Towards spatial reuse in future WLANs: a sequential learning approach

Universitat Pompeu Fabra Barcelona

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Motivation and scope

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Problem

- Popularity of WLANs
  - unlicensed, ready-to-deploy
- Bottleneck in performance
  - density, requirements, decentralization, coexistence

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Aim of this thesis

- Machine Learning (ML) approach
- Worthiness of decentralization

Summary of contributions

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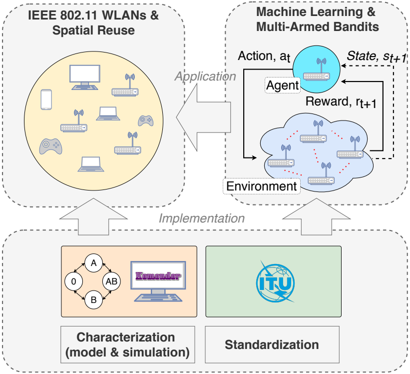

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   - Tutorial
   - Characterization and model
   - Performance evaluation

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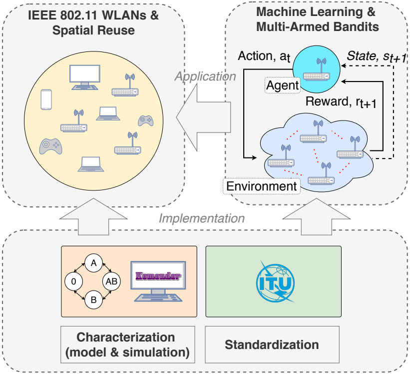

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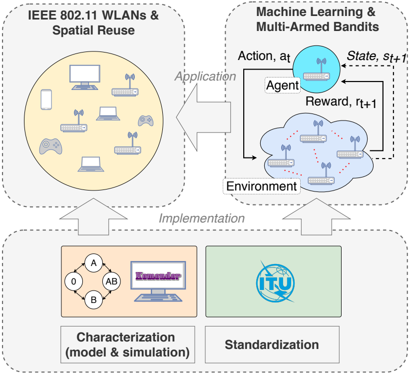

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2. Multi-player setting for SR
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    - Study on performance gains in realistic scenarios
3. Practical aspects for adopting ML in communications
    - Architectural considerations
    - Reliability on AI/ML

Table of contents

Outline

Spatial Reuse in a nutshell

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Methods to address density in wireless networks

- **Time:** scheduling, medium access adaptation
- **Frequency:** Dynamic spectrum access, Dynamic channel bonding
- **Space:** Directional transmissions, Interference cancellation, *Transmit power control*, *Sensitivity adjustment*

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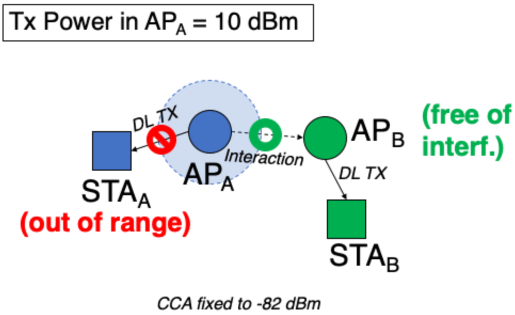
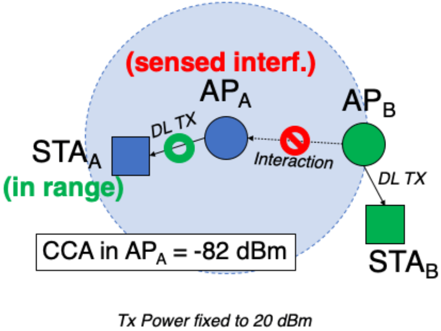
User's goals

- Increase transmission opportunities (TXOPs)
- Improve throughput
- Reduce delay

Effects of tuning the transmit power



Effects of tuning sensitivity



Spatial reuse techniques in wireless networks

- **Spatial Reuse Techniques**
  - CS/CCA adaptation
    - Analysis: [ZZNZ08, JCH14]
    - Iterative methods: [SKVT18, Rop18]
    - Pre-defined solutions: [MII15, OB15]
    - Global solutions: [Nak14, ART+16]
  - Power control
    - Iterative methods: [LLL+14, Che05]
    - Pre-defined solutions: [CC07, THN+11]
    - Global solutions: [LCC+11, TYH+14]
  - Joint CS/CCA adaptation & Power control
    - Analysis: [YYN+17, IYY+19]
    - Iterative methods: [JCH15b, MPB07]
    - Pre-defined solutions: [JCH15a, JCH]

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- Two mechanisms:
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  2. *Parametrized SR*
- Common features: fast source identification, sensitivity adjustment, tx power limitation

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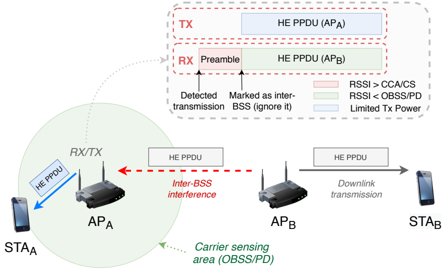

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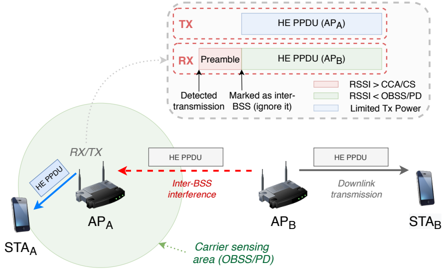

Too conservative → Moderate gains

Spatial reuse in future IEEE 802.11 amendments

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- Multi-AP coordination [Jas19]
- Exchange information and coordinate **simultaneous** Tx
- Two main proposals for IEEE 802.11be:
  1. **Coordinated SR (CSR)**
  2. PSR with beamforming/null steering

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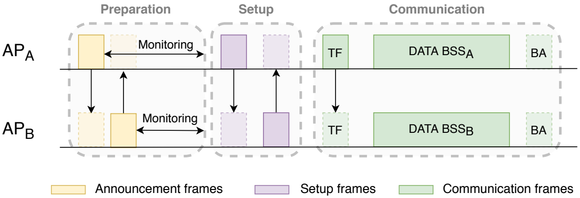

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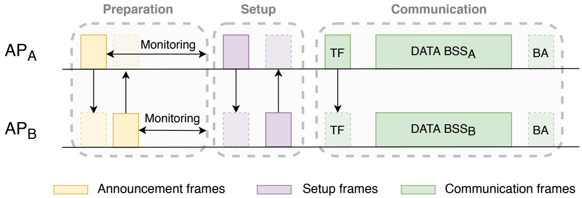


Open discussion points: extension to UL, measurement phase, role of OFDMA, optimization goals...

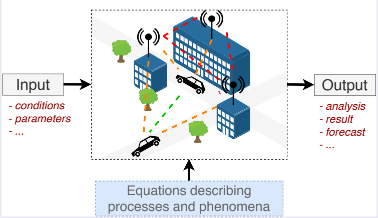
Outline

The emergence of AI for communications

The emergence of AI for communications

Model-based

- Hand-crafted solution
- Accuracy vs tractability
- Generalization



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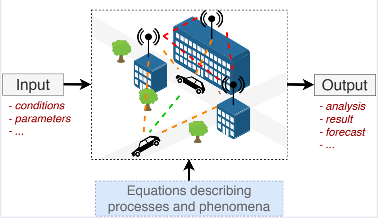

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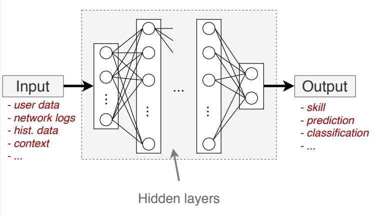
- Learn from data
- Address complexity
- Adaptability



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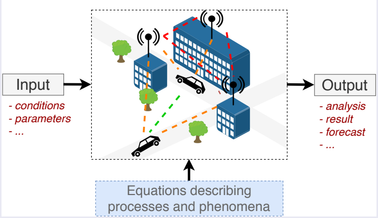

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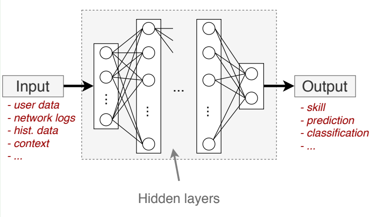
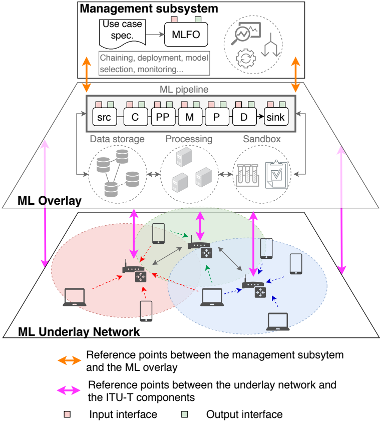


Enablers for adoption:

- Infrastructure (architecture, capacity, data)
- Reliability and trustworthiness

Machine-learning-aware communications



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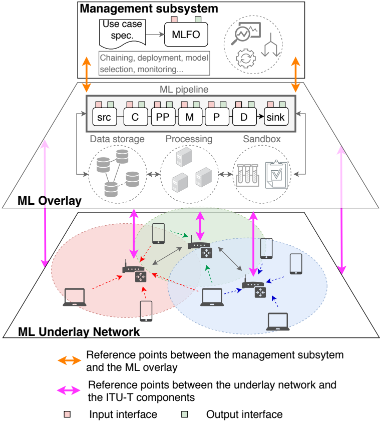

Architectural aspects

- Framework in ITU-T Y.3172 recommendation [ITU19]
- Flexibility required for decentralized WLANs

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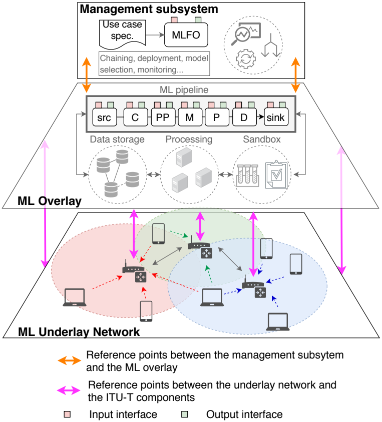

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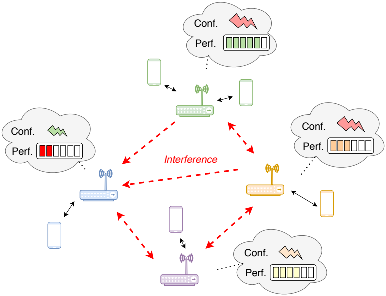
Reliability & Trustworthiness

- ML Sandbox
- **Test**, **train**, and **evaluate** ML models
- Simulators in closed-loop ML-based optimization

Multi-agent systems



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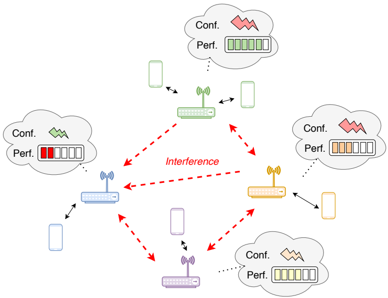

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- Distributed nature of WLANs
- Complexity of SR
- Split a big problem into sub-problems

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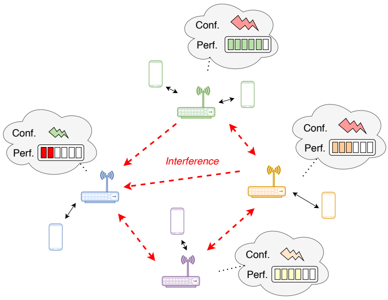

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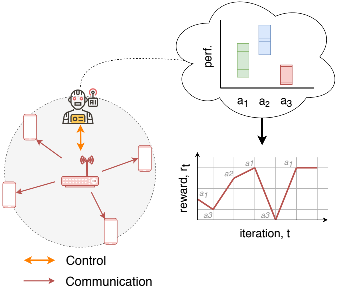
Considerations

- Conflicting requirements
- Non-stationarity / Equilibrium
- Suboptimal performance
- Nexus with Game Theory

Multi-Armed Bandits for SR



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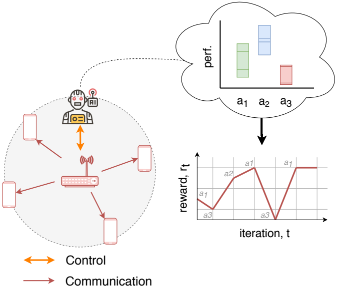

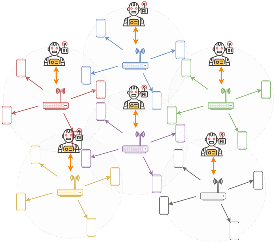

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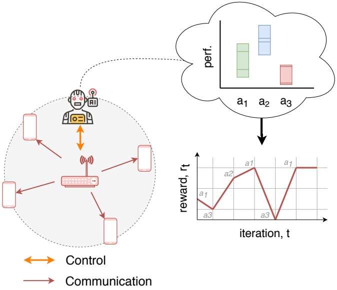

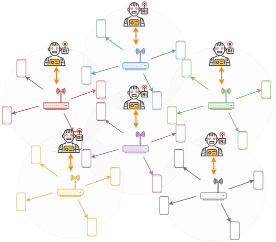

Suitability

- Bandit feedback
- Statistical characteristics
- Non-stationarity
- Fast improvements

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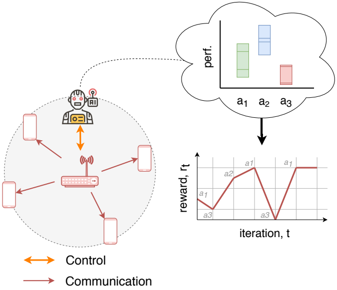

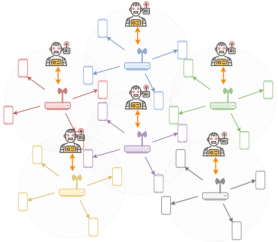

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Contribution

- Analysis: performance, convergence, adaptability
- Local vs shared information
- Algorithms: ε-greedy, UCB, EXP3, Thompson sampling

MAB-based applications for communications

Problem	Modeling	Goals	Baseline algorithms	References
Spectrum access & Channel selection	Stochastic, non-stochastic, restless, contextual, Markovian bandits	Decentralized optimal allocation, optimize number of secondary transmissions, ϵ-correct ranking	UCB, ϵ-greedy, calibrated forecasting	[AMTS11, MS15]
Power control	Non-stochastic bandits	Optimize SINR	Follow the perturbed leader, exponential weighted average	[MS14]
User association	Sleeping, Bernoulli, non-stochastic bandits	Energy saving, improve the throughput	UCB, ϵ-greedy	[MH17, CB20]
Inter-cell coordination	Adversarial, stochastic, non-stochastic, contextual bandits	Optimize inter-cell frequency resources, energy saving, map SON configurations and operator objectives	EXP3, UCB, ϵ-greedy	[CKC15, DJD17]
Dynamic rate selection	Structured, Markovian bandits	Maximize the number of packets successfully transmitted, learn changes in the channel	UCB	[CP14, ZQKJ20]
LTE/Wi-Fi coexistence	Convex bandits	Fair channel sharing	Online gradient descent	[CN18]

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Importance of models

- Represent phenomena in wireless communications
- Useful to understand particular technologies

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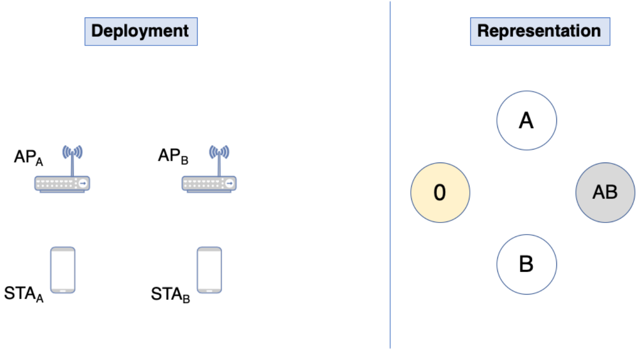
Continuous Time Markov Networks (CTMNs)

- Additive interference [BMWB19]
- Implementation of OBSS/PD-based SR
- Validate SR and understand it in toy scenarios

Continuous Time Markov Networks (I)



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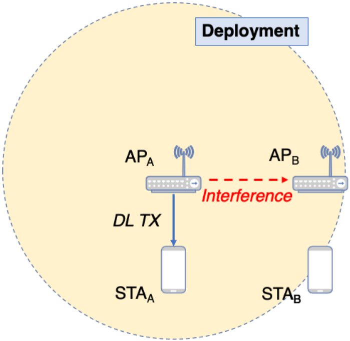

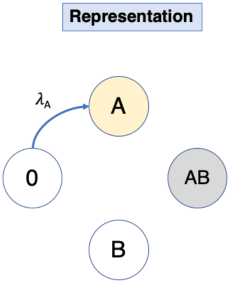

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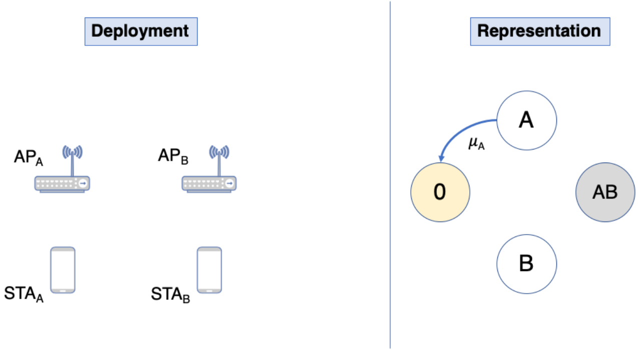

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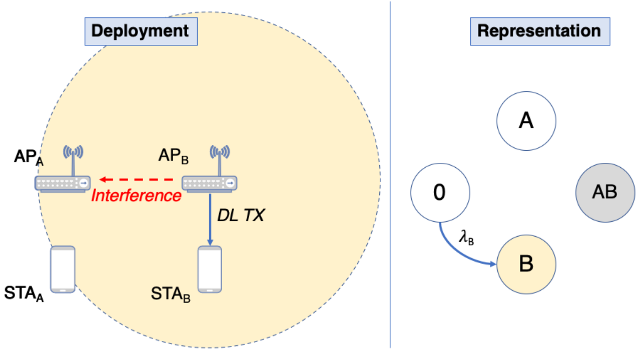

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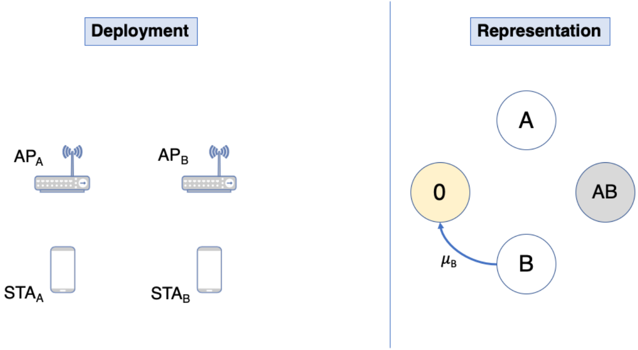

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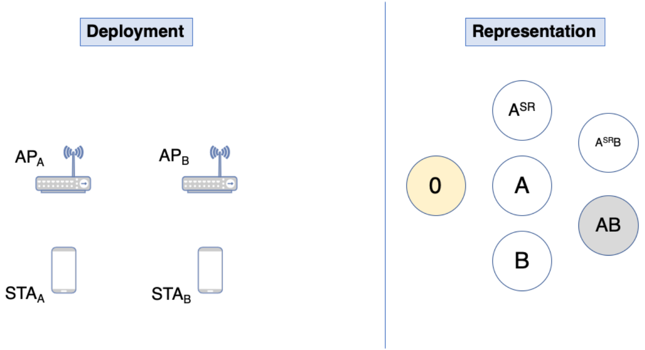

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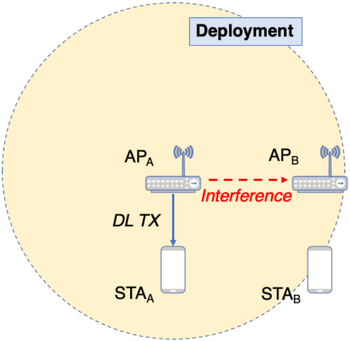

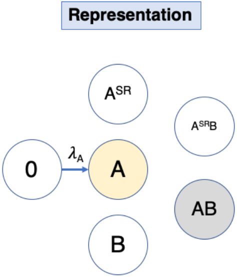

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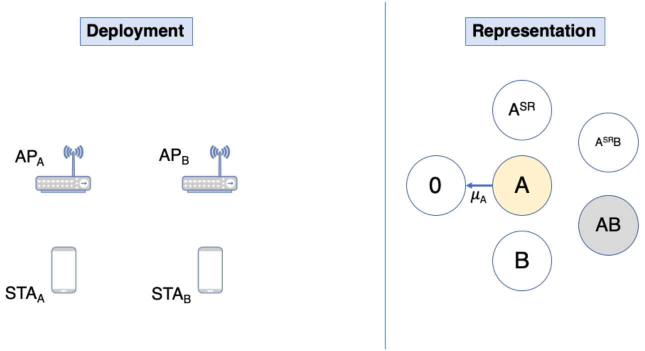

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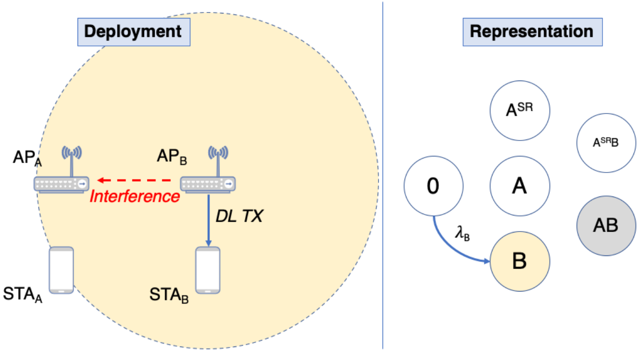

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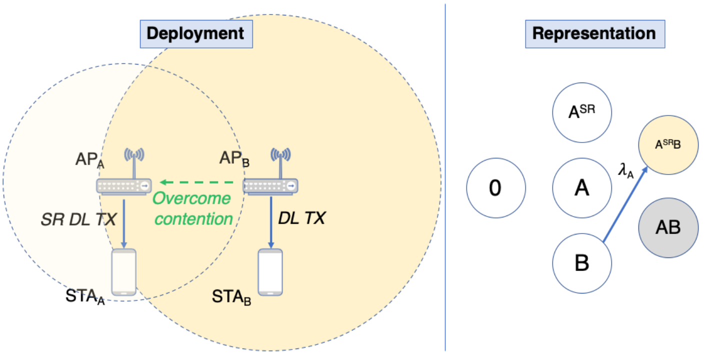

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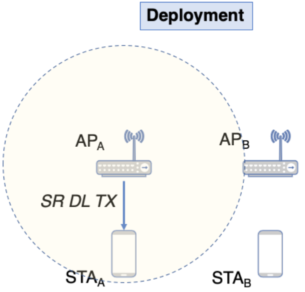

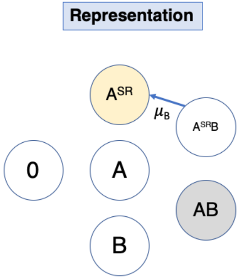

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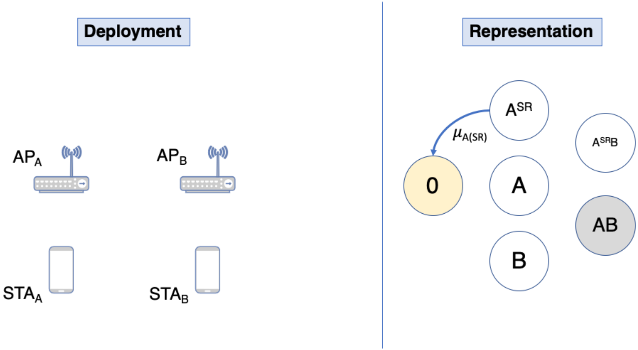

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Characterization of intelligent IEEE 802.11 WLANs

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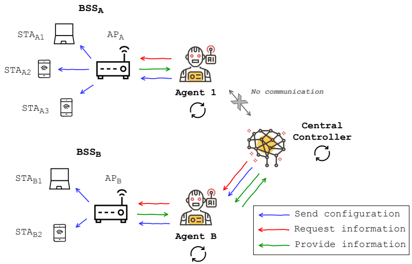
The Komondor simulator

- IEEE 802.11ax-oriented discrete-event simulator[a]
- Fast performance & ML
- Joint contribution

[a] ns-3 11ax available since late 2019



Characterization of intelligent IEEE 802.11 WLANs

The Komondor simulator

- IEEE 802.11ax-oriented discrete-event simulator[a]
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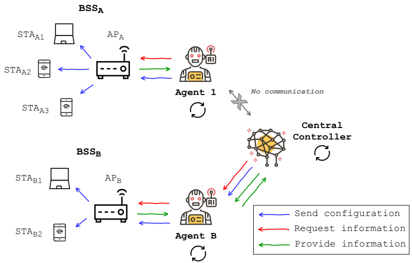

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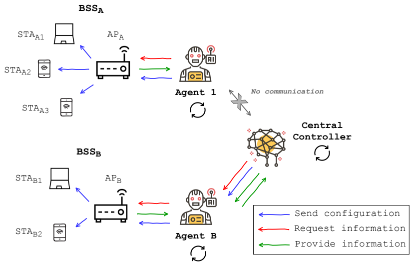

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Komondor is an open-source project: `https://github.com/wn-upf/Komondor`

Outline

Non-intrusive behavior of OBSS/PD-based SR

Finding #1: SR is a fair mechanism that allows increasing the number of simultaneous transmissions in dense OBSSs, thus enhancing the throughput in high-interference scenarios

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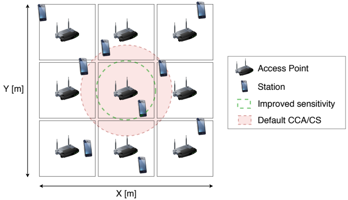

- Residential/Enterprise random scenario
- Different node densities
- Focus on BSS_A
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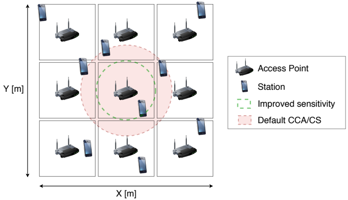

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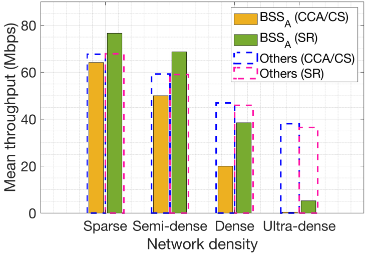

Performance gains of OBSS/PD-based SR

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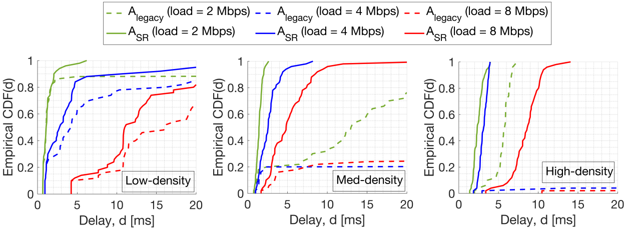

Considerations for adopting SL-based SR

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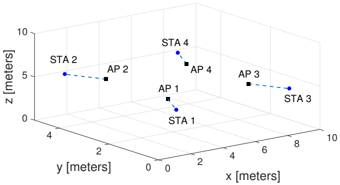

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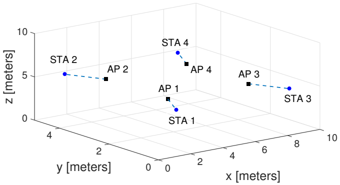

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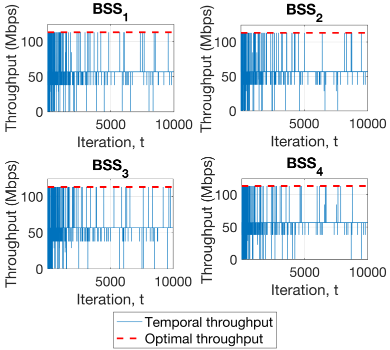

Potential of sequential learning to address SR

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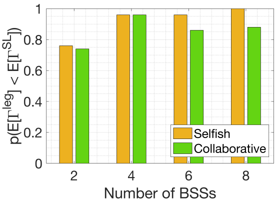

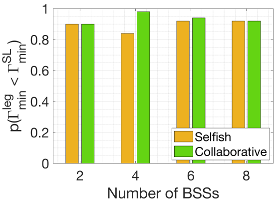

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Future of SR

- Evolution of SR towards coordinated settings
- AI/ML can enable end-to-end optimization along with other technologies (e.g., OFDMA)

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Questions

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Outline

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2. Wilhelmi, F., Cano, C., Neu, G., Bellalta, B., Jonsson, A., & Barrachina-Muñoz, S. (2019). *Collaborative spatial reuse in wireless networks via selfish multi-armed bandits.* Ad Hoc Networks.
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