A Novel Multiobjective Framework for Cell Switch-Off in Dense Cellular Networks

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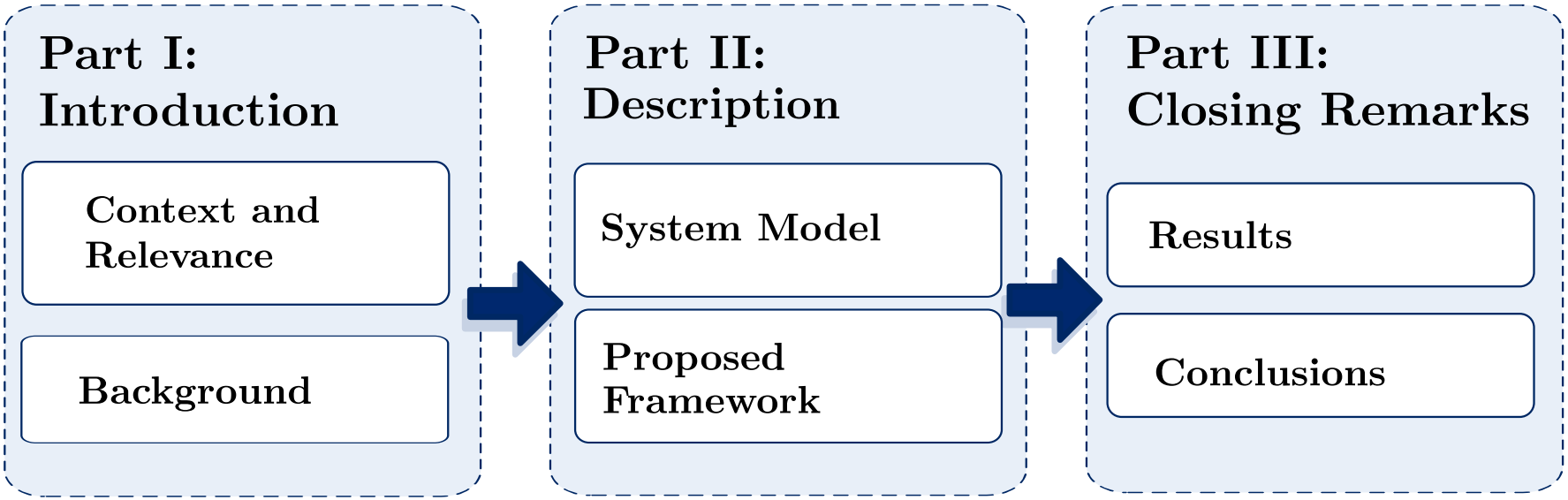
Outline


Part I:
Introduction
Context and Relevance
Background
Part II:
Description
System Model
Proposed Framework
Part III:
Closing Remarks
Results
Conclusions

Motivation

1. **Energy Efficiency** (EE) in cellular networks.
   - Cellular industry is growing **exponentially**.
   - Hyper dense small cells deployment → **boost energy consumption!**

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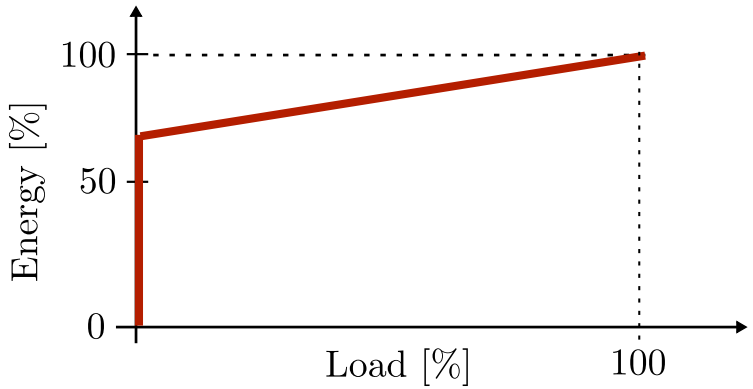
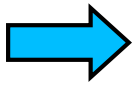
2. **Why switch-off base stations?**
   - **Energy consumption models**





Cell Switch Off (CSO)

   - Solution approach → **Multiobjective Optimization**
     - (aggregate capacity ↔ active cells).

CSO: *Problem statement & practical insights*

Main intuition

Switch off **lightly loaded** base stations to save energy.

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The challenge

The CSO problem consists in determining **the largest set of cells** that can be switched off **without compromising the QoS**.

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Theoretical aspects:

- *Deployments density.*
- *Traffic behavior.*
- *Network capacity.*
- *ICIC.*

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Theoretical aspects:

- *Deployments density.*
- *Traffic behavior.*
- *Network capacity.*
- *ICIC.*

Practical aspects:

- *Coverage.*
- *Switch on/off transitions.*
- *Architecture.*
- *Others.*

CSO: *Related work*

Ref.	Context	C1	C2	C3	C4	C5	C6
[283]	CSO	Heuristic	CE	×	×	P	Full buffer
[284]	CSO	Analytical	CE	P	×	×	Full buffer
[285]	Planning: how to deploy cell for minimizing energy consumption	Analytical	NA	P	×	NA	NA
[286]	CSO	Heuristic	CE	×	×	×	Poisson
[287]	Cell size adaptation	Heuristic	CE	×	×	×	Full buffer
[288]	An interesting RRM strategy for energy savings	Heuristic	CE	×	×	×	Poisson
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[293]	CSO	Heuristic	CE	×	✓	P	Realistic
[294]	CSO	Heuristic	SD	×	×	P	Realistic
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[298]	CSO	Heuristic	CE	×	×	×	Several models
[299]	Impact of power reduction on coverage and capacity	Analytical	NA	✓	✓	NA	Full buffer

P: Partially CE: Centralized SD: Semidistributed DI: Distributed

- **Heuristic** is the preferred approach.

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- Most of solutions require real-time **centralized** operation.

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- **Coverage analysis** is oftem missed.

Multiobjective Optimization: *Essentials*

1. **Target**: problems with conflicting criteria.

$$\mathcal{F} = \{ f_i(\mathbf{x}) \ : \ \mathbb{R}^n \to \mathbb{R}, \ i = 1, 2, \cdots, m \}$$

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2. **Structure**:
   - Design variables: $\mathbf{x} = [x_1, \ x_2, \ \cdots, \ x_n]$, $(\mathbf{x} \in \mathcal{X})$.
   - Feasible set: $\mathcal{X} = \mathcal{X}_1 \times \mathcal{X}_2 \times \cdots \times \mathcal{X}_n$, (domains).
   - Objetive space: $\mathbf{f} : \mathcal{X} \to \mathbb{R}^m$, $\mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), \ f_2(\mathbf{x}), \cdots, \ f_n(\mathbf{x})]$.
   - Constraints.

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   - Constraints.

3. **Optimality**: Pareto efficiency ($\mathbf{x}^\star$ and the set $\mathcal{X}^\star$).

$$\mathbf{x}_1 \succ \mathbf{x}_2, \iff f_i(\mathbf{x}_1) \leq f_i(\mathbf{x}_2) \quad \wedge \quad \exists \ j \ \mid \ f_j(\mathbf{x}_1) < f_j(\mathbf{x}_2)$$

$$\mathbf{x}^\star \in \mathcal{X}^\star \iff \nexists \ \mathbf{x} \in \mathcal{X} \ \mid \ \mathbf{x} \succ \mathbf{x}^\star.$$

Multiobjective Optimization: *Essentials*

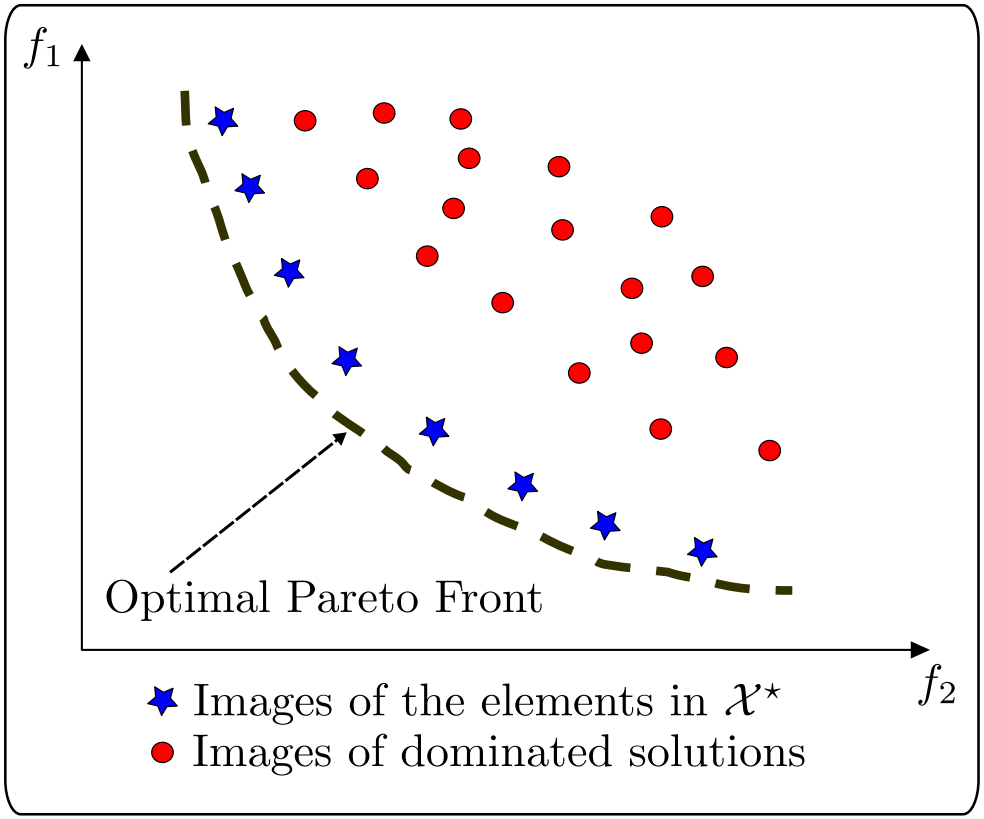
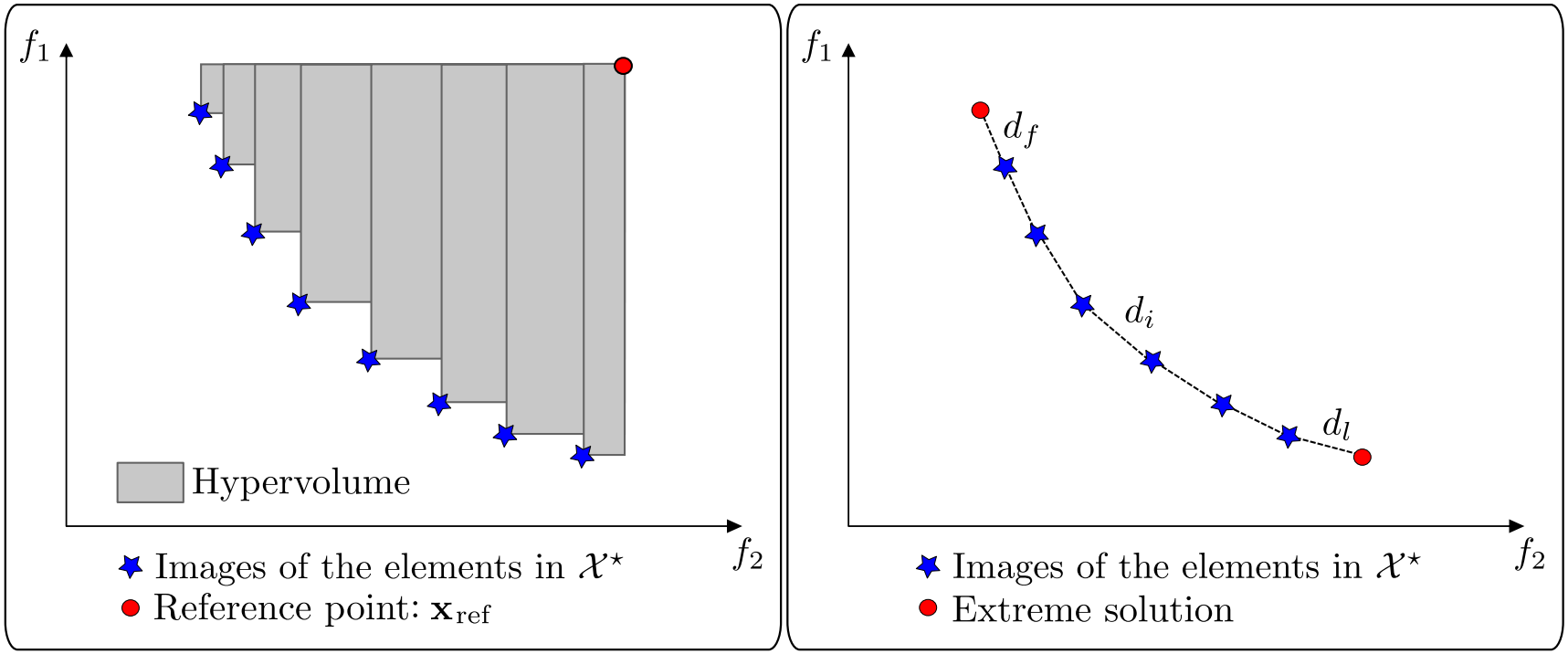


Figure: A representation of the Pareto Front.

Multiobjective Optimization: *Essentials*

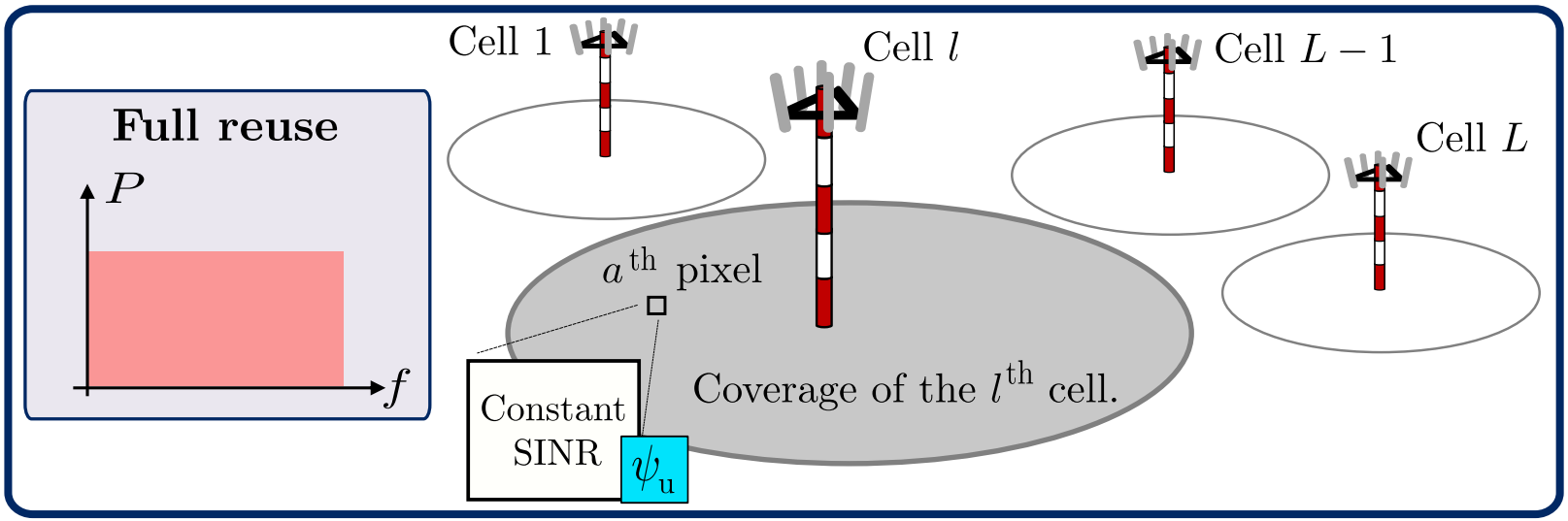


(a) The hypervolume indicator (υ). (b) The nonuniformity index (ϱ).

Figure: **Quality measures in multiobjective optimization.**

$$\upsilon(\mathcal{X}^\star, \mathbf{x}_{\text{ref}}) = \Lambda\left(\bigcup_{\mathbf{x}\in\mathcal{X}} \hat{\mathbf{x}} \mid \mathbf{x} \prec \hat{\mathbf{x}} \prec \mathbf{x}_{\text{ref}}\right) \qquad \varrho = \frac{d_f + d_l + \sum_{i=1}^{N-1} |d_i - \bar{d}|}{d_f + d_l + \bar{d}\,(N-1)}$$

System Model



- **Downlink of an OFDMA cellular network** $\rightarrow$ L cells.
- **Target** $\rightarrow$ Average ICI conditions (full reuse).
- **Any topology**: $\rightarrow$ Network geometry ($\mathbf{G} \in \mathbb{R}^{A \times L}$).
- **Flexible analysis**: $\rightarrow$ Operator-defined QoS policies.

System Model: *Terminology*

1. **Network Operation Point** (NOP)
   - $\mathbf{x} \in \{0,1\}^L$ (design variable).
   - $|\mathcal{X}| = (2^L - 1)$ (search space).
2. **Network Energy Level** (NEL)
   - $\mathcal{X}_j = \{\mathbf{x} \in \mathcal{X} \,|\, \mathbf{x} \cdot \mathbf{1} = j\}$ (a set of NOPs).

System Model: *Formulation*

1. **Cell selection**

$$\mathbf{R}_{\mathrm{RS}} = \mathbf{G} \cdot \mathrm{diag}\left(\mathbf{p}_{\mathrm{RS}} \odot \mathbf{x}\right)$$

2. **SINR figures** ← actual ICI.

$$\mathbf{\Psi} = \left[\left(\mathbf{S} \odot \mathbf{G}\right) \cdot \left(\mathbf{p}_{\mathrm{D}} \odot \mathbf{x}\right)\right] \oslash \left[\left[\left(\mathbf{S}^{\mathrm{c}} \odot \mathbf{G}\right) \cdot \left(\mathbf{p}_{\mathrm{D}} \odot \mathbf{x}\right)\right] \oplus \sigma^2\right]$$

3. **Coverage aspects**
   - Minimum received power: $\mathbf{R}_{\mathrm{RS}}\left(a, l^{\star}\right) \geq P_{\mathrm{min}}^{\mathrm{Rx}}$.
   - Minimum SINR: $\mathbf{\Psi}\left(a\right) \geq \psi_{\mathrm{min}}$.

$$\mathbf{H}\left(a\right) = \mathrm{u}\left(\mathbf{\Psi}\left(a\right) - \psi_{\mathrm{min}}\right) \cdot \mathrm{u}\left(\mathbf{R}_{\mathrm{RS}}\left(a, l^{\star}\right) - P_{\mathrm{min}}^{\mathrm{Rx}}\right) \cdot \log_2(1 + \mathbf{\Psi}\left(a\right))$$

System Model: *Objective functions*

1. **Number of active cells** (f_1)

$$f_1 = \mathbf{x} \cdot \mathbf{1}$$

2. **Weighted Network Capacity** (f_2)

$$f_2 = (B \cdot A) \cdot \Big[\Big[(\mathbf{H} \odot \boldsymbol{\Gamma})^{\mathrm{T}} \cdot \mathbf{S}\Big] \odot \mathbf{n}\Big] \cdot \mathbf{1}$$

System Model: *Multiobjective problem*

$$\begin{aligned} \text{minimize} \quad & \left[\; f_1(\mathbf{x}), \;\; -f_2(\mathbf{x}) \; \right] \\ \text{subject to:} \quad & \\ & \frac{(\mathbf{v}^{\mathrm{T}} \cdot \mathbf{1})}{A} \leq \kappa_{\mathrm{COV}} \\ & \mathbf{x} \in \{0,1\}^L, \; \mathbf{x} \neq \mathbf{0} \end{aligned}$$

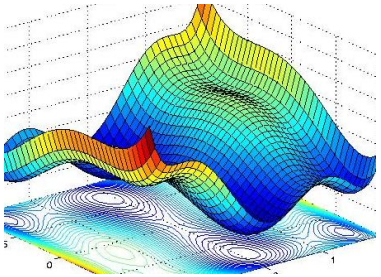
Solution tool:

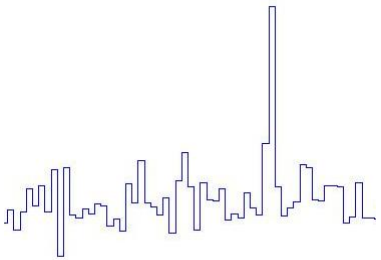
- **Multiobjective Evolutionary Algorithms (MOEAs).**

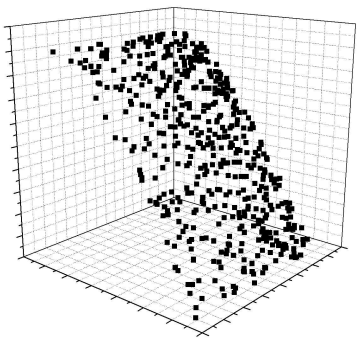
MOEAs: *An approach to CSO*

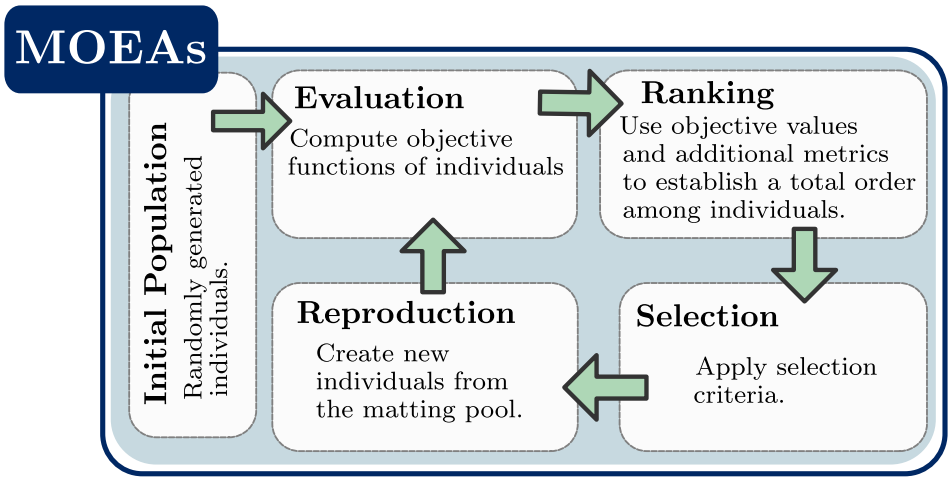
$f_1 \Longrightarrow$ **discontinuities**

$f_2 \Longrightarrow$ **non-convex, local optima**









The Non-dominated Sorting Genetic Algorithm II (**NSGA-II**)

[Deb *et al.*] @ **IEEE Trans. on Evolutionary Computation.**
A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II

CSO: *Conceptual solution design*

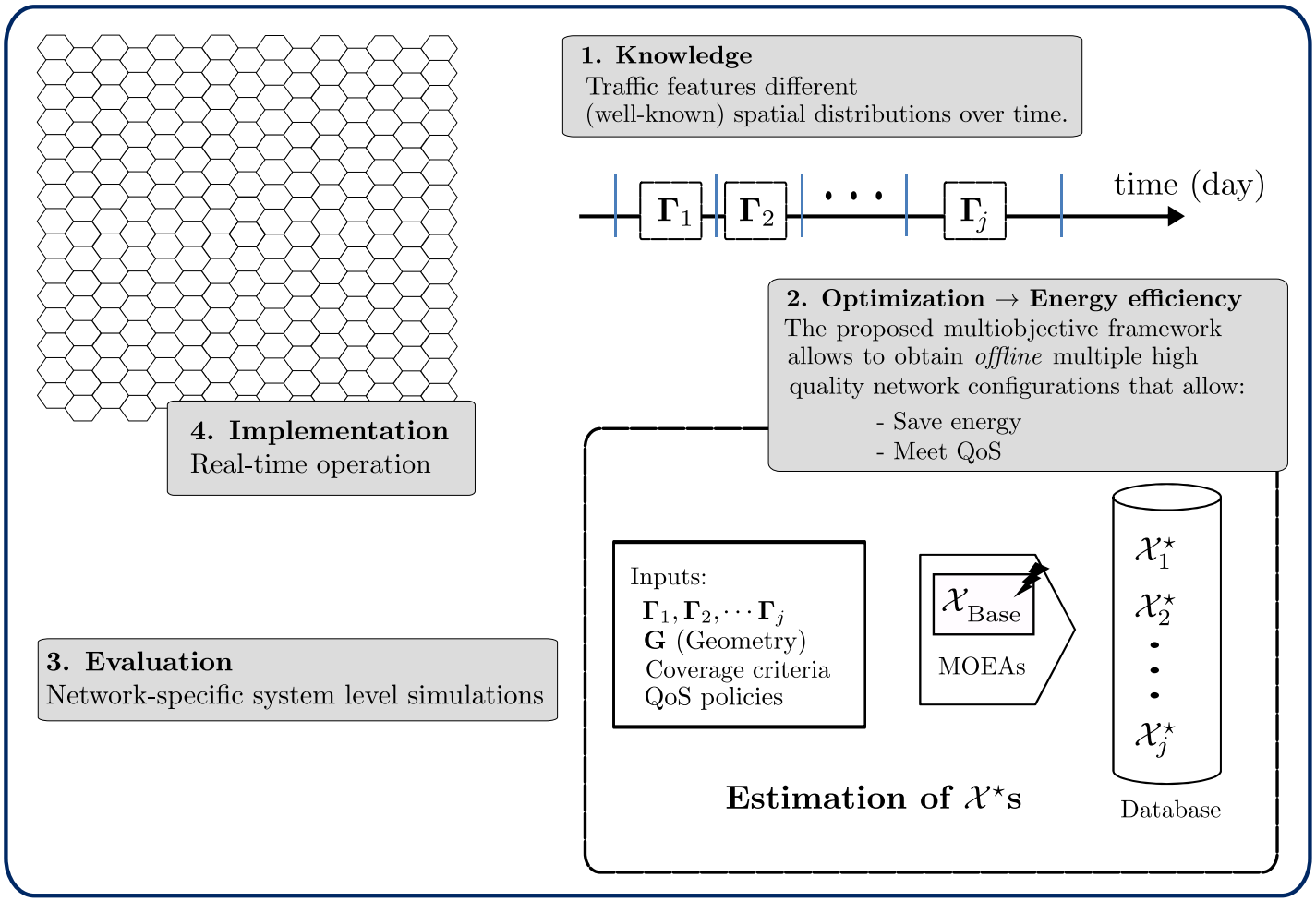


Figure: Conceptual design of the proposed framework.

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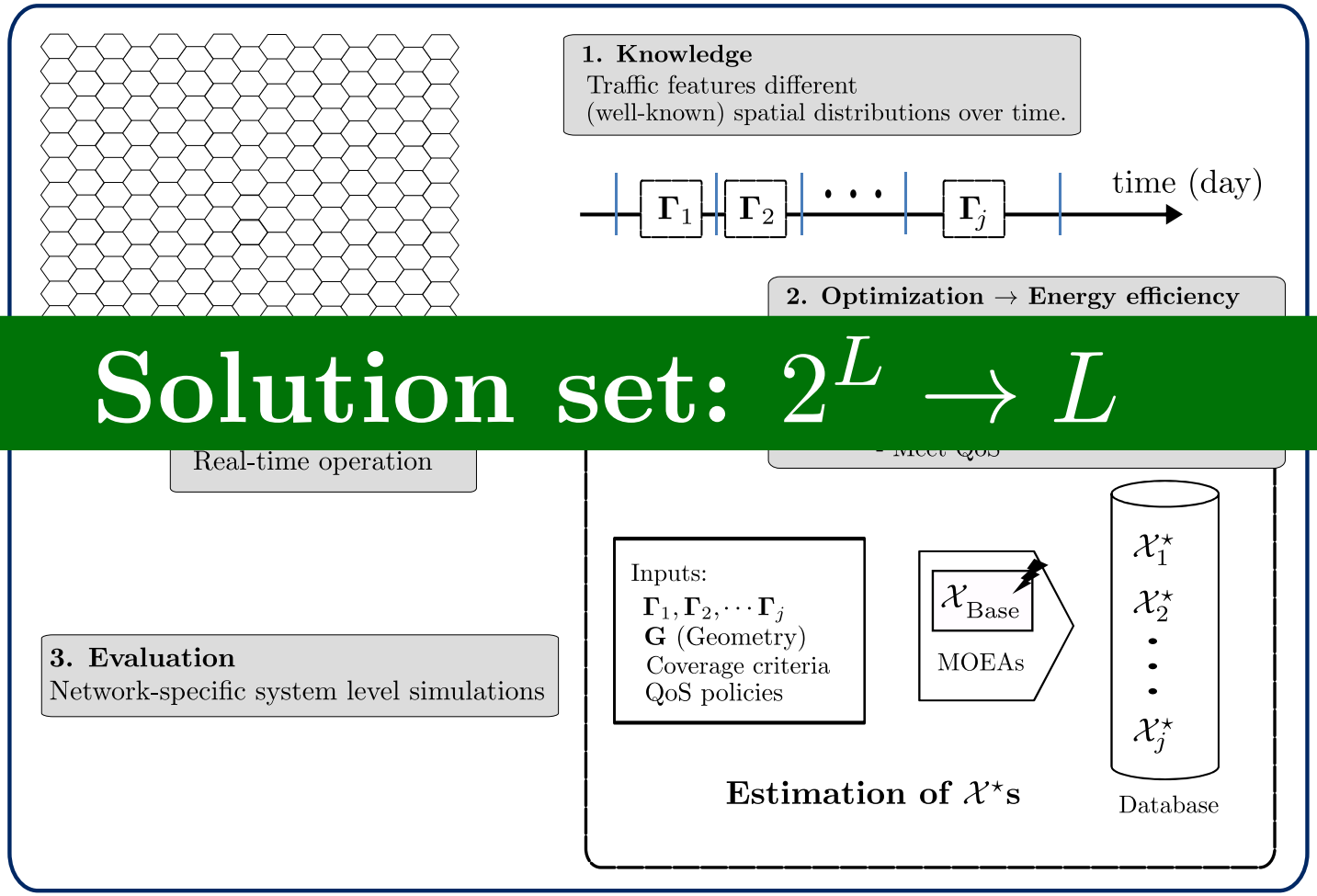


Figure: Conceptual design of the proposed framework.

Results: *Test case and evaluation setting*

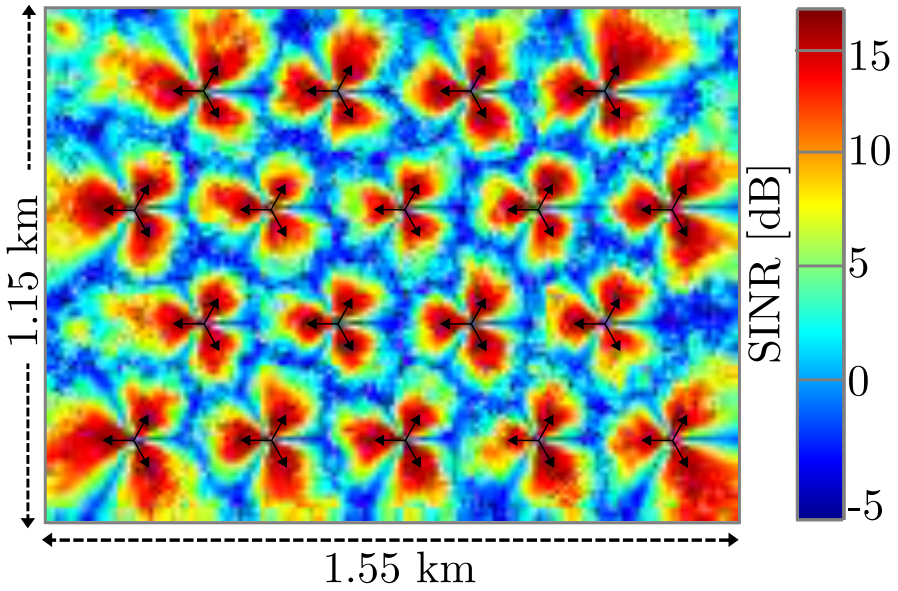


Figure: Small dense deployment.

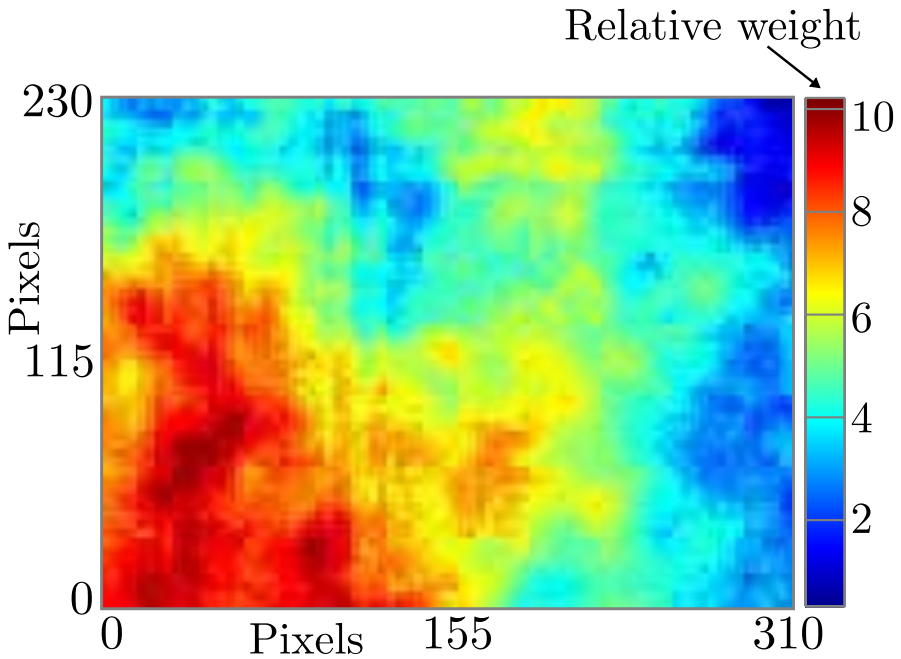
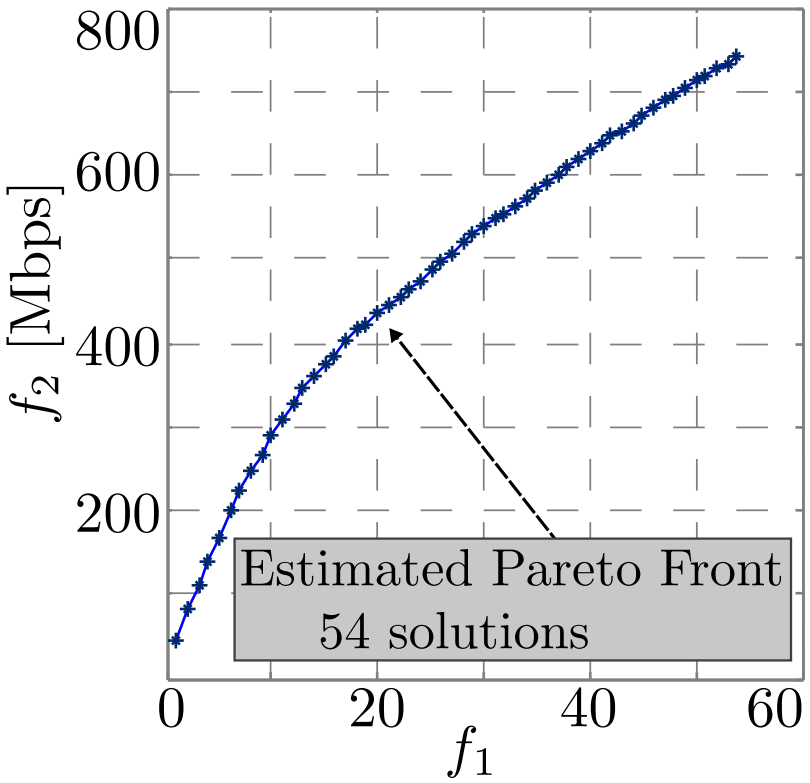


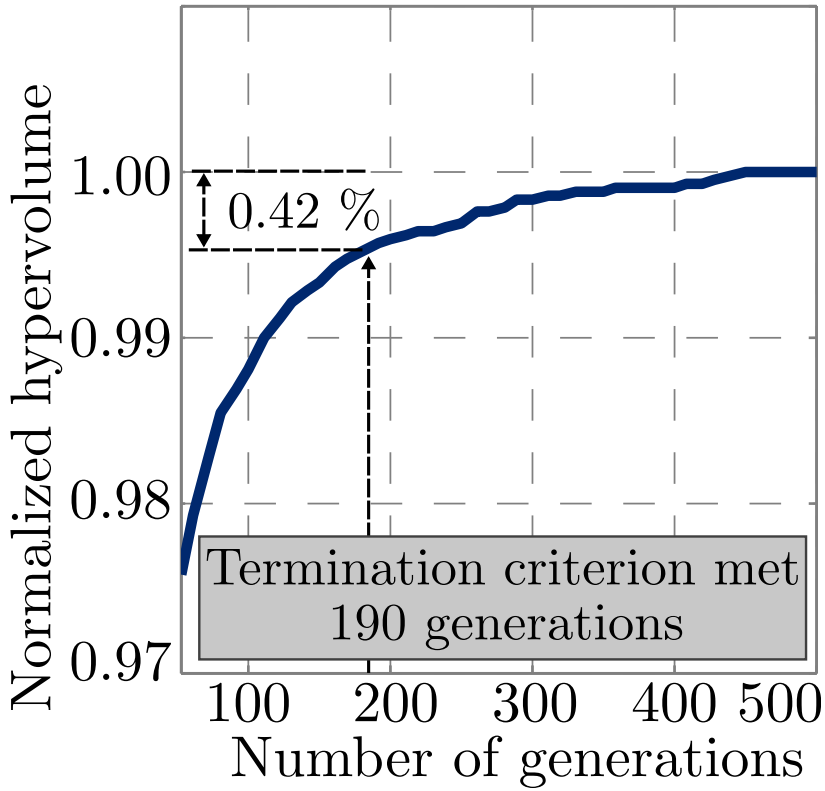
Figure: Traffic distribution ($\mathbf{\Gamma}$).

Minimum SINR (ψ_{min})	-7.0 dB
Minimum received power ($P_{\text{min}}^{\text{Rx}}$)	-123 dBm
Outage threshold (κ_{COV})	2.0 %

Results: *Estimation of the Pareto Front*



(a) Estimated Pareto Front.



(b) Convergence pattern (NSGA-II).

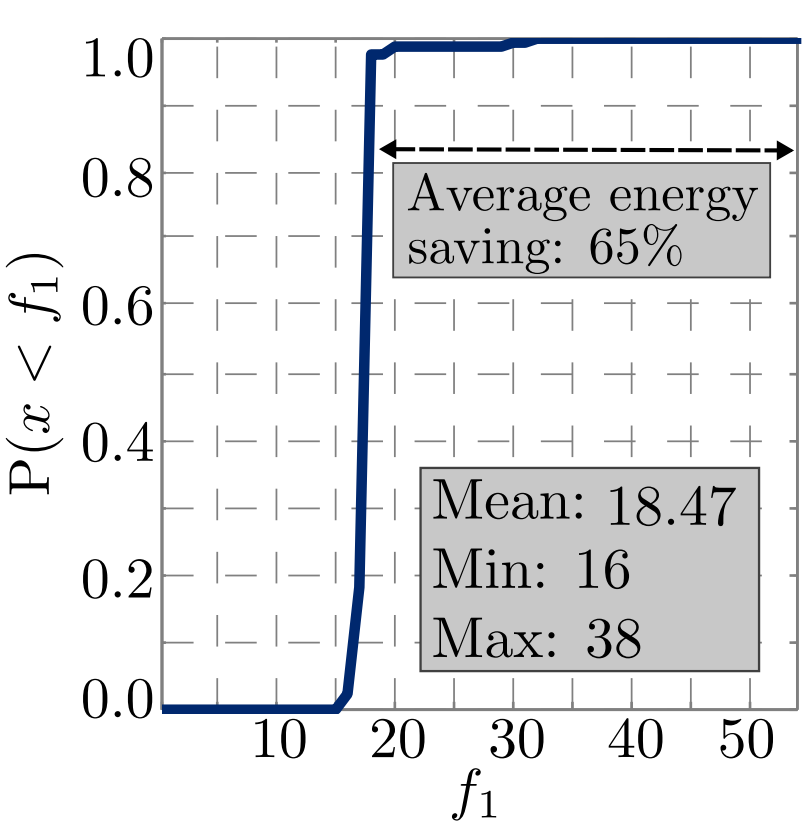
Figure: Estimation of nondominated solutions: the set $\mathcal{X}^\star$

Results: *Evaluation of NOPs and QoS*

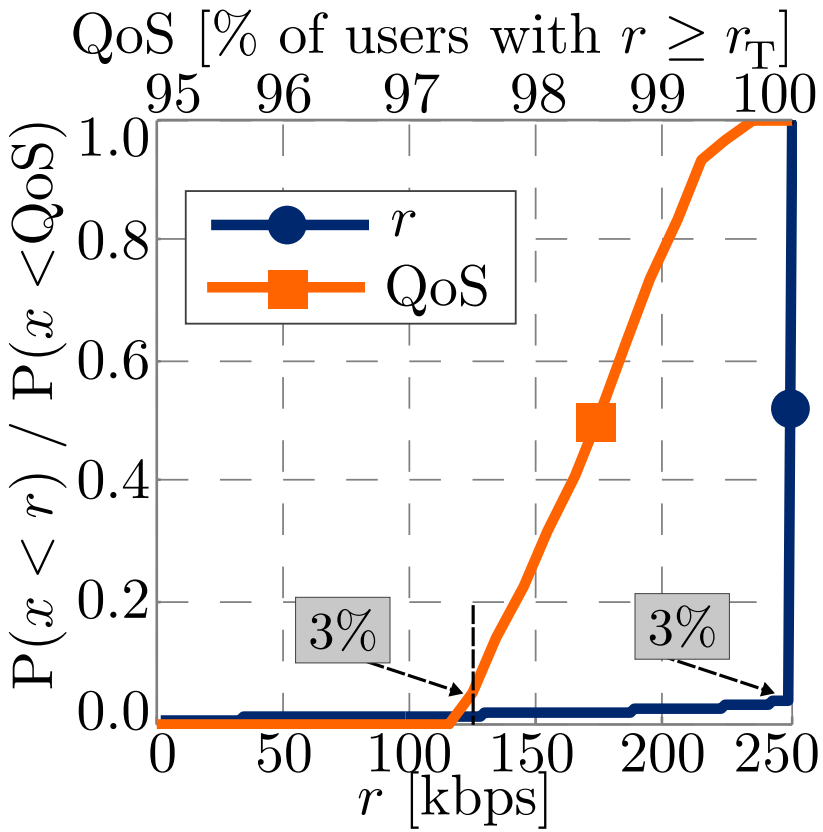
System level simulations setting:

1. **Scheduling** → *Best first* ($r_{\mathrm{T}} = 250$ kbps).
2. **QoS** → Satisfaction $\geq 97.5\%$.
3. **QoS checking interval** → 1 s.
4. **System bandwidth** → 5.4 MHz.
5. **Users distribution** → ($\mathbf{\Gamma}$, λ)
   - Inter-arrival time (exponential, $1/\lambda = 0.075$ s).
   - Session time (exponential, $1/\mu = 60$ s).
6. **Two methodologies:**
   - NOP selection based on NEL sorting (binary search).
   - Single NEL performance evaluation.

Results: *Evaluation of NOPs and QoS*



(a) NEL selection CDF.



(b) Performance.

Figure: NOP selection based on NEL sorting: solutions in $\mathcal{X}^\star$

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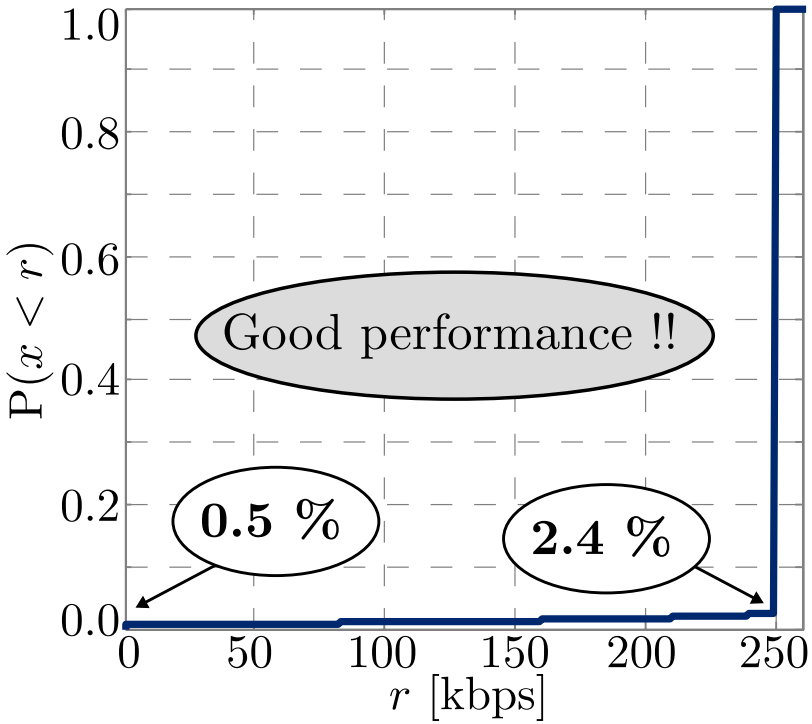
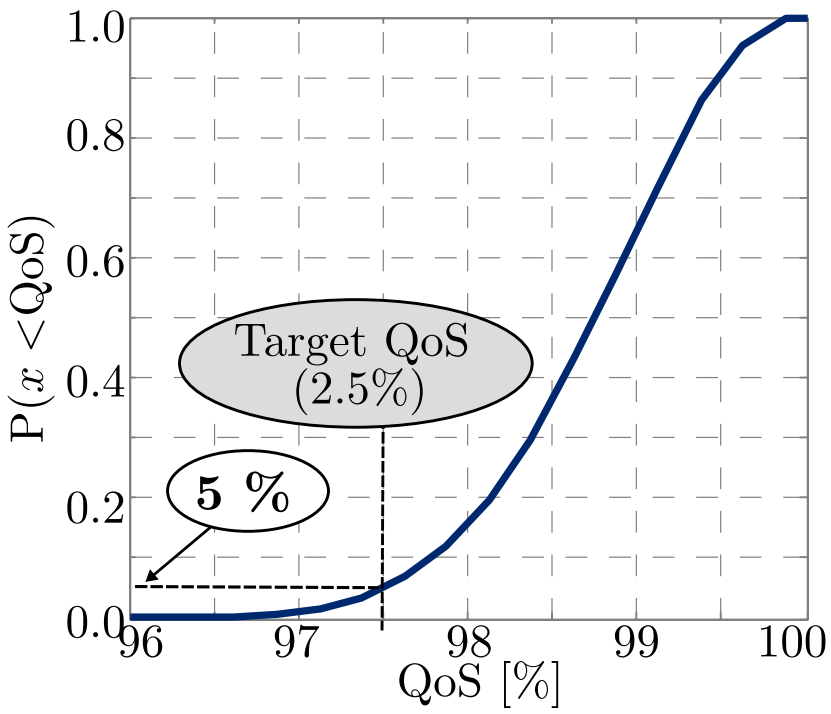


(a) Users rate.



(b) QoS.

Figure: Single NEL performance evaluation: **NEL=18**.

Results: *Evaluation of NOPs and QoS*

Benchmarks:

1. **Cell Zooming** algorithm.

   [Z. Niu *et al.*] @ **IEEE Communications Magazine.**
   Cell Zooming for Cost-Efficient Green Cellular Networks. **2010**.

2. ***Improved* Cell Zooming** algorithm.

   [F. Alaca *et al.*] @ **IEEE Globecom 2012.**
   A Genetic Algorithm based Cell Switch-Off Scheme for Energy Saving in Dense Cell Deployments.

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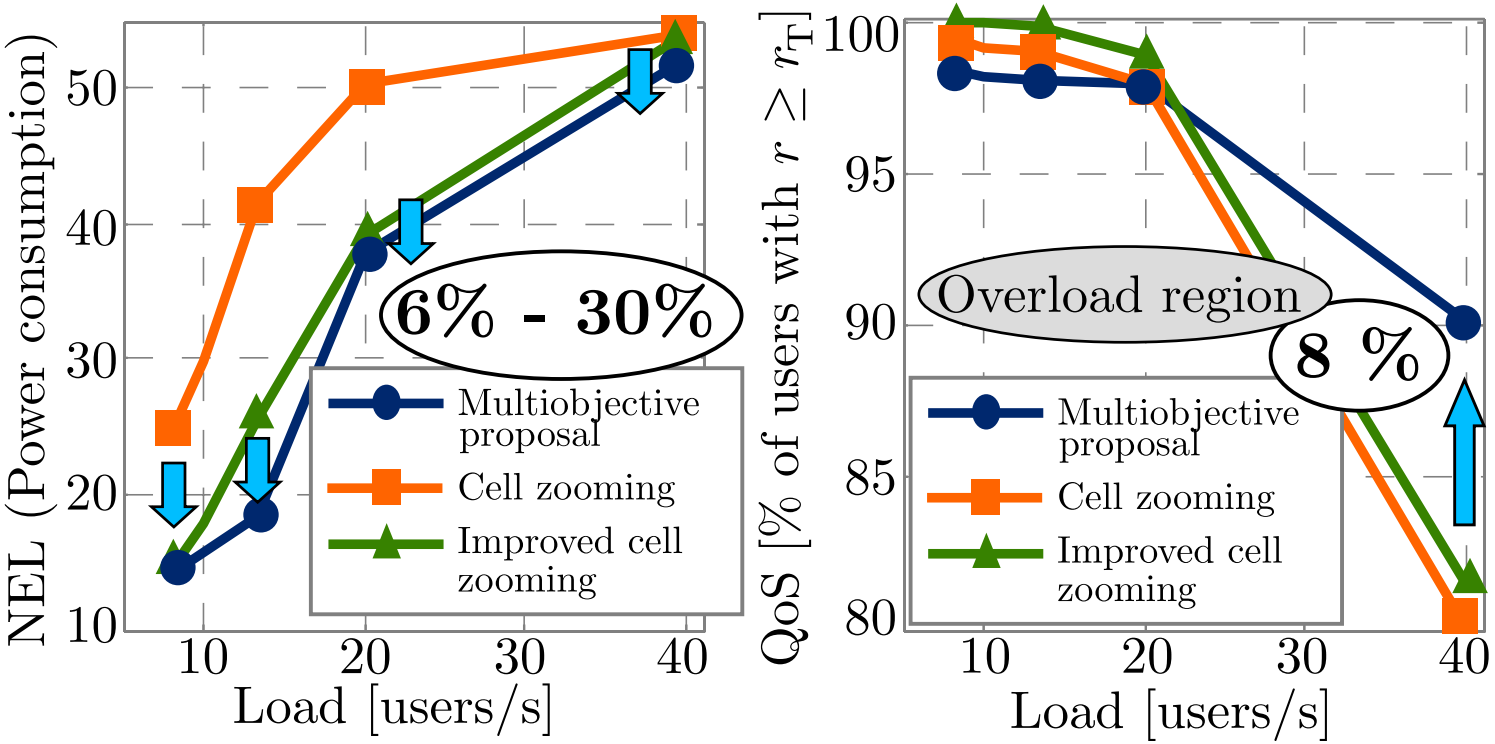


(a) NEL sel. vs. system load (b) QoS vs. system load

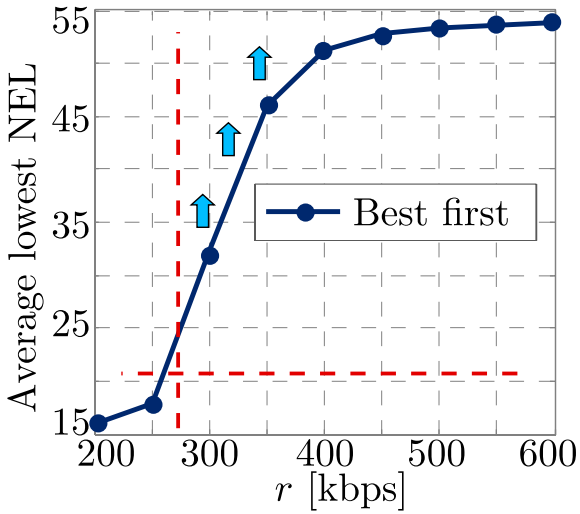
Figure: Performance comparison among several CSO schemes

Results: *Evaluation of NOPs and QoS*

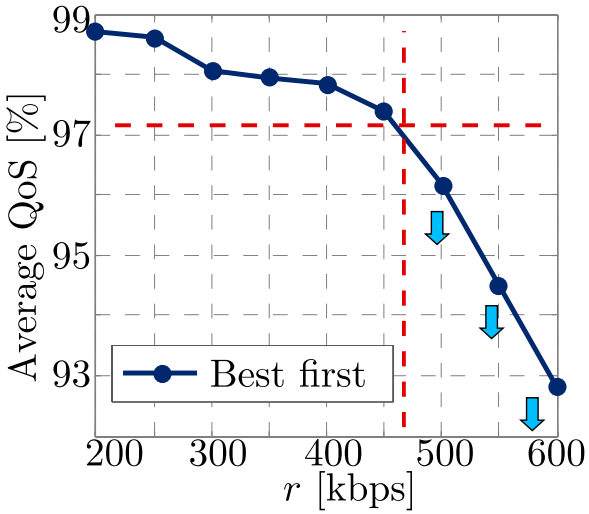
Table: Performance indicators: **feasibility**

Scheme	NEL	QoS	Handovers	Transitions
$\mathbf{x}_{18} \in \mathcal{X}^\star$	18.00	**97.81**	0.00	0.00
NOP sel. (NEL sorting)	18.47	**98.74**	7.14	0.31
Cell zooming	41.45	**99.05**	**57.56**	**3.47**
Improved cell zooming	25.36	**99.87**	**80.14**	**7.47**

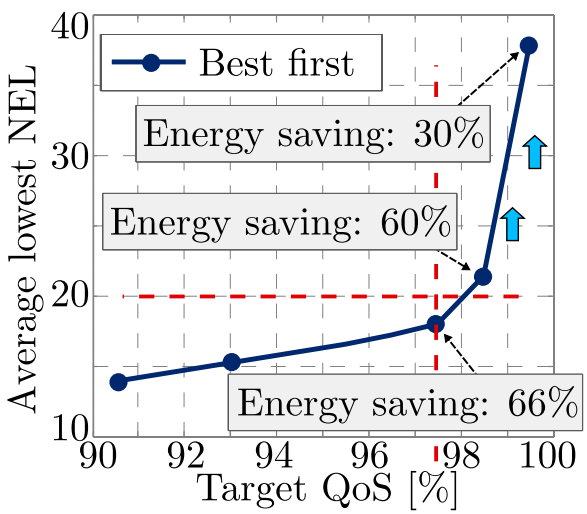
Results: *Evaluation of NOPs and QoS*



(a) NEL vs. target rate



(b) QoS vs. target rate



(c) NEL vs. QoS

Figure: Impact of operational parameters: **tradeoffs**

Conclusions

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   - *Network/traffic-specific* characterization → Pareto eff. NOPs.

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   - Low real-time complexity.
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   - Low real-time complexity.
   - Less transitions/handovers.
3. **Merit** → excellent performance.

Thanks !!

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