ProBeam: A Practical Multicell Beamforming System for Small-cell Networks

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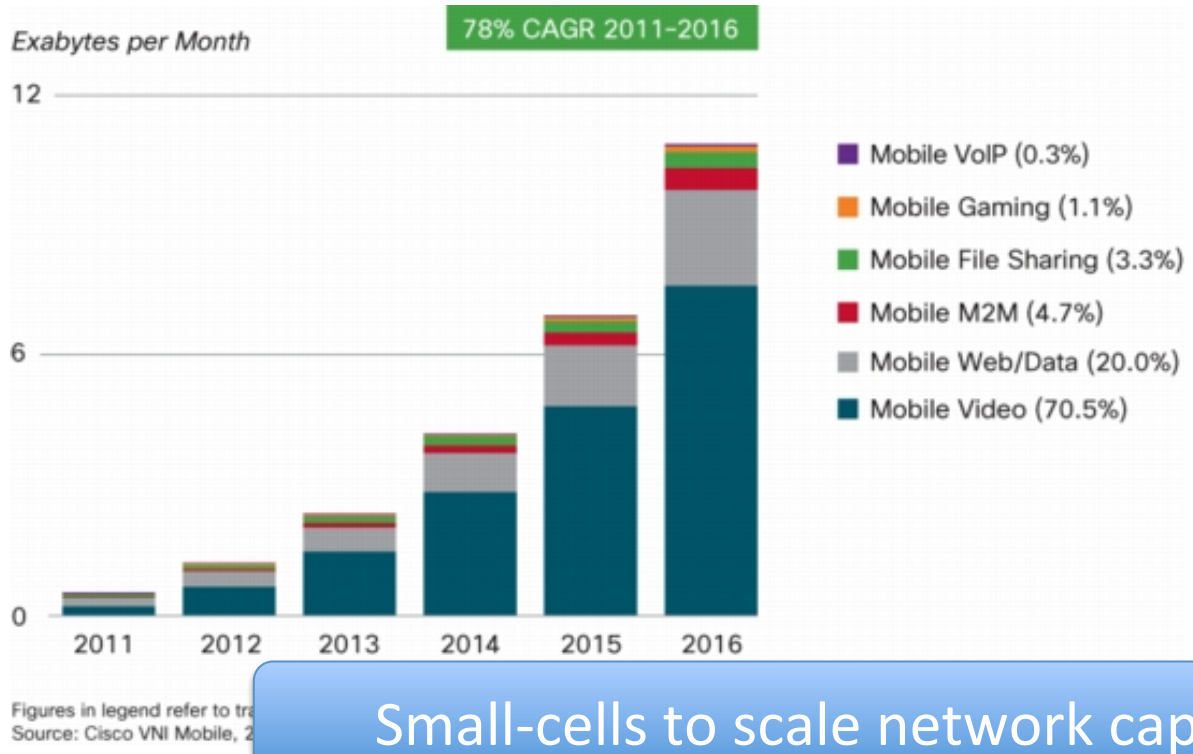
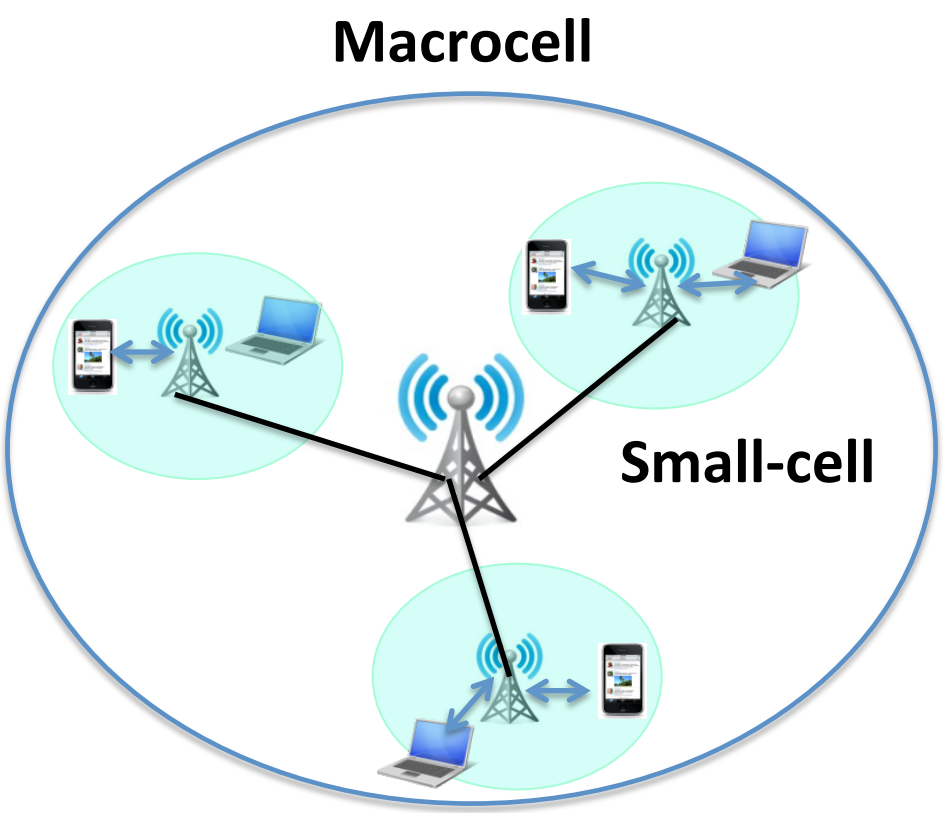
Motivation for small-cells

- Proliferation of handheld devices
- Traffic destined to mobile devices rapidly increases



Small-cells to scale network capacity

Why small-cell?

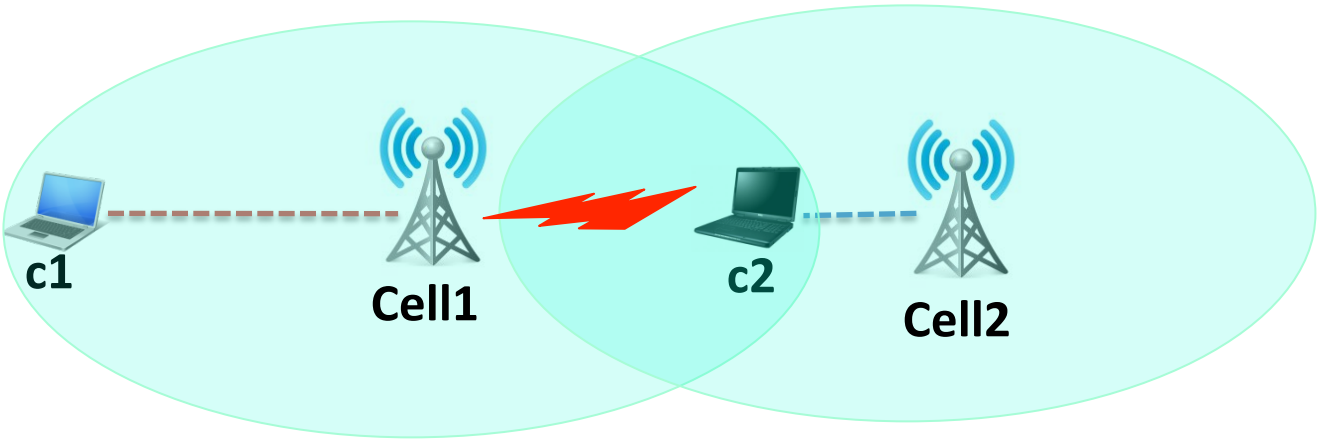


- Short range, low cost and low power AP
- Reuse macro spectrum

Benefits

- ➢ Coverage (higher quality like)
- ➢ Spectral efficiency
- ➢ Lower power

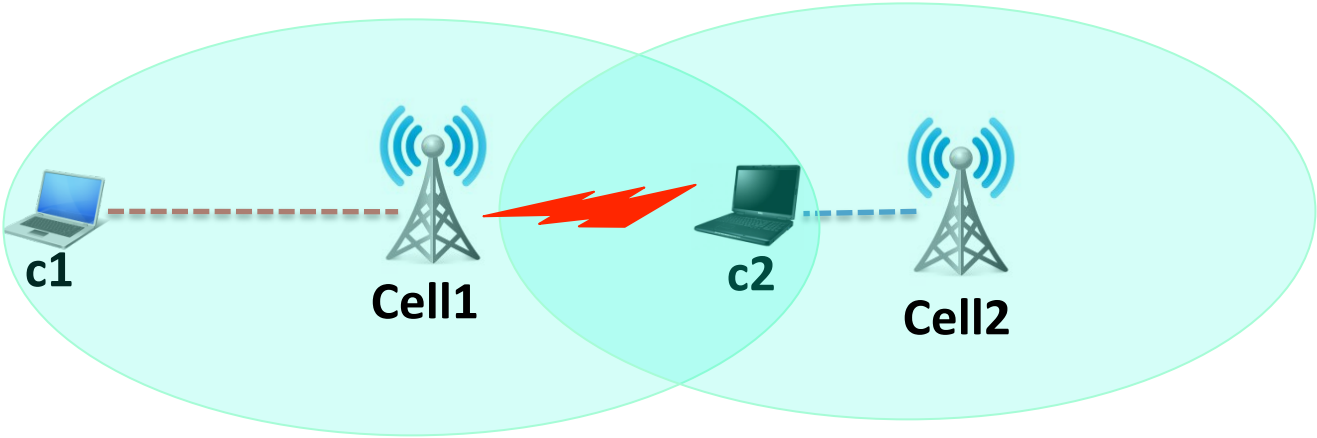
Challenges in small-cell networks



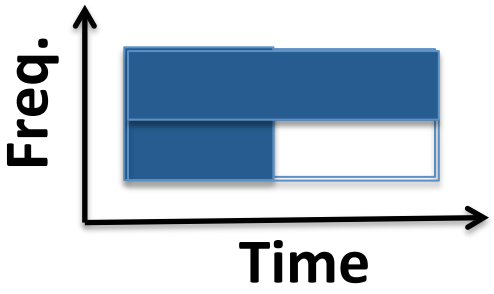
- Dense and un-coordinated deployment

➢ High interference -> degraded performance

Solution1: Resource isolation

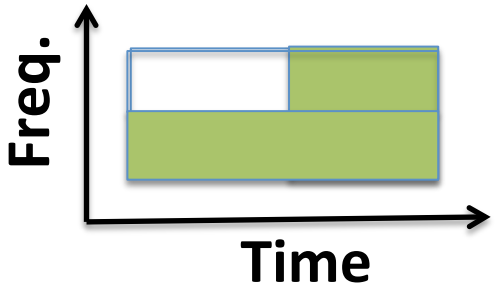


Resource allocation for cell1

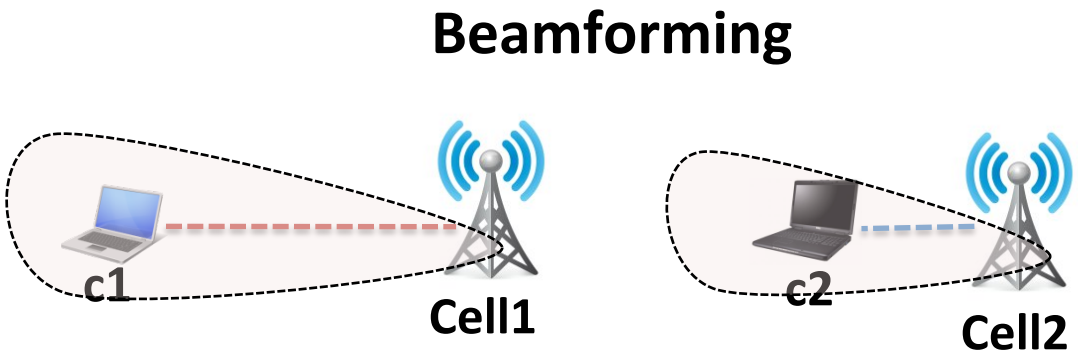


Time or Frequency resource isolation

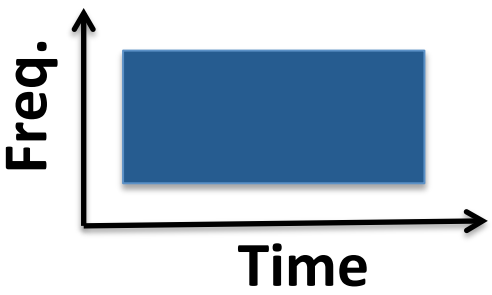
Resource allocation for cell2



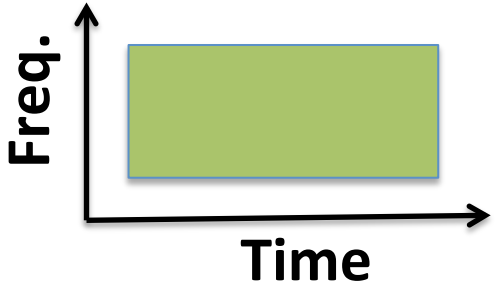
Solution2: Spatial reuse



- The abililty to transmit energy in specific directions
- Weighting the signals transmitted from an antenna array



Space (spatial reuse)



Prior works

Time or Frequency resource isolation

- Efficient resource management scheme
  - FERMI [MobiCom '11]
  - RADION [MobiHoc '12]

Space (spatial reuse)

- Beamforming
  - DIRC [SigComm '09]
  - Speed [MobiCom '10]

- **Not consider client association**
- **Per-pkt based conflict graph**
- **Reuse schedule determination**
- **Not practical in OFDMA**

Our focus

- Goal
  - leverage beamforming to maximize spatial reuse with small-cells
- Practical constraints (beam patterns)
  - change at coarse time scales (not per-frame due to overhead, complexity and feasibility)
  - depend on the set of client associated with the cell (influences SNR/interference differently to clients)
  - depend on the throughput received
    --> tied to scheduling and fairness model assumed

Outline

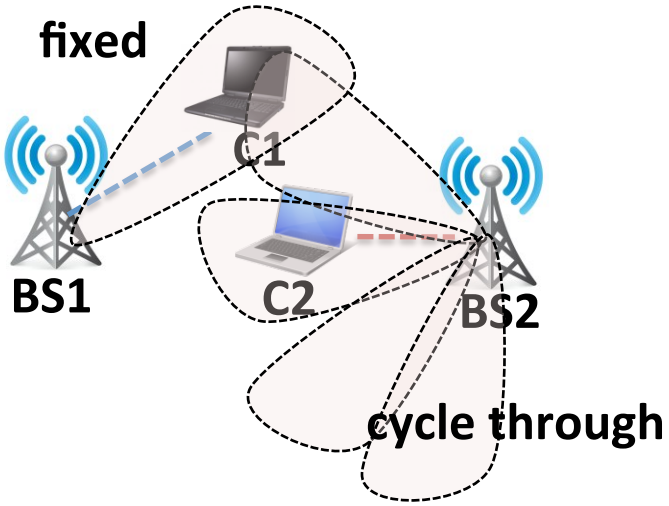
- Challenges in small-cell networks
- Motivation
  - Coordinated beamforming
  - Joint client association
- ProBeam
  - SINR estimation
  - Joint beam selection and client association
- Evaluation and conclusion

Motivation1: Coordinated beamforming

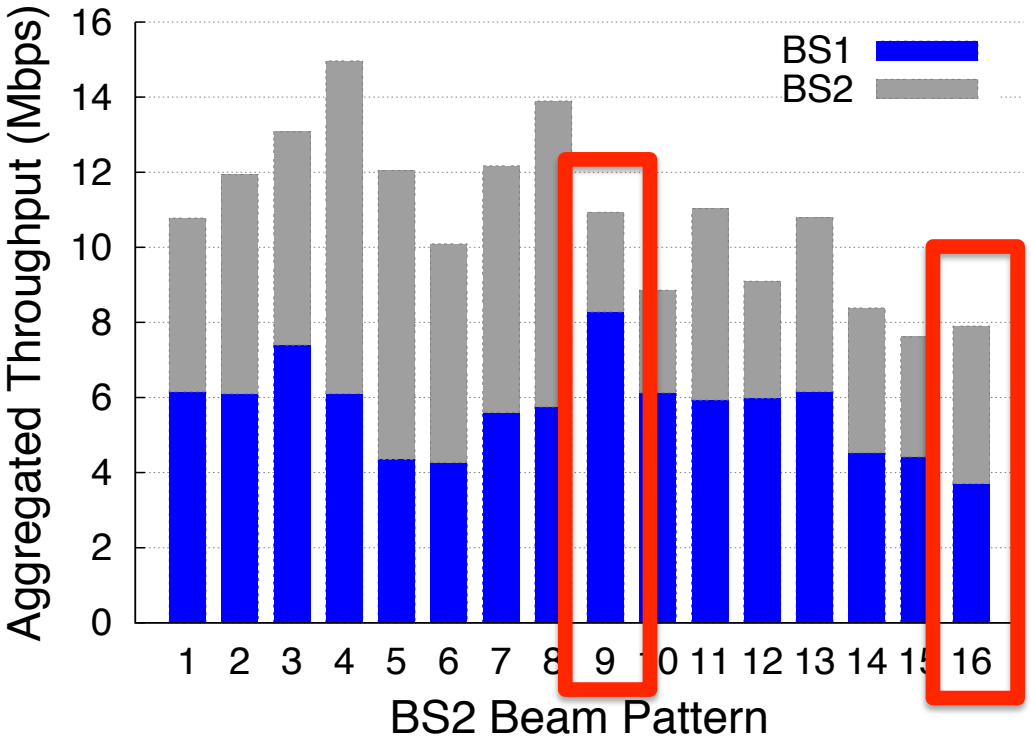
- Benefits
  - Increase link capacity via improved SNR
  - Increase network capacity via reduced interference

    -> higher spatial reuse

Observation1

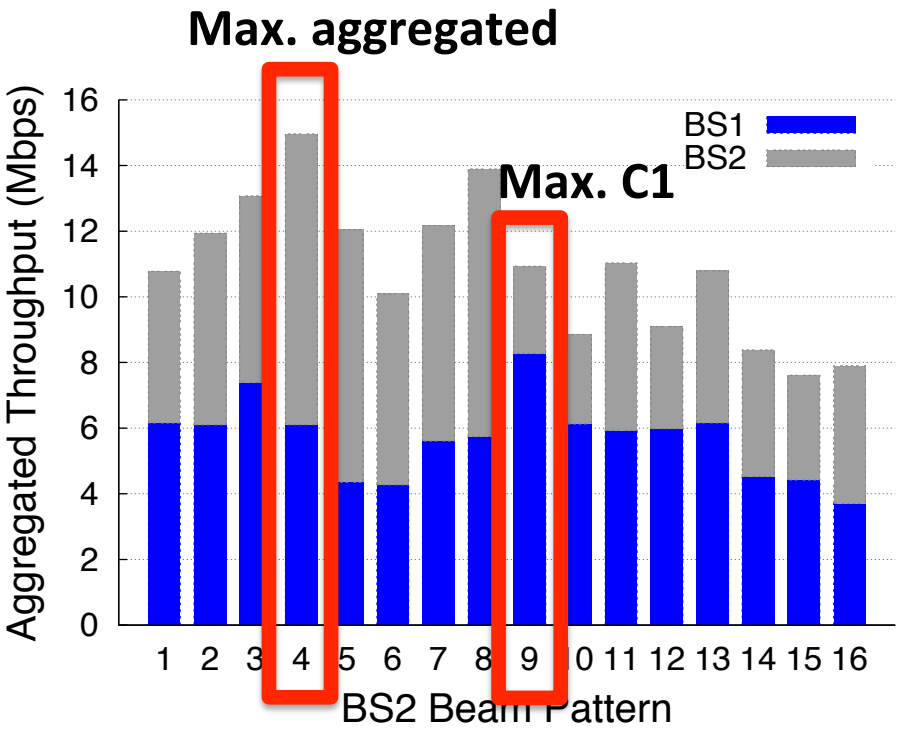


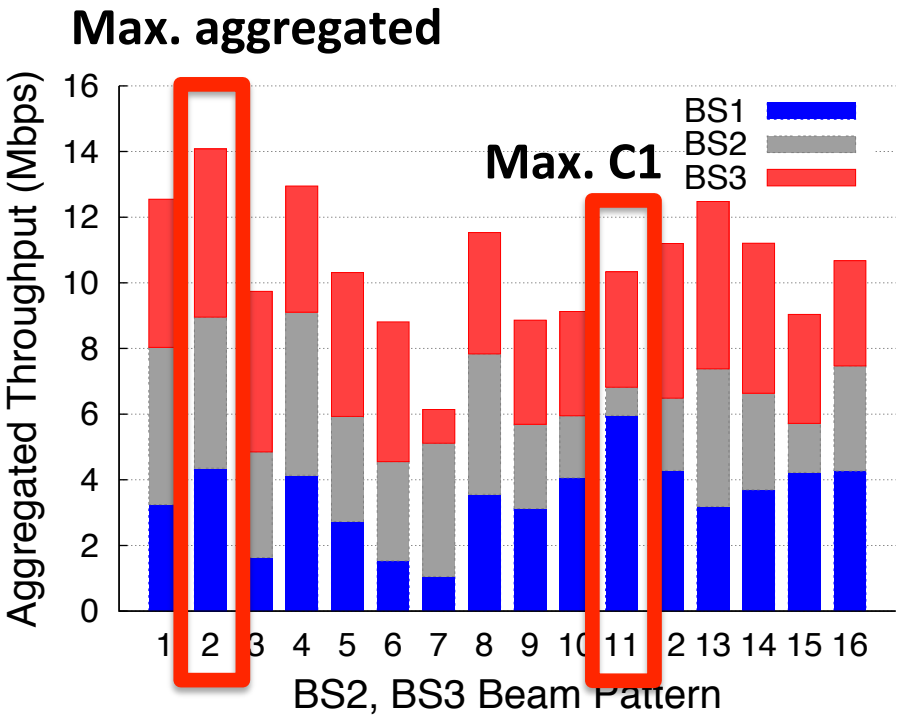
Two cell network



Interference projected by neighboring BS depends on the beam selection

Observation2

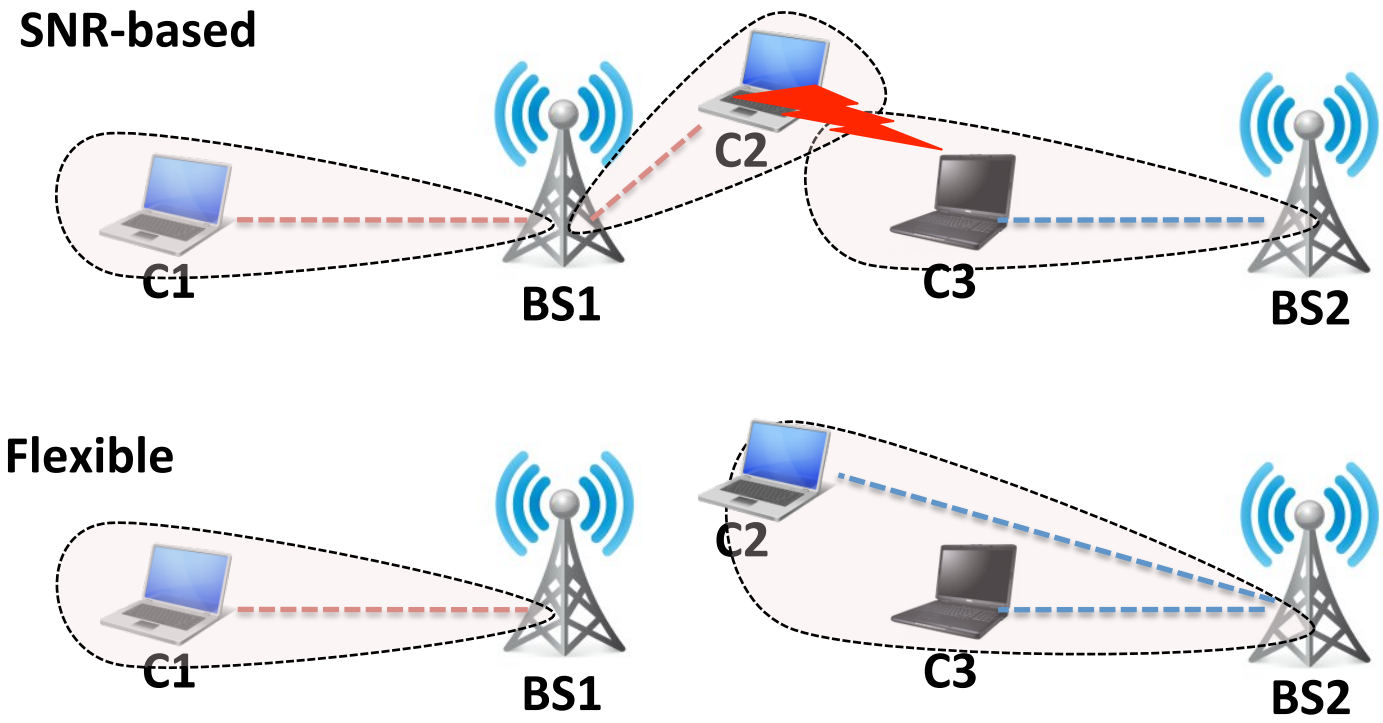




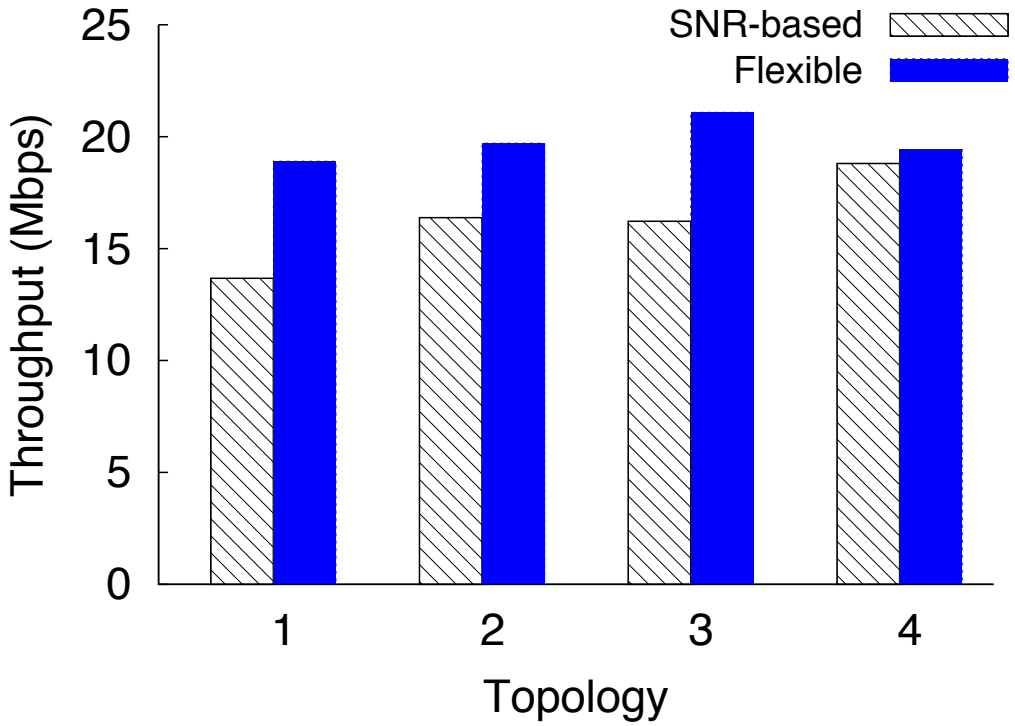
Well-coordinated beamforming increases 40%

Motivation2: Joint client association

- How to associate clients?



Throughput gain



Jointly address client association with beam selection

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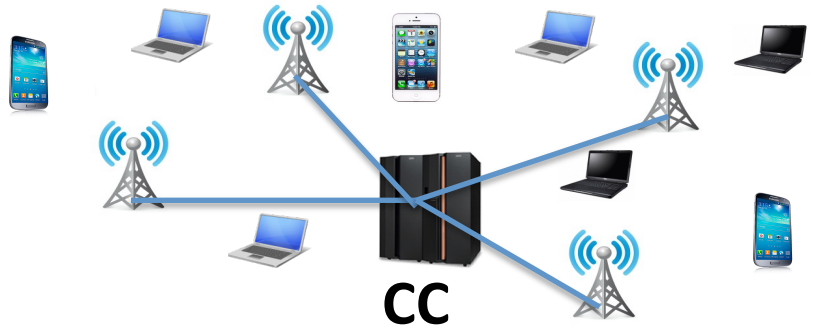
Problem

Large-scale enterprise/outdoor deployment of small-cells



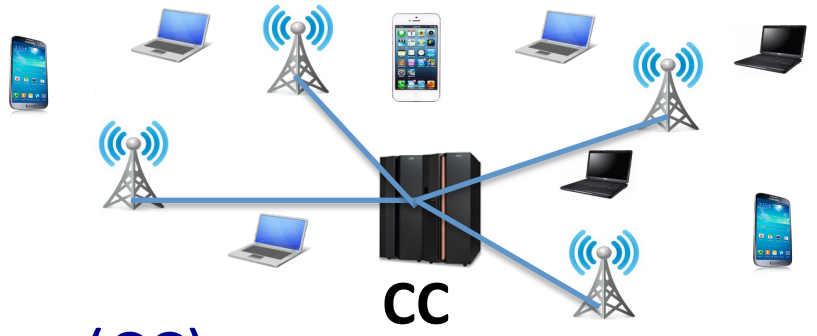
- Problem
  1. Selecting beam patterns for each small-cell to increase the spatial reuse and improve the link quality
  2. Optimizing the client association with given small-cells
- Hardness
  - Selecting beam pattern: $O(k^n)$
  - Finding optimal association: $O(n^m)$
  - Finding both beam pattern for each cell and client associations are not easy

k: # of beam patterns
n: # of small-cells
m: # of clients

Decouple beam selection from client association

ProBeam

Large-scale enterprise/outdoor deployment of small-cells



- ProBeam central controller (CC)
  - Interference estimation for beamforming from each BS
  - Joint beam selection and client association
  - Scheduling

Key component1: SINR estimation

- SINR measurement: $O(k^n)$ required
- ProBeam: SINR estimation
  - Measures SNR, INR from all cells, O(kn)

k: # of beam patterns
n: # of small-cells

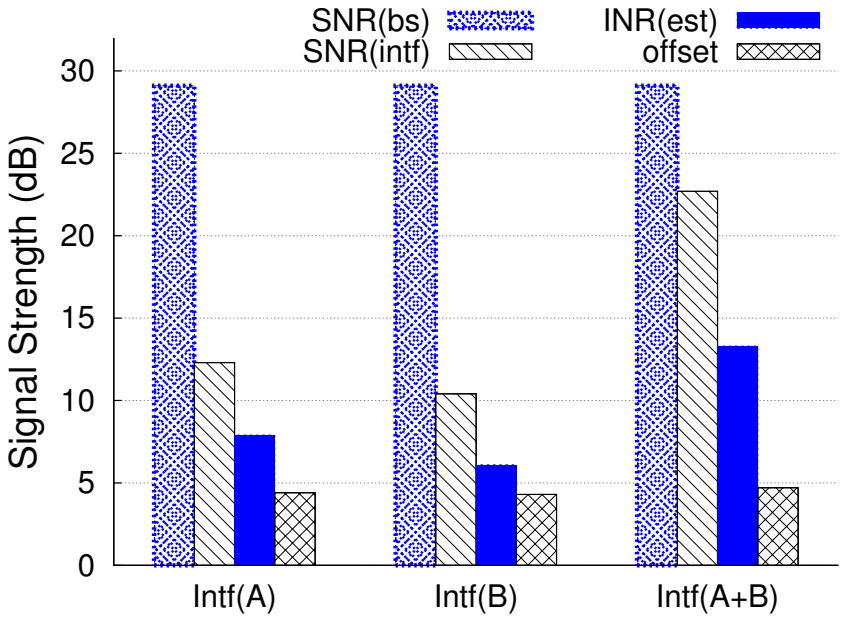
$$SINR_{i,j} = \frac{SNR_{i,j}}{\sum_{k \neq i} INR_{k,j} + 1} \qquad (INR + 1 \approx INR)$$

$$SINR(dB) = SNR(dB) - INR(dB)$$

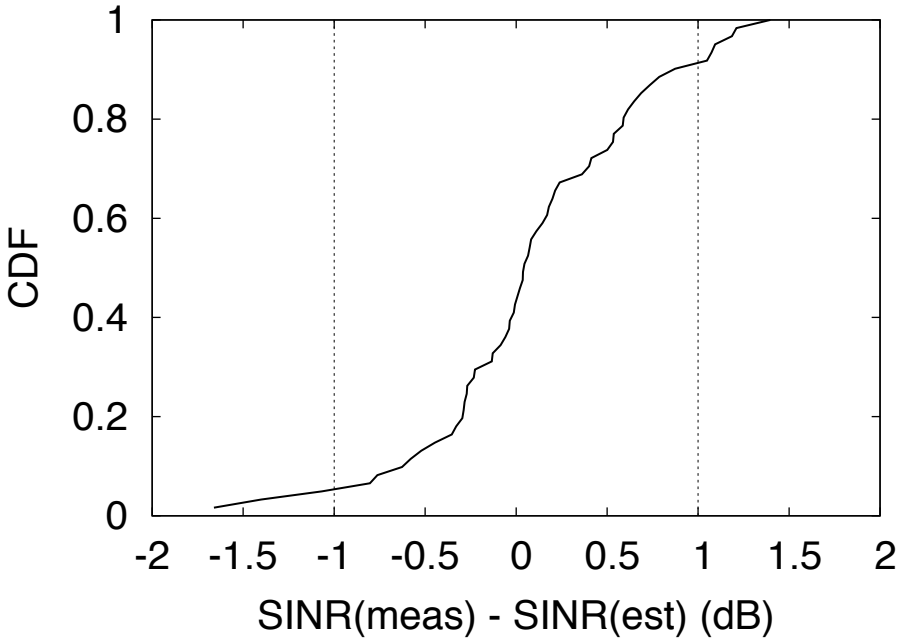
SINR can be estimated from its SNR from the desired BS and aggregated INR from all interfering BSs

SINR estimation

SINR estimation verification



95% of estimation ≤ 1dB error



$$SINR_{i,j,\pi}(dB) = SNR_{i,j,\pi(i)}(dB) - 10\log_{10}(\sum_{k \neq i} SNR_{k,j,\pi(k)}) + \beta(dB)$$

Key component2: CABS algorithm

- Joint client association and beam selection
  - Input: client's SNR measurements
  - Output: beam selection $\pi(i)$ and client association $X = \{x_{j,i}\}$

for each cell; change the beam pattern

for … terns

Ma…

$(\pi$ … $\forall j \in K$

- **NP-hard problem**
- **CABS is a ½-approximation algorithm under proportional fairness**
- **However, its performance is within 96% of upper bound**

*proportional fairness (avg. throughput) $U(t_{j,i}^{\pi}) = \log(t_{j,i}^{\pi})$

If utility is not increasing; skip this clients

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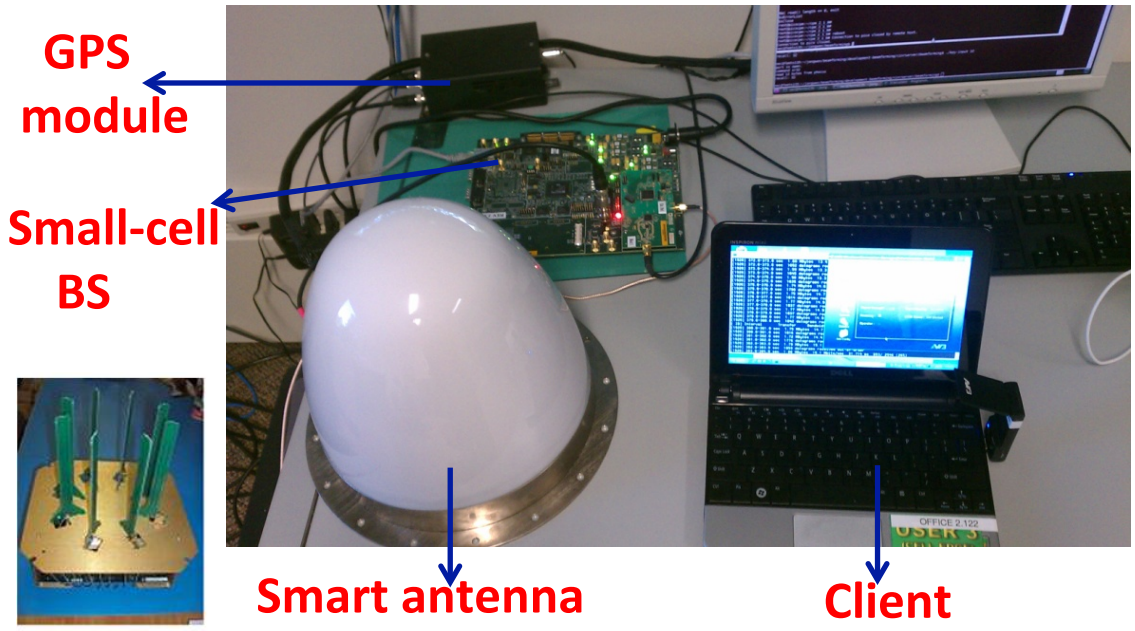
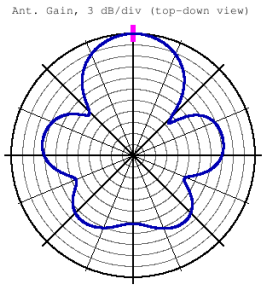
Implementation

- Implemented on PicoChip WiMAX testbed
- Each BS has an eight element phased array antenna

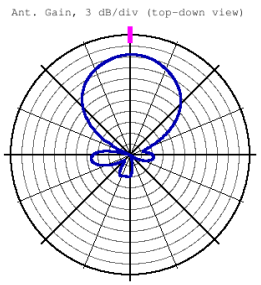
One set of small-cell network



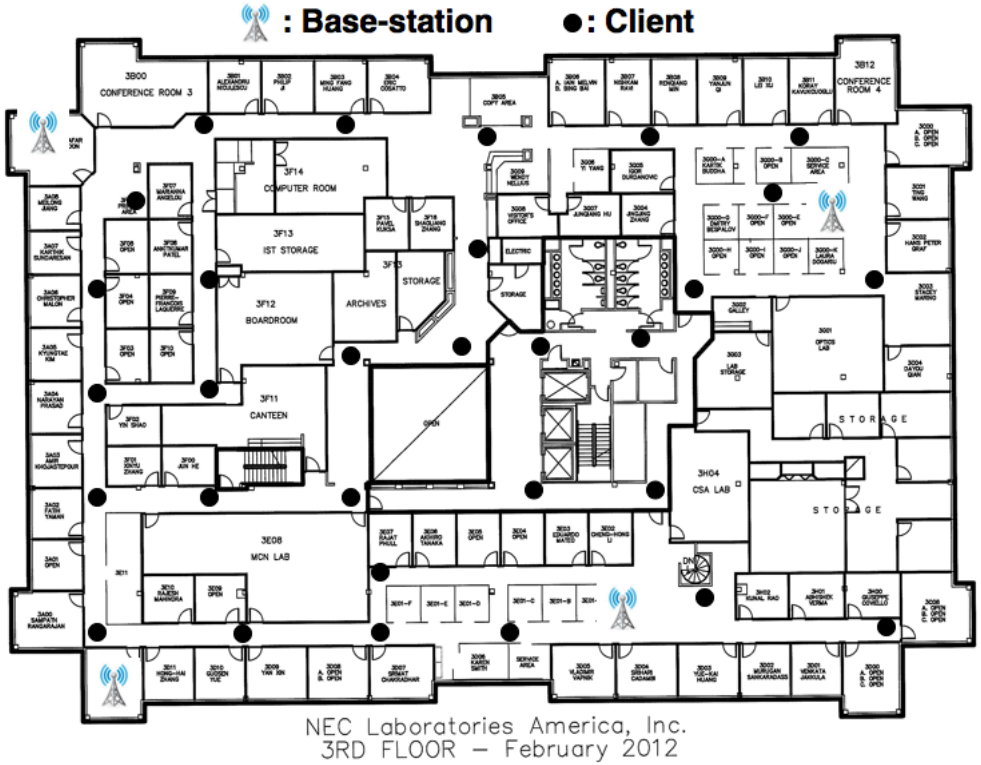
High gain pattern



Low side-lobe



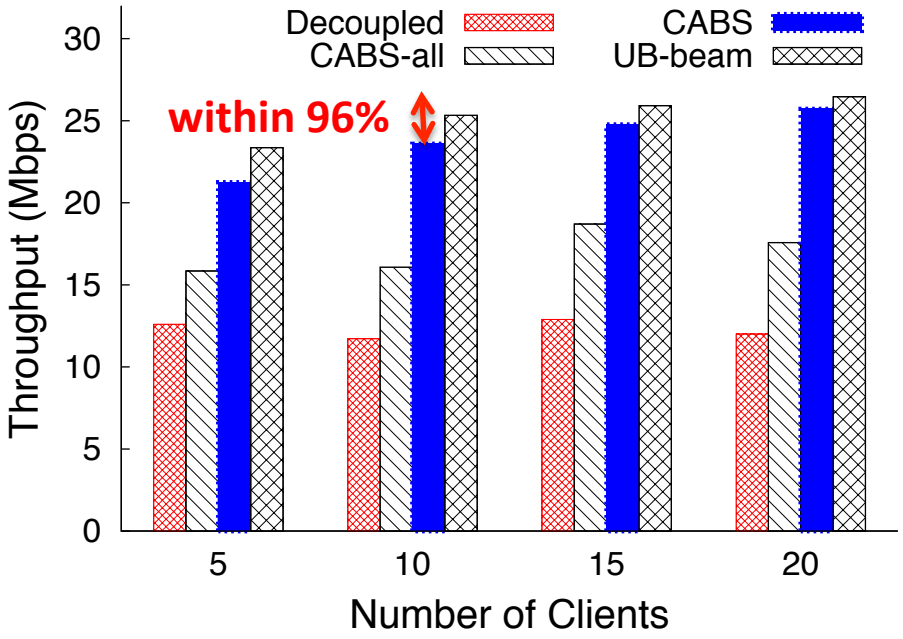
Testbed

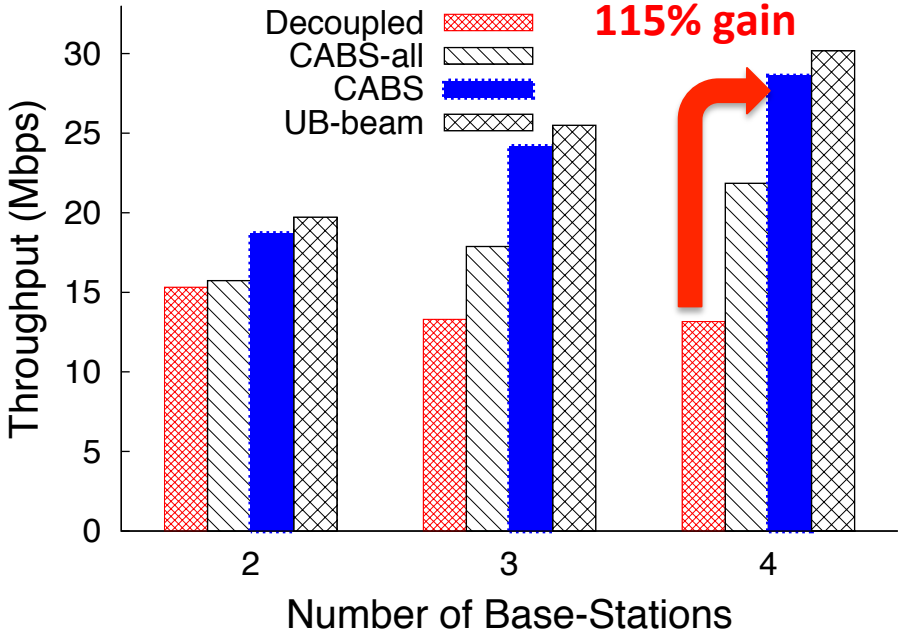


- 4 Small-cells with directional antenna
- 16 directional patterns + 1 omni pattern
- 30 Client locations
- 4x17=68 measurements at each location

Throughput gain

- **Decoupled: find best beam pattern with given association**
- **CABS-all: associate all clients**
- **UB-beam: exhaustive beam search $O(k^n)$**

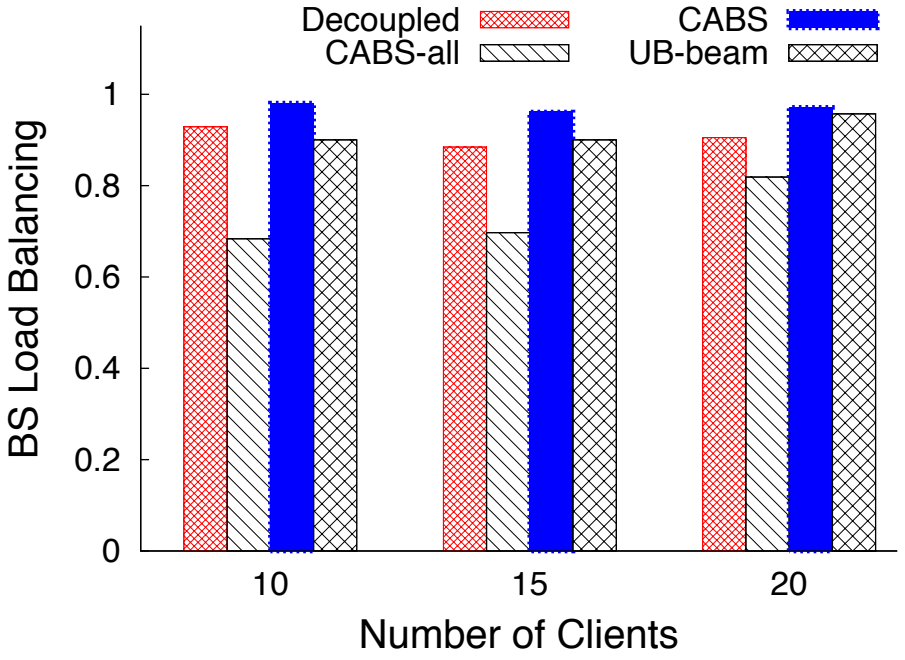




- **Removing bottleneck clients from scheduling in an epoch improves the spatial reuse**
- **…pach**

Fairness

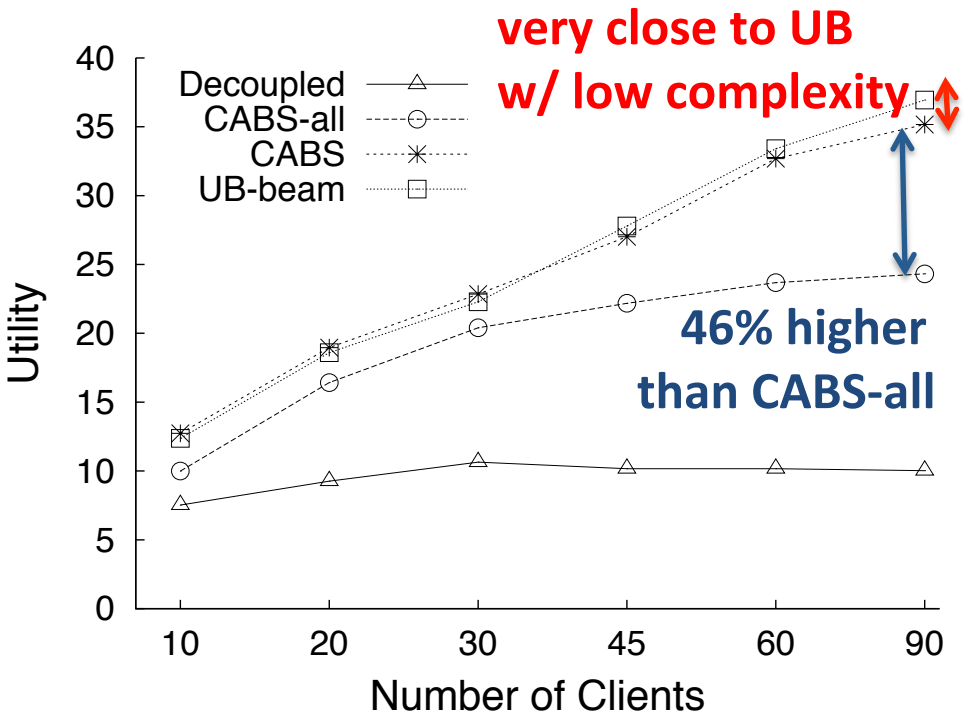
- Load balancing: fairness index among the number of clients associated with each BS

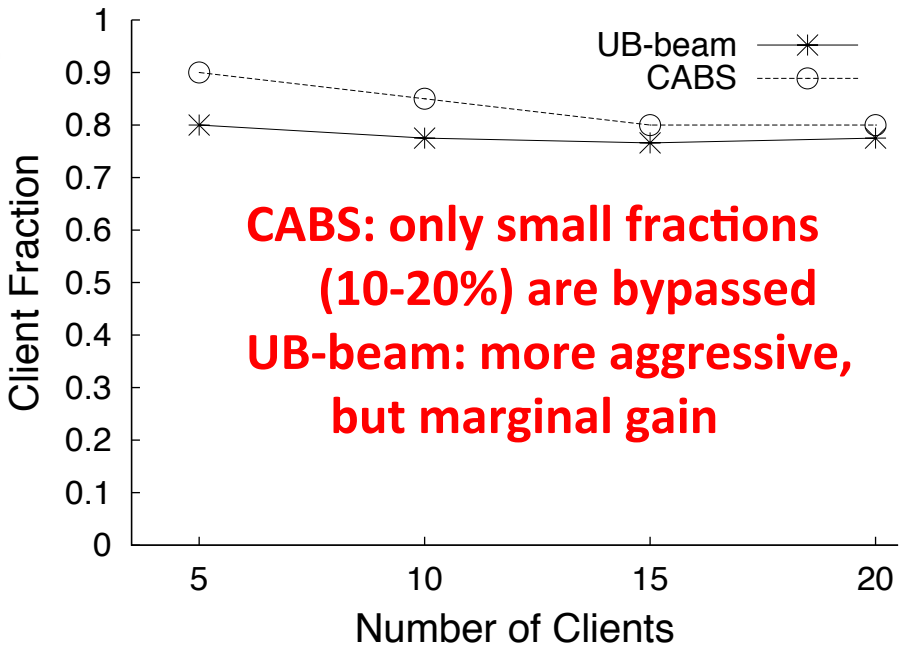


CABS is close to 1

Utility / Fairness (association)

- Utility: captures both throughput and fairness





Maximizing reuse gains without compromising on fairness

Conclusion

- Decoupling beamforming from client scheduling is necessary
- Jointly address client association with beamforming
- Implemented on a real WiMAX testbed with commercial, off-the-shelf clients
- Applicable to LTE and LTE-A

Thank you!

- Questions?