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

**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, A2 params, ...

**Algorithm & policy negotiation**

**Spectrum info exchange**

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**Aggregate radio map**
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- Technology type: Wi-Fi
- Device list: B1 params, B2 params, ...

**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)
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- 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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$x_{ij}(k)$</td>
<td>connection state between the $j^{th}$ client and $k^{th}$ AP of the $i^{th}$ network</td>
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<tr>
<td>$p_{ij}(k)$</td>
<td>fraction of time provided by the AP to the client</td>
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<tr>
<td>$r_{ij}(k)$</td>
<td>effective bit rate</td>
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<tr>
<td>$B_{ik}$</td>
<td>set of co-channel foreign APs within carrier sense range</td>
</tr>
<tr>
<td>$C_{ik}$</td>
<td>set of co-channel foreign APs outside carrier sense but within interference range (potential hidden nodes)</td>
</tr>
</tbody>
</table>
 Optimization Problem

Intra-network Optimization:

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

subject to: \[ p_{ij}(k) = \frac{1}{\sum_{j' \in U_i} x_{ij'}(k)} \quad \forall k \in A_i, j \in U_i \]
\[ \sum_{k \in A_i} x_{ij}(k) = 1 \quad \forall j \in U_i \]
\[ x_{ij}(k) \in \{0, 1\} \quad \forall k \in A_i, j \in U_i \]

Cooperative inter-network Optimization:

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

subject to: \[ p_{ij}(k) = \frac{1}{\sum_{j' \in U_i} x_{ij'}(k) \cdot (1 + |B_{ik}|)(1 + \alpha|C_{ik}|)} \quad \forall k \in A_i, j \in U_i, i \in [1, N] \]
\[ \sum_{k \in A_i} x_{ij}(k) = 1 \quad \forall j \in U_i, i \in [1, N] \]
\[ x_{ij}(k) \in \{0, 1\} \quad \forall k \in A_i, j \in U_i, i \in [1, N] \]

This information is through info-sharing between networks
Simulation Details

• Both are non-linear integer programs:
  – \((2 + \varepsilon)\) 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

CDF

90% of Clients above 230 Kbps
90% of Clients above 550 Kbps
Clustered Deployment Results

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

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

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

Typical architecture of the WLAN control plane
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
Example Usage

1. Inter-network Cooperation:

   - Accept Messages of Type: Monitor, Parameter: Channel, From IP: X
   - Other Control Messages
   - Type of Coordination Agreement
   - Channel Monitor Messages

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

   - Set Flow Rule: Forward Client Authentication Messages to IP: X
   - Other Control Messages
   - Authentication Messages
Example Usage

3. Automatic failover to distributed control from central control:

- Controller refreshes rule periodically
- Match Fields
  | Msg Type | Parameters | IP | Port | ... | Action
  |----------|------------|----|------|------|--------
  | 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

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Frequency Domain</td>
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<tr>
<td>Time Domain</td>
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<tr>
<td>Physical Characteristics</td>
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<tr>
<td>Receiver Characteristics</td>
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<tr>
<td>Adaptation Logic</td>
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<th>Aggregate Information</th>
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<tr>
<td>Estimated aggregate interference power map: dBm v/s location &amp; frequency table</td>
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<tr>
<td>Estimated spectrum occupancy ranking: Ordered list of most-free frequencies</td>
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</tbody>
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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?
Motivating Example

Default Selection: Closest AP

Intra-Network Optimization

Inter-Network Optimization
| $|A_i|$ | $|U_i|$ | 10 $\%$ile throughput(Mbps) | Mean throughput(Mbps) |
|---|---|---|---|
| | | Least | Intra | Coop. | Least | Intra | Coop. |
| 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 |