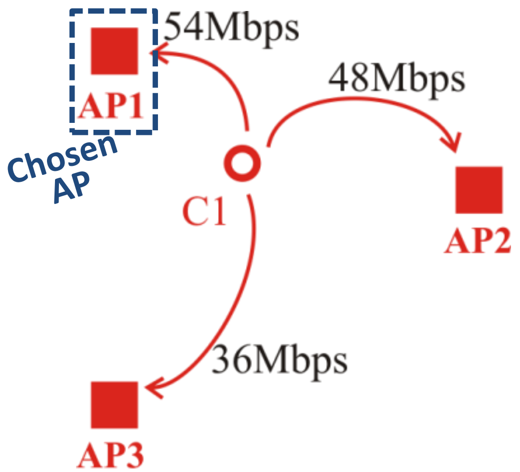
Thanks !

Questions?

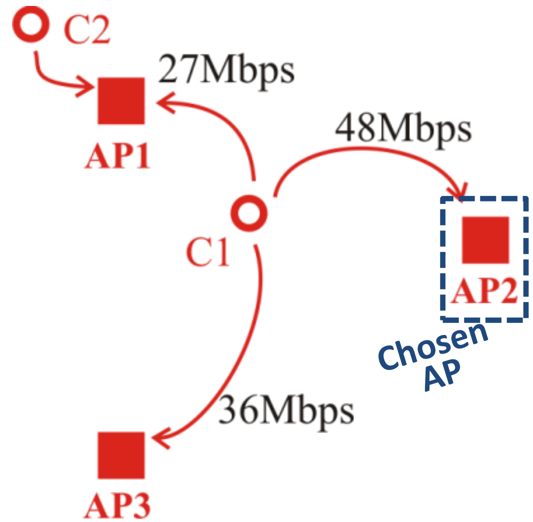
Extras

Motivating Example

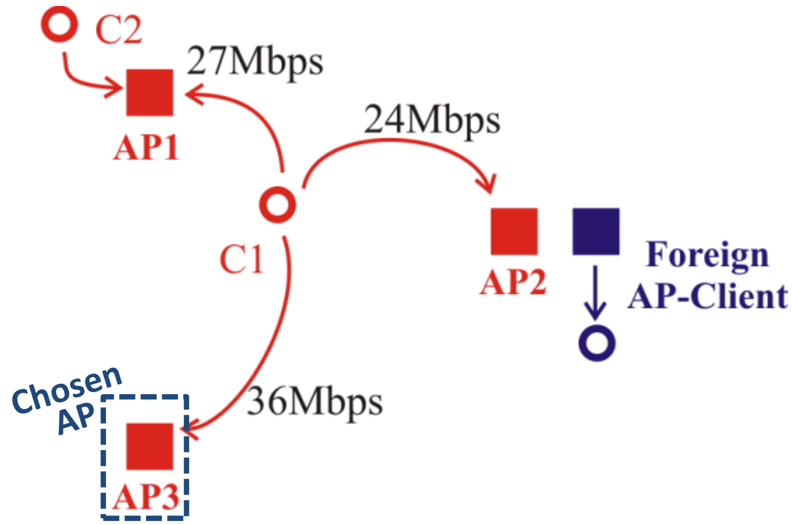
Default Selection: Closest AP



Intra-Network Optimization



Inter-Network Optimization



$\lvert A_i \rvert$	$\lvert U_i \rvert$	10 %ile throughput(Mbps)			Mean throughput(Mbps)		
		Least Dist.	Intra Optim.	Coop. Optim.	Least Dist.	Intra Optim.	Coop. Optim.
15	150	0.09	0.13	0.19	0.7	0.66	0.62
25	150	0.1	0.14	0.27	0.78	0.77	0.71
35	150	0.11	0.14	0.31	0.85	0.85	0.77
25	50	0.21	0.33	0.64	1.95	2.17	2
25	150	0.1	0.14	0.27	0.78	0.77	0.71
25	250	0.07	0.09	0.17	0.49	0.47	0.43