Fair and Efficient Operation of Virtualized Dense 802.11 WLANs: Challenges and Enablers

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Motivation: Dense networks

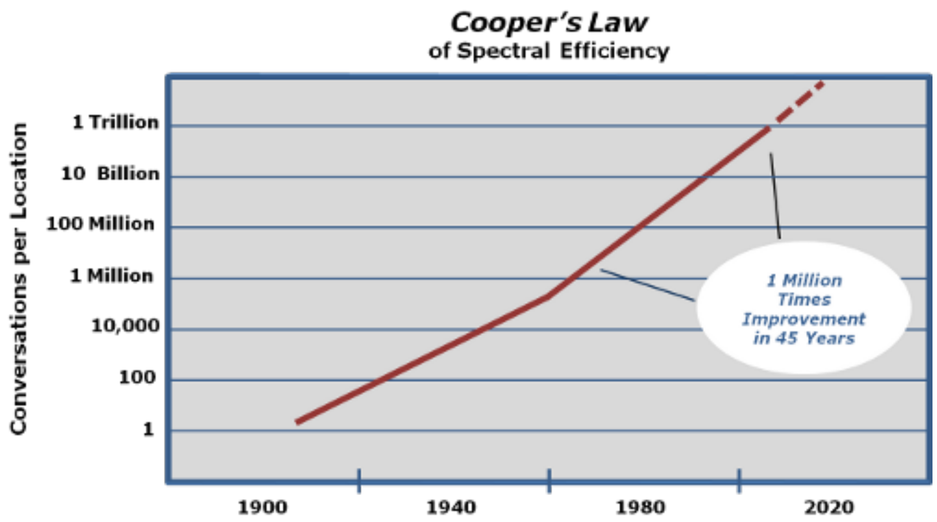
- Scenario
  - 5000 people/km^2
    - London, Madrid
  - 20% mobile, demanding 1 Mbps
  - 1 Gbps/km^2

http://www.ict-crowd.eu

- Demand is expected to increase ten-fold in the next 5 years
  - Cisco Visual Networking Index 2010-2015

Cooper's Law (I)

- Rate of improvement in use of the radio spectrum for personal communications has been essentially uniform for 104 years



http://www.arraycomm.com/technology/coopers-law/

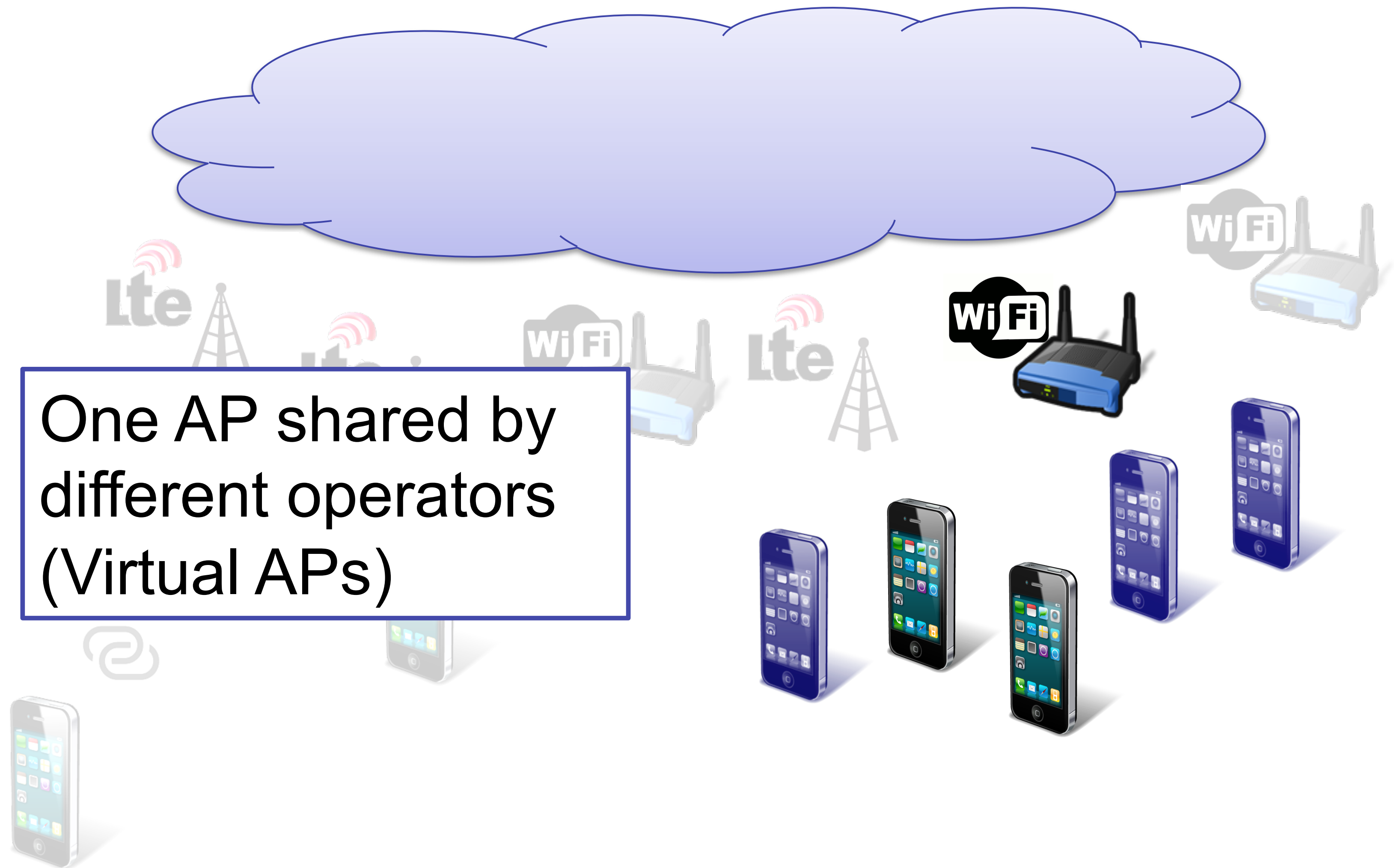
Cooper's Law (II)

- 10^6 improvement in the last 45 years:
  - 25x: being able to use more spectrum
  - 5x: ability to divide the radio spectrum into narrower slices (frequency division)
  - 5x: FM, time division multiplexing, and various approaches to spread spectrum
  - 1600x: confining the area used for individual conversations to smaller and smaller areas

Dense deployments

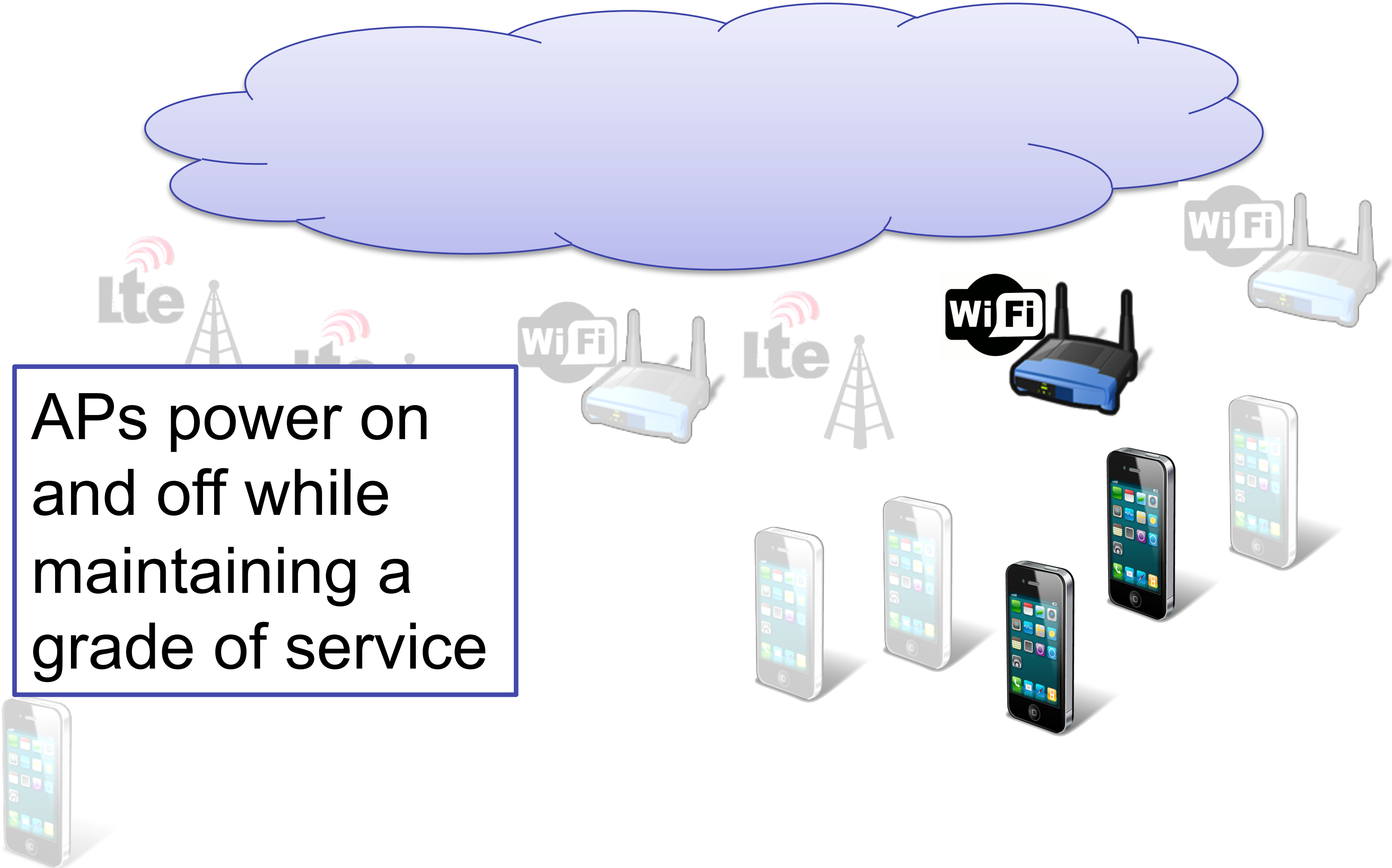
Scenario & Outline

Part I: Virtualized WiFi Access



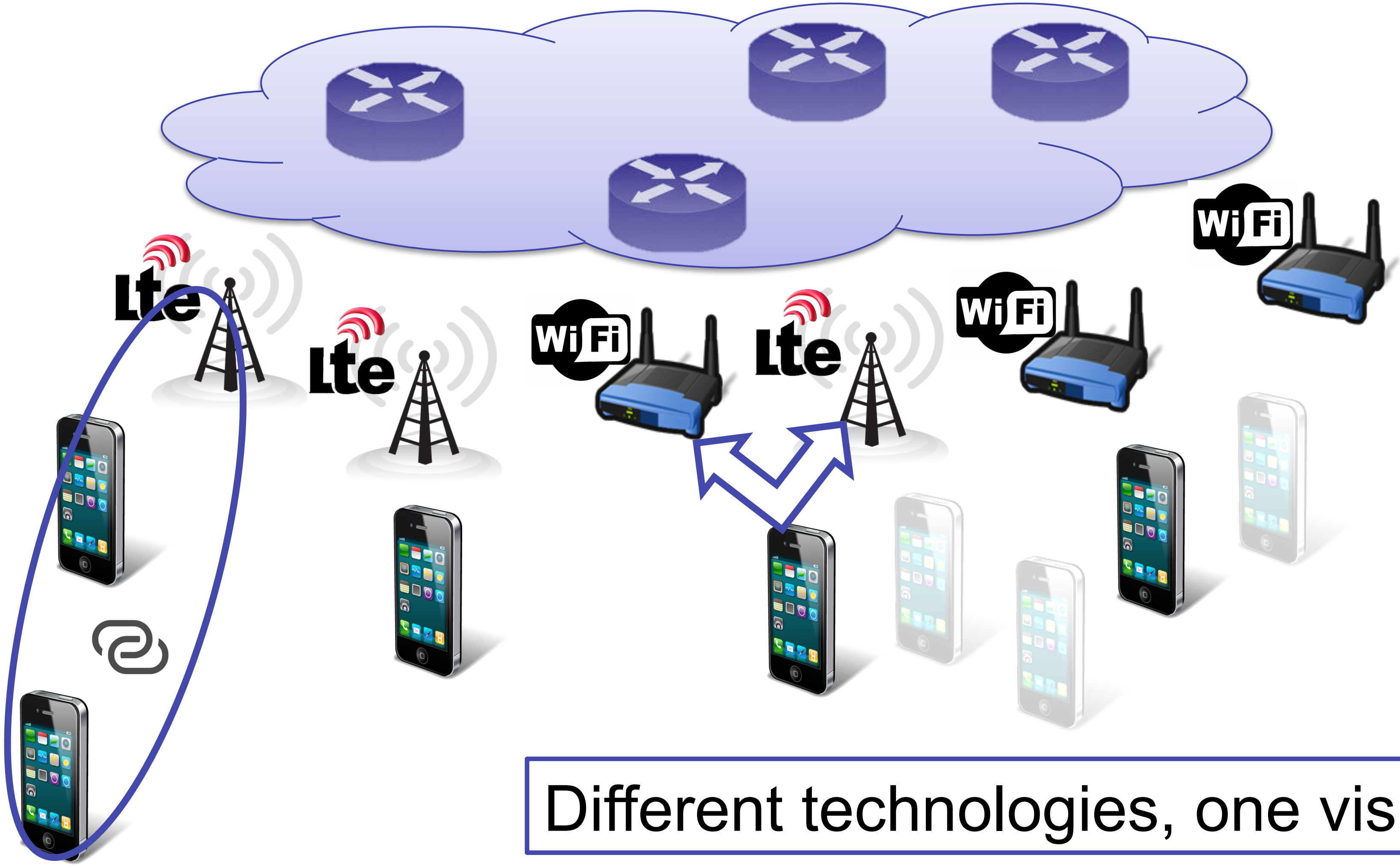
One AP shared by different operators (Virtual APs)

Part II: Infrastructure on Demand (WiFi)



APs power on and off while maintaining a grade of service

Part III: Controlling all together



Different technologies, one vision

Part I: Optimizing a Virtualized WiFi Access

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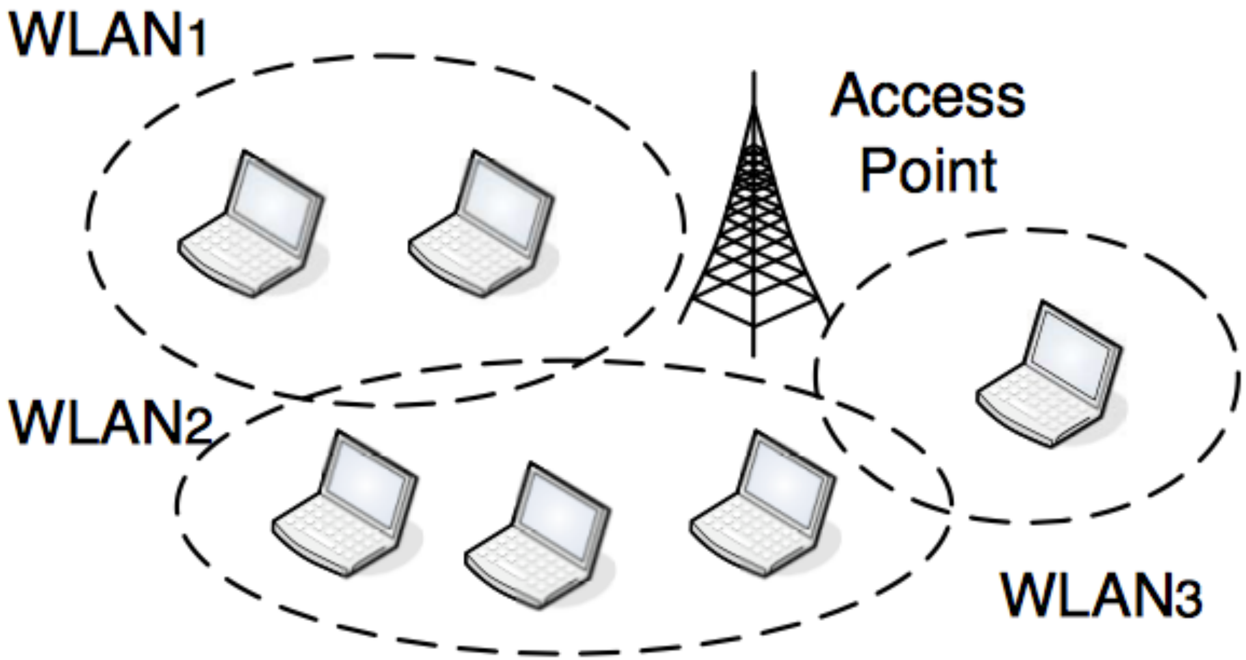
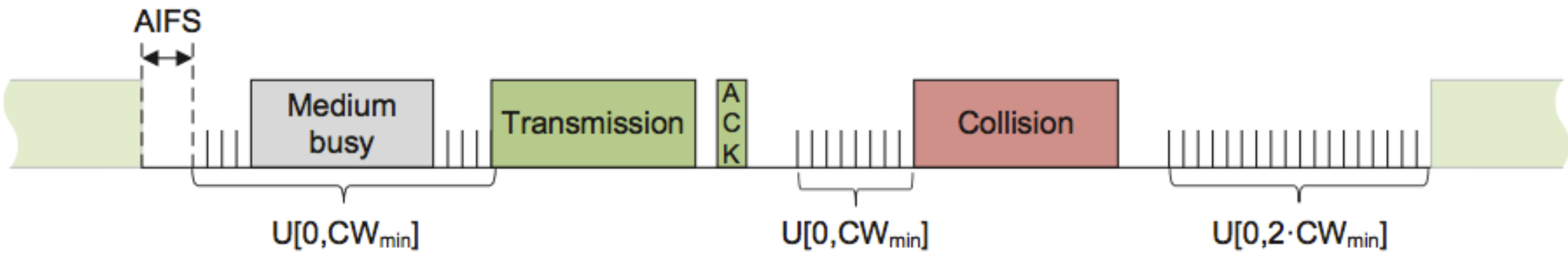
Scenario and Challenge



- $WLAN_2$ gets 50% of the BW
- $WLAN_1$ the 66% of the remaining BW

System Model



- N virtual WLANs
- Each with n_i stations, CW_i
- All in range of each other, good links
- All clients in saturation conditions
  - Focus on UL (DL is easier)

System Model

- A station transmits in a slot time with prob.

$$\tau_i = \frac{2}{CW_i + 1}$$

- Throughput obtained by VAP_i

$$R_i = \frac{\mathbb{E}[\text{Payload } VAP_i]}{\mathbb{E}[\text{slot length}]} = \frac{S_i L}{P_e T_e + (1 - P_e) T_o}$$

- Where

$$P_e = \prod (1 - \tau_k)^{n_k}$$

$$S_i = n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{k \neq i} (1 - \tau_k)^{n_k} = \frac{n_i \tau_i}{1 - \tau_i} P_e$$

Optimization objectives

1) All VAPs get the same throughput when the network is loaded, regardless of n_i's

$$R_i = R_j \quad \forall i, j$$

2) The overall network performance is maximized

$$\max \sum R_i$$

Computing the optimal configuration

- 1st objective:

$$\frac{n_i \tau_i}{1-\tau_i} = \frac{n_j \tau_j}{1-\tau_j}, \text{ assuming } \tau_i \ll 1 \rightarrow n_i \tau_i \approx n_j \tau_j$$

- 2nd objective:

$$\frac{dR_i}{d\tau_i} = 0 \rightarrow \tau_i^* = \frac{1}{N n_i}\sqrt{\frac{2T_e}{T_o}}, CW_i^* = \frac{2}{\tau_i^*} - 1$$

About the optimal point of operation

- When all nodes use the optimal CW*

$$P_e^* = \prod_k \left(1 - \frac{1}{Nn_k}\sqrt{\frac{2T_e}{T_o}}\right)^{n_k} \approx e^{-\sqrt{\frac{2T_e}{T_o}}}$$

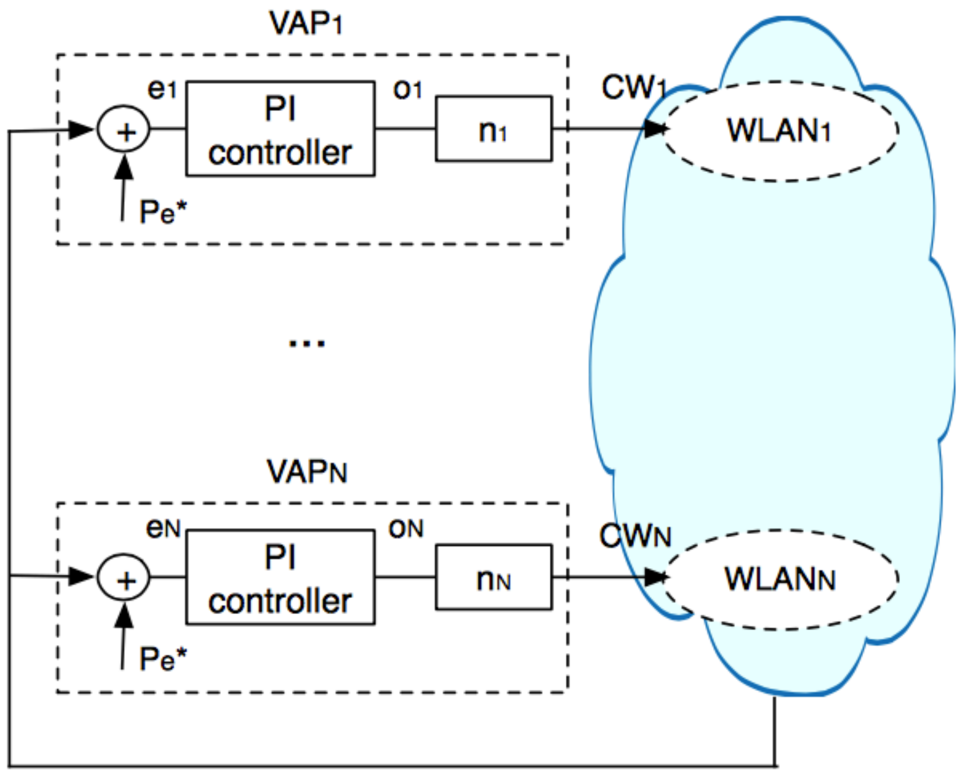
- **Result**: under optimal operation, the probability of an empty slot is constant (independent of N, n_i's).

Control-theoretic optimization of VAPs

- Use P_e^* as a *reference signal*, to assess how far the network is operating from the optimal point and react accordingly
- Challenge: how to properly react
  - Too quick: system may turn unstable
  - Not quick enough: poor performance
- Approach: use control theory

Control theoretic optimization of VAPs

- Each VAP runs an independent PI controller
- All running on the same device
- Each with error signal e_i and output signal o_i



Design of C-VAP: error signal

- Objectives where
  1) Maximize throughput
  2) Provide fairness

- Error signal: the sum of two terms

$$e_{opt} = P_e^* - P_e$$

$$e_{fair,i} = (N-1)S_i - \sum_{j \neq i} S_j$$

Design of C-VAP: error signal

- Adding both terms

$$e_i = e_{opt} + e_{fair,i} = P_e^* - P_e + (N-1)S_i - \sum_{j \neq i} S_j$$

- There exists a **unique** solution to the system e_i=0, that satisfies

$$e_{opt} = e_{fair,i} = 0 \ \forall i$$

Design of C-VAP: configuration of PI

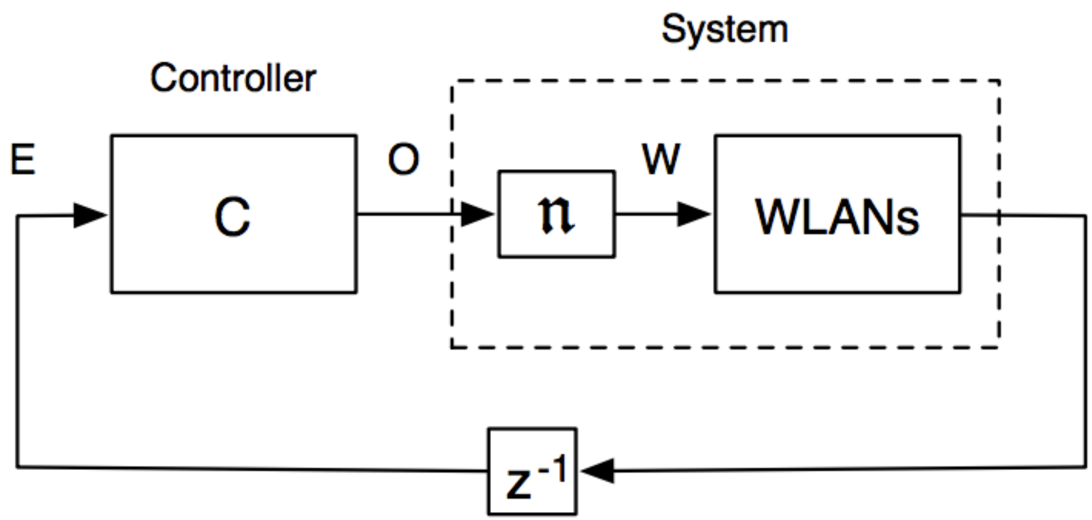
- Each VAP runs a PI controller
- z-transform of the controller

$$C_{PI}(z) = K_P + \frac{K_I}{z-1}$$

- Need to set the right trade-off
  - Stability under steady-state conditions
  - Reaction to changes

Controller Analysis

- Model



- With

$$E = \begin{pmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{pmatrix}, O = \begin{pmatrix} o_1 \\ o_2 \\ \vdots \\ o_N \end{pmatrix} \text{ and } W = \begin{pmatrix} CW_1 \\ CW_2 \\ \vdots \\ CW_N \end{pmatrix}.$$

Controller Analysis

- Relation between E and W

$$W(z) = \mathfrak{N} \cdot O = \mathfrak{N} \cdot C \cdot E(z),$$

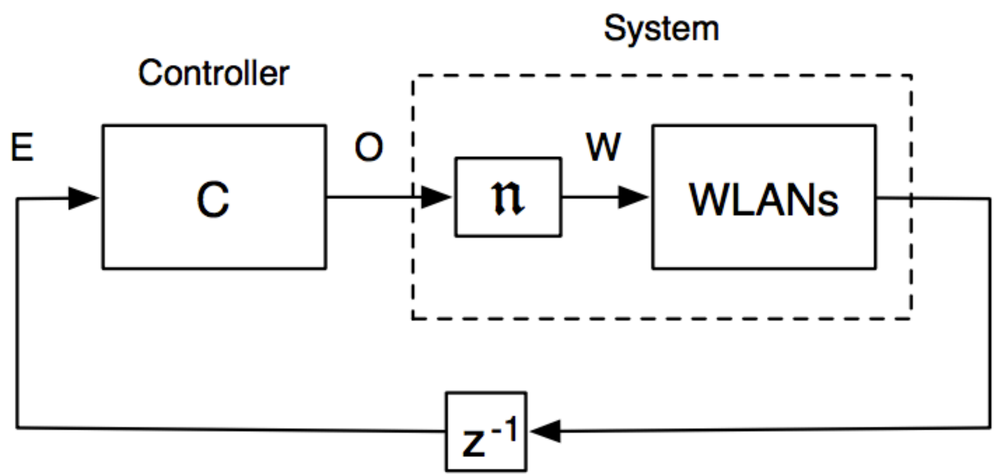
- With

$$\mathfrak{N} = \begin{pmatrix} n_1 & 0 & \cdots & 0 \\ 0 & n_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & n_N \end{pmatrix},$$

$$C = \begin{pmatrix} C_{PI}(z) & 0 & \cdots & 0 \\ 0 & C_{PI}(z) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & C_{PI}(z) \end{pmatrix},$$

Controller Analysis & Configuration

- Challenge: find the transfer function H that takes as input o_i's and provides e_i's, which is a non-linear relation



- Solution: linearize it around the desired point of operation

Controller Configuration

- To ensure stability, enforce zeros of the pole polynomial of $(I-z^{-1}CH)^{-1}C$ fall within the unit circle

$$K_I < K_P < \frac{NT_o}{P_e^* T_e} + \frac{1}{2}K_I$$

- Apply *Ziegler-Nichols* to find the right trade-off

$$K_P = 0.4\frac{T_o}{P_e^* T_e}$$

$$K_I = \frac{0.2}{0.85}\frac{T_o}{P_e^* T_e}$$

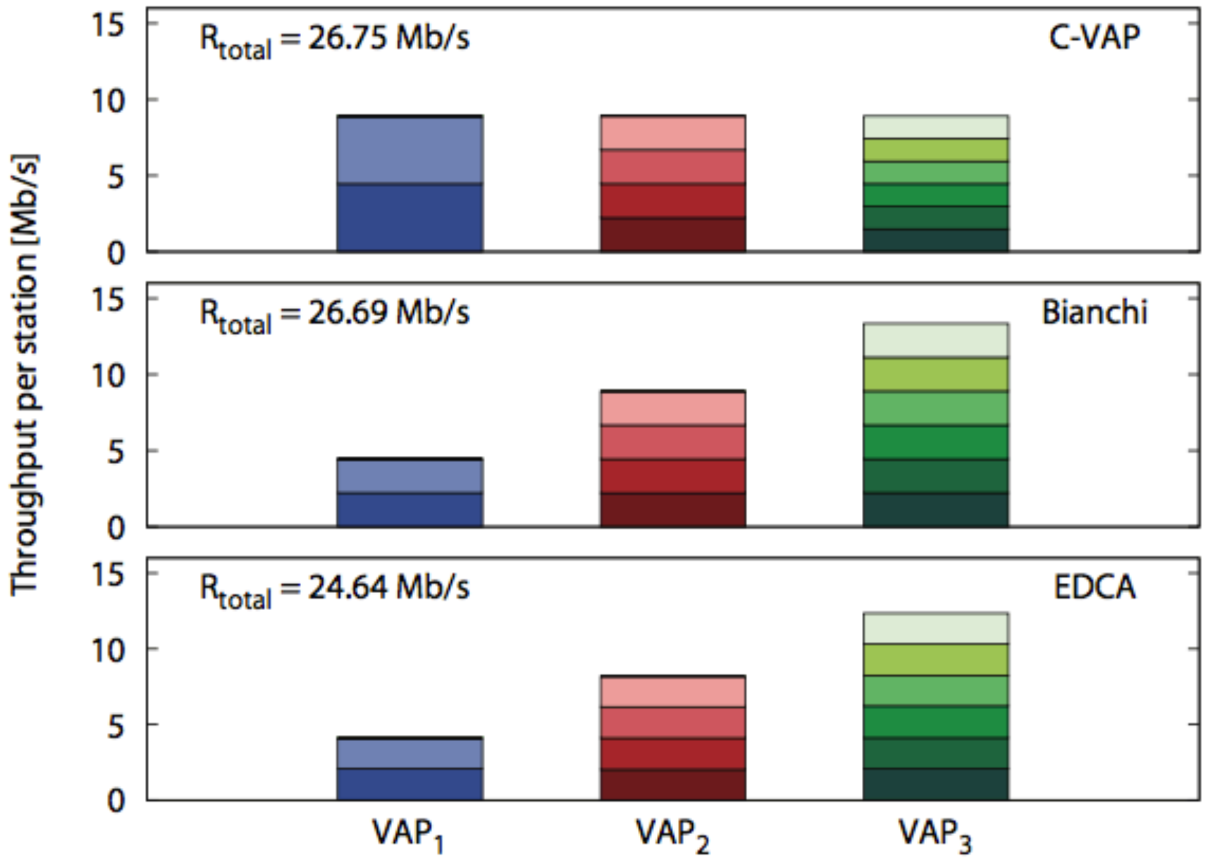
Evaluation - Sims

- IEEE 802.11a PHY
- No: noise, hidden terminals, capture effect
- 1000 B frames
- 10 simulation runs, 5’ each

- Compare C-VAP vs.
  – Default EDCA configuration (‘EDCA’)
  – Static, throughput-optimal CW (‘Bianchi’)

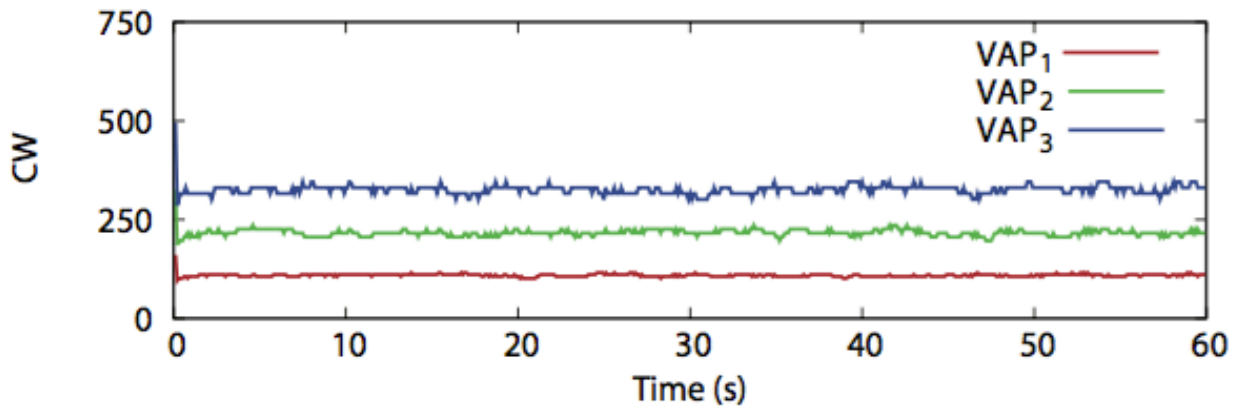
Throughput (and Fairness)

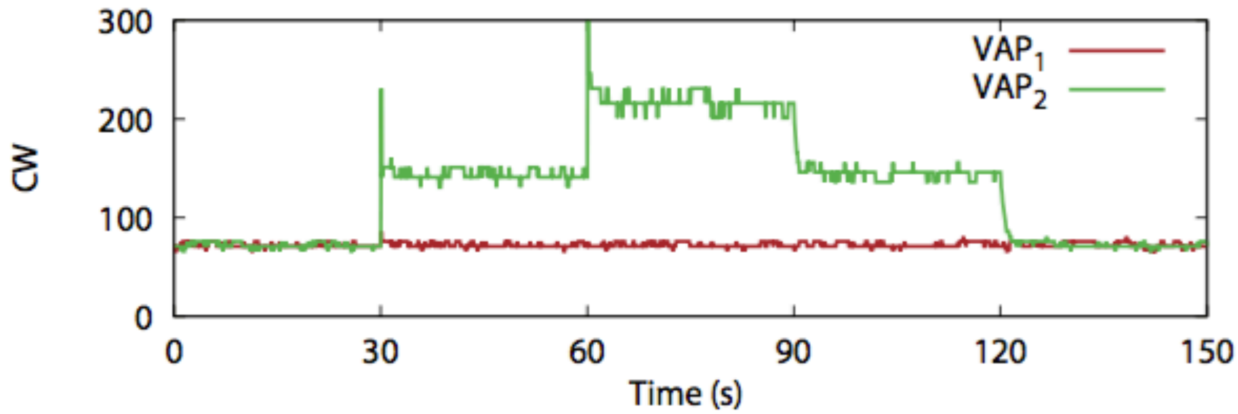
- 3 VAPs, with n={2,4,6} saturated stations



Validation of the Configuration

- Stability: $n_i = 5 \cdot i$

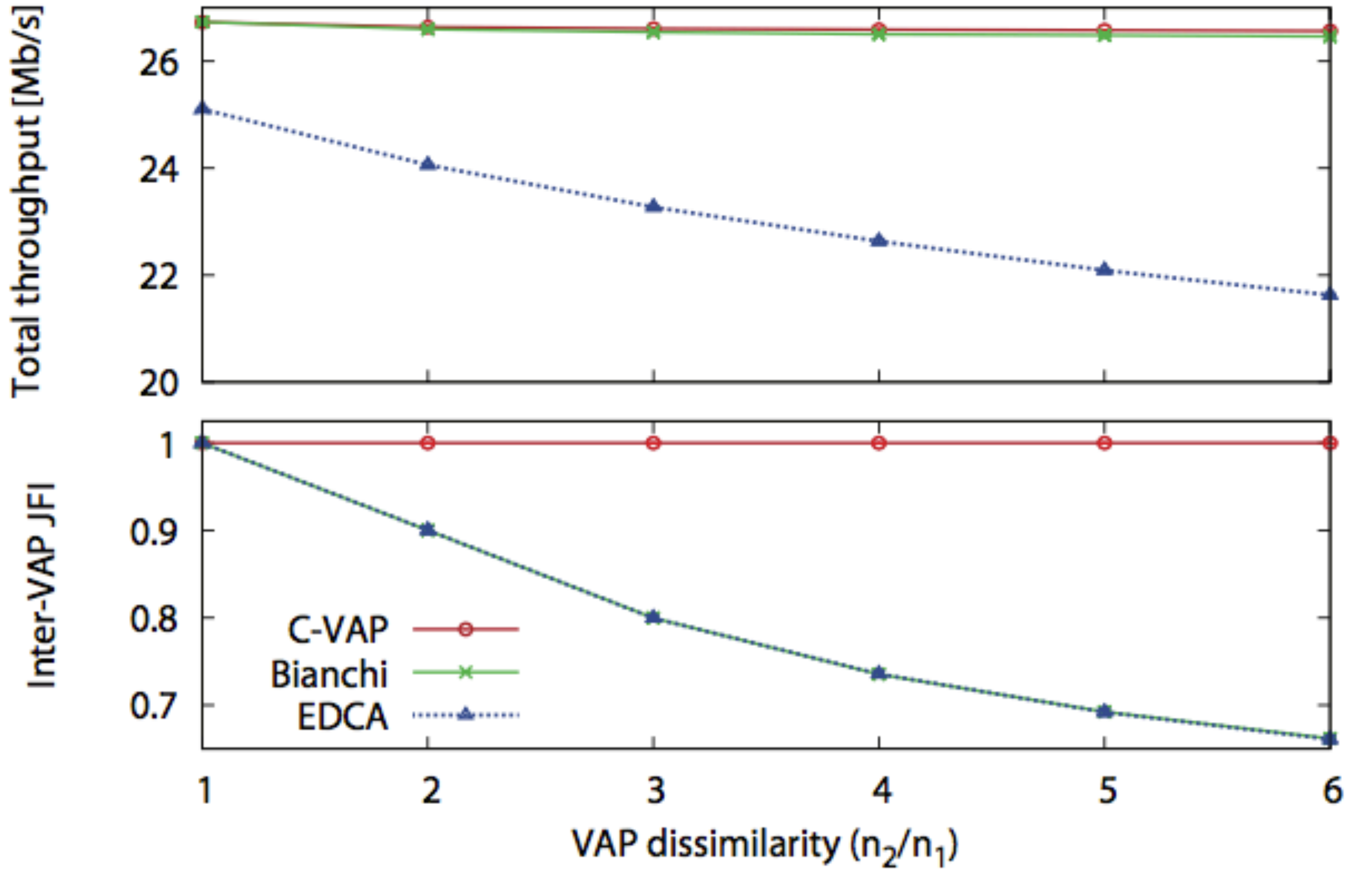




- Reaction: adding / removing 5 stations

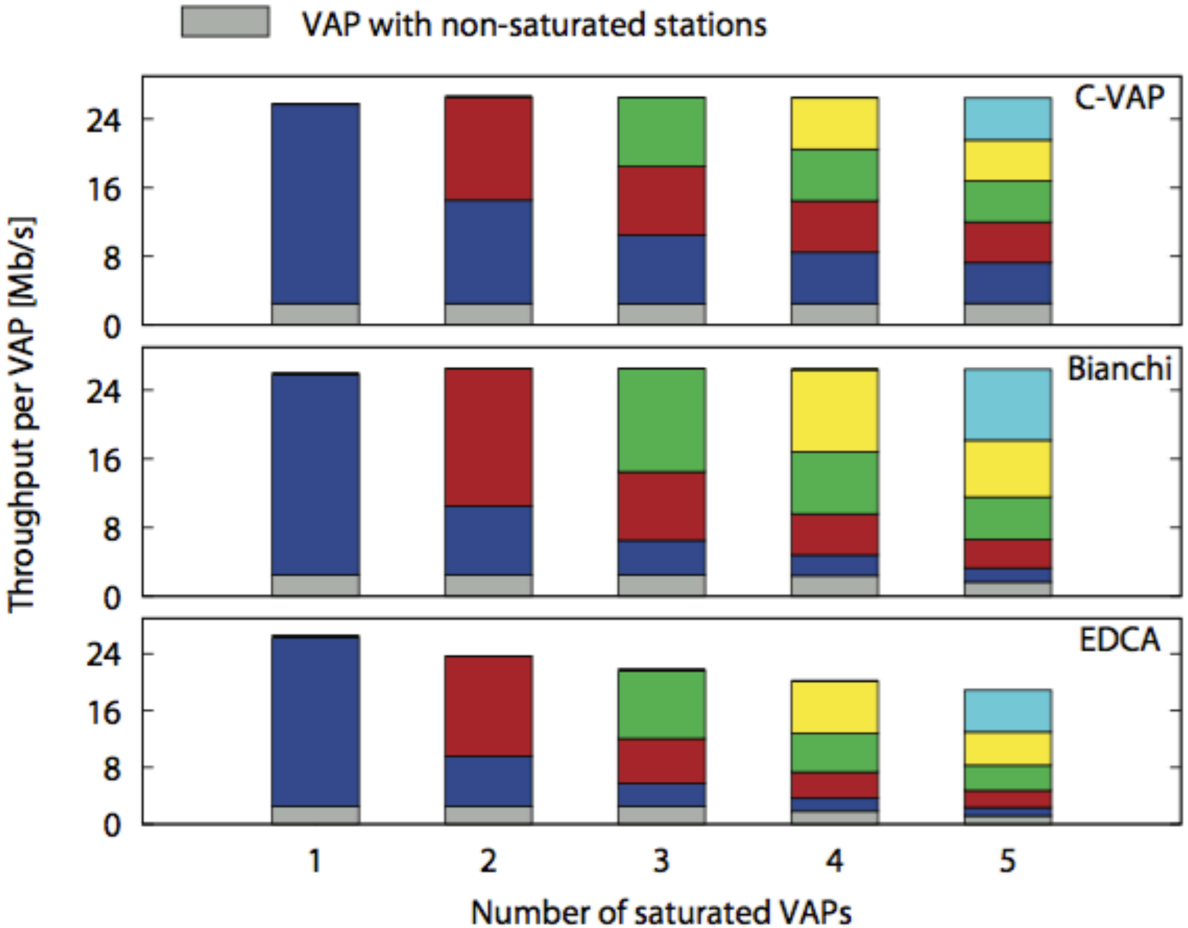
Impact of ≠ number of users

- 2 VAPs, n_1=5, n_2 varies



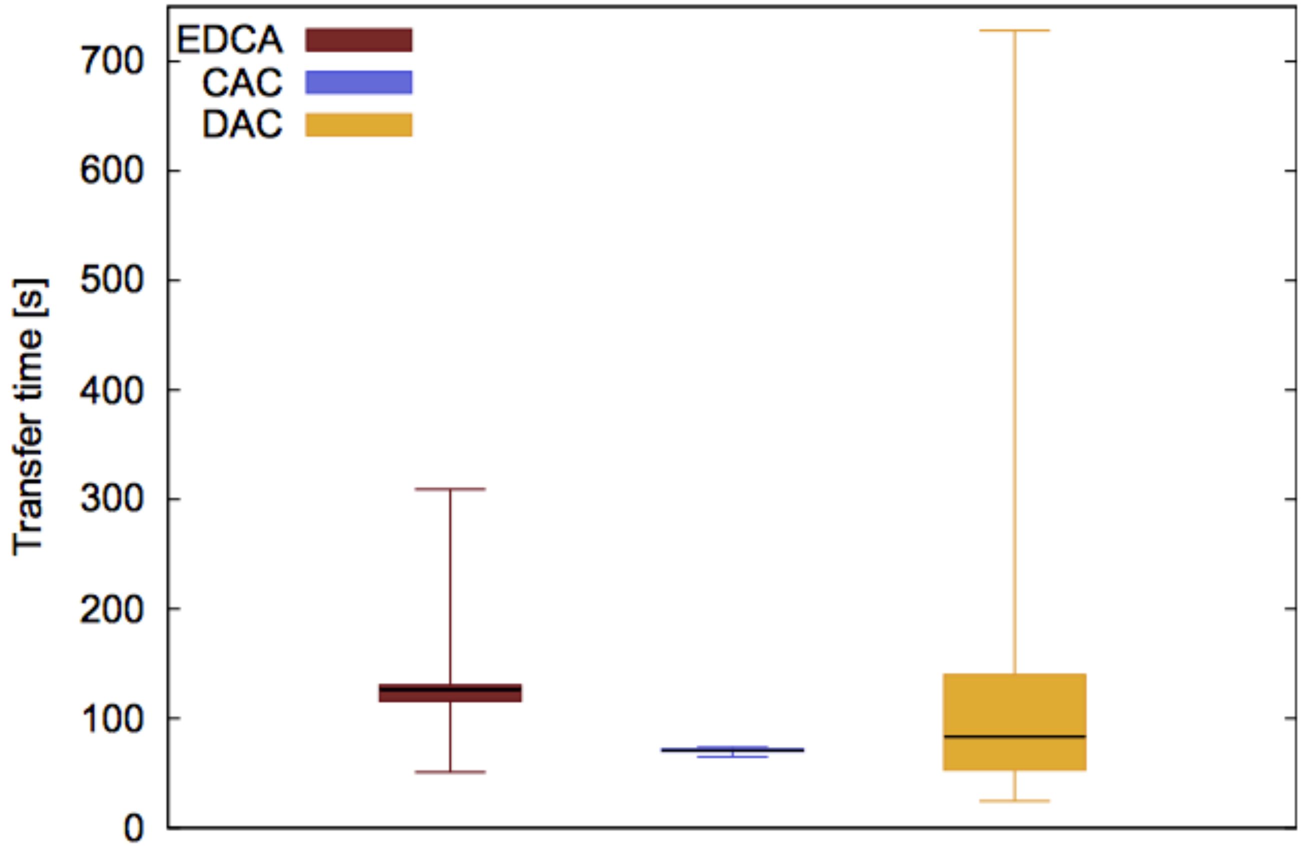
Mixed Traffic Conditions

- VAP_0: 5 non-sat (500 kbps), VAP_i: n_i sat



Extra: Non-saturation with CAC

- Similar algorithm (CAC), real devices
- 17 nodes
- TCP
- 10 MB



(a) $\lambda^{-1} = 30$ [s]

Summary

- C-VAP is implementable with existing hw
  - E.g. Broadcom BCM 4318 adapter
  - Virtual APs with hostapd
  - Count and measure slots
  - Broadcast CW configuration
- C-VAP maximizes performance
  - Throughput, fairness
  - Adapts to changes
  - Sat and non-sat conditions

Publications

Providing Throughput and Fairness Guarantees in Virtualized WLANs through Control Theory, A. Banchs, P. Serrano, P. Patras, M. Natkaniek, *Springer Mobile Networks and Applications, vol. 17, no. 4, August 2012.*

Control Theoretic Optimization of 802.11 WLANs: Implementation and Experimental Evaluation, P. Serrano, P. Patras, A. Mannocci, V. Mancuso, A. Banchs, *Elsevier Computer Networks, vol. 57, no. 1, January 2013.*

Providing Service Guarantees in 802.11e EDCA WLANs with legacy stations, A. Banchs, P. Serrano, L. Vollero, *IEEE Transactions on Mobile Computing, vol. 9, 2010*

Part II: WiFi Access Infrastructure on Demand

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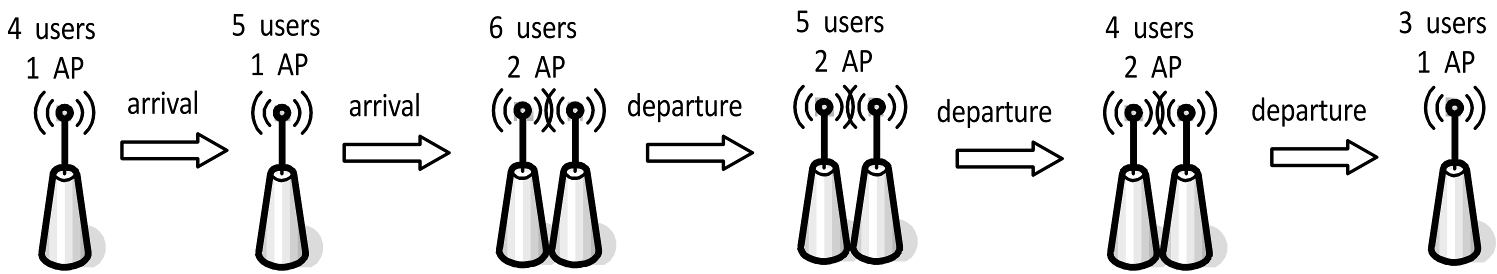
Motivation

- To cope with large traffic demands: increase the density of Access Points to increase capacity
- But when the network usage is low: need to switch off the APs (while maintaining coverage).



Example of powering on/off process for N_h = 5 and N_l = 3

Motivation

- Analytical model: first step to be able to configure these thresholds
- Not the first to analyze the scenario, e.g.
  - M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “A simple analytical model for the energy-efficient activation of access points in dense WLANs,” in Proceedings of e-Energy ’10. New York, NY, USA: ACM, 2010, pp. 159–168
  - A. P. C. da Silva, M. Meo, and M. A. Marsan, “Energy-performance trade-off in dense wlans: A queuing study,” Computer Networks, vol. 56, no. 10, pp. 2522 – 2537, 2012
- But these previous works consider zero start-up times

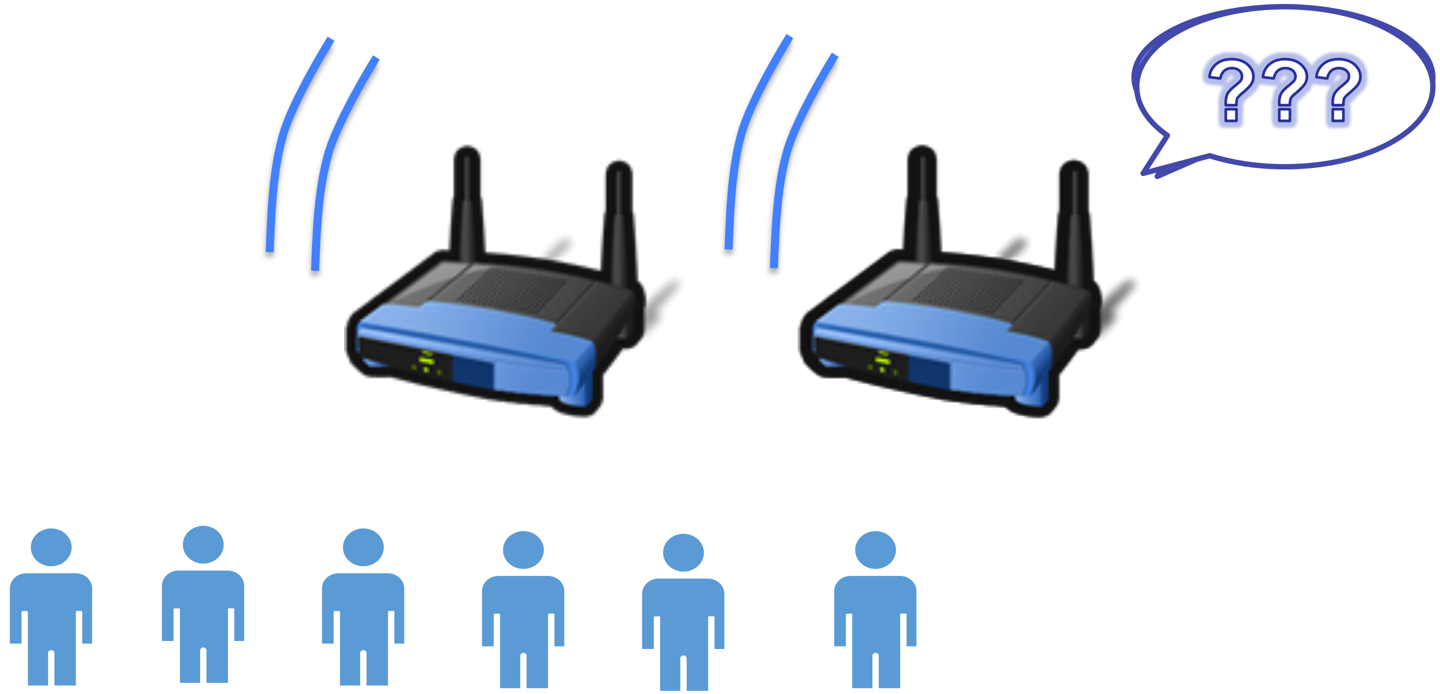
Some measurements

- Linksys WRT54GL with OpenWRT: 45s from powered off until it starts broadcasting beacon frames

OpenWrt
Wireless Freedom

From	To	Time
OFF	ON (2.7 W)	45 s
ON	OFF	3 s

Implications



Objective: characterize the impact of T_{on}

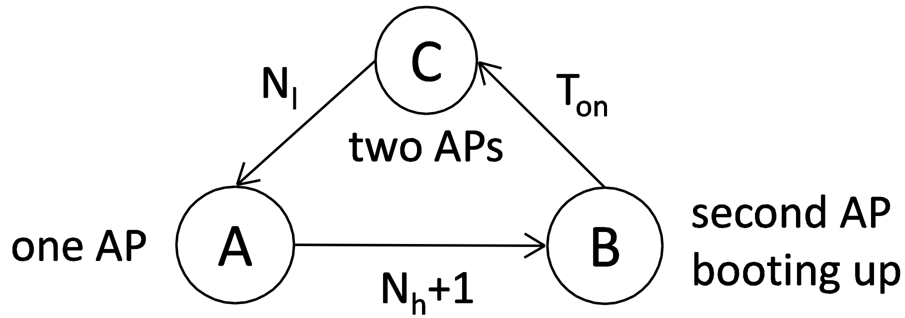
Model assumptions

- Two identical APs, same coverage area
  - The model for 3+ AP is on the way
- User arrives according to Poisson
- Demand exponential amount of work
- Threshold-based policy for 2nd AP
  - N_h+1 user arrives: ON
  - N_l users: OFF
- Users are moved in 0 time between APs

Performance Analysis

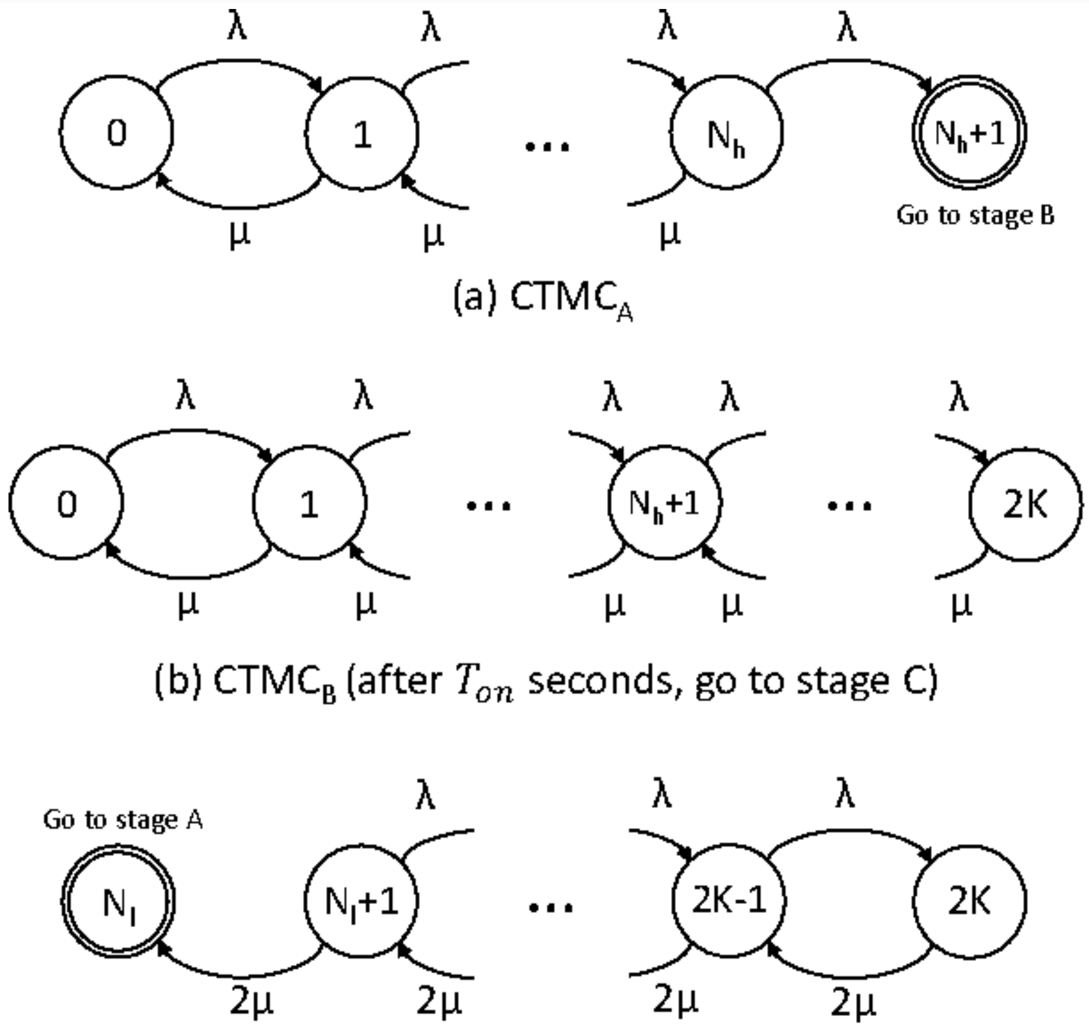
- There are 3 stages
  - Stage A: Only AP 1 operating
  - Stage B: AP 1 operating, AP 2 is booting-up
  - Stage C: both APs are operating

- 3 transitions
  - A -> B: N_h+1 users
  - B -> C: T_{on} passed
  - C -> A: N_l users



Each stage

- $CTMC_A$
  - AP 1 ON
  - AP 2 OFF
- $CTMC_B$
  - AP 1 ON
  - AP 2 Boot
- $CTMC_C$
  - AP 1 ON
  - AP 2 OFF



(a) $CTMC_A$

(b) $CTMC_B$ (after T_{on} seconds, go to stage C)

(c) $CTMC_C$

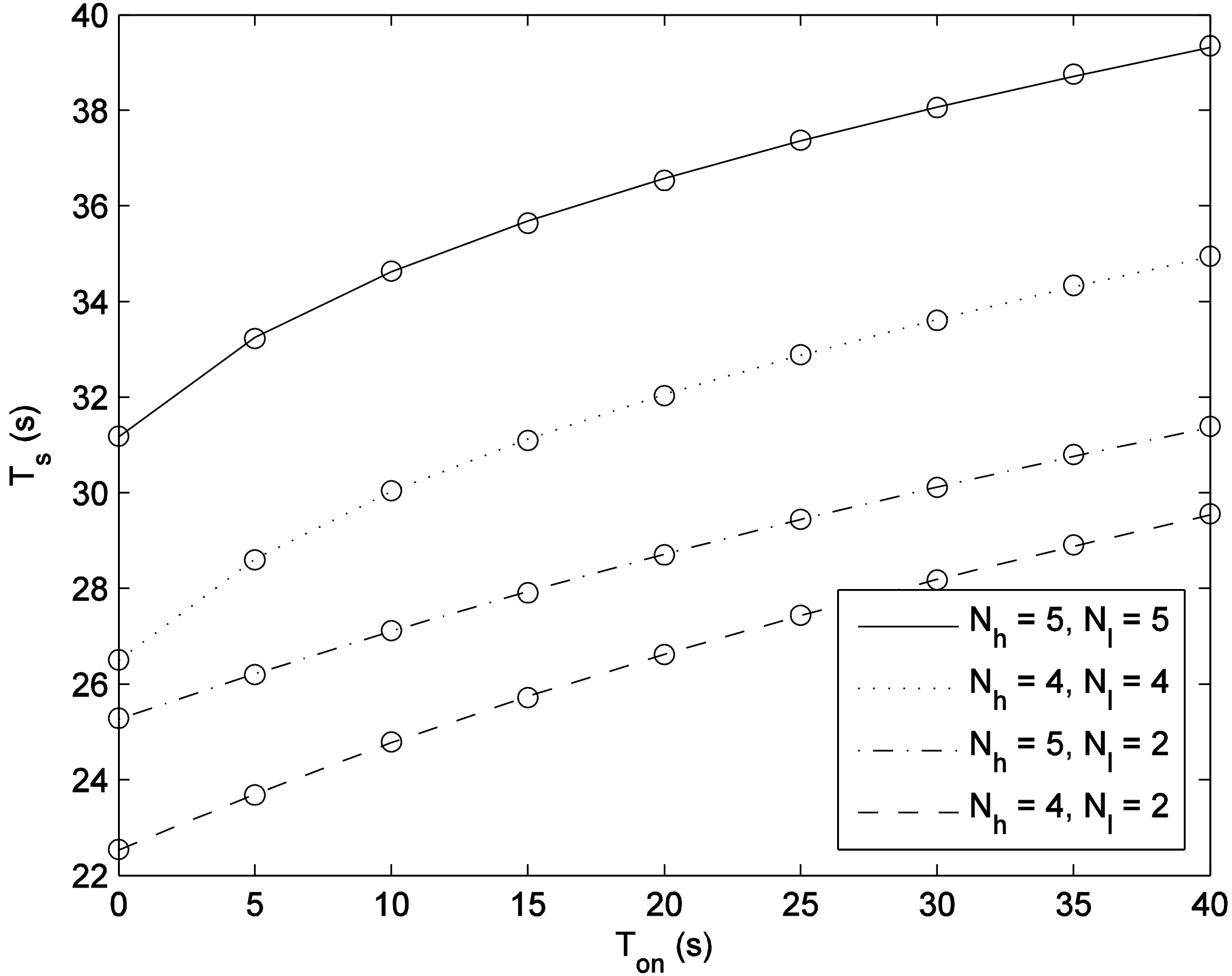
Evaluation – Total Delay

2K = 10 users

λ = 0.1 arrivals/s

1/μ = 10 s

$$\rho \triangleq \frac{\lambda}{2\mu} = \frac{1}{2}$$



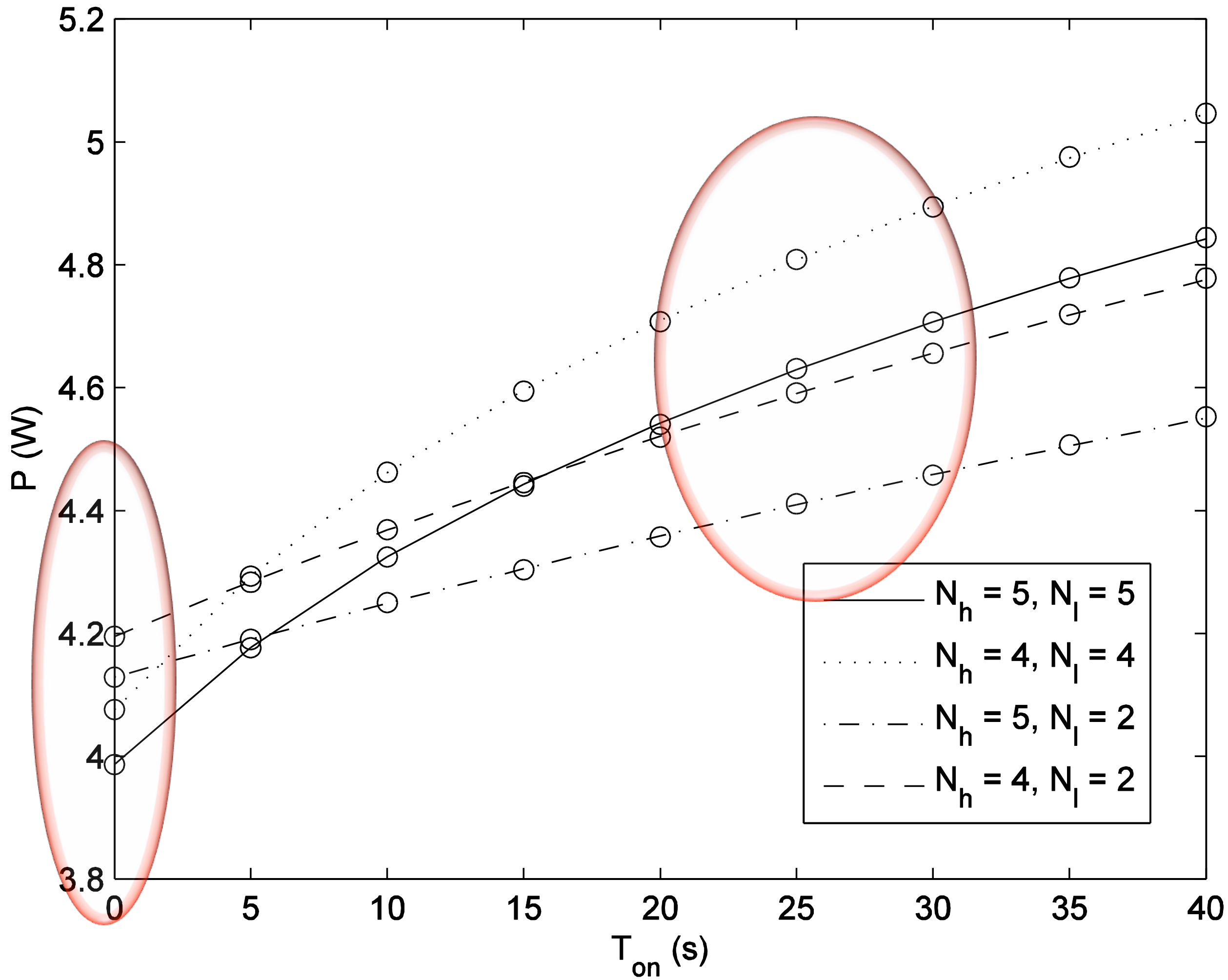
Evaluation – Power consumption

2K = 10 users

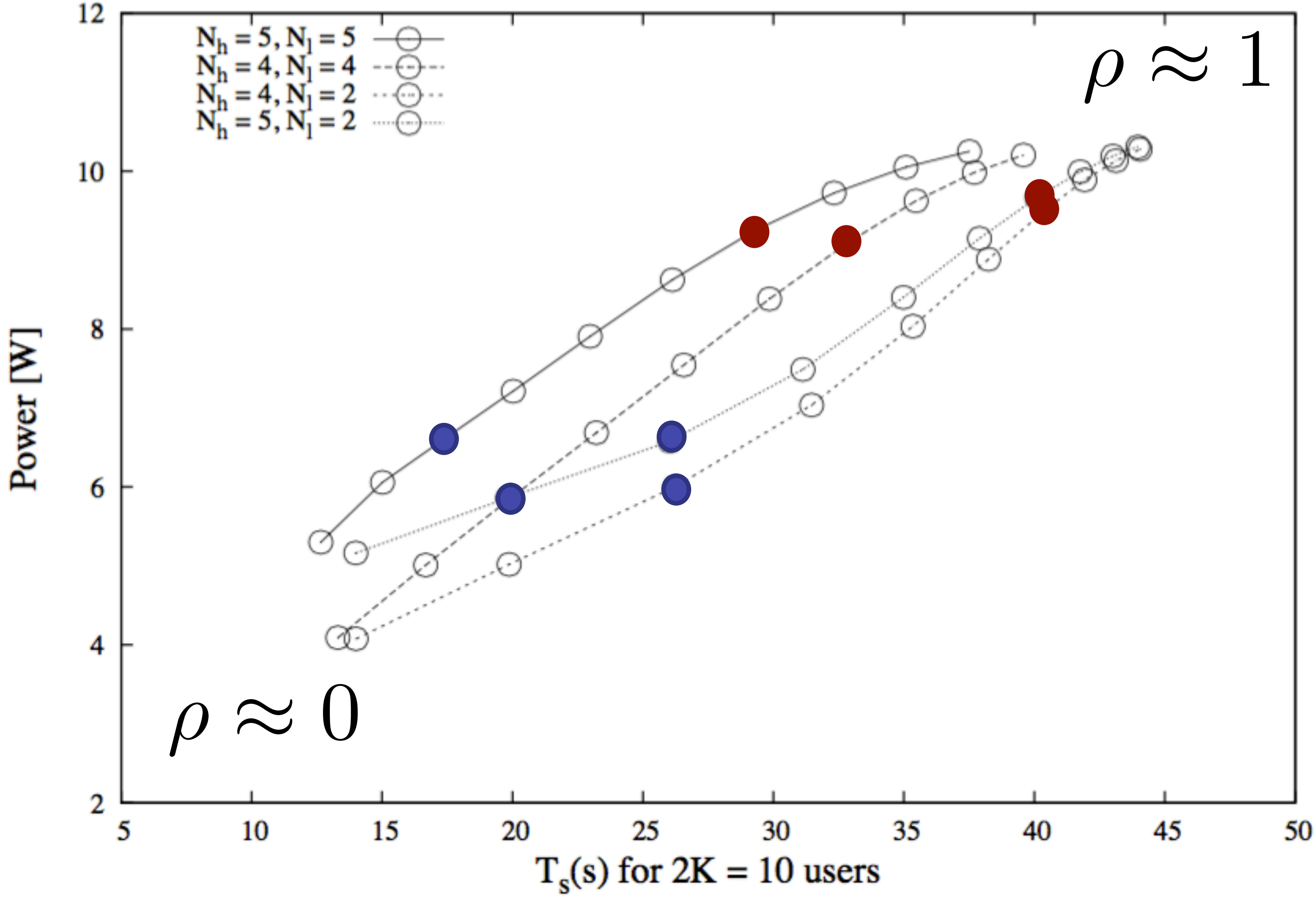
λ = 0.1 arrivals/s

1/μ = 10 s

P=3.5 W



Perf. vs. Consumption (T_{on}=30 s)



Ongoing work

- Model for 3+ APs
  - Account for 802.11g, 802.11a
  - Comp. complex, but less than sims.
- Performance – consumption trade-off
  - Specify a policy
  - Take into account load
- Third energy state
  - Instead of OFF, Sleep

Publications

Modeling the Impact of Start-Up Times on the Performance of Resource-on-Demand Schemes in 802.11 WLANs, J. Ortín, P. Serrano, C. Donato, *Sustain IT - The 4th IFIP Conference on Sustainable Internet and ICT for Sustainability, Madrid, Spain, April 2015*

SOLOR: Self-Optimizing WLANs with Legacy-Compatible Opportunistic Relays, A. Garcia-Saavedra, Balaji Rengarajan, Pablo Serrano, Daniel Camps-Mur, Xavier Costa-Perez, *IEEE/ACM Transactions on Networking (accepted)*

Part III: Energy-Aware Traffic Engineering based on OpenFlow

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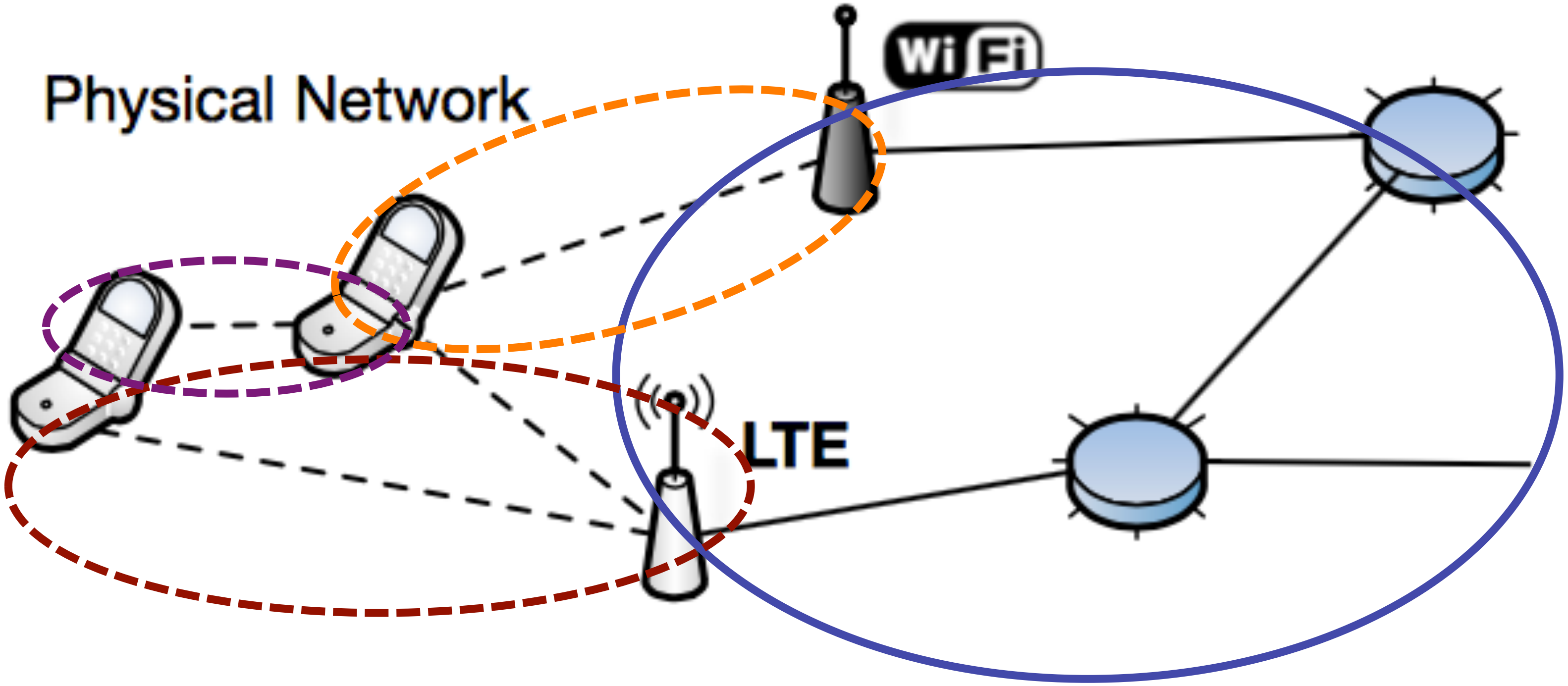
Motivation

- Future Wireless Networks
  - Dense, heterogeneous, & novel paradigms
- Software Defined Networking
  - Centralized control
  - Suited for traffic engineering

Challenge: multi-tech TE

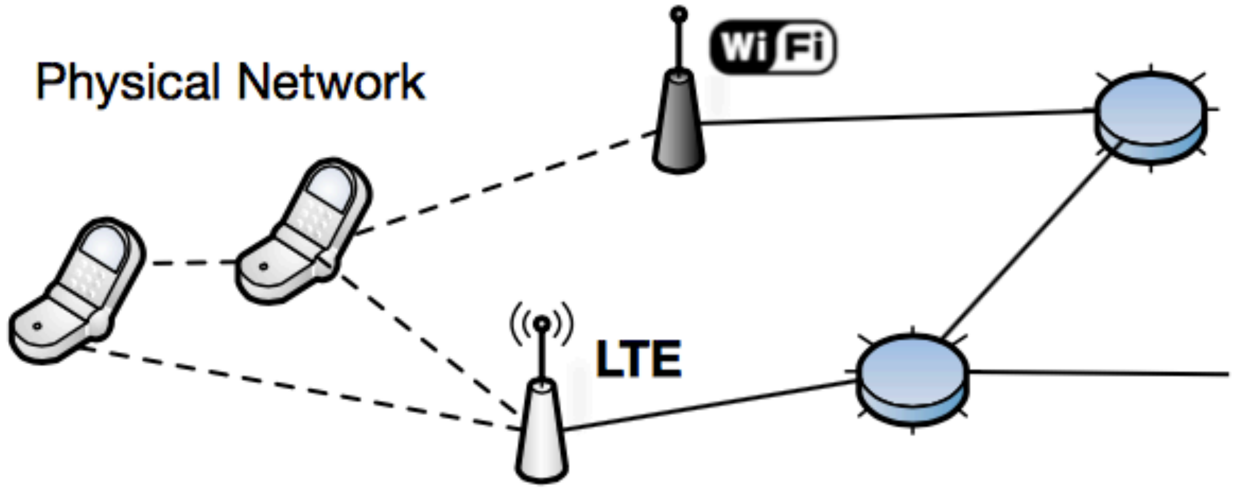


Objective: centralized control & optimization

Energy-Aware TE

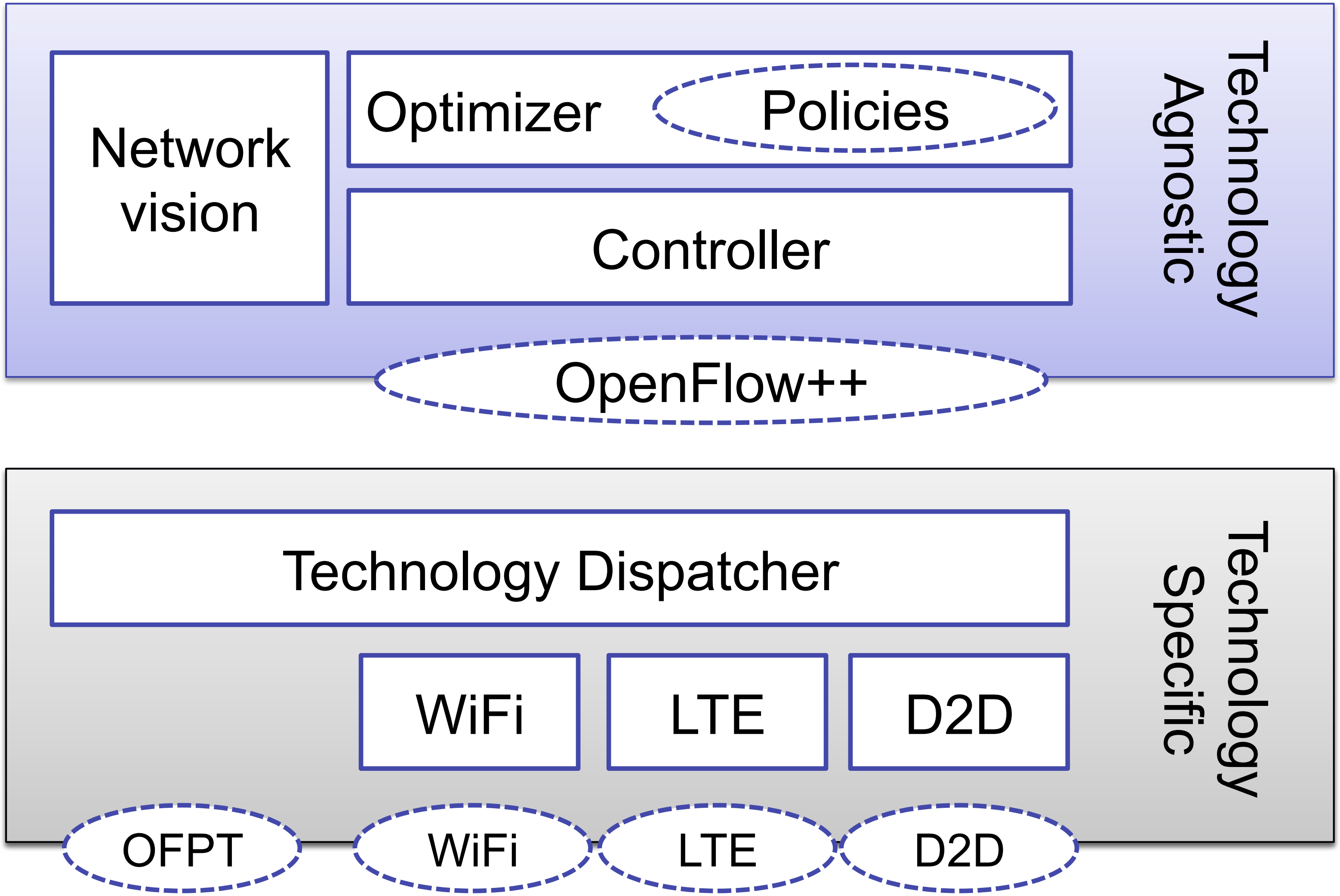
- SDN: traffic engineering in the core
  - Bring energy awareness
- Power on/off elements
  - Standardized primitives
- Control mobile's point of attachment
  - Network Initiated handovers
  - Inter-tech
- Maintain an updated network vision
  - Wireless, mobile clients

Abstracted vision of a network



Framework: OFTEN

Open Flow framework for Traffic Engineering in mobile Networks with energy awareness



Maintaining the network vision

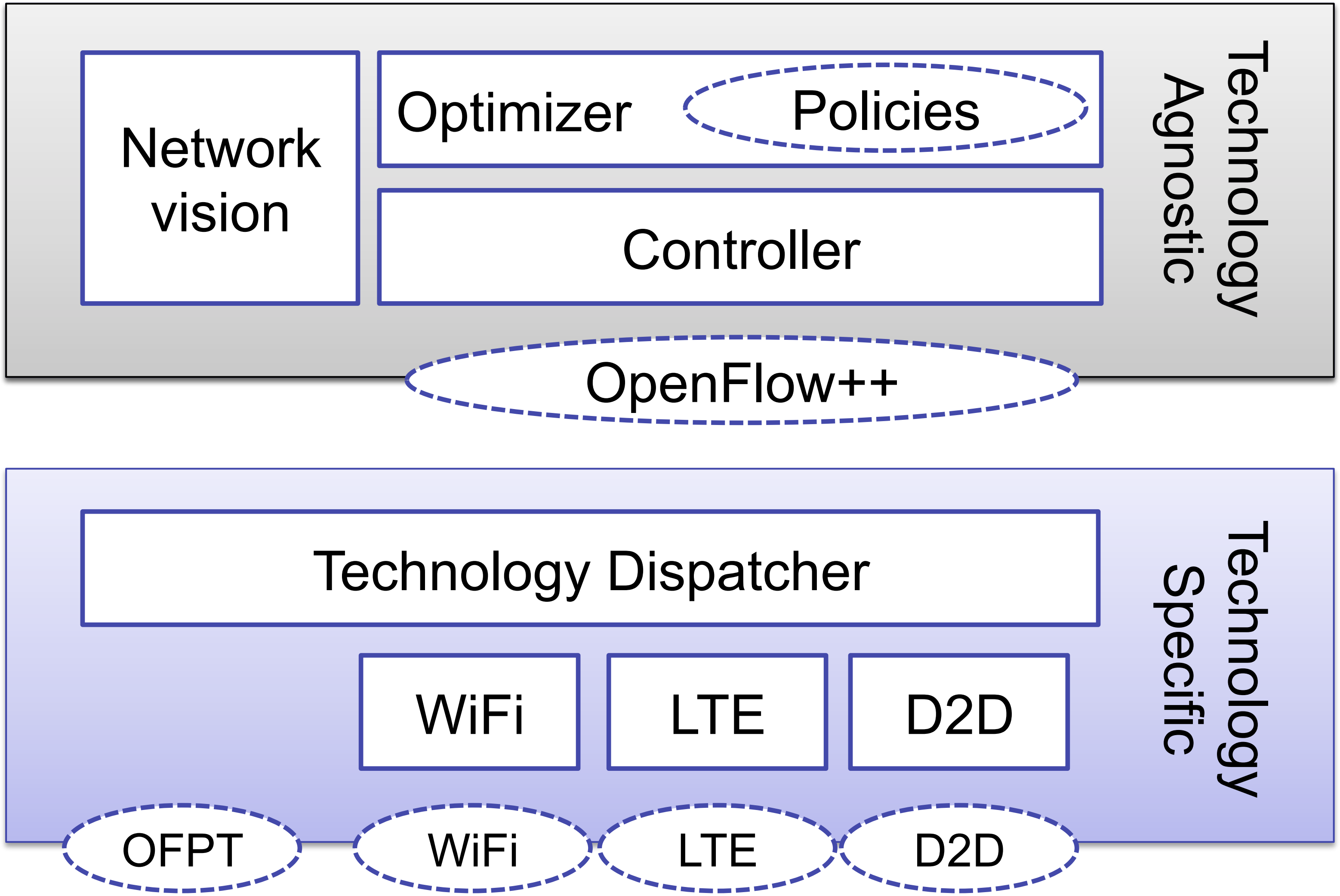
- Wired Nodes (APs or eNBs)
  - Default OpenFlow, perform the usual OFPT_HELLO exchange.
  - Nodes that can be (de)activated, announce this feature (e.g., OFPT_FEATURES_REPLY)
- Wireless Clients
  - Points of Attachment act on their behalf (TCP FIN when the link is no available)
  - Capacity can be updated via curr_speed and max_speed
  - Usage of the links can be easily tracked with per-flow counters

Committing a new configuration

- Changing the point of attachment
  - A client has a number of links available, only one active at a time
  - Usual OFPT_FLOW_MOD message (processed by tech-specific at PoA)

- Switching on/off resources
  - No proper OFPT primitive available
  - OFPT_EXPERIMENTER

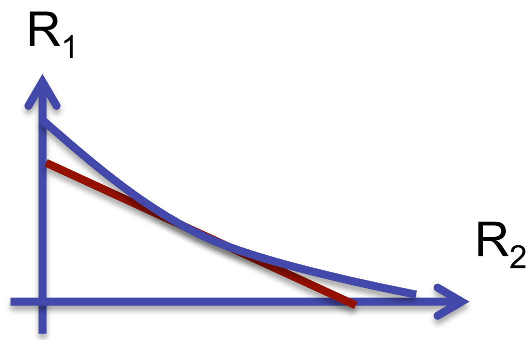
Framework: OFTEN



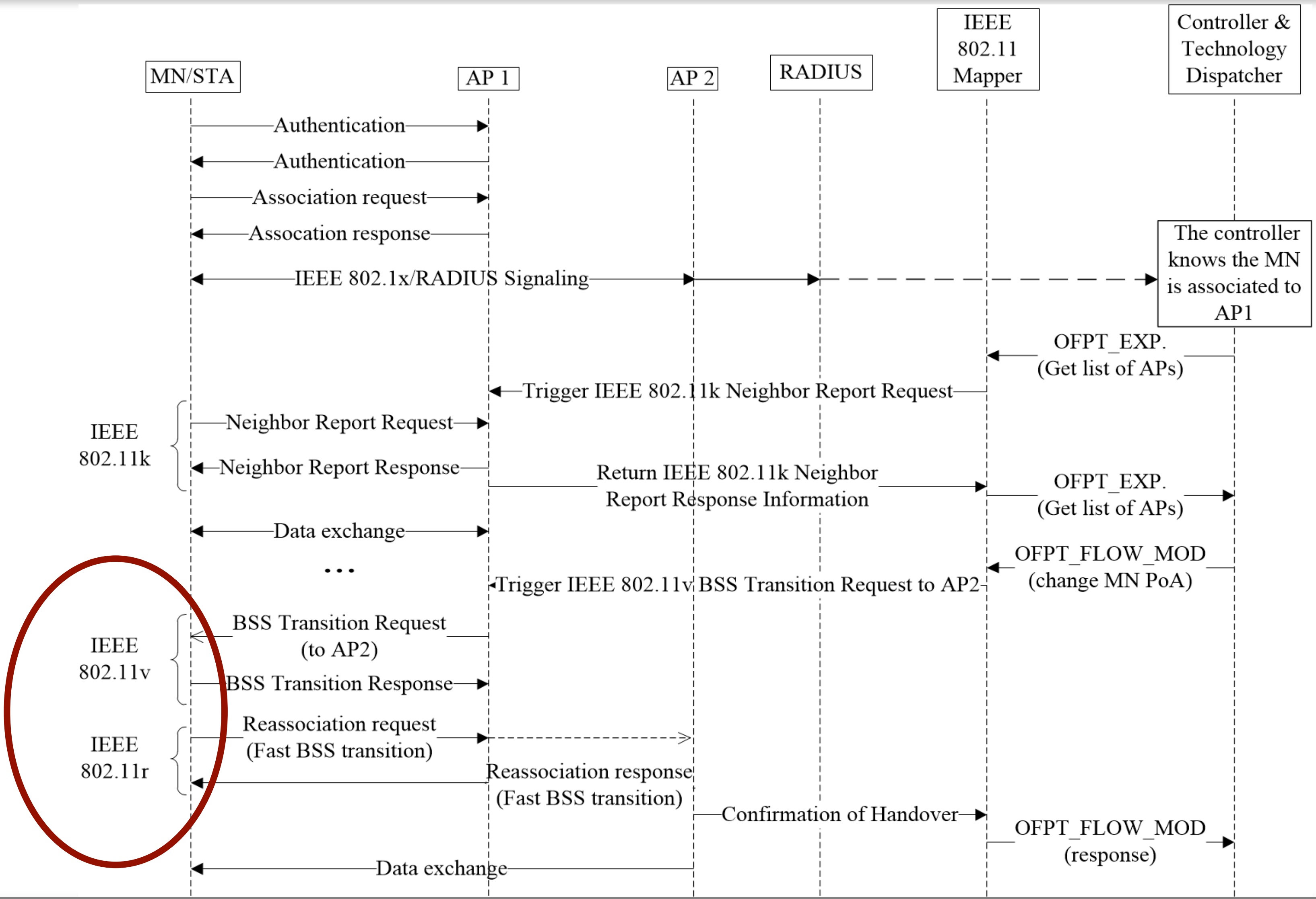
Technology Specific: 802.11 (I)

- Network vision: many tools
  - Probe Request
  - Passive scanning
  - Neighbour report (802.11k)

- Link Capacities
  - (RSSI, Mbps)
  - Linearized capacity model



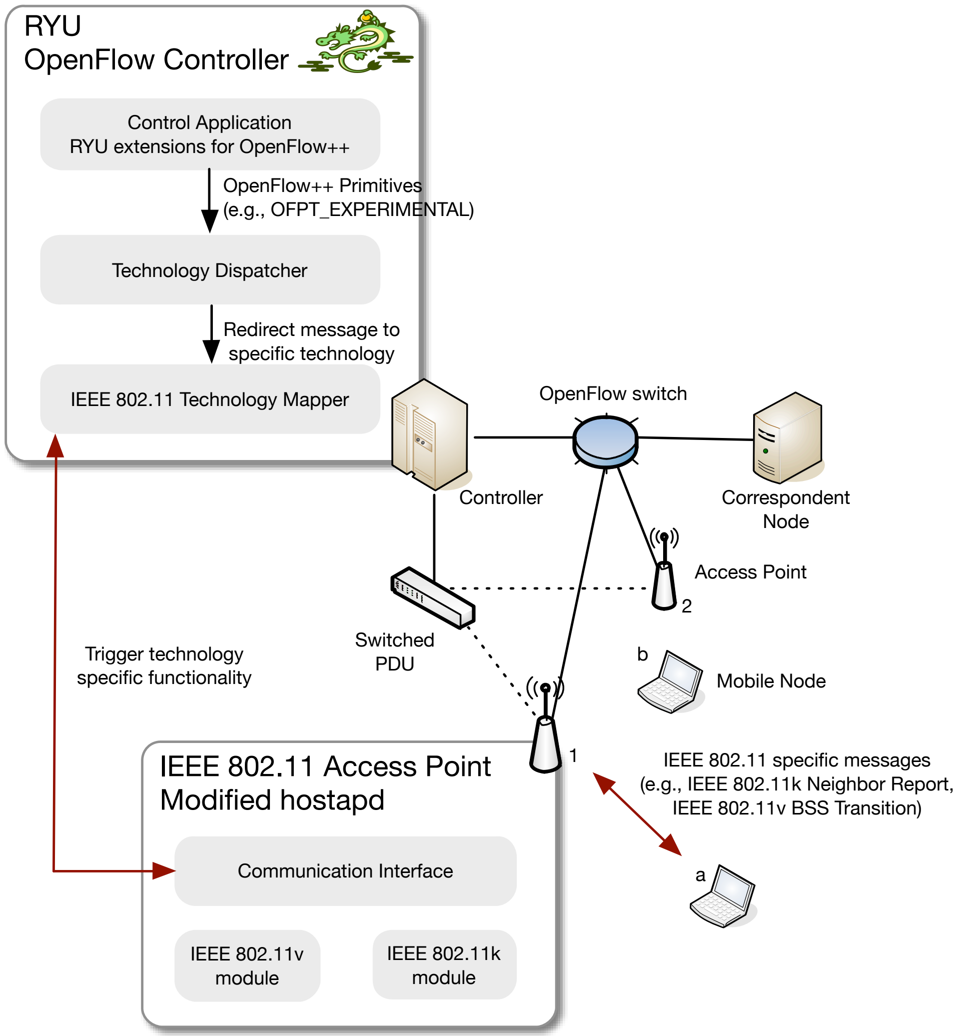
802.11 (II) – NIHO is feasible



Tech. Specific: Cellular and D2D

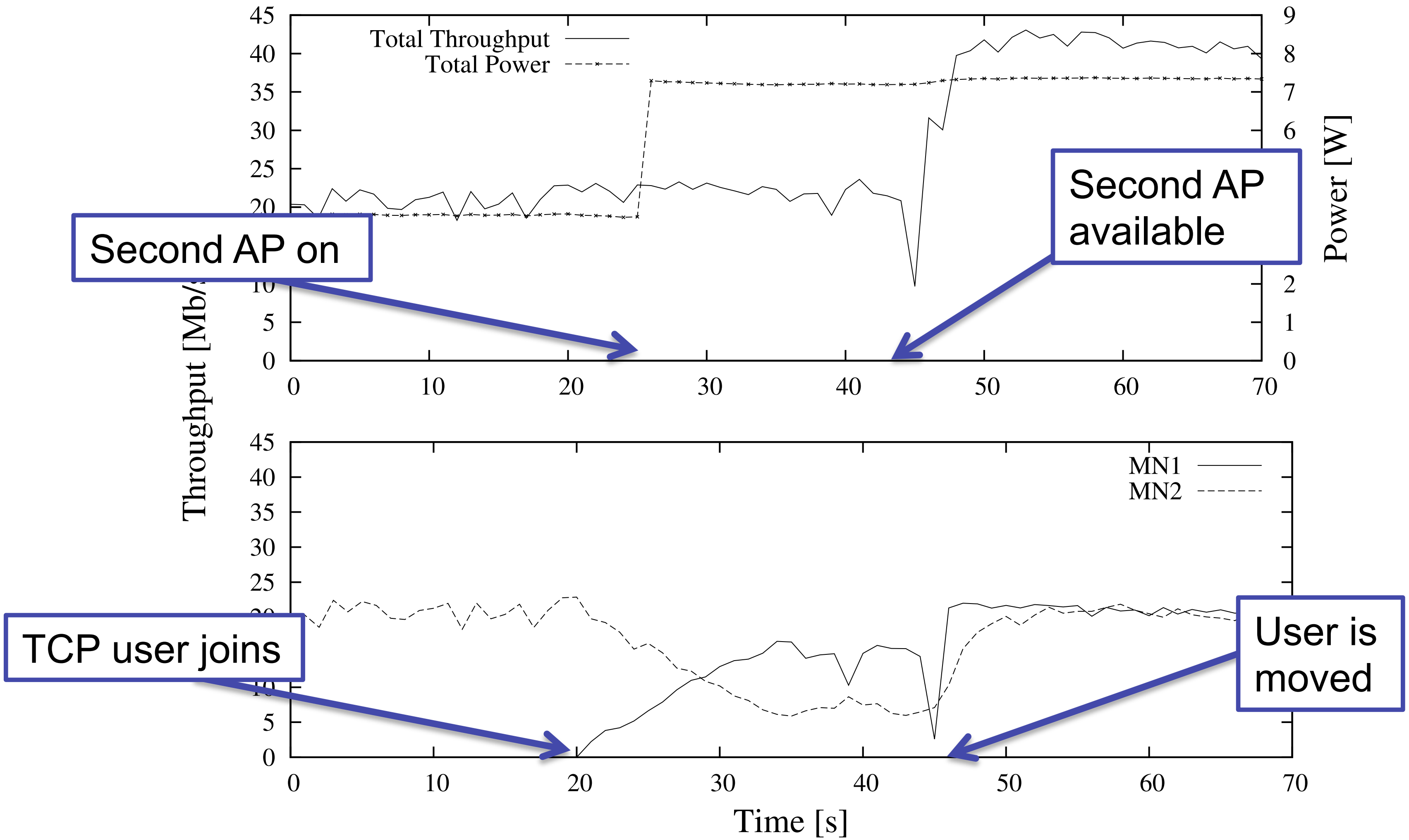
- 3GPP-based networks
  - involve more complex procedures,
  - but also tend to favor a centralized control and reporting
  - Inactive users are less accurately located
  - Might be an Issue for Infrastructure on Demand
- Device to device mapping
  - Need to update the device [SOLOR]
  - Collaboration: Utility vs. cost

Proof of Concept



- Clients
  - Small Linus PCs
- Desktop machines
  - Controller
  - FreeRADIUS
  - CN, Switch
- Mobility
  - Bicasting
- Switched PDU

Proof of Concept



Publications

An OpenFlow Architecture for Energy Aware Traffic Engineering in Mobile Networks, C. Donato, P. Serrano, A. de la Oliva, A. Banchs, C. J. Bernardos, *IEEE Network (accepted)*

Throughput and energy-aware routing for 802.11 based Mesh Networks, A. de la Oliva, A. Banchs, P. Serrano, *Elsevier Computer Communications, vol. 35, no. 12, July 2012*

An Architecture for Software Defined Wireless Networking, C. J. Bernardos, A. de la Oliva, P. Serrano, A. Banchs, L. M. Contreras, H. Jin, J. C. Zúñiga, *IEEE Wireless Communications, vol. 21, no. 6, June 2014, pp. 52--61.*

Many Thanks!

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