PoMeS: Profit-Maximizing Sensor Selection for Crowd-Sensed Spectrum Discovery

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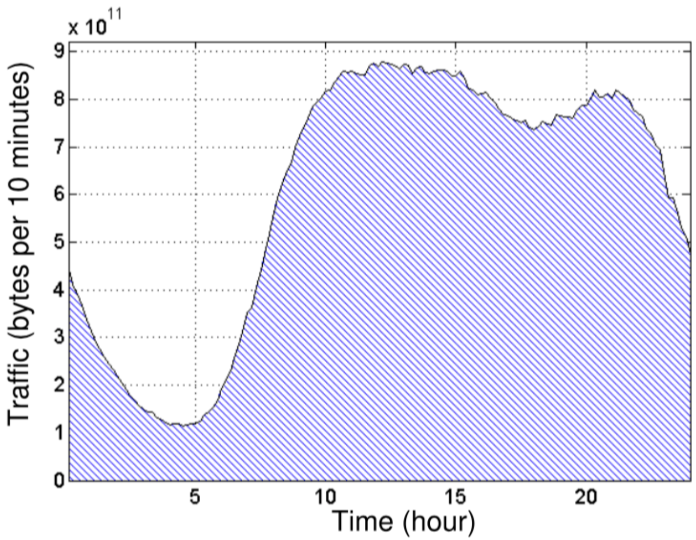
Joint work with: Gürkan Gür (ZHAW, Switzerland), Anatolij Zubow (TU Berlin, Germany)

High variation in a cellular network's load



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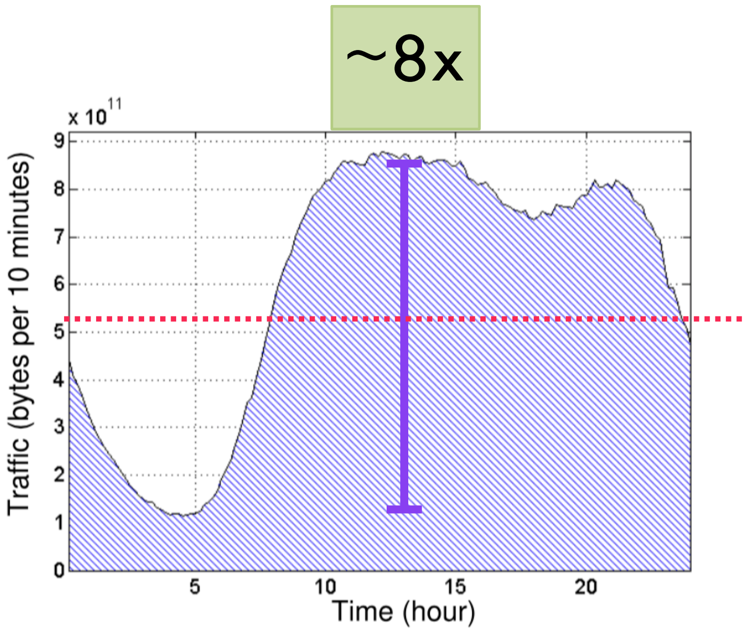

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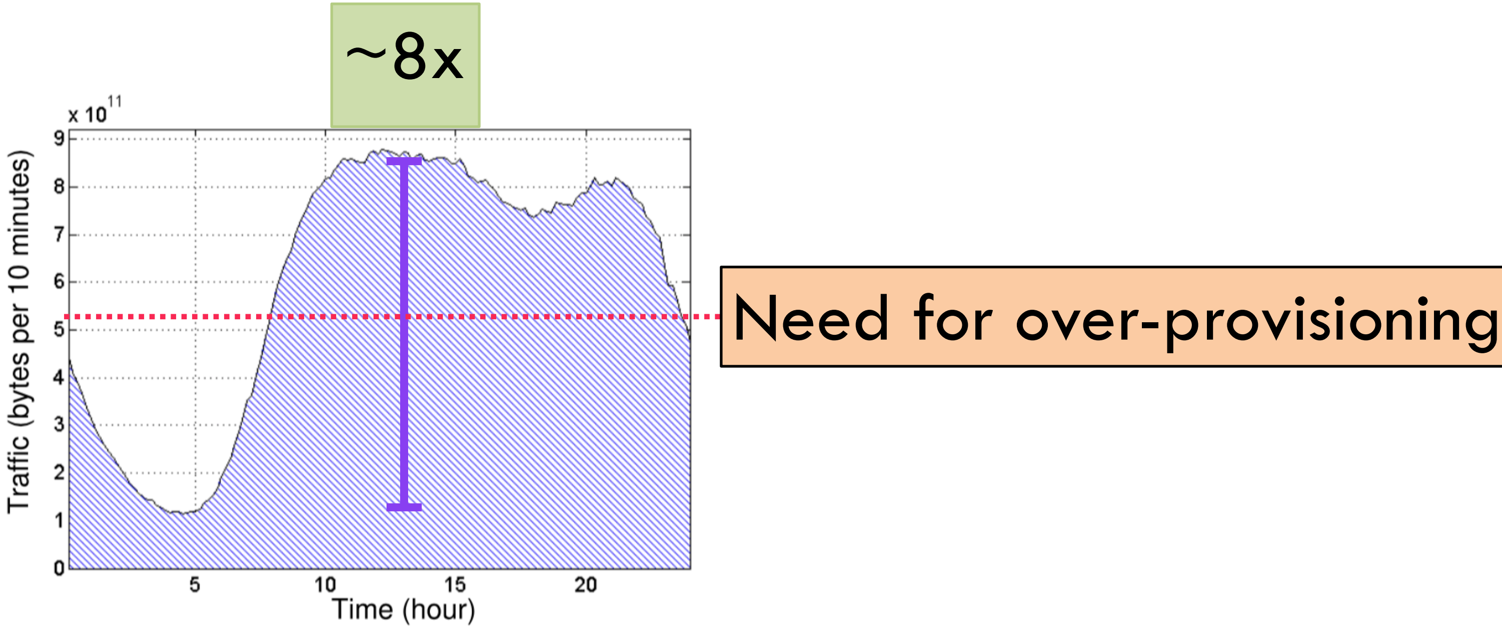

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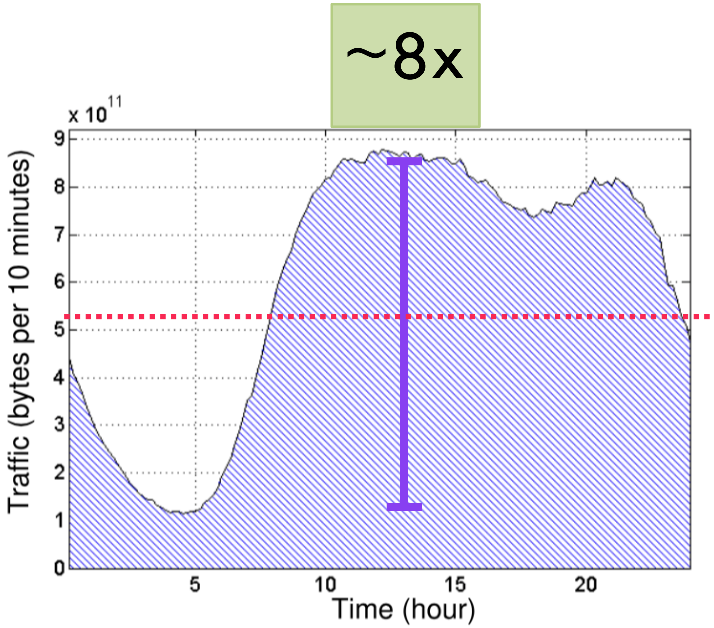

Need for over-provisioning

Capacity expansion via secondary spectrum rather than costly capacity over-provisioning

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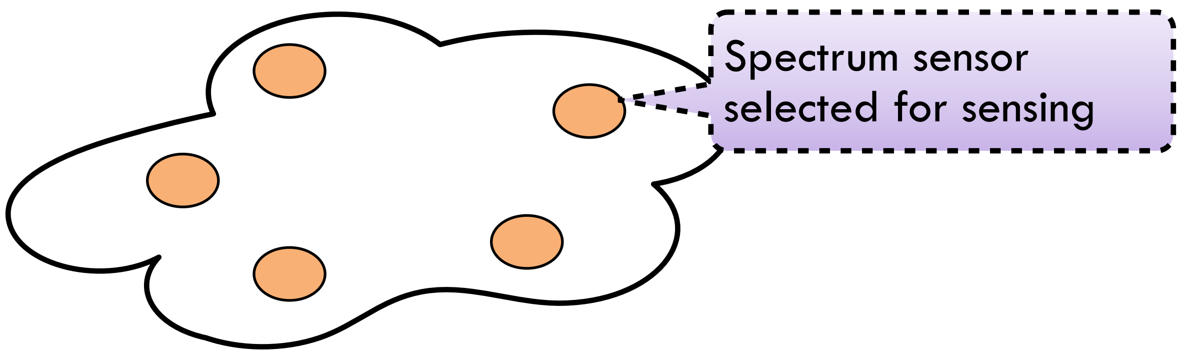
Crowd-sourcing based spectrum-discovery

- Rather than deploying its own infrastructure, the MNO launches crowd-sensing campaign



Crowd-sourcing Spectrum Sensing

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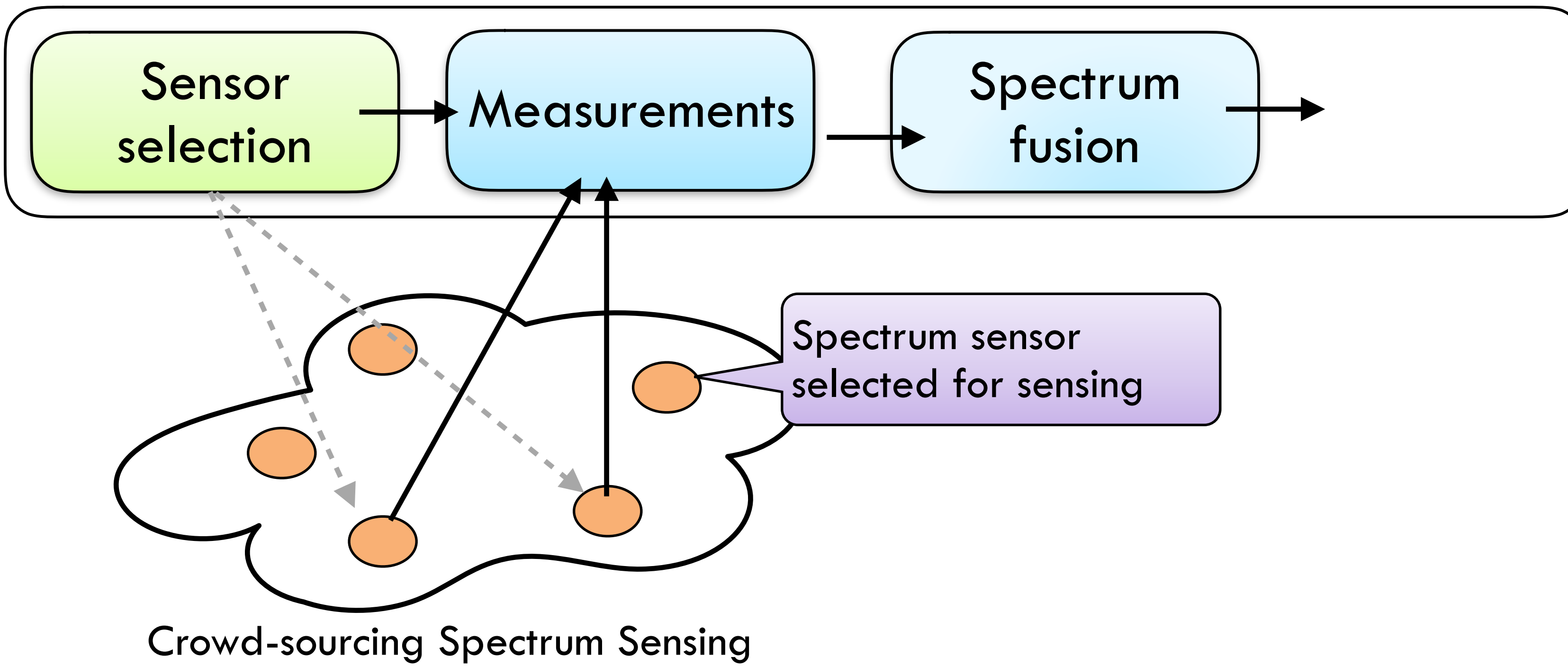

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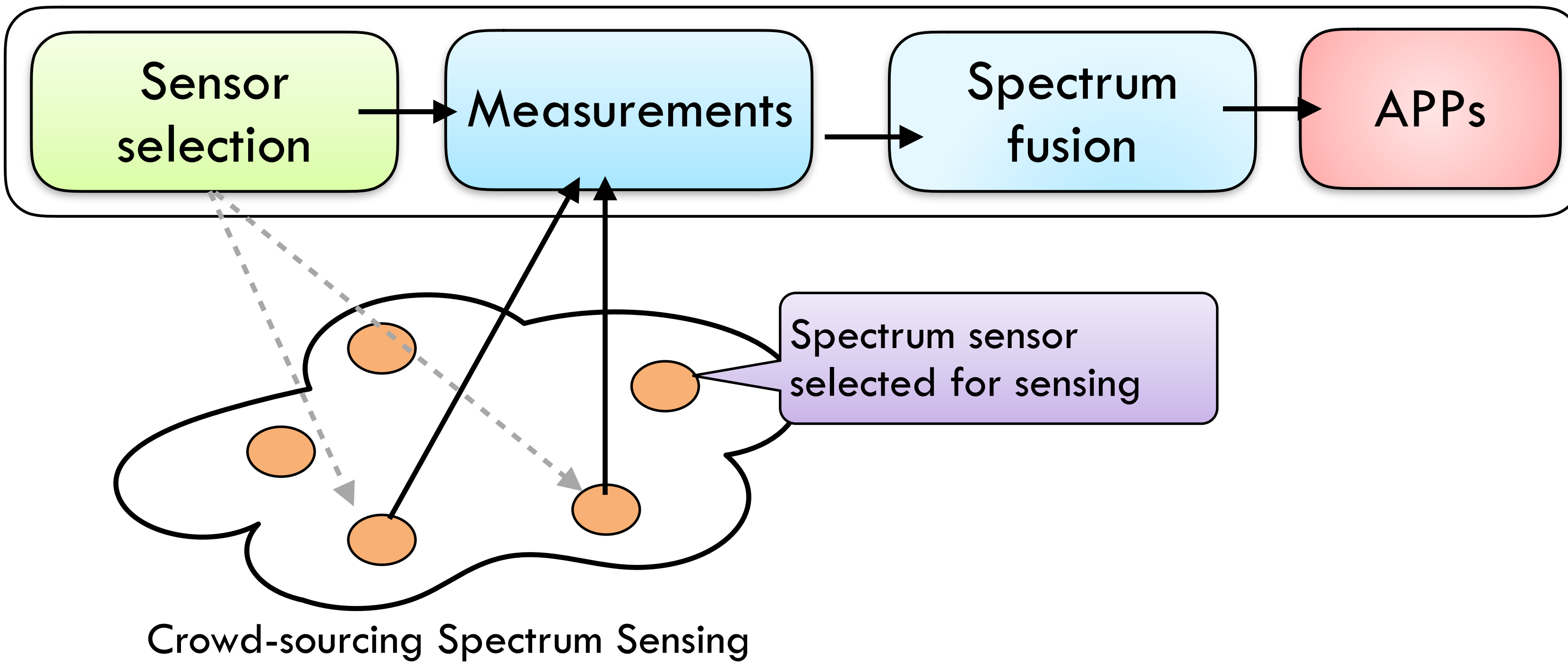

Applications of crowd-sourcing based spectrum sensing

- Spectrum monitoring for better policy making
- Spectrum patrolling for detecting spectrum misuse
  - Chakraborty et al. Spectrum patrolling with crowdsourced spectrum sensors, *IEEE* INFOCOM 2018
- Radio Environment Map generation and spectrum queries
  - Chakraborty et al. Specsense: Crowd-sensing for efficient querying of spectrum occupancy, IEEE INFOCOM 2017
  - Ying et al. Pricing mechanism for quality-based radio mapping via crowdsourcing, IEEE GLOBECOM 2016

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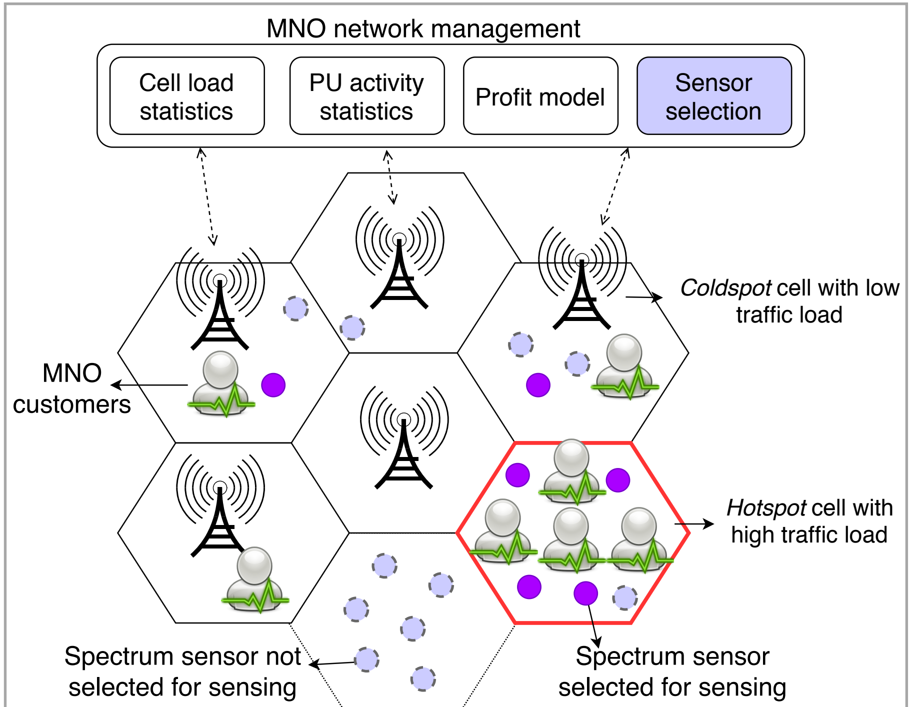
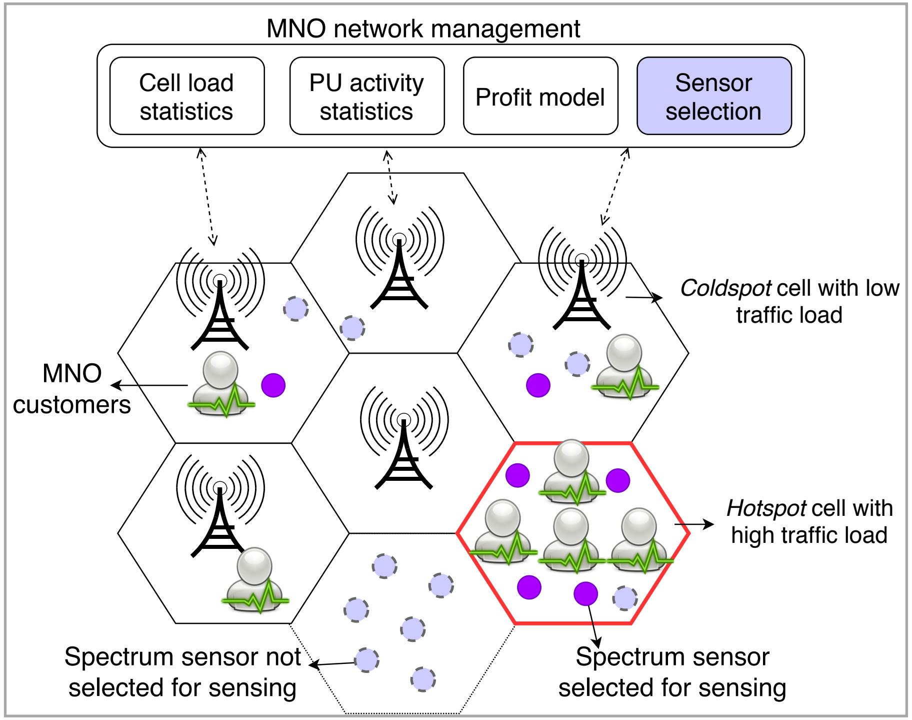
PoMeS: crowd-sourcing based spectrum discovery for MNO capacity expansion

PoMeS: profit-maximizing sensor selection



PoMeS: profit-maximizing sensor selection



- How many sensors to use for spectrum discovery?
  - Monetary cost of spectrum sensing
  - A limited budget for crowd-sensors
  - Expected traffic in each cell
    - Hot spot cells vs cold spot cells
    - Varying expected PU traffic
  - Required sensing accuracies asserted by the regulatory bodies

Goal: maximize the profit while meeting the regulatory requirements

- Regulations: might be overly-conservative resulting in wasteful sensing by the sensors
  - High PU detection accuracy (>0.90)
  - Low false alarm probability (<0.10)
- Oblivious to the PU traffic or secondary network's traffic

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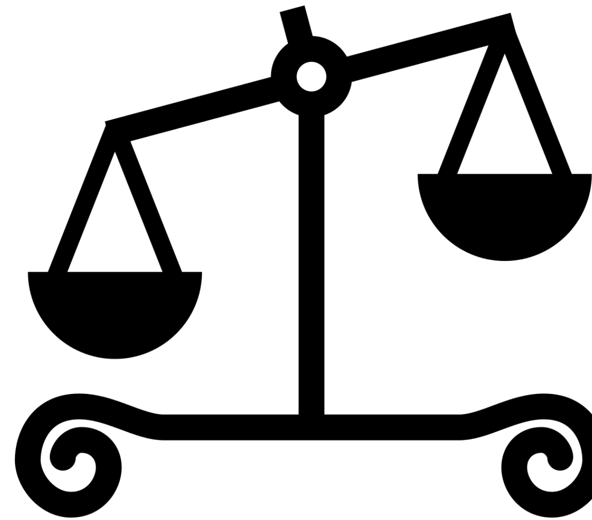
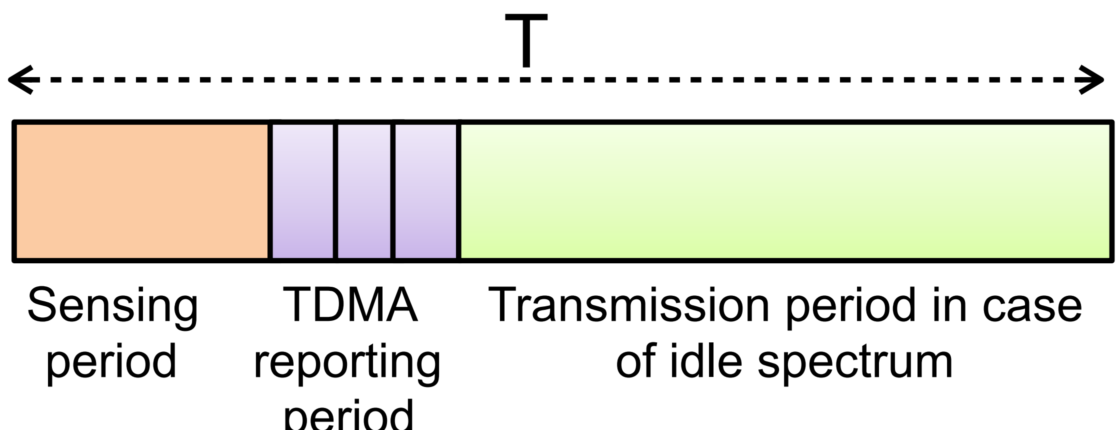


PoMeS: different accuracy at each cell, but monetary penalty if the required accuracy not met

Spectrum-sensing model

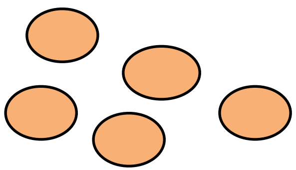
- PU statistics are available at the MNO
- Sensor accuracies are identical and Pd, Pf known by the MNO
- Sensors' sensing price is identical
- Majority decision combining
- Sensing period, reporting period



MNO’s net profit

Sensing cost

Expenses for crowd-spectrum sensing

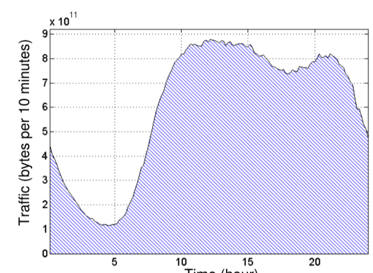


Collision cost

Penalty paid if spectrum sensing accuracy is lower than required

Income

from its customers served through the discovered spectrum



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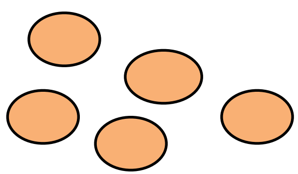

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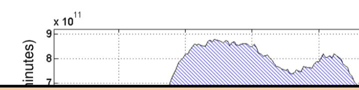

How many sensors are selected?

Price of each sensor

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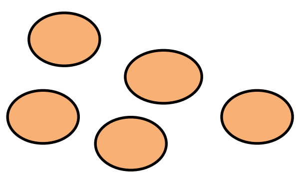
MNO's net profit

Sensing cost

Expenses for crowd-spectrum sensing



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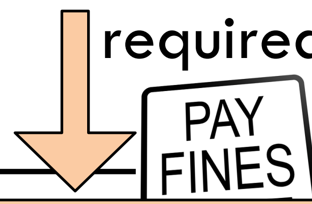

Income

from its customers served through the discovered spectrum

Achieved sensing accuracy

Required accuracy

Penalty policy

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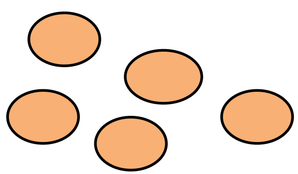
MNO’s net profit

Sensing cost

Expenses for crowd-spectrum sensing



Collision cost

Penalty paid if spectrum sensing accuracy is lower than required

Income

from its customers served through the discovered spectrum

Demand in each cell

Discovered spectrum in each cell

Price of each served request

Utility of spectrum sensing with *m* sensors

- Utility *U(m)*: expected discovered and useable spectrum if *m* sensors sense the spectrum

$$\mathcal{U}(m) = p_o B \left(\frac{T - T_s - mT_r}{T} \right) (1 - Q_f(m))$$

- p_o: Probability that PU channel is idle
- B: PU channel's bandwidth (Hz)
- $\frac{T - T_s - mT_r}{T}$: Sensing efficiency (after overheads of sensing and reporting)
- $Q_f(m)$: Probability of false alarms in sensing

How many requests can be served with this discovered spectrum?

Discovered spectrum

Spectral efficiency of the MNO

$$R_i^{max} = \min(r_i, \frac{\mathcal{U}_i \kappa}{c_{min}}). \text{ requests/sec}$$

Number of requests in this cell-i

Required minimum resources per request

Income of *cell-i*

- Each served request translates into some monetary gain

$$R_i^{max} = \min(r_i, \frac{\mathcal{U}_i \kappa}{c_{min}}). \text{ requests/sec}$$

$$\Pi_i^+ = \mu R_i^{max}$$

Service cost paid for each served request

Expenses of cell-i : sensing cost

Sensing cost

$$\Pi_i^- = N_i \mu_s \beta_s$$

- N_i: Number of sensors
- μ_s: Unit sensing price
- β_s: Frequency of sensing

Collision penalty cost

$$\mu_c \Delta Q_{d,i} R_{max}^i$$

- μ_c: Penalty price
- $\Delta Q_{d,i}$: Difference between the desired and achieved sensing accuracy

$$\Delta Q_{d,i} = \max(0, Q_d^* - Q_{d,i})$$

Optimal sensor selection problem

$$\max_{N_i} \sum_{A_i \in \mathscr{A}} R_i^{max}\mu - N_i\mu_s\beta_s - \mu_c R_i^{max} \max(0, \Delta Q_{d,i} - Q^*)$$

$$\sum_{A_i \in \mathscr{A}} \mu_s\beta_s N_i \leqslant \mathscr{B}$$

Available budget for sensors

$$N_i \leqslant \lfloor \frac{T - T_s}{T_r} \rfloor$$

$$N_i \geqslant 0$$

Optimal sensor selection problem

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Available budget for sensors

$$N_i \leqslant \lfloor \frac{T - T_s}{T_r} \rfloor$$

Coupling constraint. NP-hard!

De-couple via allocating the budget first.

(i) budget allocation problem (ii) exhaustive search in each cell

$\mathscr{B}$udget allocation for K cells

- **Equal budget per cell (EQ):**
  - # of sensors upper-bounded by:

$$N_{max} = \min(\lfloor \frac{T - T_s}{T_r} \rfloor, \lfloor \frac{\mathscr{B}}{K\mu_s\beta_s} \rfloor)$$

- **PROP:** Budget proportional to the serving capacity of the cell

$$\mathscr{B}_i = \frac{R_i^{max}\mathscr{B}}{\sum_{A_i \in \mathscr{A}} R_i^{max}}$$

- Incremental gain based greedy assignment (**INGA**)
- Baselines:
  - satisfying (Q^*_d, Q^*_f) required by the regulatory body (**REG**) with **EQ or PROP** budget allocation

Polynomial complexity:

EQ, PROP: $\mathscr{O}(KN_{max})$

INGA: $\mathscr{O}(KN\log(N))$

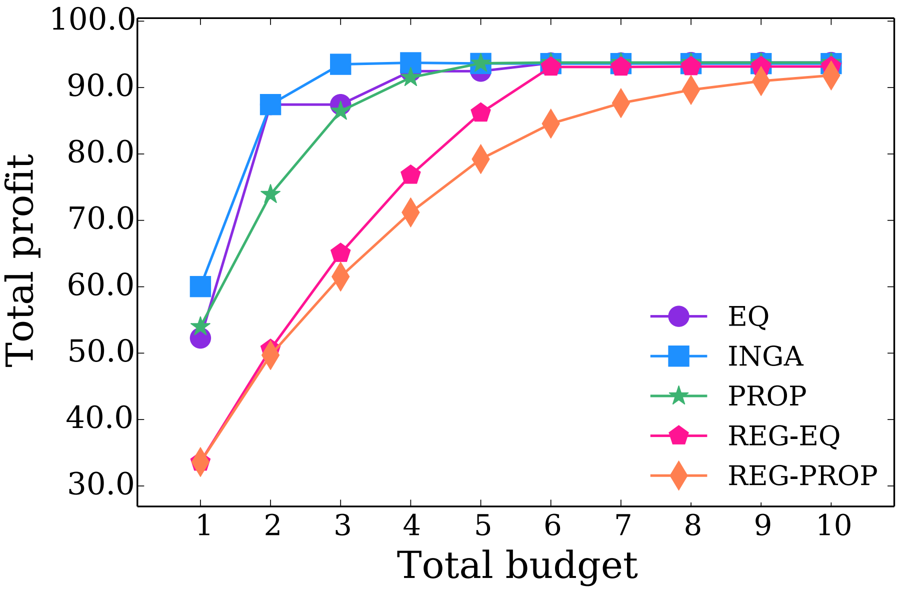
Simulation-based performance analysis of PoMeS

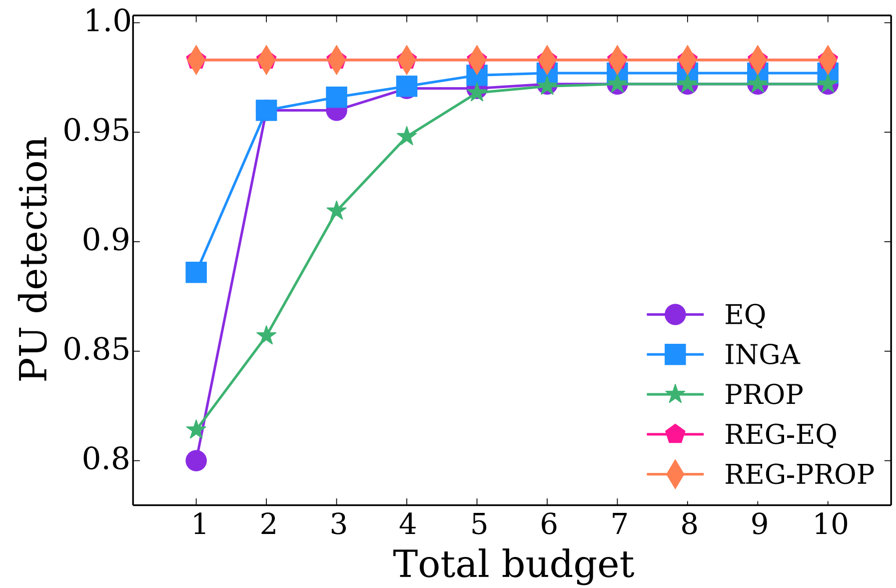
- Impact of increasing budget
- Impact of cell traffic load
- Impact of hot-spots (cell-load variation)

Parameters

- $K = 2000$ cell sites
- PU activity = [0.2, 0.8]
- $\mu_s = 1$, $\mu = 1$, $\mu_c = 5$,
- $\kappa = 10$ bps/Hz, $(P_d, P_f) = (0.8, 0.1)$, and $(Q^*_d, Q^*_f) = (0.98, 0.05)$
- Randomly σ of the cells as hotspots
- $R\sigma$ fraction of the requests from hotspots
- Coldspot traffic: $(1-R\sigma)$ fraction of the requests

Impact of budget: B = [1-10] sensors/cell





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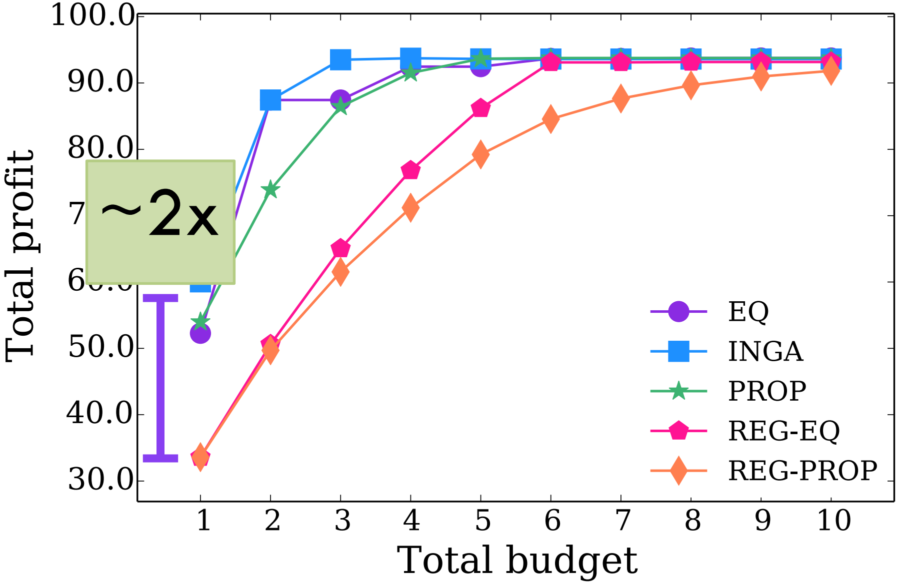

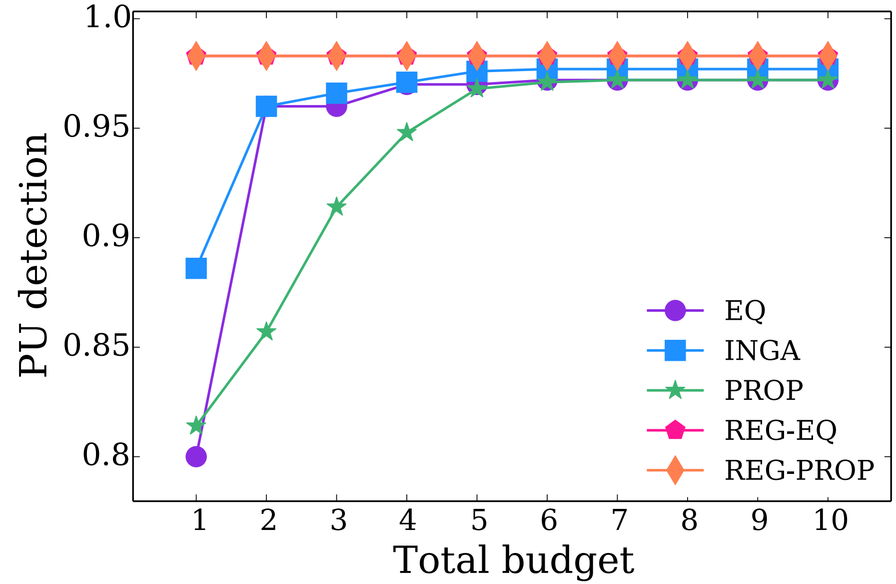

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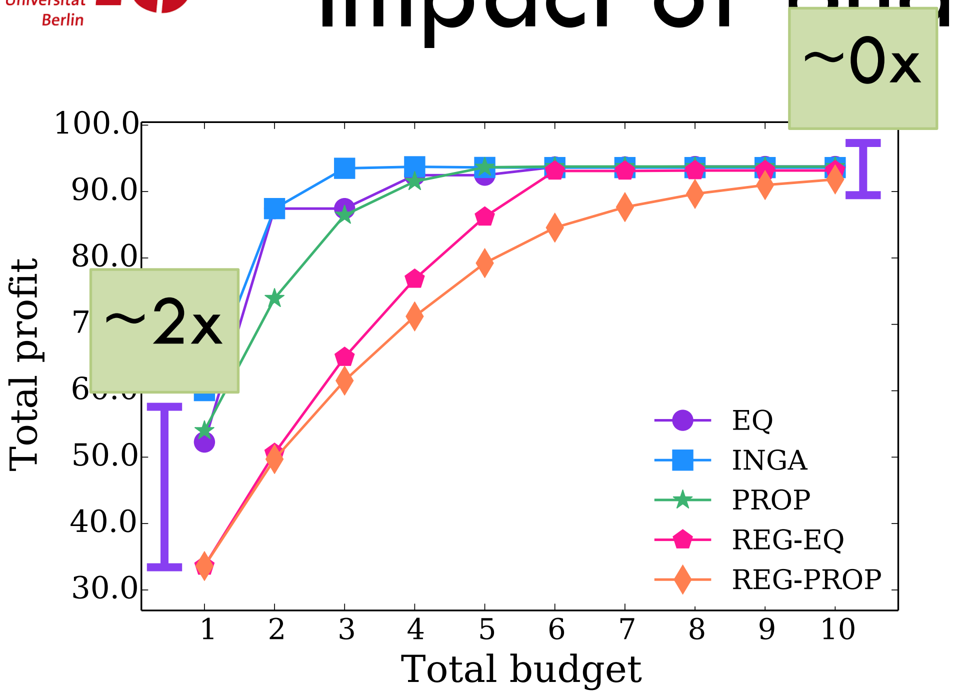

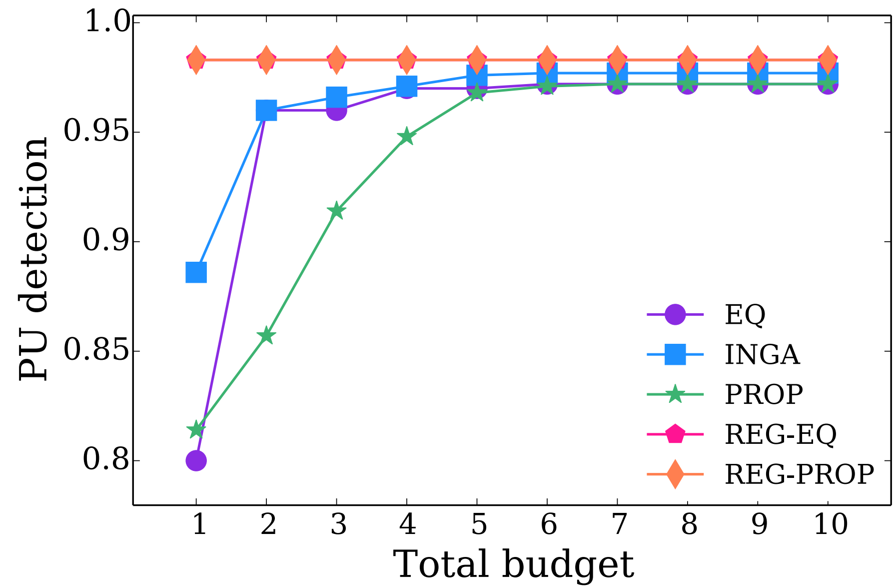

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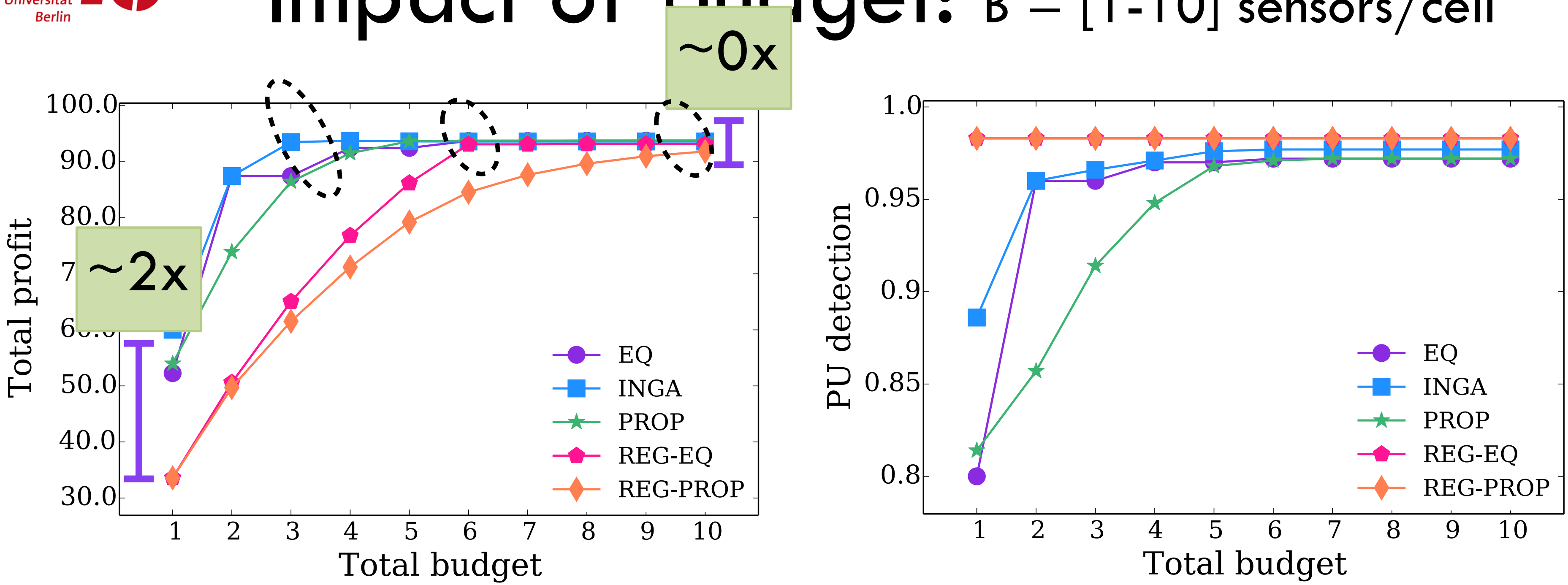

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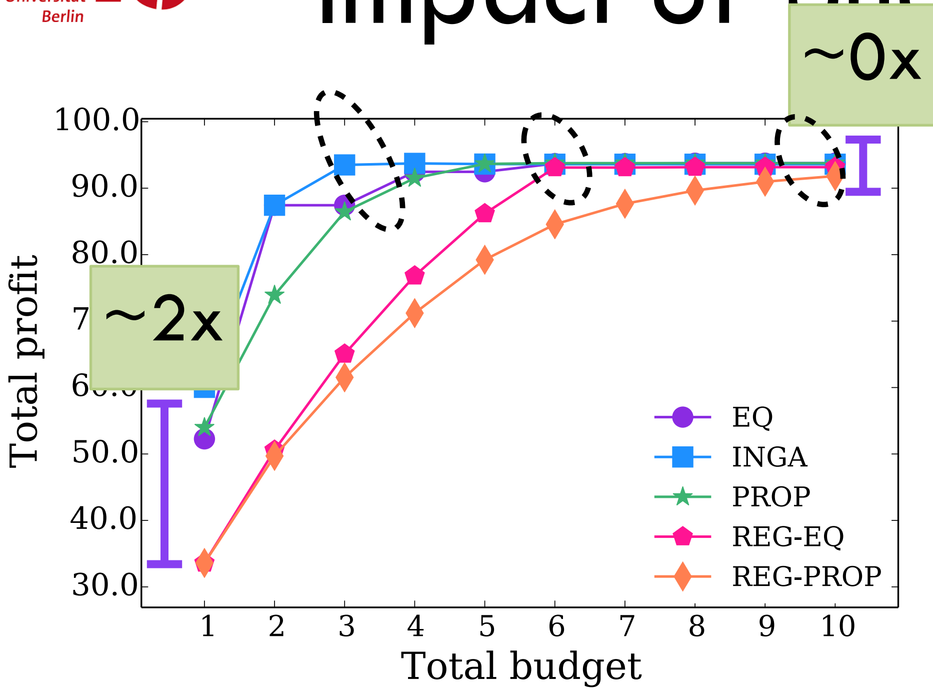

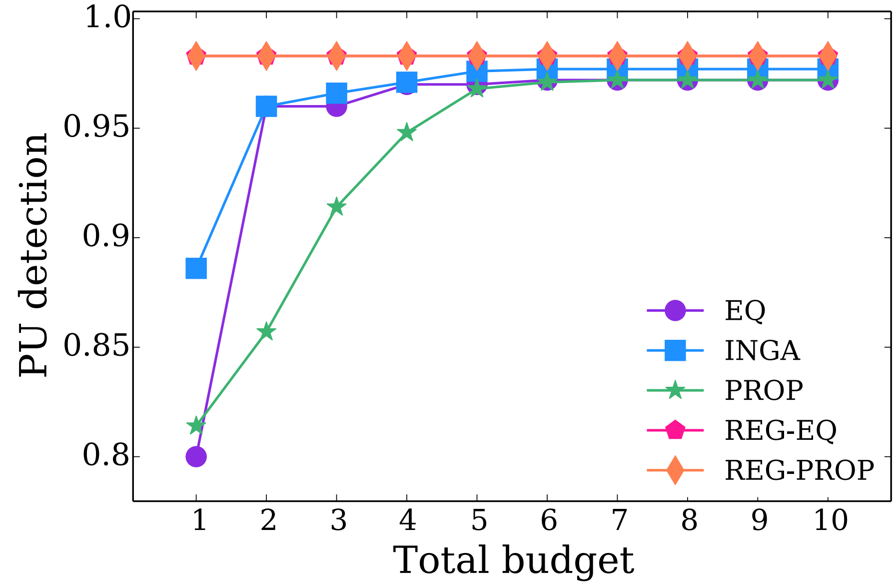

Saturation in profit due to diminishing returns: deploying more sensors only increases the capacity marginally

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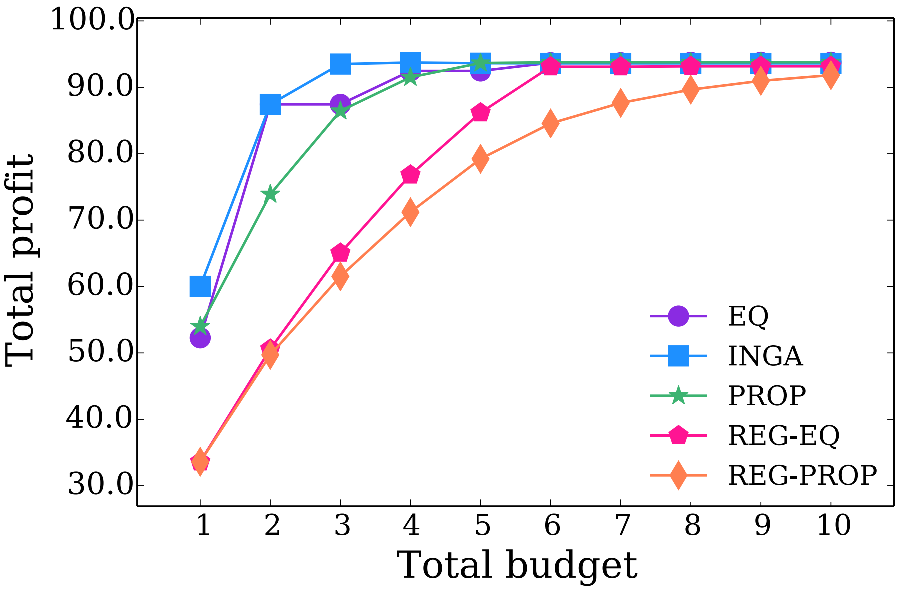

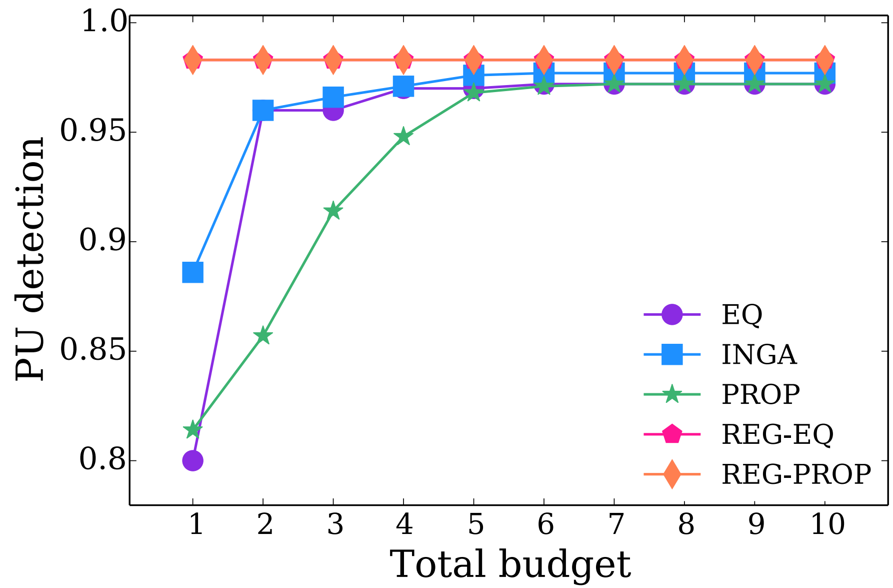

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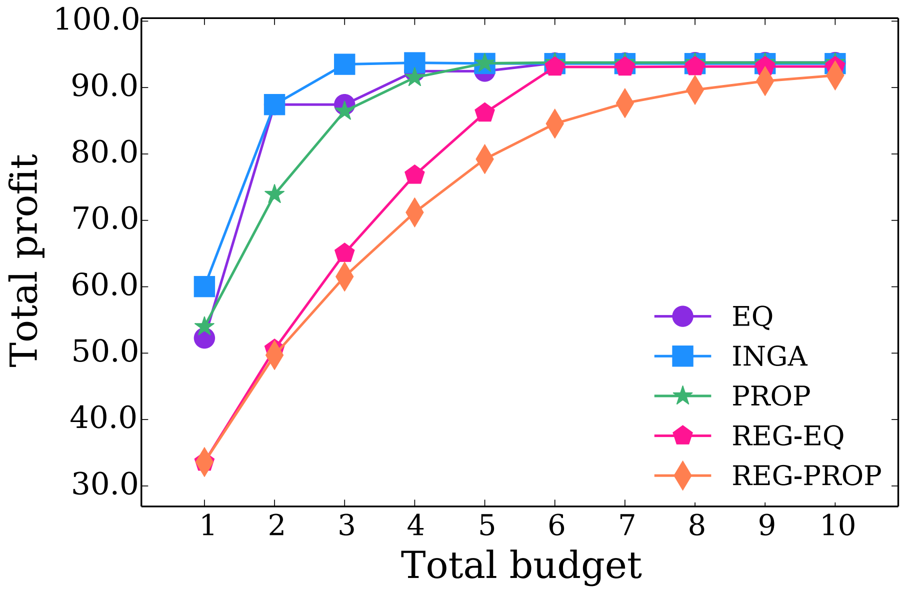
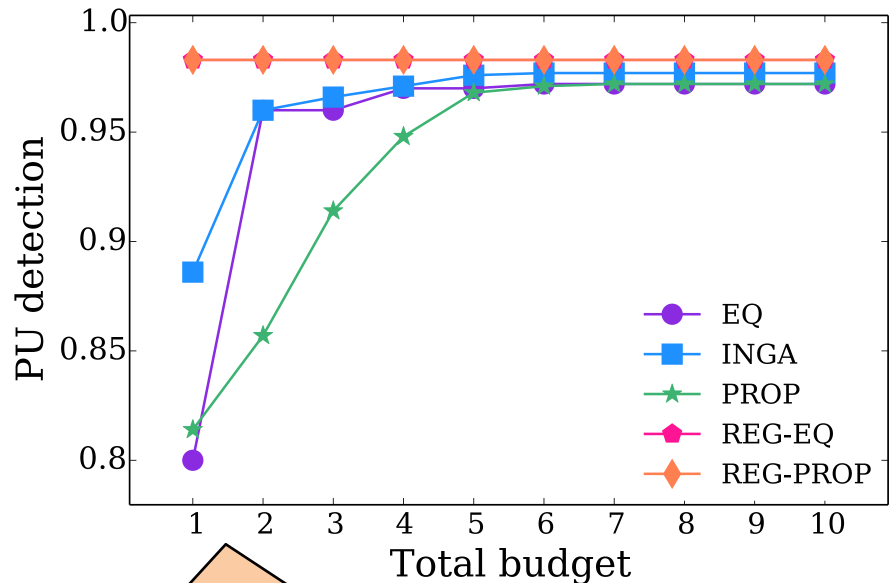
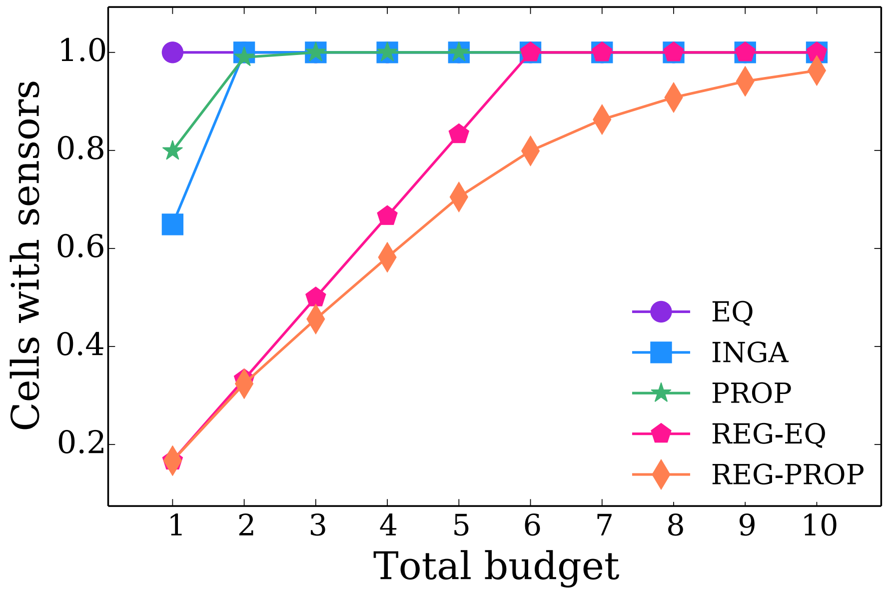




Under low budget, sacrifice from sensing accuracy

Which cells enjoy the capacity expansion?



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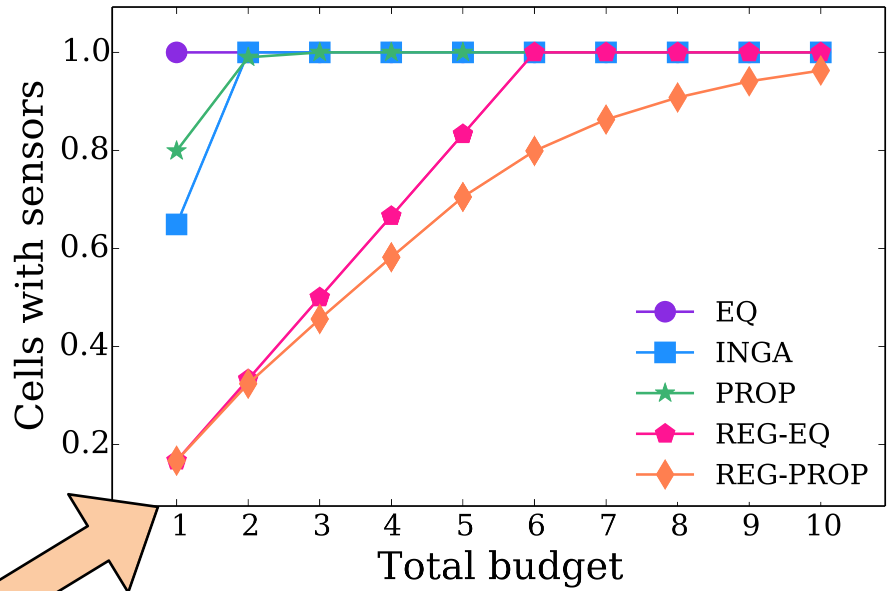
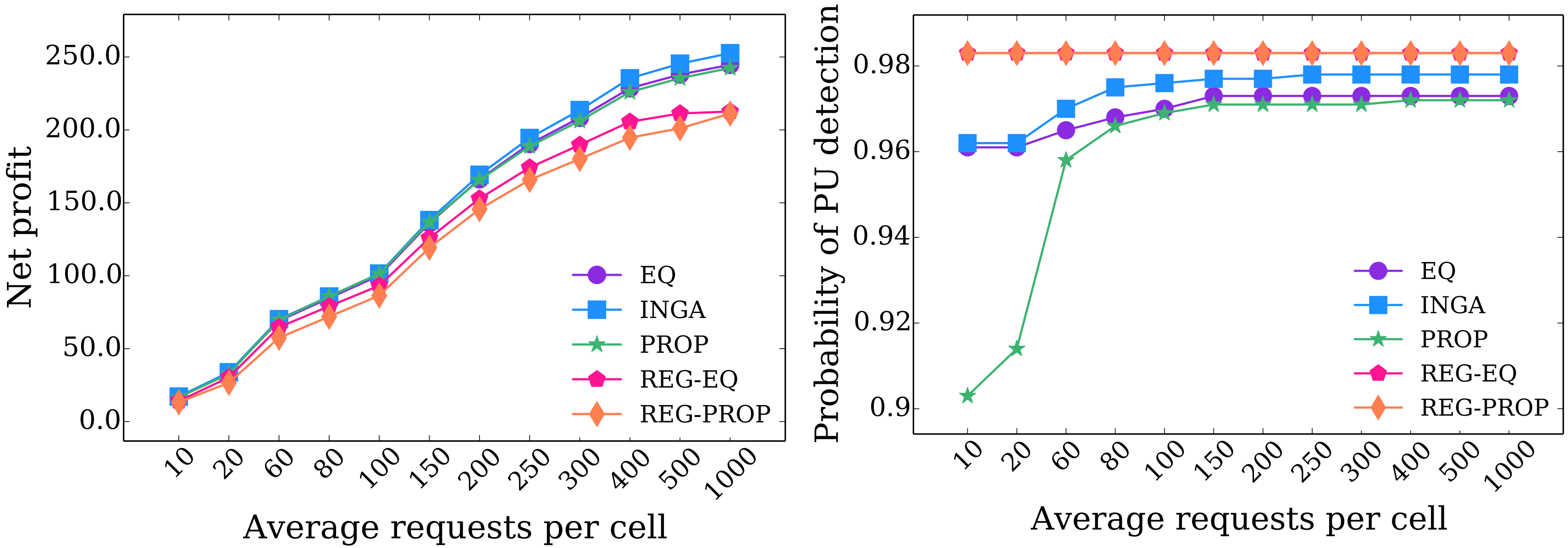


Low budget: capacity expansion over all cells with our heuristics
17% of the cell sites vs 65-100%

Impact of cell-load



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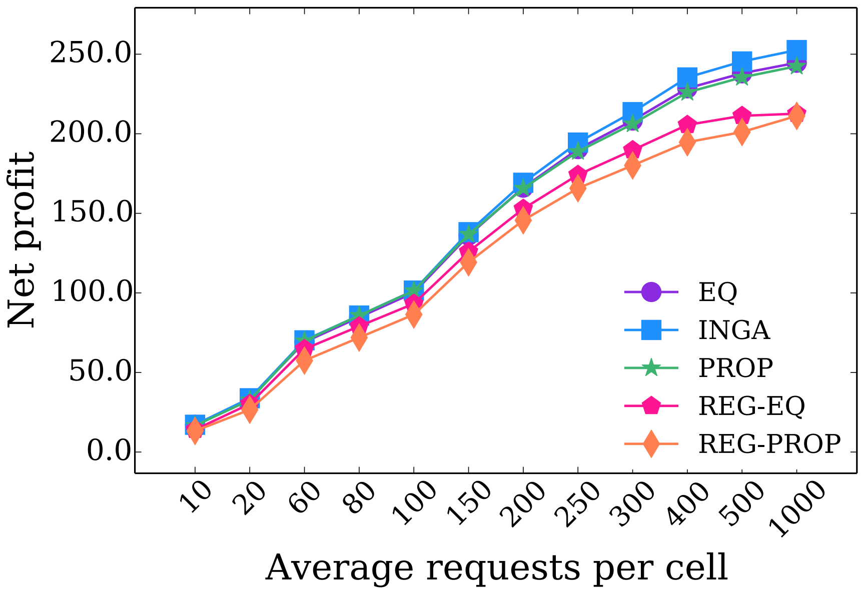
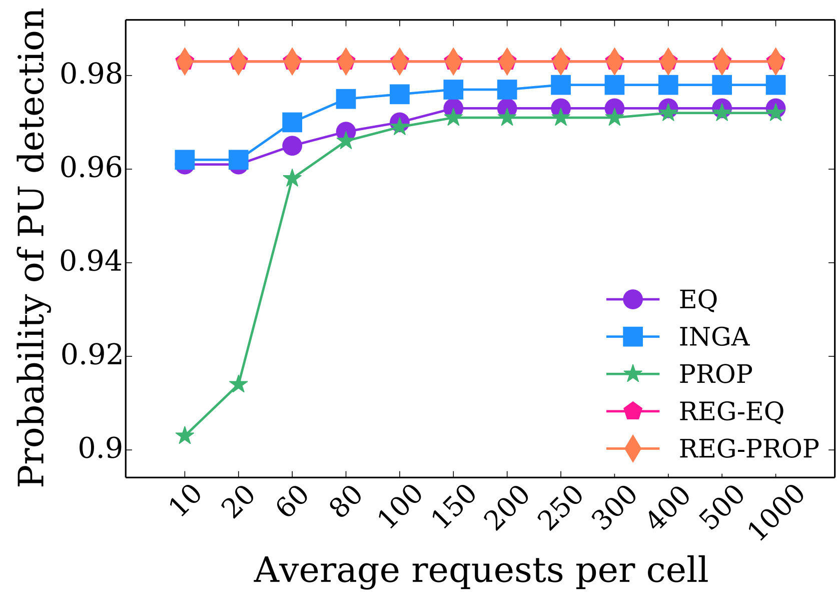


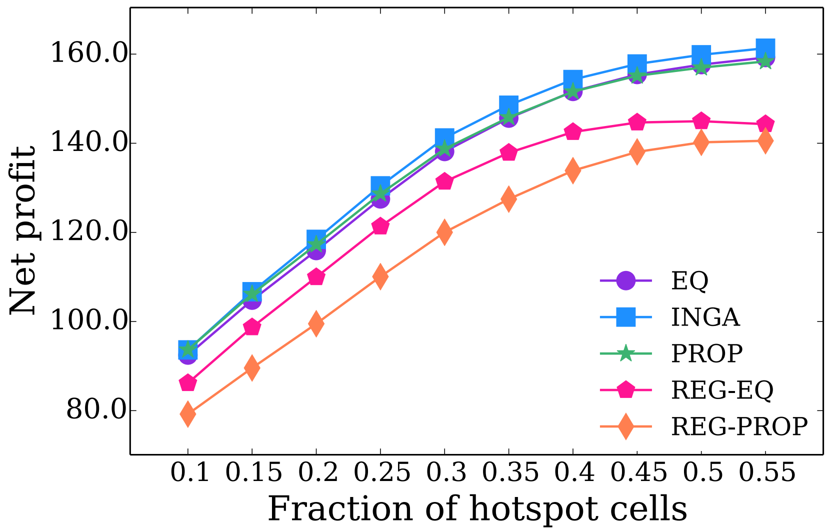


- INGA > PROP or EQ by about 5%

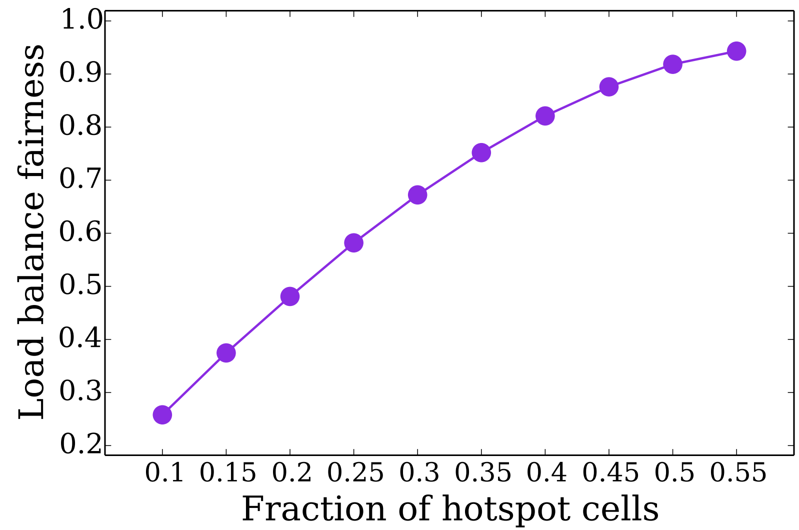
- REG-EQ over-performs REG-PROP for about (5-15%) depending on the setting

- Lower sensing accuracy only under low load

Impact of hot-spots



Jain's fairness index in terms of cell load



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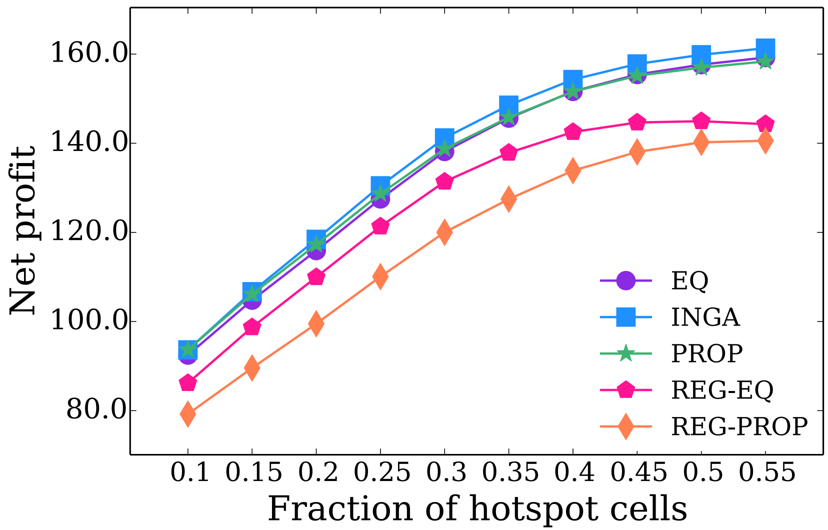

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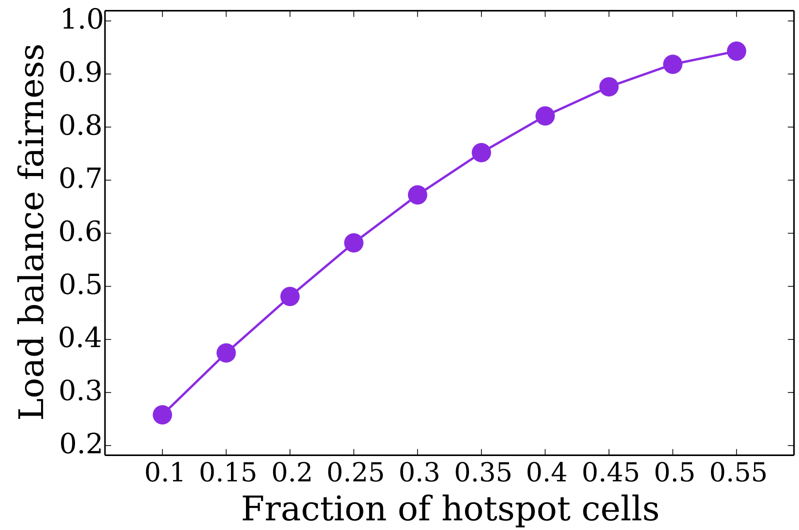

- Under a more uniform traffic load, profit is higher
- The relative performance of our schemes exhibit the same trend

Take-aways

- **Problem:**
  - Capacity over-provisioning results in a high cost at an MNO
- **PoMeS:**
  - Capacity expansion via opportunistic spectrum access
  - Crowd-sourced spectrum sensing
  - Select sensors considering MNO's net profit
    - Load of each cell, PU spectrum activity, required spectrum sensing accuracy, each sensor's cost and accuracy
- **Key results**
  - Lower sensing accuracy only when the network load is low and budget for spectrum sensing payment is limited
  - Distributing the budget equally for regulation-confirming schemes results in higher profit
- **Future work:** heterogenous sensors in terms of accuracy and cost

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