

# Will ML Disrupt Wi-Fi?

## Status and Future of ML Adoption in Wi-Fi

<https://mlwifitutorial.github.io/>

Boris Bellalta, **Katarzyna Kosek-Szott, Szymon Szott, Francesc Wilhelmi**

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  - Coexistence of radio technologies in unlicensed bands
  - Application of ML in IEEE 802.11 networks
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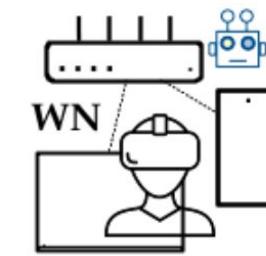
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  - Channel access
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NOKIA  
BELL  
LABS

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## Wi-Fi Meets ML: A Survey on Improving IEEE 802.11 Performance With Machine Learning

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Anatolij Zubow<sup>✉</sup>, Senior Member, IEEE, and Falko Dressler<sup>✉</sup>, Fellow, IEEE

**Abstract**—Wireless local area networks (WLANs) empowered by IEEE 802.11 (Wi-Fi) hold a dominant position in providing Internet access thanks to their freedom of deployment and configuration as well as the existence of affordable and highly interoperable devices. The Wi-Fi community is currently deploying Wi-Fi 6 and developing Wi-Fi 7, which will bring higher data rates, better multi-user and multi-AP support, and, most importantly, improved configuration flexibility. These technical innovations, including the plethora of configuration parameters, are making next-generation WLANs exceedingly complex as the dependencies between them and their joint optimization usually have a nonlinear impact on network performance. This complexity is further increased in the case of dense deployments and coexistence in shared bands. While classical optimization approaches fail in such conditions, machine learning (ML) is able to handle complexity. Much research has been put on using ML to improve Wi-Fi performance and so far it is slowly being adopted in existing deployments. In this paper, we adopt a structured approach to describe the various application areas where ML is applied. To this end, we analyze over 100 papers in the field, providing readers with an overview of the main trends. Based on this review, we identify specific open challenges and provide general future research directions.

**Index Terms**—Wi-Fi, WLAN, IEEE 802.11, machine learning, deep learning, artificial intelligence.

### I. INTRODUCTION

WIRELESS local area networks (WLANs), standardized

VDE ITG Award 2023



# Previous Tutorial

**Machine Learning and  
Wi-Fi: Confluences,  
Ongoing Activities, and  
Ways Forward**

Francesc Wilhelmi,  
Szymon Szott, Katarzyna  
Kosek-Szott, and Boris  
Bellalta



<https://mlwifitutorial.github.io/>

# Outline

## Part 1: Introduction. Why Wi-Fi may want to adopt AI/ML?

- Wi-Fi overview: A 30-year path from IEEE 802.11b to IEEE 802.11be, and beyond
- Open challenges in Wi-Fi: Dealing with complexity and uncertainty
- Requirements of next-gen Wi-Fi networks

## Part 2: A primer on AI/ML through Wi-Fi-related problems

- Wi-Fi & ML: A two-sided relationship
- Examples of ML types (supervised, unsupervised, and reinforcement learning) for Wi-Fi
- Novel trends in ML applied in Wi-Fi: deep learning, reinforcement learning, online learning, federated learning

## Part 3: Online learning for responsive Wi-Fi networks

- Wi-Fi with multi-armed bandits
- Reinforced-lib: our open-source library
- Overview of tools and resources.

## **Coffee break (10:30-11:00)**

## Part 4: Adoption of ML for Wi-Fi: architecture and standardization

- ML integration in Wi-Fi through the ITU-T architectural framework
- Current status in standardization

## Part 5: Open challenges, future research directions, and summary

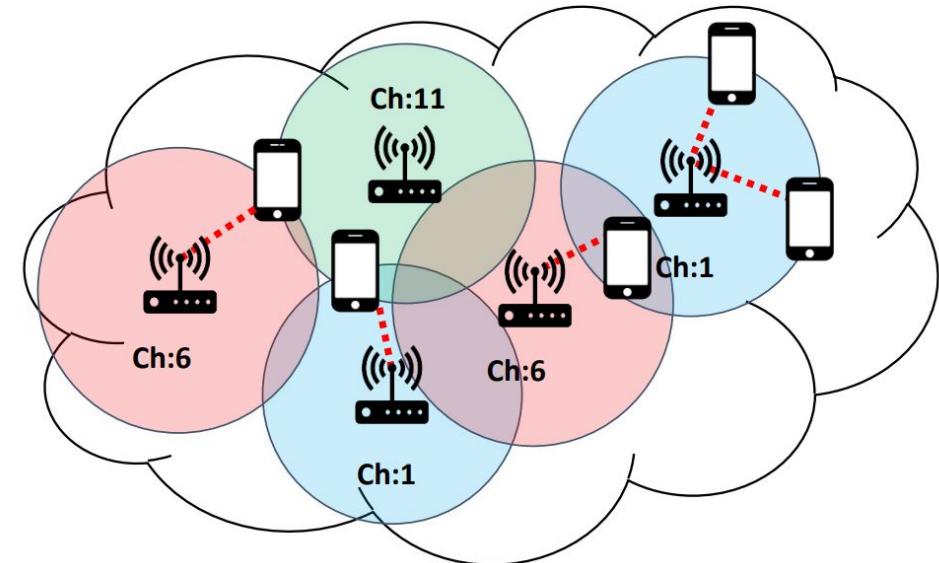
- Open challenges and future research directions; Synergies with other disruptive technologies
- Current AI/ML trends: LLM and Generative AI
- Summary and takeaways
- Q&A

# 1 Introduction

Why Wi-Fi may want to adopt AI/ML?

# IEEE 802.11 Standard

- **PHY/MAC specs**
  - Data plane
  - Management and control
- Operation in **unlicensed bands**
  - **Decentralized spectrum sharing**
  - Coexistence with other technologies
- **Variety of scenarios**
  - Dense, dynamic, diverse, and uncontrolled
  - Wireless broadband access
  - Real-time communication



**Uncertainty**  
(varying channel conditions,  
channel access contention)

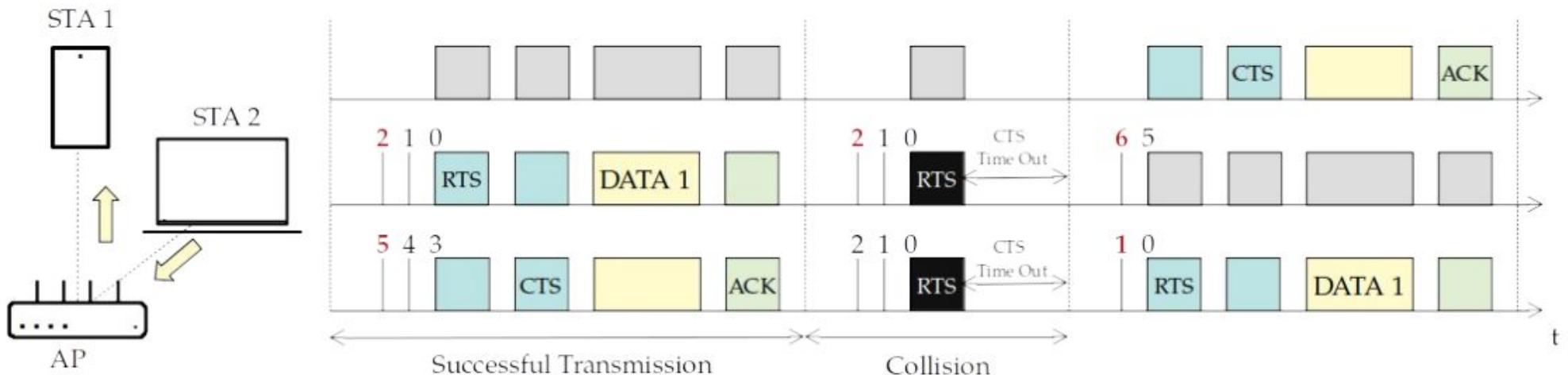
# How does Wi-Fi work?

DCF + ARQ

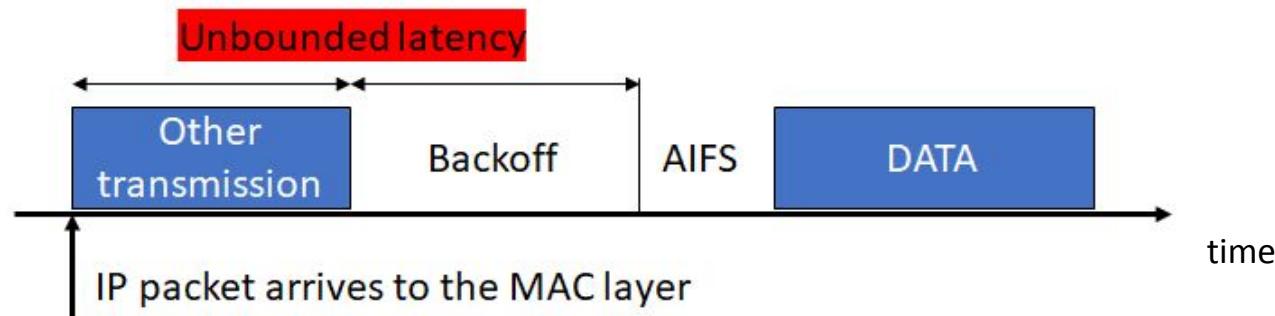
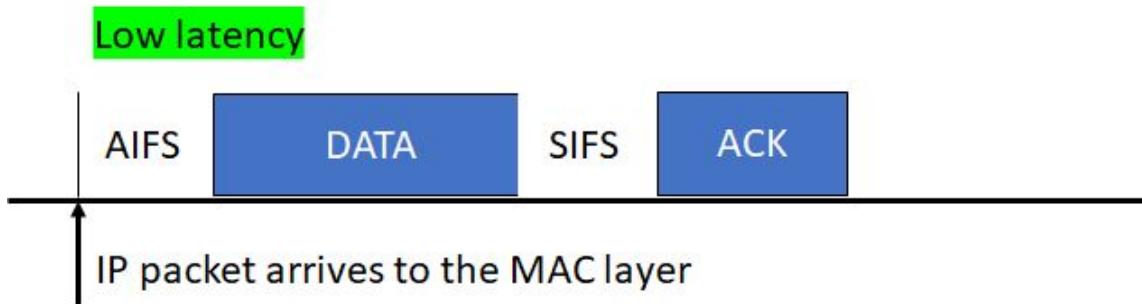
EDCA adds more tx queues

RTS/CTS mechanism reduces  
collision time

- DCF: CSMA + Backoff (CA) + ARQ
- EDCA: DCF + Multiple Access Categories for Traffic Differentiation

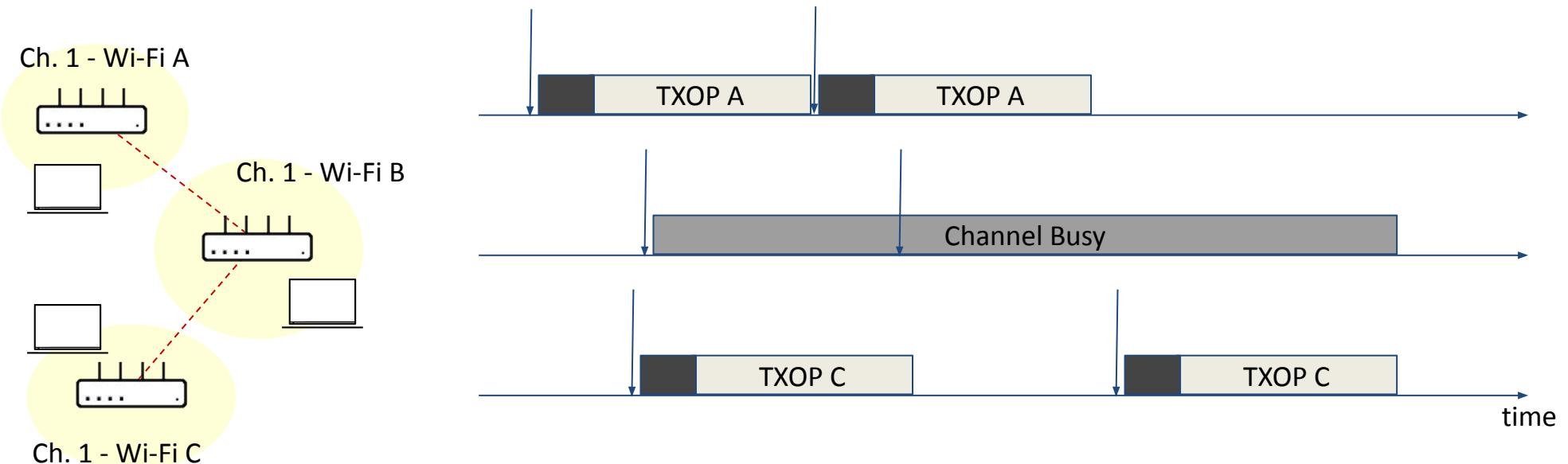


# Contention-based Channel Access: Unbounded latency



# Coexistence with other unlicensed technologies and Wi-Fi networks

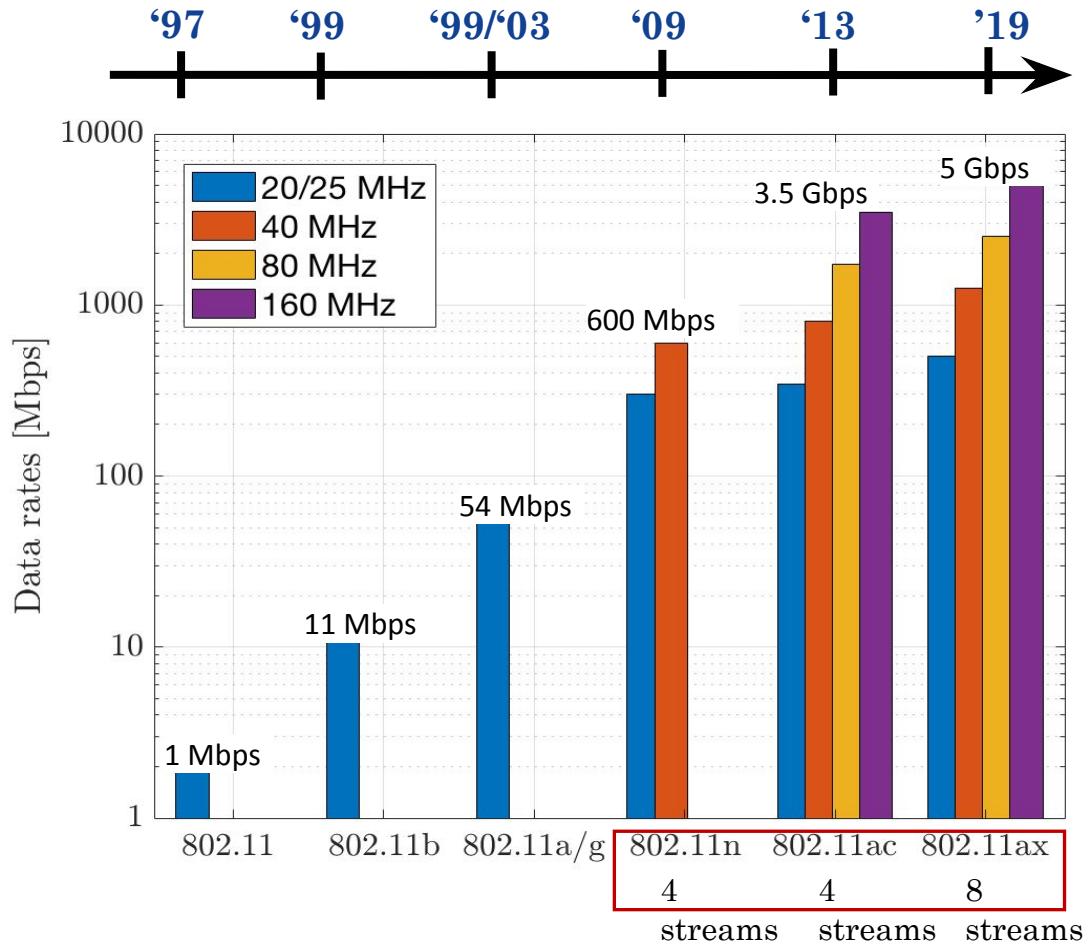
- Performance of a target Wi-Fi network depends on the activity of other Wi-Fi networks within its coverage, and operating in the same channel



**Wi-Fi B may not have access to the channel (starvation): low throughput and high delays!**

# Evolution of Wi-Fi

- **802.11n (Wi-Fi 4) [2.4 & 5 GHz]**
  - Single-user MIMO
  - Packet aggregation
- **802.11ac (Wi-Fi 5) [5 GHz]**
  - Multi-user MIMO (DL)
  - Channel bonding
- **802.11ax (Wi-Fi 6) [5 & 6 GHz]**
  - OFDMA
  - Multi-user MIMO (UL)
- **802.11be (Wi-Fi 7) [2.4, 5 & 6 GHz]**
  - Multi-link operation
  - First products available on the market
  - Final version expected by the end of 2024



# Wi-Fi 6



# New 802.11 Amendments

## Increased Complexity

- Plethora of parameters
- New mechanisms (e.g., MU transmissions, MLO, MAPC)
- Optimal configuration outside of the standard scope
- Joint parameter optimization: non-linear!

**Requirements of emerging apps  
and use cases**

**Uncertainty of wireless channel**

Band [GHz]	2.4, 5, 6, ...
Channel number	32, 36, 40, ...
Channel width [MHz]	20, 40, 80, ...
Guard interval [ns]	800, 1600, ...
Coding rate	1/2, 2/3, 3/4, 5/6, ...
Modulation	BPSK, QPSK, 16-QAM, 64-QAM, ...
Spatial streams	1, 2, ...
Contention window	15, 31, 63, ...
...	...

# Wi-Fi Use-cases Have Different Requirements

- Broadband Internet access
- Teleconference/video streaming, remote work and education
- Cloud-supported productivity: fast content/file exchange in collaborative environments
- (Cloud) Gaming, VR/AR/Metaverse XR
- Industrial applications: system & plant control (machines, robots, IoT)

**Requirements**

Low-latency, high-throughput, high-reliability  
Stable connectivity & predictable performance

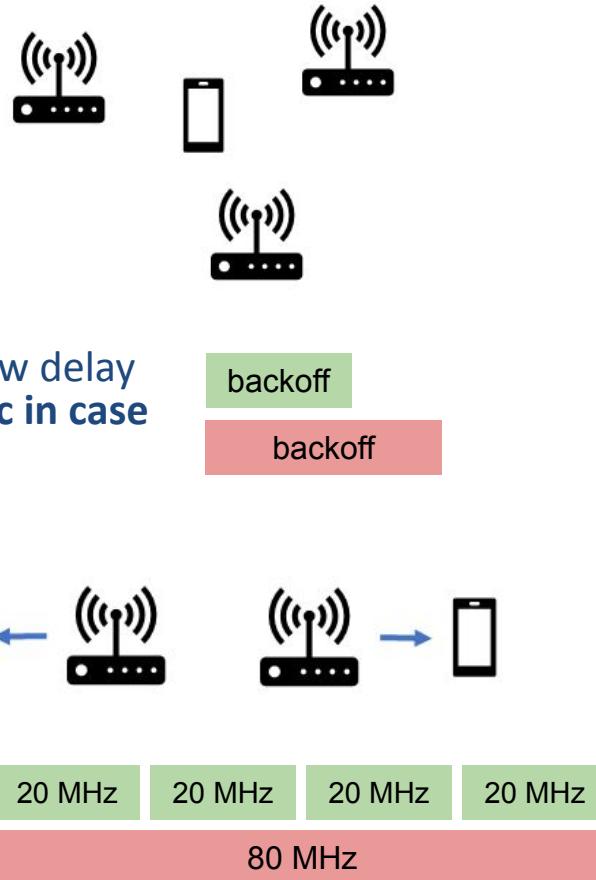
# When AI/ML May Be Useful?

- **Adaptation to different environments**
  - Find satisfactory configurations of IEEE 802.11 MAC/PHY parameters
  - Recognize conditions: LOS/NLOS, interferers, coexisting technologies, ...
- **Smart decisions**
  - AP selection, wait/transmit (e.g. in MLO), CW/MCS selection, ...
- **Improve parameter estimation**
  - Beamforming coefficients, overhead reduction, ...
- ...

In ML, “*algorithms can learn from training data without being explicitly programmed*”

# Performance Trade-offs

- AP selection (if multiple APs available, on different channels)
  - RSSI only: Better channel quality, **risk to overload** a single AP;
  - Load-based: **Low channel quality**;
- Channel access parameters (CWmin, CWmax)
  - Low values: fast channel access with low number of contenders (low delay and high throughput), the opposite otherwise; **may be problematic in case of hidden nodes**;
- Spatial Reuse: Increase PD threshold & Decrease Tx. Power
  - Higher chances to transmit (low delay & high throughput);
  - **Lower MCSs** (longer transmissions, lower throughput);
- Using wide channels:
  - Higher rates (high throughput, low delay), but **higher contention** (the opposite);





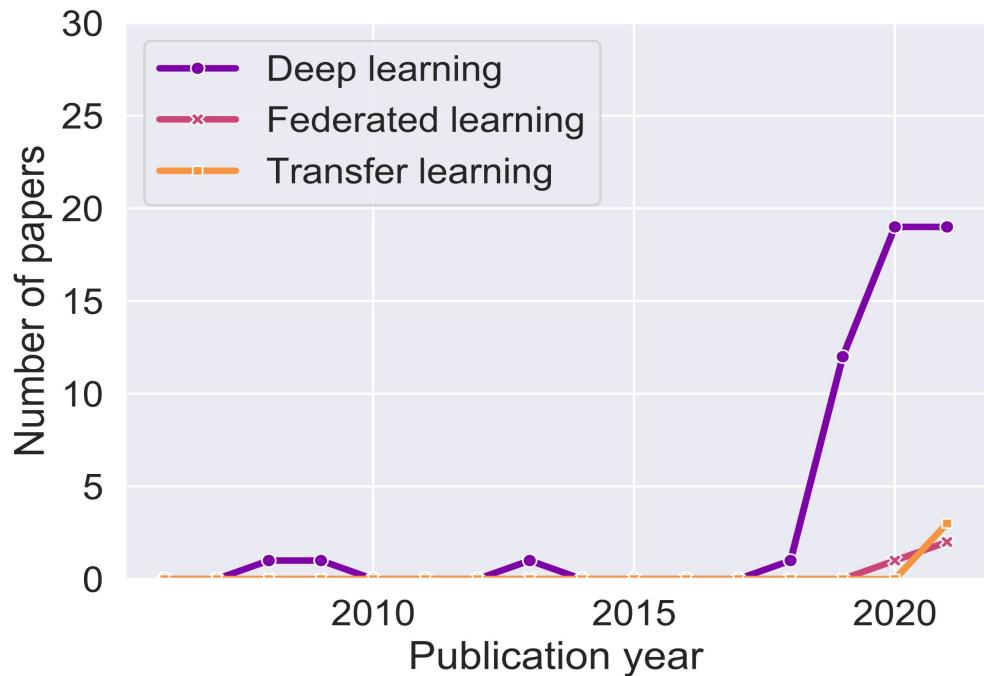
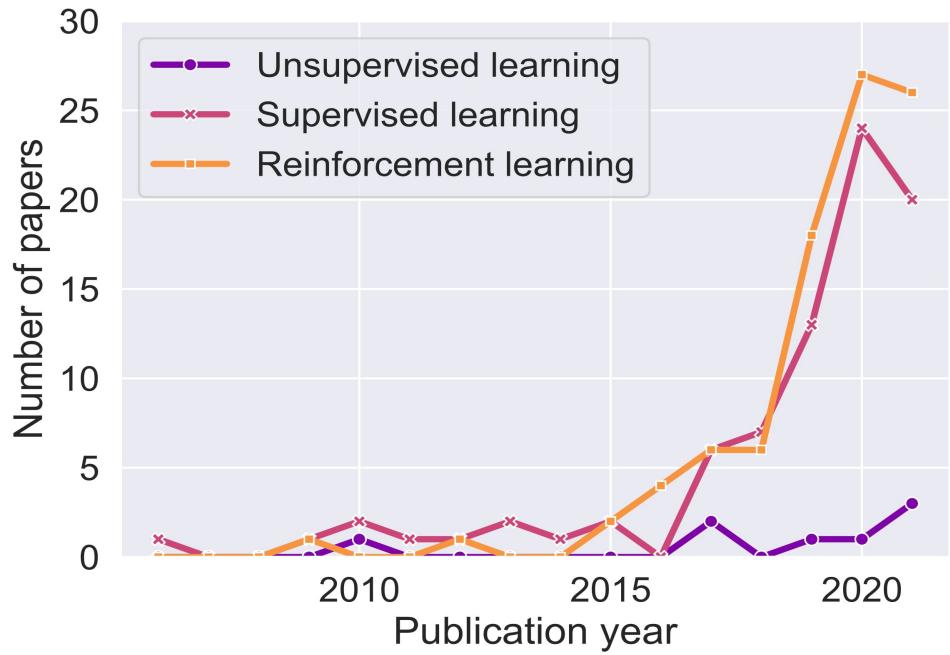
# ML Applications to 802.11 Performance Improvement

802.11 area	ML objective	ML methods	Improvement
Channel access	Select CW value, modify CW update rule	Mostly RL	Higher throughput
Link adaptation	Select transmission rate Predict link-layer throughput	Mostly RL SL	Higher throughput
PHY	Classify signal source, de-noise signals estimate interference	Mostly SL	Higher accuracy
Beamforming	Select beam sector, beamwidth, transmit power, predict channel characteristics	Mostly SL	Higher throughput, reduced exploration time
Multi-user operation	Select users, schedule RUs	SL and RL	Higher throughput
Spatial reuse, channel bonding	Select channel, transmit power, carrier sense threshold	Mostly RL	Higher throughput, lower latency

More details in our survey: <https://ieeexplore.ieee.org/document/9786784>



# Which ML methods are used?

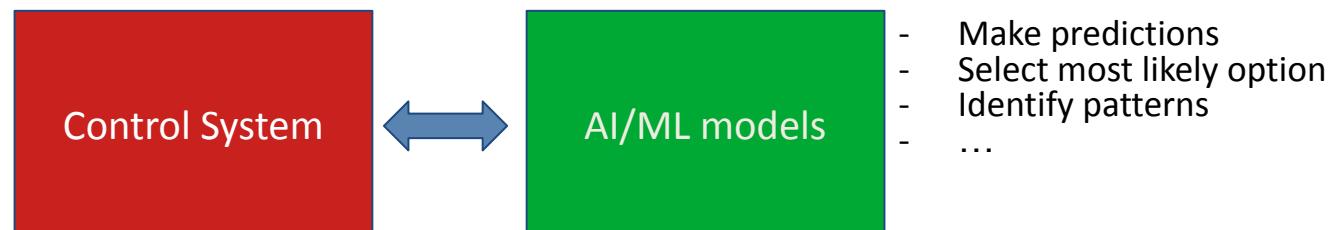


# Wi-Fi augmented with AI/ML

- Should we expect that the use of ML techniques will...
  - **improve raw ‘performance’** (i.e., throughput, delay and reliability)?
  - **improve QoE** in general (i.e., better AP selection)?
  - contribute to **avoid BSS ‘starvation’** in dense scenarios?
  - contribute to **improve the performance** of some functionalities?
  - **contribute to reduce ‘overheads’** by reducing the amount of exchanged data?
- Should we achieve any **quantitative targets/explicit gains**?

# Control System + AI/ML models

- To use AI/ML models we often have to also develop a control system (code) able to get the most of them.
- This control system uses AI/ML models to improve its decisions
  - E.g. tests multiple configurations using a NN model able to predict the Wi-Fi throughput, and chooses the one that is best performing.
- and is the final responsible of the obtained outcome.



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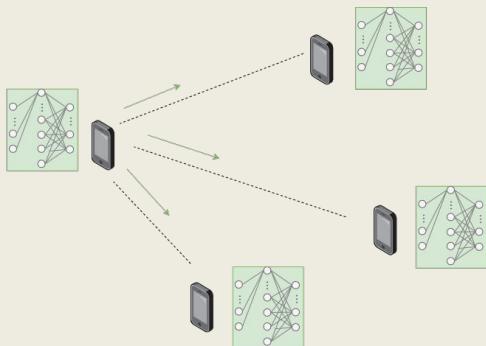
# 2

## A Primer on AI/ML through Wi-Fi-related problems

# Wi-Fi for ML & ML for Wi-Fi: A two-sided relationship

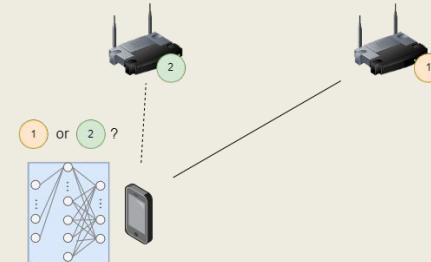
## Wi-Fi for ML

- Rise of decentralization in ML (distributed/collective/federated intelligence)
- Real-time adaptation in ML applications
- Reach end-users, typically available wirelessly
- Wireless communications have become essential fuel for AI/ML
- Joint ML & communication optimization



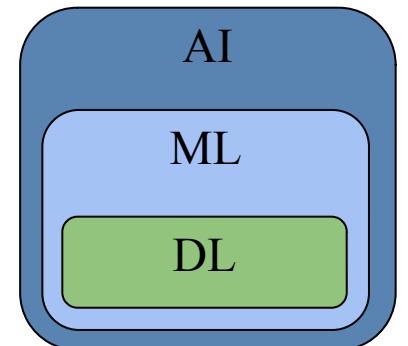
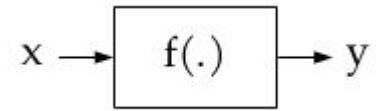
## ML for Wi-Fi

- ML to address relevant problems in Wi-Fi
  - Network management & configuration
  - Advanced troubleshooting & anomaly detection
  - Network optimization (e.g., channel access, transmit power adaptation, MCS selection optimization, etc.)
- On-top solutions vs Native AI/ML



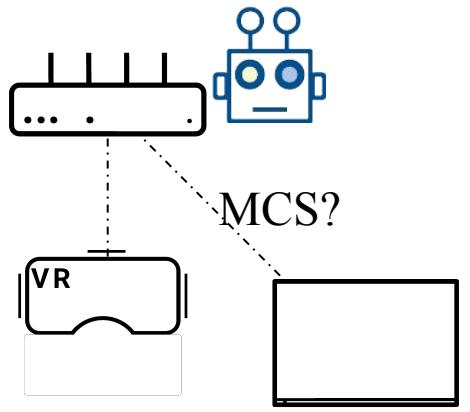
# Artificial Intelligence and Machine Learning

- **Artificial Intelligence:** collect/sense (get the data), reason (interpret the data), act (based on how the data is interpreted), enjoy (or not) the result, and self-correct / adapt.
  - AI uses ML techniques to extract “knowledge” (learn) from the data
  - Data + ML Algorithms + Reasoning + Actions → (A)Intelligence
- **Machine Learning:** Set of algorithms / techniques / mechanisms that are able to learn from data.
  - **Learn:** map output to inputs, i.e., build the function  $f(\cdot)$  that represents the ‘knowledge’
  - General mechanisms, not explicitly programmed for a single family of functions  $f(\cdot)$ ; In some cases, their performance/learning bounds are known
- **Deep Learning:** Includes learning the relevant ‘features’ of the model.



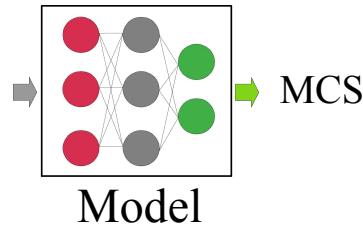
# Building models

- The ML model is  $f(\cdot)$ , it describes a system.
- ML enables to model **extremely complex systems** by characterizing the hidden relationships between input parameters  $\mathbf{x}$  (features) and outputs  $\mathbf{y}$  (labels).
  - ML vs analytical models: ML models use ‘real data’
- **Example:** To train a model able to suggest the best MCS to exchange data between the AP and laptop.



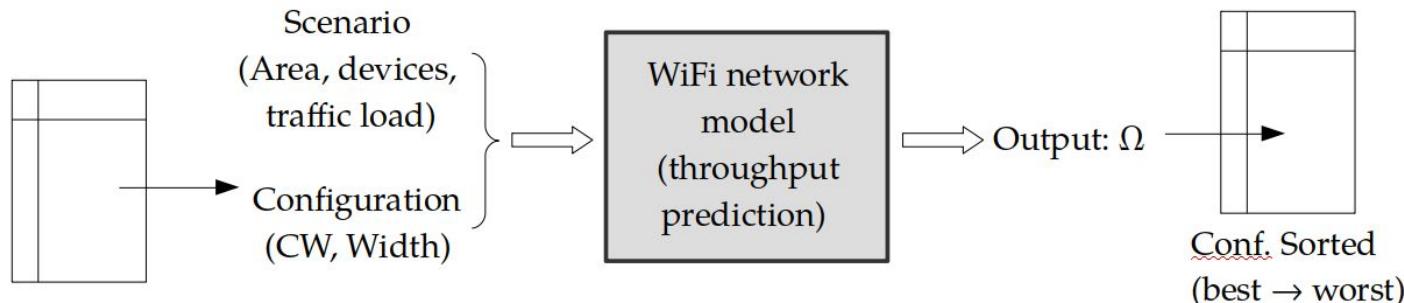
## Features

- RSSI
- Throughput
- PER
- Coll. prob.
- SS
- Bandwidth



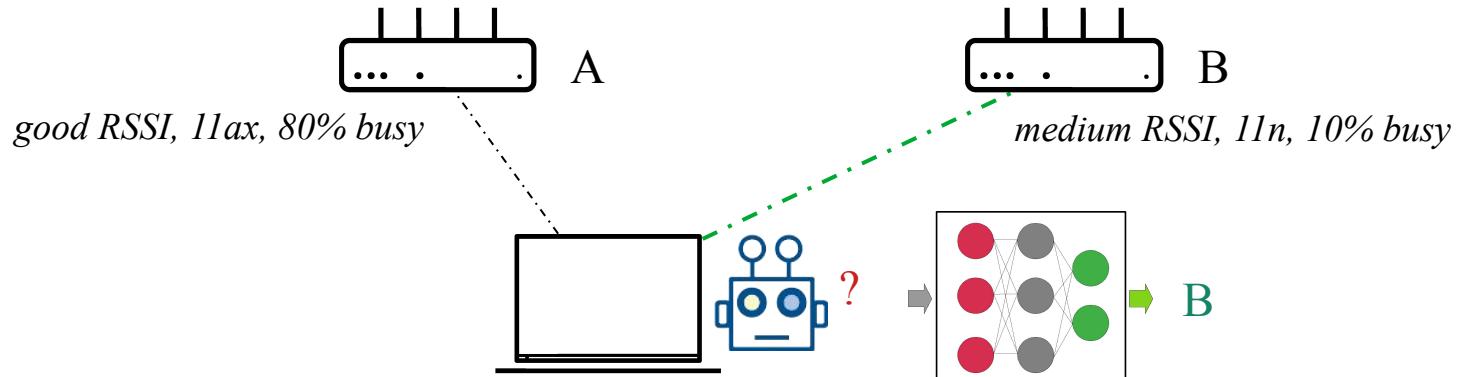
# Why is having a model useful?

- A model can give us some useful information before taking (better) decisions.
- It can predict what will be the ‘performance’ (output) given a certain configuration (input).
- **Example 1:** Given a certain scenario, we want to find the configuration that maximizes the throughput



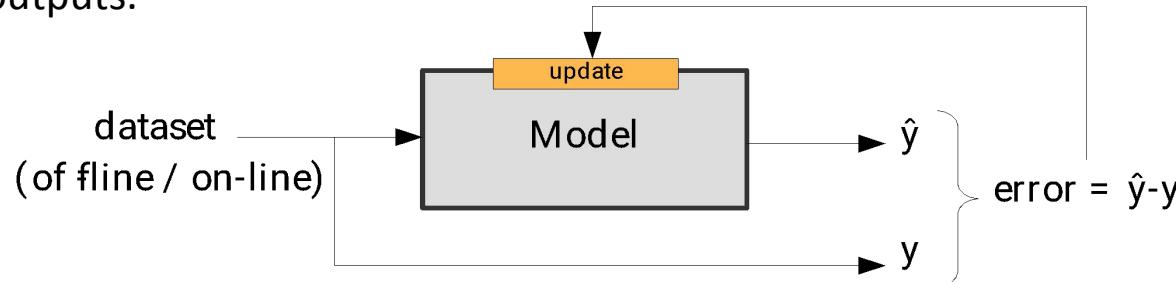
# Why is having a model useful?

- A model can give us some useful information before taking (better) decisions.
- It can predict what will be the ‘performance’ (output) given a certain configuration (input).
- **Example 2:** After gathering data from different APs (load, number of associated clients, technology & capabilities, RSSI, etc.) a STA can sequentially predict the best AP to associate.



# ML techniques build models from data (training)

- Two training cases:
  - **Off-line**: using a static dataset (present from the beginning).
  - **On-line**: the dataset is created in real-time, so the model is updated as more data is collected.
- Training is based on minimizing the error between what is known (in the dataset) and predicted (by the model) outputs.

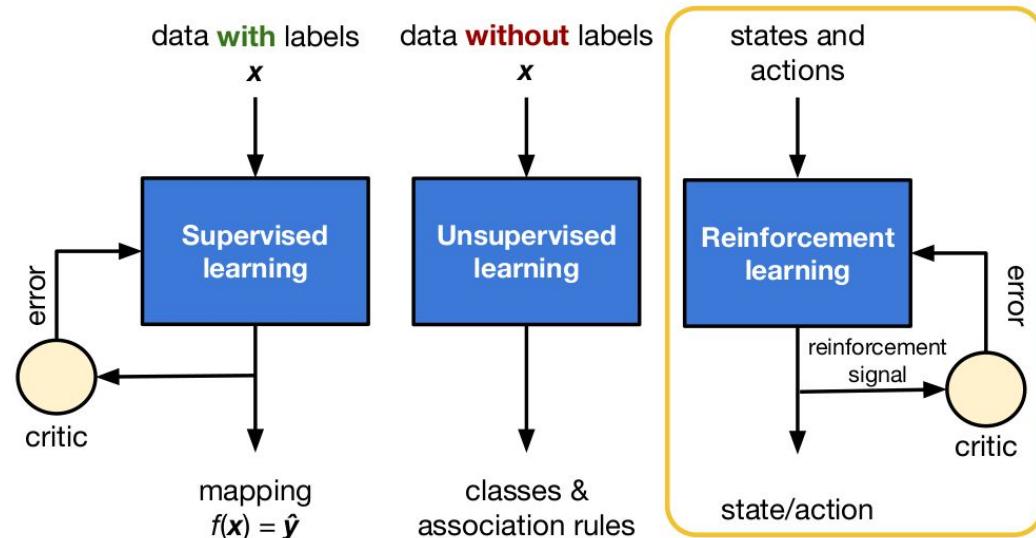


*A model can be first trained off-line, deployed and then improved with on-line training*

- Models should be as general as possible: the aim is not to exactly map inputs and outputs, but to learn the context behind any existing relationship (no overfitting).

# Taxonomy of ML models

- Supervised Learning (SL)
- Unsupervised Learning (UL)
- Reinforcement Learning (RL)

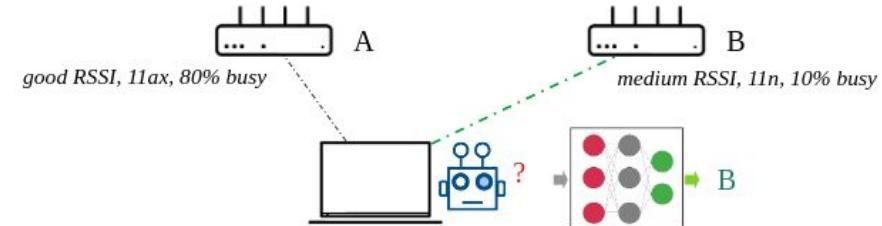
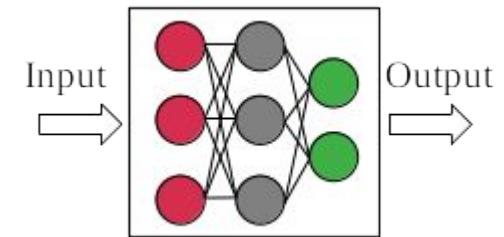
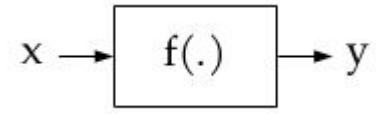


- How are these models trained?
  - Centralized; Decentralized / Distributed
  - Single player; Multiple players

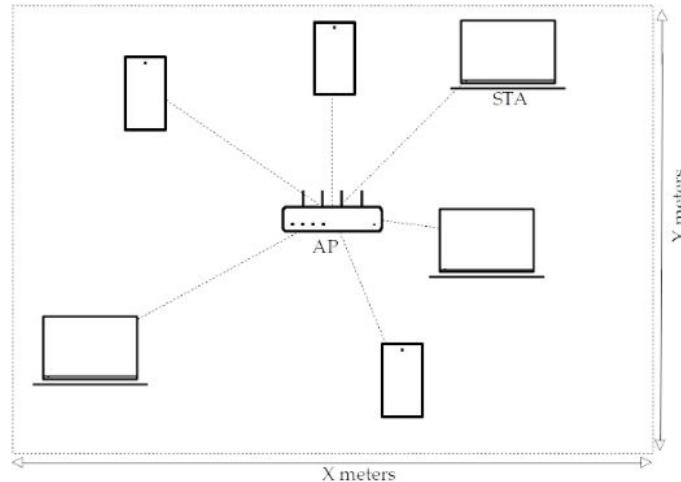
Ex: Distributed Federated Learning

# Supervised Learning

- **Goal:** Training data includes  $x$  and  $y$ , so the goal is to learn  $f(\cdot)$
- **Dataset:** We need a consolidated dataset to train the model, retraining as the dataset updates
- **Techniques:** Time series analysis, regressions, vector machines, decision trees, neural networks, etc.
- **Main uses:** Prediction (output is a real value), classification (output is a label, e.g., 0 or 1)
- **Wi-Fi example:** AP selection
  - The STA uses a trained model that predicts which is the best AP to associate. The input of the model should consist of the info gathered by the STA for each AP.



# Performance Prediction with Linear Regression



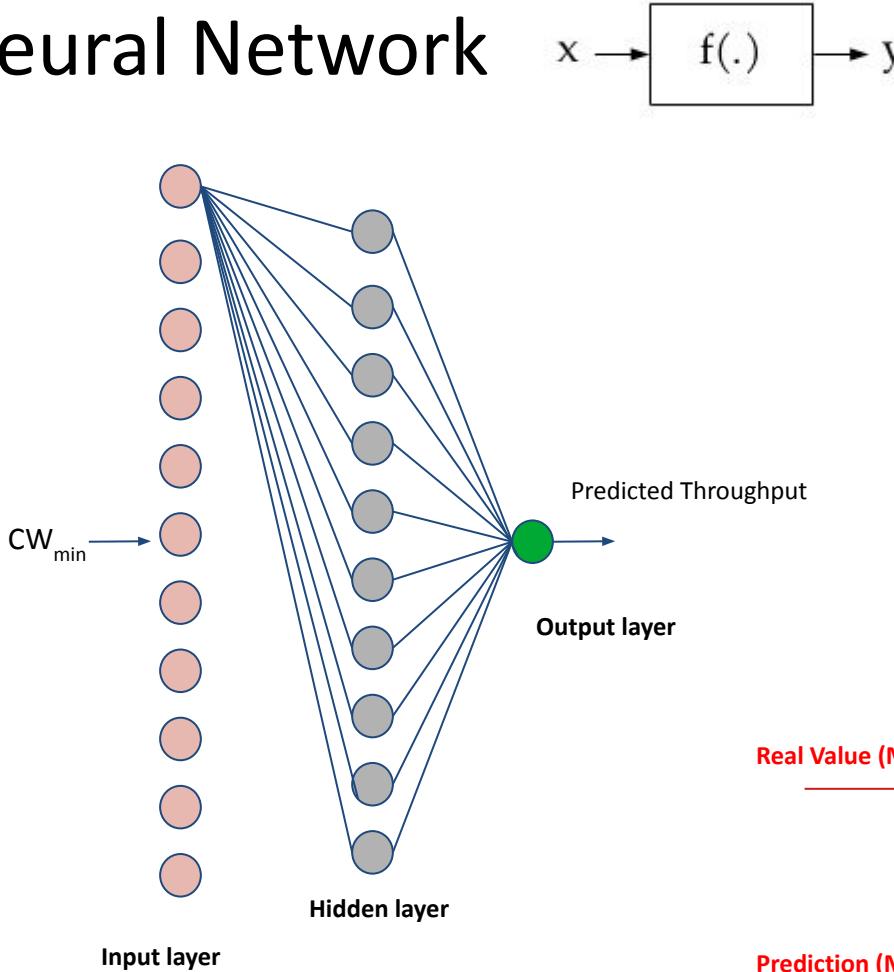
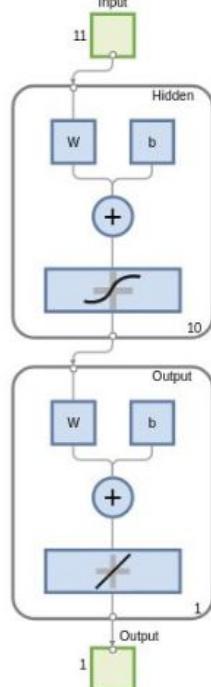
10k simulations → train model → validate model



Working example in Google Colab

[https://github.com/mlwifitutorial/mobicom2023/blob/main/Colab%20notebooks/Wi\\_Fi\\_Linear\\_Regression\\_Example.ipynb](https://github.com/mlwifitutorial/mobicom2023/blob/main/Colab%20notebooks/Wi_Fi_Linear_Regression_Example.ipynb)

# Example: Neural Network



Train a neural network to map predictors to continuous responses.

#### Data

Predictors: input - [100000x11 double]

Responses: output - [100000x1 double]

input: double array of 100000 observations with 11 features.

output: double array of 100000 observations with 1 features.

#### Algorithm

Data division: Random

Training algorithm: Levenberg-Marquardt

Performance: Mean squared error

#### Training Results

Training start time: 03-Aug-2022 07:36:30

Layer size: 10

	Observations	MSE	R
Training	71000	0.1711	0.9965
Validation	15000	0.1692	0.9966
Test	14000	0.1685	0.9966

```
>> test = input(1294,:);
>> output(1294)
```

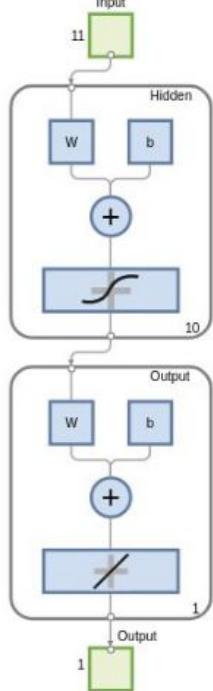
ans =

Real Value (Mbps) → 6.7500e+00

```
>> y = NN_Throughput.Network(test')
```

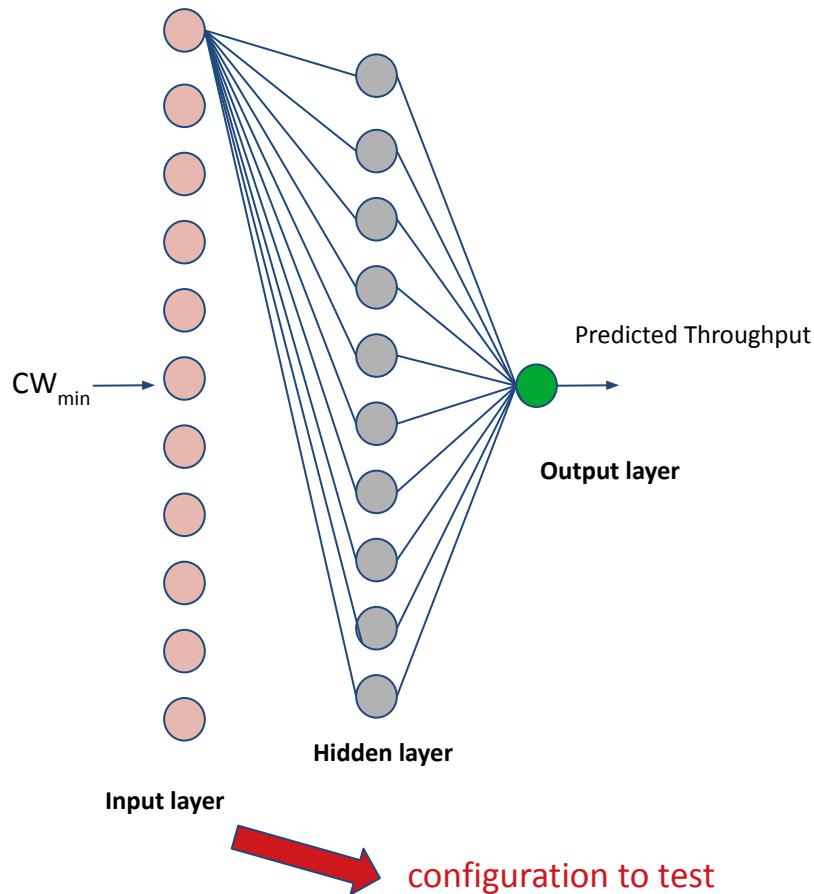
y =
Prediction (Mbps) → 6.0449e+00

# Example: Neural Network

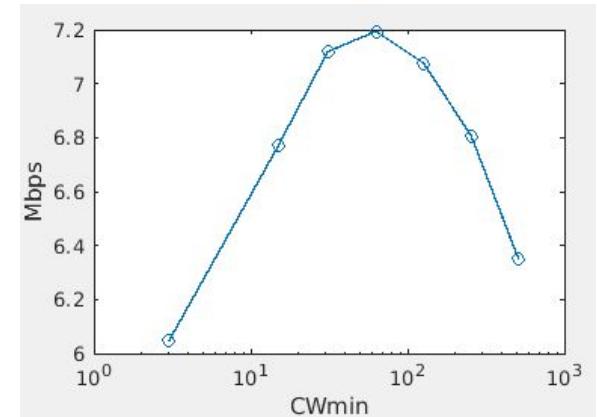


Matlab NN representation

$$x \rightarrow f(\cdot) \rightarrow y$$

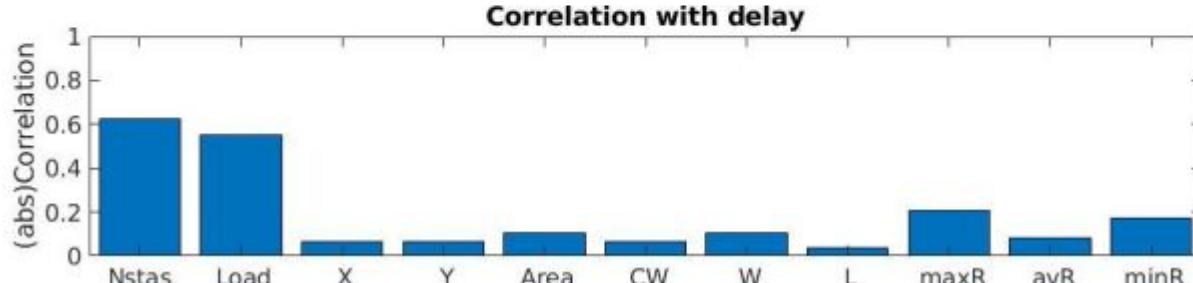
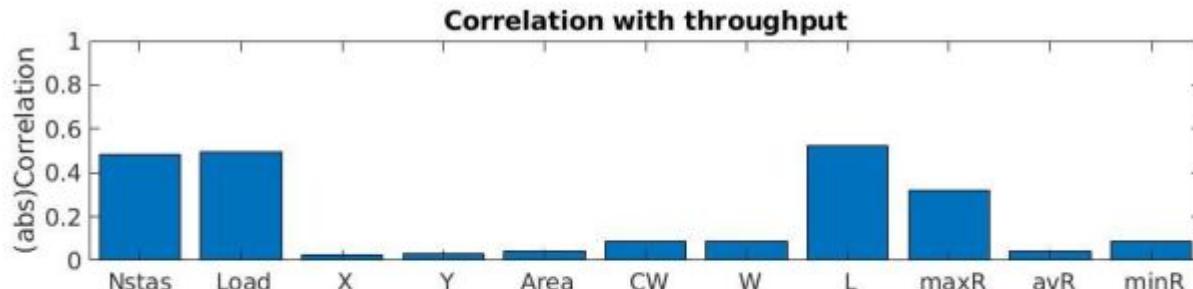


We can use the NN model to try different  $CW_{min}$  values to see which is the best performing one.



# How to define the feature set?

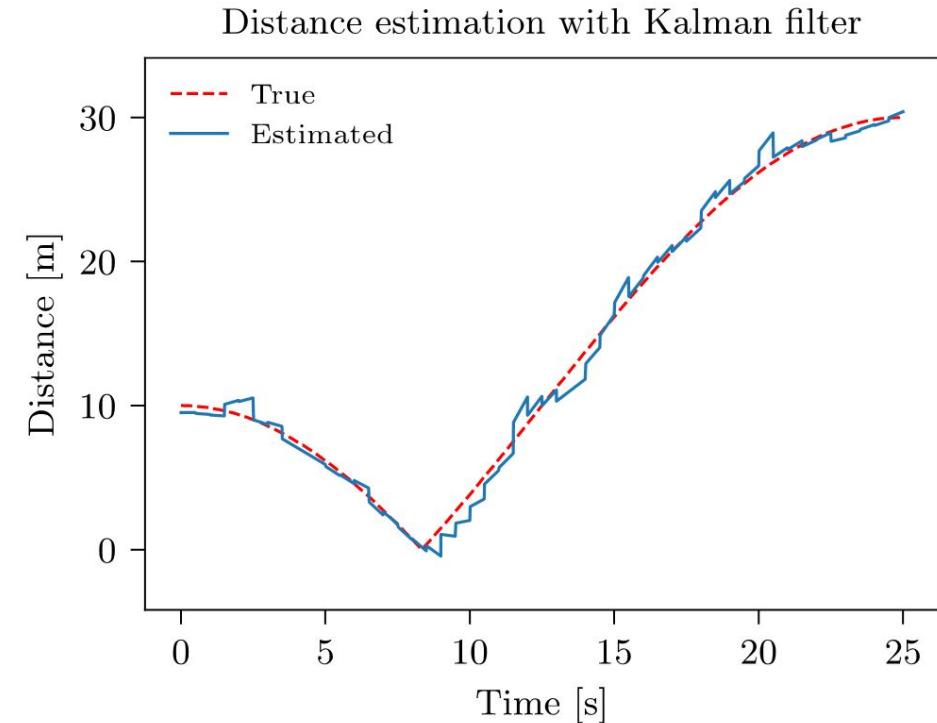
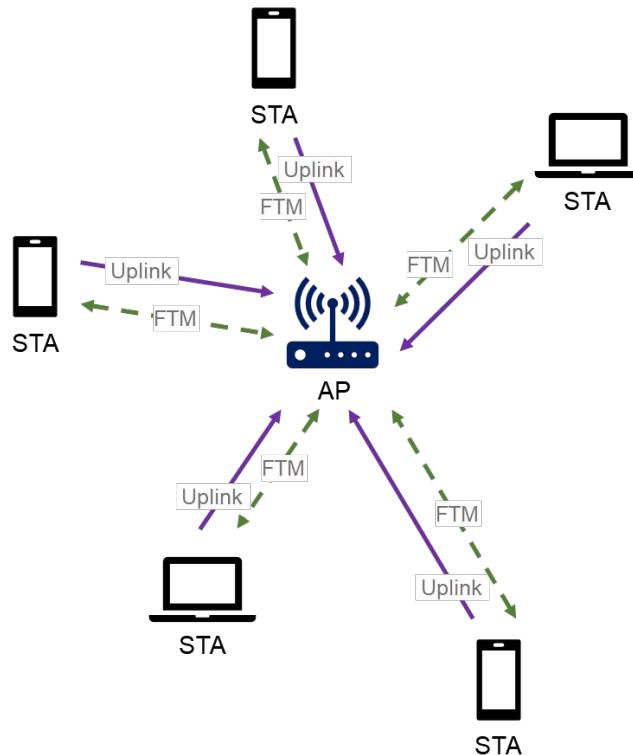
- We can study the cross-correlation between the desired output and the input features from the dataset, discarding those that show a low value.



...or rely on deep learning solutions to choose the most appropriate ones.

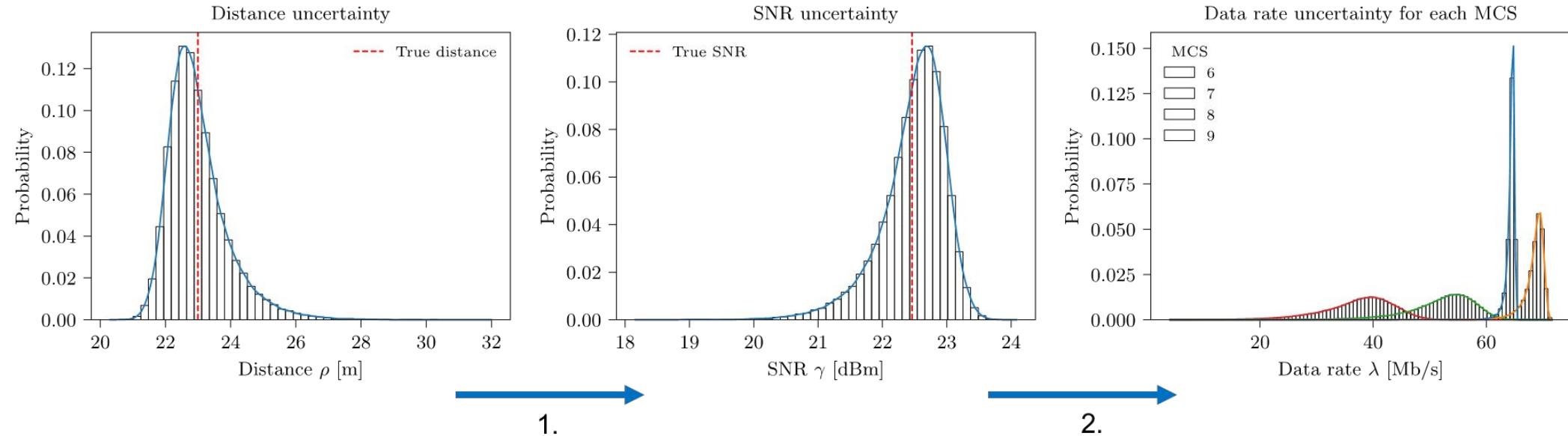
# FTMRate

<https://github.com/ml4wifi-devs/ftmrate>



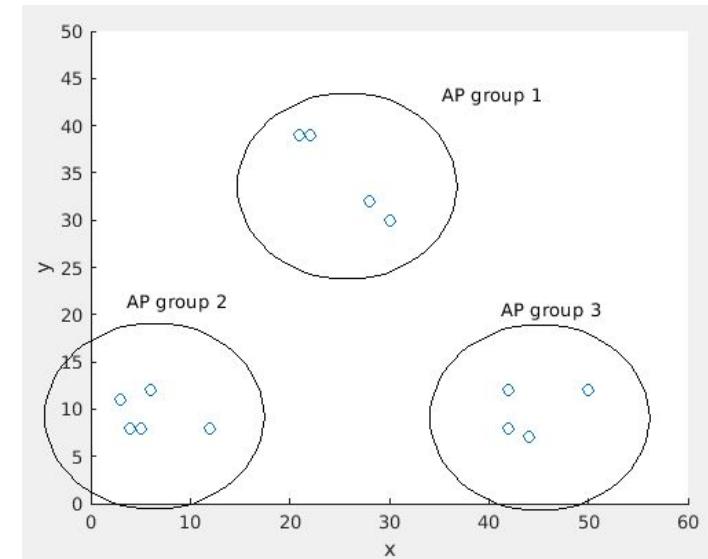
# FTMRate

<https://github.com/ml4wifi-devs/ftmrate>



# Unsupervised Learning

- **Goal:** Find patterns/trends/similarities in a dataset when only the features are available
- **Dataset:** We need a consolidated dataset to train the model, retraining it as the dataset updates
- **Techniques:** K-means, Self-Organizing Maps (SOMs), hidden Markov model (HMM), Auto encoders (AEs), Principal Component Analysis (PCA), Restricted Boltzmann machine (RBM), fuzzy C-means, etc.
- **Main uses:** Cluster the data in similar groups
- **Wi-Fi example**
  - AP selection from a dataset that contains only the features. Then, identifying which APs are similar may reduce the ‘testing’ phase by only requesting association to an AP of each representative ‘cluster’.



# Unsupervised Learning: CSI overhead reduction

- Source: Deshmukh, Mrugen, Mahmoud Kamel, Zinan Lin, Rui Yang, Hanqing Lou, and Ismail Güvenç. "**Intelligent Feedback Overhead Reduction (iFOR) in Wi-Fi 7 and Beyond.**" In 2022 IEEE 95th Vehicular Technology Conference (VTC2022-Spring), pp. 1-5. IEEE, 2022.
- "Instead of feeding back the angles to represent one CSI vector, we propose the iFOR algorithm, which feeds back an index from a set of candidates that represent a diverse set of CSI feedback"
- Clustering N vectors in M (e.g., 1024, 10 bits): K-means.
- The M vectors are known at the AP and the stations.
- A station measures the CSI, and selects the candidate vector with a lower euclidian distance to the measured.
- Only the index (10 bits) is exchanged.

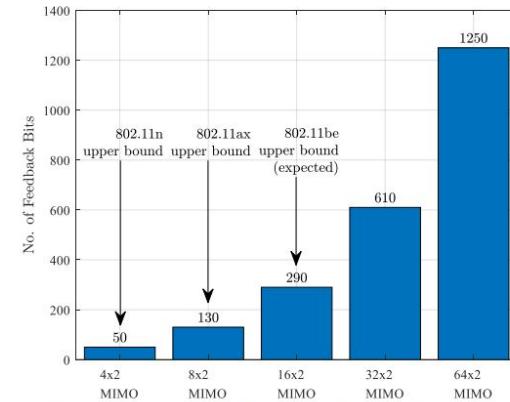


Figure 2 Comparing feedback overhead (in bits) for different MIMO configurations per subcarrier group.

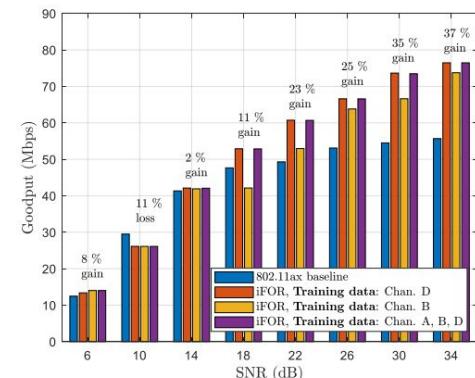
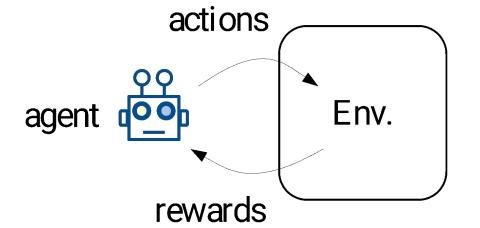


Figure 6 Goodput comparison for payload = 5000 bytes.

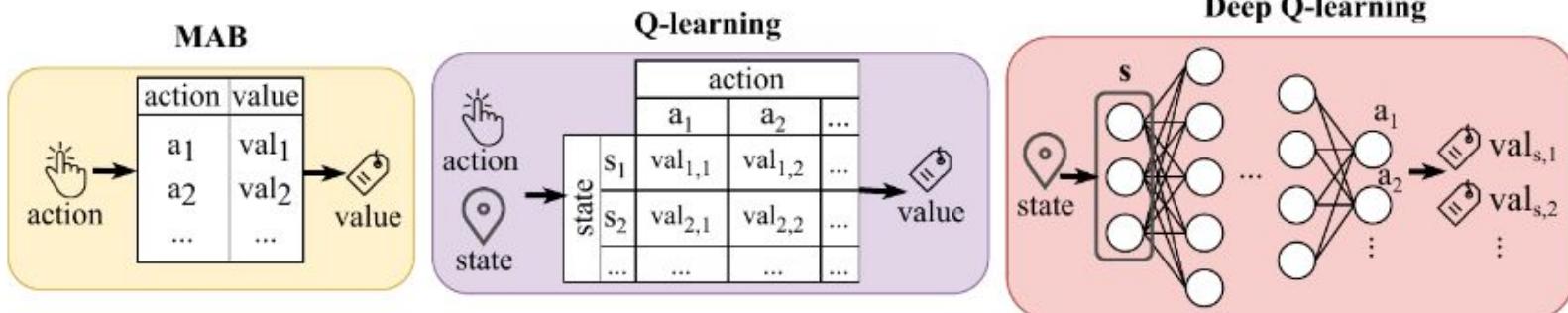
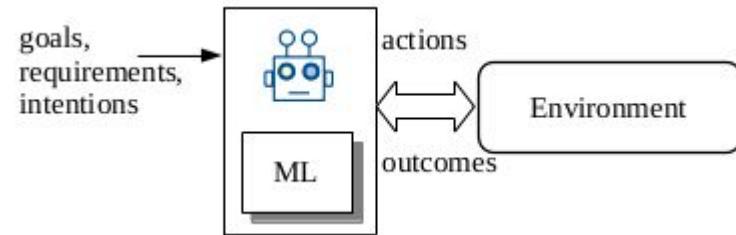
# Reinforcement Learning

- **Goal:** Learn from experience (relationship between actions and rewards)
- **Dataset:** sequence of actions and rewards obtained
- **Techniques:** Multi-armed Bandits, Q-learning, DQL
- **Main uses:** Adaptive systems in dynamic environments
- **Wi-Fi examples: exploration – exploitation tradeoff**
  - AP selection by trying and rating different APs
  - Dynamic channel selection: given a set of unknown channels, we need to find the best one (the empty one)
  - Dynamic configuration of Tx Power and CCA to support Spatial Reuse
  - etc.



# Reinforcement Learning

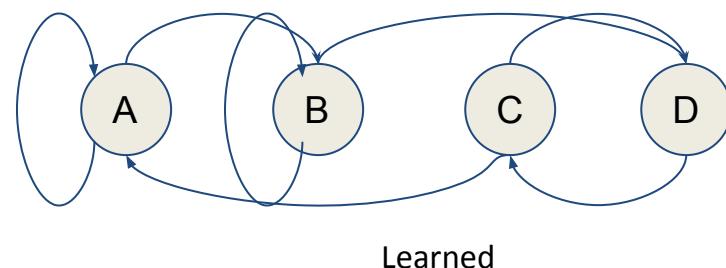
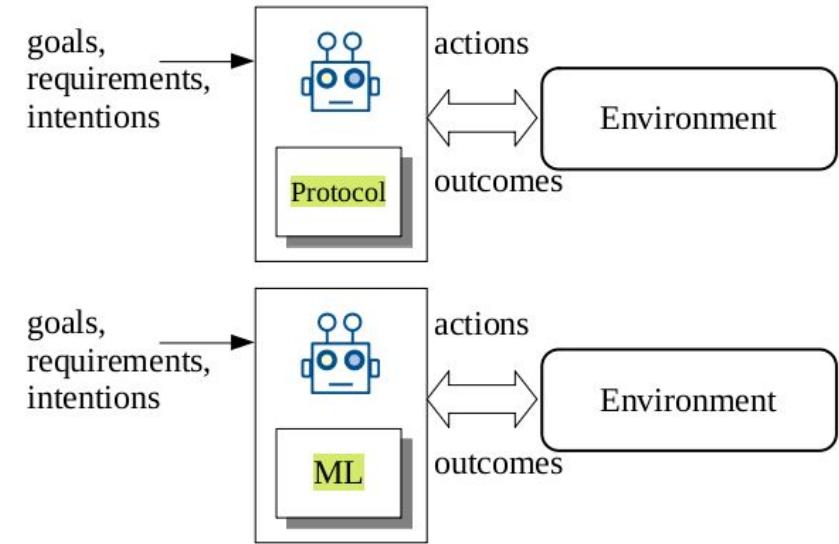
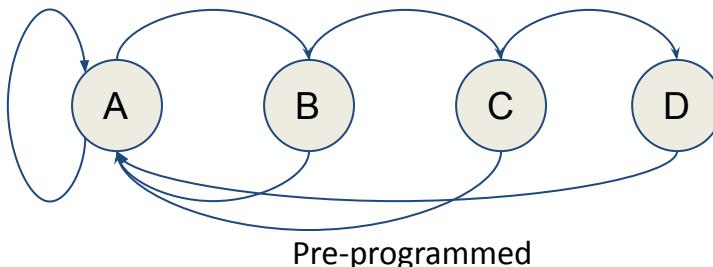
- An '**agent**' learns by interacting with the 'environment'
  - The agent can play different 'actions'
  - For each action, the agent receives a 'reward'
  - If possible, the agent may characterize the environment through a set of 'states'
- The **ML algorithm** tells the agent how to select the actions to maximize the reward



# RL vs standard ‘rule-based’ protocols?

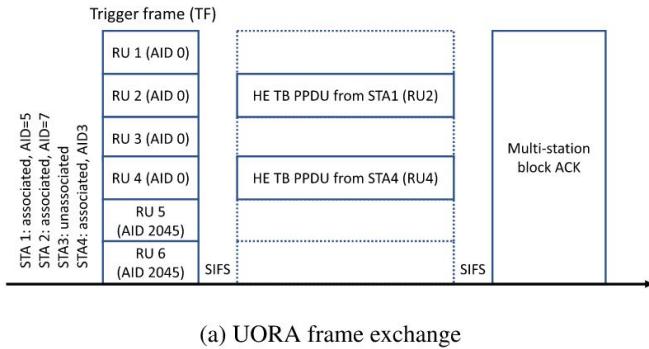
- RL naturally adapts to different situations.
  - but...
    - ... requires time to learn.
    - ... higher computational resources.
- The two approaches can be also combined.

**Example:** We can learn the protocol.



# RL vs standard ‘rule-based’ protocols?

## 802.11ax Example: UORA



	STA1, initial OBO=3	STA2, initial OBO=6	STA3, initial OBO=4	STA4, initial OBO=2
RU1 (AID 0)	OBO-4--1 (Set OBO=0, randomly select one RU)			
RU2 (AID 0)		OBO-4=2	-	
RU3 (AID 0)			-	
RU4 (AID 0)			-	
RU5 (AID 2045)	-	-	OBO-2=2	-
RU5 (AID 2045)	-	-		-
	Select new OBO	Resume OBO in next TF	Resume OBO in next TF	Select new OBO

(b) OBO decrementation after TF reception

### OBO decrementation

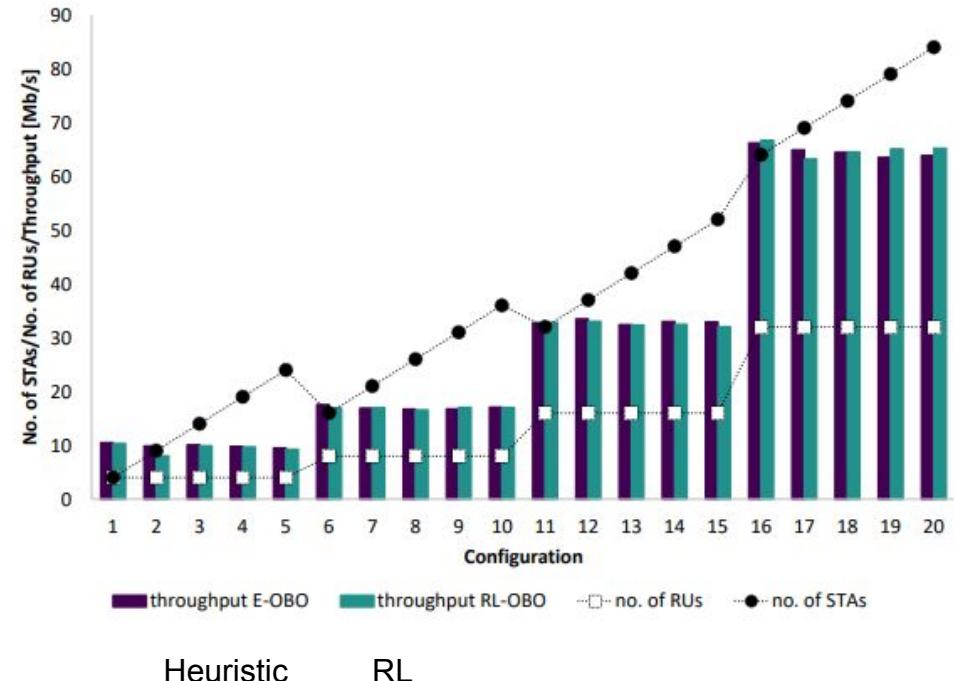
- Standard: fixed
- Efficient OBO: variable, depending on recent observations (heuristic) [1]
- RL-based OBO: variable, based on a trained DQL model [2]

[1] K. Kosek-Szott and K. Domino, “An efficient backoff procedure for IEEE 802.11ax uplink OFDMA-based random access,” IEEE Access, vol. 10, pp. 8855–8863, 2022

[2] Kosek-Szott, Katarzyna, Szymon Szott, and Falko Dressler. "Improving IEEE 802.11 ax UORA Performance: Comparison of Reinforcement Learning and Heuristic Approaches." IEEE Access 10 (2022): 120285-120295.

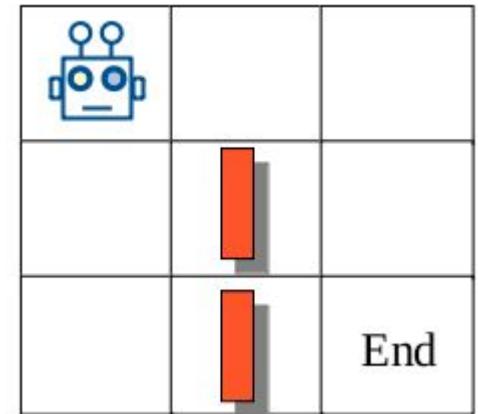
# RL vs standard ‘rule-based’ protocols? UORA example

Conclusions: “The simulation results confirm that the proposed approach gives satisfactory results in various dynamic settings; however, when compared to E-OBO, RL-OBO does not provide meaningful advantages. Both mechanisms provide similar outcomes (i.e., throughput, channel access fairness, efficiency) and, therefore, the need for RL-OBO training and appropriate configuration of ML-related hyperparameters becomes a disadvantage.”



# Actions, Rewards and States

- Consider the case of a robot moving in a map.
  - Each position of the map is a ‘**state**’: (x,y)
  - **Actions**: the movements that can be done in each state: U, D, R, L
  - **Rewards**: how close is the robot to the end; and/or if there is an obstacle.
  - *Moving results in a reward, but also moves the system to a new state.*
- *Learning the model means knowing what to do (action to play) at every state.*



*It is not clear how to define states in Wi-Fi, as sometimes the state is equivalent to the ‘action’ (i.e., the selected AP or channel).*

*Wireless scenarios are hardly ‘static’, and so the same action may have different outcomes.*

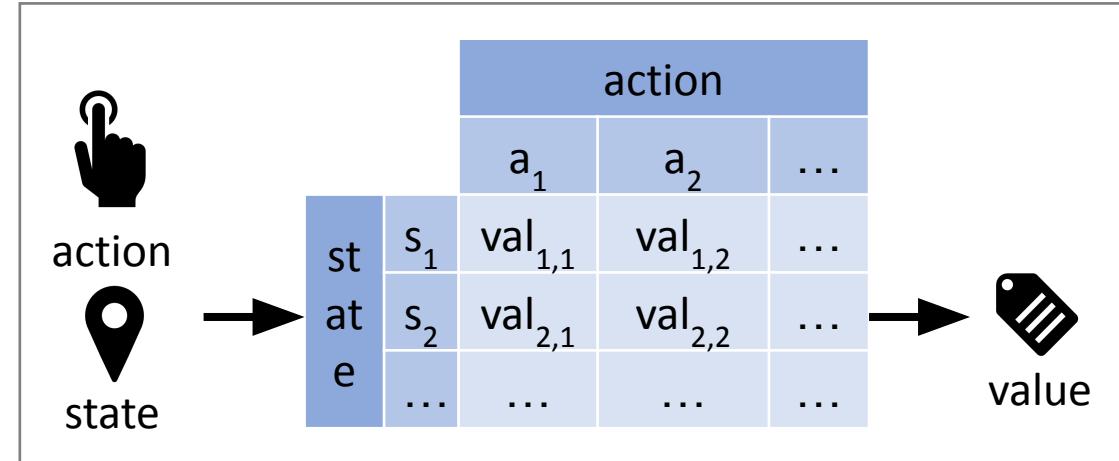
# Designing Rewards

- A key aspect since it guides the behavior of the RL algorithm
- It can be a single value (last action), an average, the sum...
  - Last value: fluctuations;
  - Average: low response, as it depends on the past
- **Q-learning rule:** trade-off between past, current and future rewards
- Some algorithms require normalized rewards (i.e., [0,1])
- So?
  - For each problem, test different ones, and select the one working better.



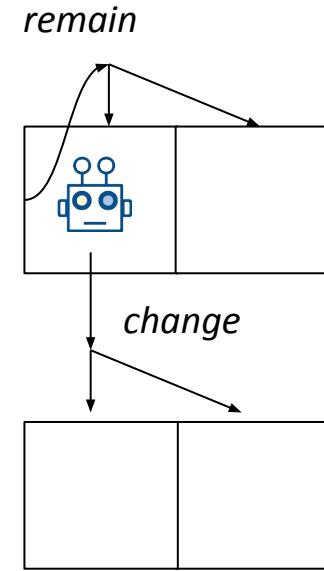
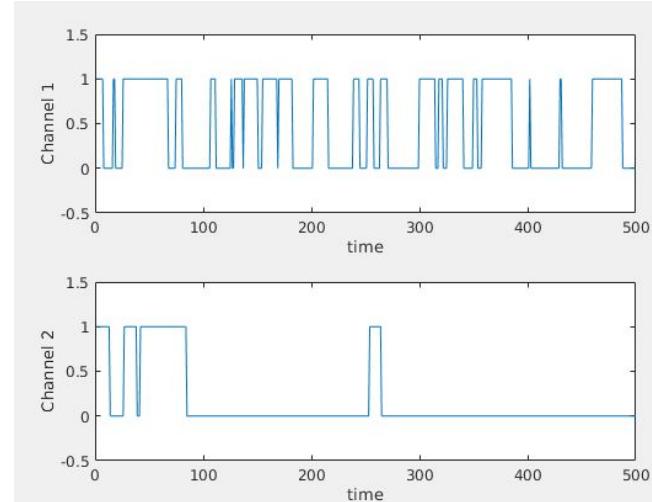
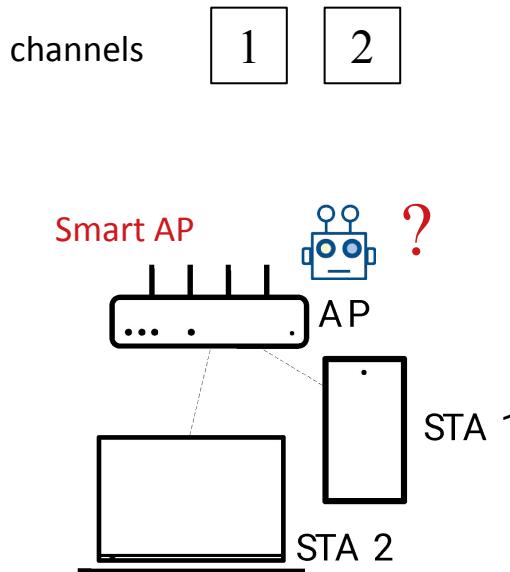
# Q-learning

- It requires states:
  - Same or different actions depending on the state
  - Actions can result in a ‘change’ of state
  - Rewards depend on the state
- We need a mechanism to explore the environment
  - e.g.,  $\epsilon$ -greedy
- We need a mechanism to update Q-table based on the obtained rewards (Bellman eq.)



$$Q^{\text{new}}(s_t, a_t) = (1 - \alpha)Q(s_t, a_t) + \alpha \left( r_t + \gamma \max_a Q(s_{t+1}, a) \right)$$

# Example: Channel Selection (Q-learning)

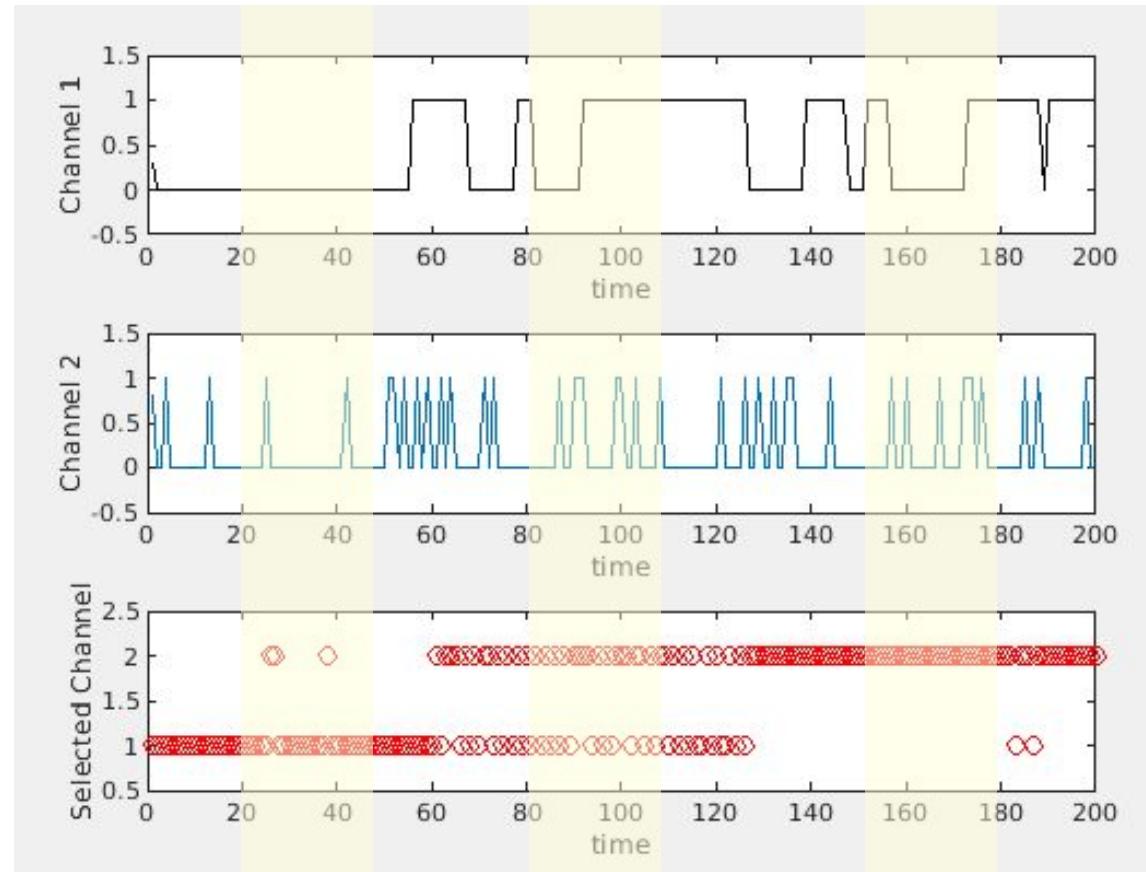
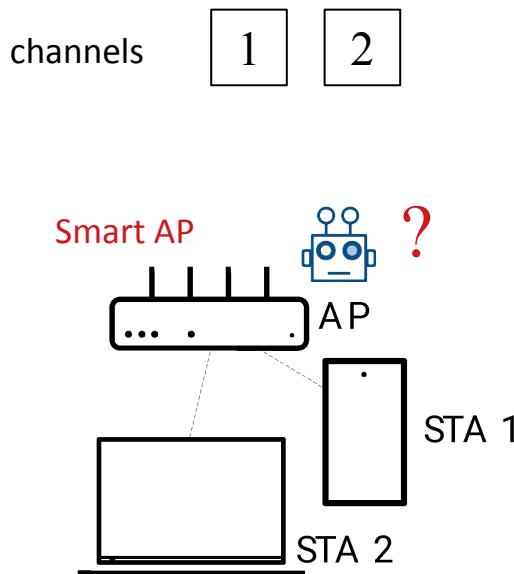


*A channel can be busy or empty*

**Actions:** remain in the same channel; change channel

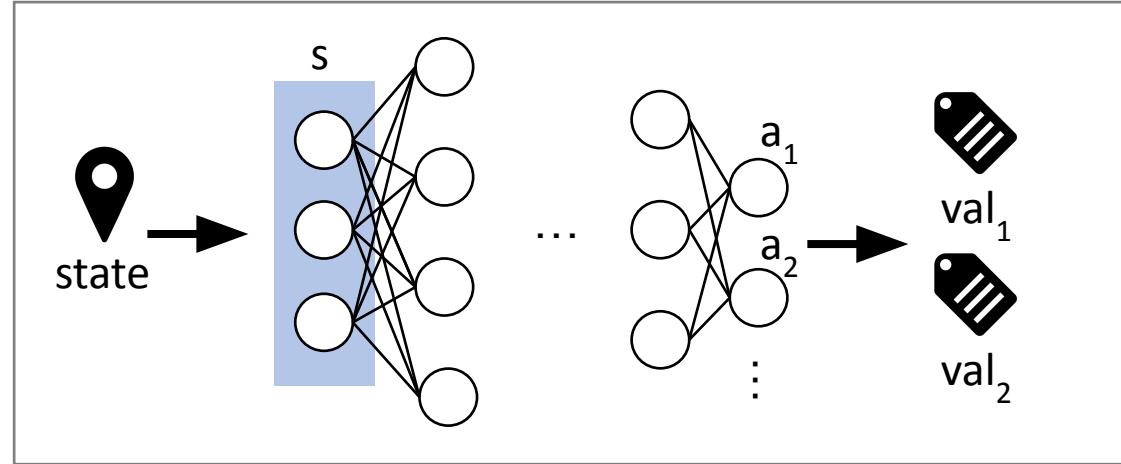
**States:** channel 1 and empty; channel 1 and busy; channel 2 and empty; channel 2 and busy

# Example: Channel Selection (Q-learning)



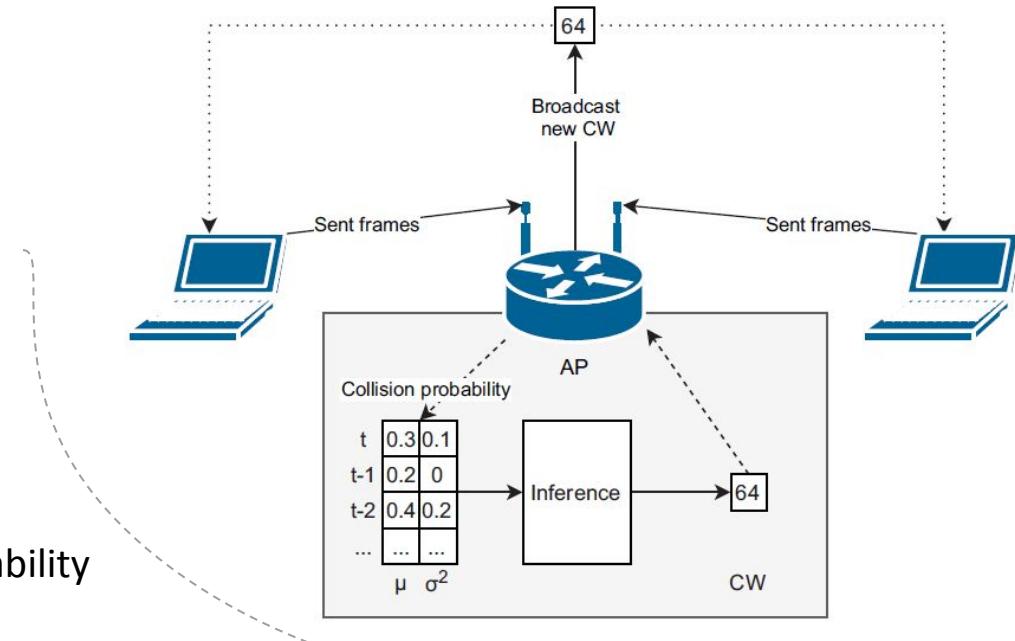
# Deep Q-learning (DQN)

- **Problem:** Accurate learning of the Q-table is difficult (or impossible) and time consuming when the number of states is large as the agent needs to go through all the different states and actions several times.
- **Solution:** Model the Q-table response with a (Deep) Neural Network.
  - If the system is in state ‘ $s$ ’, the agent asks the (D)NN to predict the reward the agent will obtain if it plays any of the available actions in state ‘ $s$ ’.
  - The agent selects the action with a higher predicted ‘reward’.
  - DQN’s additional deep neural network allows for more efficient extrapolation of rewards **for yet unseen states** as compared to basic Q-learning.
- **Challenge:** to train on-line the (D)NN, as it may require large CPU/GPU resources.



# Example: DQN for CW optimization

- Agent - installed at the AP
- State - status of all connected devices
- Action - select CW (value of integer  $a$ )
- Reward - network throughput
- Observation - collision probability
- DNN:  $8 \times 128 \times 64$
- Exploration: random action w/ low probability



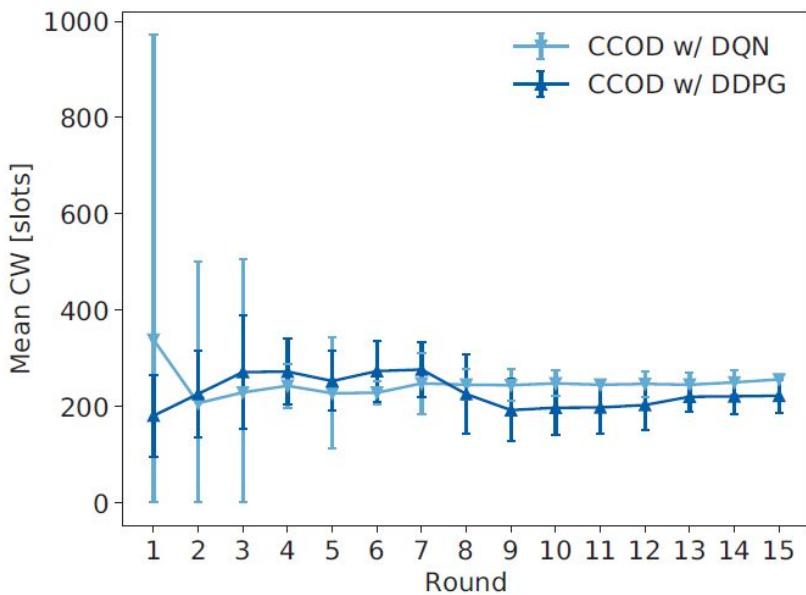
$$CW = \lfloor 2^{a+4} \rfloor - 1$$

$$a \in [0, 6]$$

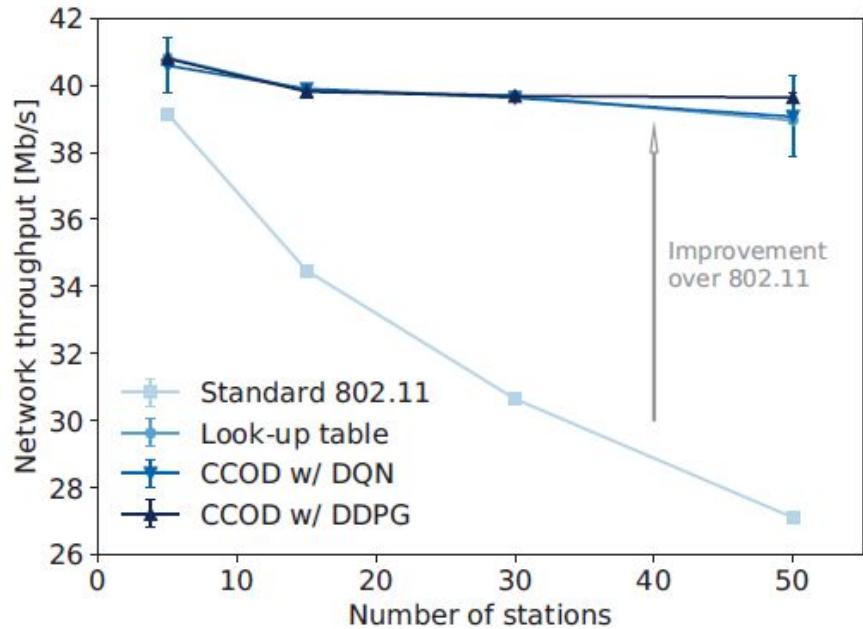
Wydmański, Witold, and Szymon Szott. "Contention window optimization in IEEE 802.11ax networks with deep reinforcement learning." In 2021 IEEE Wireless Communications and Networking Conference (WCNC).

# Example cont'd

- DQN - Discrete action space
- DDPG - Continuous action space



Mean selected CW in consecutive training rounds  
(static scenario: 30 stations)



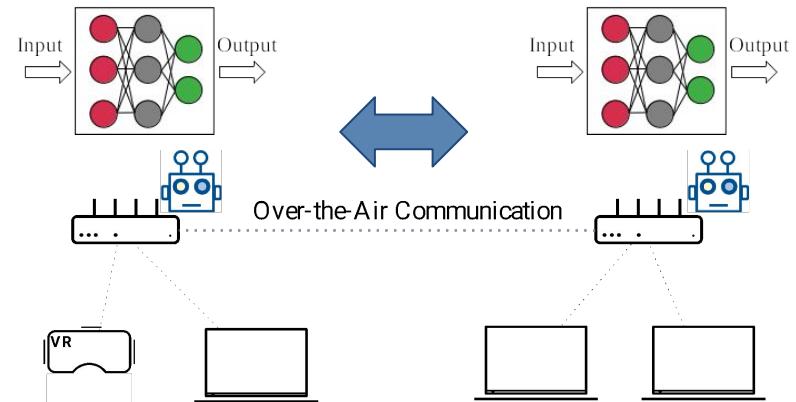
Throughput improvement over 802.11

# Federated Learning

- **Federated Learning:** devices exchange their locally trained ‘global’ models.
  - Centralized or distributed.
  - The ‘global’ model is re-trained locally using the data gathered by each device.
  - Only the ‘model’ is shared by participating devices. **Data is kept local (privacy advantages + saves overheads).**
    - SL: the weights of a NN
    - RL: Q-table, instantaneous rewards
  - **The global model aggregates the weights from the local updates computed by clients (typically, FedAvg is adopted)**
  - *Could improve system stability in ‘adversarial’ situations*
- **Example / Proposal**
  - To leverage the over the air MAPC framework to exchange local models to support DFL in next-gen. Wi-Fi networks

**Algorithm 1** Federated Averaging (FedAvg)

```
1: for  $t = 1, 2, \dots, T$  do
2:   for  $k \in \mathbb{K}_{tr}$  do in parallel
3:     Pull  $\mathbf{w}_t$  from central server:  $\mathbf{w}_{t,0}^{(k)} = \mathbf{w}_t$ 
4:     for  $e = 1, \dots, E$  do
5:       Update model:  $\mathbf{w}_{t,e}^{(k)} = \mathbf{w}_{t,e}^{(k)} - \eta_t \nabla l_{t,e}^{(k)}$ 
6:     end for
7:     Push  $\mathbf{w}_{t+1}^{(k)} \leftarrow \mathbf{w}_{t,E}^{(k)}$ 
8:   end for
9:   FedAvg:  $\mathbf{w}_{t+1} = \frac{1}{|\mathbb{K}_{tr}|} \sum_{k \in \mathbb{K}_{tr}} \mathbf{w}_{t+1}^{(k)}$ 
10: end for
```



# Transfer Learning: an example

- Source: Iturria-Rivera, Pedro Enrique, Marcel Chenier, Bernard Herscovici, Burak Kantarci, and Melike Erol-Kantarci. "Cooperate or not Cooperate: Transfer Learning with Multi-Armed Bandit for Spatial Reuse in Wi-Fi." *arXiv preprint arXiv:2211.15741* (2022).
- Each AP has an agent in charge of selecting the best TxPower and CCA threshold.
- Before selecting an action, the reward is predicted using a DNN, which is trained for each scenario (context)
- In dynamic scenarios, when there is a context change, the previous trained DNN is ‘transferred’ to the new one: a) completely, or b) partially (a subset of layers).

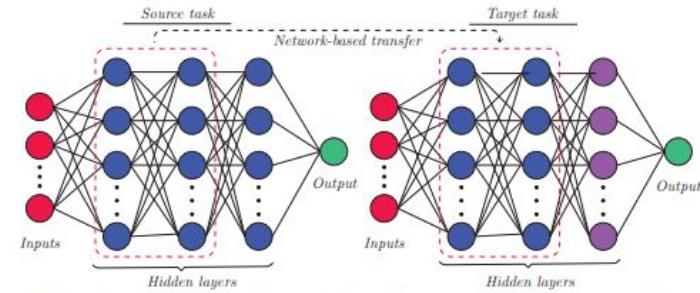
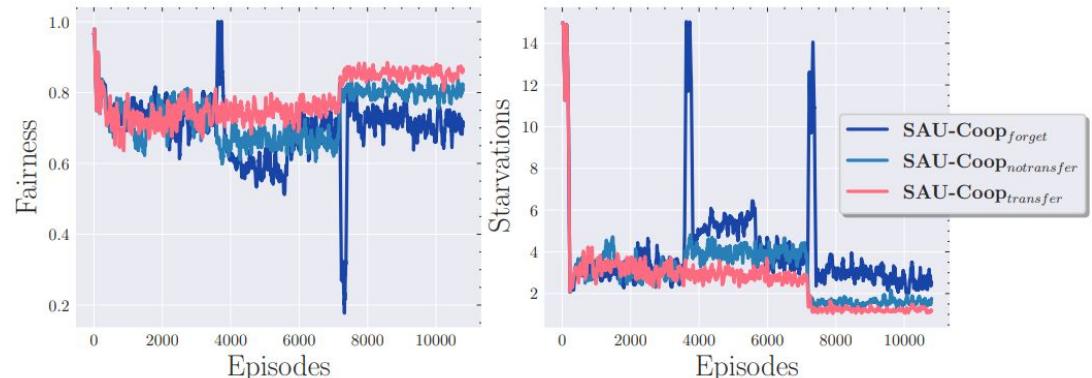


Fig. 2: Network-based transfer learning: the neural network source task’s hidden layers are reutilized in the target network



# Re-cap

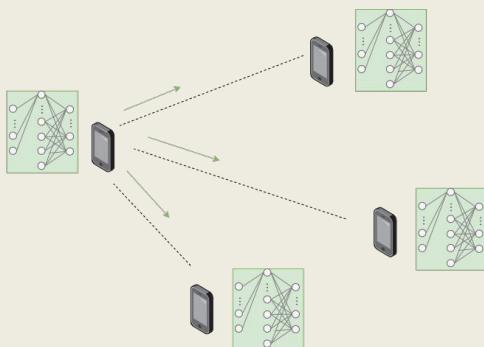
- Machine Learning → techniques to create ‘models’ **from data**
  - Supervised Learning: Make predictions, classify
  - Unsupervised Learning: leverage similarity
  - Reinforcement Learning: interact with the environment
- Training and deploying models:
  - Off-line vs On-line
  - Centralized vs Distributed
- Use-cases / Examples:
  - Pre-trained SL models for AP selection (association)
  - RL for CW/channel selection in dynamic environments

The capability of ML to go beyond rule of thumb strategies by automatically learning (and adapting) to (un)seen situations can cope with heterogeneous wireless network scenarios

# Wi-Fi for ML & ML for Wi-Fi: A two-sided relationship

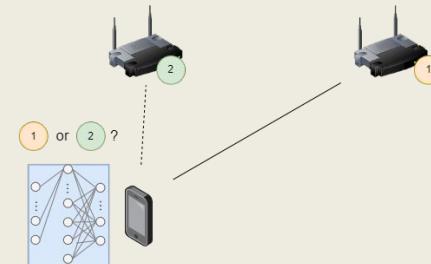
## Wi-Fi for ML

- Rise of decentralization in ML (distributed/collective/federated intelligence)
- Real-time adaptation in ML applications
- Reach end-users, typically available wirelessly
- Wireless communications have become essential fuel for AI/ML
- Joint ML & communication optimization



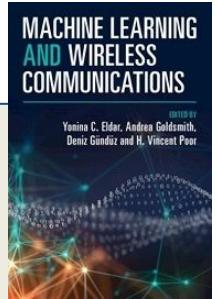
## ML for Wi-Fi

- ML to address relevant problems in Wi-Fi
  - Network management & configuration
  - Advanced troubleshooting & anomaly detection
  - Network optimization (e.g., channel access, transmit power adaptation, MCS selection optimization, etc.)
- On-top solutions vs Native AI/ML



# Wireless for ML: Ongoing work & relevant directions

- AI/ML operations relying on wireless links
  - Exchange data/model parameters
  - Multi-agent coordination
  - Distributed training/inference
- Wireless resources have an impact on AI/ML methods
  - Provide timely results (e.g., spectrum resources)
  - Reliability, error-free transmissions (e.g., SINR)
  - Energy consumption (e.g., transmit power)



## "Machine learning and wireless communications"

Yonina C. Eldar, Andrea Goldsmith,  
Deniz Gündüz, H. Vincent Poor

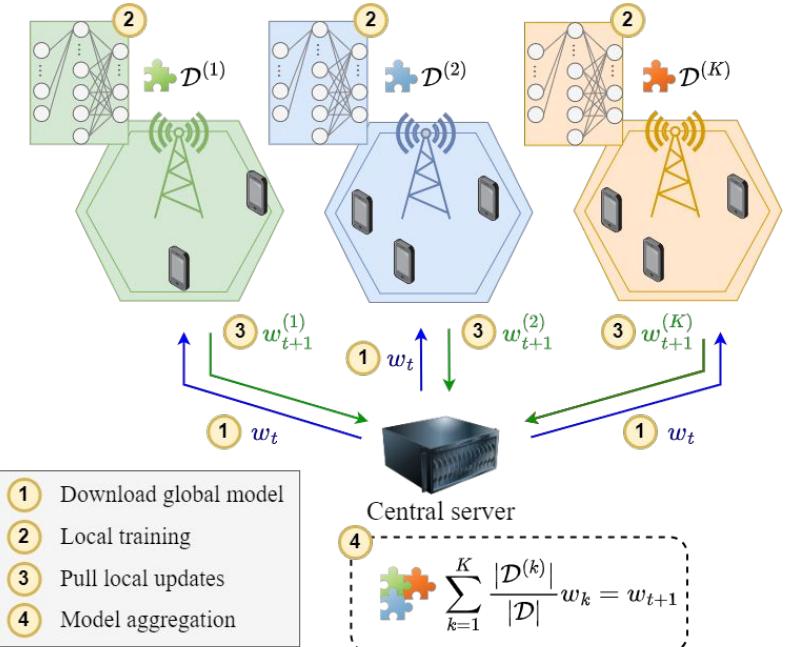
- Collaborative learning over WNs
- Optimized FL in WNs with constrained resources
- Quantized FL
- Over-the-air-computation
- Federated knowledge distillation
- Differential privacy in wireless FL
- Timely wireless edge interference

# Examples

- Distributed learning over Wi-Fi:
  - Guerra, E., Wilhelmi, F., Miozzo, M. and Dini, P. (2023), "[\*\*The Cost of Training Machine Learning Models over Distributed Data Sources\*\*](#)," in IEEE Open Journal of the Communications Society, doi: 10.1109/OJCOMS.2023.3274394.
- Over-the-air-computation
  - Amiri, M. M., & Gündüz, D. (2022). "[\*\*Over-the-Air Computation for Distributed Learning over Wireless Networks.\*\*](#)" Machine Learning and Wireless Communications, 434.

# Distributed learning over Wi-Fi

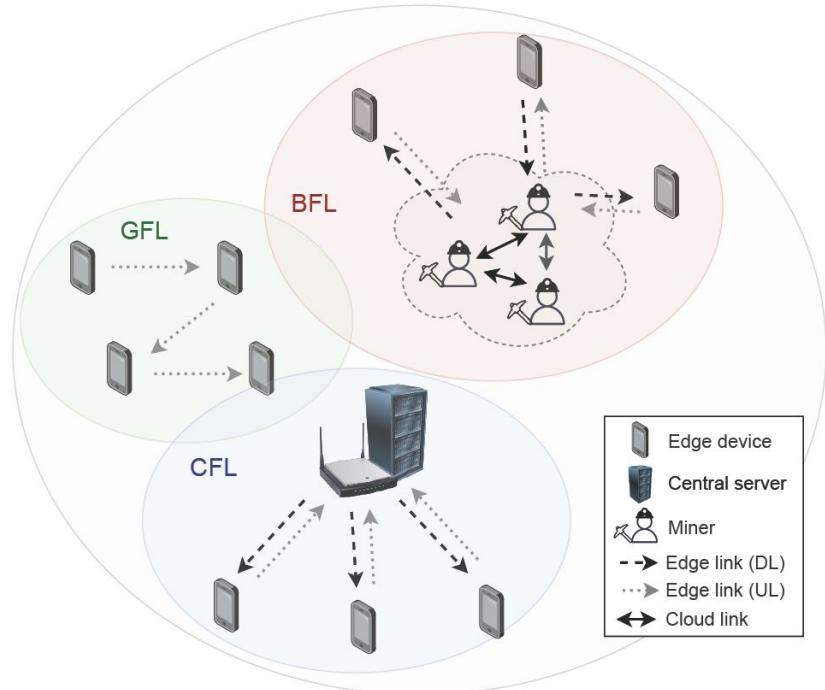
- Distributed ML trend
  - Improve efficiency of computation and communication resources
  - Bring AI optimization closer to users
  - Robustness, enhanced privacy, security...
- Federated Learning (FL)
  - FL devices exchange model weights rather than data
  - Communication efficiency
  - Improve scalability + Enhance privacy
- Strong dependency on (wireless) communication links
  - Significant cost of communication (overhead, energy)
  - Impact of communication latency into ML performance



# Distributed learning over Wi-Fi

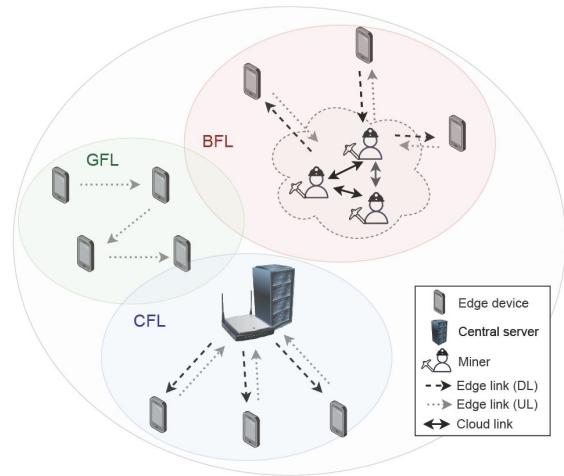
Guerra, E., Wilhelmi, F., Miozzo, M. and Dini, P. (2023), "[The Cost of Training Machine Learning Models over Distributed Data Sources](#)," in IEEE Open Journal of the Communications Society, doi: 10.1109/OJCOMS.2023.3274394.

- Three different FL settings
  - a. **Centralized Federated Learning (CFL):** traditional setting with a central orchestrating server
  - b. **Blockchained Federated Learning (BFL):** the central server is replaced by a distributed ledger
  - c. **Gossip Federated Learning (GFL):** purely decentralized setting with P2P interactions
- Cost of training ML models
  - a. Computation
  - b. **Communication:**
    - Cloud link & Edge link (UL/DL)



# Distributed learning over Wi-Fi

Guerra, E., Wilhelmi, F., Miozzo, M. and Dini, P. (2023), "[The Cost of Training Machine Learning Models over Distributed Data Sources](#)," in IEEE Open Journal of the Communications Society, doi: 10.1109/OJCOMS.2023.3274394.



Algorithm	Time complexity	Communication Overhead
CFL	$O(RmE D_{\max}  w )$	$2Rm w $
BFL	$O(R( w m^2 + E D_{\max}  w m + 2^l + m w N_B))$	$R( w m^2 +  w m + m w N_B)$
GFL	$O(RmE D_{\max}  w )$	$Rm w $

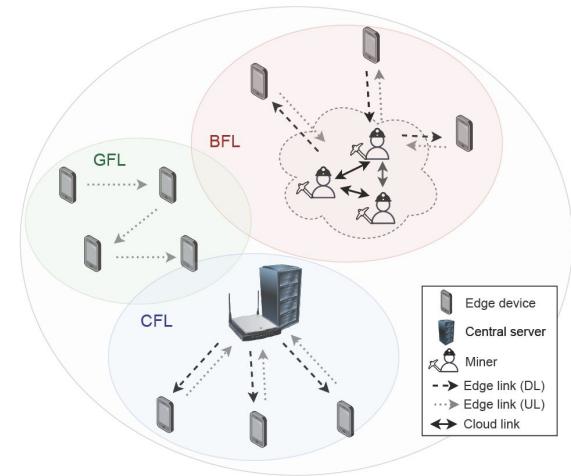
↗ Number of FL rounds   
 ↗ Model size (kB)   
 ↗ Number of clients/devices   
 ↗ Number of blockchain nodes

## Size of popular ML models:

- FFNN = 800 KB
- CNN = 2.33 MB
- Resnet50 = 48 MB
- VGG19 = 79 MB

# Distributed learning over Wi-Fi

Guerra, E., Wilhelmi, F., Miozzo, M. and Dini, P. (2023), "[The Cost of Training Machine Learning Models over Distributed Data Sources](#)," in IEEE Open Journal of the Communications Society, doi: 10.1109/OJCOMS.2023.3274394.



## Results of training a CNN in each setting for IID and non-IID (in parentheses) dataset distributions:

Acc. Training	Acc. Validation	Acc. Test	Conv. Time (s)	Comp. Energy (%)	Tot. Energy (Wh)	Comm. overhead (GB)
CFL	0.99 (0.97)	0.97 (0.9)	0.96 (0.91)	125883.47 (124869.07)	99.65 (99.51)	201.68 (141.69)
BFL	0.99 (0.97)	0.97 (0.9)	0.96 (0.91)	131488.87 (130555.3)	99.95 (99.95)	1329.65 (1273.95)
GFL	0.99 (0.67)	0.8 (0.22)	0.8 (0.22)	114217.66 (107854.86)	99.93 (99.84)	319.77 (143.22)

- Most of the energy spent is devoted to computation tasks (i.e., ML model training)
  - The communication energy is computed based on the power used for transmission
- **The communication overheads are significant**
  - Need for a new class of traffic: AI/ML category (under discussion in standardization)

A significant portion of the literature analyzes ways to decrease the communication overheads generated by FL (compression, quantization, resource allocation, etc.)

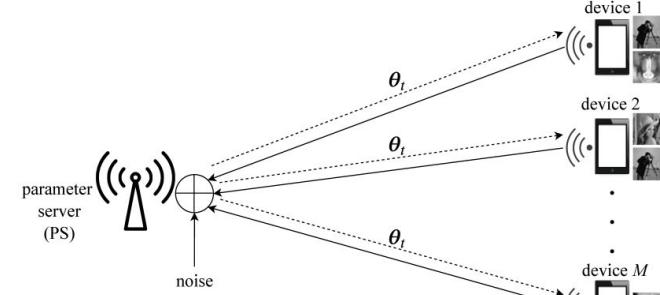
Yang, Z., Chen, M., Saad, W., Hong, C. S., & Shikh-Bahaei, M. (2020). Energy efficient federated learning over wireless communication networks. *IEEE Transactions on Wireless Communications*, 20(3), 1935-1949

# Examples

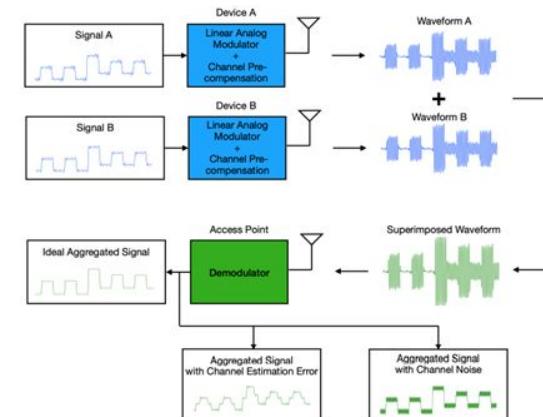
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- Over-the-air-computation
  - Amiri, M. M., & Gündüz, D. (2022). "[\*\*Over-the-Air Computation for Distributed Learning over Wireless Networks.\*\*](#)" Machine Learning and Wireless Communications, 434.

# Over-the-air-computation (OAC)

- OAC leverages interference from simultaneous transmissions for ML model aggregation/averaging
- The medium performs the computation (signal superposition)
- Reduce the number of computations
- The underlying communication infrastructure needs to be aware of the mechanism:
  - Schedule devices
  - Synchronization
  - Power control



Amiri, M. M., & Gündüz, D. (2020). Machine learning at the wireless edge: Distributed stochastic gradient descent over-the-air. *IEEE Transactions on Signal Processing*, 68, 2155-2169.



Chen, M., Yang, Z., Saad, W., Yin, C., Poor, H. V., & Cui, S. (2020). A joint learning and communications framework for federated learning over wireless networks. *IEEE Transactions on Wireless Communications*, 20(1), 269-283

# Outline

## Part 1: Introduction. Why Wi-Fi may want to adopt AI/ML?

- Wi-Fi overview: A 30-year path from IEEE 802.11b to IEEE 802.11be, and beyond
- Open challenges in Wi-Fi: Dealing with complexity and uncertainty
- Requirements of next-gen Wi-Fi networks

## Part 2: A primer on AI/ML through Wi-Fi-related problems

- Wi-Fi & ML: A two-sided relationship
- Examples of ML types (supervised, unsupervised, and reinforcement learning) for Wi-Fi
- Novel trends in ML applied in Wi-Fi: deep learning, reinforcement learning, online learning, federated learning

## Part 3: Online learning for responsive Wi-Fi networks

- Wi-Fi with multi-armed bandits
- Reinforced-lib: our open-source library
- Overview of tools and resources.

## **Coffee break (10:30-11:00)**

## Part 4: Adoption of ML for Wi-Fi: architecture and standardization

- ML integration in Wi-Fi through the ITU-T architectural framework
- Current status in standardization

## Part 5: Open challenges, future research directions, and summary

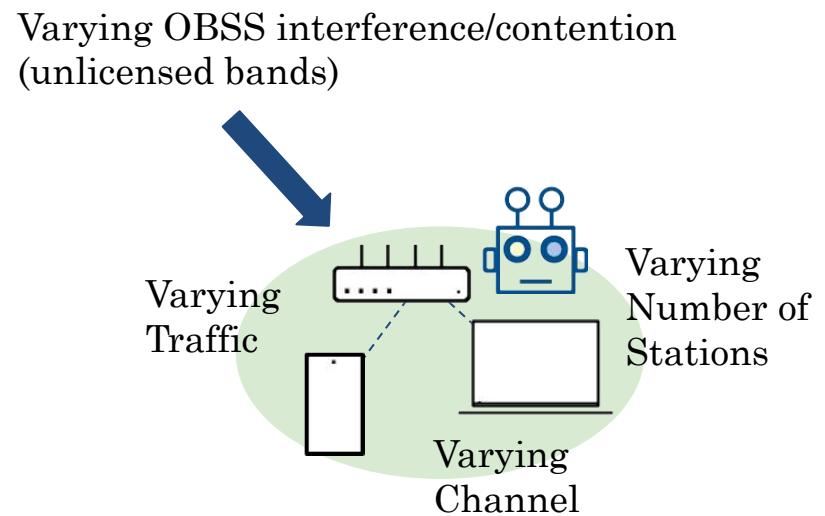
- Open challenges and future research directions; Synergies with other disruptive technologies
- Current AI/ML trends: LLM and Generative AI
- Summary and takeaways
- Q&A

3

## Online learning for responsive Wi-Fi networks

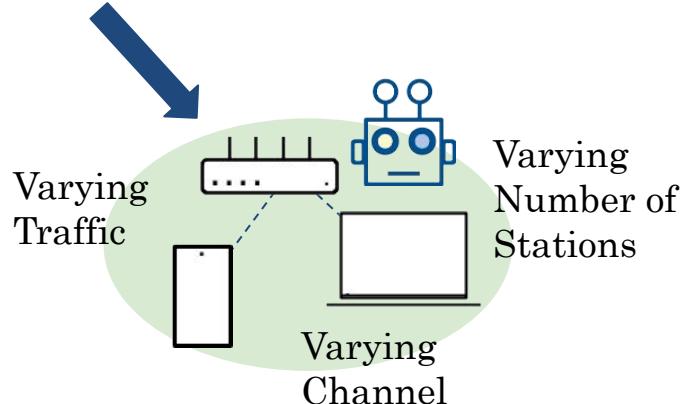
# Motivation

- There are multiple random phenomena that could affect Wi-Fi performance
  - Variable traffic
  - Variable channel conditions
  - Variable number of contenders
  - Variable OBSS interference/contention
- Environment changes fast: is it stationary or non-stationary?
  - Hard to find an ‘optimal’ configuration for all conditions
- Can ‘AI/ML’ agents deployed in AP / stations help?
  - It will need to learn and react fast
  - One big ‘agent’ or multiple ‘small agents’?

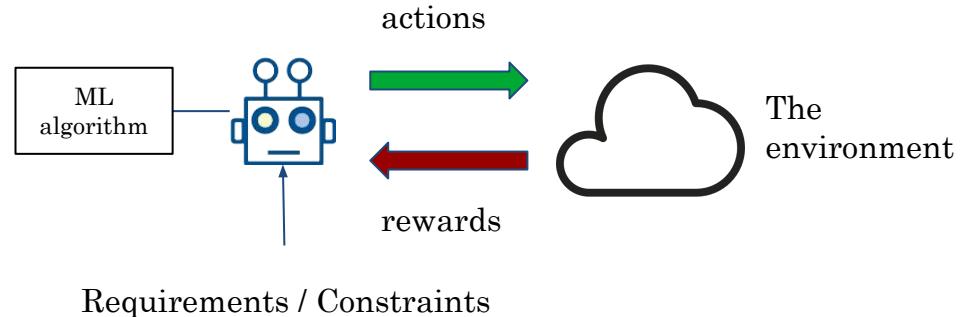


# Motivation

Varying OBSS interference/contention  
(unlicensed bands)



The ML algorithm controls how the 'agent' explores (collects new information) and exploits what has already learnt

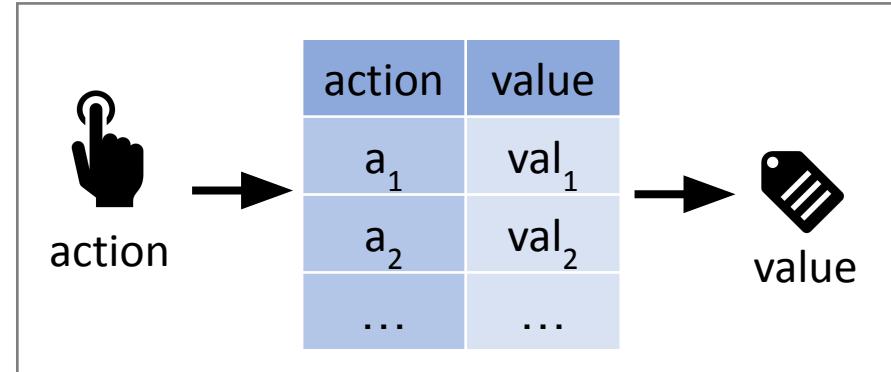


**Goal:** achieve the requirements using the minimum possible resources

**Multi-armed Bandits (MABs)** seem good candidates as light-weight ML algorithms to drive the exploration / exploitation trade-off

# Multi-armed Bandits (MABs)

- Sequential interaction between the ‘agent’ and the environment:
  - action 1 → reward 1; action 2 → reward 2
- No states (or just a single state), only actions and rewards.
- Exploration-exploitation trade-off. The agent:
  - **Explores**: selects an action ‘randomly’
  - **Exploits**: selects the action with higher reward from the table
- Different approaches: simple, low-computing res.
  - $\epsilon$ -greedy, Thompson Sampling, UCB, EXP3, etc.
- **Contextual MABs** take into account different situations:
  - E.g. AP selection at home, at work
  - Moving to a new ‘context’ may allow to reuse past info.



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## Algorithm 1: Implementation of Thompson sampling.

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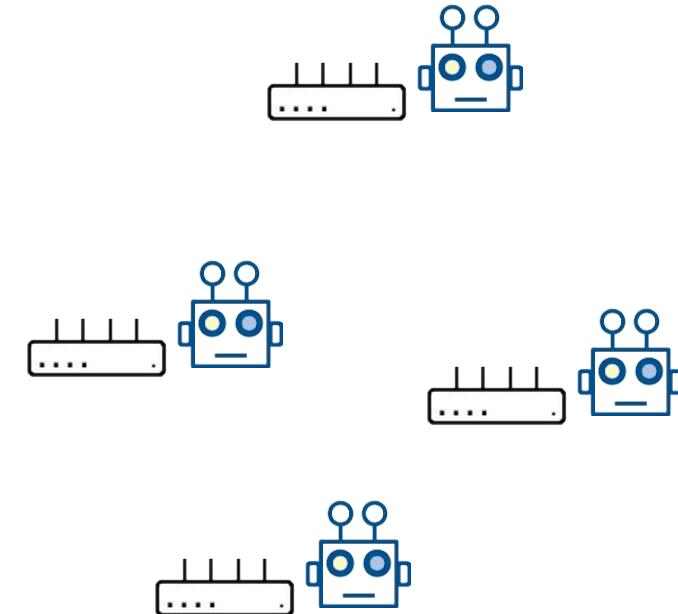
```
Input : set of possible actions,  $\mathcal{X} = \{x_1, \dots, x_N\}$ 
1 Initialize: for each arm  $x_i \in \mathcal{X}$ , set  $\hat{\mu}_i = 0$  and  $n_i = 0$ 
2 while active do
3   For each arm  $x_i \in \mathcal{X}$ , sample  $\theta_i(t)$  from  $\mathcal{N}(\hat{\mu}_i(t), \sigma_i^2(t))$ 
4   Select arm  $x_i = \underset{i=1, \dots, N}{\operatorname{argmax}} \theta_i(t)$ 
5   Observe and compute the reward experienced  $r_i(t)$ 
6    $\hat{\mu}_i(t) \leftarrow \frac{\hat{\mu}_i(t) \cdot n_i(t) + r_i(t)}{n_i(t) + 2}$ 
7    $n_i(t) \leftarrow n_i(t) + 1$ 
8 end
```

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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*, 88, 129-141.

# Single vs Multi-agent set-ups

- Multiple devices/networks trying to find a good configuration may result in a never-end story.
- Even if there is a joint action, it is unlikely that all agents choose the ‘right’ action at the ‘right’ moment.
- That optimal action for the entire network may be suboptimal for some individual ‘agents’, and so the equilibrium is fragile.
- To solve this problem,
  - temporal randomization can be applied (learn by turns): Agents learn only in certain periods of time. Idea: the best for me, it is the best for the others (not always true)
  - sharing information, and reaching consensus (federated learning)



# Multi-armed Bandits (MABs) - To know more

Baseline:

- Katehakis, M. N., & Veinott Jr, A. F. (1987). The multi-armed bandit problem: decomposition and computation. *Mathematics of Operations Research*, 12(2), 262-268.
- Gittins, J., Glazebrook, K., & Weber, R. (2011). Multi-armed bandit allocation indices. John Wiley & Sons.
- Auer, P., Cesa-Bianchi, N., & Fischer, P. (2002). Finite-time analysis of the multiarmed bandit problem. *Machine learning*, 47(2-3), 235-256.
- Auer, P., Cesa-Bianchi, N., Freund, Y., & Schapire, R. E. (1995, October). Gambling in a rigged casino: The adversarial multi-armed bandit problem. In *Foundations of Computer Science, 1995. Proceedings., 36th Annual Symposium on* (pp. 322-331). IEEE.

Overviews:

- Bubeck, S., & Cesa-Bianchi, N. (2012). Regret analysis of stochastic and nonstochastic multi-armed bandit problems. *Foundations and Trends® in Machine Learning*, 5(1), 1-122.
- Vermorel, J., & Mohri, M. (2005, October). Multi-armed bandit algorithms and empirical evaluation. In *European conference on machine learning* (pp. 437-448). Springer, Berlin, Heidelberg.

# MAB Examples

- Channel selection

- We introduce 3 basic MAB algorithms
- S. Barrachina-Muñoz, et al.. "[Multi-armed bandits for spectrum allocation in multi-agent channel bonding WLANs.](#)" IEEE Access 9 (2021): 133472-133490.

- AP selection in multi-AP networks

- A good lesson from multi-agent environments
- M. Carrascosa, et al. "[Multi-armed bandits for decentralized AP selection in enterprise WLANs.](#)" Computer Communications 159 (2020): 108-123.

- Reinforced-lib – universal RL library

- Analysis of MABs for rate selection:  $\epsilon$ -greedy, UCB, TS, EXP3, Softmax

## Is the research community using MABs?

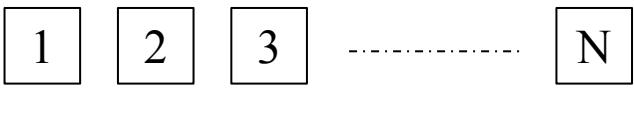
- Check our survey! Many papers using MABs.
- Some recent ones (Google Scholar)

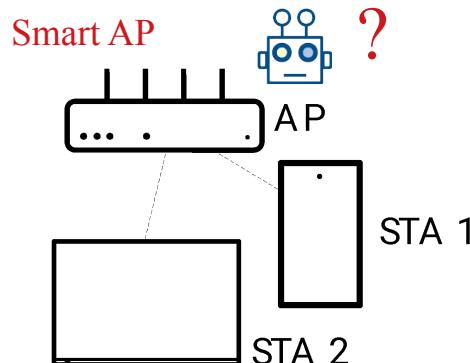
The screenshot shows a Google Scholar search results page. The search query is "Multi armed bandits Wi-Fi 802.11". The results are filtered to show "About 71 results (0.08 sec)". The results are listed in descending order of relevance. Each result includes a title, author(s), and a snippet of the abstract. There are also "Save" and "Cite" buttons for each result.

- Rate Adaptation with Correlated Multi-Armed Bandits in 802.11 Systems**  
Y Tong, J Fan, X Cai, Y Chen - 2023 IEEE/CIC International ..., 2023 - ieexplore.ieee.org  
... adaptation problem as a **multi-armed bandit** (MAB) problem ... , we build up an indoor **802.11n** test bed. The proposed rate ... essential mechanism in **802.11** or **Wi-Fi** systems that adapts ...  
☆ Save ☆ Cite
- Meta-Bandit: Spatial Reuse Adaptation via Meta-Learning in Distributed Wi-Fi 802.11 ax**  
PE Iturria-Rivera, M Chenier, B Herscovici... - IEEE Networking ..., 2023 - ieexplore.ieee.org  
... on meta-learning and **multi-arm bandits**. Simulation results show ... and contextual **multi-armed bandits** in the **802.11ax SR** ... scheme, each Contextual **MultiArmed Bandit** (CMAB) agent ...  
☆ Save ☆ Cite Related articles
- [HTML] Mitigating starvation in dense WLANs: A multi-armed Bandit solution**  
A Bardou, T Begin, A Busson - Ad Hoc Networks, 2023 - Elsevier  
... With the recent **802.11ax** amendment to the IEEE standard commercialized as **Wi-Fi 6**, WLANs ... To overcome these difficulties, we frame this problem as a MAB (**Multi-Armed Bandit**) ...  
☆ Save ☆ Cite Cited by 2 Related articles All 6 versions
- [HTML] A Multiarmed Bandit Approach for LTE-U/Wi-Fi Coexistence in a Multicell Scenario**  
I Diógenes do Rego, JM de Castro Neto, SFG Neto... - Sensors, 2023 - mdpi.com  
... throughput for both **Wi-Fi** and Long Term Evolution (LTE). Our new solution applies an **Multi-Armed Bandit** (MAB) approach to provide a coexisting framework between **Wi-Fi** and LTE-U ...  
☆ Save ☆ Cite All 9 versions
- [HTML] WiGig access point selection using non-contextual and contextual multi-armed bandit in indoor environment**  
EM Mohamed - Journal of Ambient Intelligence and Humanized ..., 2023 - Springer  
... office environment, where a **multi-band** WiGig APs containing 2.4/5 GHz **Wi-Fi** and 60 GHz ... by IEEE **802.11ad**, where  $\mathcal{V}(T), \mathcal{B}(T)$  can be expressed as (IEEE **802.11ad** Standard 2012); ...  
☆ Save ☆ Cite Cited by 5 Related articles All 2 versions
- [HTML] Use of Logarithmic Rates in Multi-Armed Bandit-Based Transmission Rate Control Embracing Frame Aggregations in Wireless Networks**  
S Cho - Applied Sciences, 2023 - mdpi.com  
... **802.11g** and **802.11 ... 802.11g** standard in both of the stationary and non-stationary scenarios. In Section 5, we evaluate the performance of the proposed algorithms with the IEEE **802.11** ...  
☆ Save ☆ Cite All 3 versions

Since 2019: About 457 results (0.07 sec)

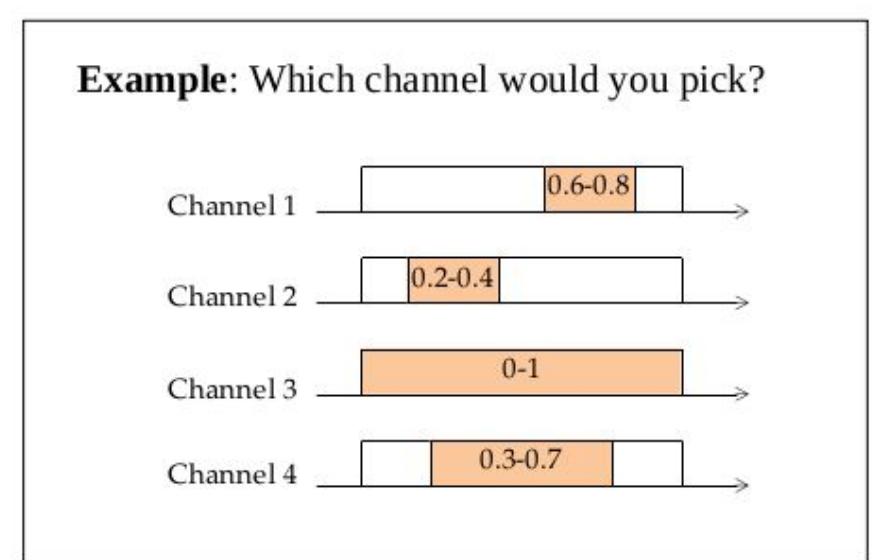
# Example: Channel Selection (MABs)

channels      $\rho(i)$  = Occupancy of channel  $i$  [0,1]  
(measured every 1 second)



Reward using channel  $i$ :  $1 - \rho(i)$

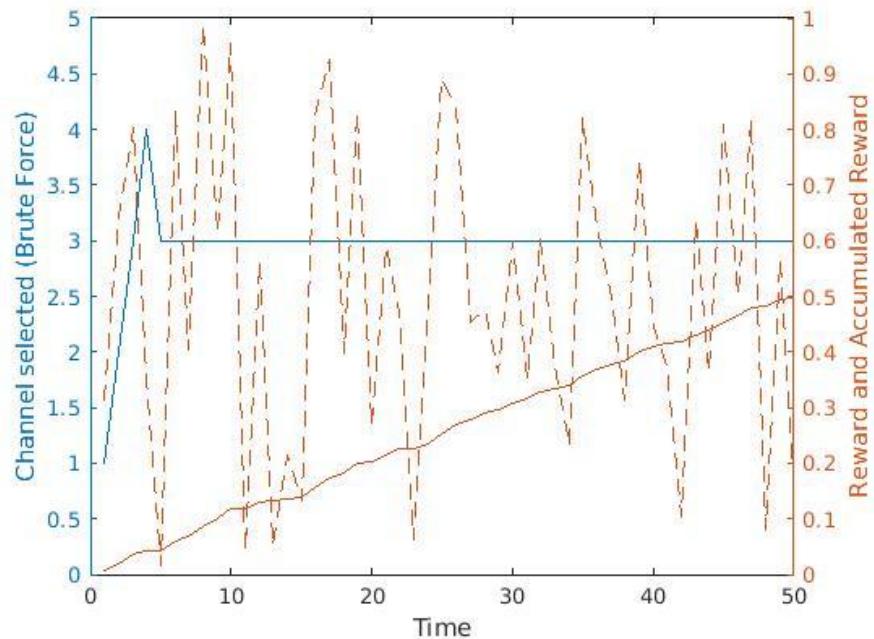
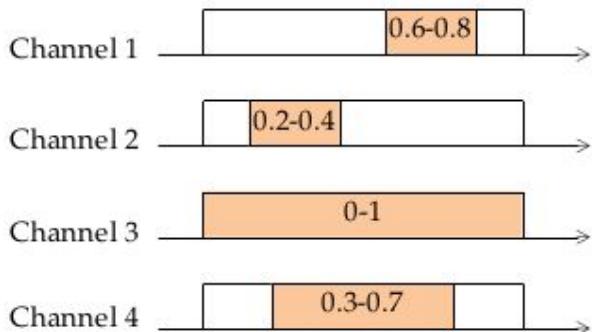
*Only the channel in use can be measured*



# Sequential Exploration (Brute Force)

- We check sequentially all channels, and select the 'best' one for the rest of the time.

**Example:** Which channel would you pick?



# $\varepsilon$ -greedy

- Direct implementation of the Exploitation / Exploration trade-off
  - Explore with probability  $\varepsilon$
  - Exploit with probability  $1-\varepsilon$
- Performance of  $\varepsilon$ -greedy can be improved by:  
*[Not a general rule, depends on the problem]*
  - Updating the value of  $\varepsilon$  as the system is learning
  - Adjusting how the average reward for every action is selected (i.e., weighted average)

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**Algorithm 1:** Multi-Armed Bandits ( $\varepsilon$ -greedy)

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**Input:**  $\mathcal{A}$ : set of possible actions  $\{a_1, \dots, a_K\}$

**1 Initialize:**  $t = 1, \varepsilon_t = \varepsilon_0, r_{k,0} = 0, \forall a_k \in \mathcal{A}$

**2 while** *active* **do**

**3 Select**  $a_k \begin{cases} \text{argmax}_{k=1, \dots, K} r_{k,t-1}, & \text{with prob. } 1 - \varepsilon \\ k \sim \mathcal{U}(1, K), & \text{otherwise} \end{cases}$

**4 Observe** the channel occupancy  $\rho_{k,t}$

**5 Compute** the reward  $r_{k,t} = (1 - \alpha)r_{k,t-1} + \alpha(1 - \rho_{k,t})$

**6**  $\varepsilon_t \leftarrow \varepsilon_0 / \sqrt{t}$

**7**  $t \leftarrow t + 1$

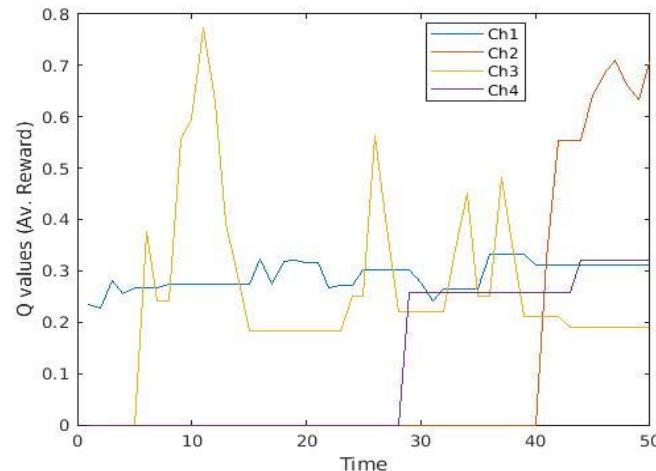
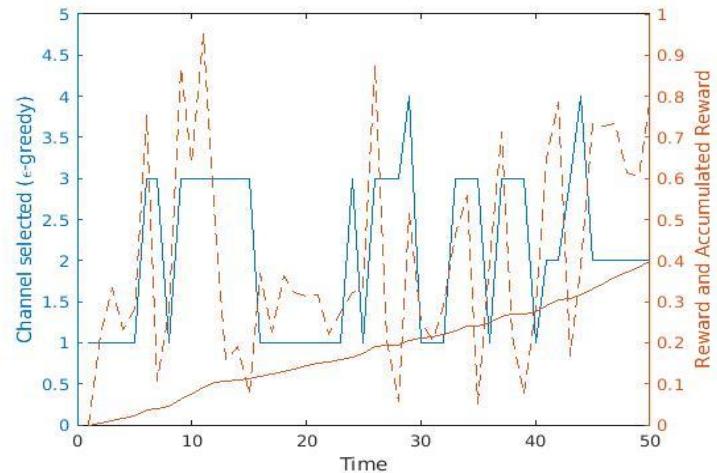
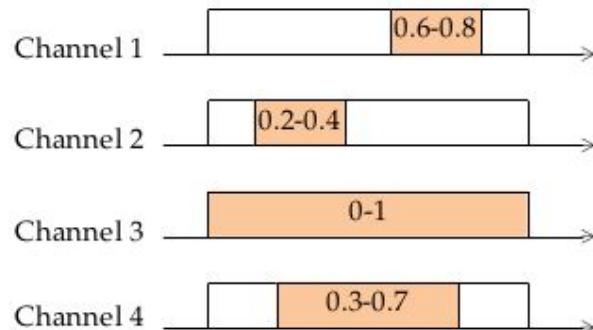
**8 end**

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# $\varepsilon$ -greedy

- N=4 channels
- 1 episode, 50 iterations
- $\alpha=0.5$ ;  $\varepsilon_0=0.2$  (constant)

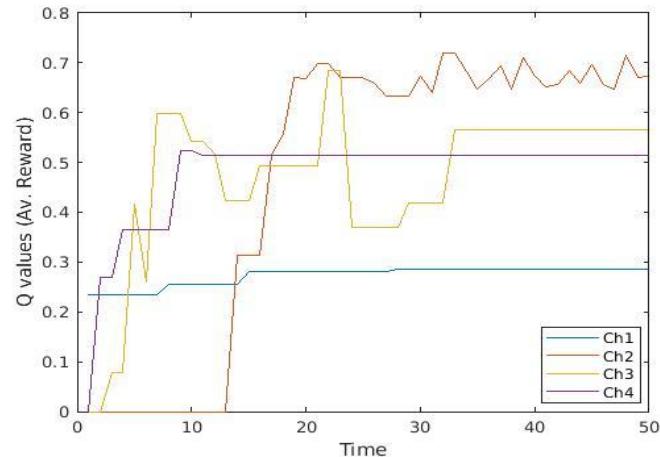
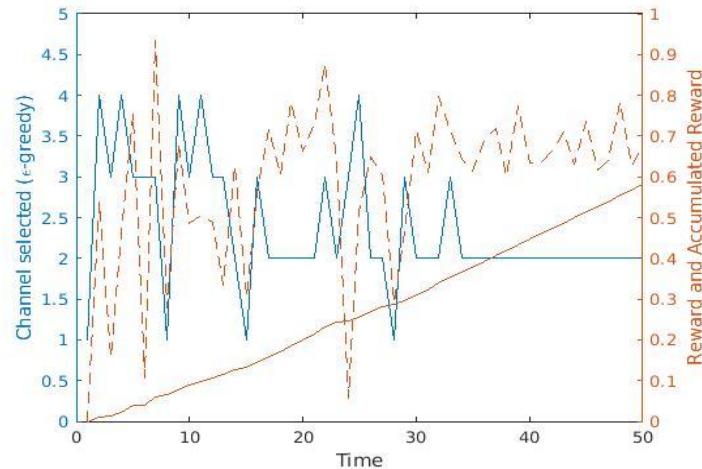
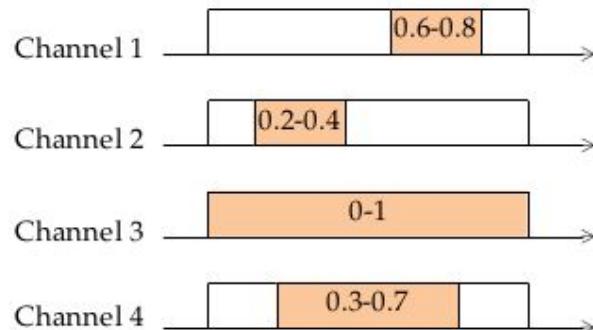
**Example:** Which channel would you pick?



# $\epsilon$ -greedy

- N=4 channels
- 1 episode, 50 iterations
- $\alpha=0.5$ ;  $\epsilon_0=0.8$  (reduces 0.02 per step)

**Example:** Which channel would you pick?



# Thompson sampling

- For each action, we estimate the av. reward, and adjust the variance proportionally to the number of times we played that action in the past:
  - the variance ‘captures’ how much confident we are on the future reward we will obtain when playing a certain arm.*
- TS includes the ‘consolidated’ knowledge of a certain action when deciding to take it or not: i.e., playing arm 1 may give me higher reward, but I have more uncertainty.

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**Algorithm 2:** Multi-Armed Bandits Thompson Sampling
 

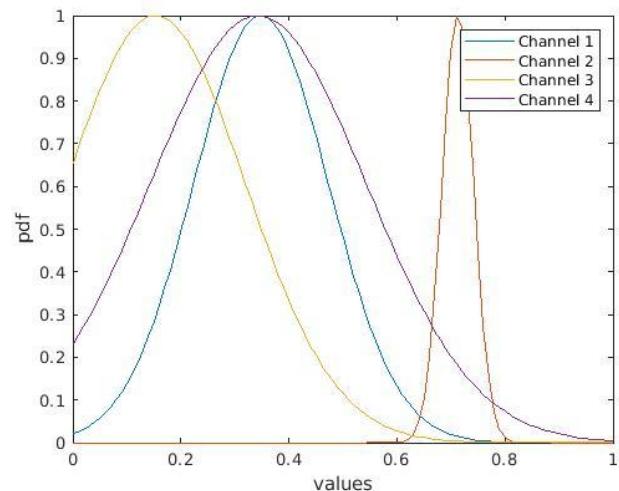
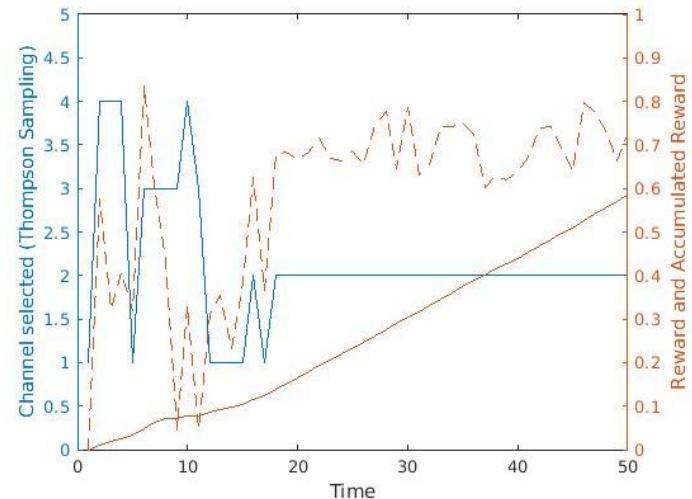
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```

1 Initialize:  $t = 1$ , for each arm  $a_k \in \mathcal{A}$ , set  $r_{k,0} = 0$  and  $n_k = 0$ 
2 while active do
3   For each arm  $a_k \in \mathcal{A}$ , sample  $\theta_k(t)$  from normal distribution  $\mathcal{N}(r_{k,t-1}, \frac{1}{n_k+1})$ 
4   Play arm  $a_k = \operatorname{argmax}_{k=1,\dots,K} \theta_k(t)$ 
5   Observe the channel occupancy  $\rho_{k,t}$ 
6   Compute the reward  $r_{k,t} = (1 - \alpha)r_{k,t-1} + \alpha(1 - \rho_{k,t})$ 
7    $n_k \leftarrow n_k + 1$ 
8    $t \leftarrow t + 1$ 
9 end

```

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# UCB - Upper Confidence Bound

- Brute force + pick the best ‘action’
- Optimistic Function to explore:
  - *if I have not tried an action for a while (as it was not good), perhaps now it has changed*
- The value of ‘c’ depends on the reward range of values, and allows to adjust the exploration

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**Algorithm 3:** Multi-Armed Bandits UCB

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**Input:**  $\mathcal{A}$ : set of possible actions  $\{a_1, \dots, a_K\}$

**1 Initialize:**  $t = 1$ , play each arm  $a_k \in \mathcal{A}$  once

**2 while** active **do**

**3** Draw  $a_k = \operatorname{argmax}_{k=1,\dots,K} \left( r_k + c \sqrt{\frac{2 \ln(t)}{n_k}} \right)$

**4** Observe the channel occupancy  $\rho_{k,t}$

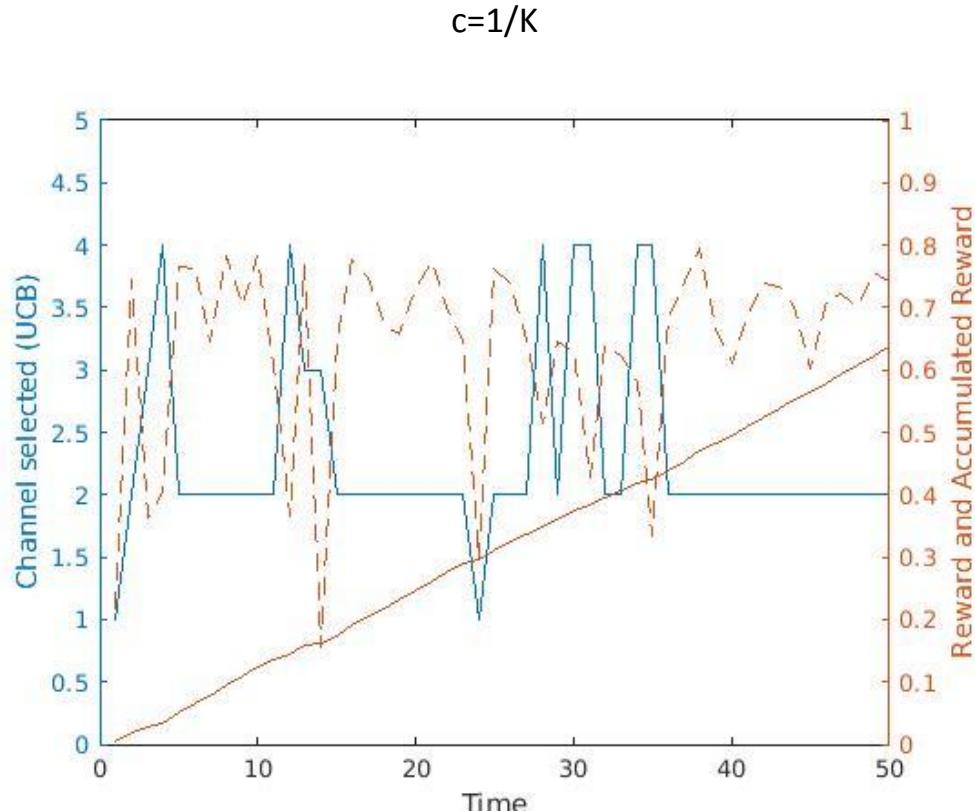
**5** Compute the reward  $r_{k,t} = (1 - \alpha)r_{k,t-1} + \alpha(1 - \rho_{k,t})$

**6**  $n_k \leftarrow n_k + 1$

**7**  $t \leftarrow t + 1$

**8 end**

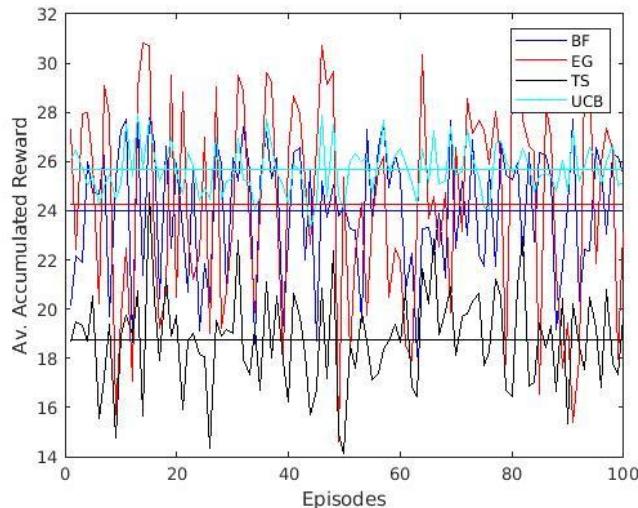
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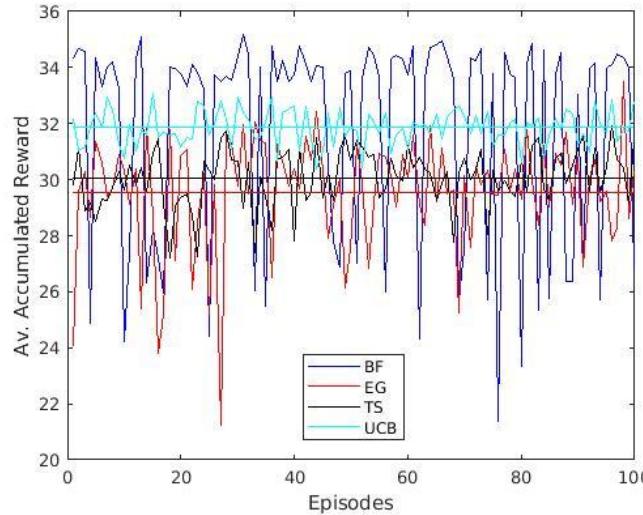
# And the winner is...

- We compare all 4 algorithms
- 100 episodes (each one of 50 iterations)
- (still 50 iterations per episode)

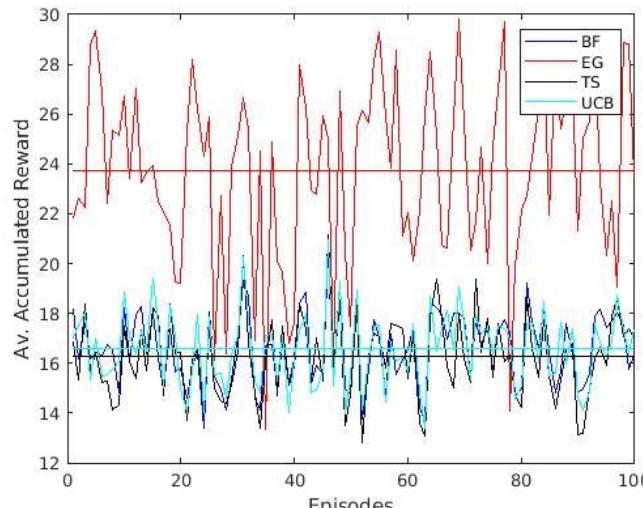
24 channels



4 channels

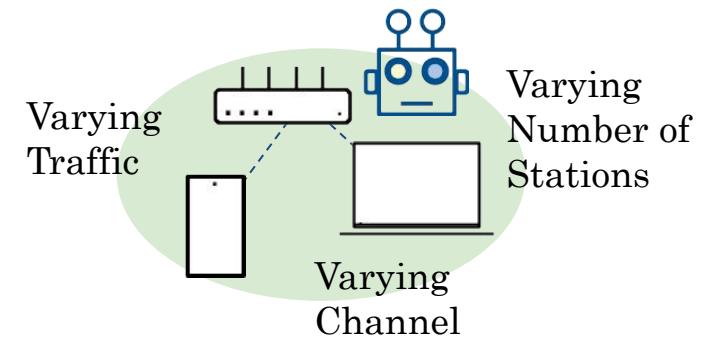


48 channels



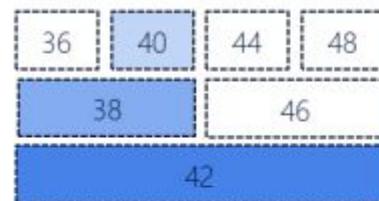
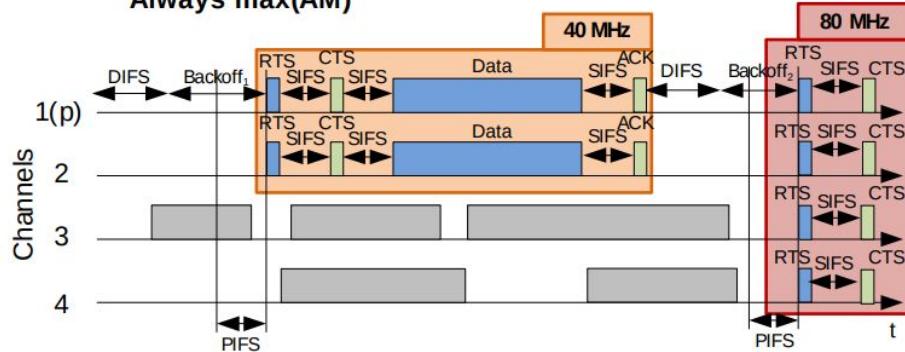
# Is it easy to implement?

- The AP stores the estimated occupancy of every visited channel (including the actual one).
- The AP switches the Wi-Fi network periodically to a new channel following the ML algorithm using 'Channel Switch Announcement' elements in beacons.
- Decision to switch (based on rewards and exploration rate) should take into account not only the channel occupancy but also network state and traffic load.
  - The AP can activate the 'channel search' agent only when current performance is below its needs.
- Inactivity periods can be used to gather statistics from the other channels if the system is stationary.

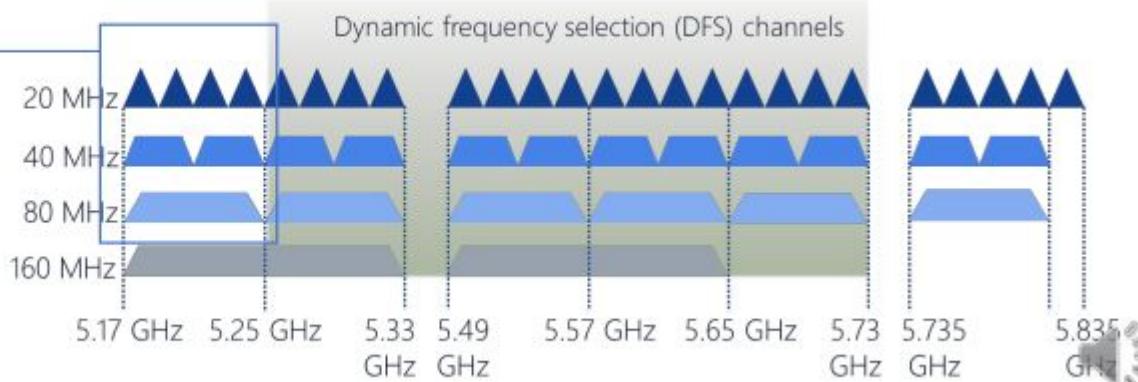


# ML-enhanced Decentralized Spectrum Allocation

Always max(AM)



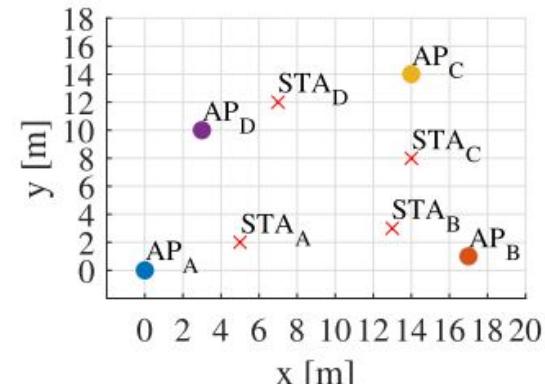
Primary 20 MHz: #40  
Secondary 20 MHz: #36  
Primary 40 MHz: #38  
Secondary 40 MHz: #46



S. Barrachina-Muñoz, et al.. "[Multi-armed bandits for spectrum allocation in multi-agent channel bonding WLANs](#)." IEEE Access 9 (2021): 133472-133490.

# ML-enhanced Decentralized Spectrum Allocation

- “Realistic” Wi-Fi simulation environment ([Komondor](#))
  - Path-loss, SINR, Dyn. Bandwidth Access, etc.
- Traffic load AP (only DL traffic): 50 Mbps
- 80 MHz available (shared by all 4 BSSs)
- W=20, 40 and 80 MHz
- 12 different channels (width, primary) → 12 actions per BSS
  - 4 x 20 MHz channels (1 position for the primary)
  - 2 x 40 MHz channels (2 positions for the primary)
  - 1 x 80 MHz channels (4 positions for the primary)



(a) Location of nodes.

	A	B	C	D
A	-	40	20	80
B	40	-	80	40
C	20	80	-	80
D	80	40	80	-

(b) Interference matrix.

*The goal is to ‘learn’ a good channel allocation as fast as possible*

# ML-enhanced Decentralized Spectrum Allocation

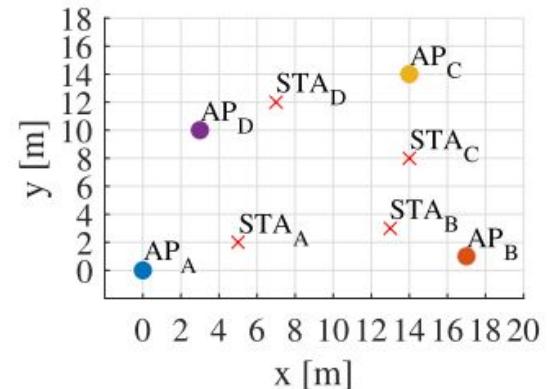
- Multi-armed Bandits (expfirst, e-greedy, TS, ...)
- Available actions correspond to the set of available channels
  - 12 actions
- Rewards are computed taking into account the actual throughput during the simulation (in intervals of 5 s)

$$R(\xi) = \xi \quad \xi_{w,t} = \frac{\Gamma_{w,t}}{\ell_{w,t}}$$

- 50 Mbps constant load (in average, Poisson traffic) per BSS
- Channel switching time not considered (few ms)

Practical considerations:

- Easy to implement on top of current 802.11 devices
- Channel switching overheads need to be considered



	A	B	C	D
A	-	40	20	80
B	40	-	80	40
C	20	80	-	80
D	80	40	80	-

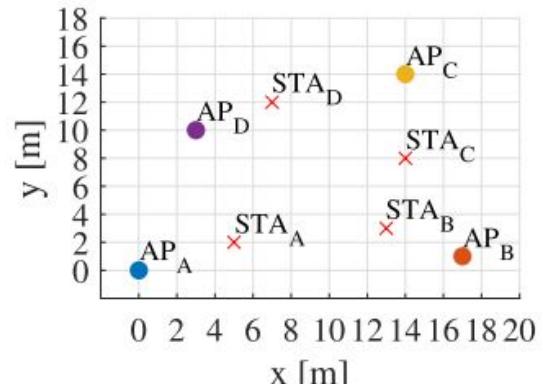
(b) Interference matrix.

# ML-enhanced Decentralized Spectrum Allocation

- expfirst:
  - sequential exploration + actions sorted by reward (and stored)
  - action change when current av. reward decreases below others
- e-greedy, TS, UCB, EXP3

The data set:

<https://zenodo.org/record/4265898#.Y5nS3NLMJ8I>

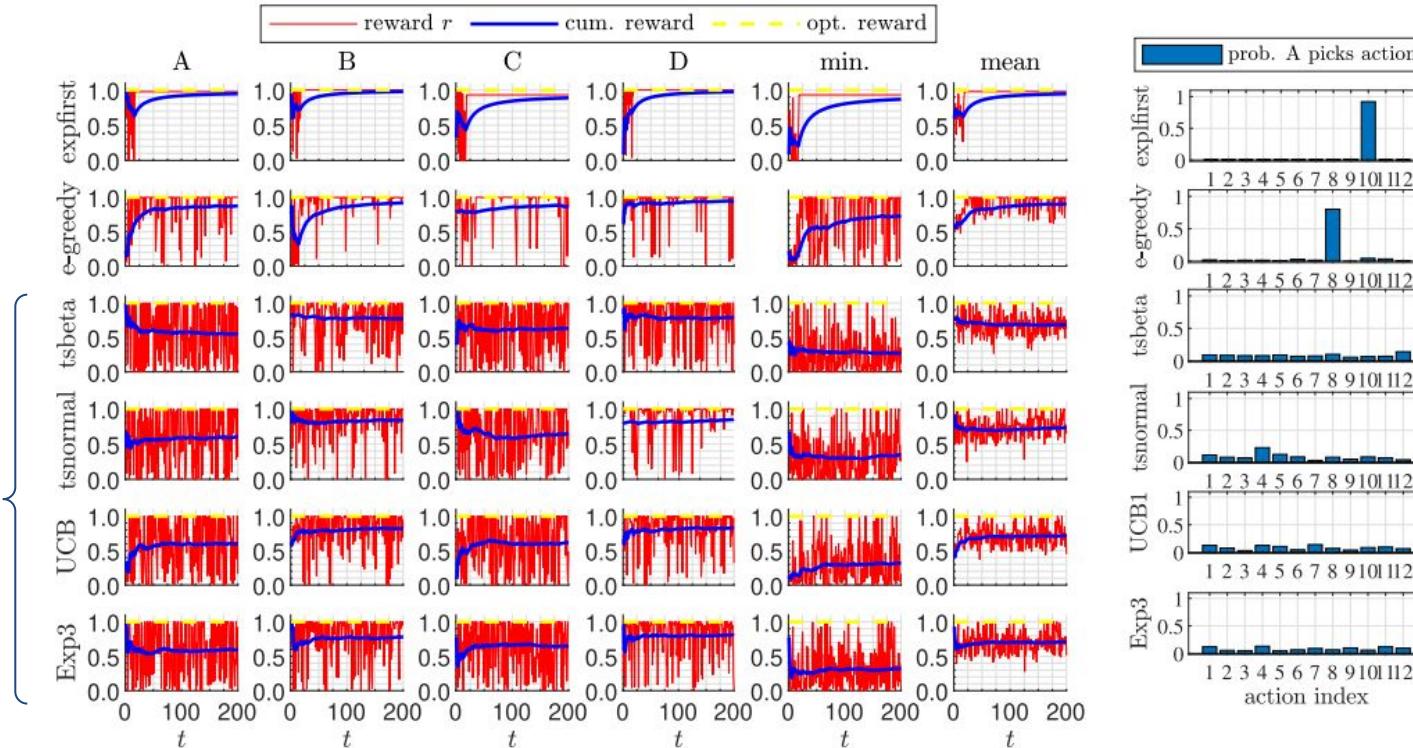


	A	B	C	D
A	-	40	20	80
B	40	-	80	40
C	20	80	-	80
D	80	40	80	-

(b) Interference matrix.

# ML-enhanced Decentralized Spectrum Allocation

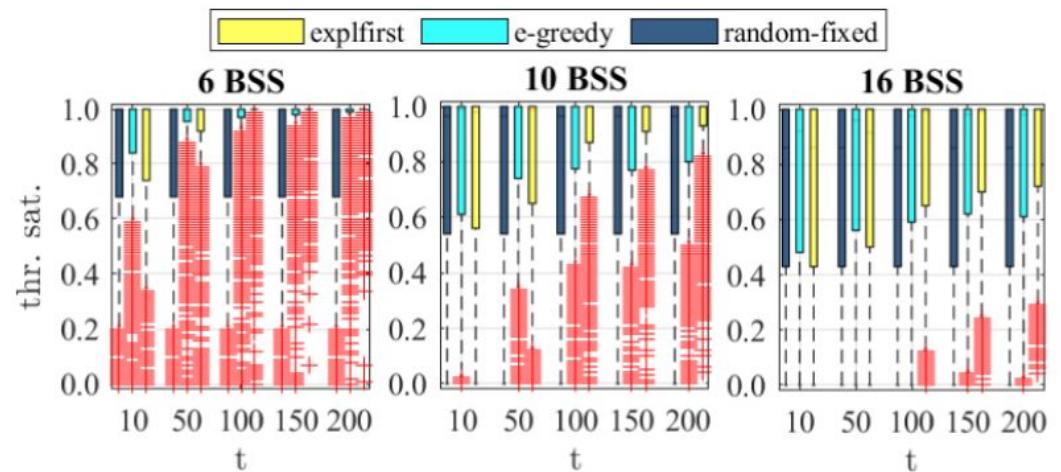
Unstable!  
Why?



Only the simplest MAB algorithms perform well → they are able to find an acceptable equilibrium

# ML-enhanced Decentralized Channel Selection

- Large deployments:
  - 20x20 m<sup>2</sup>
  - 6, 10 and 16 BSSs
- Random per BSS traffic loads: 50, 100, 150 Mbps
- W = 20, 40, 80, 160 MHz
- 160 MHz available spectrum
  - 32 combinations of channels



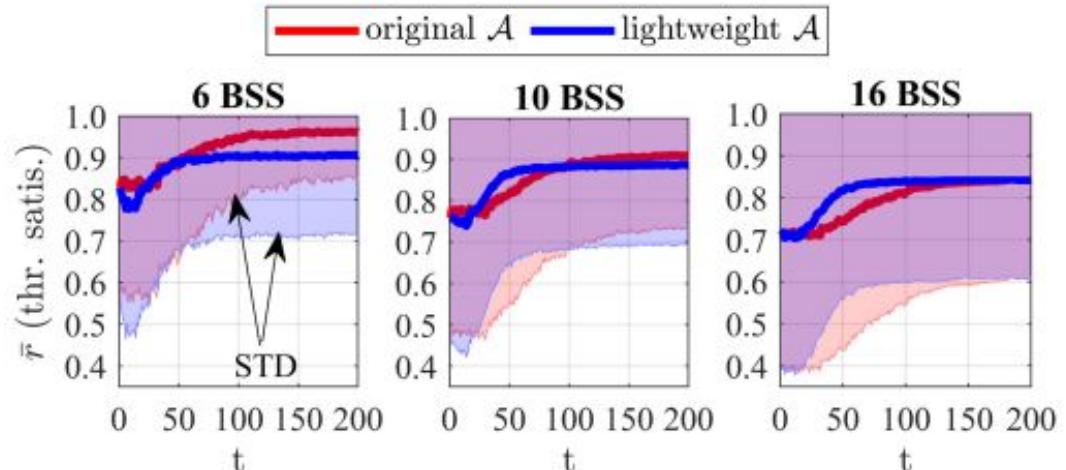
*Both exploration-first and e-greedy can learn even in high-density deployments, outperforming by far static configurations. Besides, while exploration-first performs worse than e-greedy at the early stages of the simulation, it reaches much better performance as the simulation progresses.*

# Lightweighting The Action Space

- Is it possible to increase the learning convergence speed and reach good performance levels sooner?
- To that aim, we propose lightening the action space of each agent by reducing the possible values the maximum bandwidth attribute may take: from  $b \in \{1, 2, 4, 8\}$  to  $b \in \{1, 8\}$ , i.e., to allow only single-channel ( $b = 1$ ) or to remove any bandwidth restriction ( $b = 8$ ).
- Reduced action space (16 actions instead of 32)

So, is there any rule of thumb for reducing action spaces?

Adding new actions progressively?



# Different Rewards

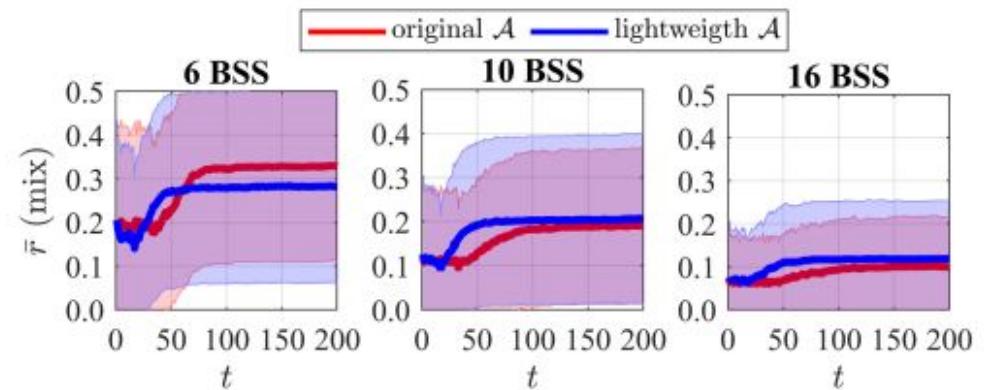
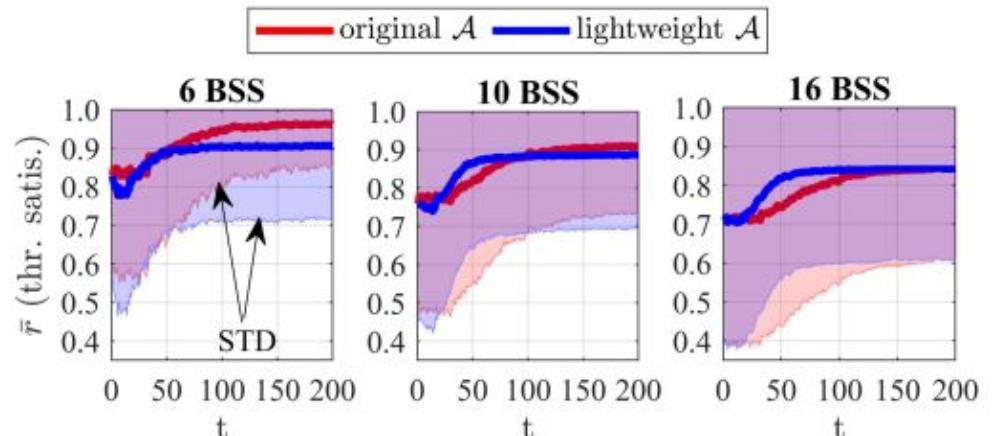
- Only throughput satisfaction:

$$R(\xi) = \xi \quad \xi_{w,t} = \frac{\Gamma_{w,t}}{\ell_{w,t}}$$

- Throughput and delay:

- Idea: *Given you get the required throughput, minimizing the delay means you are better using the available resources → more available resources for the other BSSs.*

$$R(\xi, \delta) = \xi \cdot \delta \quad \delta_{w,t} = \frac{d^*}{d_{w,t}}$$



# MAB Examples

- Channel selection
  - We introduce 3 basic MAB algorithms
  - S. Barrachina-Muñoz, et al.. "[Multi-armed bandits for spectrum allocation in multi-agent channel bonding WLANs](#)." IEEE Access 9 (2021): 133472-133490
- AP selection in multi-AP networks
  - A good lesson from multi-agent environments
  - M. Carrascosa, et al. "[Multi-armed bandits for decentralized AP selection in enterprise WLANs](#)." Computer Communications 159 (2020): 108-123.
- Reinforced-lib – universal RL library
  - Analysis of MABs for rate selection:  $\epsilon$ -greedy, UCB, TS, EXP3, Softmax

## Is the research community using MABs?

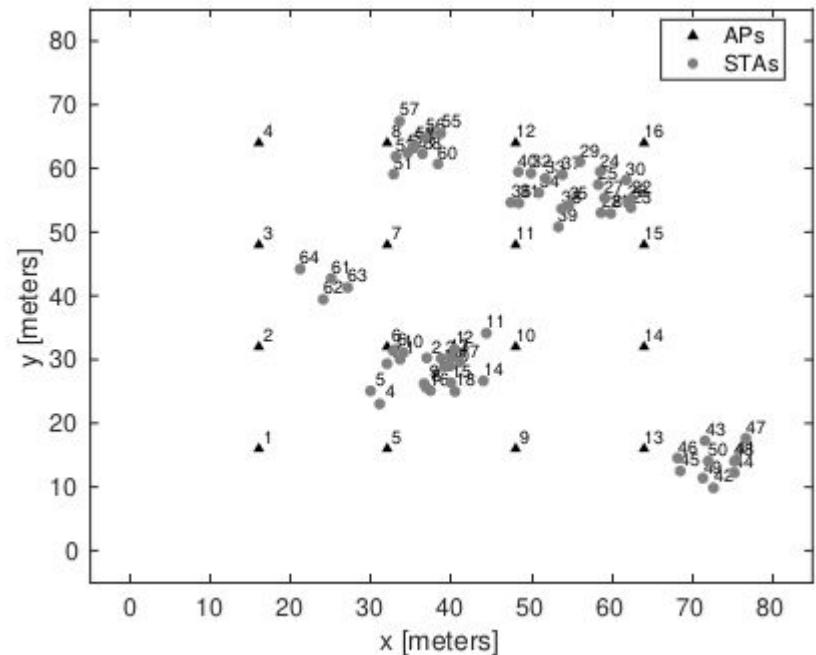
- Check our survey! Many papers using MABs.
- Some recent ones (Google Scholar)

The screenshot shows a Google Scholar search results page. The search query "Multi armed bandits Wi-Fi 802.11" is entered in the search bar. The results section shows 71 articles found in 0.08 seconds. The first result is a paper titled "Rate Adaptation with Correlated Multi-Armed Bandits in 802.11 Systems" by Y Tong, J Fan, X Cai, Y Chen, published in 2023. The second result is "Meta-Bandit: Spatial Reuse Adaptation via Meta-Learning in Distributed Wi-Fi 802.11 ax" by PE Iturria-Rivera, M Chenier, B Herscovici, published in 2023. The third result is "Mitigating starvation in dense WLANs: A multi-armed Bandit solution" by A Bardou, T Beguin, A Busson, published in 2023. The fourth result is "A Multiarmed Bandit Approach for LTE-U/Wi-Fi Coexistence in a Multicell Scenario" by I Diogenes do Rego, JM de Castro Neto, SFG Neto, published in 2023. The fifth result is "WiGig access point selection using non-contextual and contextual multi-armed bandit in indoor environment" by EM Mohamed, published in 2023. The sixth result is "Use of Logarithmic Rates in Multi-Armed Bandit-Based Transmission Rate Control Embracing Frame Aggregations in Wireless Networks" by S Cho, published in 2023.

Since 2019: About 457 results (0.07 sec)

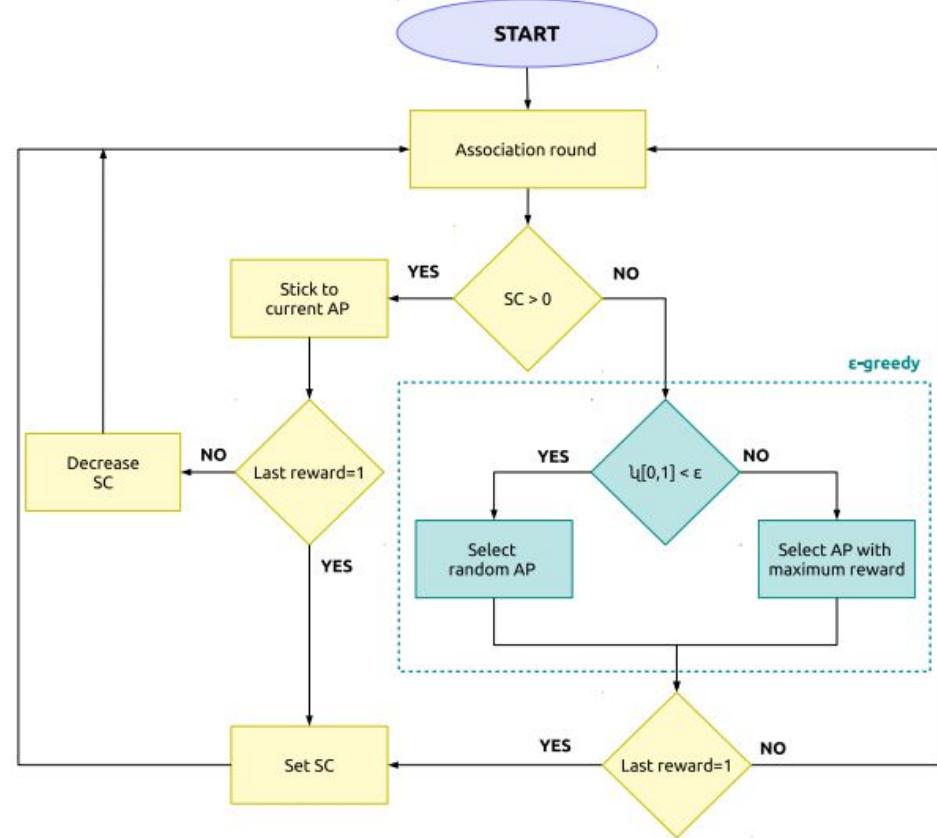
# ML-enhanced Decentralized AP selection

- Default AP selection is implemented considering only RSSI values
  - A station associates to the ‘closest’ AP
- This may cause that some APs are overloaded, while others are almost empty
- **ML solution:** STAs use an ML agent to find an AP that is good enough to satisfy their traffic requirements.
- The ML agent implements a MAB:
  - Actions: APs in sight
  - Reward: ratio Throughput/Load

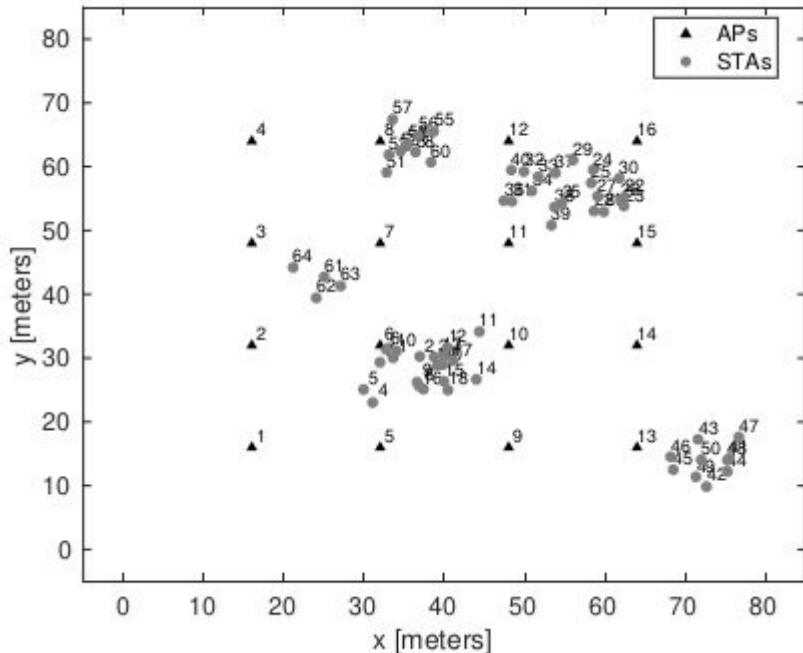


# ML-enhanced Decentralized AP selection

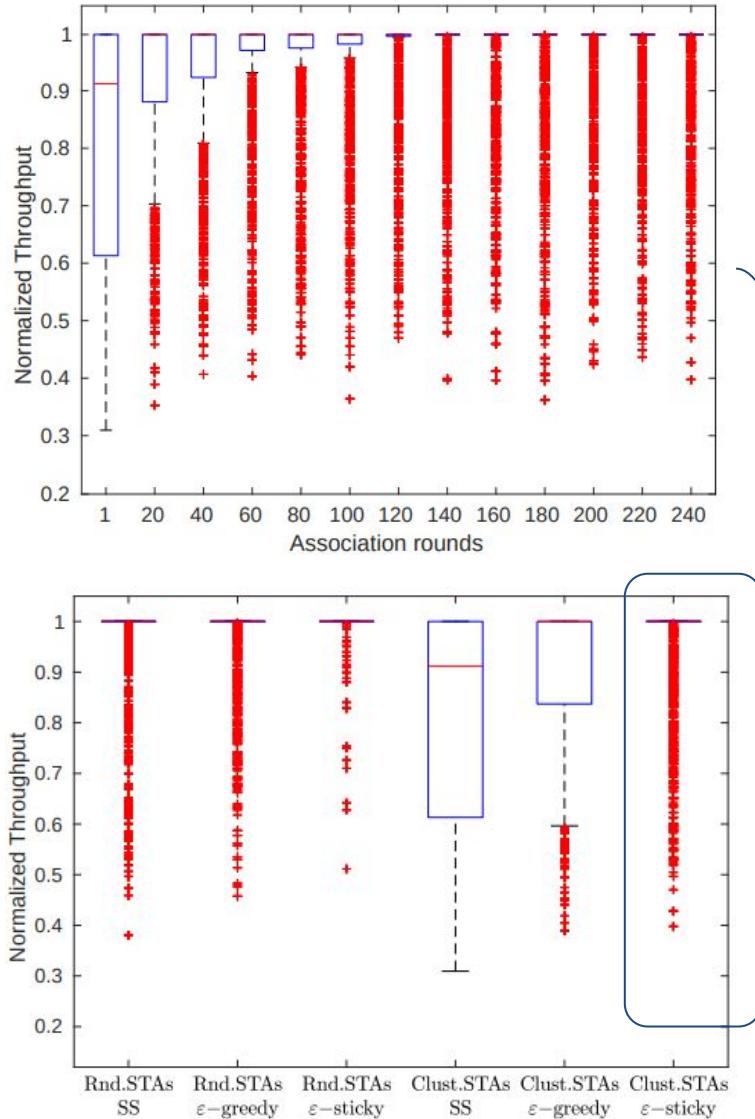
- Default  $\epsilon$ -greedy MAB is enhanced with ‘stickiness’.
- **Stickiness** aims to improve stability by reducing the number of STAs switching APs simultaneously, or in a short time interval
- **Idea:** STAs stick to the last AP that satisfied their requirements for several association rounds before switching



# ML-enhanced Dec. AP sel.



- Non overlapping channel allocation
- 16 APs, 64 STAs
- Load STA: 4 Mbps



# ML-enhanced Dec. AP sel.

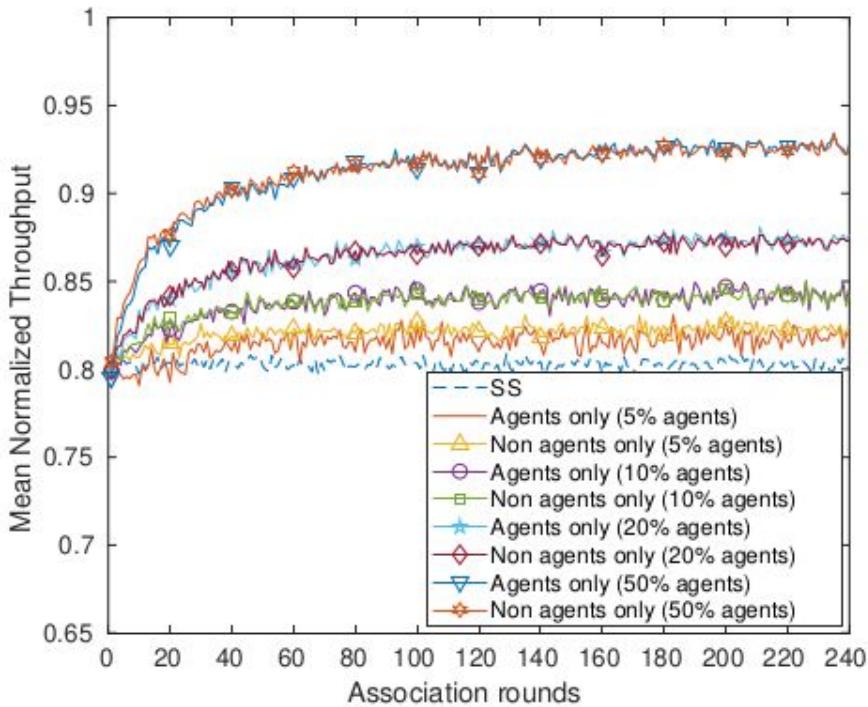


Figure 16: Mean normalized throughput of agent STAs vs. non agent STAs.

## Pros:

- Easy to implement without any major update on 802.11 devices
- All network devices benefit even if they are not ML-enhanced
- Fully decentralized solution
- Reactive, adapts to any environment

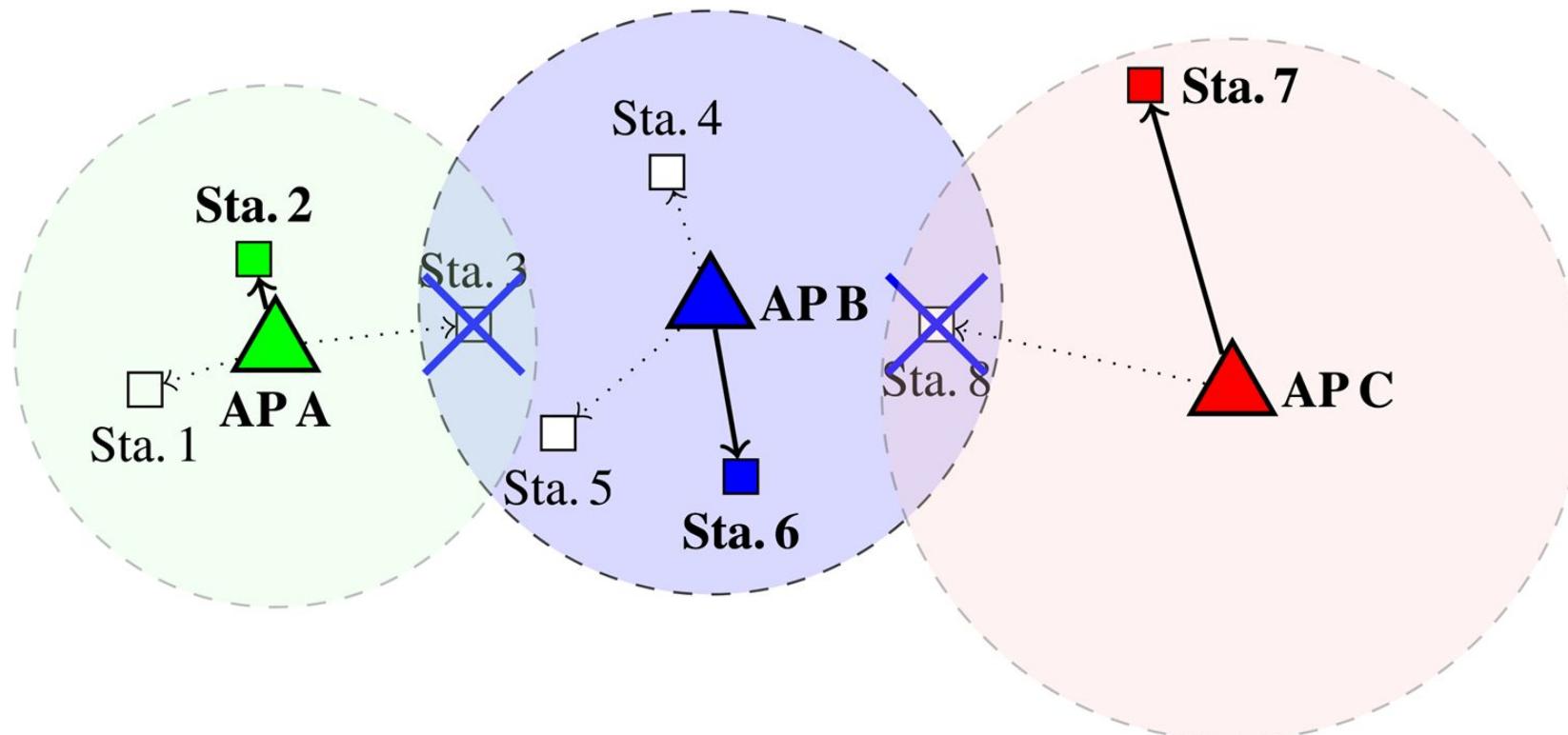
## Cons:

- Learning by interacting with the environment is required, implying periods of 'low performance' due to bad choices
- AP switching overheads

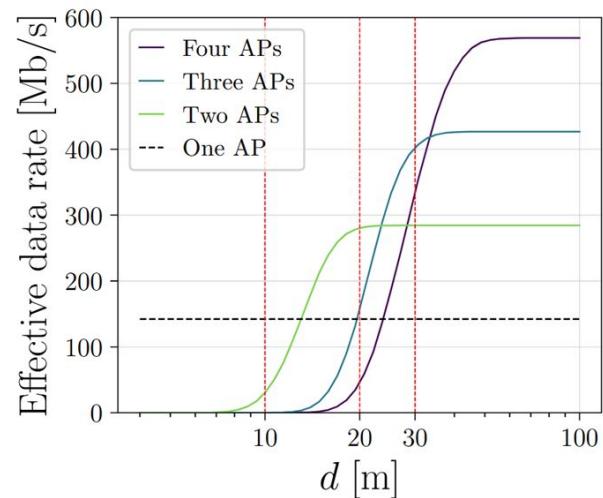
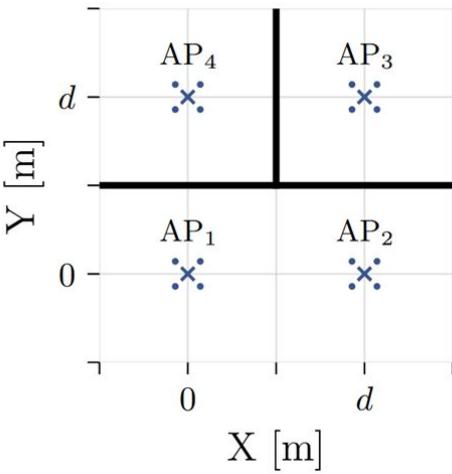
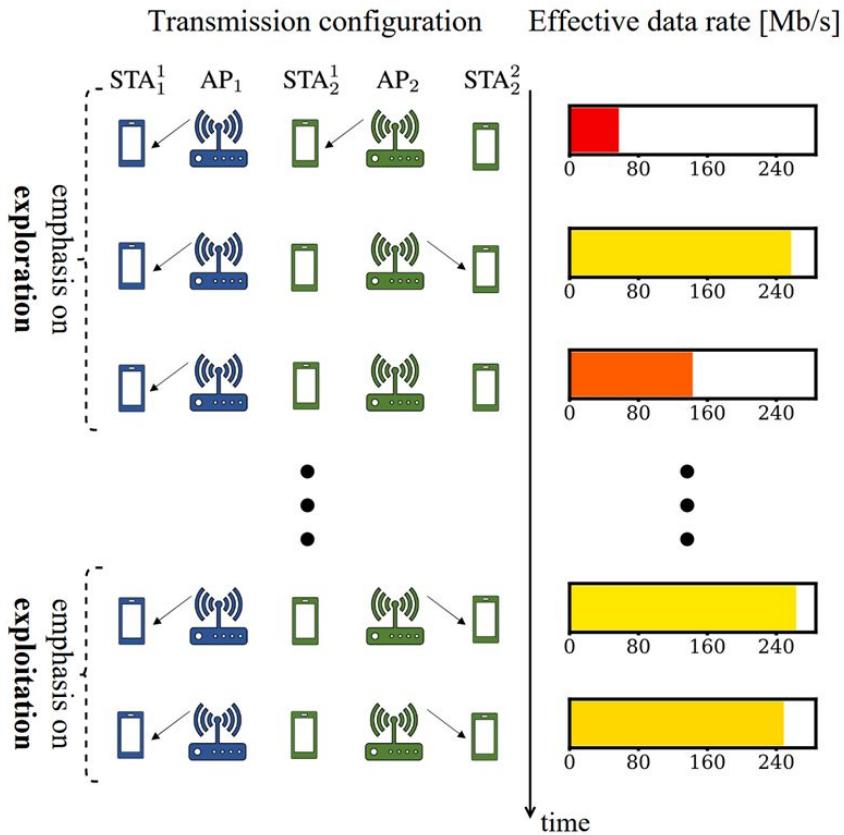
## Practical aspects:

- Temporal window to assess throughput performance

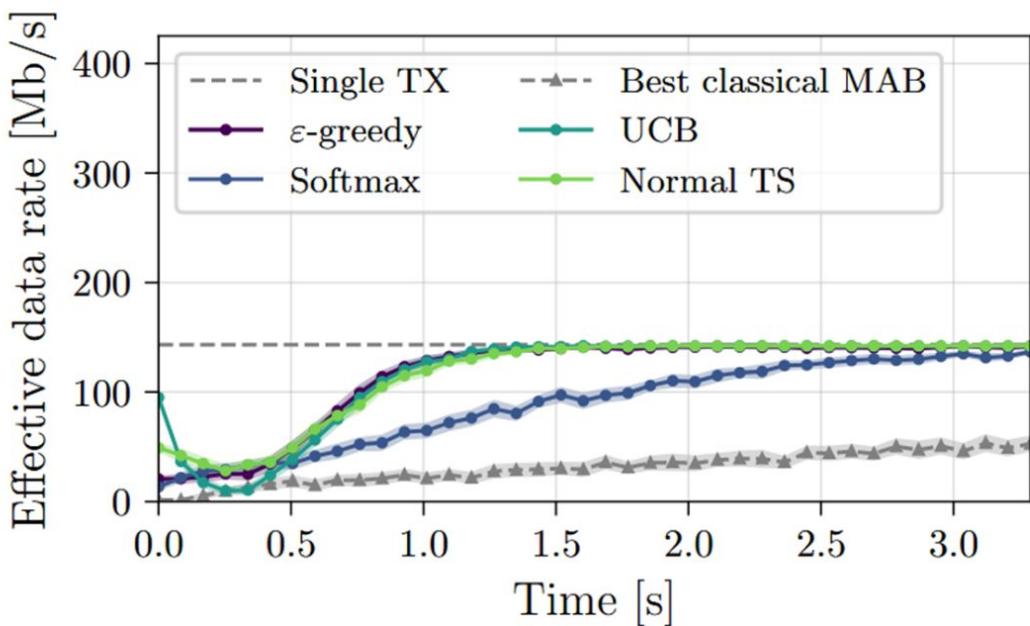
# MAPC – Coordinated Spatial Reuse



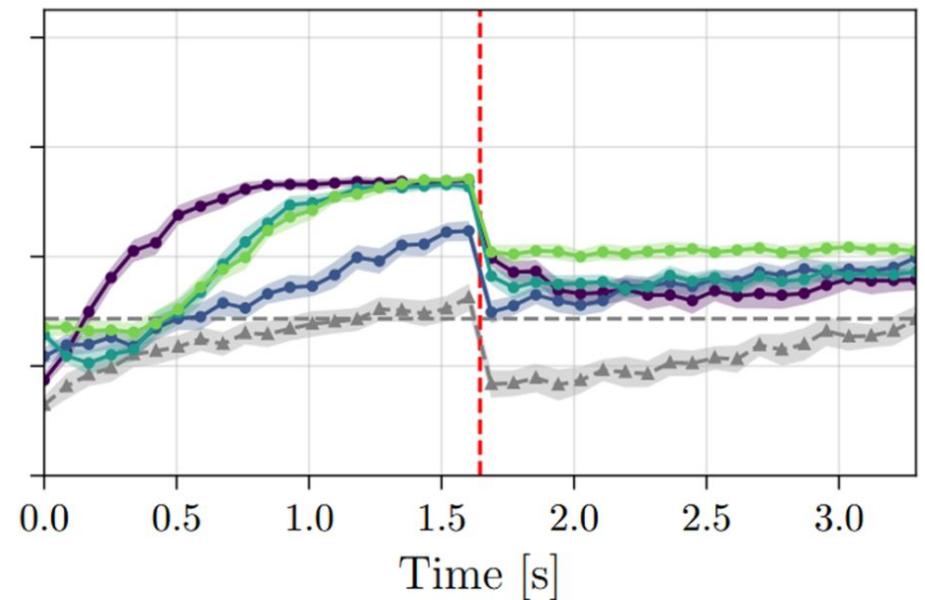
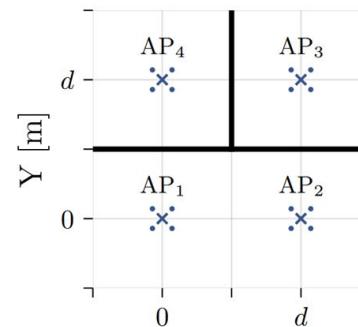
# C-SR + MAB



# C-SR + MAB



(a)  $d = 10 \text{ m}$



(b)  $d = 20 \text{ m}$

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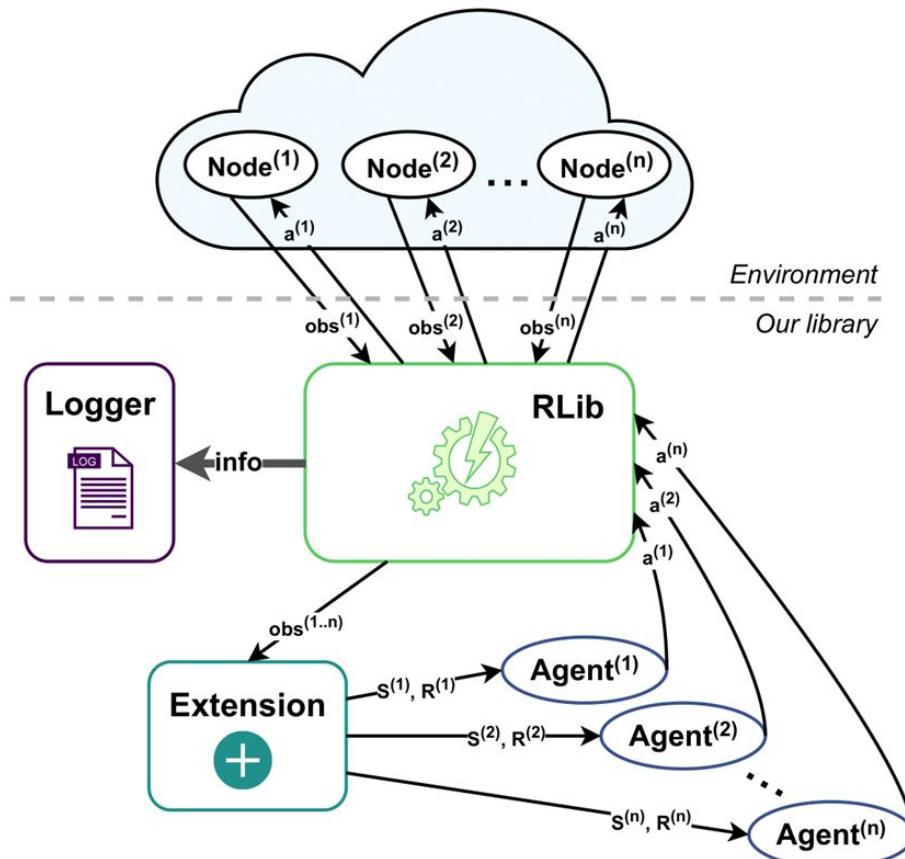
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Since 2019: About 457 results (0.07 sec)

# Reinforced-lib



<https://github.com/m-wojnar/reinforced-lib>

Wojnar, Maksymilian, Szymon Szott, Krzysztof Rusek, and Wojciech Ciezobka.  
"Reinforced-lib: Rapid prototyping of reinforcement learning solutions."  
SoftwareX 26 (2024): 101706.

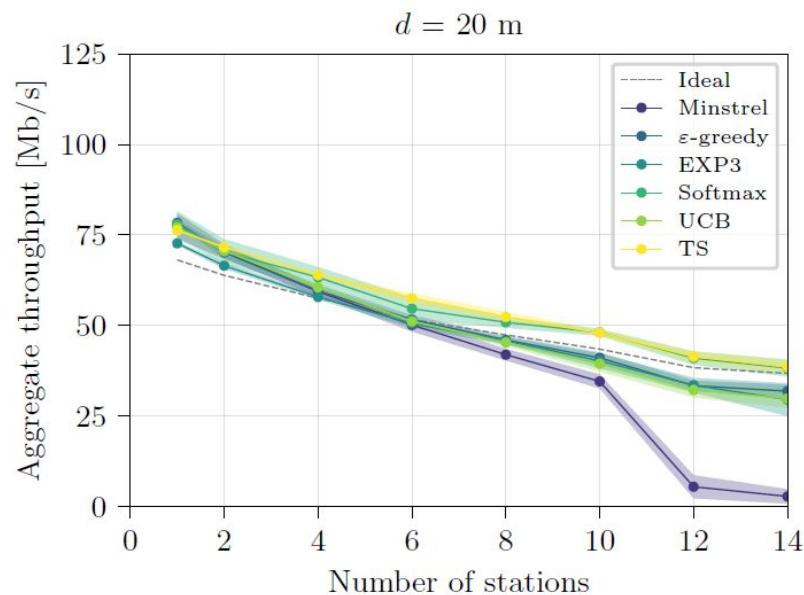
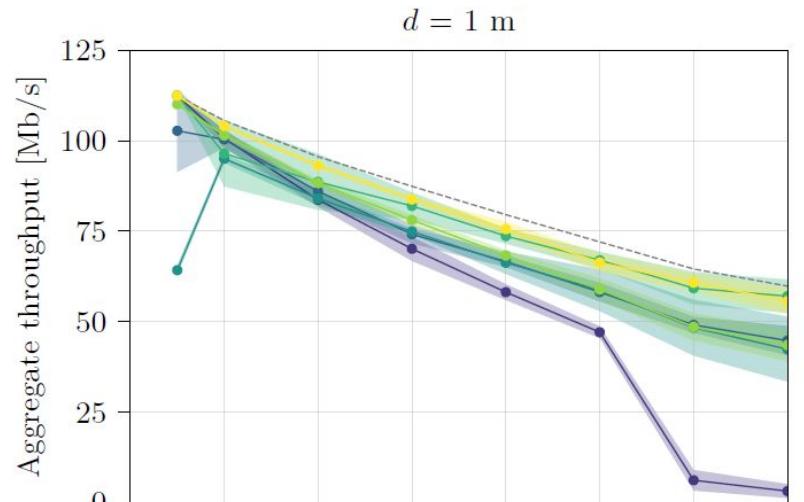
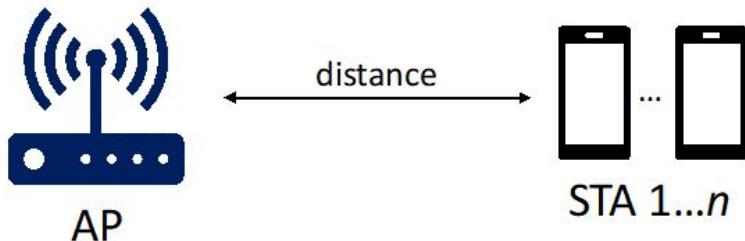
# Reinforced-lib: Features

- Open-source
- Easy-to-use
- Extensive documentation
- Support for simple (MABs) and deep RL
- Export to embedded devices
- Provided examples
  - MAB rate selection
  - DQN CW selection

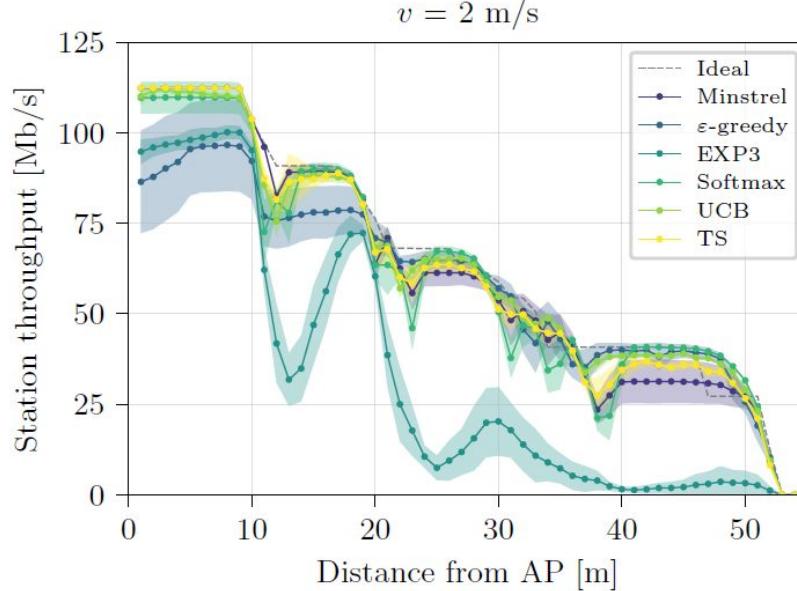
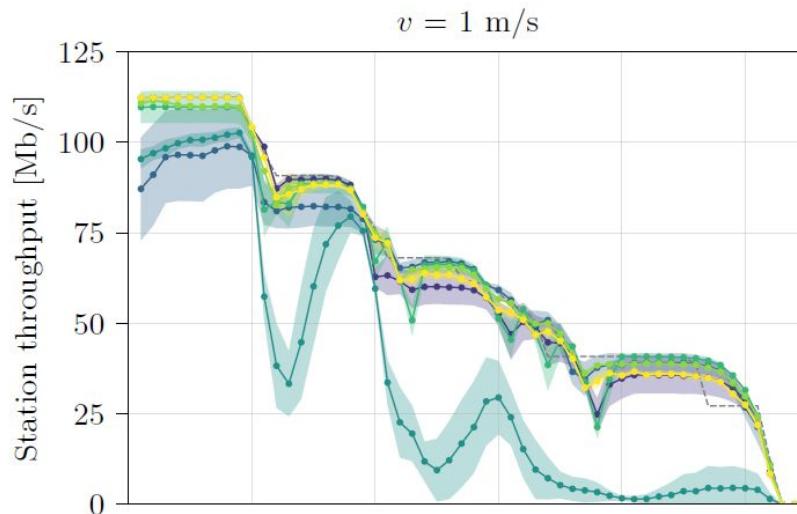
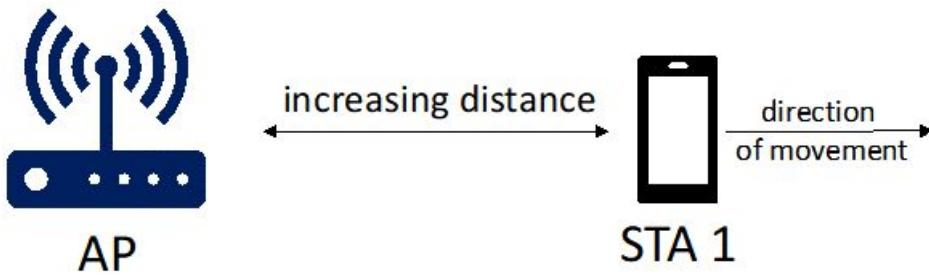
The screenshot shows the project page for 'reinforced-lib 1.0.0'. At the top, there's a search bar with the placeholder 'Search projects' and a magnifying glass icon. To the right are links for 'Help', 'Sponsors', 'Log in', and 'Register'. Below the header, the project name 'reinforced-lib 1.0.0' is displayed in large white text on a blue background. A green button labeled 'Latest version' is visible. To the right of the version number, it says 'Released: Jul 23, 2023'. Underneath the main title, there's a command line interface (CLI) snippet: 'pip install reinforced-lib'. On the left side, there's a sidebar with 'Navigation' sections: 'Project description' (which is currently selected and highlighted in blue), 'Release history', and 'Download files'. Below that is a 'Project links' section with 'Homepage' and 'Download' options. On the right side, the 'Project description' section contains the text: 'Reinforced-lib: Reinforcement learning library'. It also lists project details: 'pypi v1.0.0', 'License MPL 2.0', 'build and test passing', and 'docs passing'. The main content area describes the library as a lightweight Python library for rapid development of RL solutions, mentioning its open-source nature, ease of use, comprehensive documentation, and support for both deep reinforcement learning (DRL) and classic non-neural agents. It also notes its compatibility with JAX and its ability to export trained models to embedded devices.

**pip install reinforced-lib**

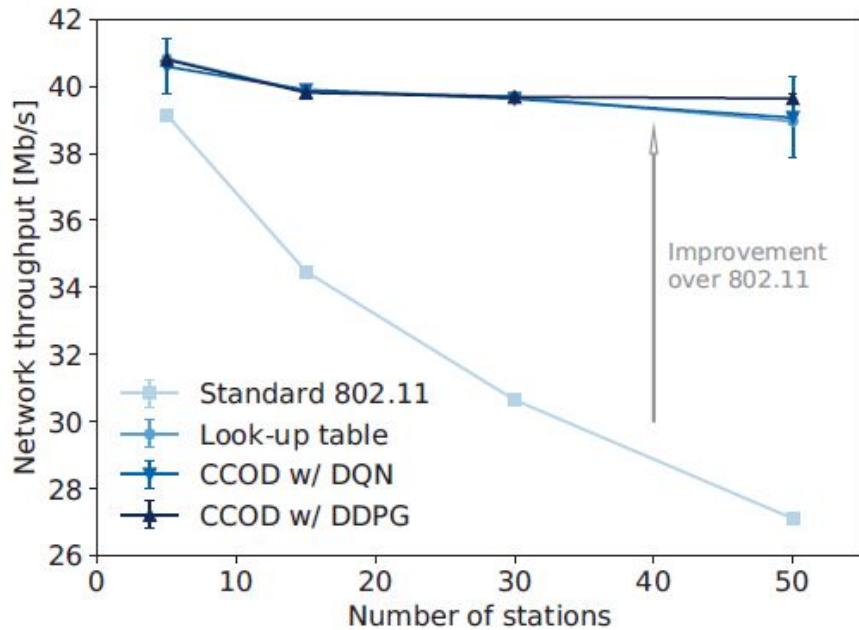
# Reinforced-lib Example: Stationary Scenario



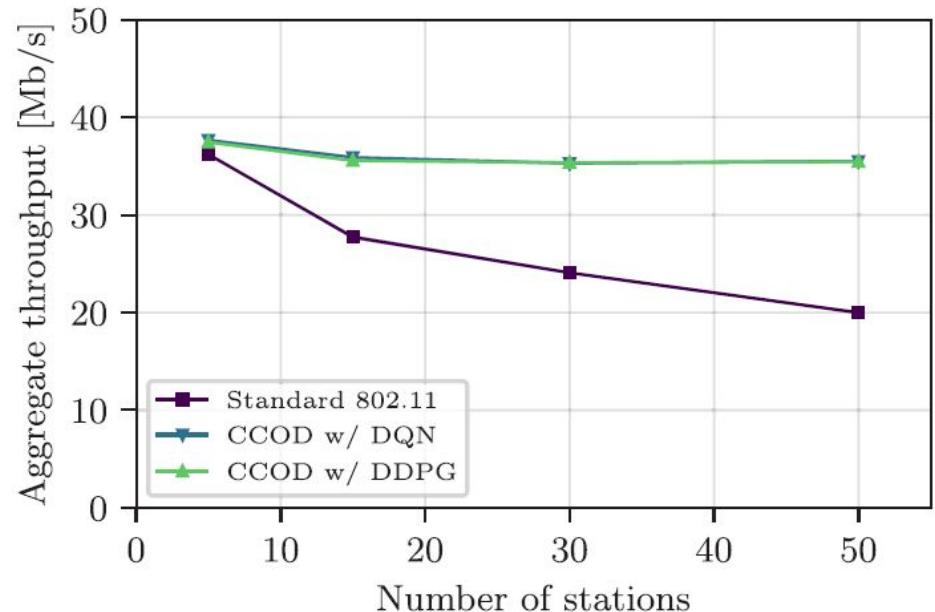
# Reinforced-lib Example: Mobile Scenario



# Repeating Existing Results



Wydmański, Witold, and Szymon Szott. "Contention window optimization in IEEE 802.11 ax networks with deep reinforcement learning." In *2021 IEEE wireless communications and networking conference (WCNC)*, pp. 1-6. IEEE, 2021.



Wojnar, Maksymilian, Szymon Szott, Krzysztof Rusek, and Wojciech Ciezborka. "Reinforced-lib: Rapid prototyping of reinforcement learning solutions." *SoftwareX* 26 (2024): 101706.

# Re-cap

- MABs are simple, but powerful algorithms to make Wi-Fi networks ML-aware
  - They implement the exploration-exploitation trade-off
  - Engineering (parameter tuning) required to suit different problems
  - Convergence / responsiveness should be addressed / improved
- Examples:
  - Channel allocation and AP selection can be enhanced with MABs
  - In dynamic environments, lightweight approaches could be the best ones in terms of the *response delay-performance* tradeoff
  - ML agents operation must contribute to reduce the environment randomness
  - Rate adaptation using MABs can improve traditional rate selection (e.g., Minstrel) algorithms
- Reinforced-lib: a tool for lightweight prototyping of RL solutions

# Overview of tools & resources

- ML frameworks, packages & libraries:
  - Pytorch: <https://pytorch.org/>
  - TensorFlow: <https://www.tensorflow.org/>
  - Keras: <https://keras.io/>
  - OpenAI Gym: <https://github.com/openai/gym>
- FL frameworks:
  - TensorFlow Federated: <https://www.tensorflow.org/federated>
  - PySyft: <https://openmined.github.io/PySyft/>
  - Flower: <https://flower.dev/>
- ML model energy consumption tracking:
  - CarbonTracker: <https://github.com/lfwa/carbontracker>
  - eco2AI: <https://github.com/sb-ai-lab/Eco2AI>
  - CodeCarbon: <https://github.com/mlco2/codecarbon>

# Outline

## Part 1: Introduction. Why Wi-Fi may want to adopt AI/ML?

- Wi-Fi overview: A 30-year path from IEEE 802.11b to IEEE 802.11be, and beyond
- Open challenges in Wi-Fi: Dealing with complexity and uncertainty
- Requirements of next-gen Wi-Fi networks

## Part 2: A primer on AI/ML through Wi-Fi-related problems

- Wi-Fi & ML: A two-sided relationship
- Examples of ML types (supervised, unsupervised, and reinforcement learning) for Wi-Fi
- Novel trends in ML applied in Wi-Fi: deep learning, reinforcement learning, online learning, federated learning

## Part 3: Online learning for responsive Wi-Fi networks

- Wi-Fi with multi-armed bandits
- Reinforced-lib: our open-source library
- Overview of tools and resources.

## **Coffee break (10:30-11:00)**

## Part 4: Adoption of ML for Wi-Fi: architecture and standardization

- ML integration in Wi-Fi through the ITU-T architectural framework
- Current status in standardization

## Part 5: Open challenges, future research directions, and summary

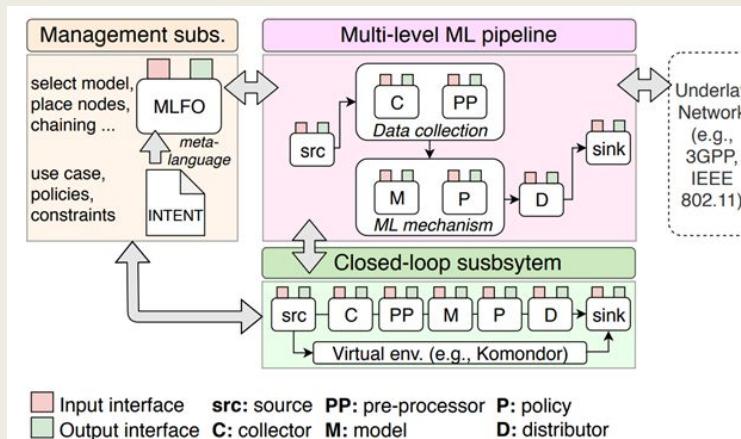
- Open challenges and future research directions; Synergies with other disruptive technologies
- Current AI/ML trends: LLM and Generative AI
- Summary and takeaways
- Q&A

# 4 Adoption of ML for Wi-Fi: architecture and standardization

# Adoption of ML in Wi-Fi

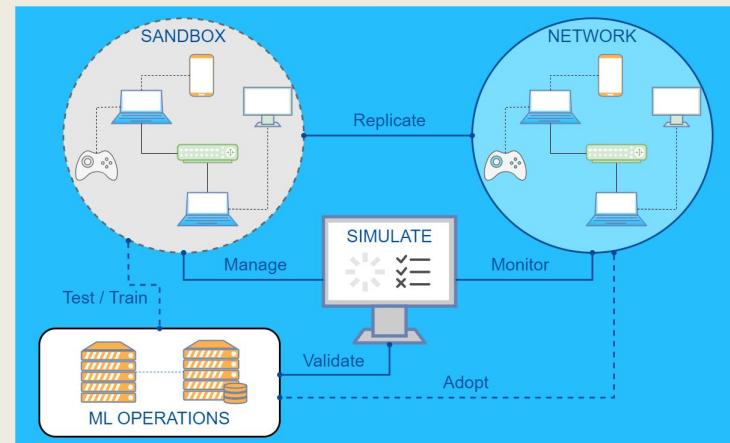
## Architectural solutions

- Need for procedures, interfaces and data elements to support ML operations
- The ITU-T ML architectural framework



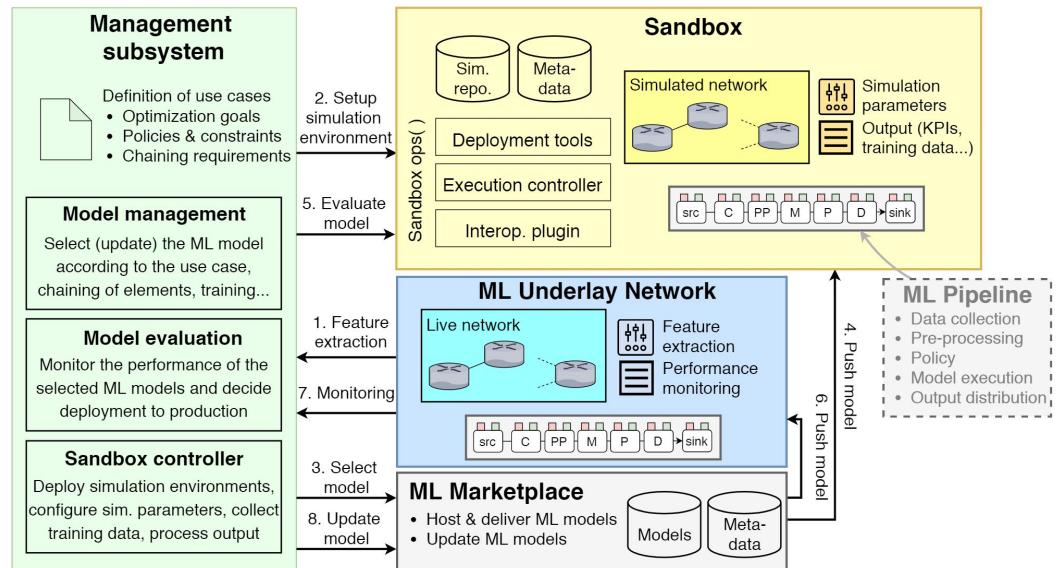
## ML Sandbox / Digital twin

- Need of tools to trust AI/ML
- The ML Sandbox allows training, testing, and evaluating AI/ML solutions before being applied to production networks
- The role of network simulators as future network digital twins



# ML Sandbox & Network Digital Twins

- Importance of network digital twinning in B5G communications
- Main responsibilities:
  - Generate data for training AI/ML models
  - Train AI/ML mechanisms offline
  - Evaluate the performance of ML models
- Exemplary challenges:
  - Interoperability
  - Accuracy
  - Flexibility

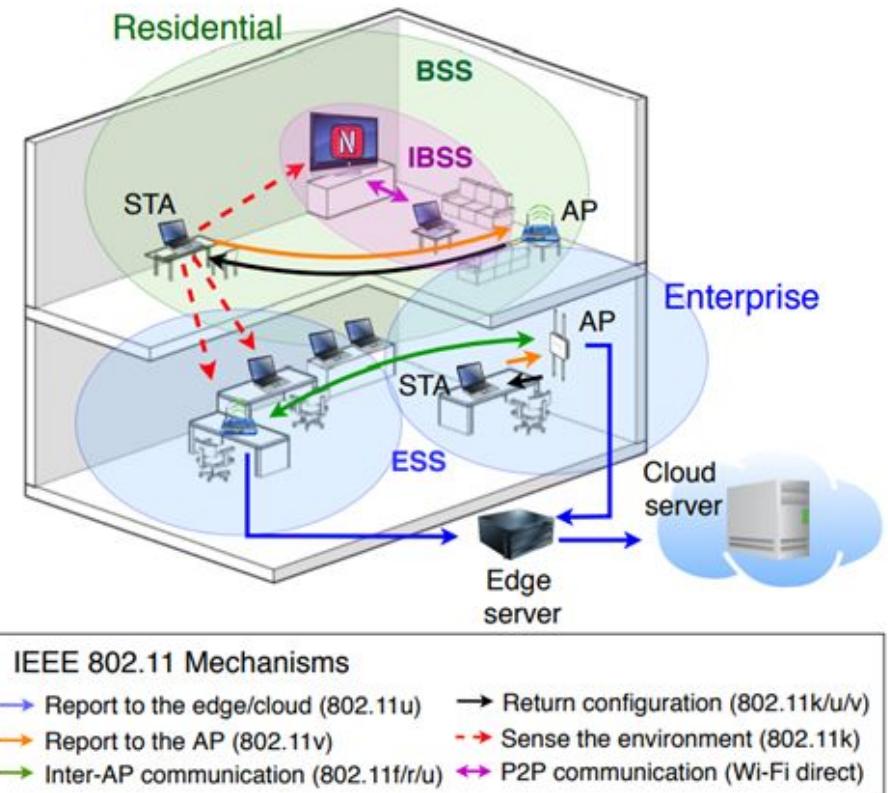


Wilhelmi, F., Carrascosa, M., Cano, C., Jonsson, A., Ram, V., & Bellalta, B. (2021). [Usage of network simulators in machine-learning-assisted 5G/6G networks](#). *IEEE Wireless Communications*, 28(1), 160-166.

# Architectural integration of AIML in Wi-Fi

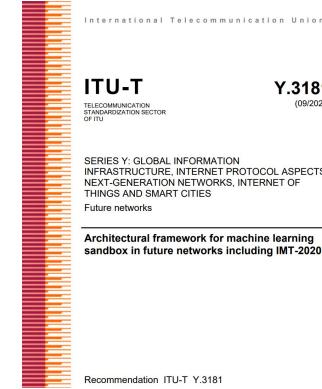
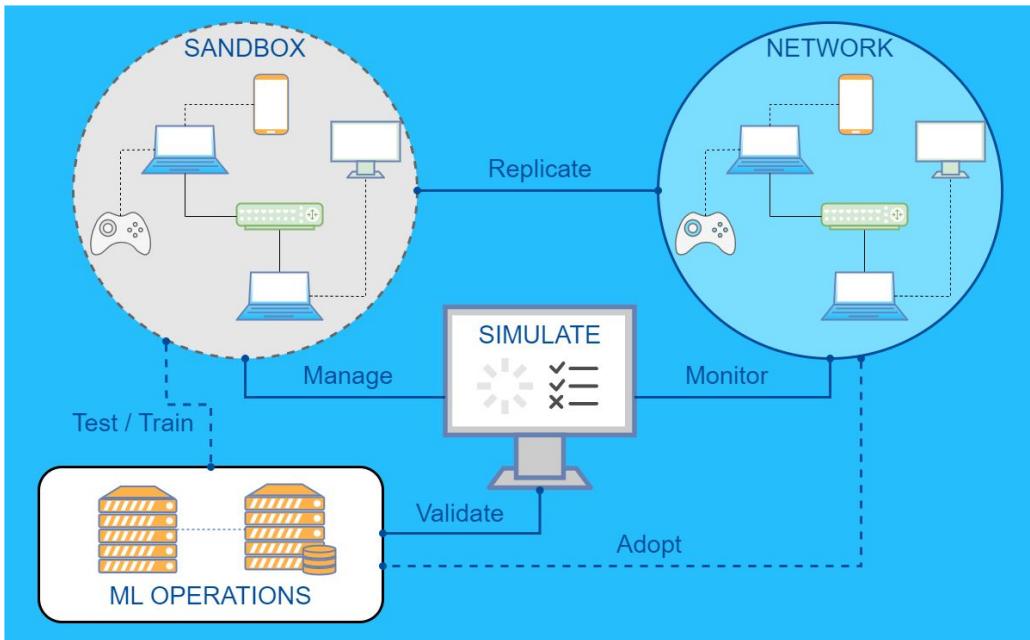
## Challenges for ML adoption in Wi-Fi

- IEEE 802.11 defines MAC/PHY only (**limited AI functionalities with respect to 3GPP**)
- **Uncertainty** due to the distributed channel access
- Different operation modes
  - Fully **decentralized**, with autonomous operation (e.g., residential)
  - **Centralized**, operated from the cloud (e.g., industrial/enterprise Wi-Fi)
  - **Coordinated**, allowing for groups of collaborating APs (e.g., Wi-Fi 8)
- Backward legacy compatibility (**fair AI solutions are required**)

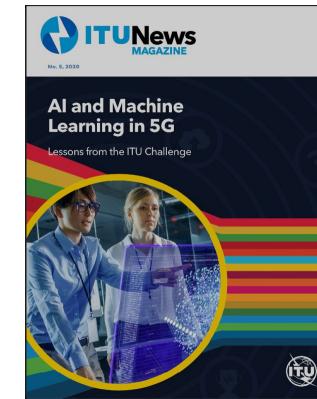


Wilhelmi, F., Barrachina-Muñoz, S., Bellalta, B., Cano, C., Jonsson, A., & Ram, V. (2020). [A flexible machine-learning-aware architecture for future WLANs](#).

# The ML Sandbox



[Y.3181 : Architectural framework for machine learning sandbox in future networks including IMT-2020](#)



F. Wilhelmi, "Building reliability and trust with network simulators and standards", [ITU News Magazine No. 5, 2020](#)

# Existing AI/ML frameworks

## ITU-T Y.3172

ITU's standardized architecture provides a common nomenclature for ML-related mechanisms so that interoperability with other networking systems is achieved

### ITU-T Y.3174

Framework for data handling to enable machine learning in future networks including IMT-2020

### ITU-T Y.3176

Machine learning marketplace integration in future networks including IMT-2020

### ITU-T Y.3182

Architectural framework for Machine Learning Sandbox in future networks including IMT-2020

## ETSI GS ZSM 002

ETSI/ZSM's architecture defines a service-centric architectural model to define at a high level a set of management services, including management, communication, and interoperation, for zero-touch network and service management

### ETSI GS ZSM 008

Cross-domain E2E service lifecycle management

### ETSI GS ZSM 009

Closed-Loop Automation

## TR 37.817

3GPP's study on Artificial Intelligence and Machine Learning (AI/ML) in 5G RAN architectures

## RP-220635

Work Item on Artificial Intelligence (AI)/Machine Learning (ML) for NG-RAN [ONGOING – from March 2022]

# The ITU-T's Flexible ML Architecture

- **ML operations**

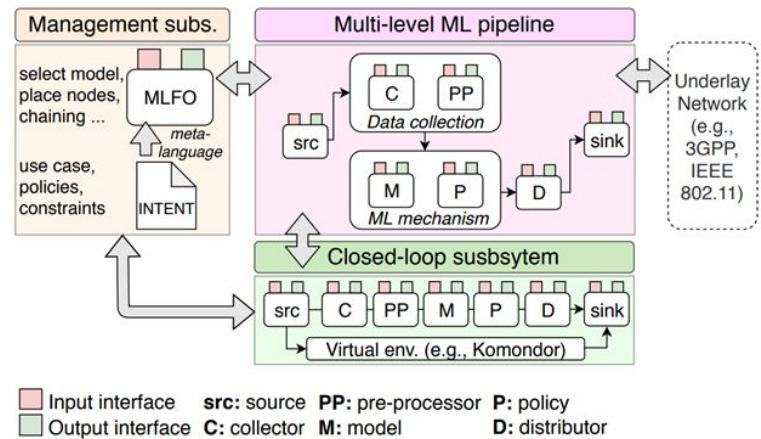
- Multiple ML pipeline nodes, instantiated for different purposes
  - Data collection, model inference, output distribution...
- Specialized M&O is required (MLFO)
  - Chain ML pipeline elements
  - Deploy models, re-train, select data, etc.

- **ML sandbox (closed-loop subsystem)**

- Safe environment to assist the ML operation
- Increase trustworthiness on AI/ML
- Speed-up model training/validation

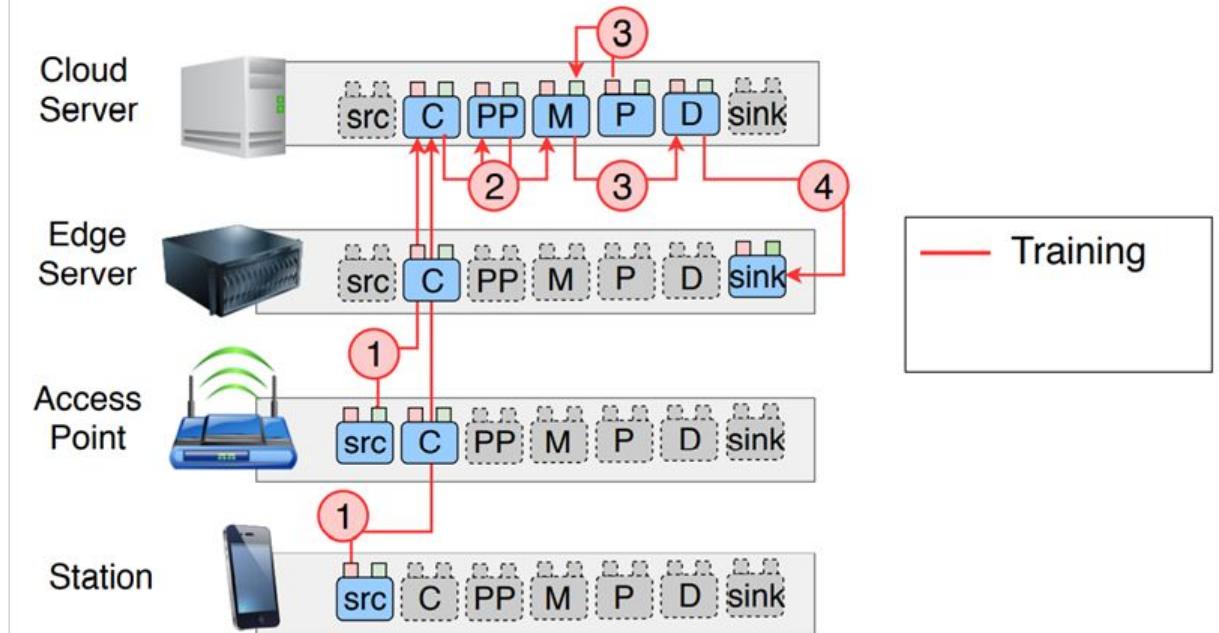
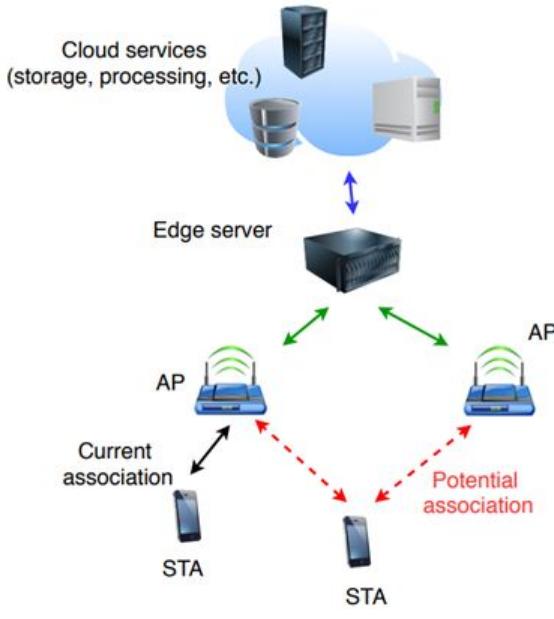
- Source (src): generates data to be used by the ML mechanism
- Collector (C): collects the data generated by sources
- Pre-processor (PP): prepares the data collected for its utilization by the ML mechanism
- ML model (M): applies the ML model specified by the intent
- Policy (P): provides a constraints/guidelines that delimit the behavior of the model
- Distributor (D): spreads the ML output across all the corresponding targets (or sinks)
- Sink: applies the ML output that is received from the distributor

Wilhelmi, F., Barrachina-Muñoz, S., Bellalta, B., Cano, C., Jonsson, A., & Ram, V. (2020). [A flexible machine-learning-aware architecture for future WLANs](#). IEEE Communications Magazine, 58(3), 25-31.



# ITU-T ML architecture's realization in Wi-Fi

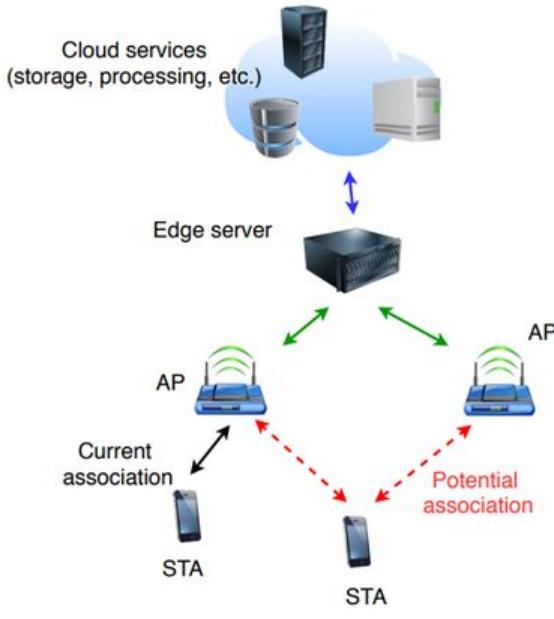
## AIML-based roaming



Wilhelmi, F., Barrachina-Muñoz, S., Bellalta, B., Cano, C., Jonsson, A., & Ram, V. (2020). [A flexible machine-learning-aware architecture for future WLANs](#). IEEE Communications Magazine, 58(3), 25-31.

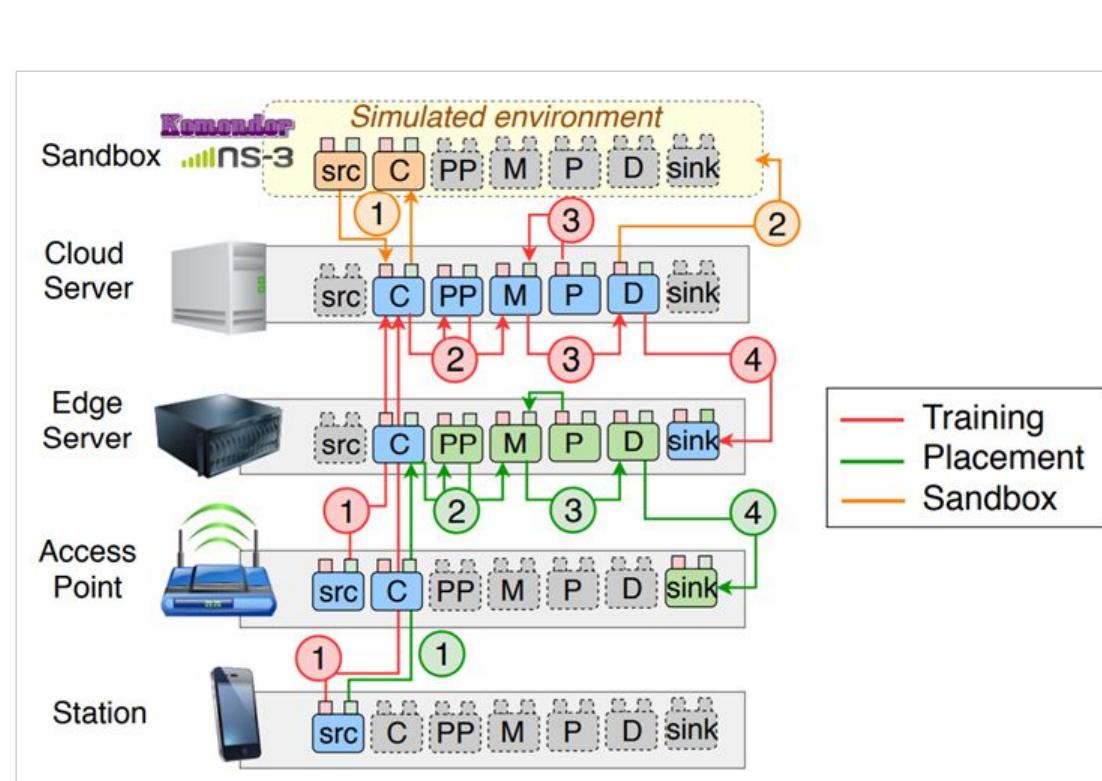
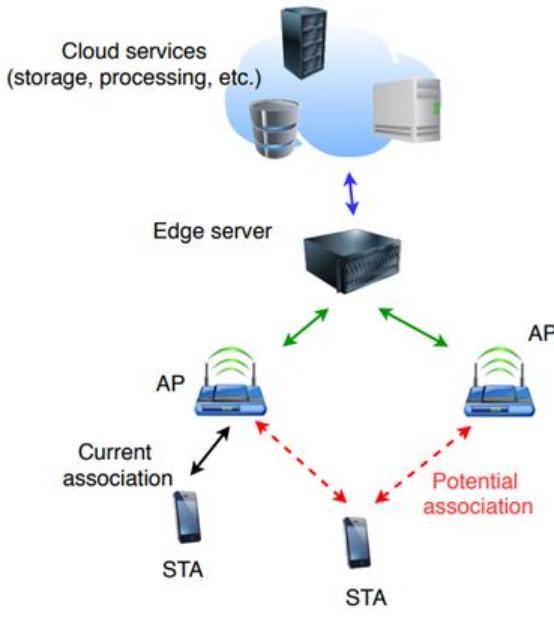
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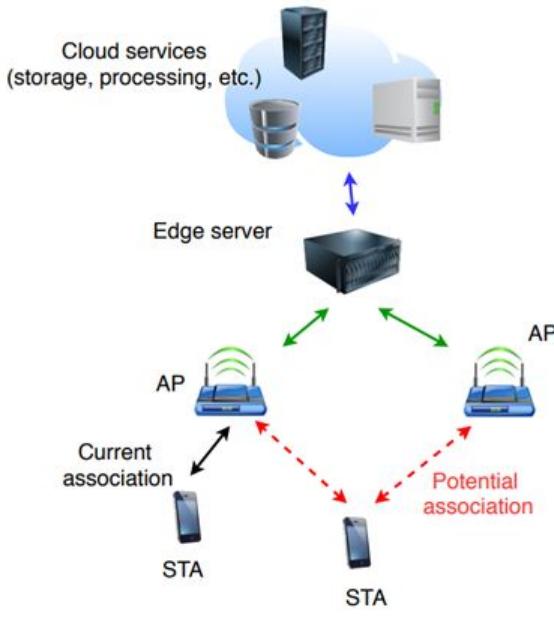
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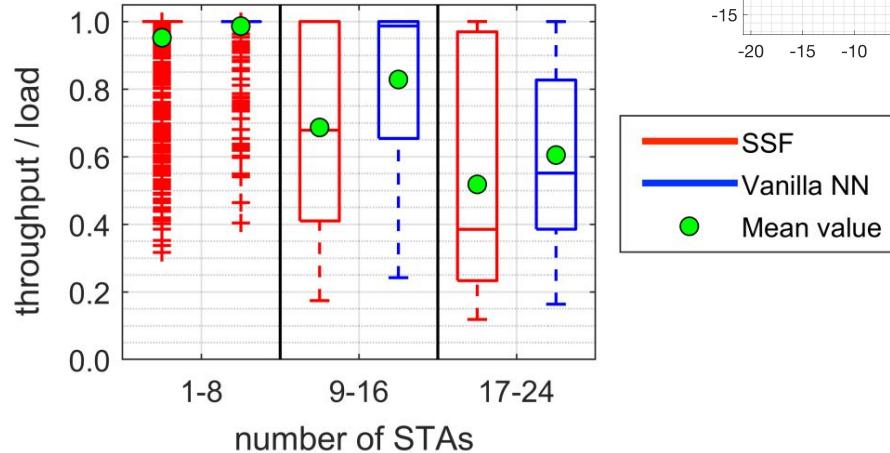
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# ITU-T ML architecture's realization in Wi-Fi

## AIML-based roaming



**Strongest Signal First (SSF) vs Machine Learning**



[GitHub - fwilhelmi/machine\\_learning\\_aware\\_architecture\\_wlans](https://github.com/fwilhelmi/machine_learning_aware_architecture_wlans)

Wilhelmi, F., Barrachina-Muñoz, S., Bellalta, B., Cano, C., Jonsson, A., & Ram, V. (2020). [A flexible machine-learning-aware architecture for future WLANs](#). IEEE Communications Magazine, 58(3), 25-31.

# Standardization: IEEE 802.11

## Artificial Intelligence Machine Learning (AIML) Topic Interest Group (TIG)

- AIML Use Cases and Features for WLAN
  - AIML-based CSI feedback compression
    - Unsupervised learning allows to reduce CSI feedback
  - Deep-learning based distributed channel access
    - DL allows to increase throughput and decrease latency (e.g., CW optimization)
  - AIML Enhanced Roaming
    - AIML can improve roaming decisions
  - AIML based Multi-AP Transmission
    - AIML can help in finding AP-STA pairs for multi-AP transmissions, etc.
  - Efficient AIML model sharing/distribution

All AIML TIG documents available @ [https://mentor.ieee.org/802.11/documents?is\\_dcn=aiml](https://mentor.ieee.org/802.11/documents?is_dcn=aiml)

# Standardization: IEEE 802.11

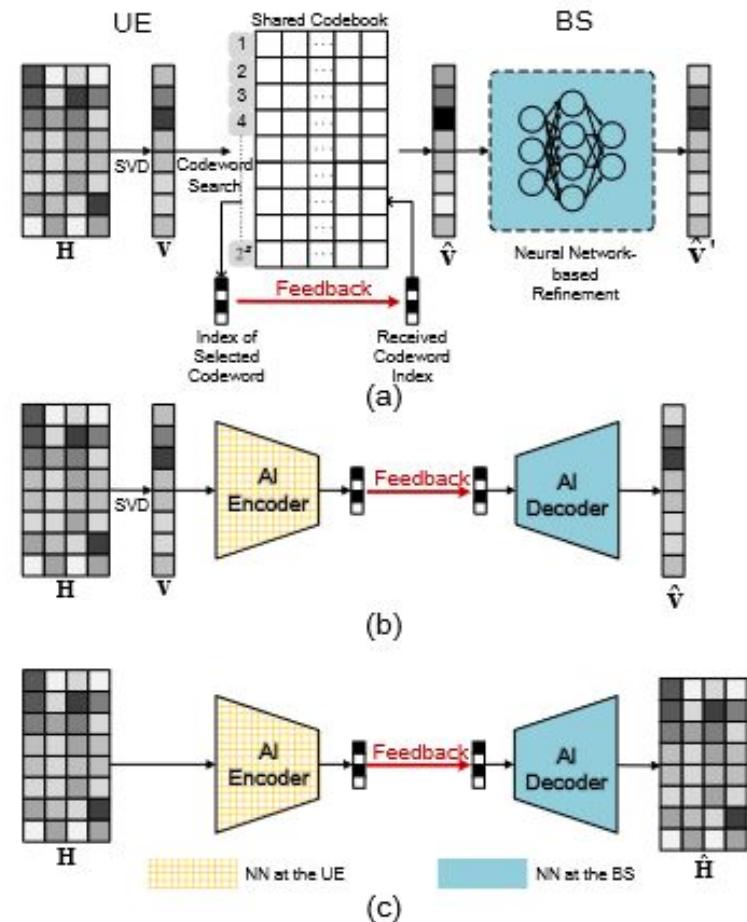
AIML-based CSI Feedback Compression ~ InterDigit

## Problem

- In 802.11ax/be the AP uses a sounding sequence for beamformee/beamformer communication
- Sounding feedback airtime overhead increases with new features (e.g., MAP + many spatial streams)

## Benefit from ML

- CSI compression
- Faster operation
- Improved throughput



Guo, Jiajia, et al. "AI for CSI feedback enhancement in 5G-advanced." *IEEE Wireless Communications* (2022).

# Standardization: IEEE 802.11

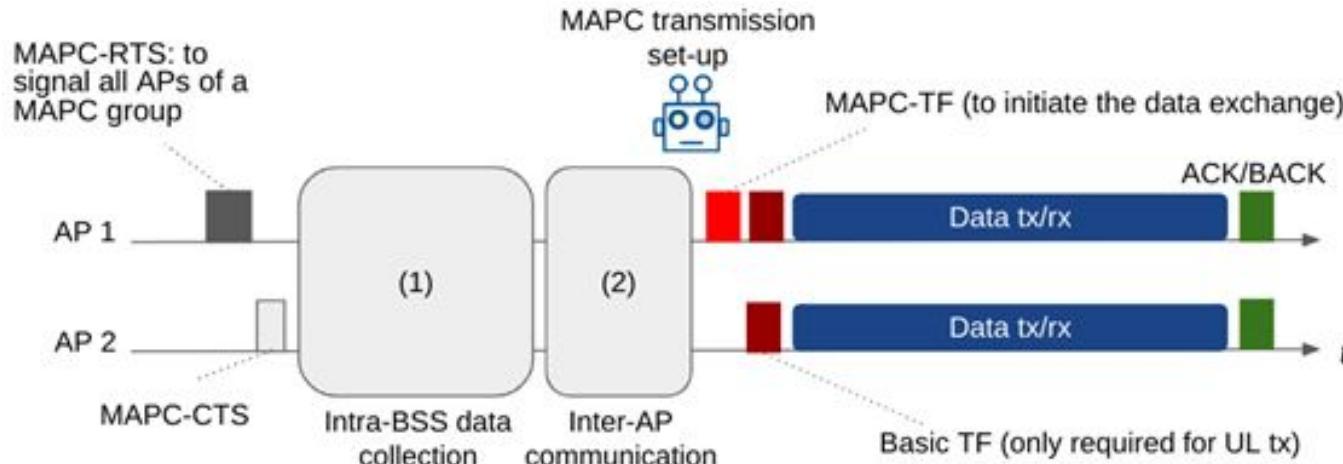
AIML-based Multi-AP Coordination ~ AGH and UPF

## Problem

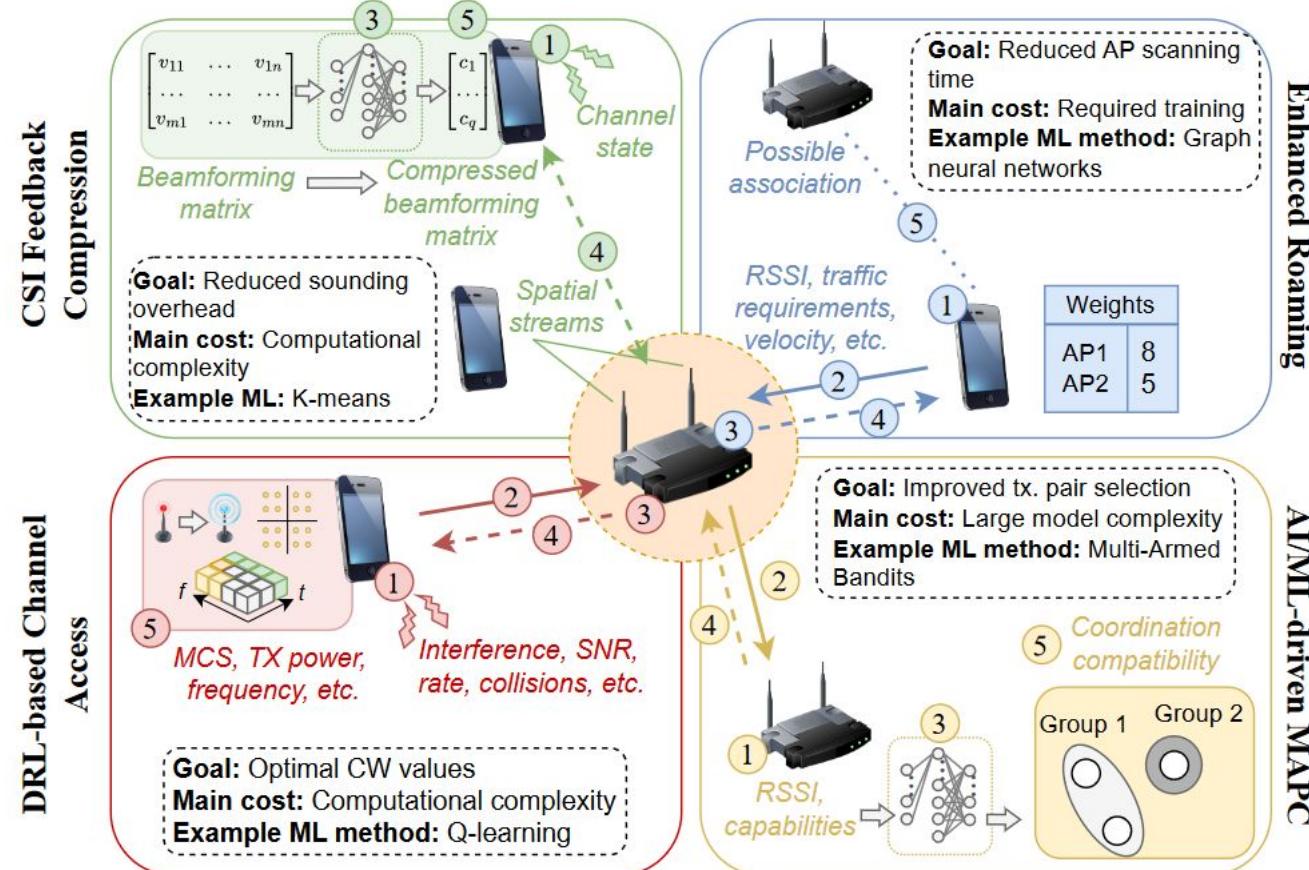
- Dense multi-AP networks suffer from co-channel interference, multi-AP coordination (MAPC) becomes necessary

## Benefit from ML

- Selection of non-colliding groups → improved utilization of radio resources



# Standardization: IEEE 802.11



- ① Collect measurements (e.g., KPIs)
- ② Exchange measurements/data for ML models
- ③ Perform ML model inference
- ④ Exchange models, outputs, decisions, commands
- ⑤ Apply output to drive operation/optimization

# Outline

## Part 1: Introduction. Why Wi-Fi may want to adopt AI/ML?

- Wi-Fi overview: A 30-year path from IEEE 802.11b to IEEE 802.11be, and beyond
- Open challenges in Wi-Fi: Dealing with complexity and uncertainty
- Requirements of next-gen Wi-Fi networks

## Part 2: A primer on AI/ML through Wi-Fi-related problems

- Wi-Fi & ML: A two-sided relationship
- Examples of ML types (supervised, unsupervised, and reinforcement learning) for Wi-Fi
- Novel trends in ML applied in Wi-Fi: deep learning, reinforcement learning, online learning, federated learning

## Part 3: Online learning for responsive Wi-Fi networks

- Wi-Fi with multi-armed bandits
- Reinforced-lib: our open-source library
- Overview of tools and resources.

## **Coffee break (10:30-11:00)**

## Part 4: Adoption of ML for Wi-Fi: architecture and standardization

- ML integration in Wi-Fi through the ITU-T architectural framework
- Current status in standardization

## Part 5: Open challenges, future research directions, and summary

- Open challenges and future research directions; Synergies with other disruptive technologies
- Current AI/ML trends: LLM and Generative AI
- Summary and takeaways
- Q&A

# 5

## Open challenges, future research directions, and summary

# Research community generates new ideas...

- **Optimizing new 802.11 features**
  - Not yet well-known how ML can improve the performance of existing features
  - What about new ones? Multi-link operation, multi-AP coordination
- **Joint parameter optimization**
  - Complex interplay between different features
  - E.g., transmit power and carrier sensing threshold, channel/link selection
- **Distributed and transfer learning; hierarchical learning**
  - Training and sharing/deploying models in a distributed way
  - Reuse of knowledge between features

# Datasets

- The existence of open-source and standardized datasets is essential for training and comparing ML-based algorithms.
- Very few datasets are currently available.
- Examples of datasets:
  - Herzen et al. provide a dataset to **predict throughput** based on basic performance metrics (e.g., **received power**, **channel width**) collected in a small testbed.
  - Karmakar et al. provide the IEEE 802.11ac performance dataset that contains information regarding **normalized throughput** achieved under five **link configuration parameters** (i.e., channel bandwidth, MCS, guard interval, MIMO, and frame aggregation) and the channel quality measured as SNR.
  - Chen et al. provide a dataset for **long-time user load prediction** in large-scale WiFi system.
- It would be beneficial to have standardized datasets, standardized means for sharing datasets (preserving privacy), and standardized procedures for data collection (to build new datasets.)

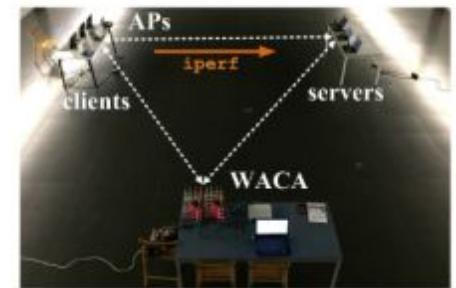
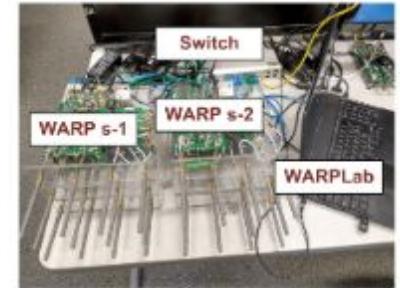
More info  
in our survey:



# New Simulation & Experimental Tools



- Wi-Fi networks are becoming extremely complex
  - Many new features and different scenarios
- We need (new) evaluation tools (and metrics) to obtain reliable and reproducible performance results: analysis, simulations, testbeds
  - Include AI/ML support
- The case of ns-3:
  - Full TCP/IP stack, Wi-Fi, community validated, open-source
  - Not all 11ax features yet implemented; some 11be ones in development (developing new features requires expertise and time)
  - **AI/ML support:** ns3-gym: OpenAI Gym integration, Reinforced-lib



# Komondor

- Open-source: [GitHub - wn-upf/Komondor: Komondor Wireless Networks Simulator](#)
- Tool to simulate IEEE 802.11 features and more
  - Low-complexity (simplified PHY/MAC)
    - Fast simulations – Very large deployments
    - Low-cost implementation of novel features, e.g., 11ax SR
    - Devise results on specific 802.11 features
  - Includes “in-house” AI/ML operations
  - Suitable for creating datasets
- Good adoption in academia
  - Cited/used in >35 research works (source: [Google Scholar](#))
  - Used in two editions of the ITU AI Challenge as a data generator [1], [2]

The screenshot shows the GitHub repository page for 'wn-upf/Komondor'. The repository is public and has 36 issues, 2 pull requests, and 13 branches. The 'Code' tab is selected, showing the commit history for the 'master' branch. There are 13 tags listed. The commits are from fwilhelmi, dated Jan 27, 2022, and involve updates to various files like README.md, .settings, Apps, Code, Documentation, .cproject, and .gitignore.

Simulator	Open-source	Source lang.	Complexity	GUI	11ax features	ML-based module
ns-3	Yes	C++	High	No <sup>1</sup>	Partial	No <sup>2</sup>
ns-2	Yes	C++/OTcl	Low	No <sup>1</sup>	No	No
OMNET++	No	C/C++	Medium	Yes	No	No
OPNET	No	C++	Medium	Yes	No	No
NetSim	No	Java	Low	Yes	No	No
<b>Komondor</b>	<b>Yes</b>	<b>C/C++</b>	<b>Low</b>	<b>No</b>	<b>Partial</b>	<b>Yes</b>

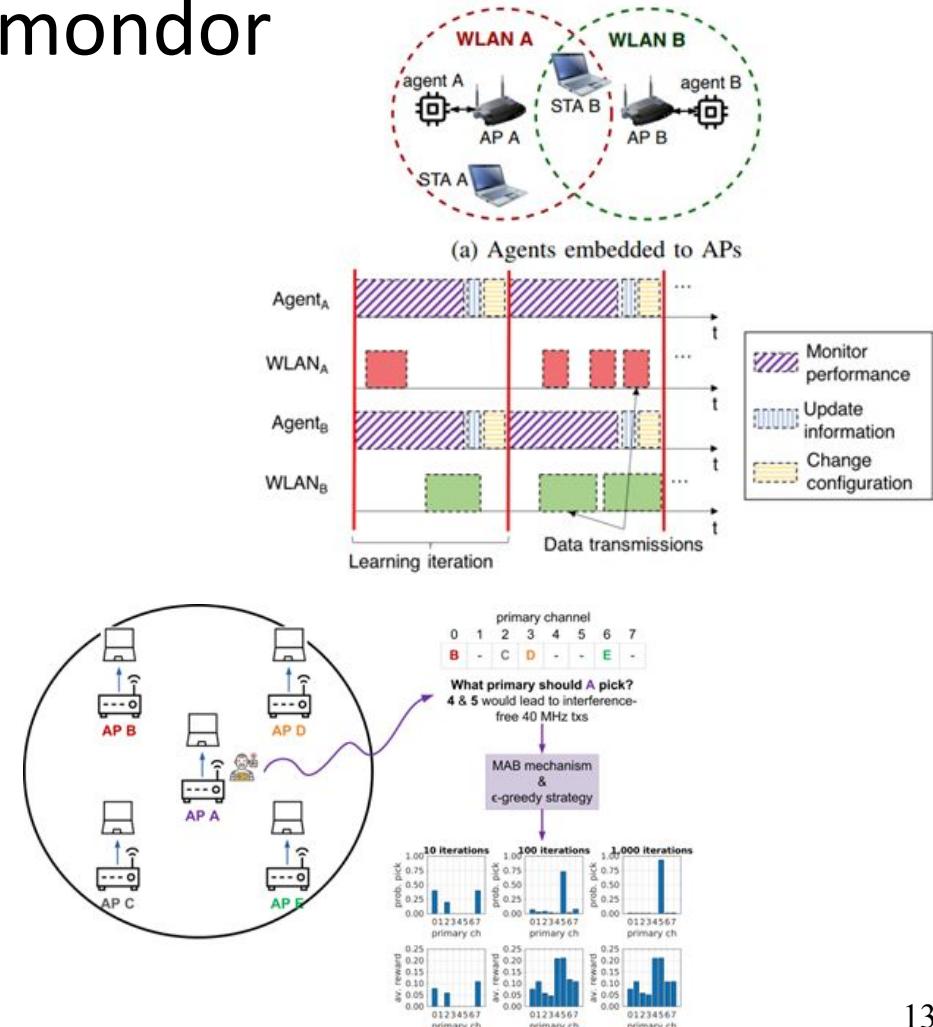
Wilhelmi, F. et al. (2021). Machine Learning for Performance Prediction of Channel Bonding in Next-Generation IEEE 802.11 WLANs. *ITU Journal on Future and Evolving Technologies, Volume 2 (2021), Issue 4 , Pages 67-79.*

Wilhelmi, F. et al. (2022). Federated Spatial Reuse Optimization in Next-Generation Decentralized IEEE 802.11 WLANs. *ITU Journal on Future and Evolving Technologies, Volume 3 (2022), Issue 2, Pages 117-133.*

Barrachina-Munoz, S., Wilhelmi, F., Selinis, I., & Bellalta, B. (2019, April). Komondor: A wireless network simulator for next-generation high-density WLANs. In *2019 Wireless Days (WD) (pp. 1-8)*. IEEE.

# Online agents operation in Komondor

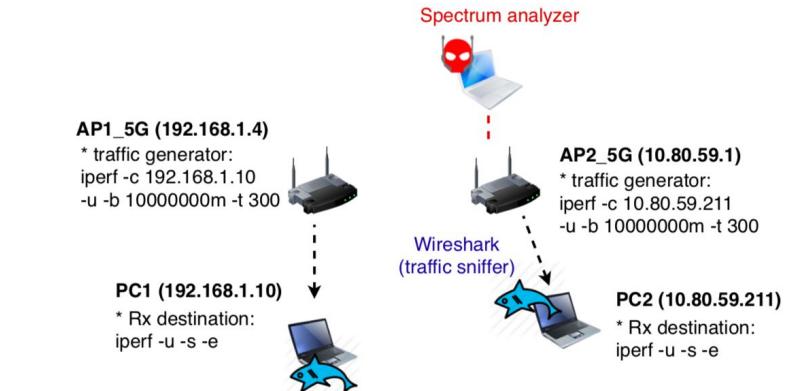
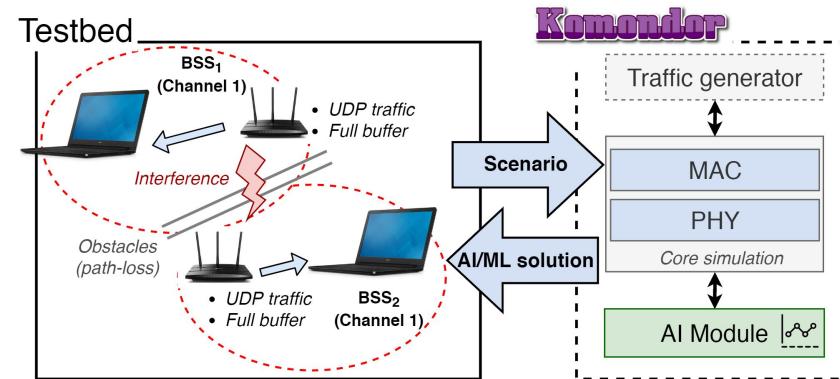
- The operation of AP and non-AP devices can be ruled by agents during simulations
- Agents run during the simulation
  - Monitoring performance (passive/reactive)
  - Internal operation (e.g., training/inference)
  - Submit configuration changes to devices
- Centralized, distributed, and decentralized modes
- An example:
  - Online learning is used by **AP A** to decide the best primary channel
  - Scenario dependency (awareness of channels' statuses)
  - Transitory vs permanent regimes



# Komondor as ML Sandbox

## Safe AIML model training ♣

- PoC on model training in Komondor
  - Characterize the real network in Komondor
  - Use AIML in Komondor to find a suitable network configuration in terms of tx power
  - Apply the configuration discovered in the simulator to the real network
- Testbed
  - 2 nearby BSSs (1 AP & 1 STA each) using the same channel
  - Full-buffer traffic generation at APs (*iperf*)
  - Traffic analysis at STAs (*Wireshark*)
  - Extra spectrum analyzer (*Aaronia*) to better understand the activity on the selected channel



# Komondor as ML Sandbox

## Safe AIML model training ♣

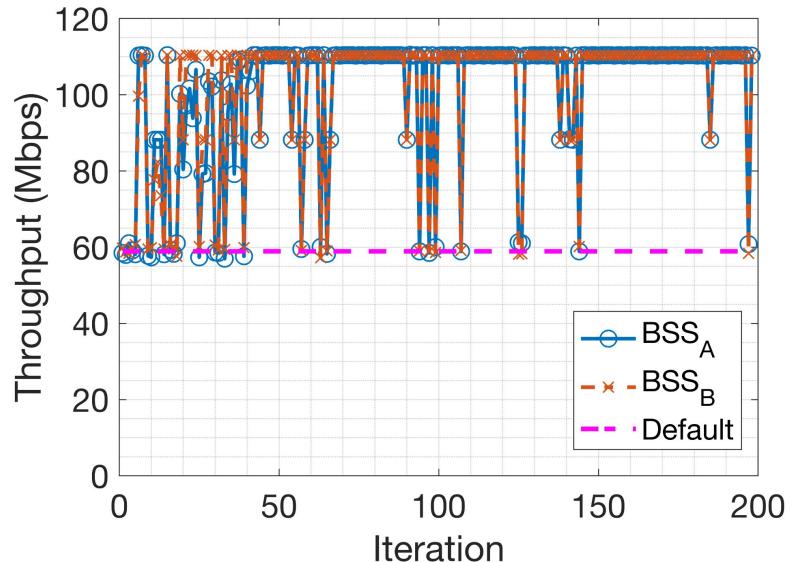
---

**Algorithm 1:** Implementation of MABs in an OBSS

---

```
1 Function MAB ( $\mathcal{P}$ );
  Input :  $\mathcal{P}$ : set of transmit power levels in  $\{1, \dots, K\}$ 
2 initialize:  $t = 0, \forall k \in \mathcal{P}$ , set  $\hat{r}_k = 0$  and  $n_k = 0$ 
3 while active do
4   For each arm  $k \in \mathcal{P}$ , sample  $\theta_k(t)$  from normal
      distribution  $\mathcal{N}(\hat{r}_k, \frac{1}{n_k+1})$ 
5   Play arm  $k = \operatorname{argmax}_{1, \dots, K} \theta_k(t)$ 
6   Observe the throughput experienced  $\Gamma_t$ 
7   Compute the reward  $r_{k,t}$ 
8    $\hat{r}_{k,t} \leftarrow \frac{\hat{r}_{k,t} n_{k,t} + r_{k,t}}{n_{k,t} + 2}$ 
9    $n_{k,t} \leftarrow n_{k,t} + 1$ 
10   $t \leftarrow t + 1$ 
11 end
```

---



- AIML method: online decentralized learning (MABs)
- Action space: {5, 7, 12, 17, 23} dBm

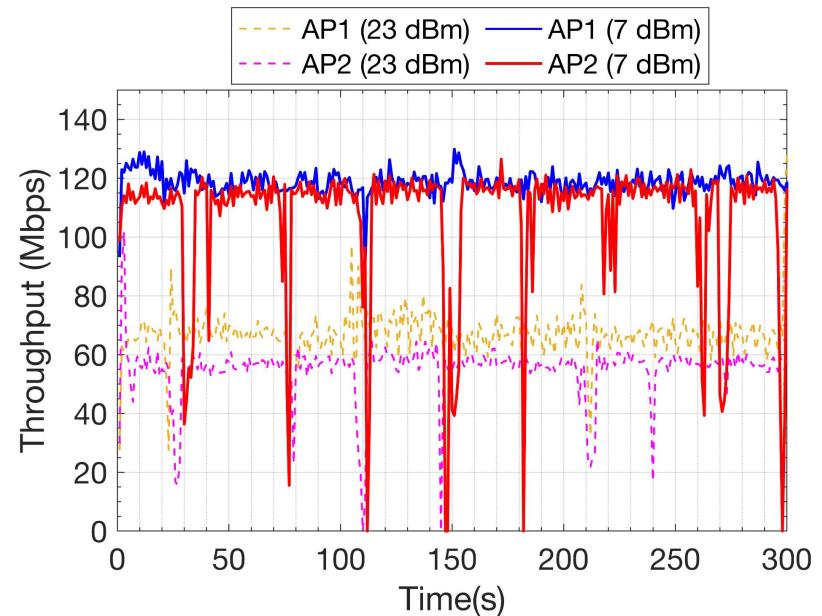
- On-simulation model training results
- 200 iterations = 200 seconds

# Komondor as ML Sandbox

Safe AIML model training ♣

- The best configuration observed in the simulator was 7 dBm (right-top Table)
- The right-bottom Figure shows the performance achieved when:
  - a. Using the default configuration (maximum power = 23 dBm)
  - b. Using the configuration discovered in the simulator (adapted power = 7 dBm)

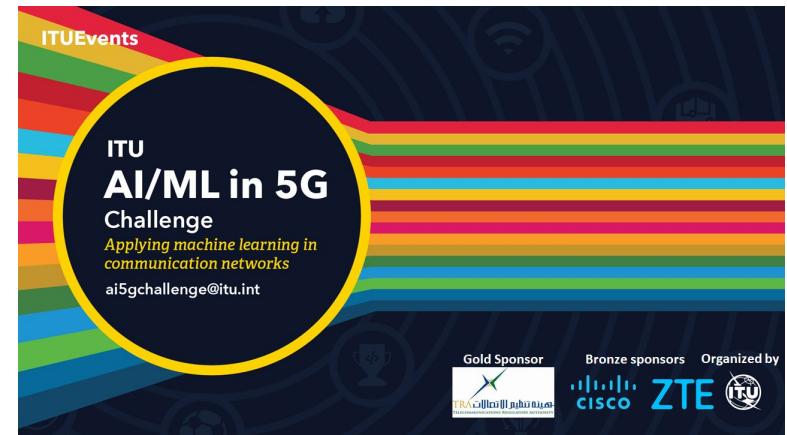
Tx Power	5 dBm	7 dBm	12 dBm	17 dBm	23 dBm
Probability	0.0804	0.7889	0.0452	0.0452	0.0503



# Komondor as ML Sandbox

## Dataset generation for AIML model training

- **Problem:** Lack of data for training AIML models
  - Proprietary solutions / Competition
  - Privacy concerns
  - Cost of data gathering & processing
- **An appealing alternative:** Generate synthetic datasets with network simulators
- Komondor datasets:
  - 2020 ITU AI Challenge - IEEE 802.11ax Dynamic Channel Bonding (DCB) dataset ♦
  - 2021 ITU AI Challenge - IEEE 802.11ax Spatial Reuse (SR) dataset ♠



Wilhelmi, F., Gómez, D., Soto, P., Vallés, R., Alfaifi, M., Algunayah, A., ... & Bellalta, B. (2021). [Machine learning for performance prediction of channel bonding in next-generation IEEE 802.11 WLANs](#). *ITU Journal on Future and Evolving Technologies*, Volume 2 (2021), Issue 4, Pages 67-79.

Wilhelmi, F., Hribar, J., Yilmaz, S. F., Ozfatura, E., Ozfatura, K., Yildiz, O., ... & Bellalta, B. (2022). [Federated spatial reuse optimization in next-generation decentralized IEEE 802.11 WLANs](#). *ITU Journal on Future and Evolving Technologies*, Volume 3 (2022), Issue 2, Pages 117-133

♦ Wilhelmi, F. (2020). [ITU-T AI Challenge] Input/Output of project "Improving the capacity of IEEE 802.11 WLANs through Machine Learning" [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.4106127>

♠ Wilhelmi, F. (2021). [ITU AI/ML Challenge 2021] Dataset IEEE 802.11ax Spatial Reuse (v1.3) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.5656866>

# AI/ML in Practice

- **Most of current results in the literature come from simulations:**
  - Many simplifying assumptions:
    - Controlled (simple) scenarios, discrete time (iterations)
    - Instantaneous and noise-free data: ideal ‘devices’ (no need to calibrate data), no estimation errors, etc.
    - No ML overheads (data and model exchange) usually considered
  - **The ‘gap’ with performance results from real implementations could be significant**
- **Engineering effort to set-up and test AI/ML solutions in practice is still required**
  - Suitable KPIs are required, including how and when to measure them
  - When should AI/ML agents be triggered?
    - Instability vs slow reaction;
    - Should ‘thresholds’ be used to activate ML mechanisms?



# AI/ML in Practice

- Performance gains in practice
  - While AI/ML MAC/PHY enhancements affecting specific mechanisms may be easy to evaluate (link parameter selection, CW adjustment, beamforming, etc.), **it may not be easy to assess other AI/ML performance gains** since they may appear only in particular situations (e.g., high loaded scenarios).
    - Example: network-controlled client device association and band steering (the AP uses AI/ML to determine when it is better to move one client from one band to another)
- Fairness issues between AI/ML-enabled devices and legacy devices
- Privacy is one of the most important future challenges

# New research directions

## Generative-Adversarial-Network (GAN)

- GAN-based wireless channel modeling
  - GAN is used to “**autonomous wireless channel modeling without complex theoretical analysis or data processing**”
  - “GAN is trained by raw measurement data to reach the Nash equilibrium of a MinMax game between a channel data generator and a channel data discriminator”
  - “The resulting channel data generator is extracted as the target channel model”
- GAN-based model-free resource allocation
  - GAN “is used to pre-train the deep-RL framework using a mix of real and synthetic data, thus creating an **experienced deep-RL framework** that has been exposed to a broad range of network conditions.”
  - “deep-RL framework applied to a multi-user orthogonal frequency division multiple access (OFDMA) resource allocation system.”
- Upcoming special issue in IEEE Network
  - Title: *The Interplay Between Generative AI and 5G-Advanced toward 6G*
  - Publication Date: September/October 2024

# New research directions

## Large Language Model (LLM)

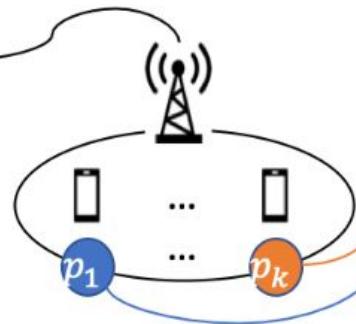
- LLM-based hardware development
  - “LLMs are used in **FPGA-based hardware development** for advanced signal-processing algorithms in wireless communication and networking”
- LLM-based anomaly resolution and optimization of mobile networks
  - Allows “capturing different KPIs of the network and the interactions between various network configuration parameters”
  - Anomaly detection based on “**troubleshooting tickets accumulated over time**”
- Collaborative multi-agent LLMs (intent driven networking)
  - Existing problem: huge parameter sizes
  - **Multi-agent light on-device LLMs collaboratively planning and solving tasks to achieve network goals**
    - Semantic communication with task specific knowledge
    - Reduced model size and computing costs
  - GPT-4 was used to generate exemplary results (next slide)

# New research directions

## Network power consumption with LLM

**Scenario:** Consider the downlink channel with one base station and  $k$  users. The noise level is the same for all users and equals to  $n$  dB. The bandwidth is  $b$  kHz. The channel gain vector is  $g$ . The initial transmission power vector is  $p$ .

**Game rule:** in each round, each user should choose its power so that its transmission rate is no less than its minimum rate and the difference (always non-negative) of its current transmitting power w.r.t. its initial power is minimized. There are  $x$  rounds for each user to choose the transmitting power.



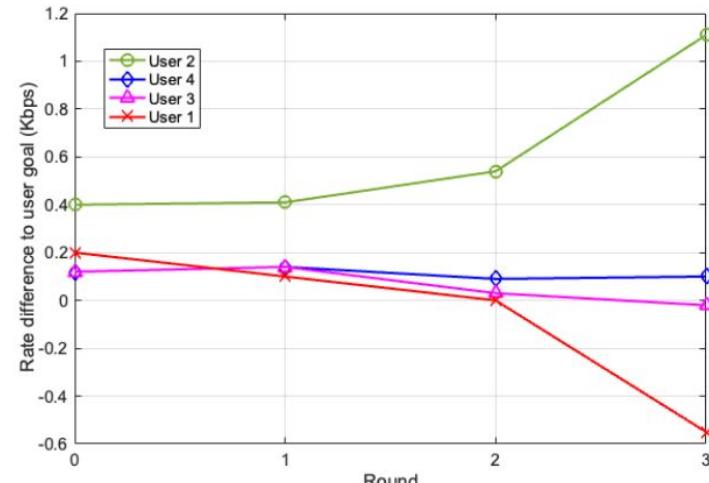
**Network goal:** reduce the total power by  $\Delta p$  W at least.

**User condition:** minimum transmission rate at  $r$  kbps.

It is currently round  $x_t$ . You are user  $k_i$ .  
In last round, transmitting power including yourself is:  $p'$   
When you calculate your transmission rate, you can use  $r_k = B \log(1 + \frac{p_k g_k}{n^2 + \sum_{i \neq k} p_i g_i})$

How will you choose your transmitting power in next round?  
Your reply should be like 'my transmitting power is ... W'

*"This use-case demonstrates that an LLM (GPT-4) can perform mathematical reasoning in a wireless communication-based problem, in order to achieve a global power saving and individual transmission rates targets"*



Source: Zou, Hang, et al. "Wireless Multi-Agent Generative AI: From Connected Intelligence to Collective Intelligence." *arXiv preprint arXiv:2307.02757* (2023).

# Summary & Take-home Messages

1. ML is a set of **general techniques** to create models for **making predictions**. They can be used to empower autonomous ‘agents’ to find suitable configurations in particular scenarios.
2. Given the decentralized nature of 802.11 deployments, the use of **RL techniques** looks like the natural choice to **dynamically improve** several features at the same time, e.g., channel selection, spatial reuse, channel access parameters, etc.
3. Performance gains in practice may not be so obvious
  - a. AI/ML enhanced 802.11 networks should improve user’s **Quality of Experience** by providing a fast response to challenging situations.
4. The **802.11 architecture should be updated** to effectively support AI/ML by adding the necessary interfaces, procedures, and data formats

# AI/ML in Wi-Fi: Standardization Challenges

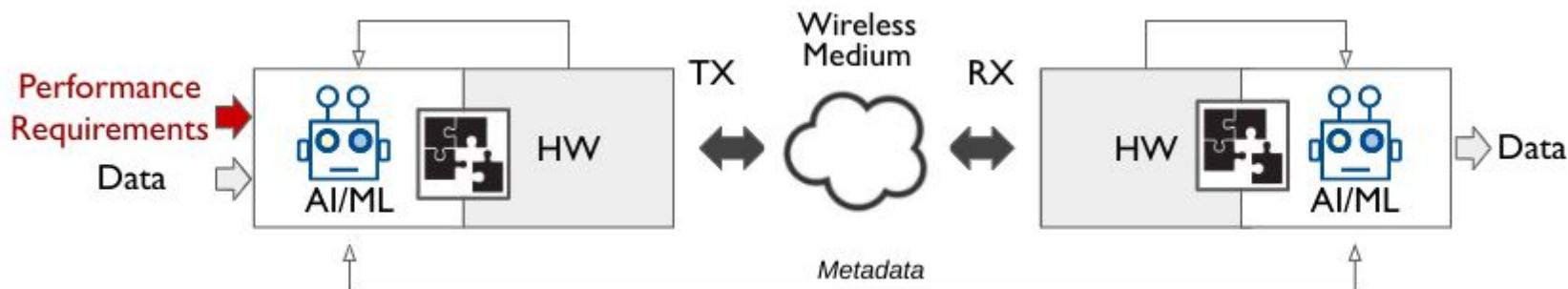
- Backward compatibility
  - fairness for legacy devices
- ML computations and overhead
  - hardware constraints (APs, stations)
  - large storage requirements
  - large communication overheads
- Interoperability
  - implementation heterogeneity (different models, different vendors)
- General concerns on AI/ML
  - security, explainability

# AI/ML in Wi-Fi: Key Enablers

- AI/ML aware infrastructure
  - ITU-T Y.3172 and ETSI GS ENI 005 frameworks
- Trustworthy AI/ML
  - Explainable AI (XAI)
- Sandboxes and network digital twins
  - Advances in AI/ML

# MLDR - Machine Learning Defined Radio

- **Chist-ERA project:** 2024-2027
- **Partners:** AGH, Supélec, U. Oulu, UPF, with the support from *Nokia, Interdigital, NetAI, DeepSig, Canon Research.*
- **Goal:** “*In this project, we aim to build a new, clean-slate AI/ML-Driven Radio (MLDR) interface. This new MLDR interface will learn to communicate by selecting and configuring the set of communication protocols and functionalities that better suit every particular use-case and scenario, thus satisfying the aforementioned hard performance requirements and efficiently using the available spectrum resources.”*

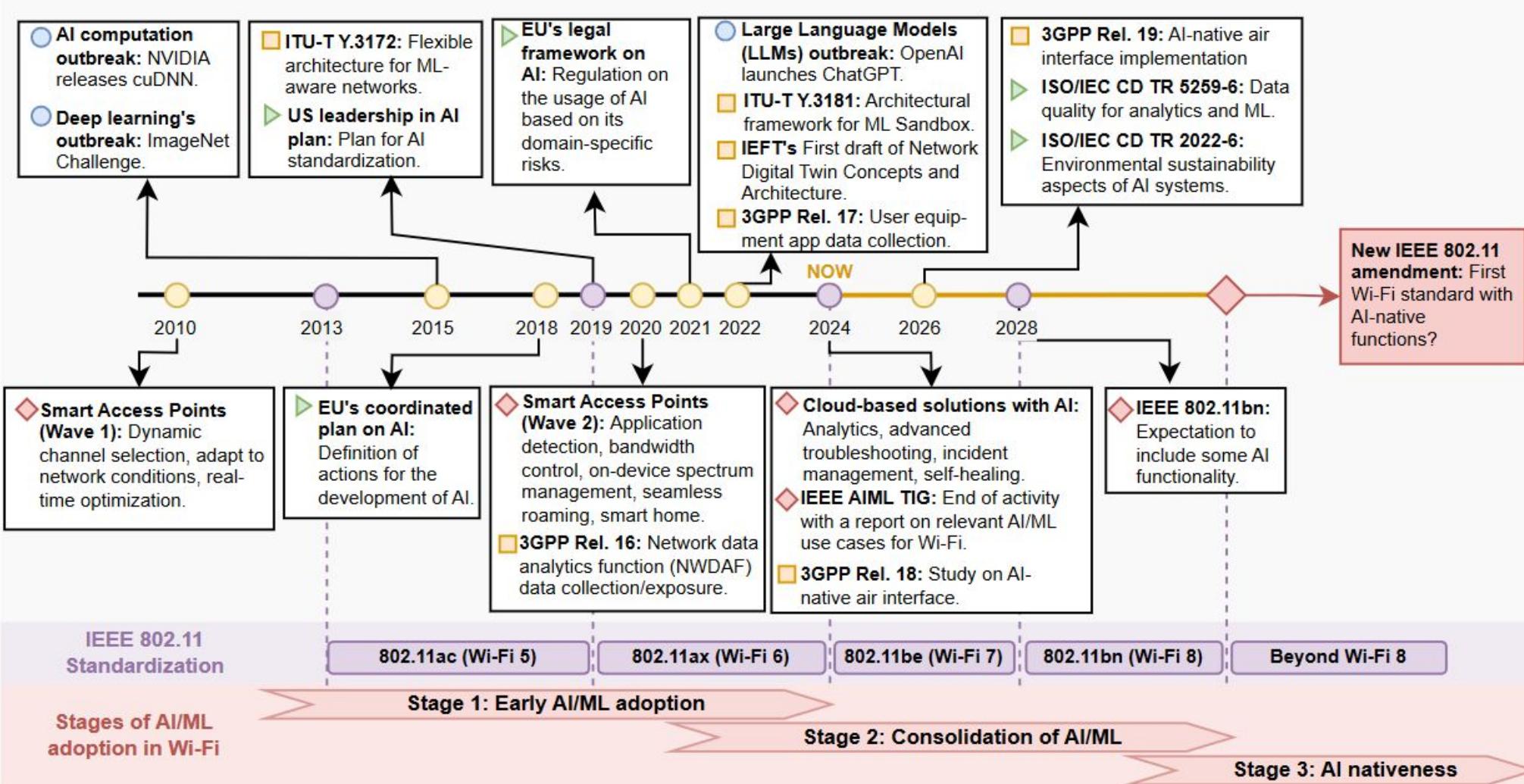


## Advances in AI/ML

## AI/ML standardization

## Advances in AI/ML for telecommunications

## AI/ML adoption in Wi-Fi



# Q&A

# Hands-on exercise

# Hands-on exercise

## Implement, Train & Evaluate an ML model

[Let's go!](#)

The screenshot shows a Jupyter Notebook interface with the following details:

- Title:** Hands-on Exercise
- File Menu:** File, Edit, View, Insert, Runtime, Tools, Help
- Toolbar:** Comment, Share, Settings, User icon
- Code/Text Buttons:** + Code, + Text
- Connect:** Connect dropdown menu
- Content Area:**
  - Section:** Machine Learning and Wi-Fi: Confluences, Ongoing Activities, and Ways Forward
  - Description:** Hands-on exercise: Implementation of a Deep Learning model for predicting the performance of IEEE 802.11ax WLANs
  - Authors:** Francesc Wilhelmi, Szymon Szott, Katarzyna Kosek-Szott, Boris Bellalta
  - Date:** October, 2023 MobiCom
- Text Content:**

In this script, we are going to train and evaluate a deep learning model to fulfill a regression task on the performance of IEEE 802.11ax Spatial Reuse (SR) networks.

The dataset used in this exercise contains simulated traces of multiple random IEEE 802.11ax WLAN deployments and it was part of the 2021 Edition of the ITU AI for Communications Challenge [1]. Further details about the original problem statement can be found here: <https://challenge.aiforgood.itu.int/match/matchitem/37>.

[1] Wilhelmi, Francesc, et al. "Federated spatial reuse optimization in next-generation decentralized IEEE 802.11 WLANs." arXiv preprint arXiv:2203.10472 (2022).

- Code Cell:**

**STEP 0:** Import all the necessary packages.

In this hands-on, we will use TensorFlow (more information here: <https://www.tensorflow.org/>), but other frameworks such as PyTorch (<https://pytorch.org/>) and Keras (<https://keras.io/>) are also very nice to explore.



Thank you!

<https://mlwifitutorial.github.io/>

<b>ML method</b>	<b>Algorithms</b>	<b>Potential applications</b>	<b>Examples of input data</b>
Supervised learning	Linear classifiers, regression methods such as Autoregressive Integrated Moving Average (ARIMA), neural networks, hidden Markov models, random forest, support vector machines, k-nearest neighbors, principal component analysis	Traffic forecasting, mobility pattern prediction, flow classification, routing, anomaly detection, spectrum management, failure detection, QoE prediction	IP traffic matrices, temporal user location, availability of routing paths, application data, channel measurements, performance metrics
Unsupervised learning	Clustering, mixture models, generative models, non-negative matrix factorization, evolutionary algorithms	Traffic classification, virtual topology design, path computation, intruder detection, signal separation	IP traffic matrices, historical end-to-end bit-rate, received symbols
Reinforcement learning	Monte Carlo, Q-learning, State-Action-Reward-State-Action (SARSA), deep Q network, actor-critic, multi-armed bandits, learning automaton, Markov decision processes	Power control, rate adaptation, routing, channel selection, spatial reuse, smart caching, traffic offloading, cognitive channel access, energy harvesting, energy efficiency	Channel measurements, link status, performance metrics (e.g., throughput, delay), server occupation, power consumption

Wilhelmi, F., Barrachina-Muñoz, S., Bellalta, B., Cano, C., Jonsson, A., & Ram, V. (2020). [A flexible machine-learning-aware architecture for future WLANs](#).

IEEE Communications Magazine, 58(3), 25-31.