Distributed Spectrum Assignment for Home WLANs

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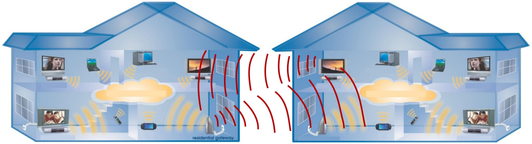
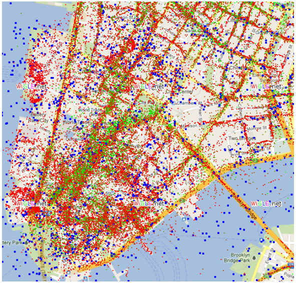
Context

Interfering neighboring wi-fi home/office networks





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- Several possible channels (center frequencies)
- Variable bandwidth (5 $\rightarrow$ 20 $\rightarrow$ 40 $\rightarrow$ 160 MHz), limited spectrum
- Non-heterogeneous density
- No central control

Goal

Joint allocation of channel center frequencies and bandwidths

Conflicting goals:

- Bandwidth$\nearrow$ $\quad\Rightarrow\quad$ Capacity$\nearrow$
- Bandwidth$\nearrow$ $\quad\Rightarrow\quad$ Interference likelihood$\nearrow$

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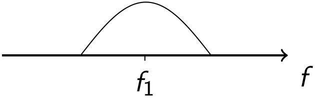

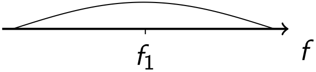

Capacity $\nearrow$

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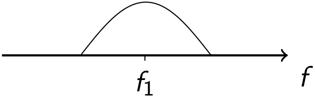
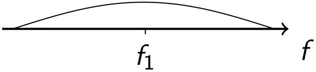
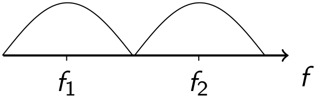
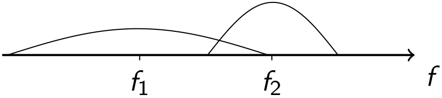




Capacity $\nearrow$





Capacity $\rightsquigarrow$?

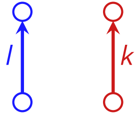
Design Goals

- Decentralized algorithm
- Global convergence guarantees
- Online for adaptivity to time-varying conditions
- Transparent to user traffic
- Practical for implementation on off-the-shelf 802.11 hardware

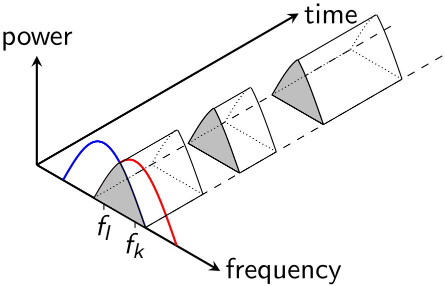
Main contribution

The first decentralized algorithm for joint center frequency and bandwidth adaptation with global convergence guarantees

Interference Model



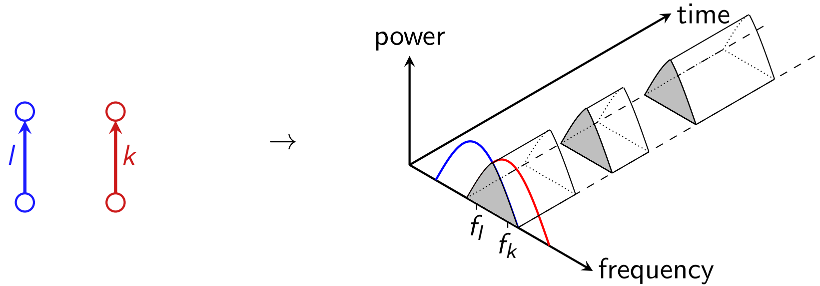
$\rightarrow$



Interference produced by k on neighbor l:

$$I_l(k) = \text{airtime}(k) \cdot \text{overlap}(k, l)$$

Interference Model



Interference produced by k on neighbor l:

$$I_l(k) = \text{airtime}(k) \cdot \text{overlap}(k, l)$$

For two BSSs A and B:

$$I_A(B) = \sum_{l \in A} \sum_{k \in B} I_l(k)$$

Optimization Objective

Explicit interference vs. bandwidth trade-off:

$$\text{minimize} \quad \mathcal{E} := \underbrace{\sum_{A} \sum_{B \in \mathcal{N}_{\mathcal{A}}} I_A(B)}_{\text{Total interference}} \quad + \quad \underbrace{\sum_{A} \text{cost}_A(b_A)}_{\text{Sum of bandwidth "costs"}}$$

- $\text{cost}_A(b_A)$ is the cost that BSS A attributes to using bandwidth b_A
- E.g., $\text{cost}_A(b_A) \propto 1/b_A$

Algorithm at BSS A

Initialization:
Pick a random configuration (f_A, b_A)

After random (exp. distributed) time intervals:
Pick a random configuration $(f_{\text{new}}, b_{\text{new}})$
Measure $e_1 := \sum_{B \in \mathcal{N}_A} (I_A(B) + I_B(A)) + \text{cost}_A(b_A)$ if A uses (f_A, b_A)
Measure $e_2 := \sum_{B \in \mathcal{N}_A} (I_A(B) + I_B(A)) + \text{cost}_A(b_{\text{new}})$ if A uses $(f_{\text{new}}, b_{\text{new}})$
Compute

$$\beta_T = \begin{cases} 1 & \text{if } e_2 < e_1 \\ \exp \frac{e_1 - e_2}{T} & \text{else} \end{cases}$$

Set $(f_A, b_A) = (f_{\text{new}}, b_{\text{new}})$ with probability β_T

Convergence

Metropolis sampling for center frequency and bandwidth

Theorem

Denote X_n the global state of the network after the n-th iteration. Consider a network where all the BSSs run our algorithm using a given parameter T. Then X_n is a Markov chain, and it converges in distribution to

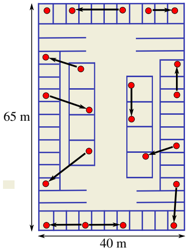
$$\pi(X) \propto e^{-\mathcal{E}(X)/T},$$

where X is a global state.

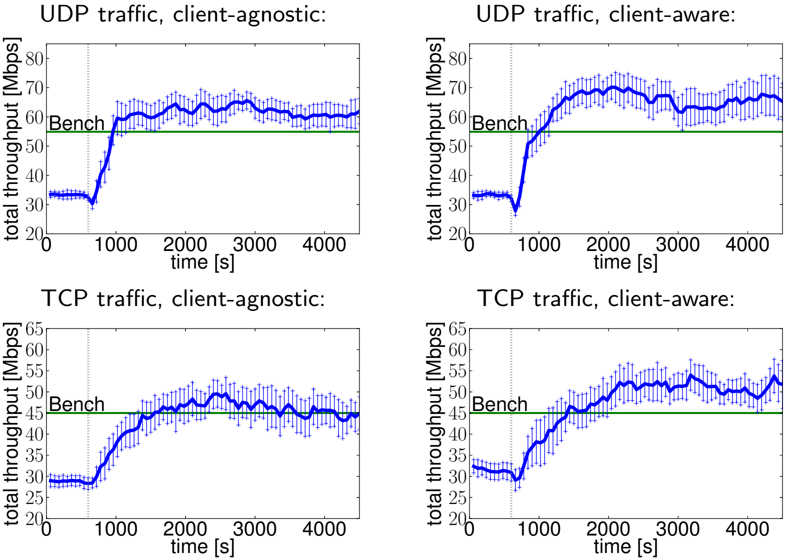
- State gets arbitrarily close to optimal for T small enough
- T encodes a trade-off between likelihood of local optima and asymptotic efficiency

Implementation

- 802.11g with 5, 10 and 20 MHz channel widths
- Interference measured by spending $\leq$ 50 ms. out-of-band
- Optional client collaboration for interference measurement
- C++ implementation using *Click* in userspace
- $\mathrm{cost}_A(b_A) = 1/b_A$



Performance Evaluation



"Bench" line: centralized graph-coloring for fixed-width channels

Simulation

- Random distribution of BSSs on the plane
- Capacity of link $l = b_l \cdot \log(1 + SINR)$

- $\mathrm{cost}_A(b_A) = c/b_A$, optimization objective becomes:

$$\text{minimize} \sum_{A} \sum_{B \in \mathcal{N}_\mathcal{A}} I_A(B) + c \cdot \sum_{A} 1/b_A$$

- $c = 0$: minimize interference
- $c \to \infty$: use largest bandwidth, irrespective of interference

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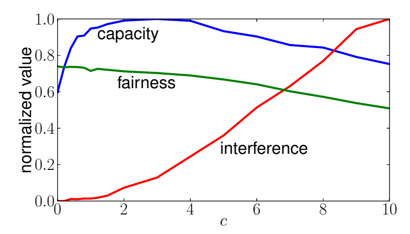

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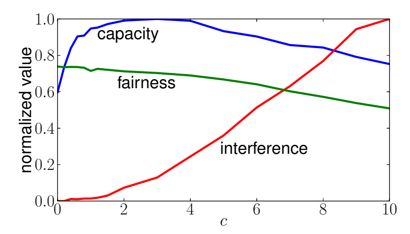
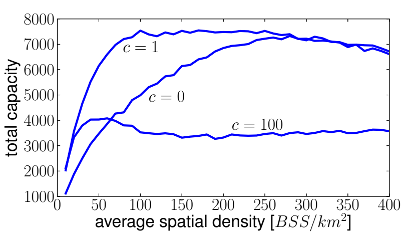
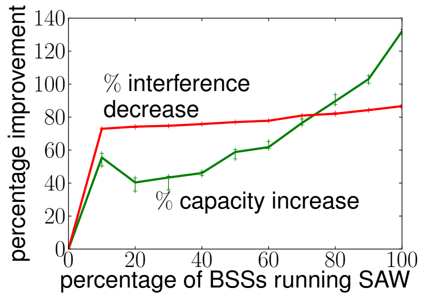




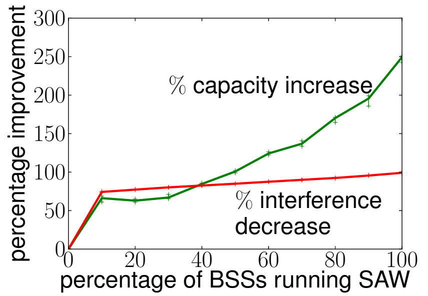
Simulation

Improvement with respect to random allocations

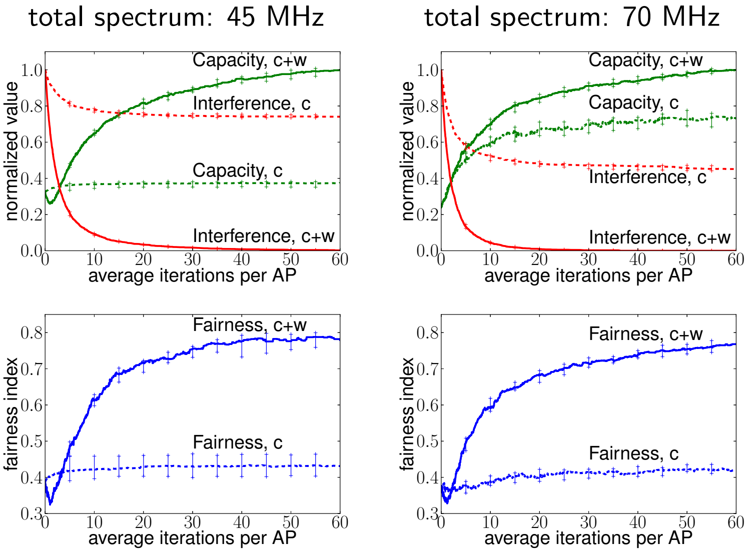
after 5 iterations:



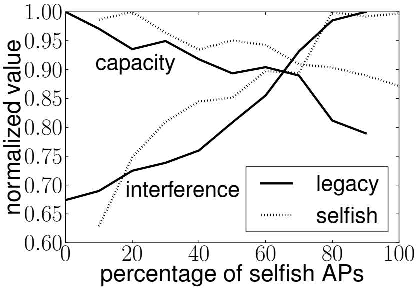
after 20 iterations:

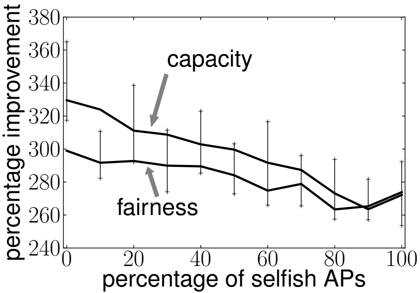


Simulation


total spectrum: 45 MHz
total spectrum: 70 MHz
normalized value
Capacity, c+w
Interference, c
Capacity, c
Interference, c+w
average iterations per AP
fairness index
Fairness, c+w
Fairness, c
0.0
0.2
0.4
0.6
0.8
1.0
0.3
0.5
0.7
0
10
20
30
40
50
60

Influence of selfish APs





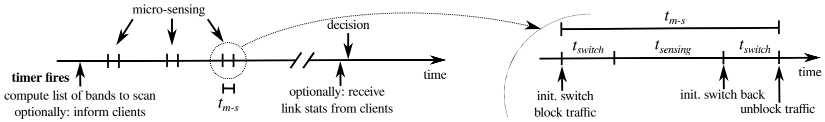
Conclusion

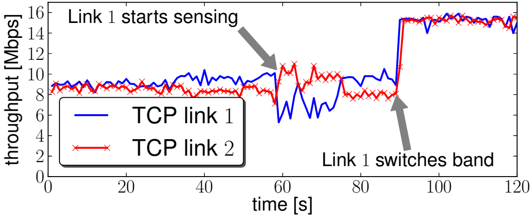
- Distributed, joint allocation of center frequencies and bandwidths
- Bandwidth influences both capacity and interference; ideal spectrum consumption should depend on network density
- Optimization of an explicit trade-off between interference mitigation and use of advantageous bandwidths
- Simple optimization objectives yield best results irrespective of network density
- Large capacity improvements, even when not all BSSs run the algorithm
- Testbed implementation shows feasibility and improvements compared to fixed-width graph coloring

Some Related Work

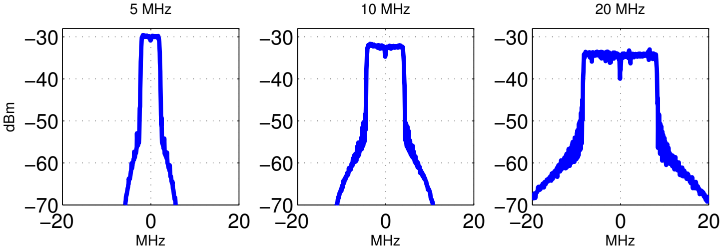
- Channel allocation / graph coloring, e.g., [Akella et al. 2005, Kauffmann et al. 2007, Duffy et al. 2011, Leith et al. 2012]
  - Main goal: minimize interference (no variable bandwidth)
- Variable bandwidth / white spaces, e.g., [Chandra et al. 2008, Bahl et al. 2009, Rayanchu et al. 2011]
  - Heuristics, no focus on self-organization

Micro-sensing



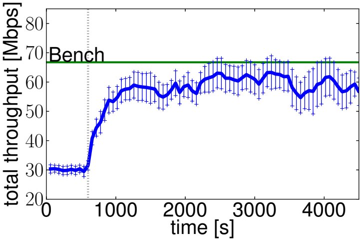


Channel widths

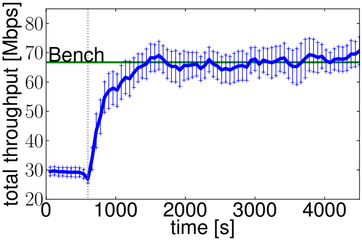


Performance Evaluation (uplink)

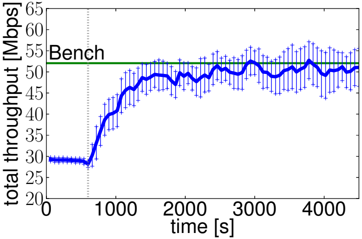
UDP traffic, client-agnostic:



UDP traffic, client-aware:



TCP traffic, client-agnostic:



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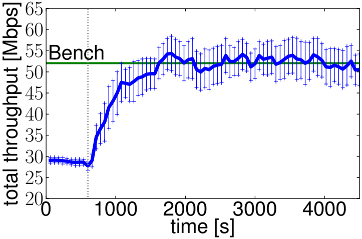

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