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Optimizing Resource Allocation in 60 GHz Wireless Access Networks

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Ericsson Research 06.03.13

Group

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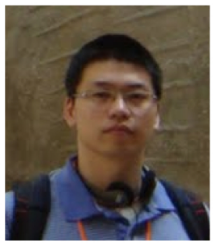

Yuzhe Xu
PhD Student

Group Activities

- Research interests
  - Wireless networking analysis and optimization with applications to 3/4/5G
  - Wireless sensor networks
  - Smart grids
  - Wireless industrial control
- Research projects
  - European Institute of Technology, Car2X Communications, 2013
  - European Institute of Technology, LTE in Smart Grids, 2013
  - Hycon2 EU project, Highly-complex and networked control systems, 2010-2014
  - Hydrobionets EU project, Autonomous control of large-scale water treatment plants based on self-organized wireless BI0MEM sensor and actuator networks, 2011-2014
  - Swedish Research Council, In-Network Optimization, 2012-1014
- Educational activities
  - Teaching at PhD, Master and Bachelor level

Outline

- Past, Present and Future in wireless communications
- 60 GHz millimeterWave wireless technology
- Optimizing resource allocation
- Distributed client association (DAA)
- Numerical analysis of DAA
- Conclusions and open research topics

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- **Past, Present and Future in wireless communications**
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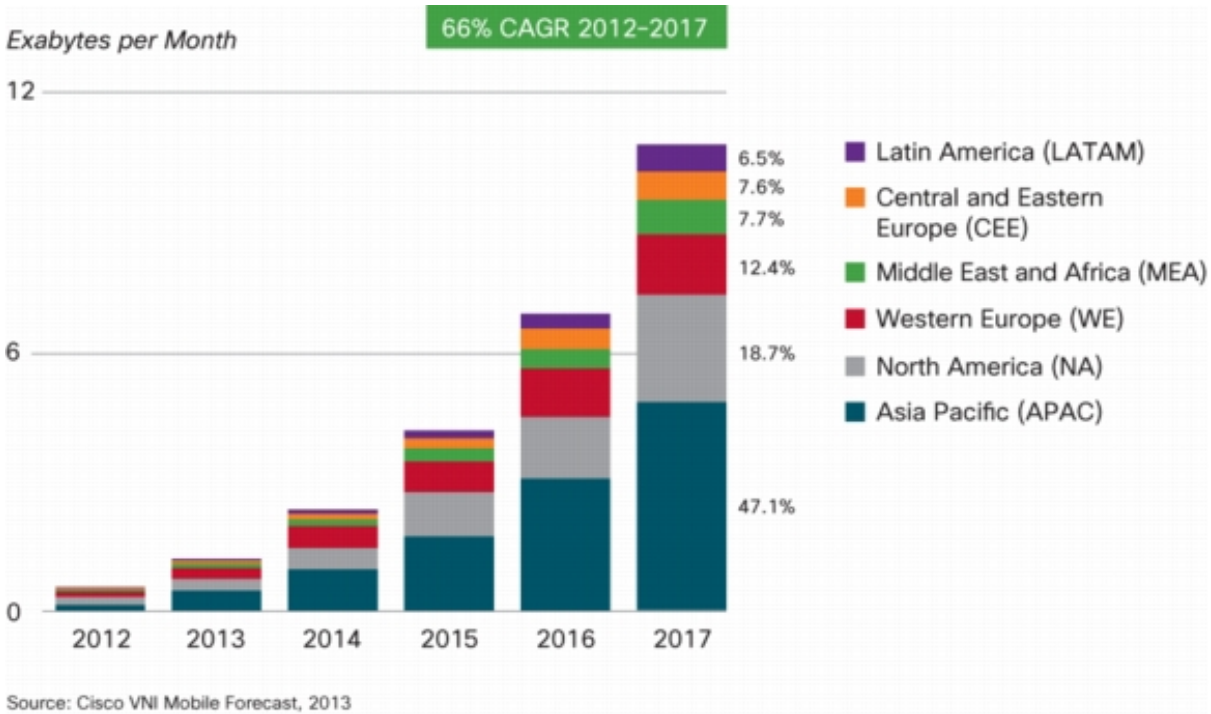
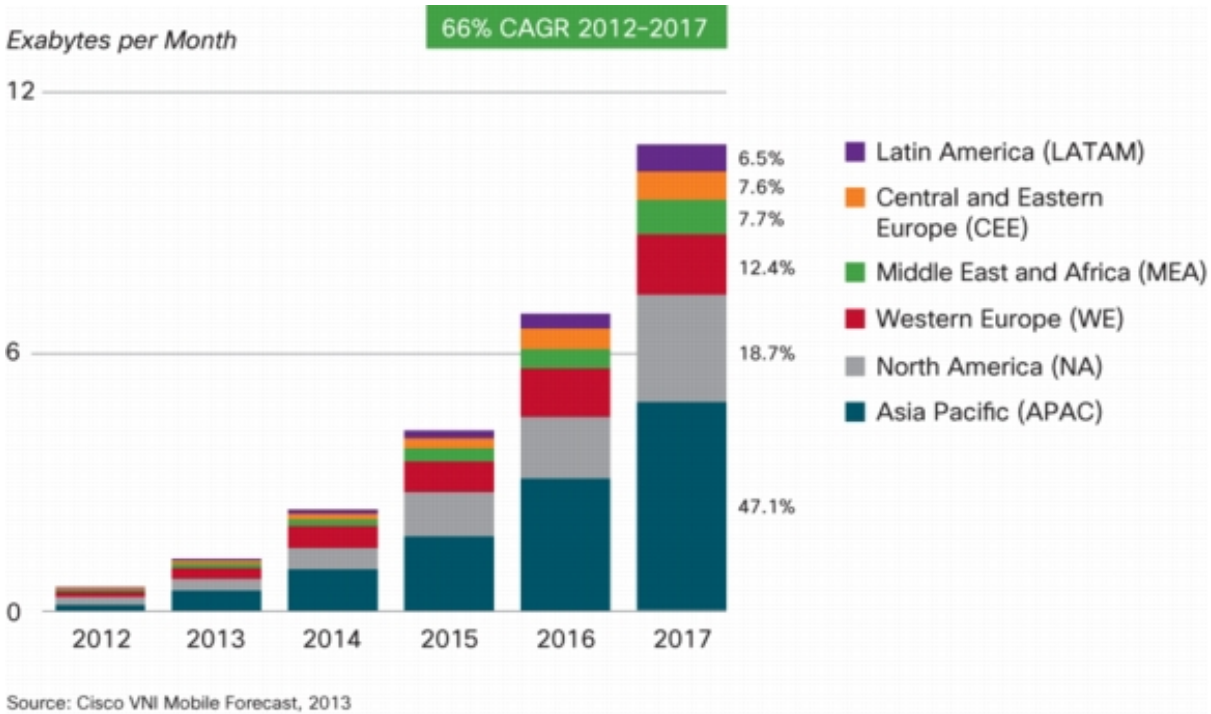
Growth of Mobile Traffic

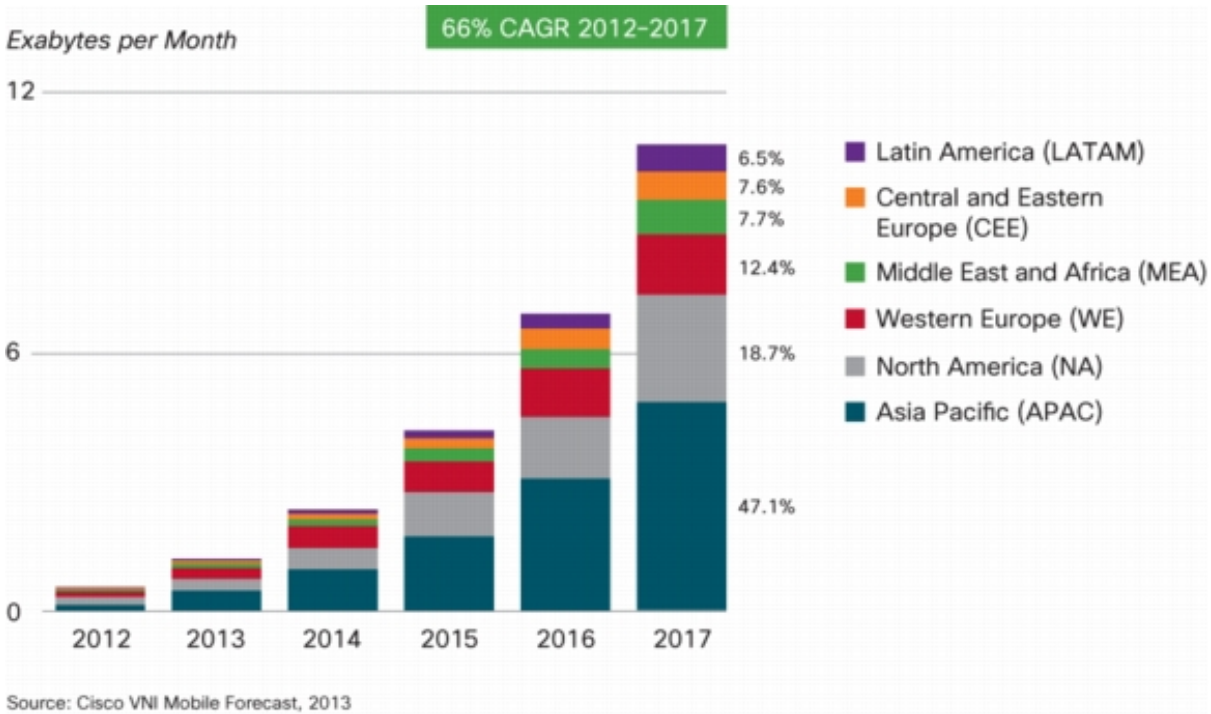


Growth of Mobile Traffic



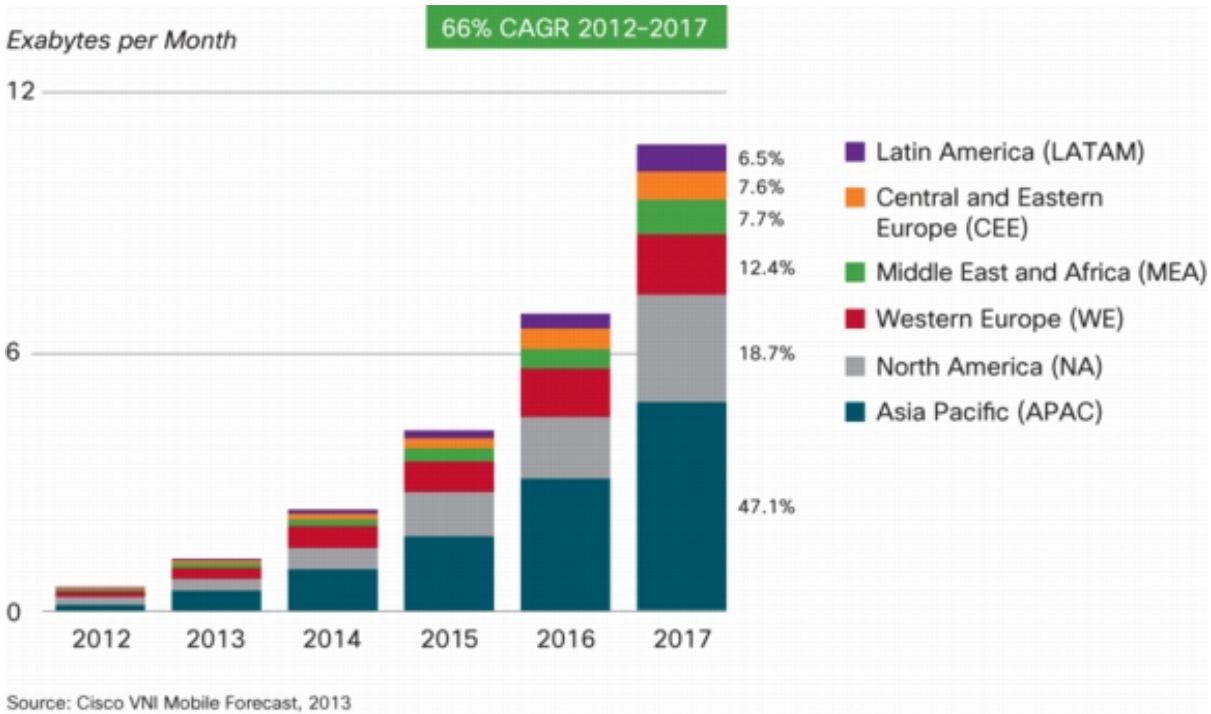
2012: 70% mobile traffic growth compared to 2011

Growth of Mobile Traffic



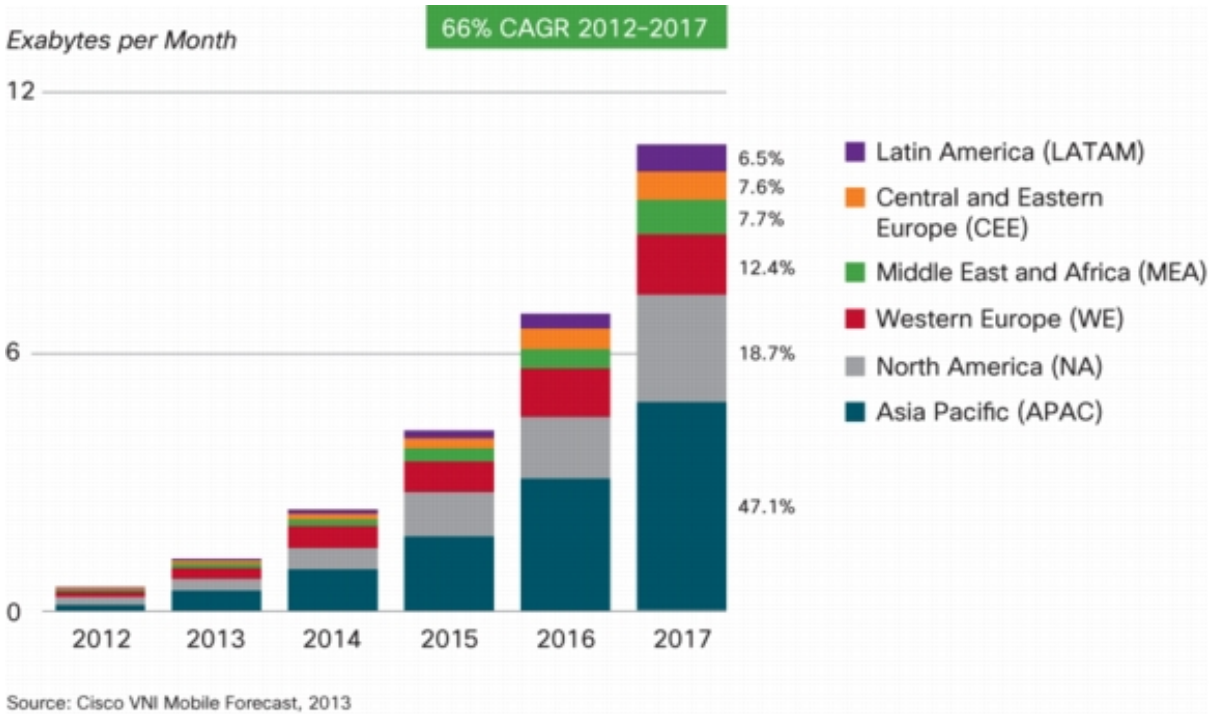
2012: 51% of the mobile traffic was video

Growth of Mobile Traffic



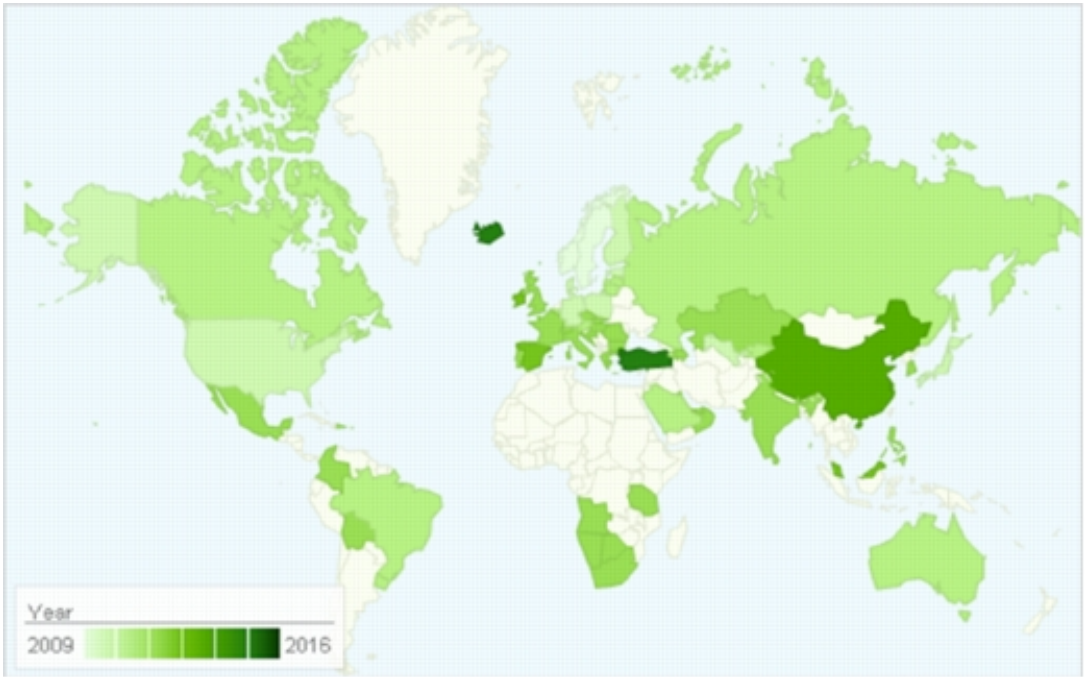
2012: 12 times the entire global internet traffic in 2000

Growth of Mobile Traffic

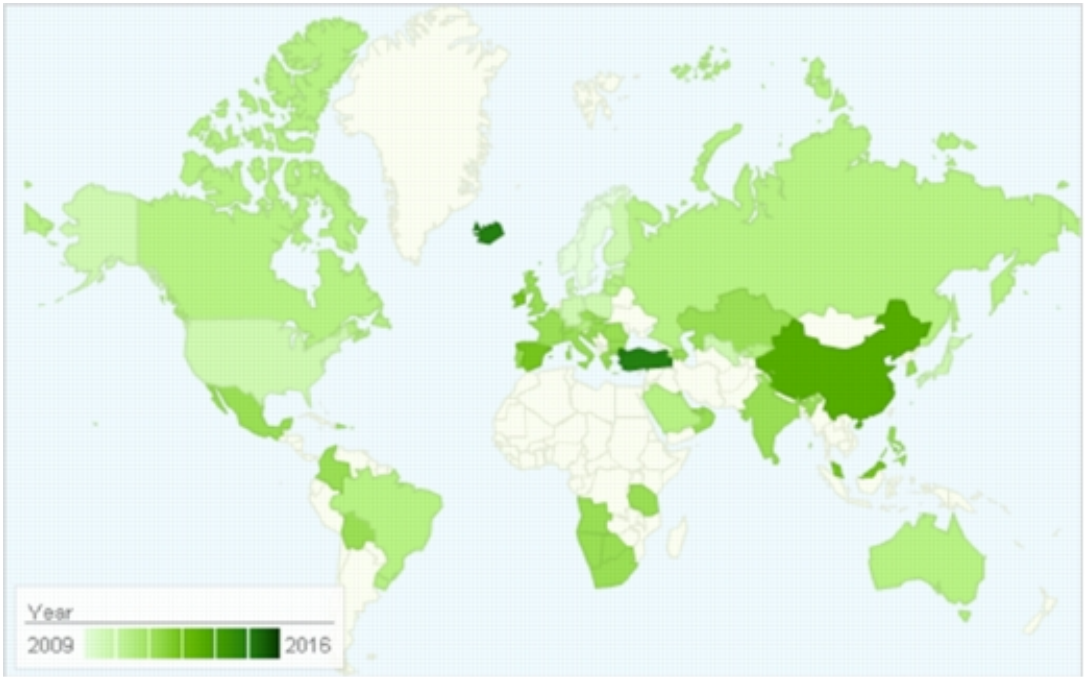


2017: 13 times higher compared to 2012

LTE Deployment

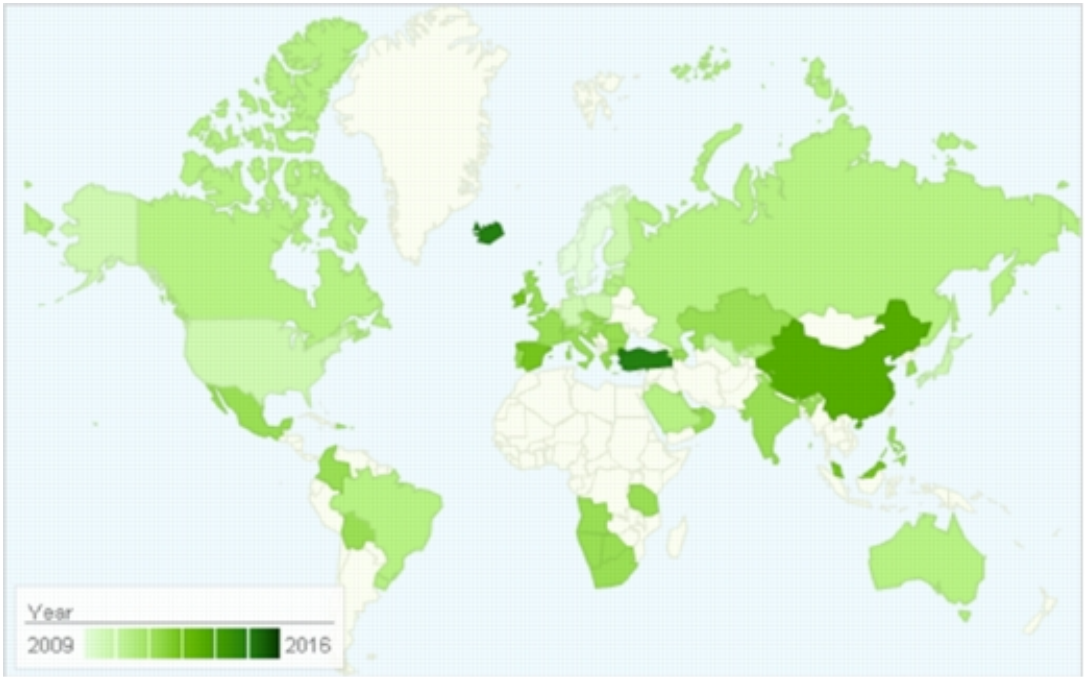


LTE Deployment



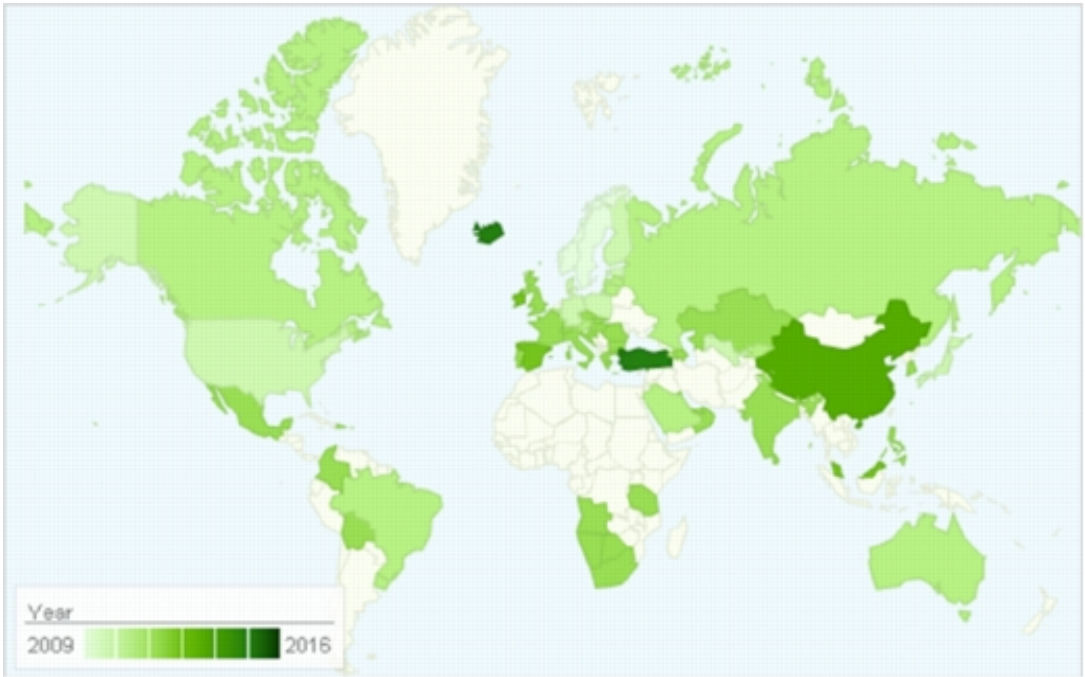
2012: 0.9% of mobile connections

LTE Deployment



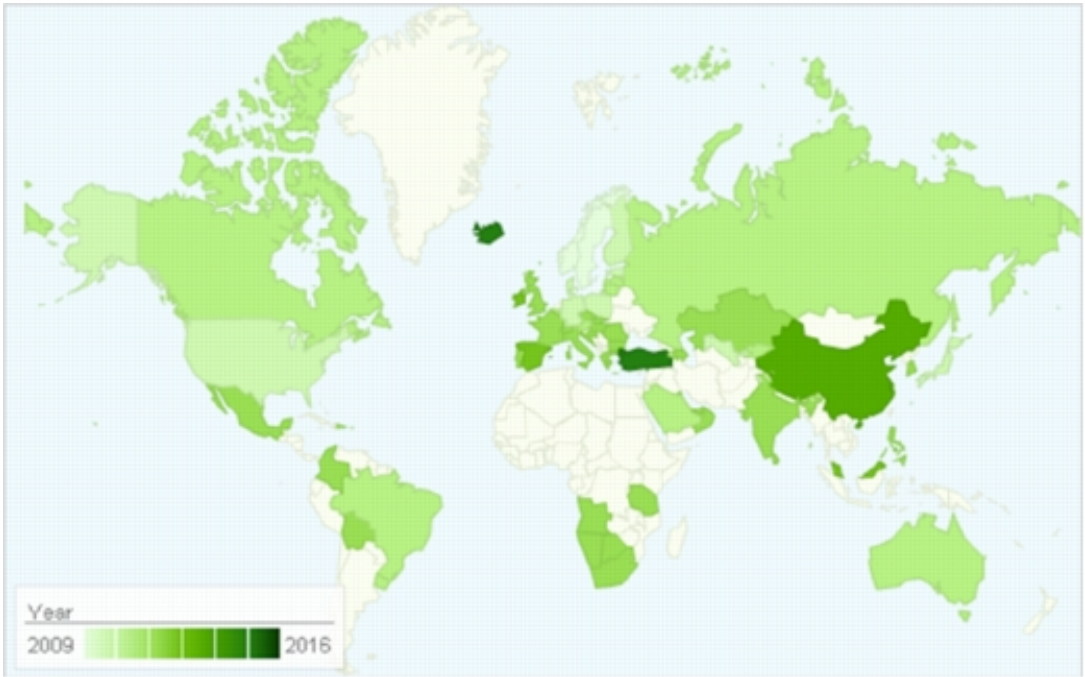
End of 2013: # of mobile connected devices > earth population

LTE Deployment



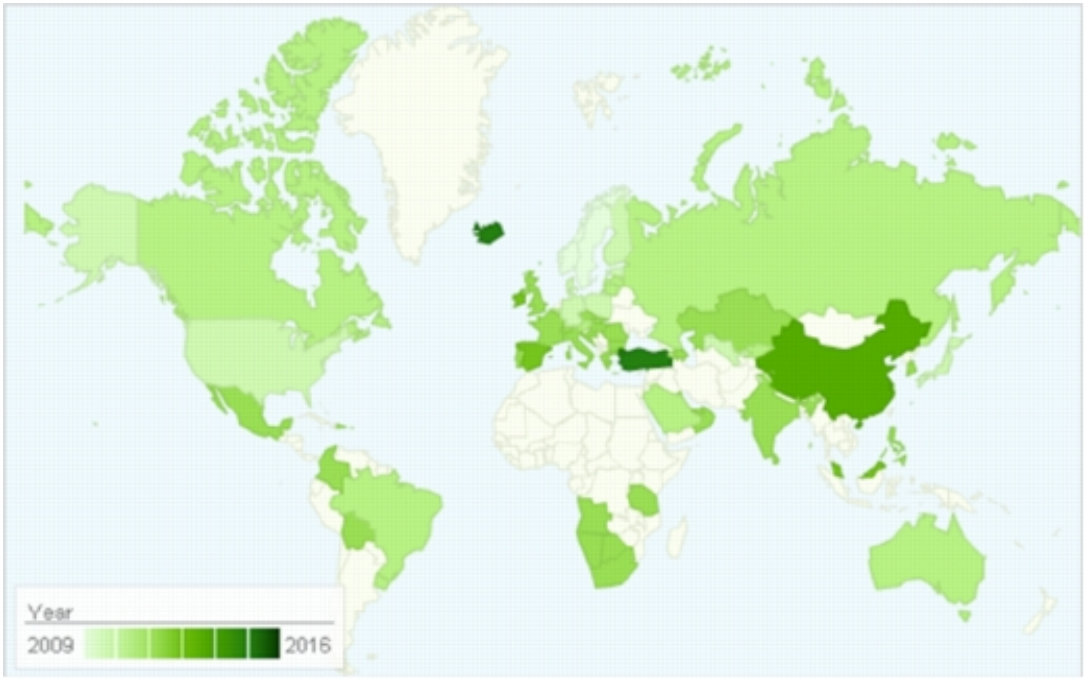
2017: 4G will represent 10% of connections and 45% of mobile traffic

LTE Deployment



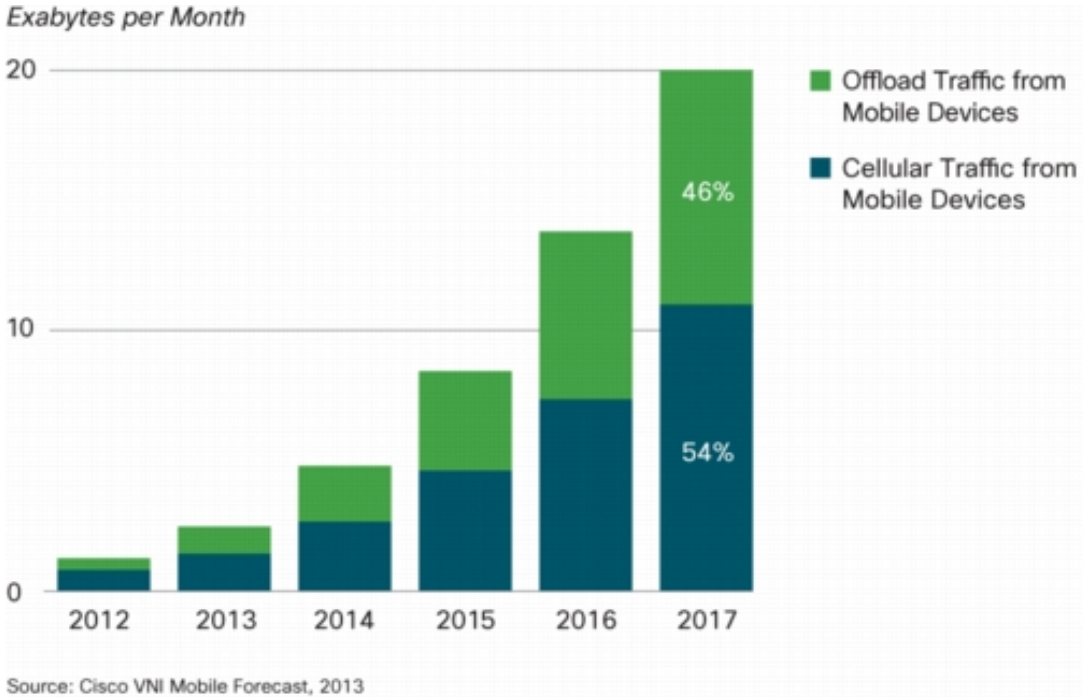
2017: 2/3 will be video

LTE Deployment



2017: 2,7 GB mobile traffic per smartphone per month

Mobile Traffic Offloading



The amount of traffic offloaded from smartphones will be 46%, and the amount of traffic offloaded from tablets will be 71% in 2017 (Cisco, 2013)

90% of all cellular base stations will be small cells by 2016 (IEEE Spectrum Magazine, Informa Telecoms & Media, 2013)

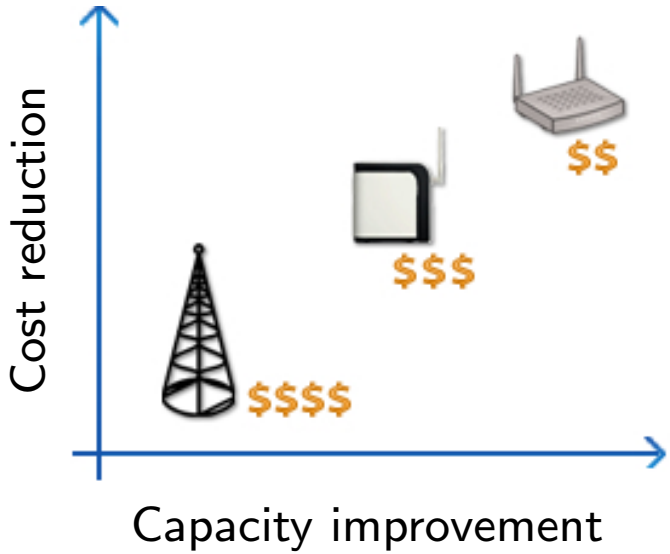
Priorities

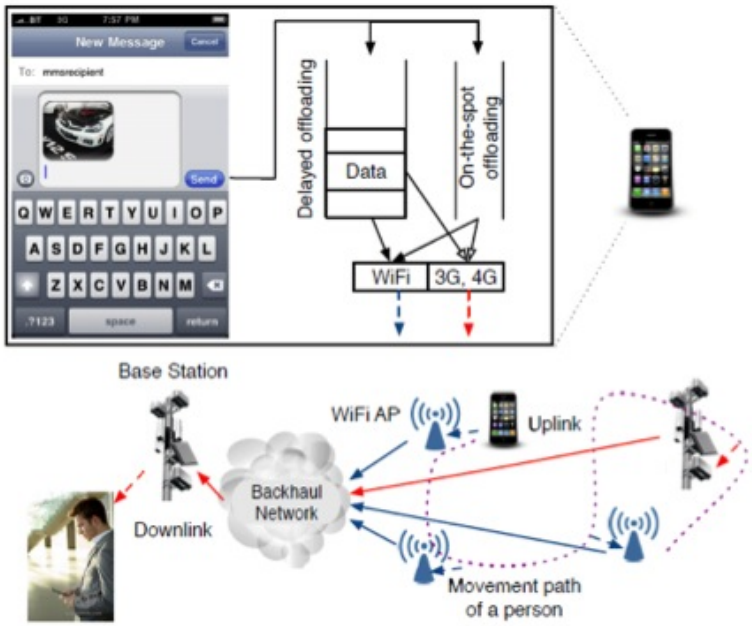
- High bandwidth
- High coverage
- Green
- Cheap

Evolution or Revolution?

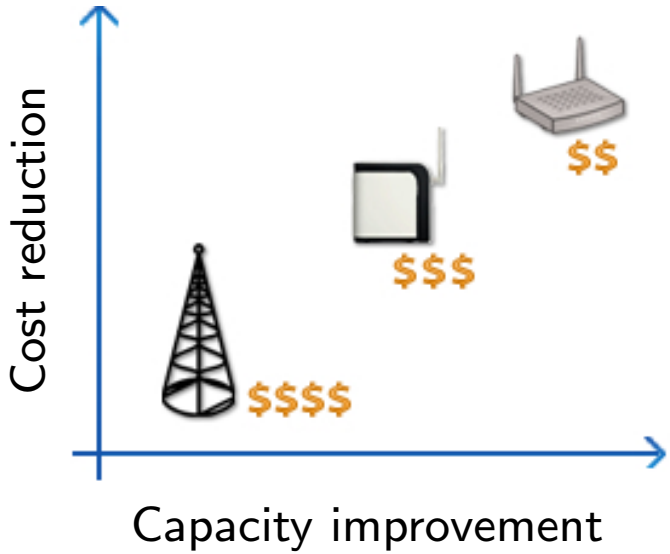
- Infrastructure moves closer to the users
- Devices communicate directly (D2D)
- Base station is “dying”
- Heterogeneous networks converge

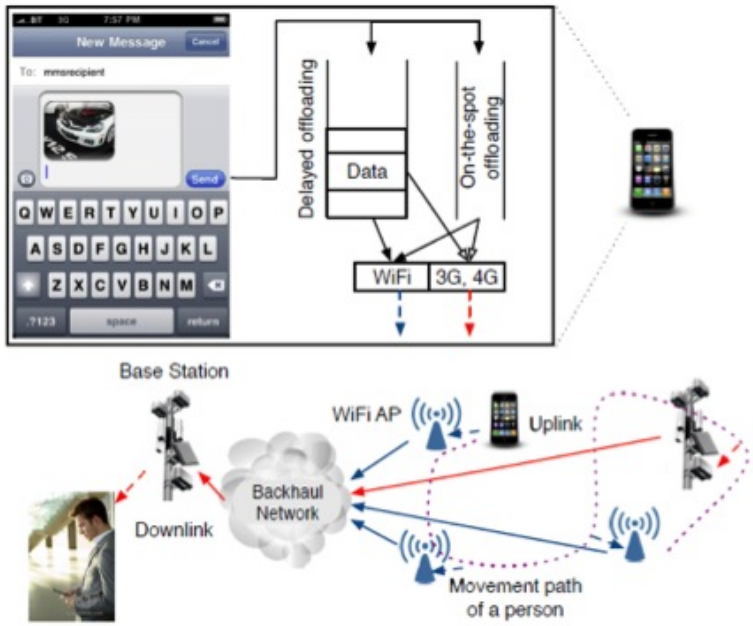
Mobile Data Offloading





Mobile Data Offloading





Are there better solutions for mobile data offloading?

Outline

- Past, Present and Future in wireless communications
- **60 GHz millimeterWave wireless technology**
- Optimizing resource allocation
- Distributed client association (DAA)
- Numerical analysis of DAA
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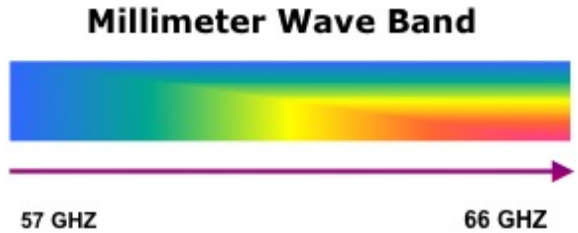
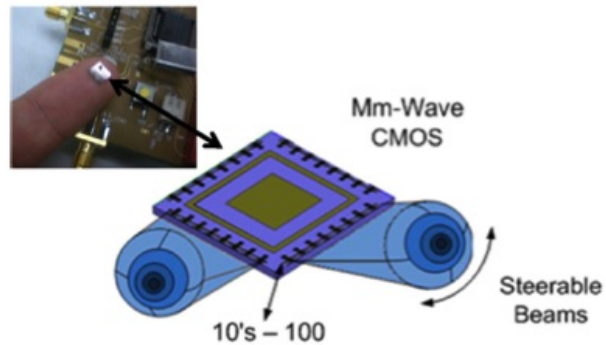
60 GHz Wireless Access Networks

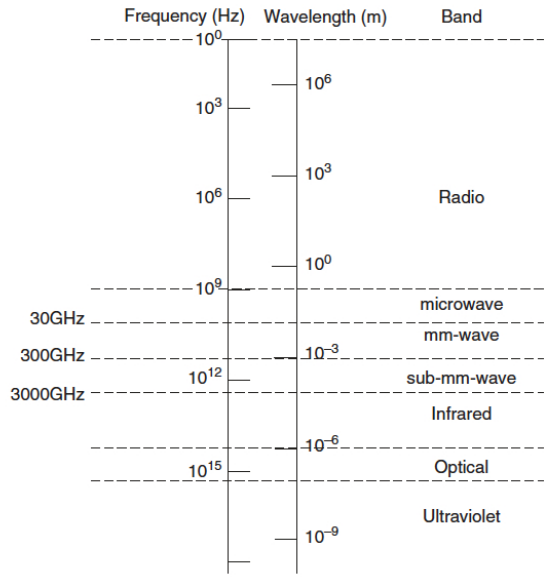
- Unlicensed short range transmissions in the 60 GHz millimeter wave (mmW) band
- Achieve Gbps communication
- Reduced interference
- Low-cost mmW transceivers

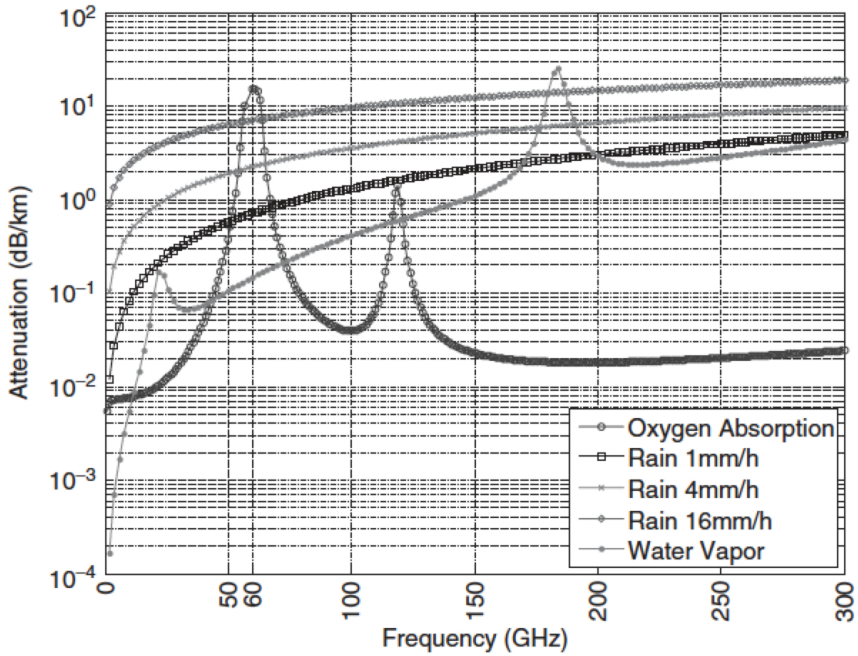




MillimeterWave Band

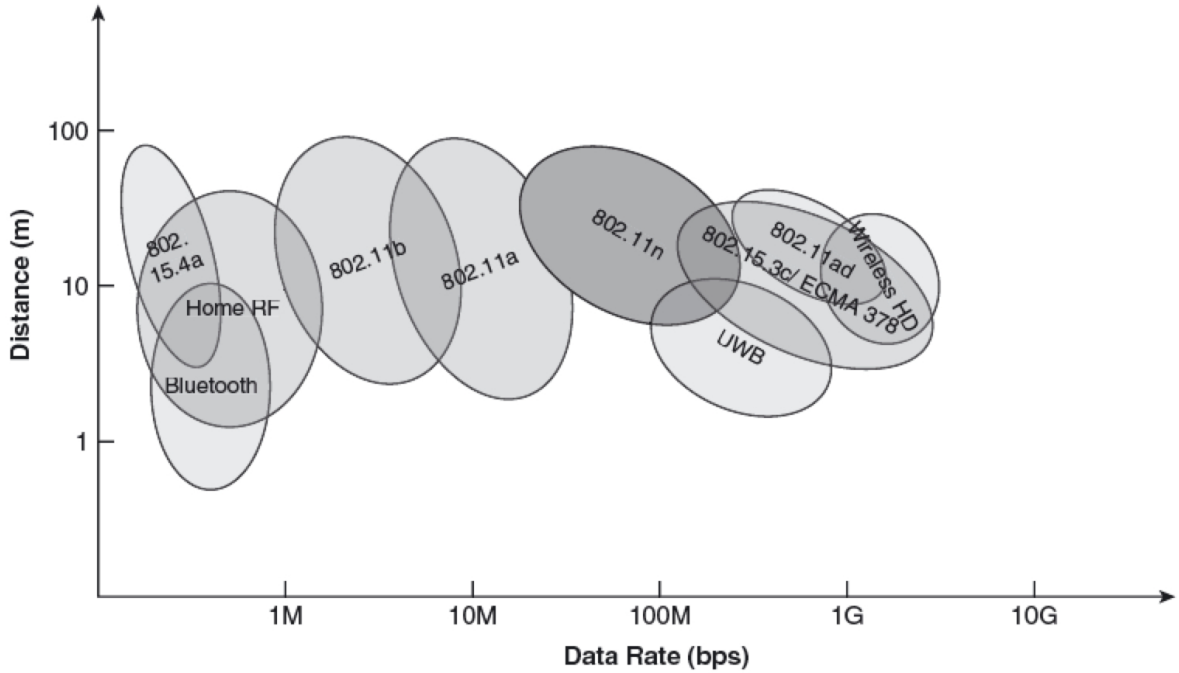
- History (J.C. Bose, 1897)
- High path loss
- High oxygen absorption





60 GHz Wireless Standards

- IEEE 802.11ad
- WiGig
- IEEE 802.15.3c
- WirelessHD
- ECMA-387



Applications

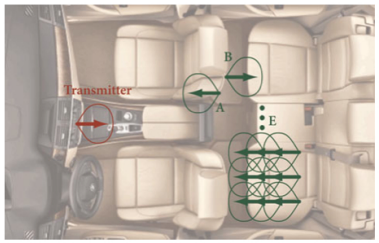
Information Shower

Wireless Gigabit Ethernet

Wireless Pills

File Transfer

In-Car Entertainment

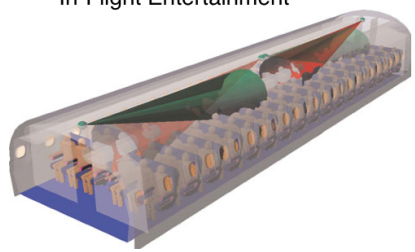


Wireless Library

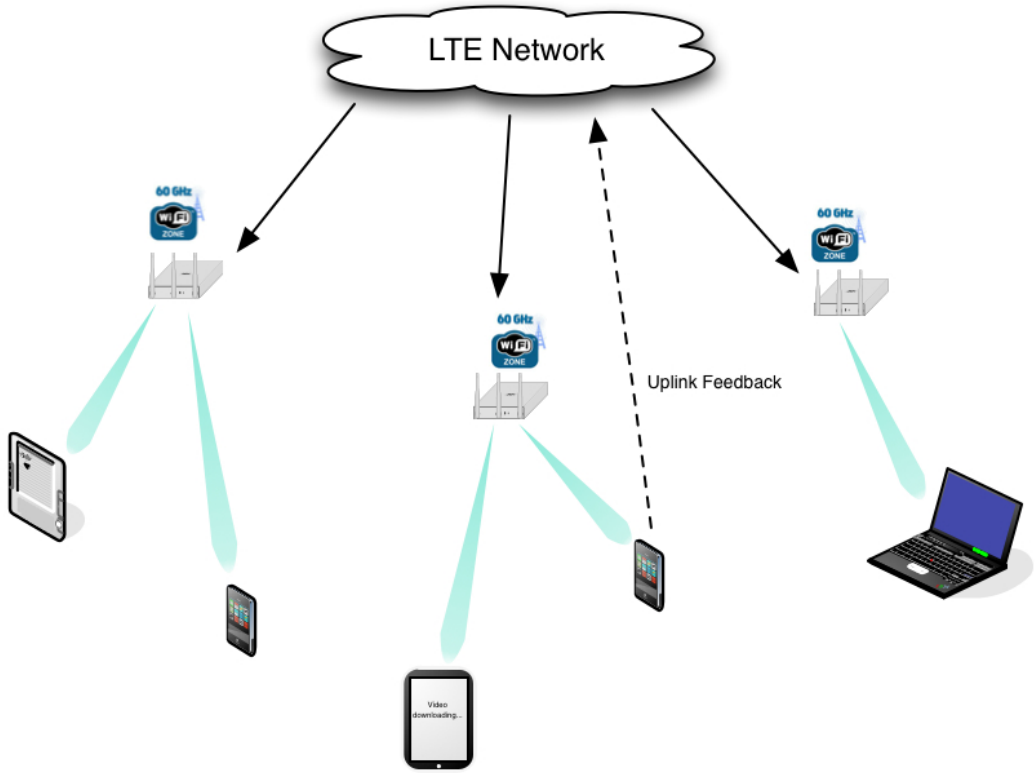
Wireless Video Cameras - Monitoring

Aircraft Structure Monitoring

In-Flight Entertainment



60 GHz to the Mobile



- 60 GHz small base stations (eg. on lamp posts)
- Downlink offload traffic in 60 GHz band with uplink LTE feedback
- 60 GHz radio on mobile device in receive-only mode

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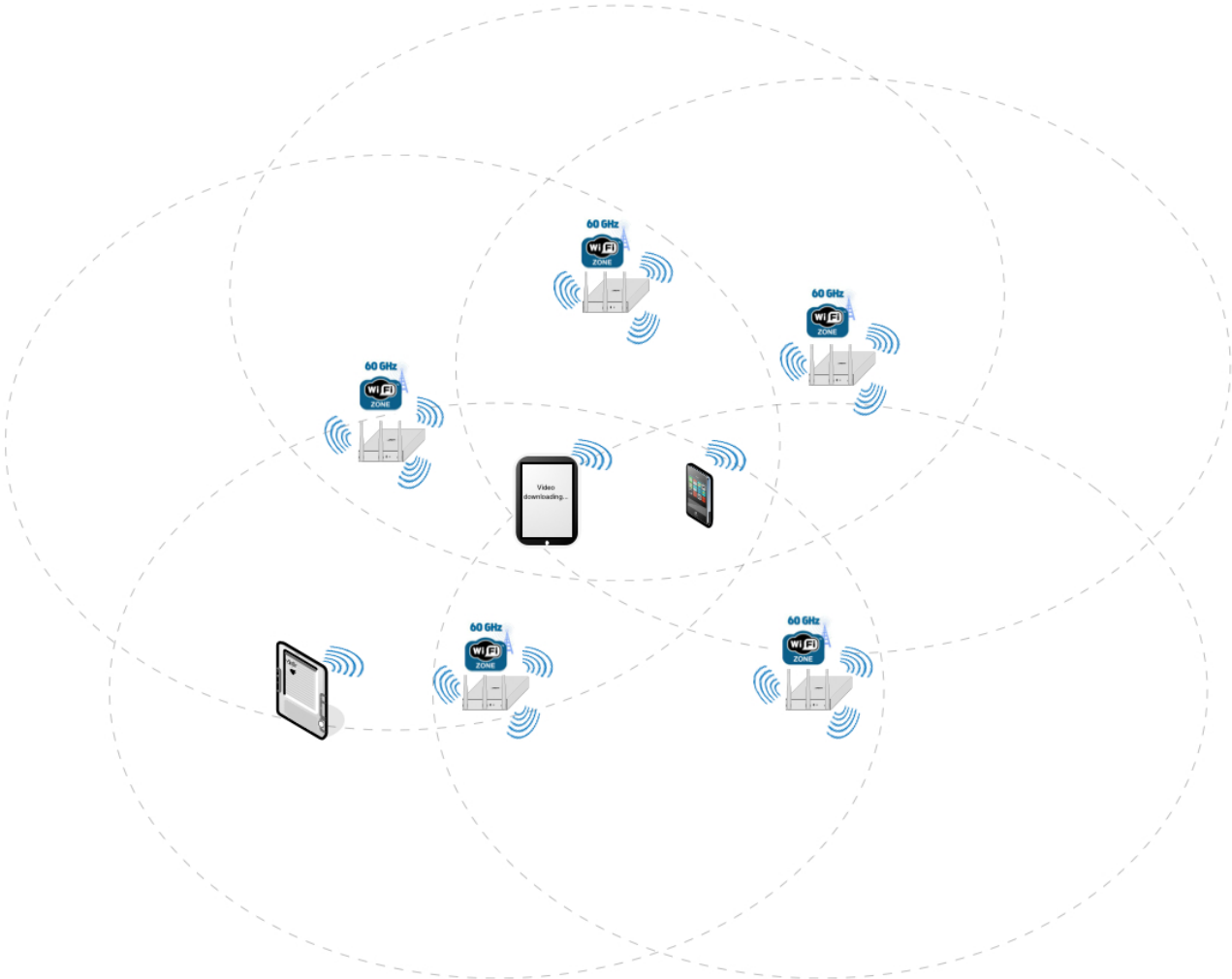
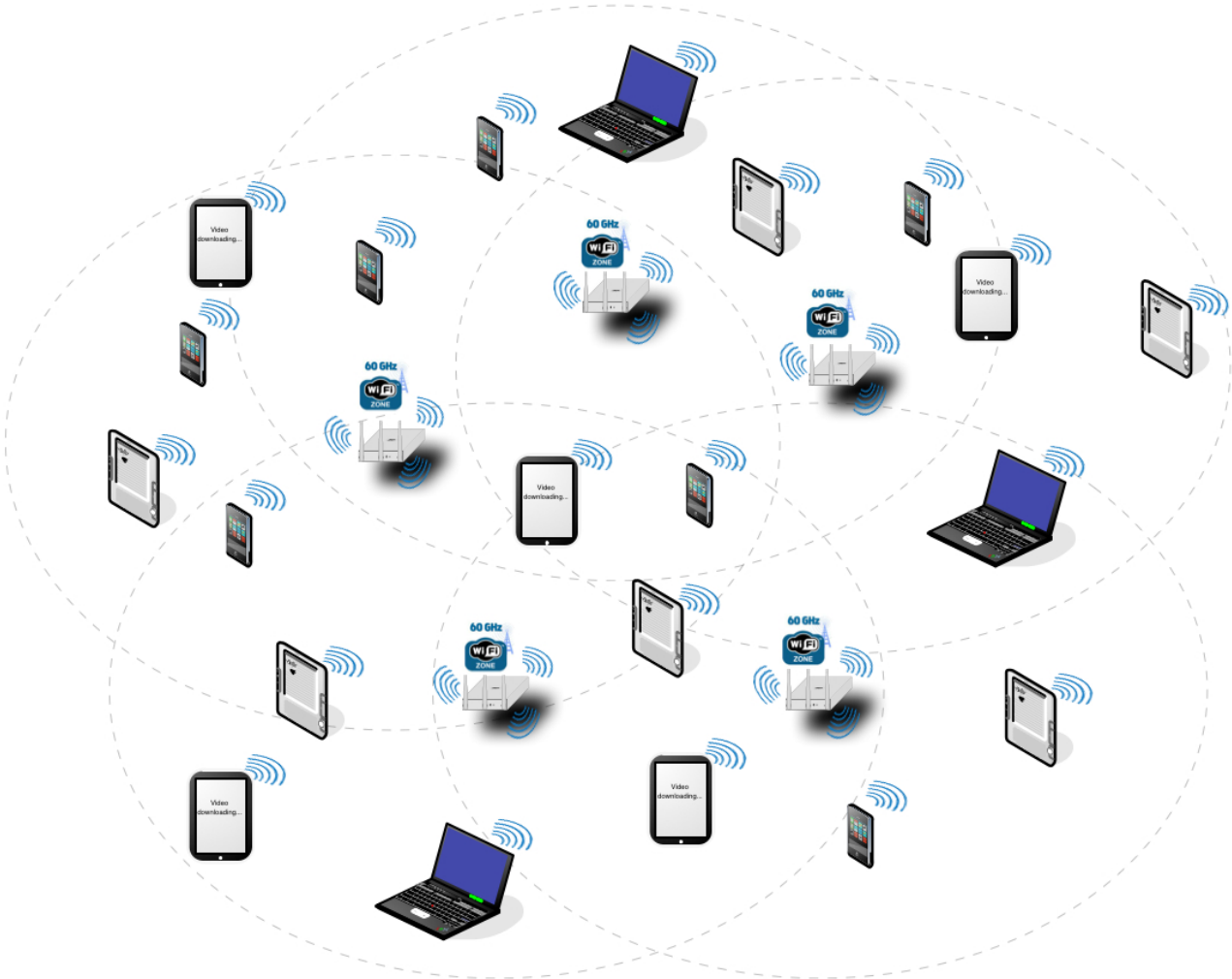
Optimizing Client Association in 60 GHz Wireless Access Networks



Optimizing Client Association in 60 GHz Wireless Access Networks

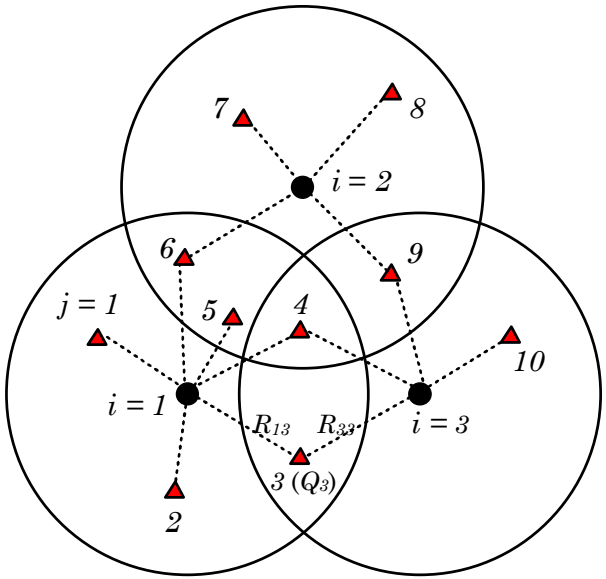


Optimizing Client Association in 60 GHz Wireless Access Networks

- **Goal**: Minimize the maximum access point (AP) utilization in the network and ensure fair load distribution
- **Solution**: Distributed algorithm for client association based on Lagrangian duality theory and subgradient methods
- **Results**: Theoretical and numerical analysis

G. Athanasiou, P. C. Weeraddana, C. Fischione and L. Tassiulas, "Optimizing Client Association in 60 GHz Wireless Access Networks", *arXiv:1301.2723, Cornell University Library*, 2013 [Online]. Available: `http://arxiv.org/abs/1301.2723`

System Model



W	System bandwidth
P_{ij}	Transmission power of AP i to client j
G_{ij}	Power gain from AP i to client j
N_0	Power spectral density of the noise
I_j	Interference spectral density at client j
$\mathcal{M}_i$	Set of clients that can be associated to AP i
$\mathcal{N}_j$	Set of APs that client j could be associated with

- $\mathcal{N} = \{1, \ldots, N\}$ APs and $\mathcal{M} = \{1, \ldots, M\}$ clients
- Achievable rate from AP i to client $j \in \mathcal{M}_i$ is

$$R_{ij} = W \log_2 \left(1 + \frac{P_{ij} G_{ij}}{(N_0 + I_j) W} \right)$$

- Q_j is the demanded data rate of client j

System Model

- Channel utilization between AP i and client j is

$$\beta_{ij} = \frac{Q_j}{R_{ij}}$$

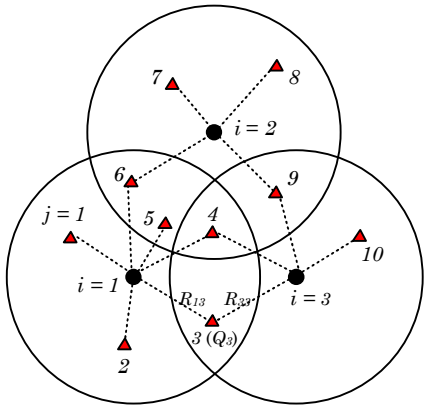
- Utilization of AP i is

$$\sum_{j \in \mathcal{M}_i} \beta_{ij} x_{ij}$$

- $(x_{ij})_{j \in \mathcal{M}_i}$ are binary decision variables, which indicate the client association

$$x_{ij} = \begin{cases} 1 & \text{if client } j \text{ is associated to AP } i \\ 0 & \text{otherwise} \end{cases}$$

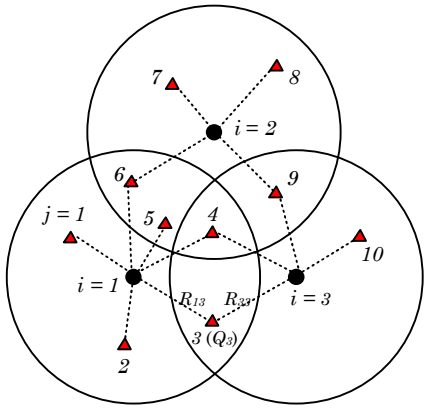
Client Association Problem Formulation



$$\begin{aligned}
\text{minimize} \quad & \max_{i \in \mathcal{N}} \ \textstyle\sum_{j \in \mathcal{M}_i} \beta_{ij} \ x_{ij} \\
\text{subject to} \quad & Q_j x_{ij} \leq R_{ij}, \ i \in \mathcal{N}, j \in \mathcal{M}_i \\
& \textstyle\sum_{i \in \mathcal{N}_j} x_{ij} = 1, \ j \in \mathcal{M} \\
& x_{ij} \in \{0, 1\}, \ j \in \mathcal{M}, i \in \mathcal{N}_j
\end{aligned}$$

- Variable: $(x_{ij})_{i \in \mathcal{N}, \ j \in \mathcal{M}_i}$
- Main problem parameters: $(\beta_{ij})_{i \in \mathcal{N}, j \in \mathcal{M}_i}$, $(Q_j)_{j \in \mathcal{M}}$, $(R_{ij})_{i \in \mathcal{N}, j \in \mathcal{M}_i}$
- Constraints: a) The demand of client j is less or equal to the achievable rate from AP i to client j, b) Client j can only be assigned to one AP, c) The decision variables are binary

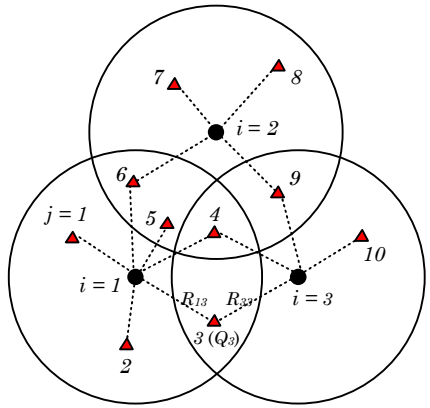
Equivalent Epigraph Form



$$
\begin{aligned}
\text{minimize} \quad & t \\
\text{subject to} \quad & \textstyle\sum_{j \in \mathcal{M}_i} \beta_{ij}\ x_{ij} \leq t,\ i \in \mathcal{N} \\
& \textstyle\sum_{i \in \mathcal{N}_j} x_{ij} = 1,\ j \in \mathcal{M} \\
& x_{ij} \in \{0,1\},\ j \in \mathcal{M}, i \in \mathcal{N}_j
\end{aligned}
$$

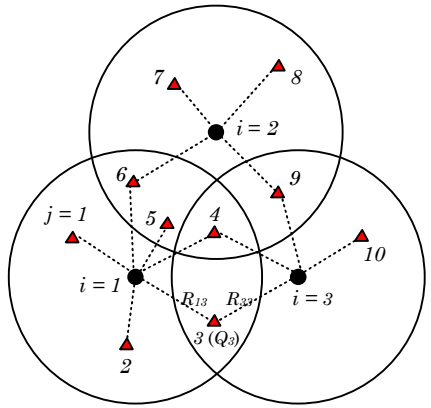
- Variable: $(x_{ij})_{i \in \mathcal{N},\ j \in \mathcal{M}_i}$ and t
- Main problem parameters: $(\beta_{ij})_{i \in \mathcal{N}, j \in \mathcal{M}_i}$
- Mixed integer linear program (MILP)

Solution Method Challenges



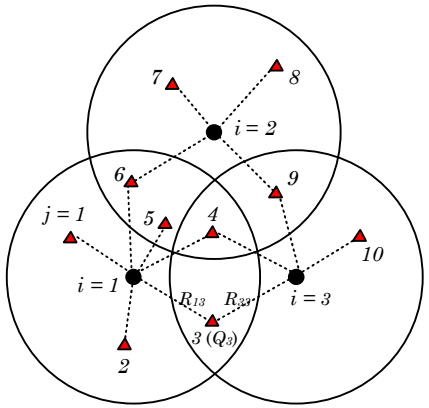
- Existing **MILP** solvers are **centralized**
- Typically based on global branch and bound algorithms $\Rightarrow$ the **worst-case complexity grows exponentially** with the problem size
- **Even small** problems, with a few tens of variables, can take a **very long time**

Solution Method Challenges



- Existing **MILP** solvers are **centralized**
- Typically based on global branch and bound algorithms $\Rightarrow$ the **worst-case complexity grows exponentially** with the problem size
- **Even small** problems, with a few tens of variables, can take a **very long time**
- **Our approach: Lagrangian duality + Subgradient methods $\Rightarrow$ decentralized**

Lagrangian Duality



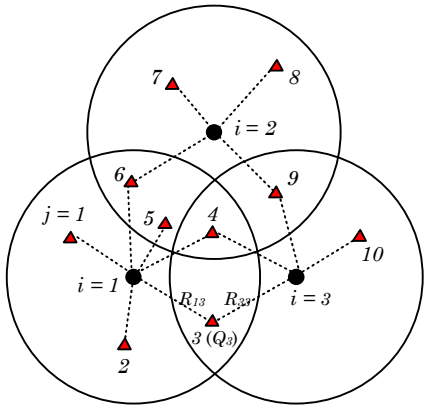
Partial Lagrangian

$$L(t, \mathbf{x}, \boldsymbol{\lambda}) = t + \sum_{i \in \mathcal{N}} \lambda_i \left(\sum_{j \in \mathcal{M}_i} \beta_{ij} x_{ij} - t \right)$$

$$= t \left(1 - \sum_{i \in \mathcal{N}} \lambda_i \right) + \sum_{j \in \mathcal{M}} \sum_{i \in \mathcal{N}_j} \beta_{ij} \lambda_i x_{ij}$$

$\boldsymbol{\lambda} = (\lambda_i)_{i \in \mathcal{N}}$: multipliers for the first set of inequality constraints

Lagrangian Duality



Partial Lagrangian

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$$= t\left(1 - \sum_{i\in\mathcal{N}} \lambda_i\right) + \sum_{j\in\mathcal{M}} \sum_{i\in\mathcal{N}_j} \beta_{ij}\lambda_i x_{ij}$$

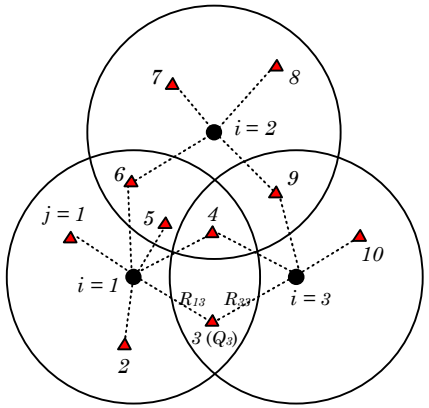
$\boldsymbol{\lambda} = (\lambda_i)_{i\in\mathcal{N}}$: multipliers for the first set of inequality constraints

Dual function

$$g(\boldsymbol{\lambda}) = \inf_{\substack{t\in\mathbb{R} \\ \mathbf{x}\in\mathcal{X}}} L(t,\mathbf{x},\boldsymbol{\lambda})$$

$$\mathcal{X} = \left\{ \mathbf{x}=(x_{ij})_{j\in\mathcal{M},i\in\mathcal{N}_j} \,\middle|\, \sum_{i\in\mathcal{N}_j} x_{ij}=1,\ x_{ij}\in\{0,1\},\ j\in\mathcal{M}\ i\in\mathcal{N}_j \right\}.$$

Lagrangian Duality



Dual problem

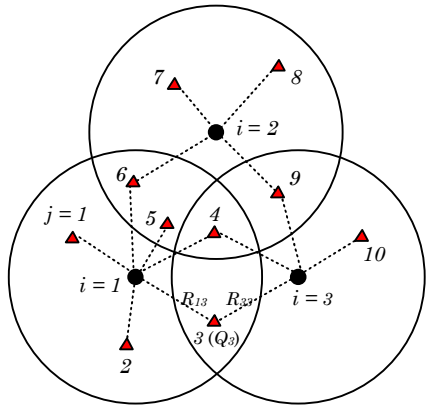
$$\begin{aligned} \text{maximize} \quad & g(\boldsymbol{\lambda}) = \textstyle\sum_{j\in\mathcal{M}} g_j(\boldsymbol{\lambda}) \\ \text{subject to} \quad & \textstyle\sum_{i\in\mathcal{N}} \lambda_i = 1 \\ & \lambda_i \geq 0, \ i \in \mathcal{N} \end{aligned}$$

- Variables: $\boldsymbol{\lambda} = (\lambda_i)_{i\in\mathcal{N}}$
- $g_j(\boldsymbol{\lambda})$ is the optimal value of the **subproblem**

$$\begin{aligned} \text{minimize} \quad & \textstyle\sum_{i\in\mathcal{N}_j} \beta_{ij}\lambda_i x_{ij} \\ \text{subject to} \quad & \mathbf{x}_j \in \mathcal{X}_j \ , \end{aligned}$$

with the variable $\mathbf{x}_j$.

Lagrangian Duality



Dual problem

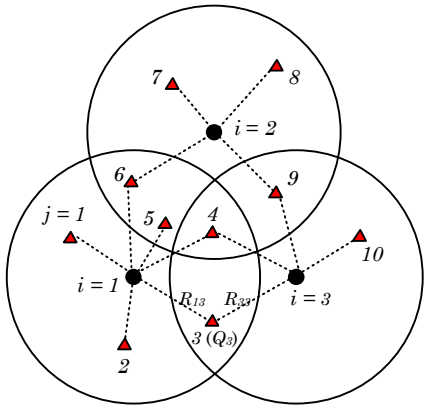
$$\begin{aligned} \text{maximize} \quad & g(\boldsymbol{\lambda}) = \textstyle\sum_{j\in\mathcal{M}} g_j(\boldsymbol{\lambda}) \\ \text{subject to} \quad & \textstyle\sum_{i\in\mathcal{N}} \lambda_i = 1 \\ & \lambda_i \geq 0, \;\; i \in \mathcal{N} \end{aligned}$$

- Variables: $\boldsymbol{\lambda} = (\lambda_i)_{i\in\mathcal{N}}$
- $g_j(\boldsymbol{\lambda})$ is the optimal value of the **subproblem**

$$\begin{aligned} \text{minimize} \quad & \textstyle\sum_{i\in\mathcal{N}_j} \beta_{ij}\lambda_i x_{ij} \\ \text{subject to} \quad & \mathbf{x}_j \in \mathcal{X}_j \;, \end{aligned} \longrightarrow \text{solved @ client } j$$

with the variable $\mathbf{x}_j$.

Subgradient Method



Subgradient method to solve dual problem

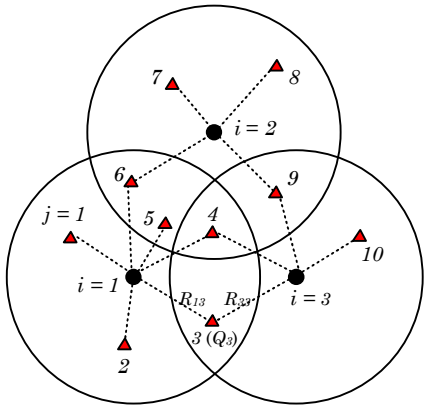
$$\boldsymbol{\lambda}^{(k+1)} = P\big(\boldsymbol{\lambda}^{(k)} - \alpha_k \mathbf{u}^{(k)}\big)$$

- P: Euclidean projection onto the unit simplex $\Pi = \{\boldsymbol{\lambda} \,|\, \sum_{i\in\mathcal{N}} \lambda_i = 1, \lambda_i \geq 0\}$
- $\alpha_k > 0$ is the kth step size
- $\mathbf{u}^{(k)} = \left(u_i^{(k)}\right)_{i\in\mathcal{N}}$: a subgradient of $-g$ at $\boldsymbol{\lambda}^{(k)}$, where

$$u_i^{(k)} = -\sum_{j\in\mathcal{M}_i} \beta_{ij} x_{ij}^{\star} \ ,$$

and $(x_{ij}^{\star})_{j\in\mathcal{M}_i}$ is the solution of the ith subproblems with $\boldsymbol{\lambda} = \boldsymbol{\lambda}^{(k)}$

Subgradient Method



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price update

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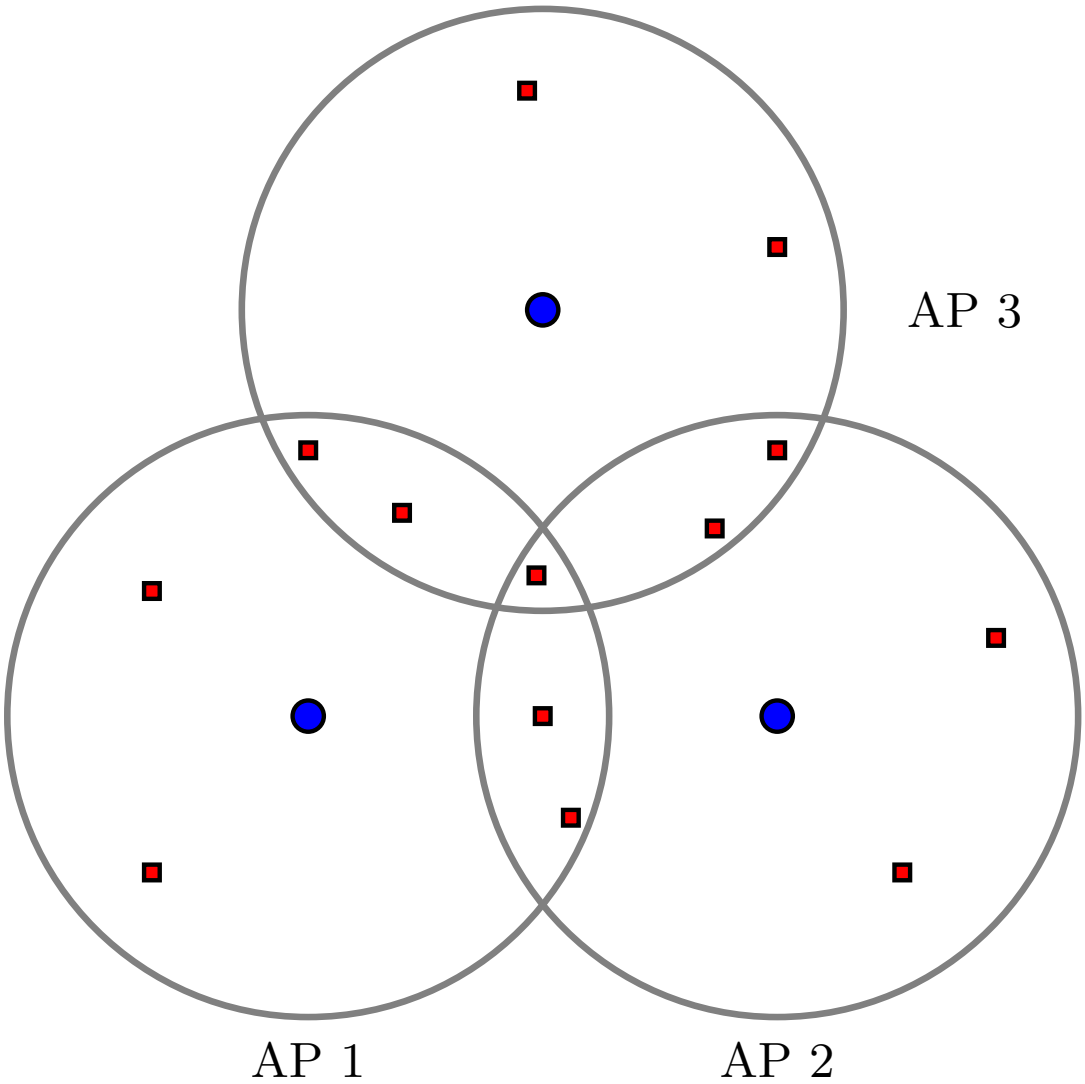
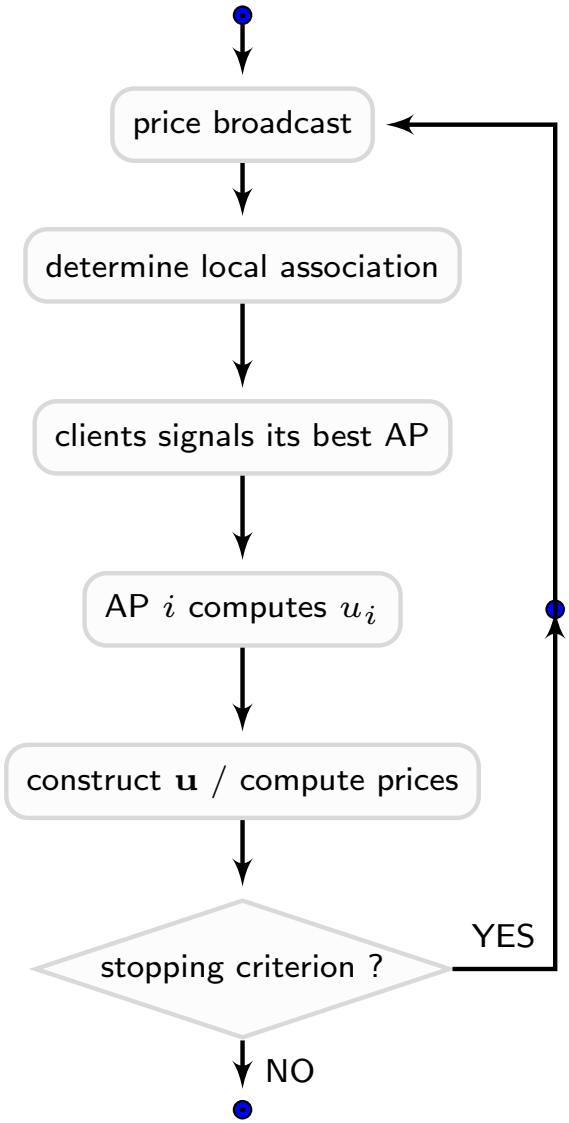
Outline

- Past, Present and Future in wireless communications
- 60 GHz millimeterWave wireless technology
- Optimizing resource allocation
- **Distributed client association (DAA)**
- Numerical analysis of DAA
- Conclusions and open research topics

DAA Illustration





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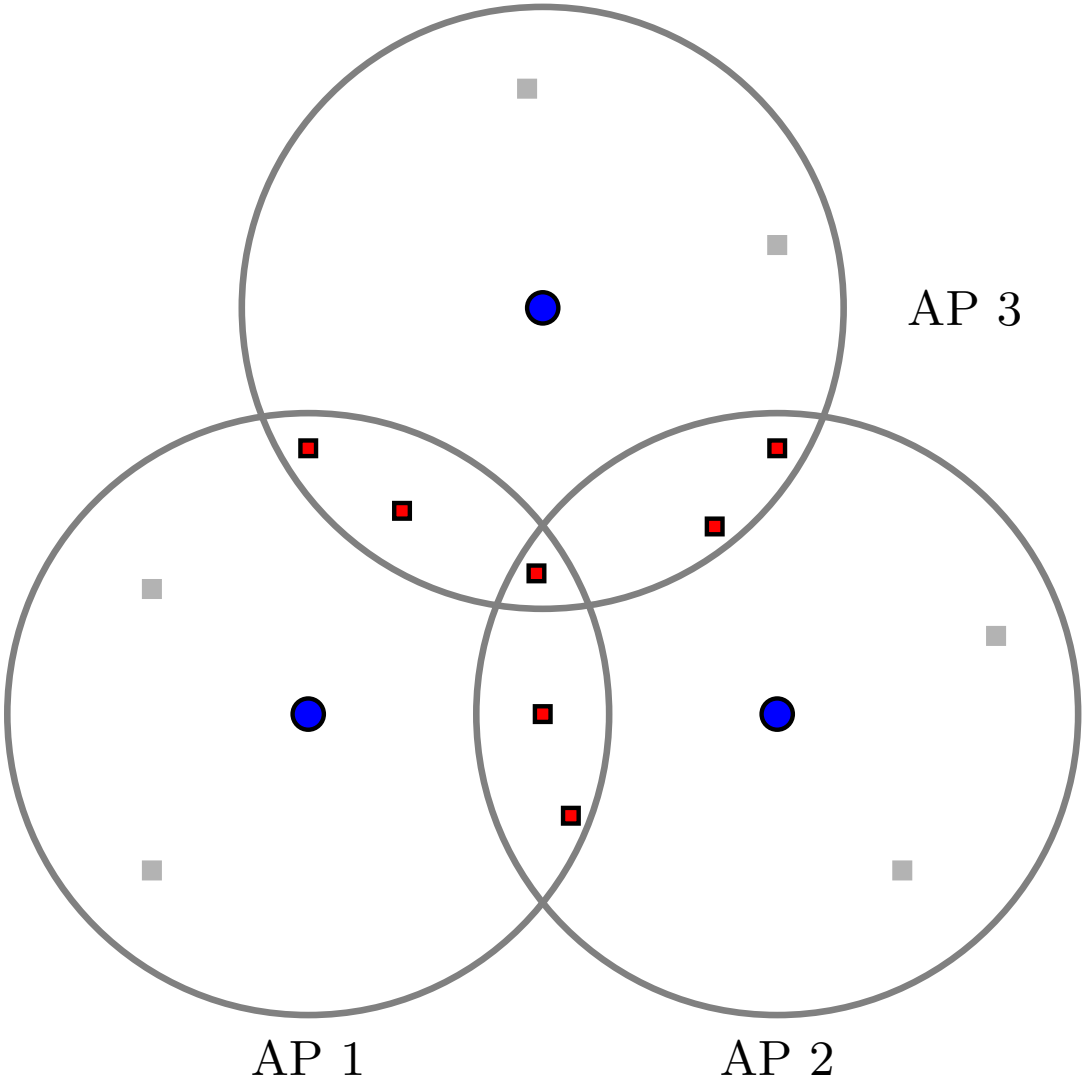

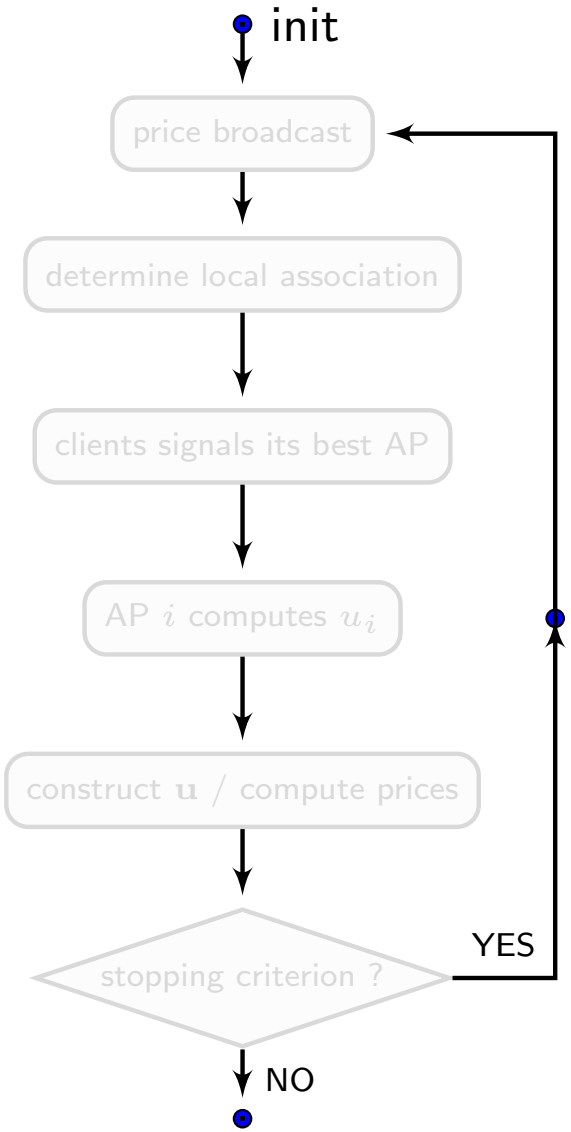

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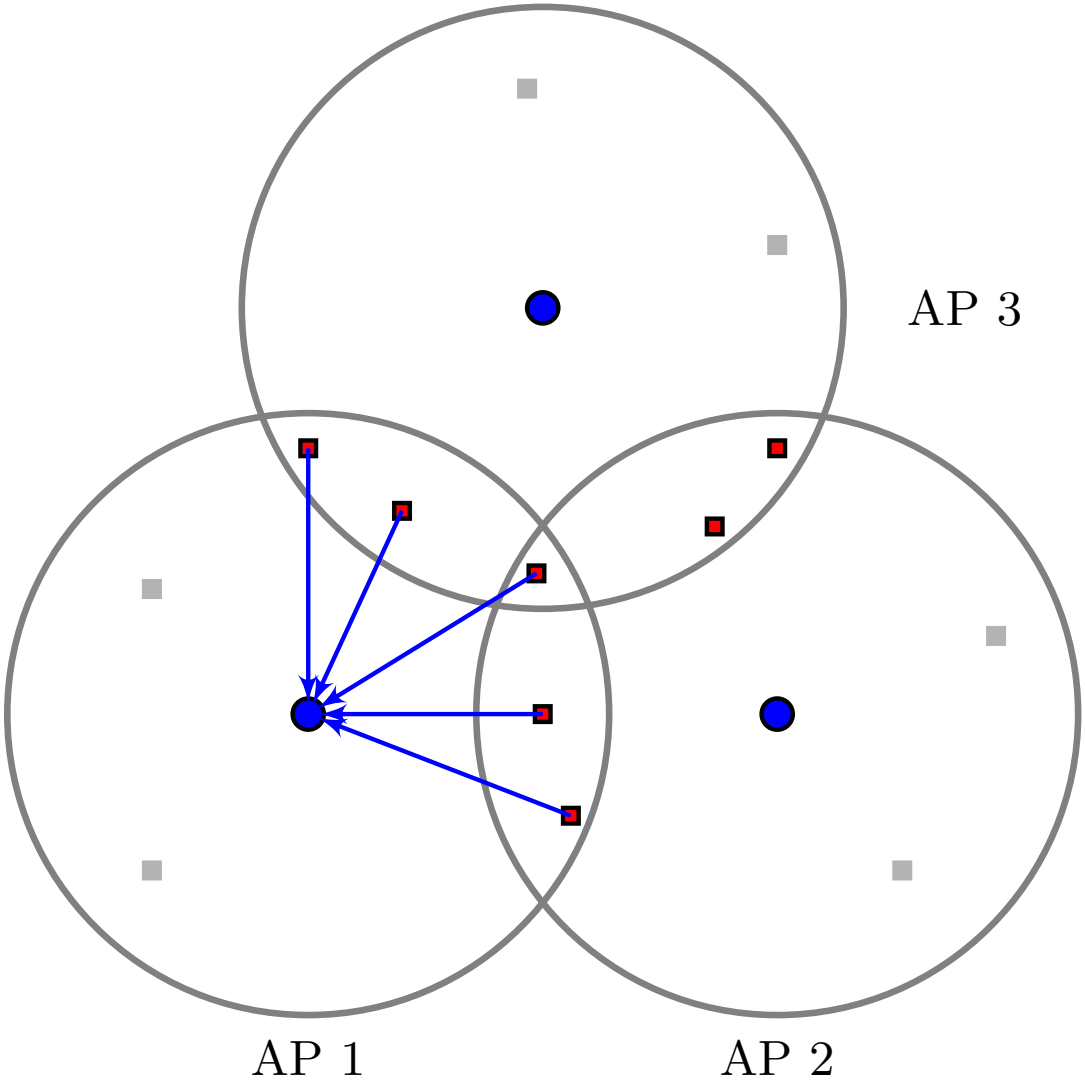

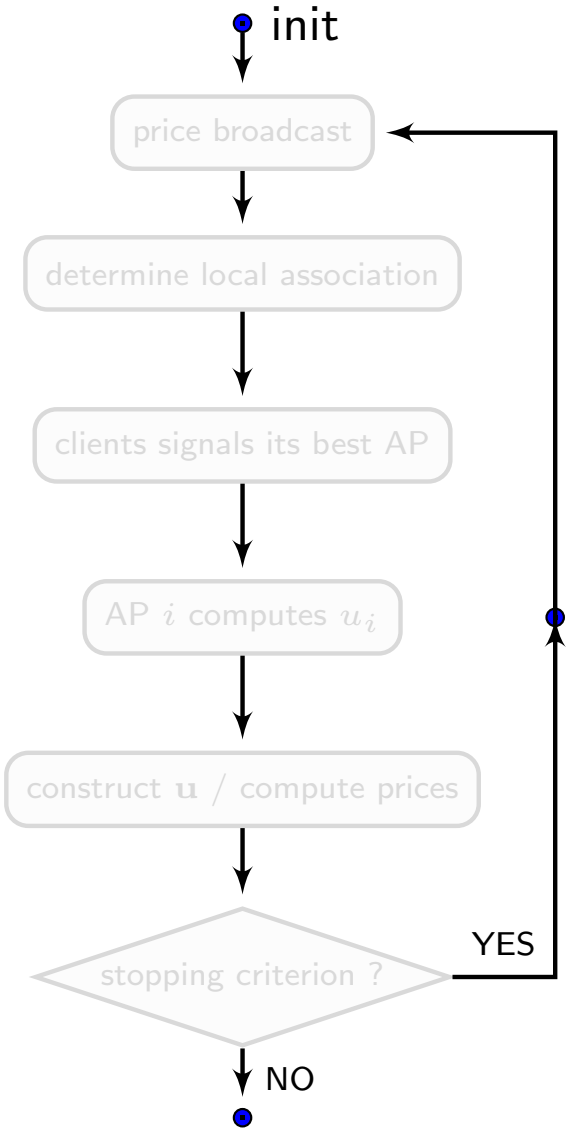

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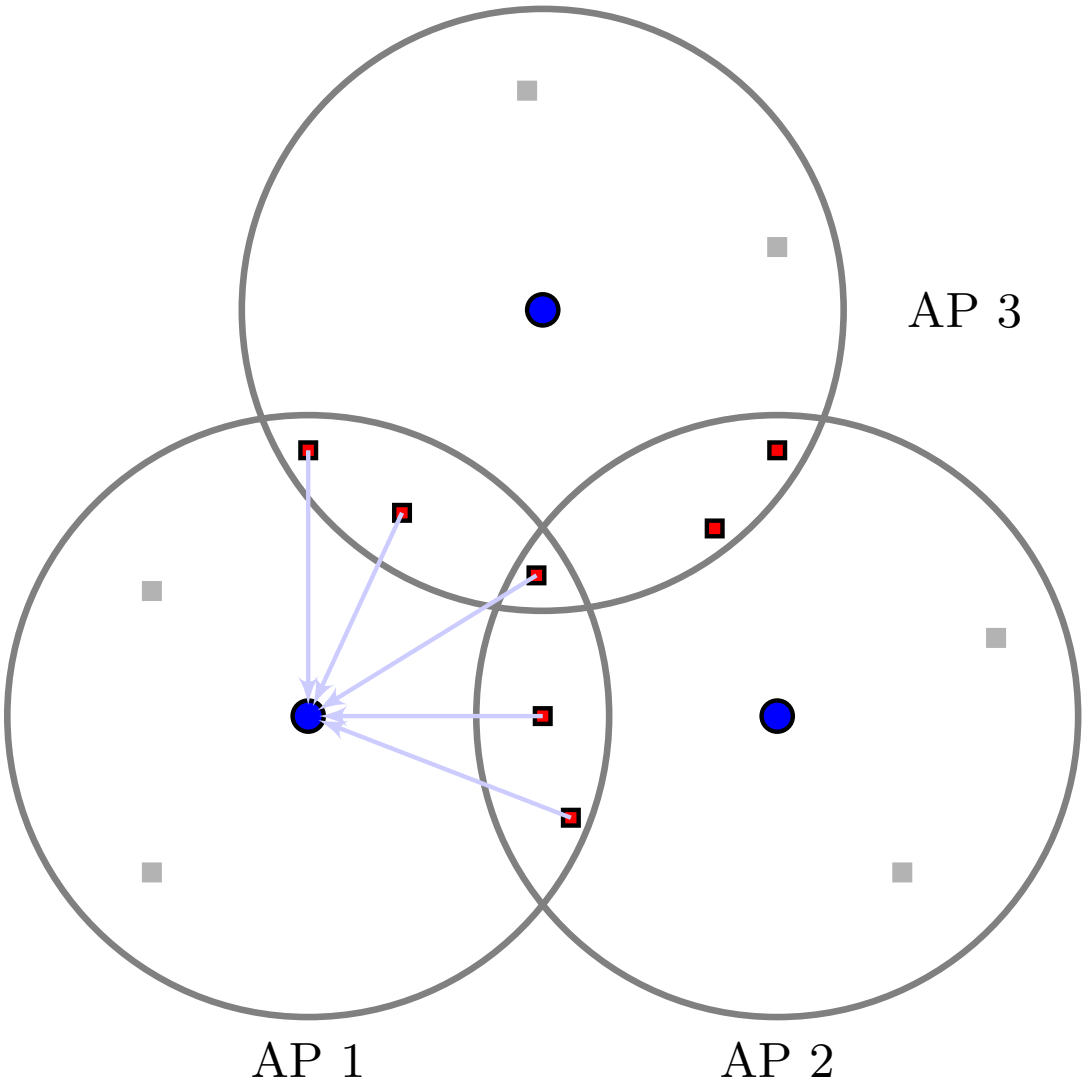

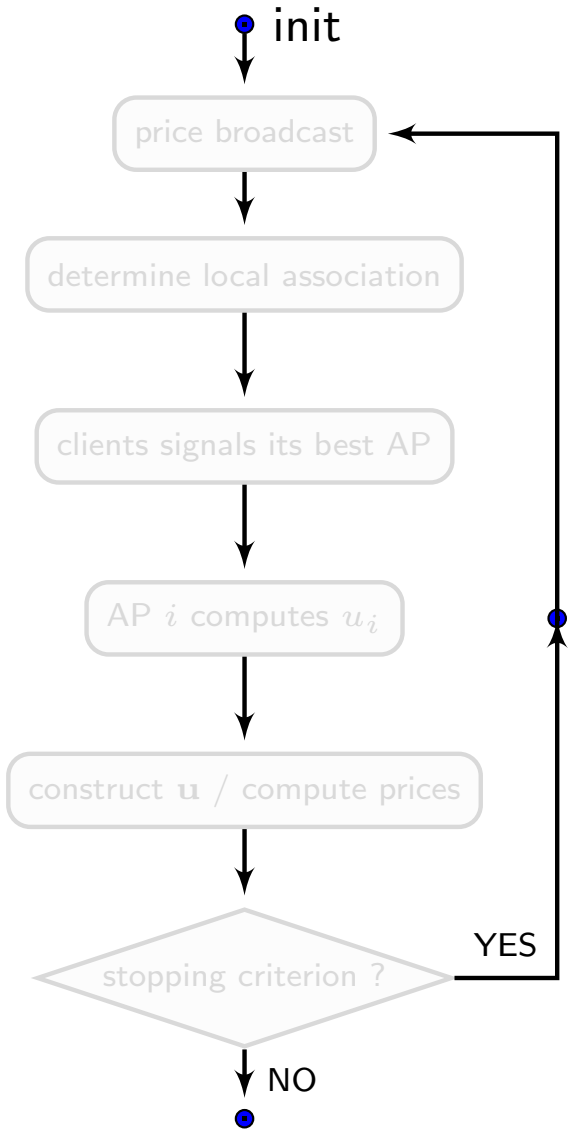

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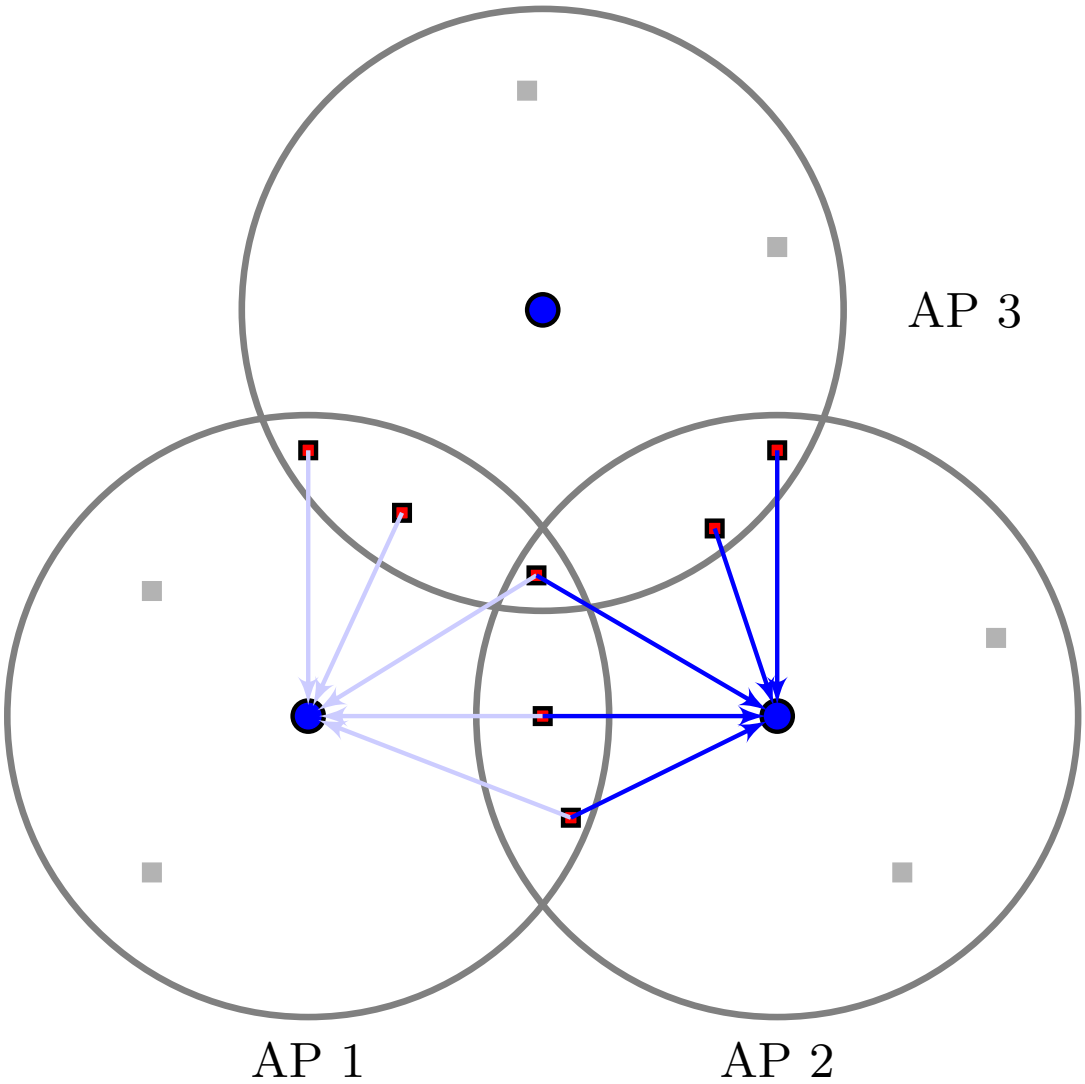

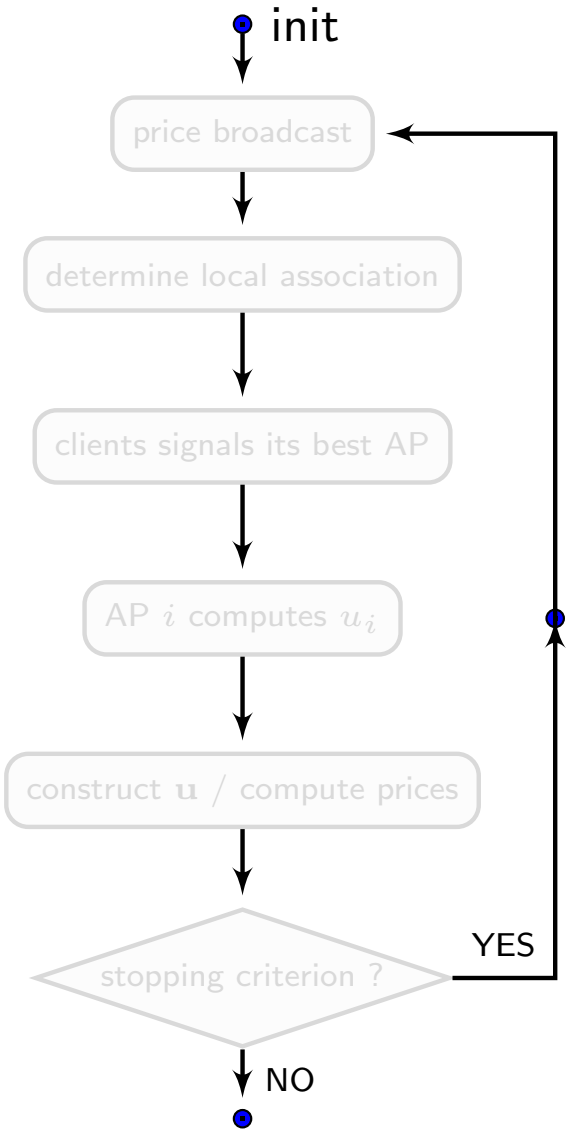

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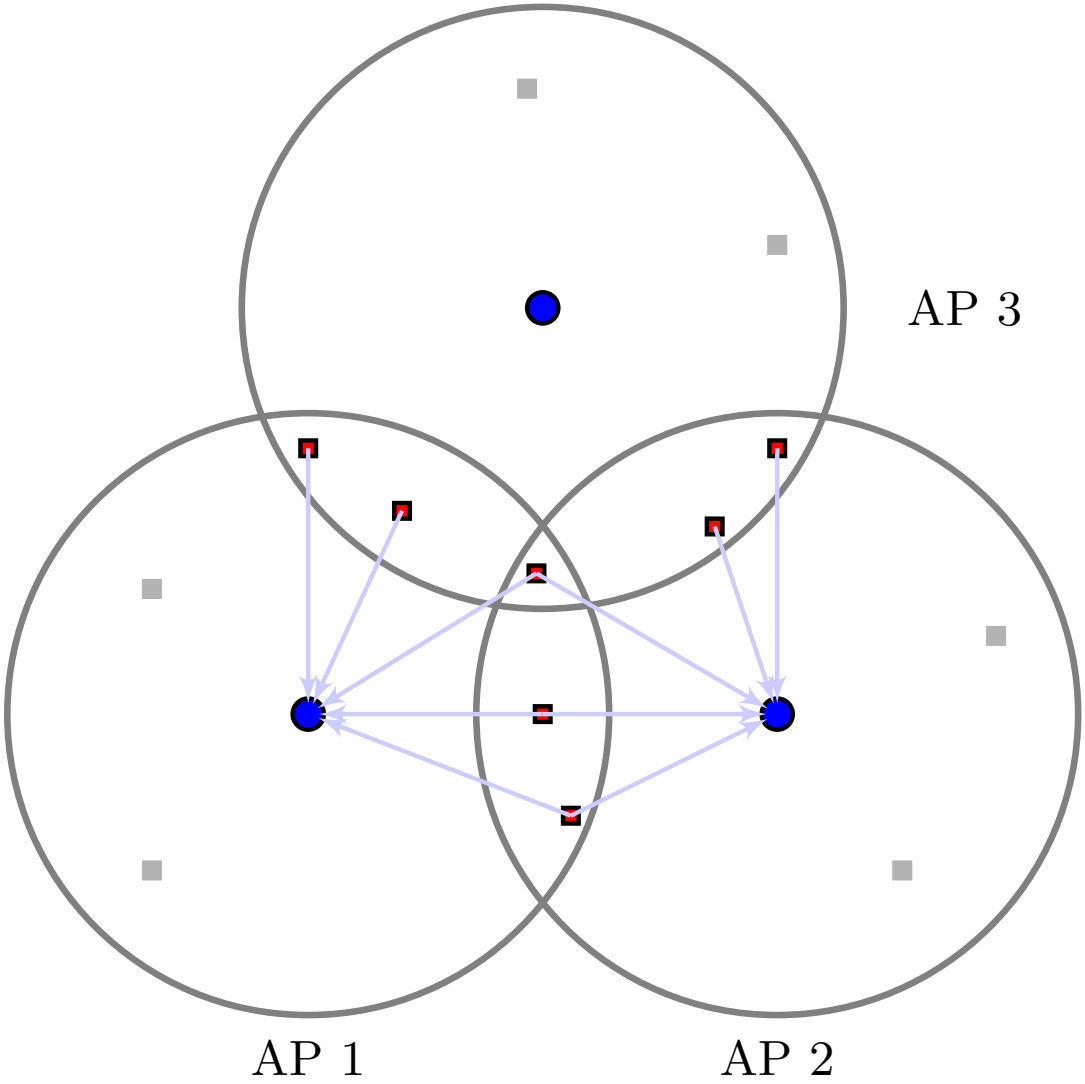

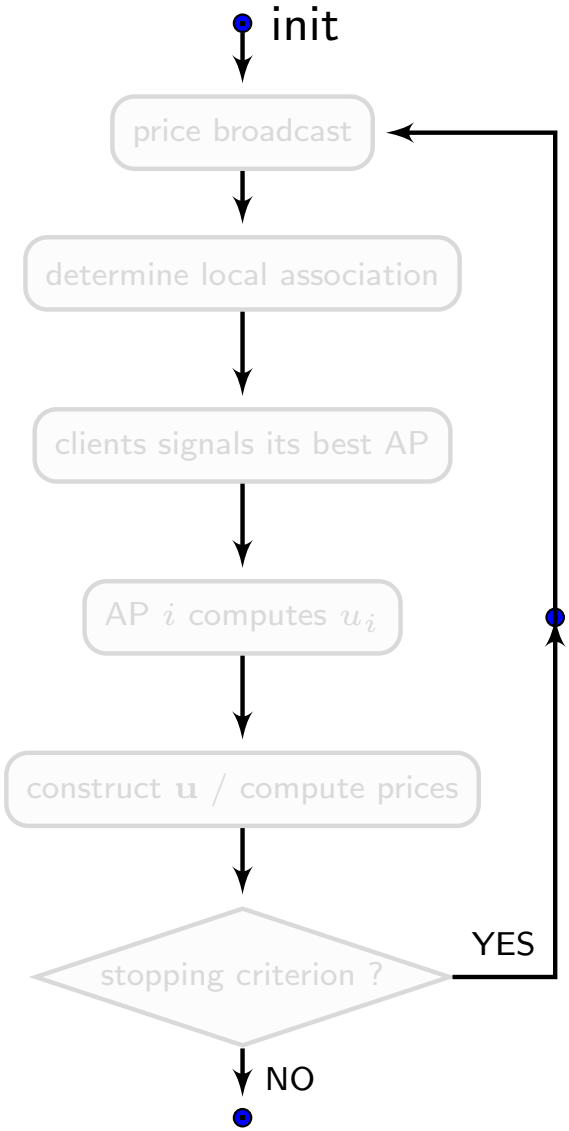

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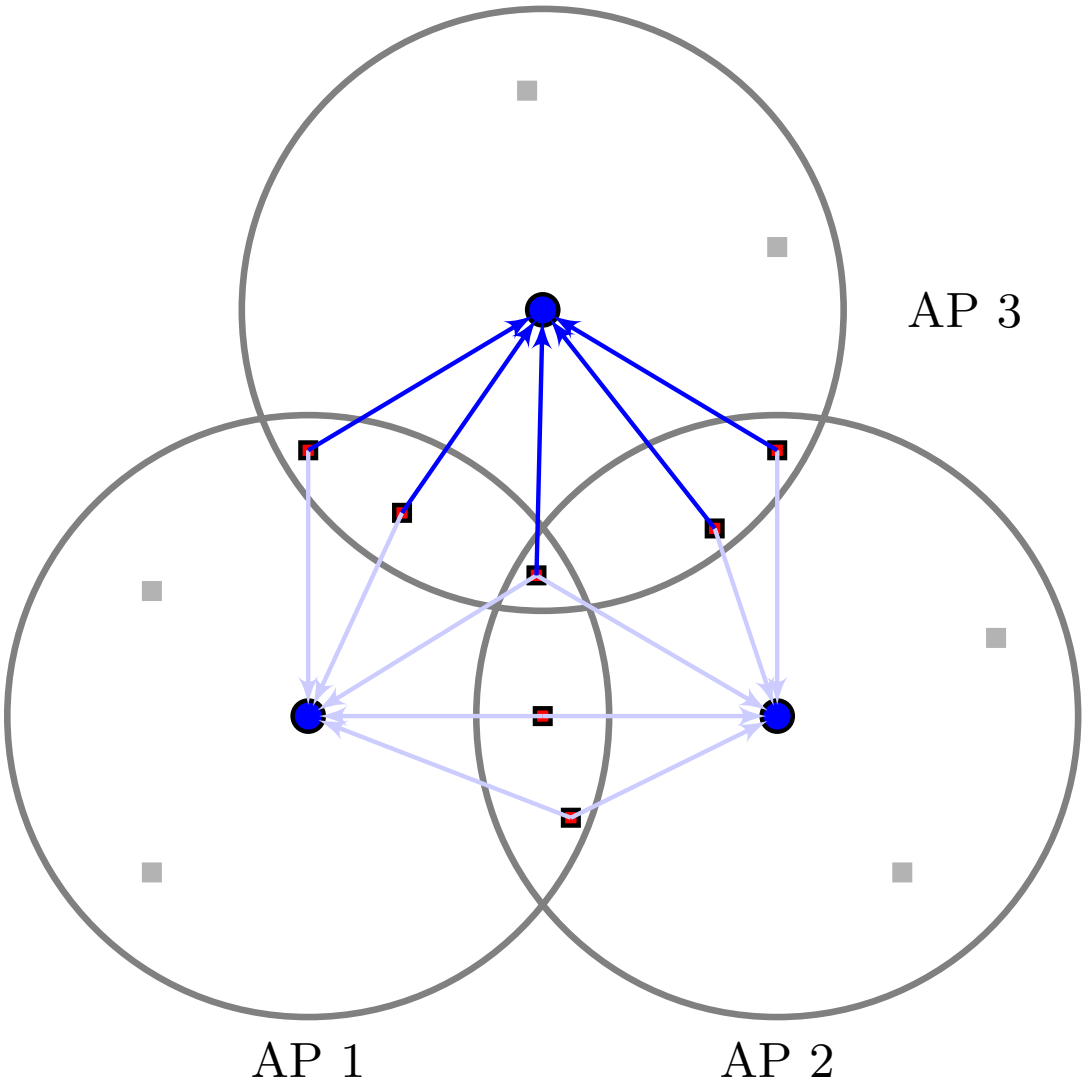

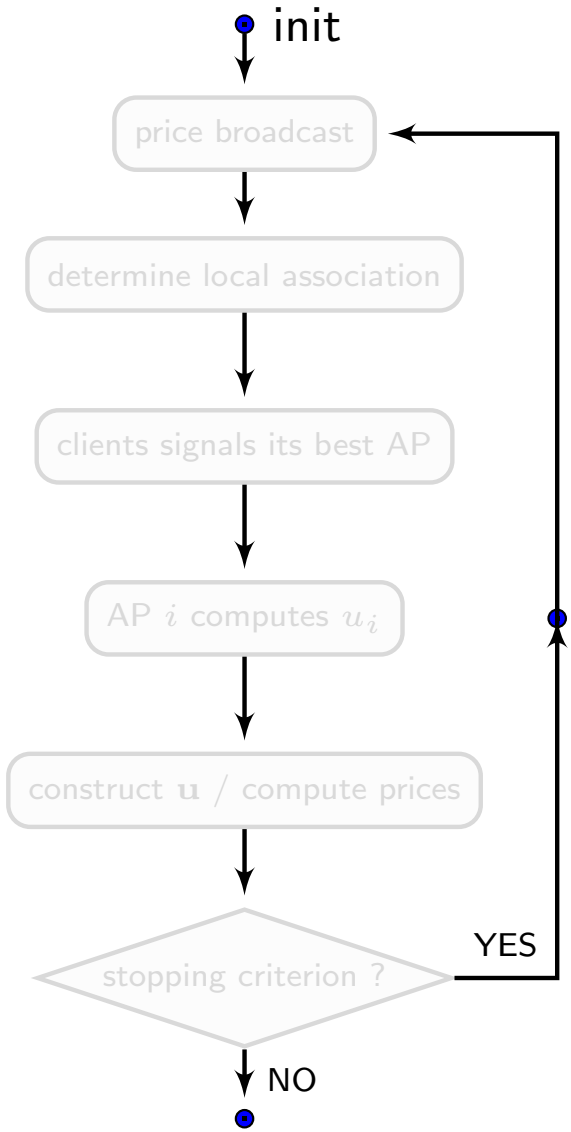

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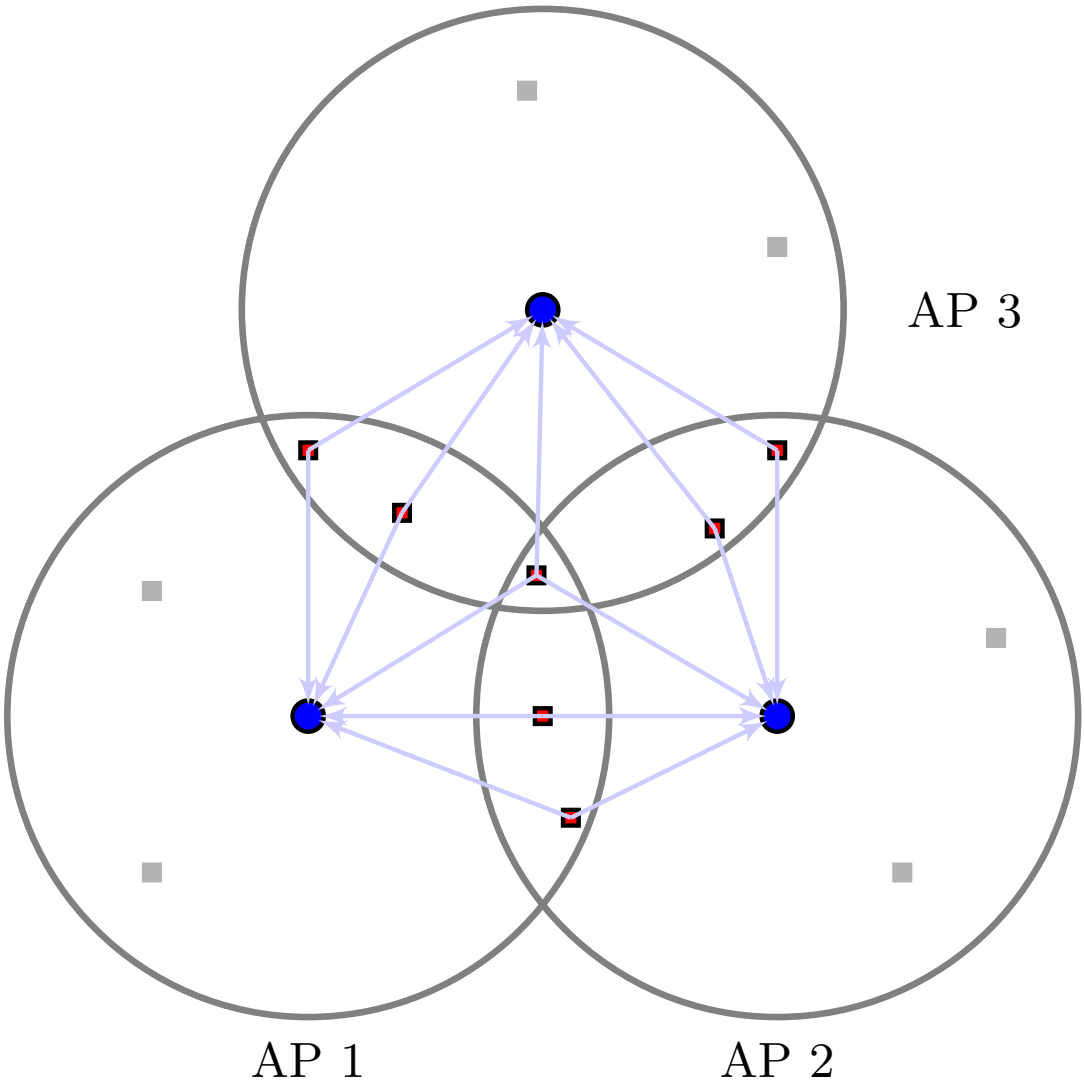

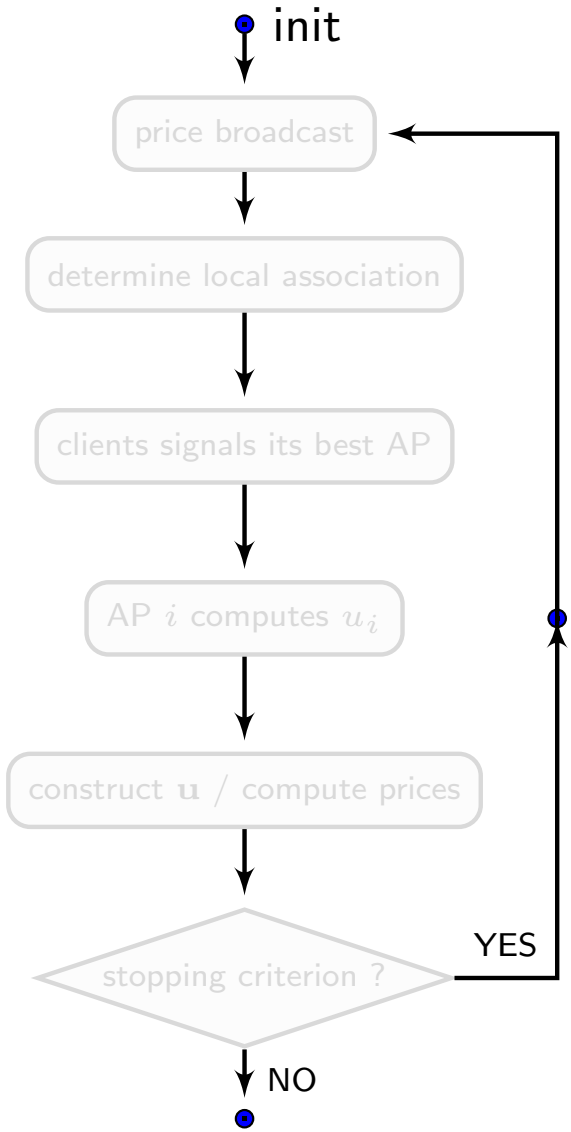

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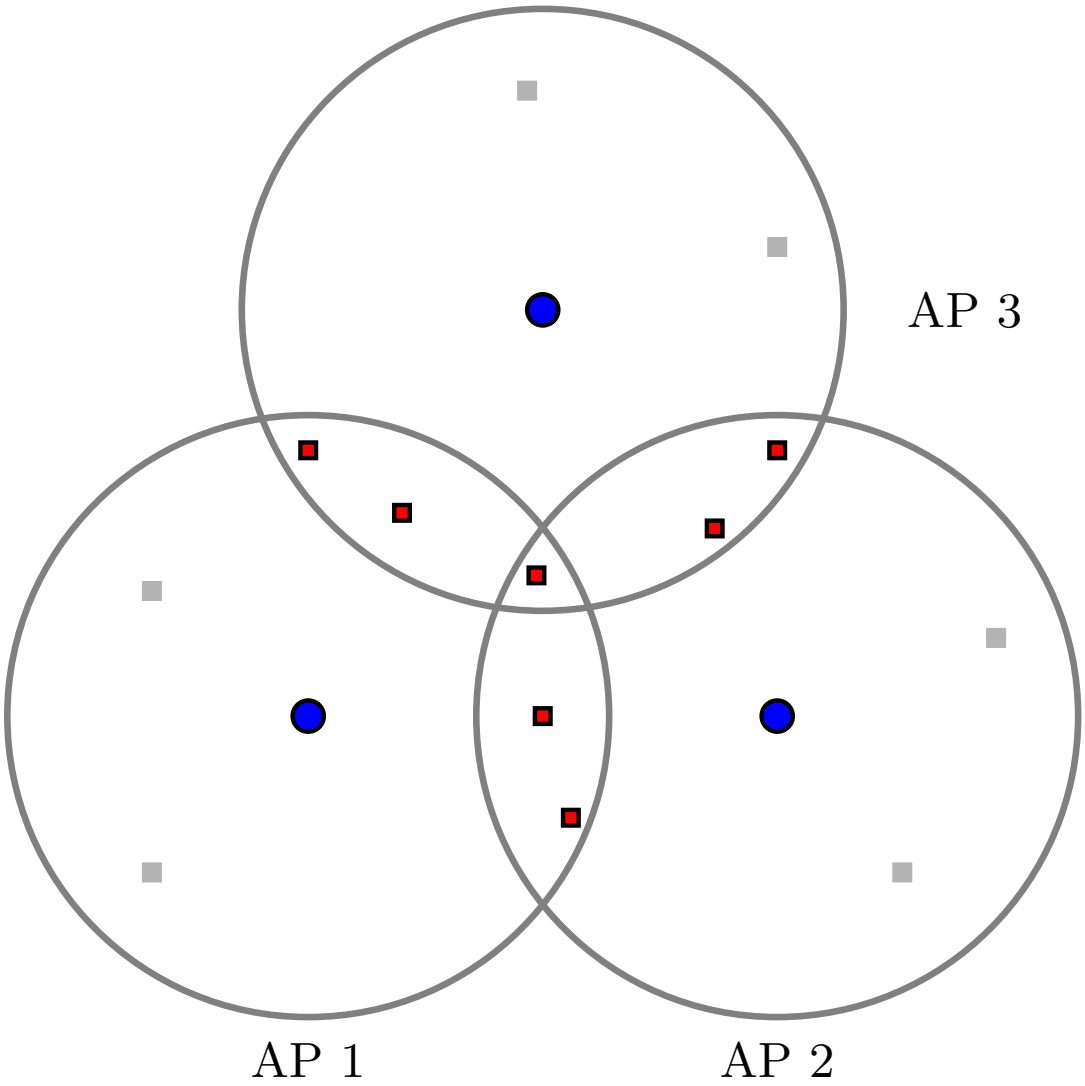

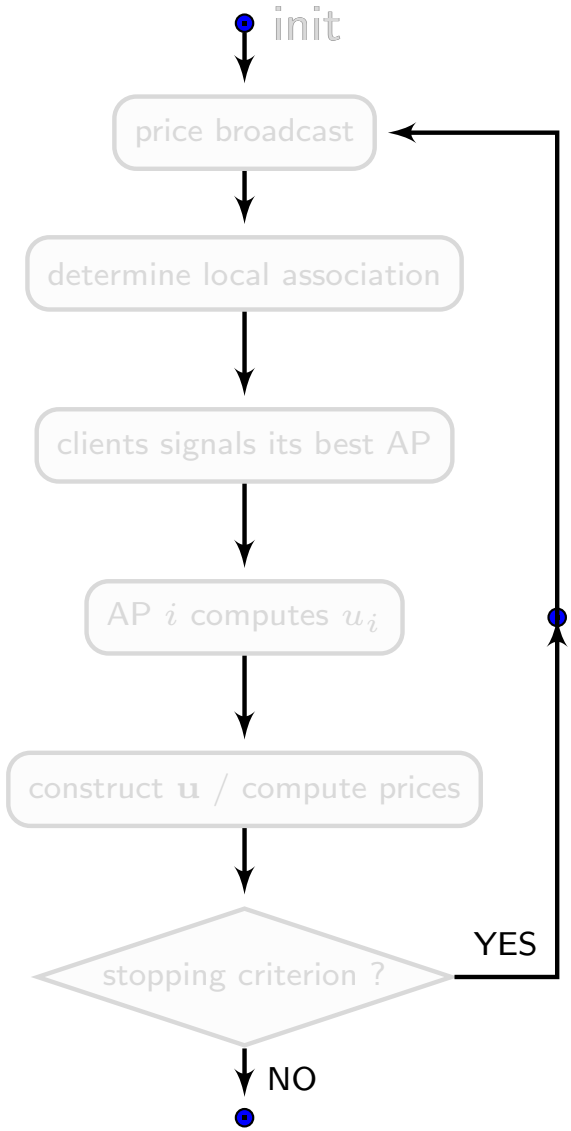

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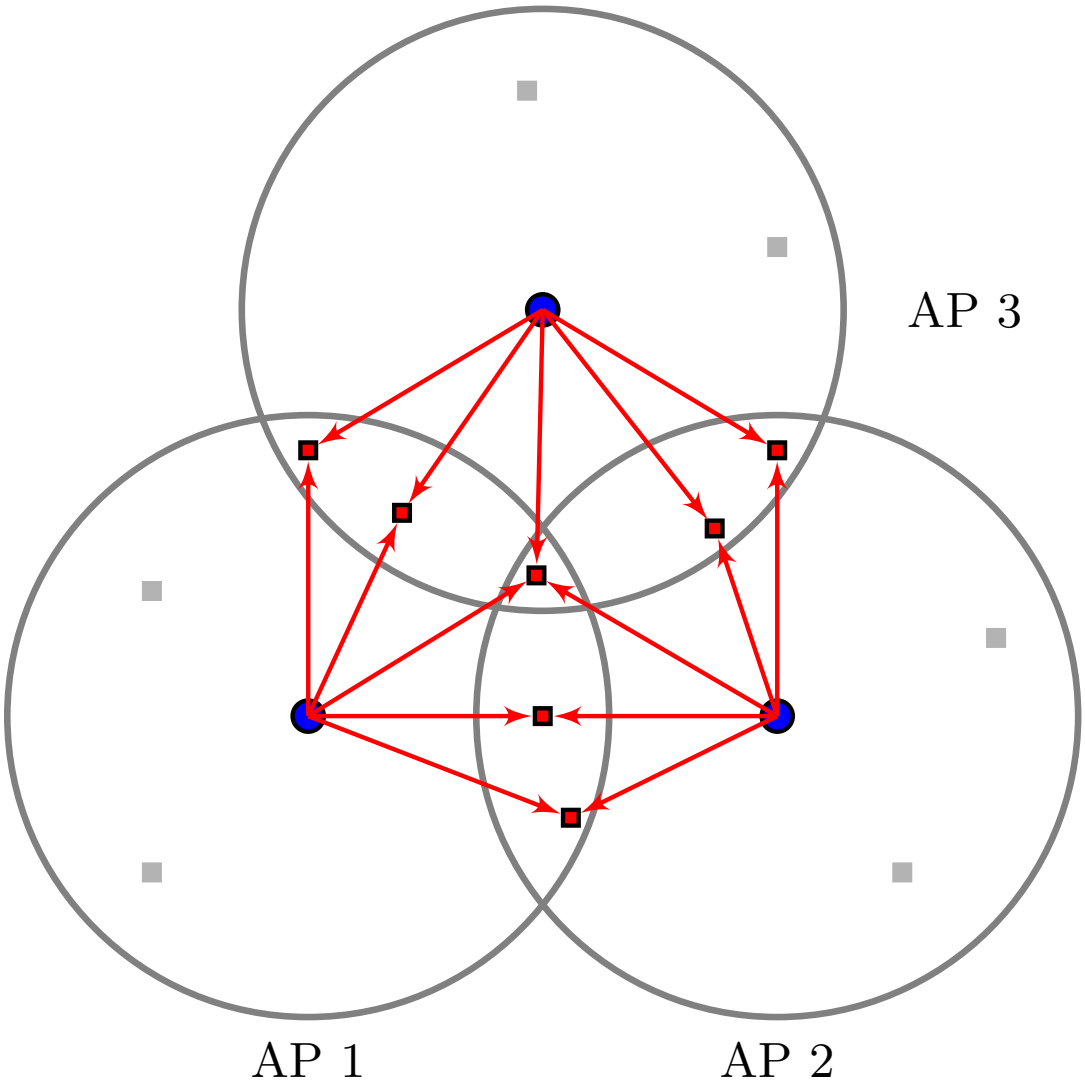

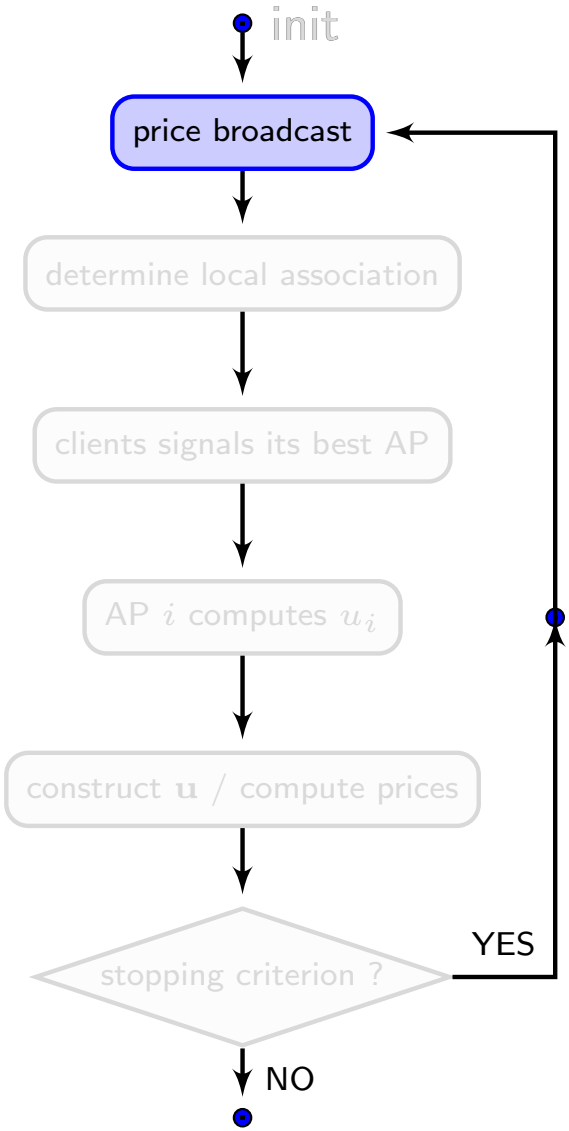

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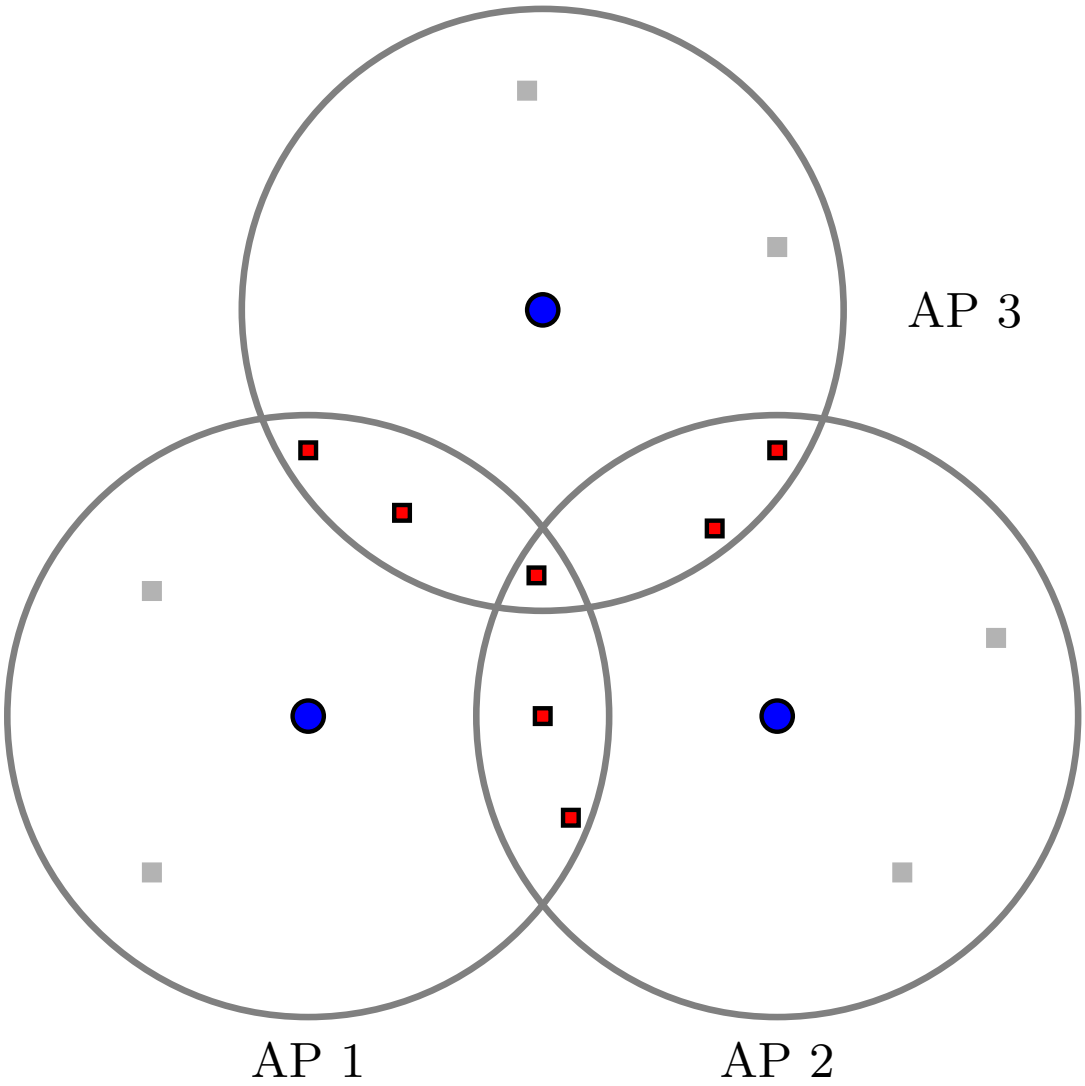

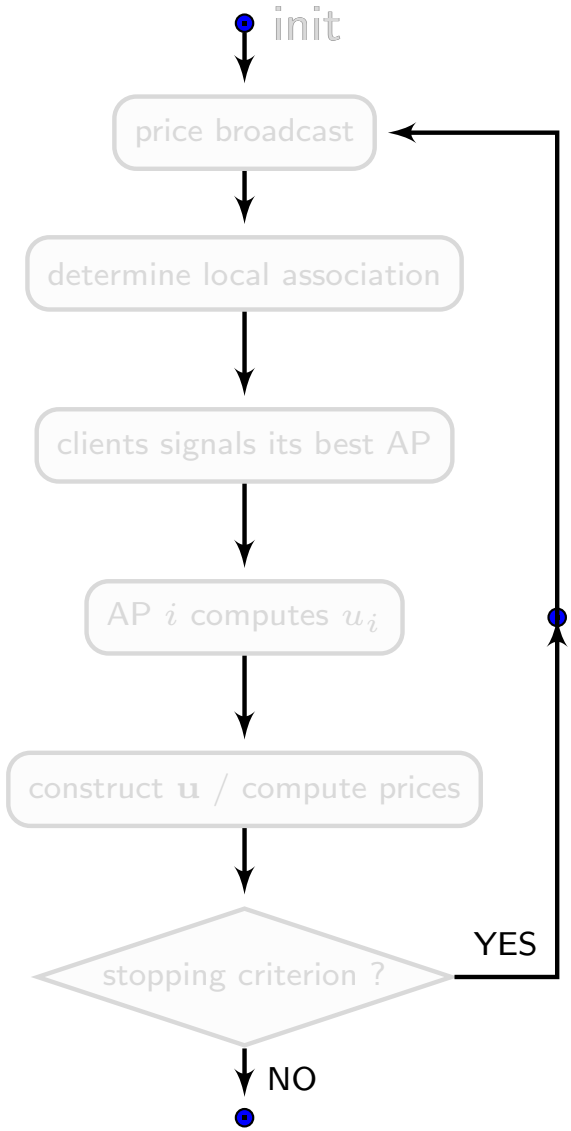

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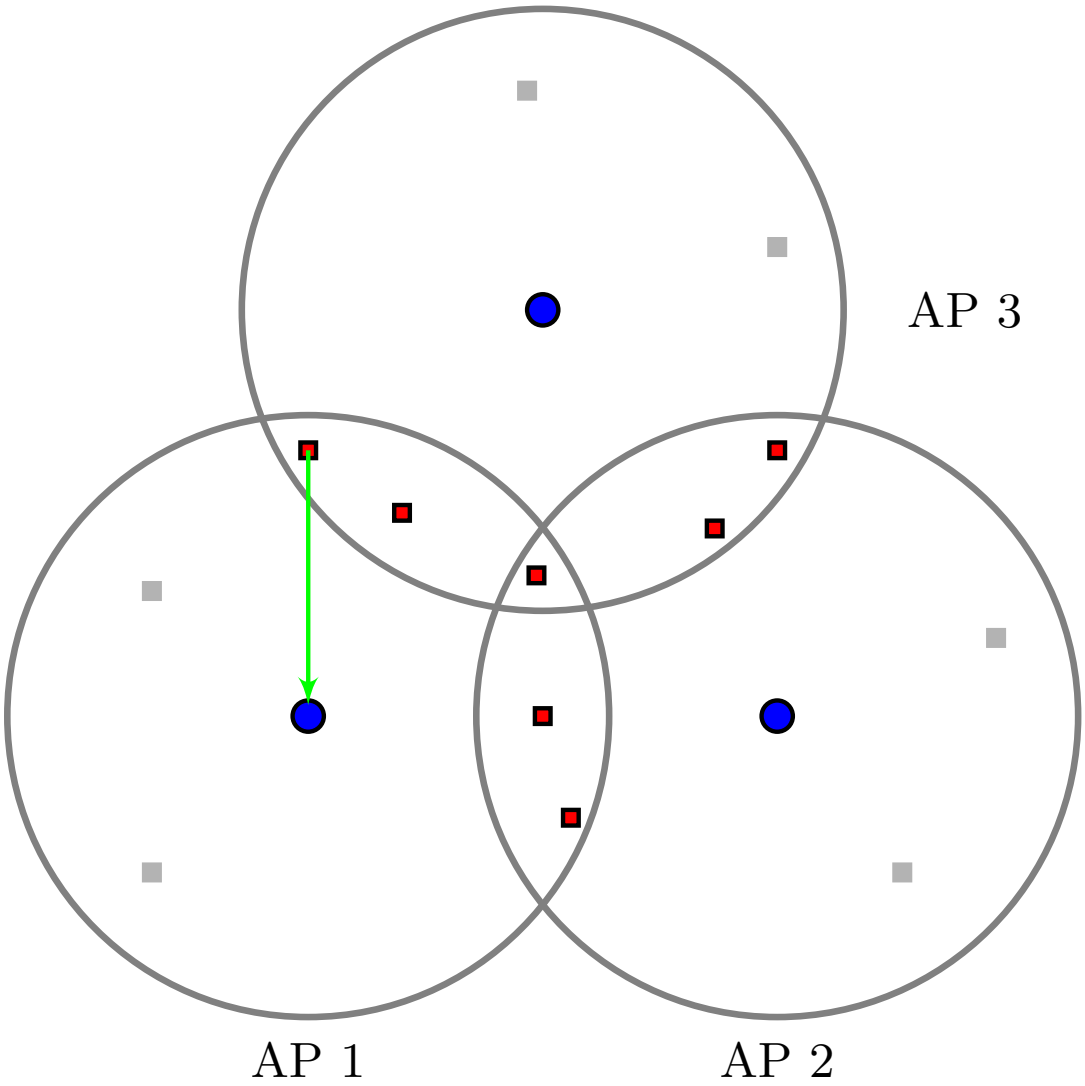

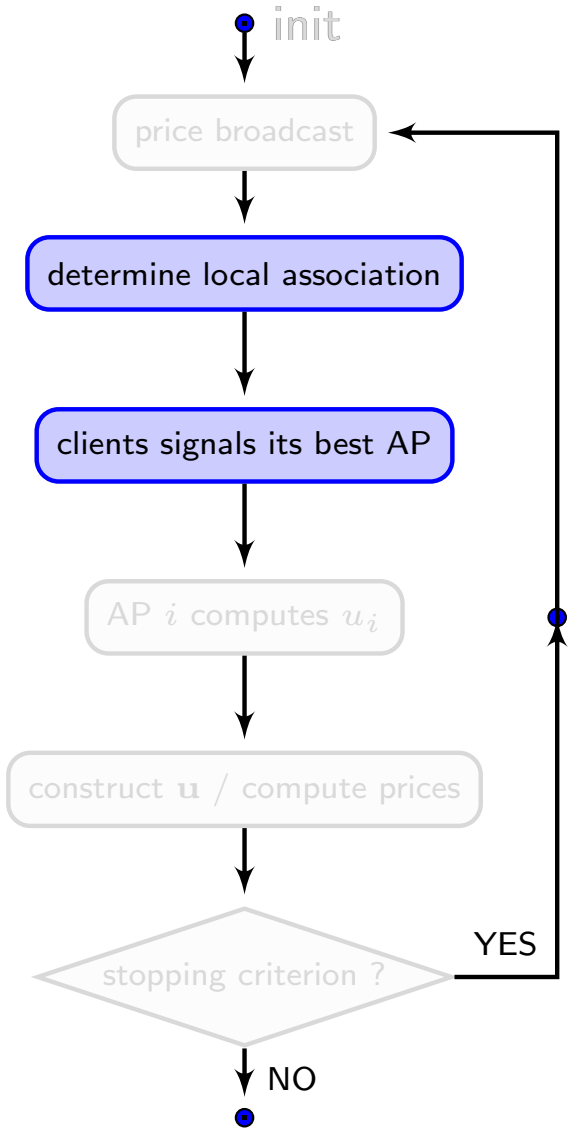

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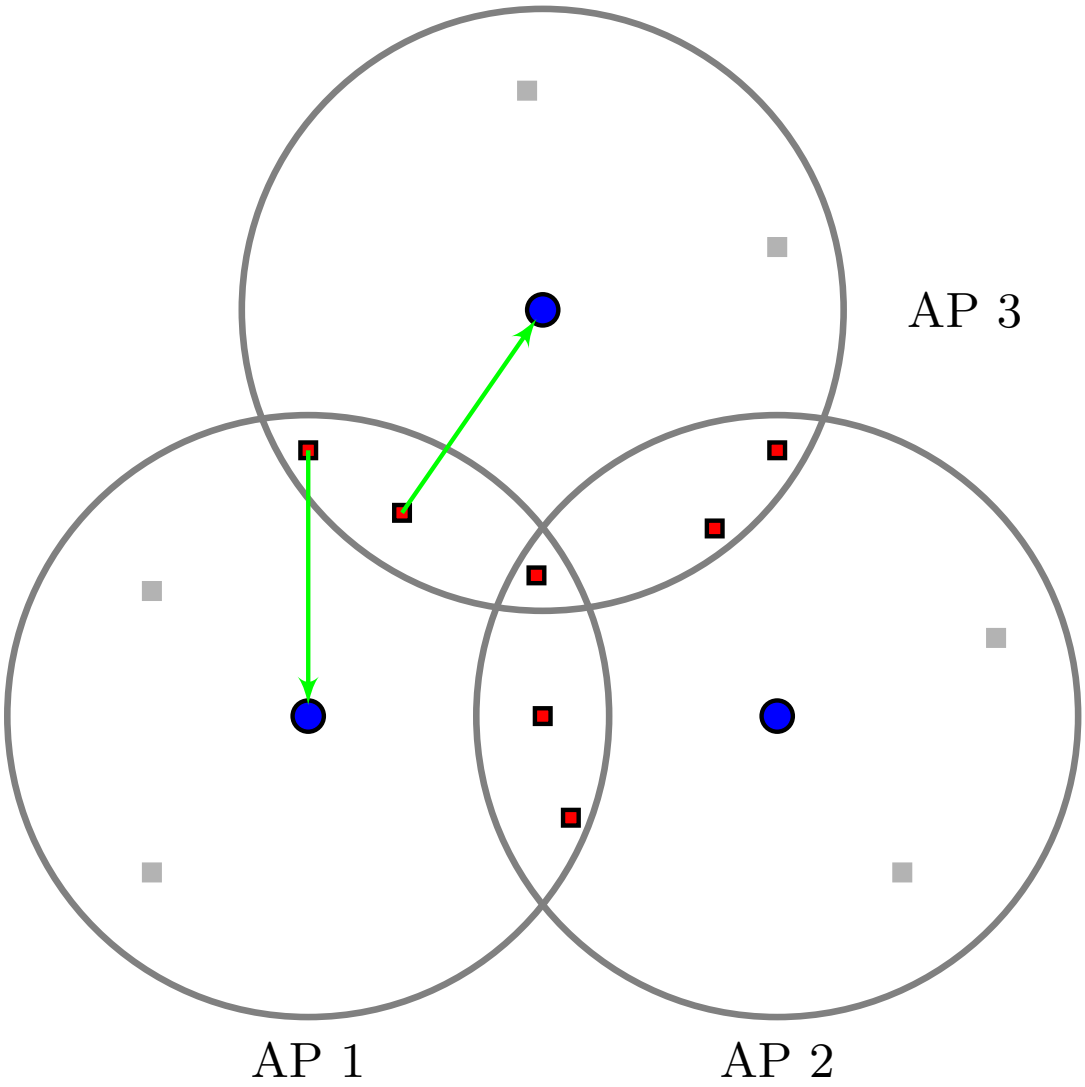

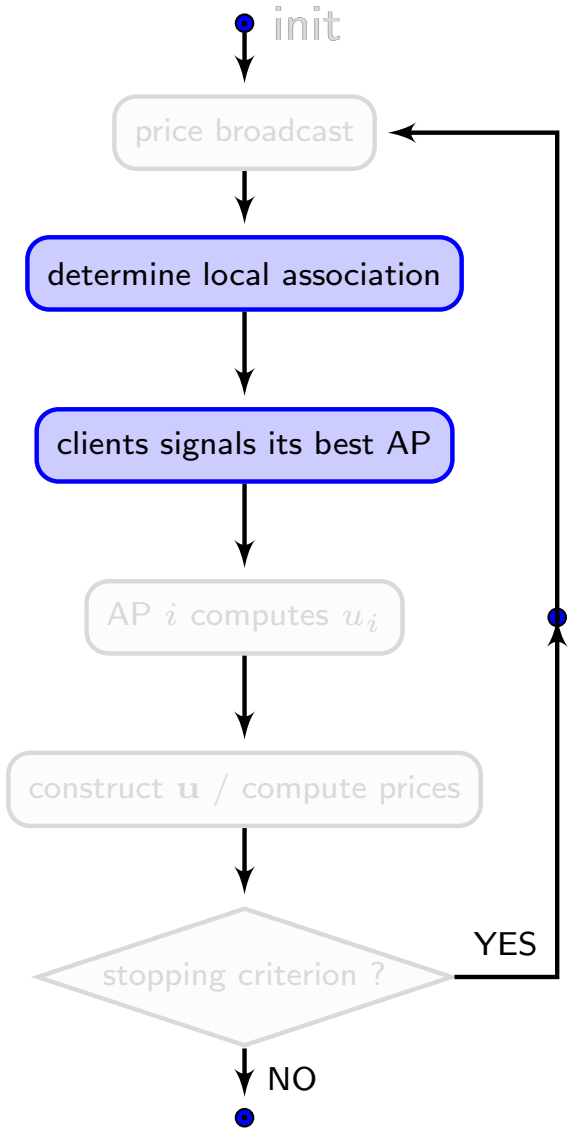

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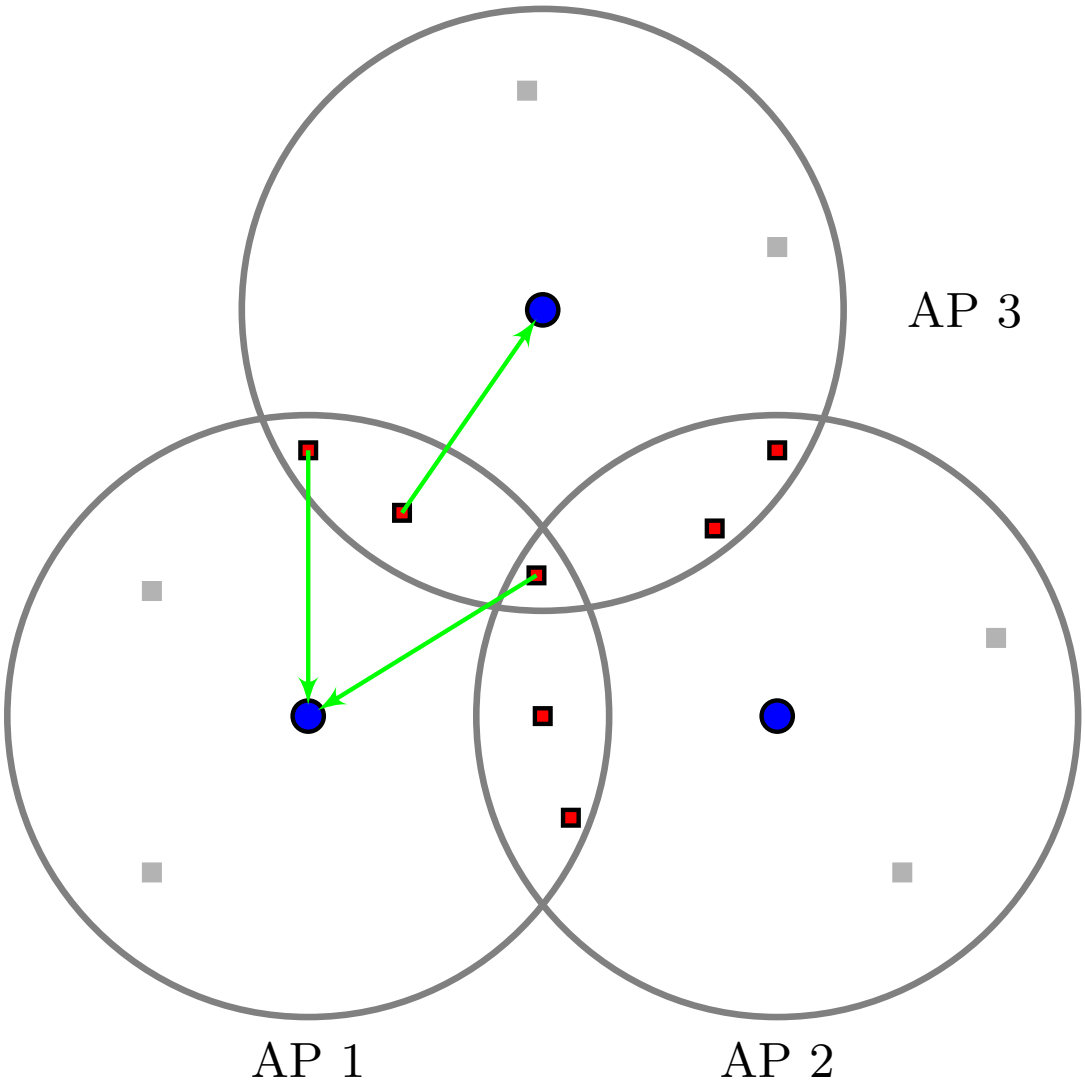

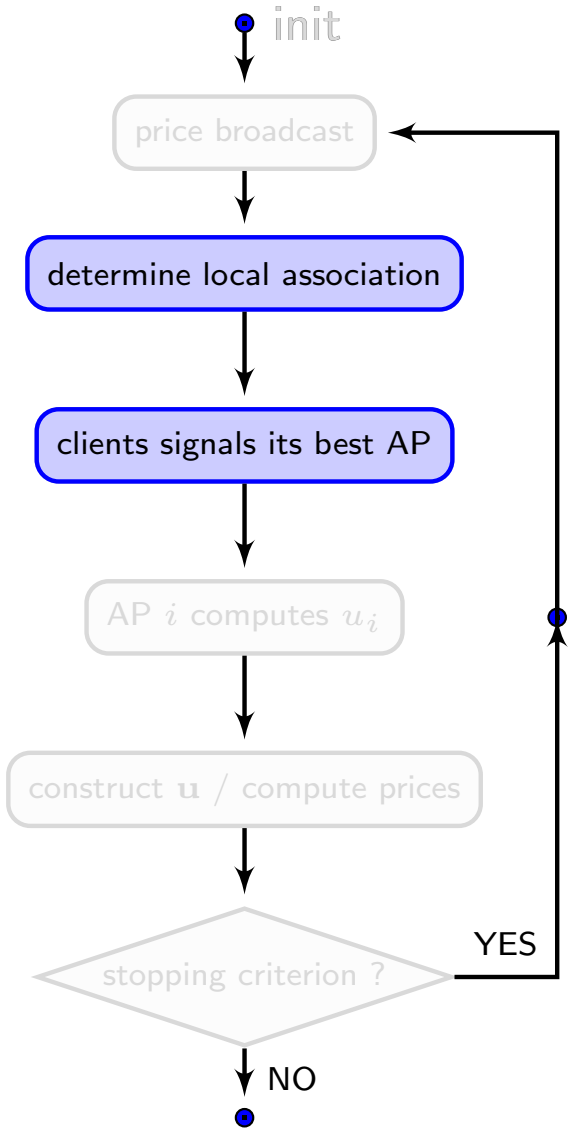

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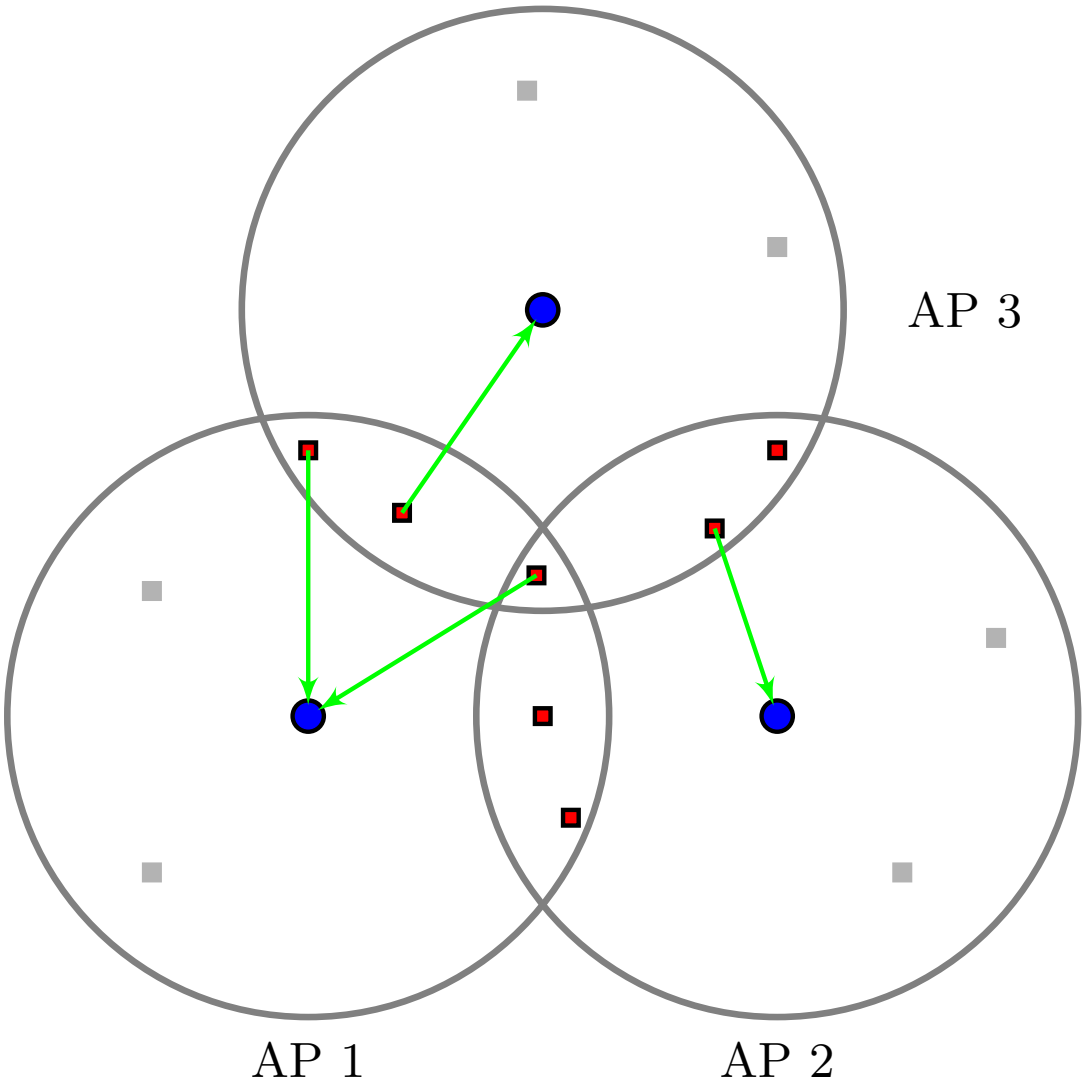

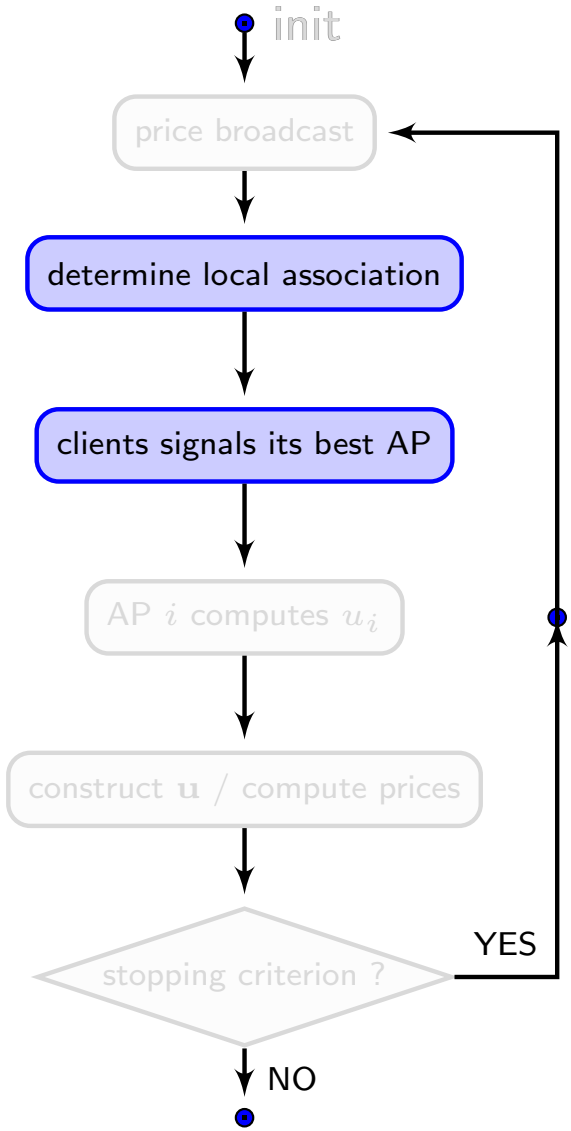

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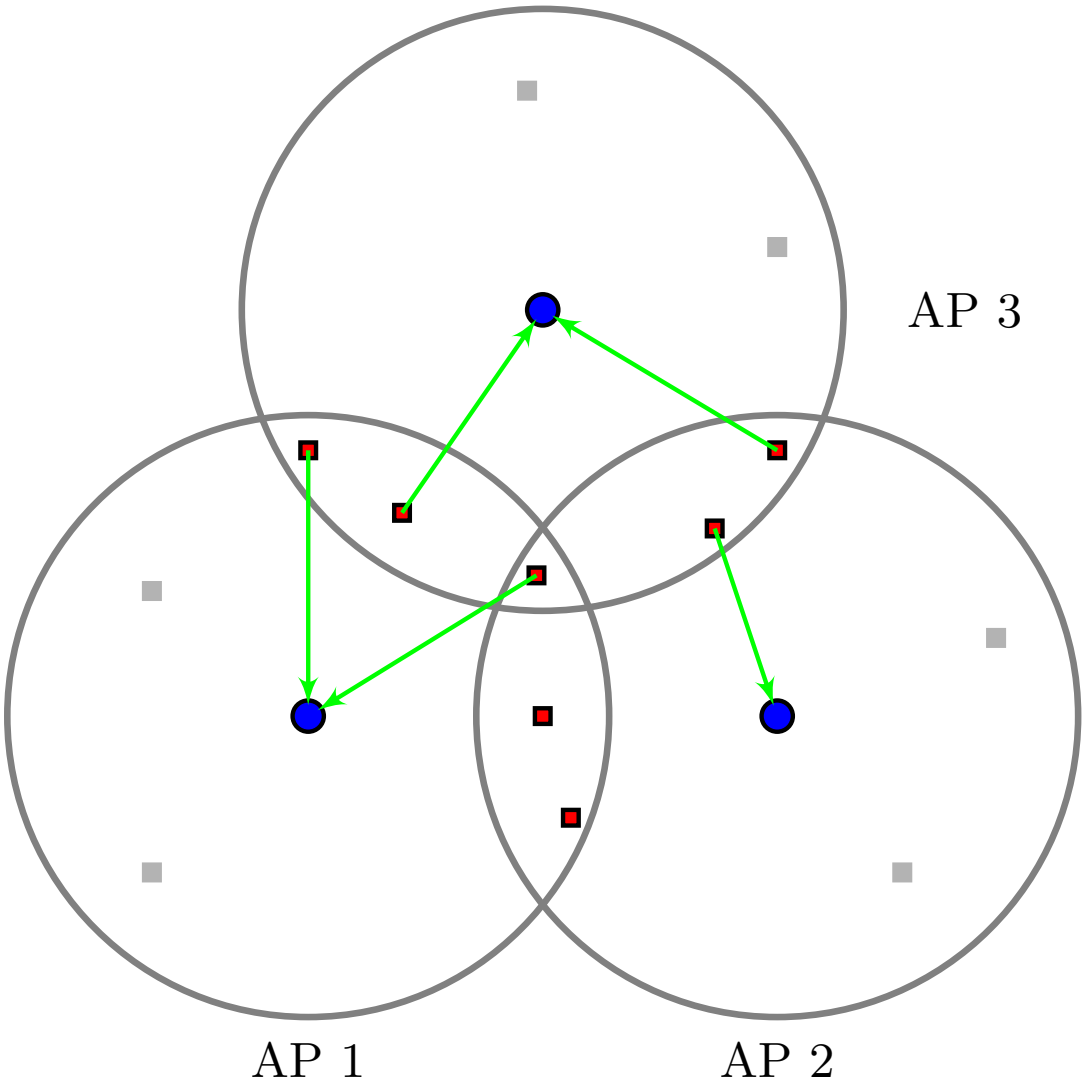

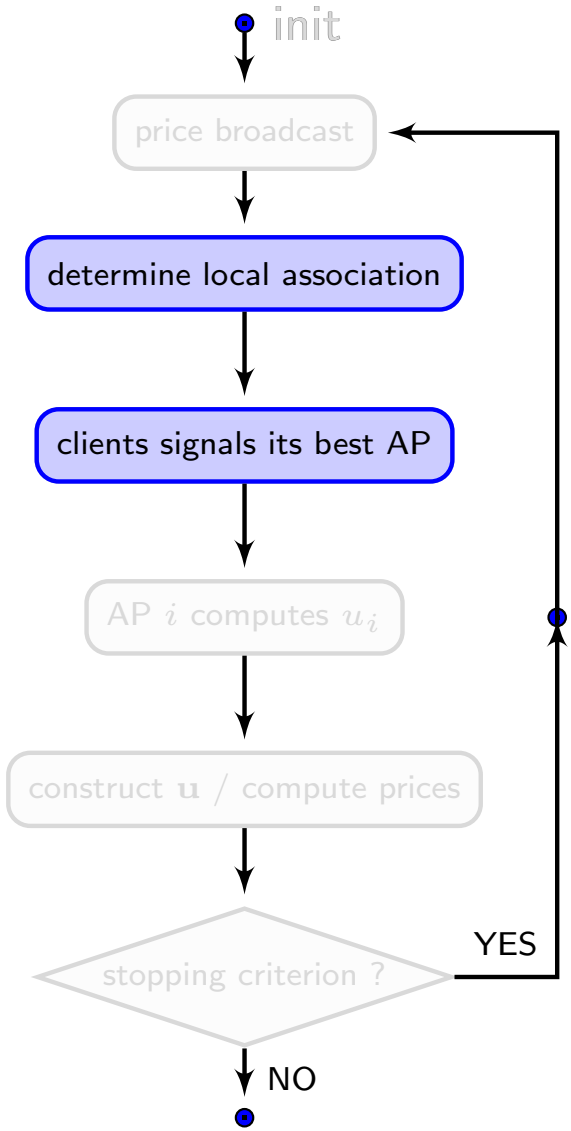

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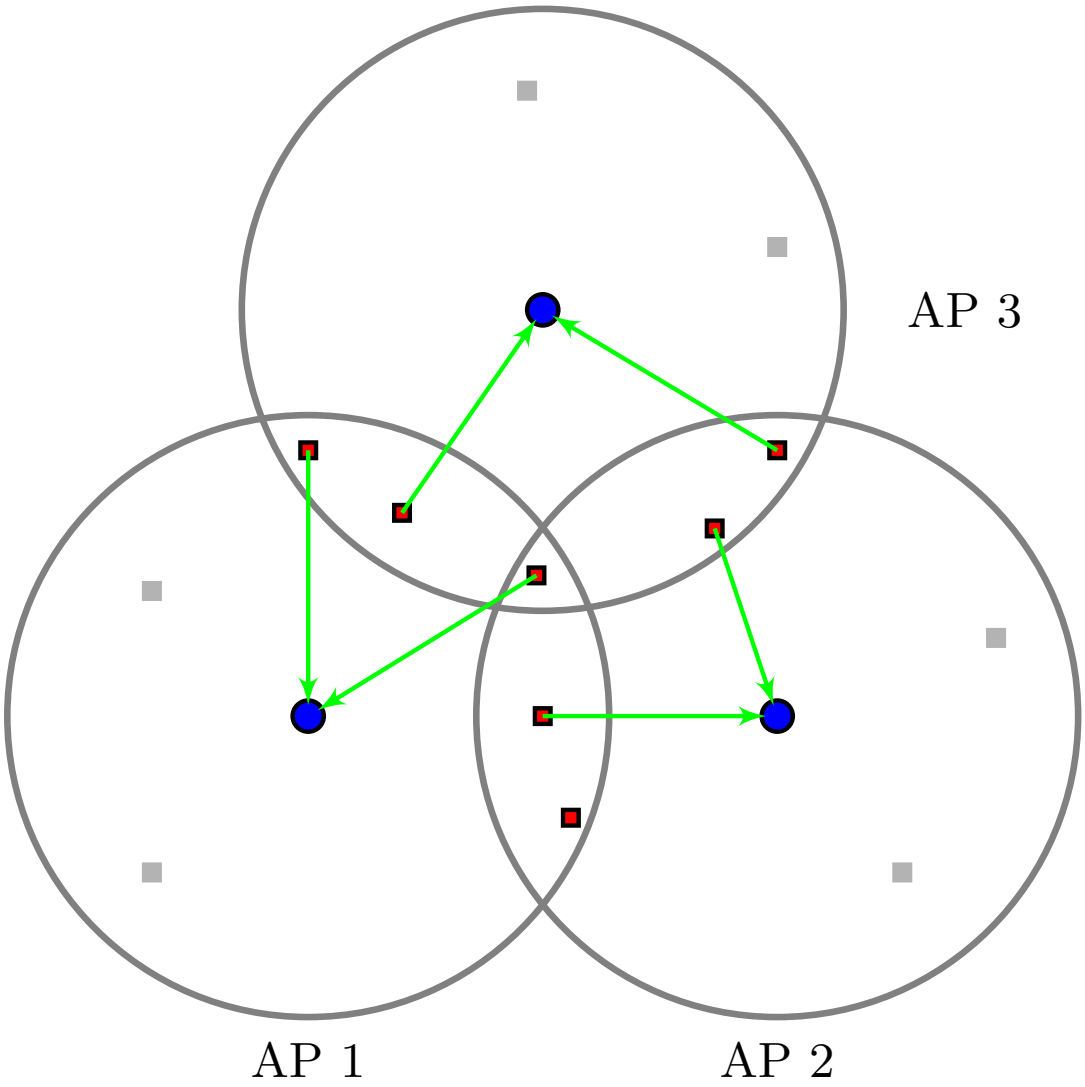

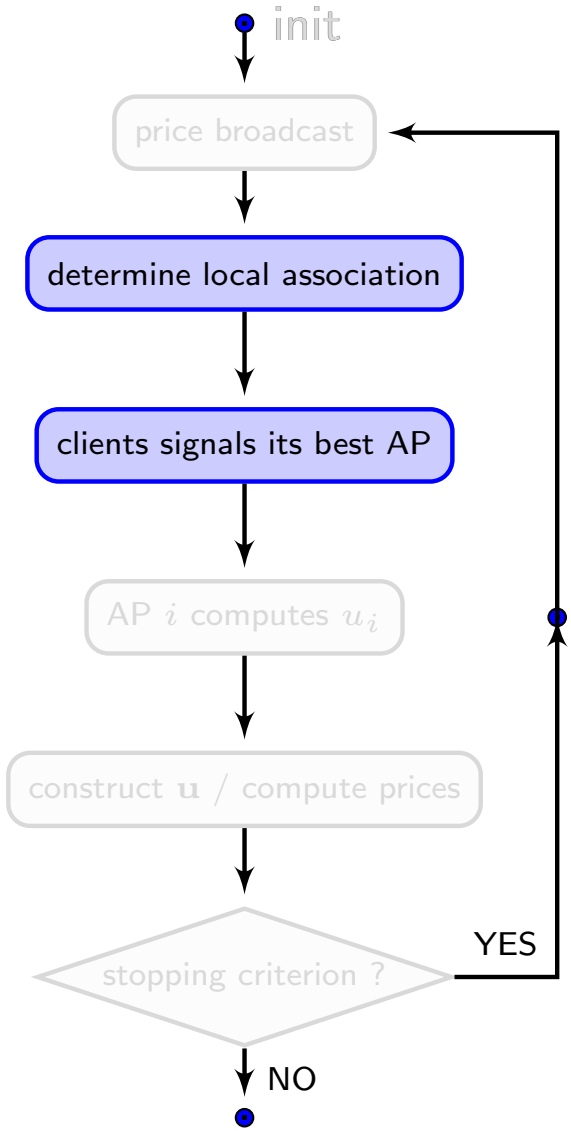

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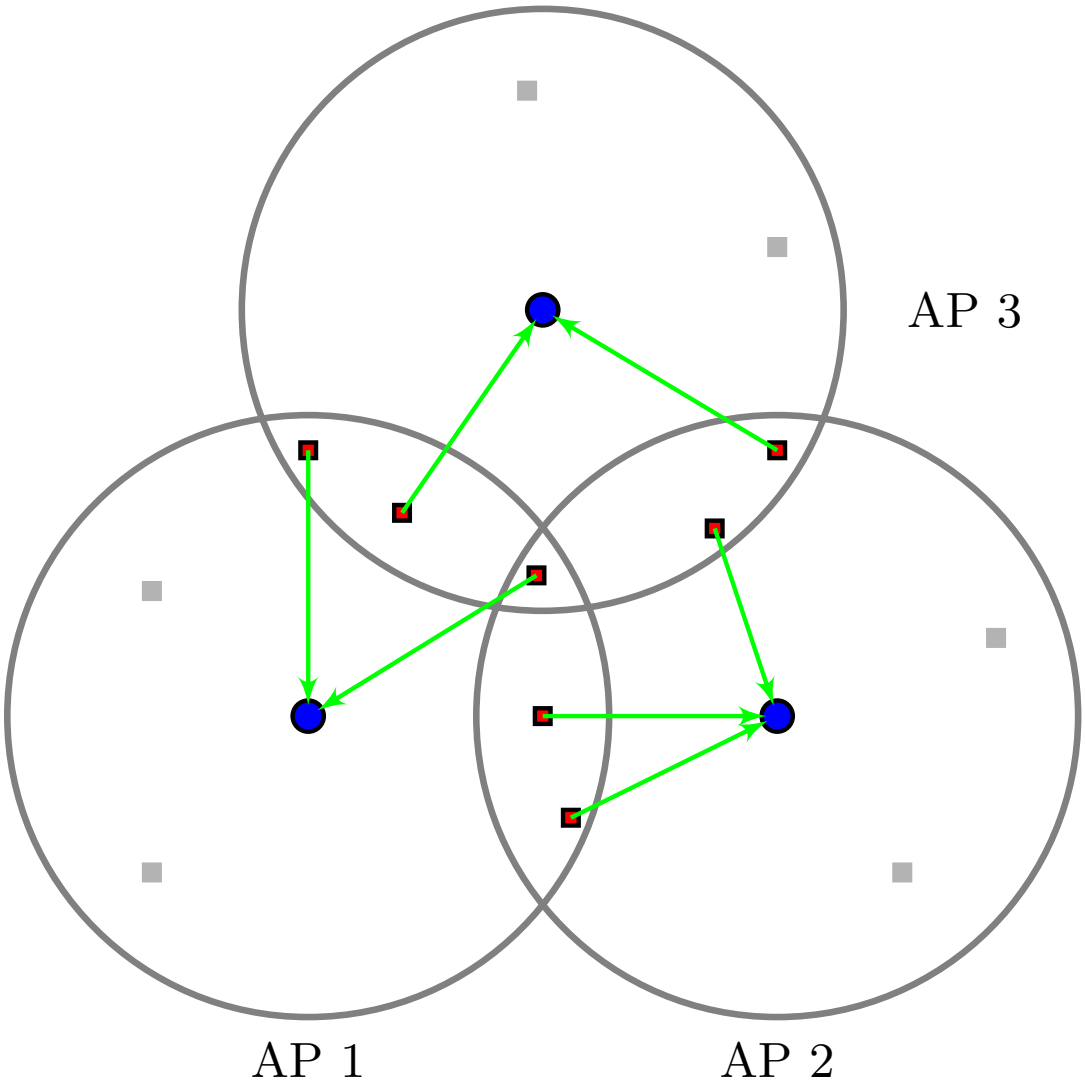

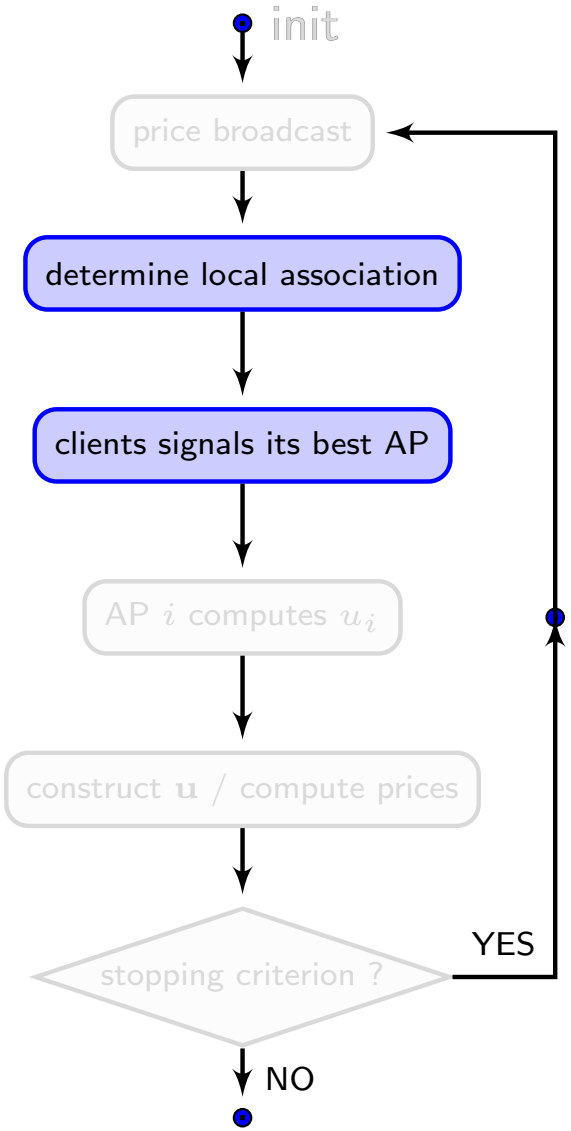

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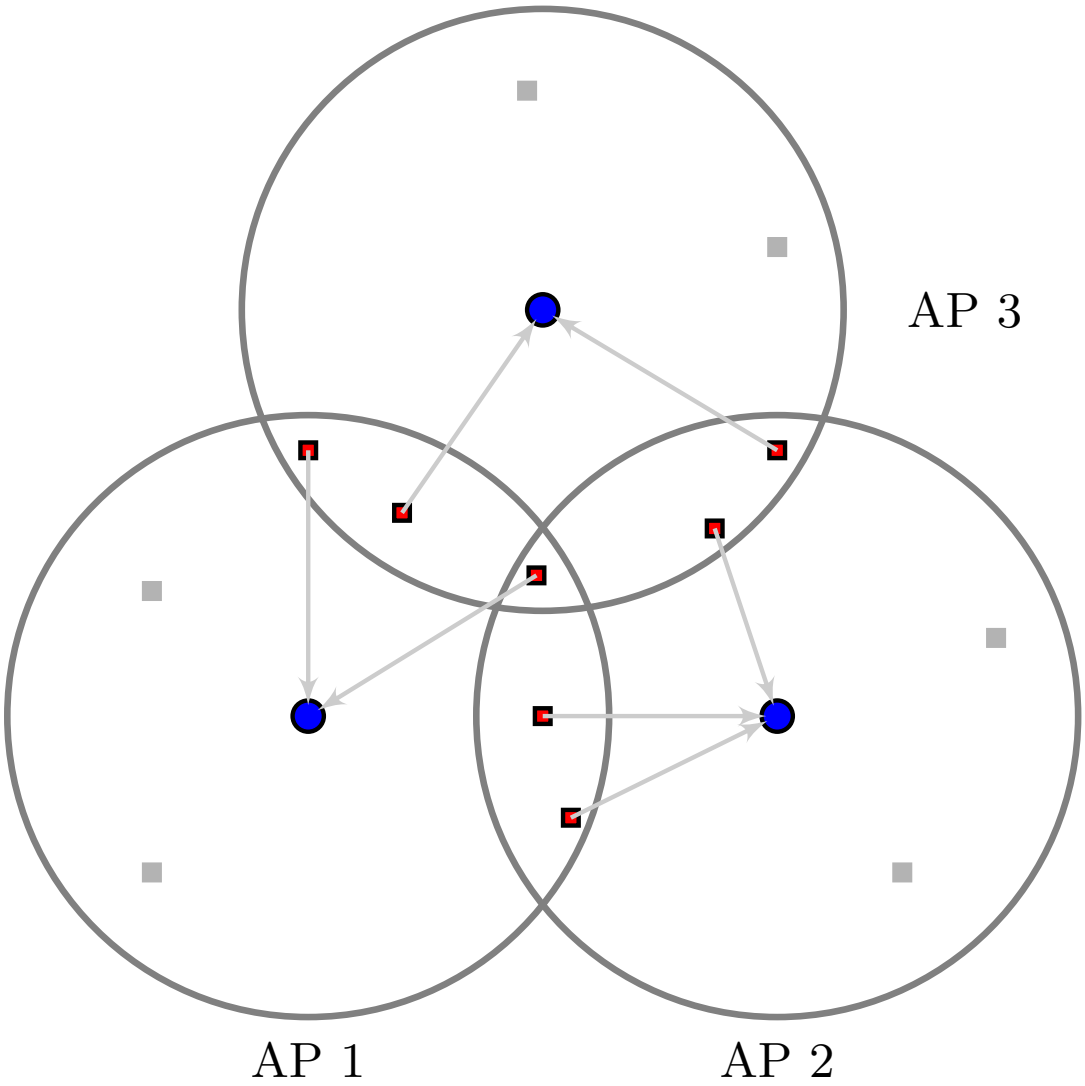

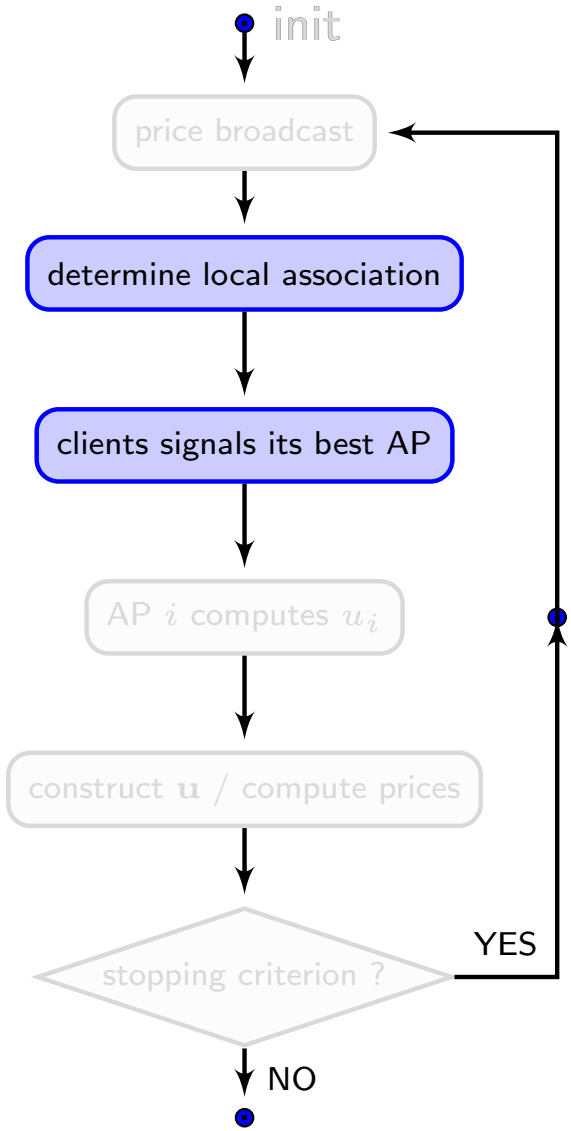

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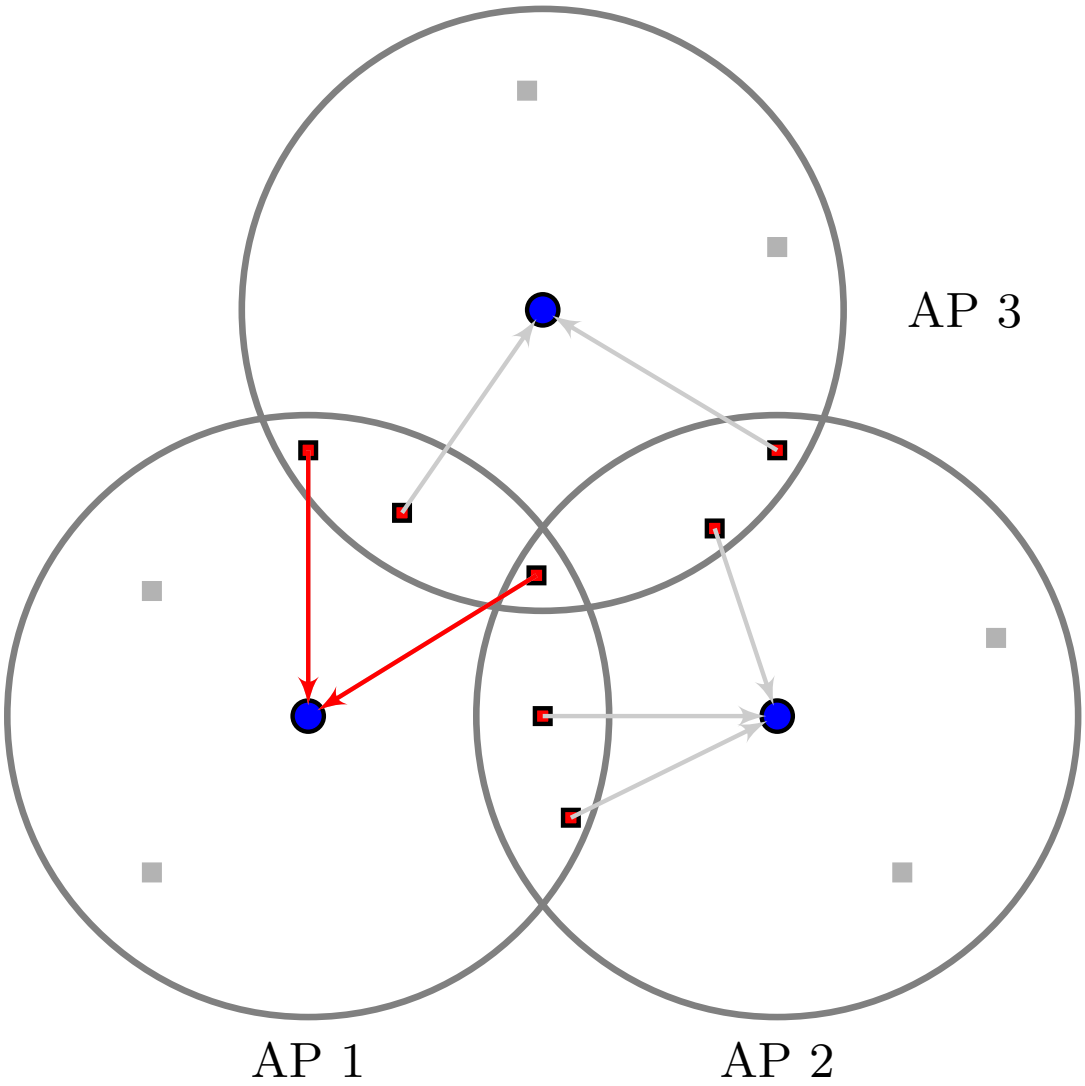

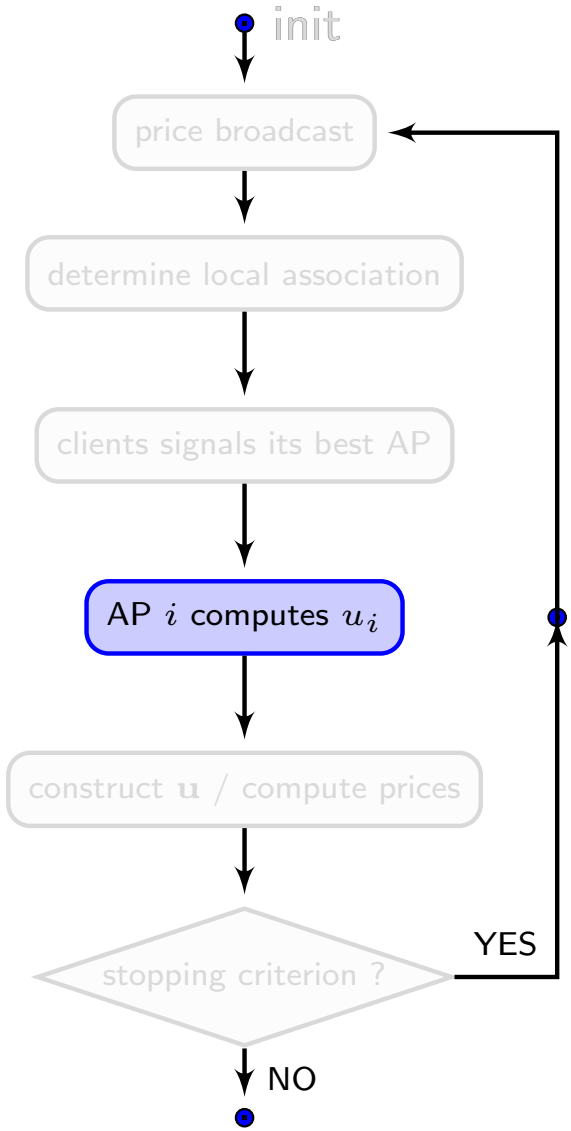

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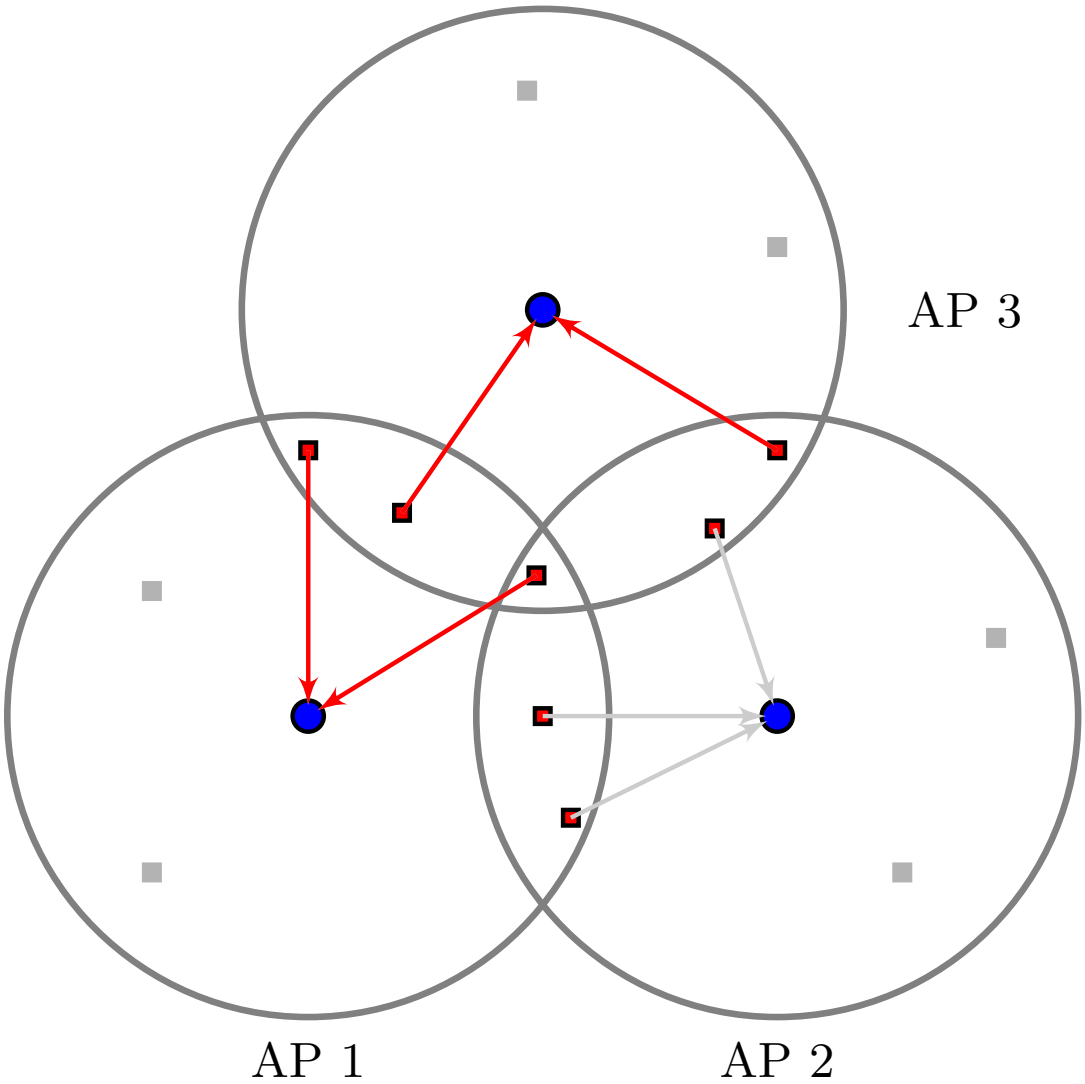

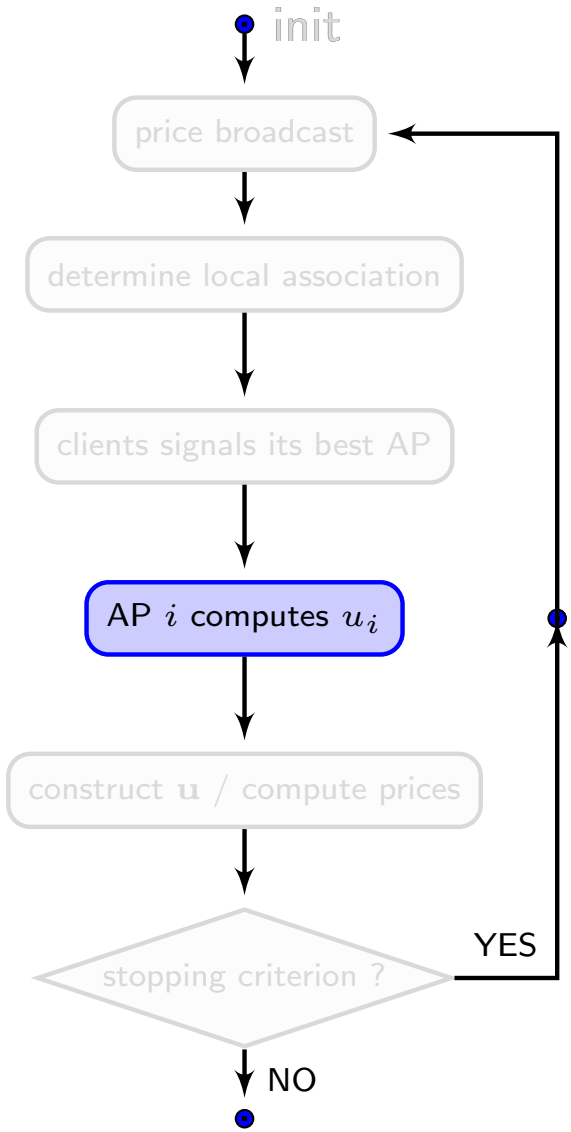

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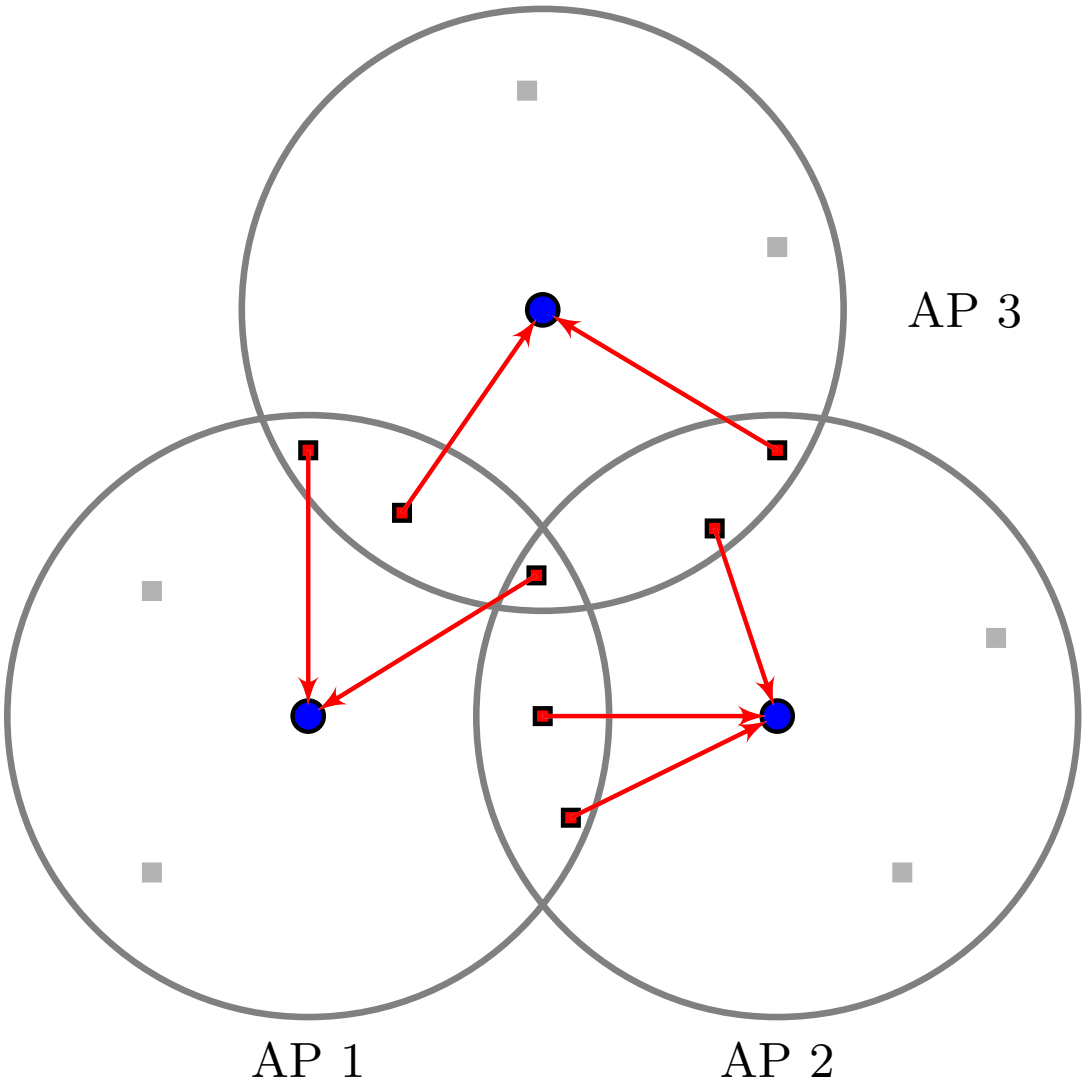

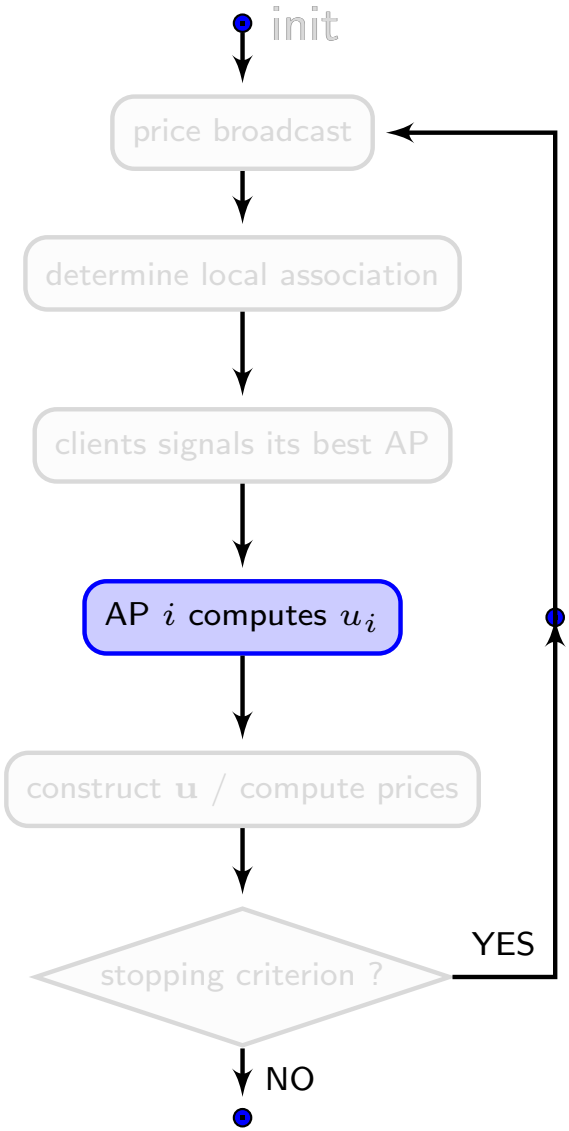

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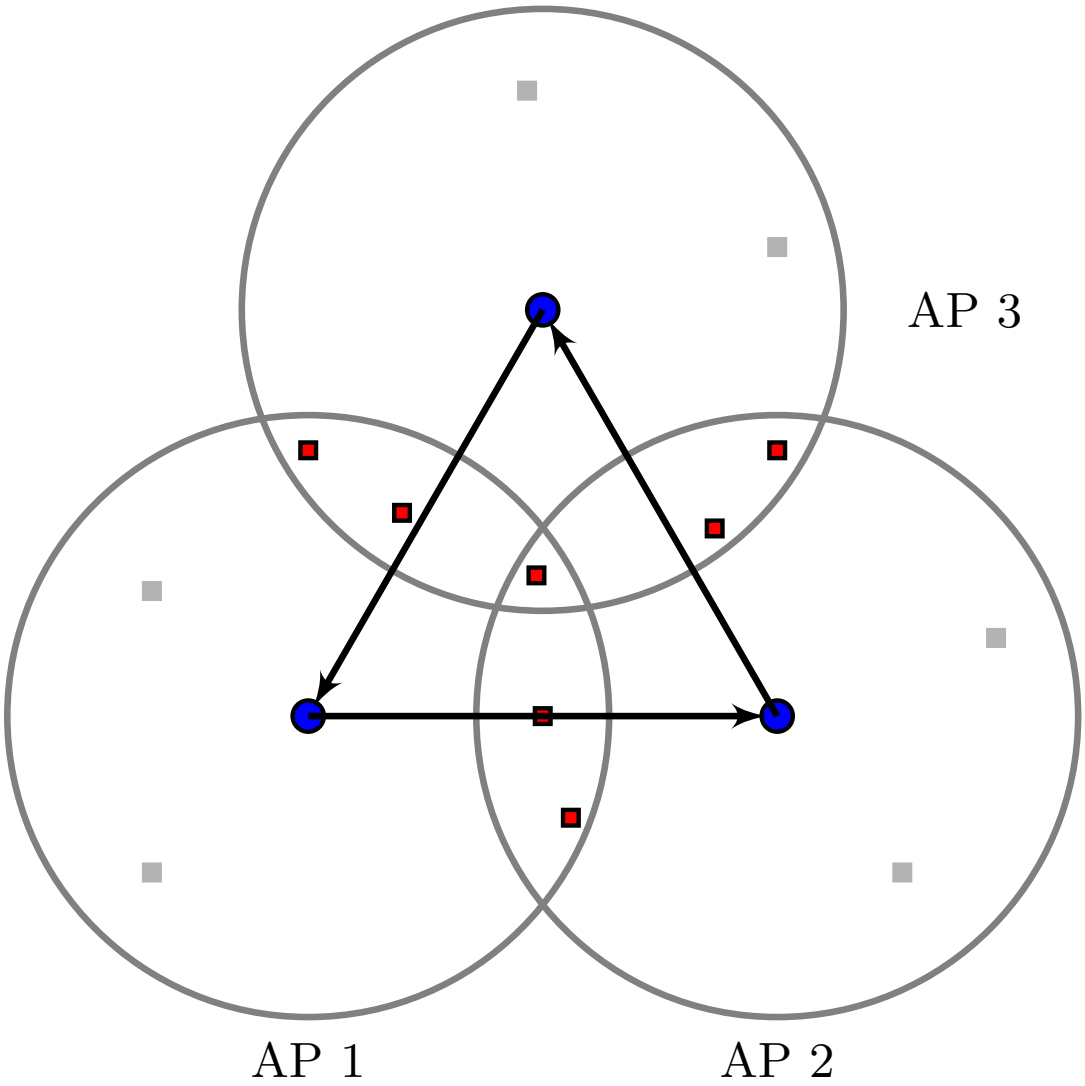

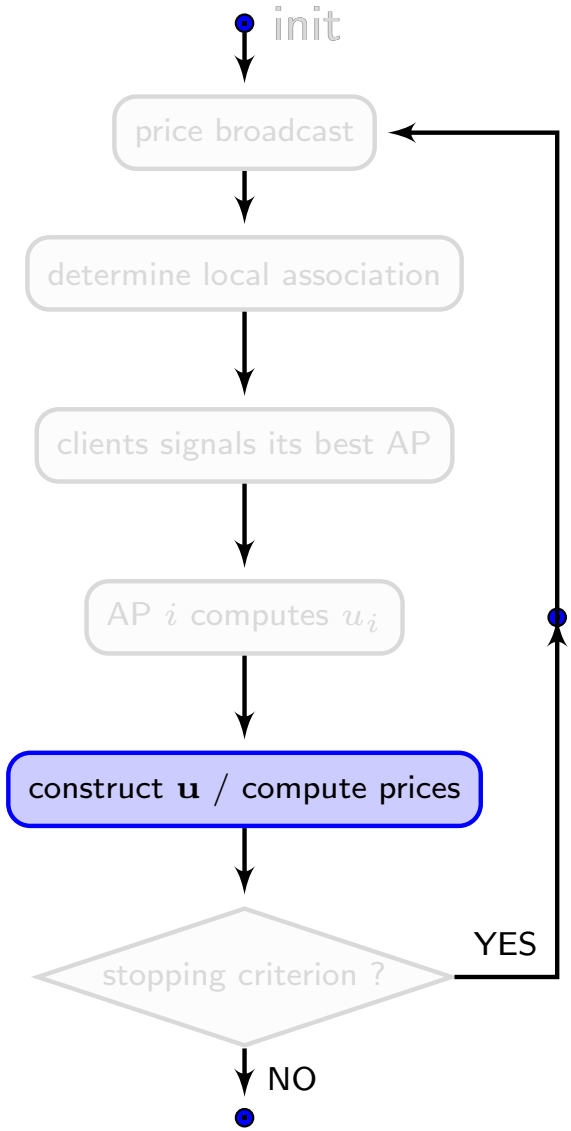

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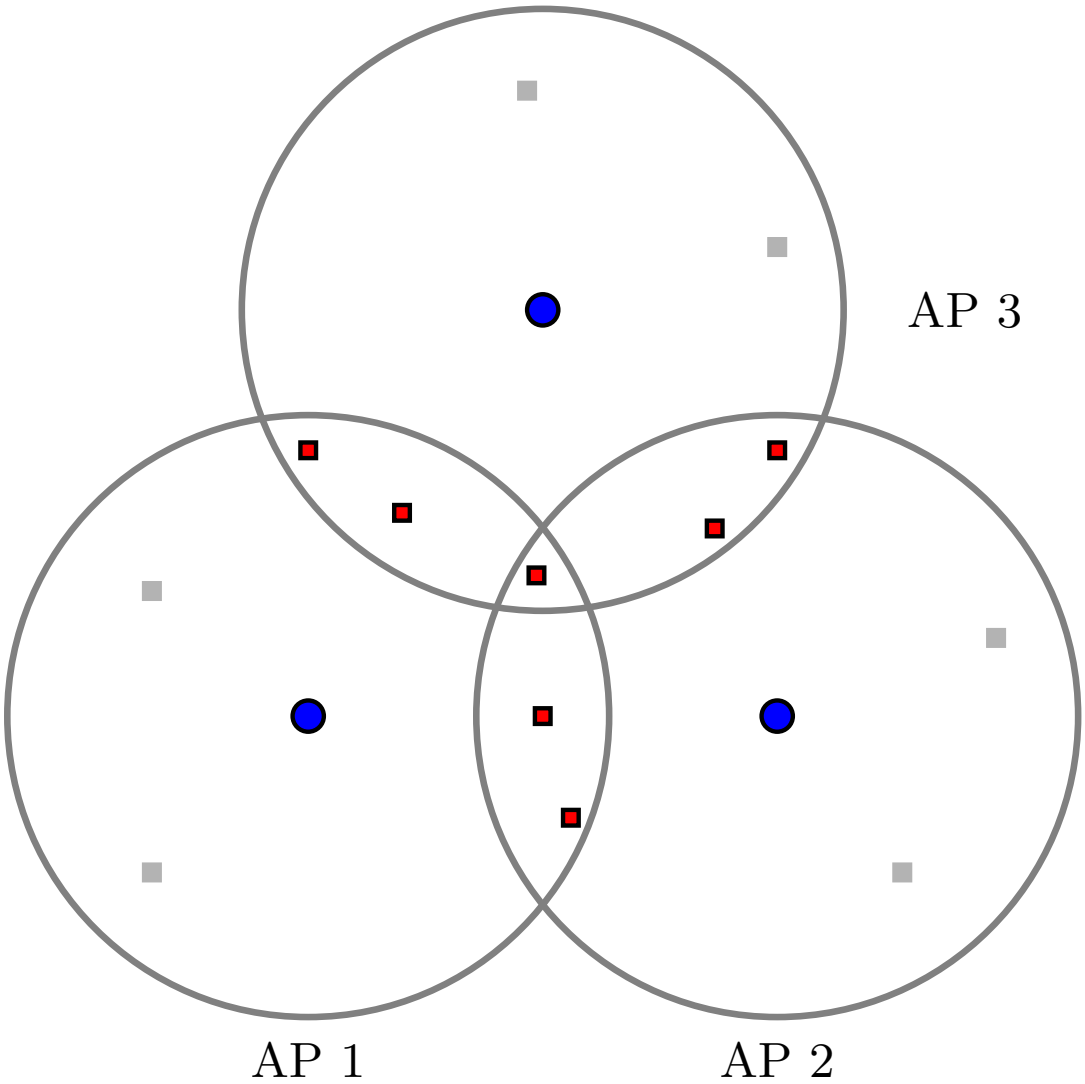
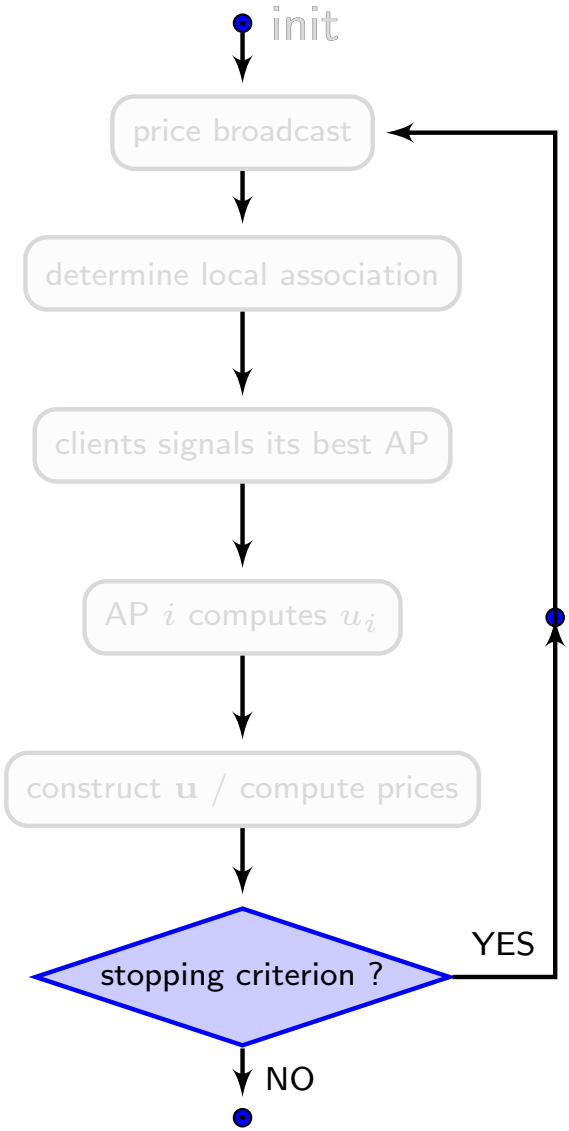
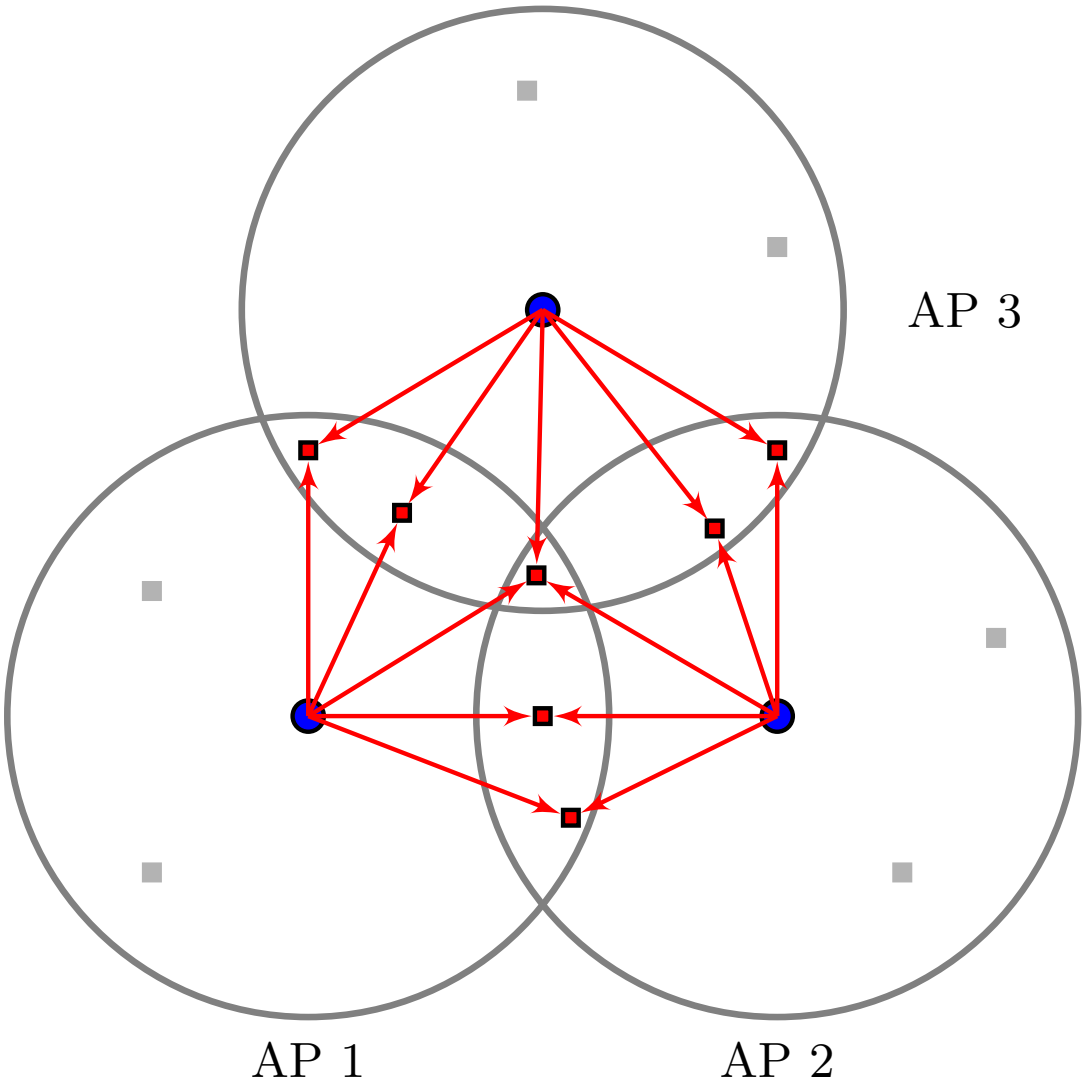
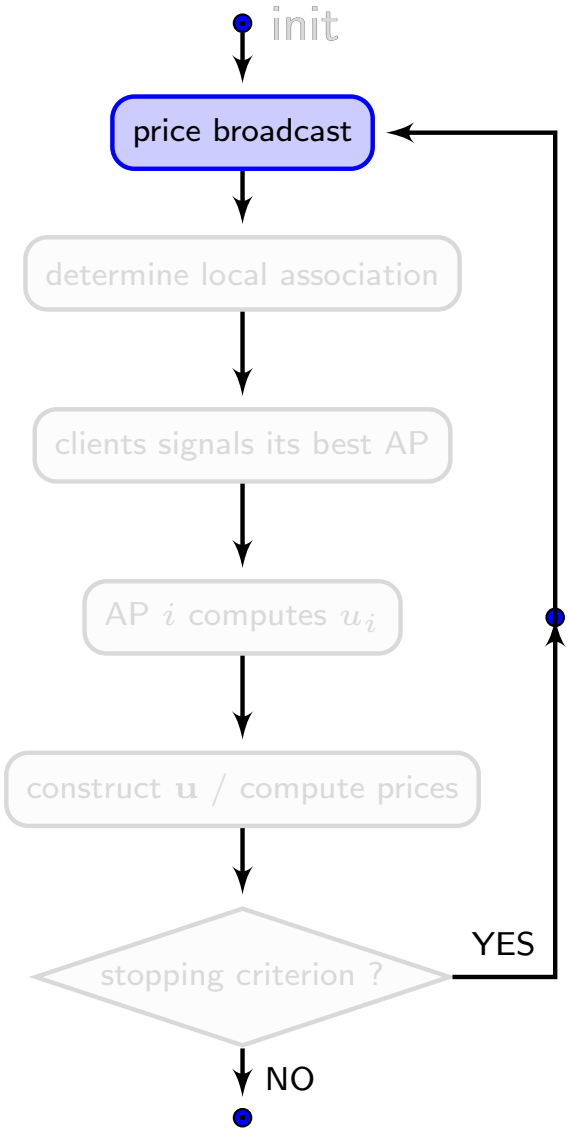




DAA Illustration





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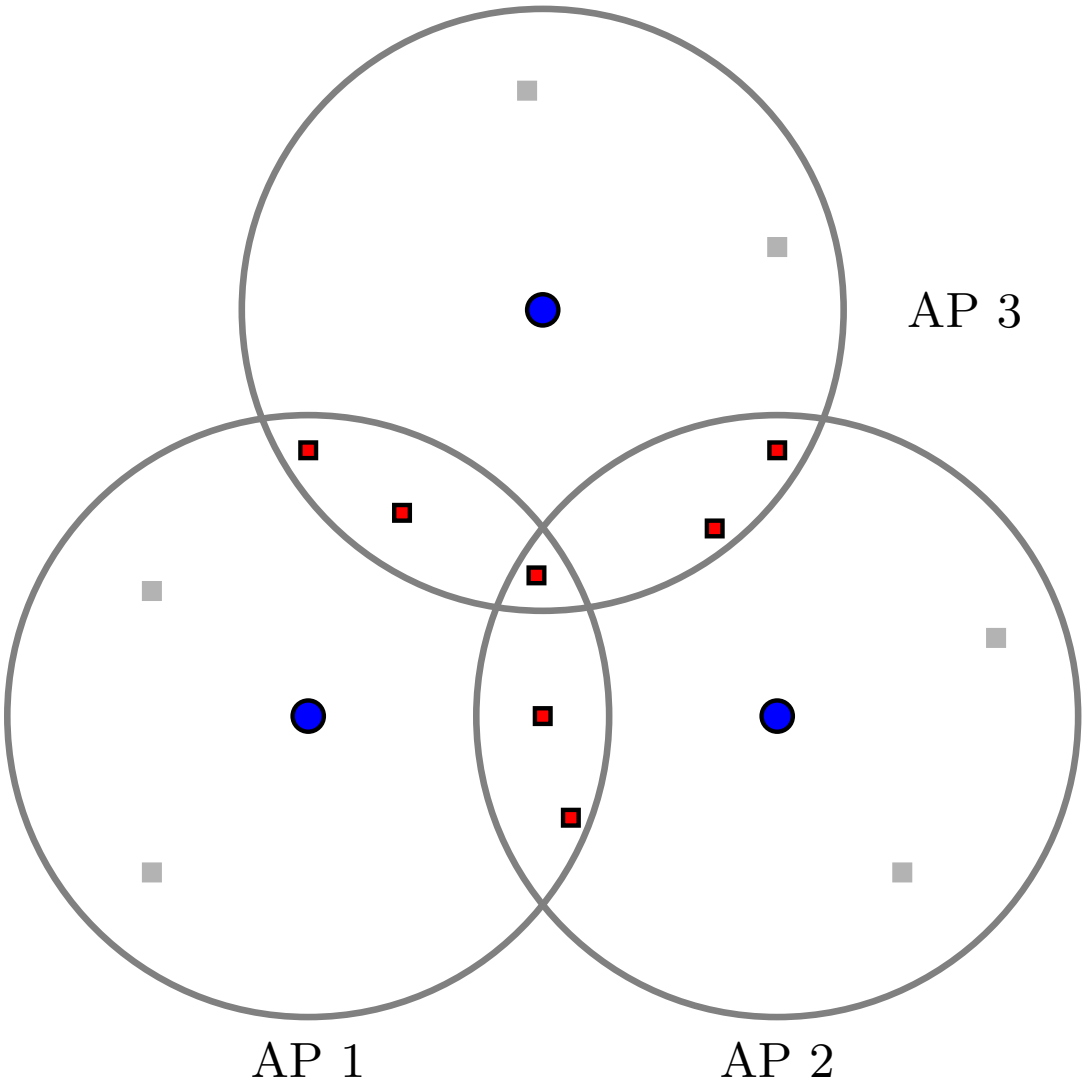

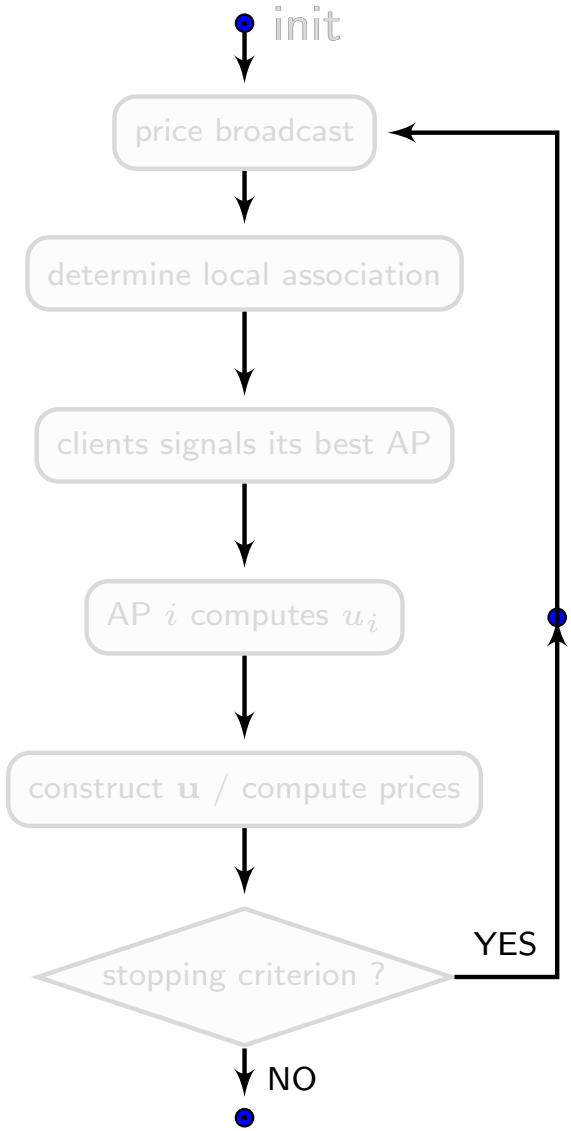

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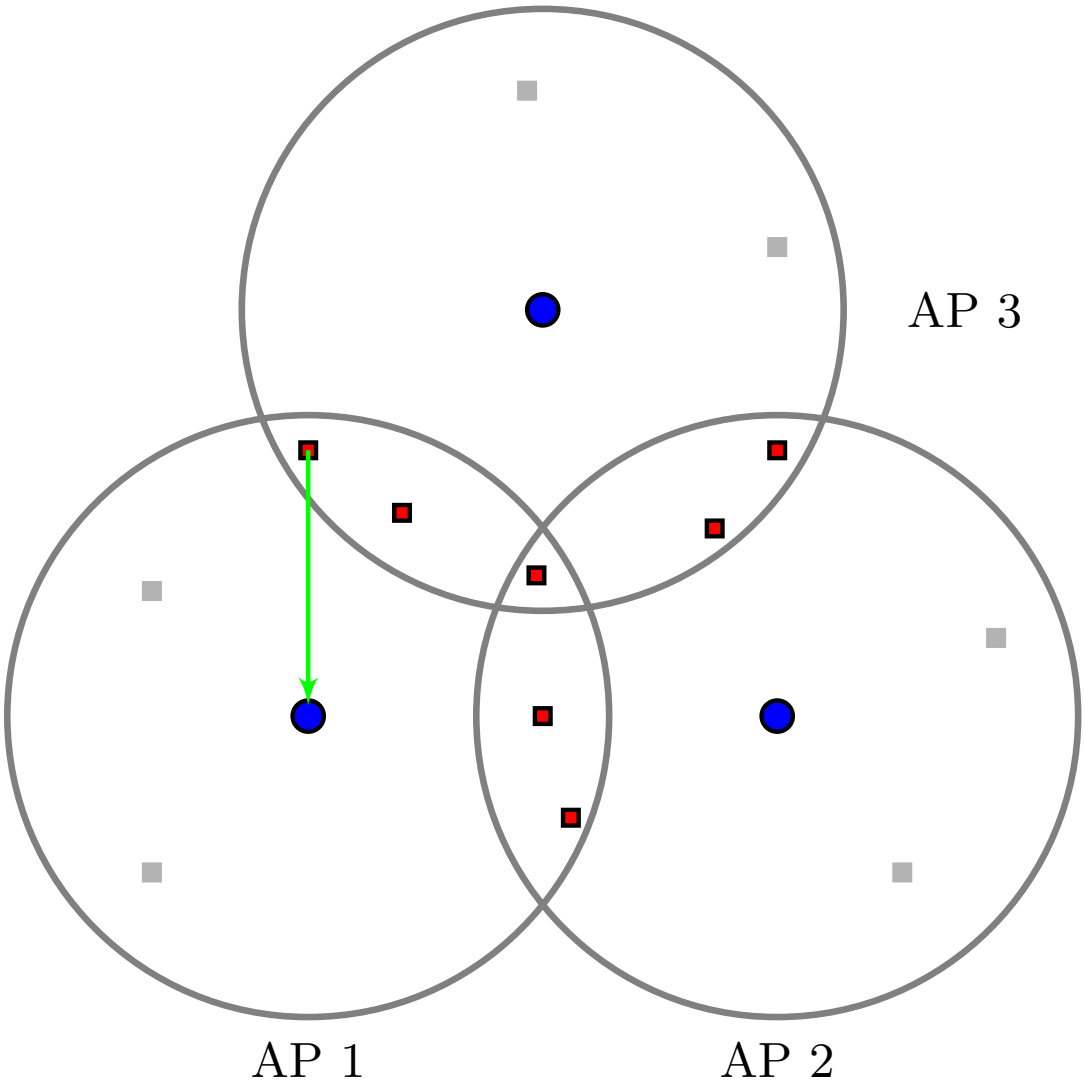

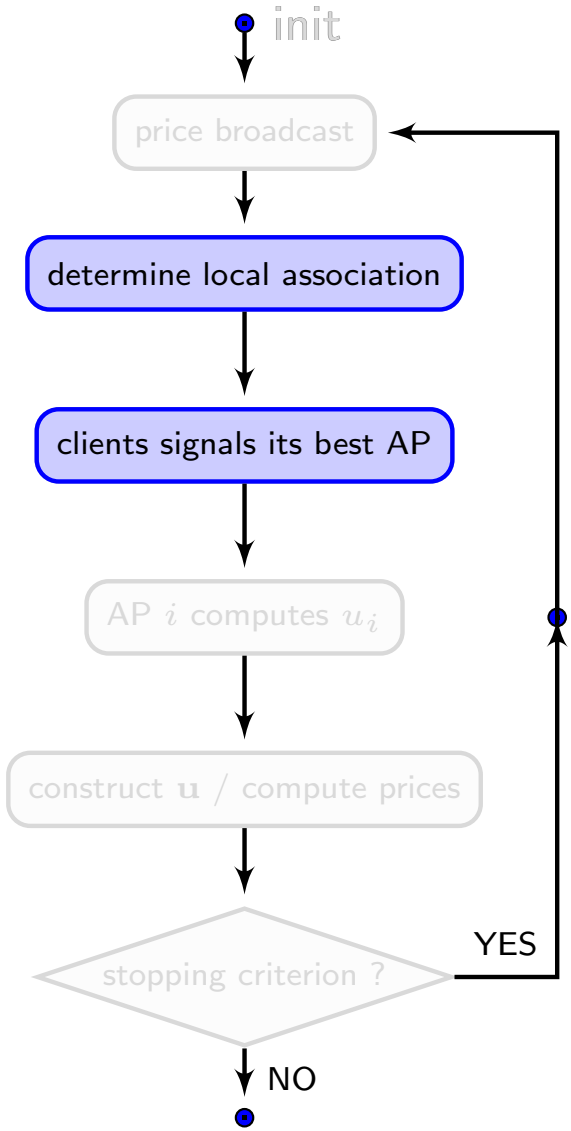

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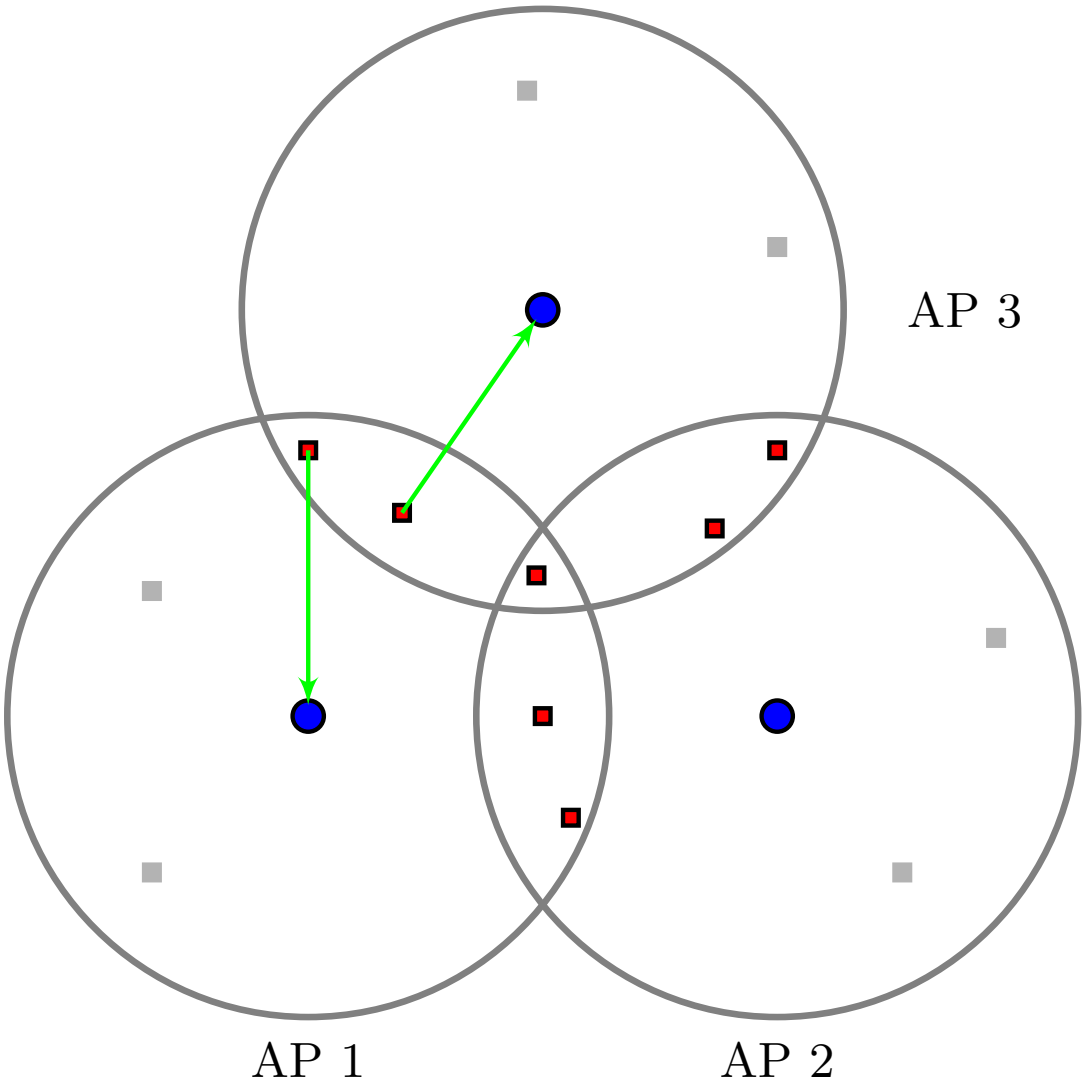

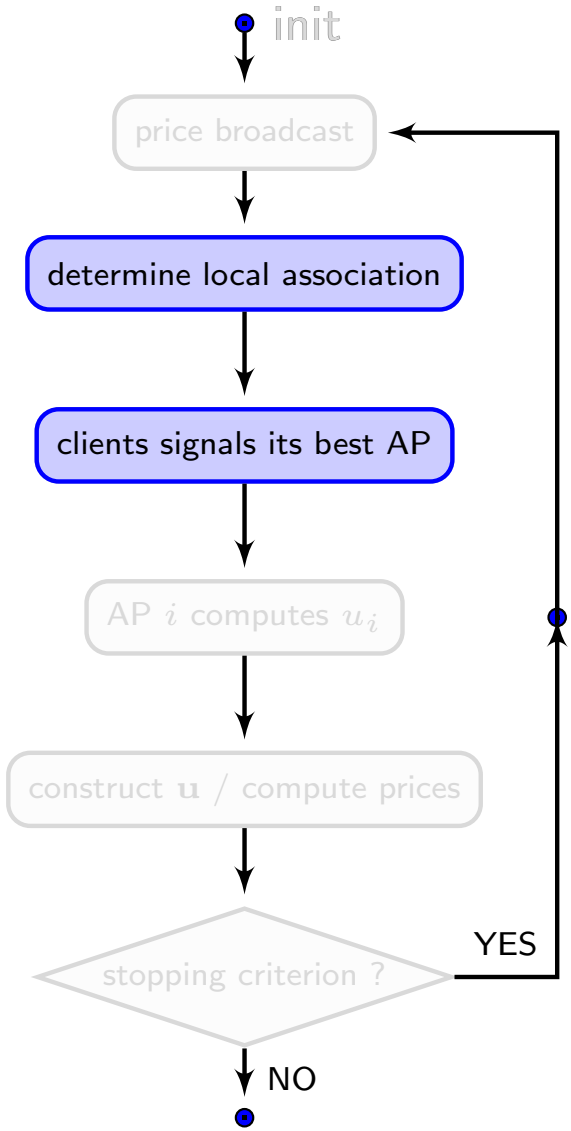

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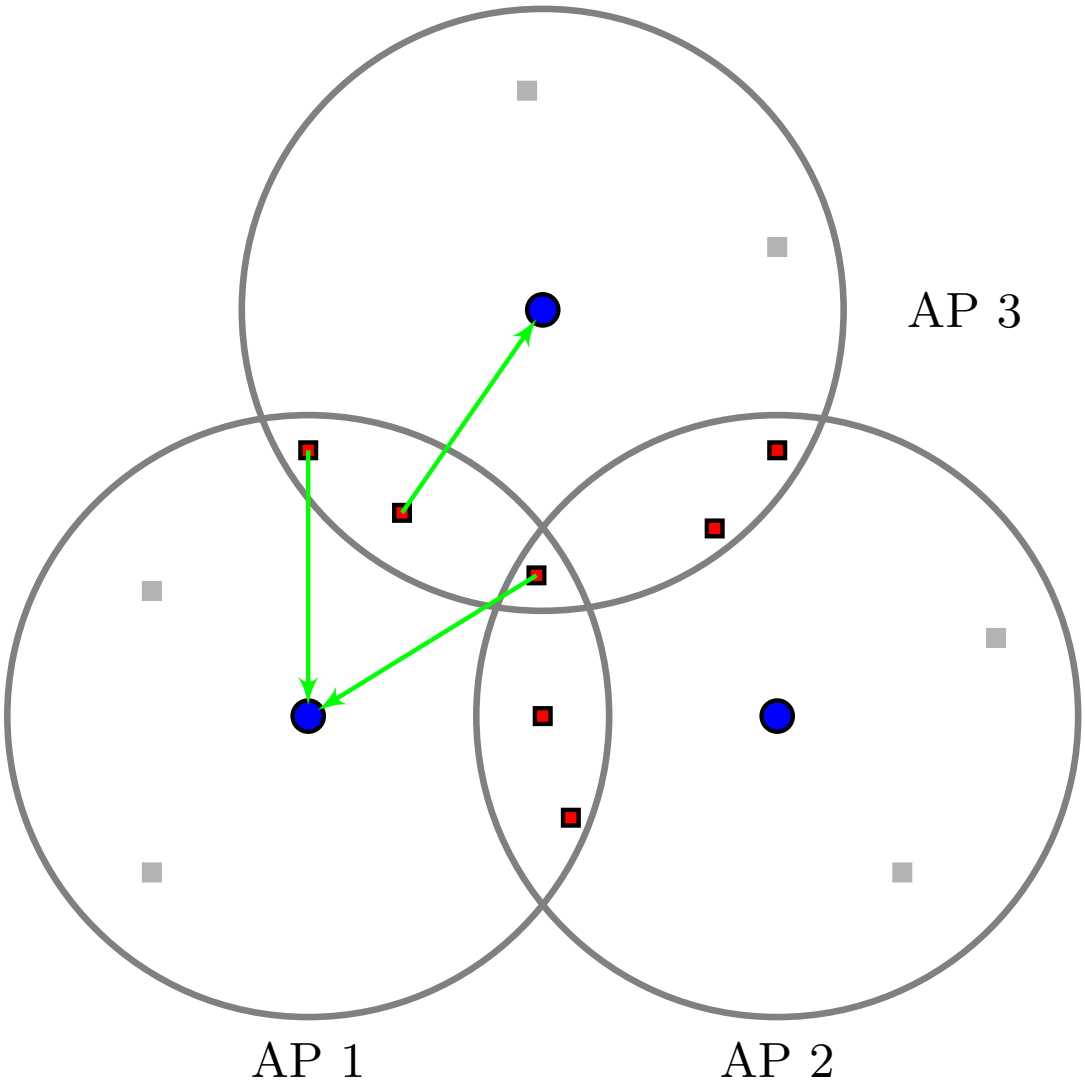

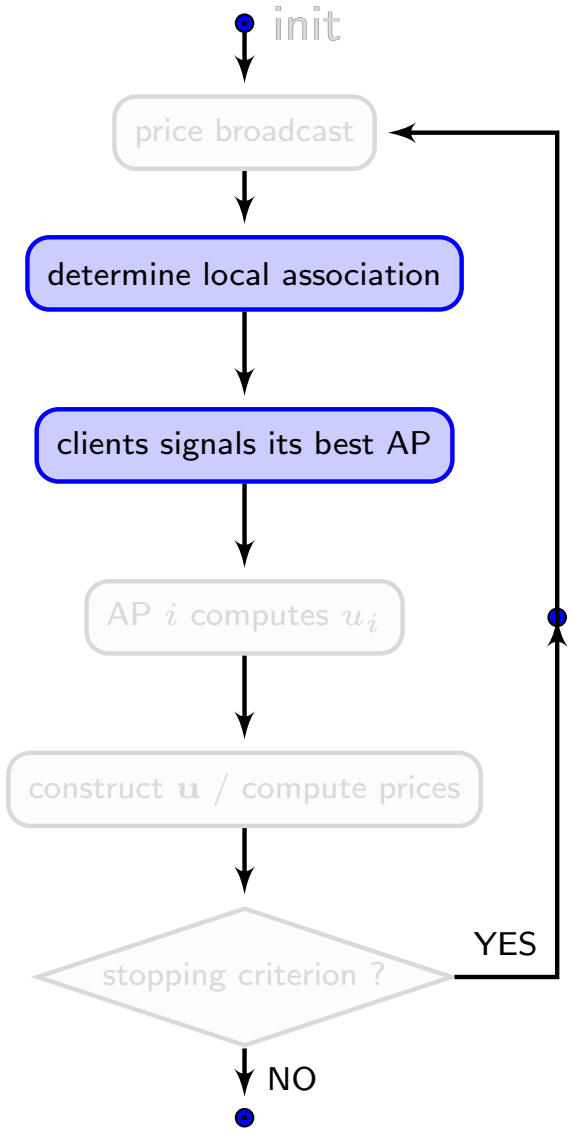

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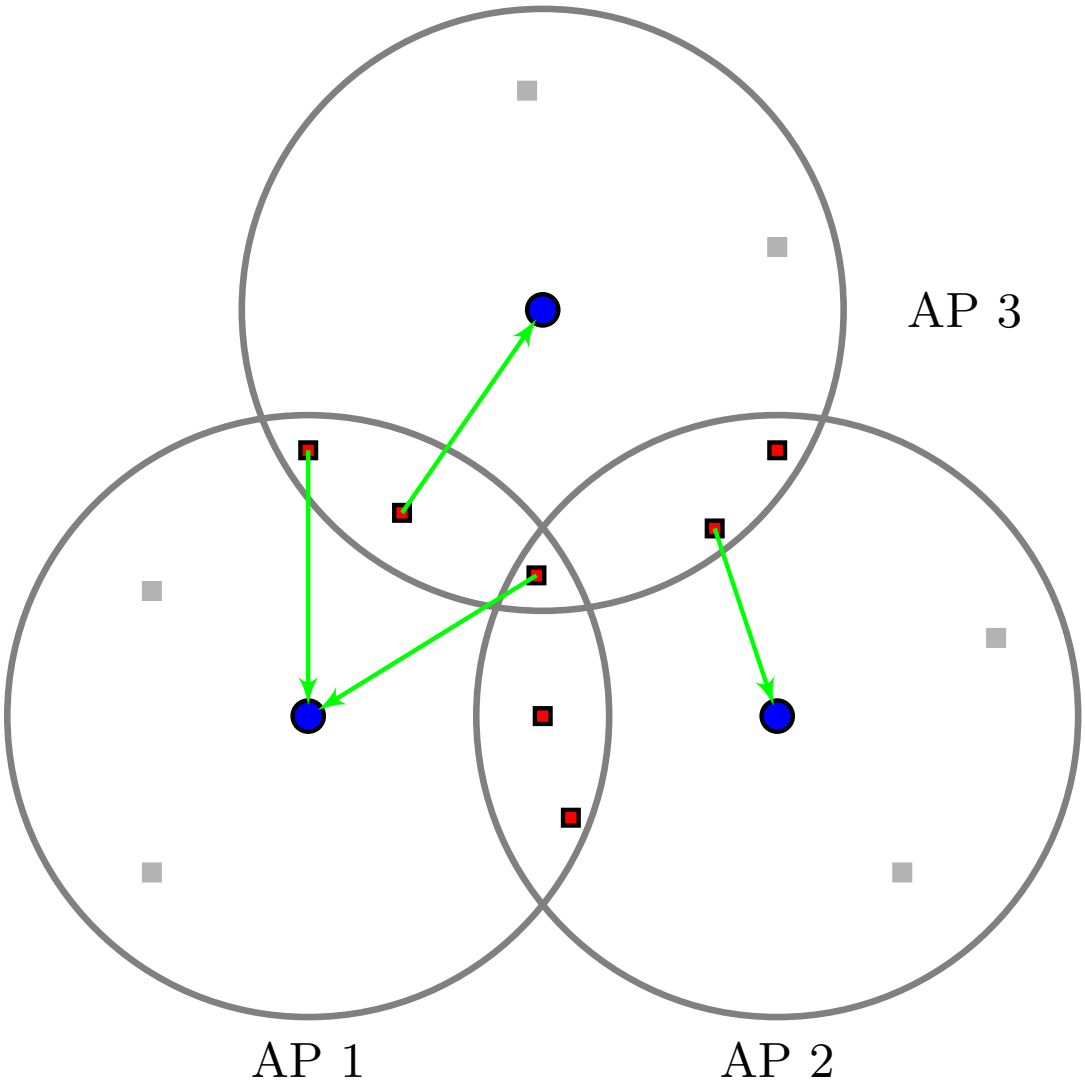

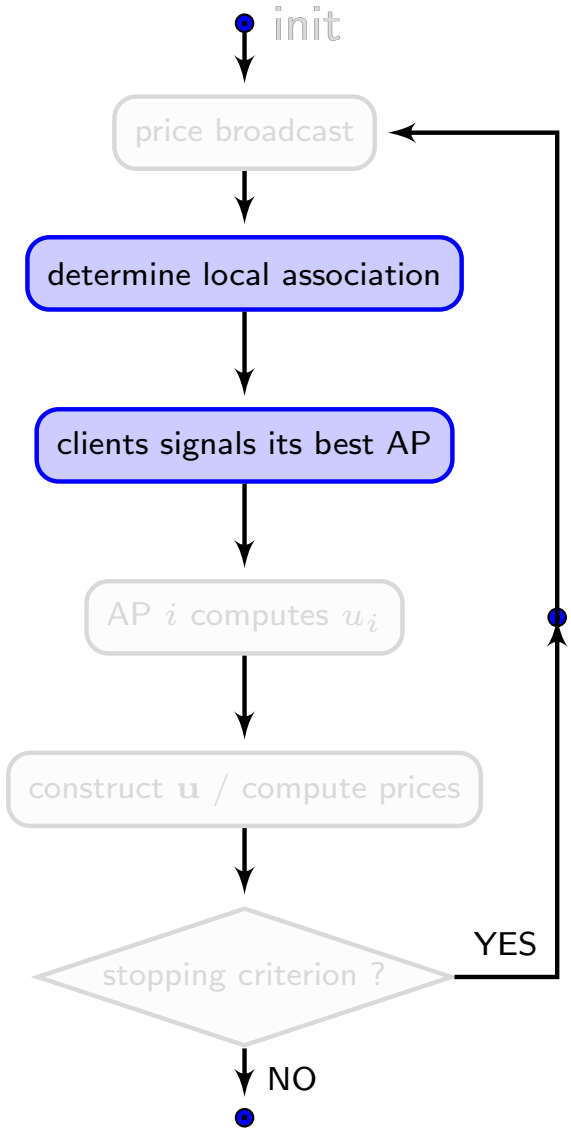

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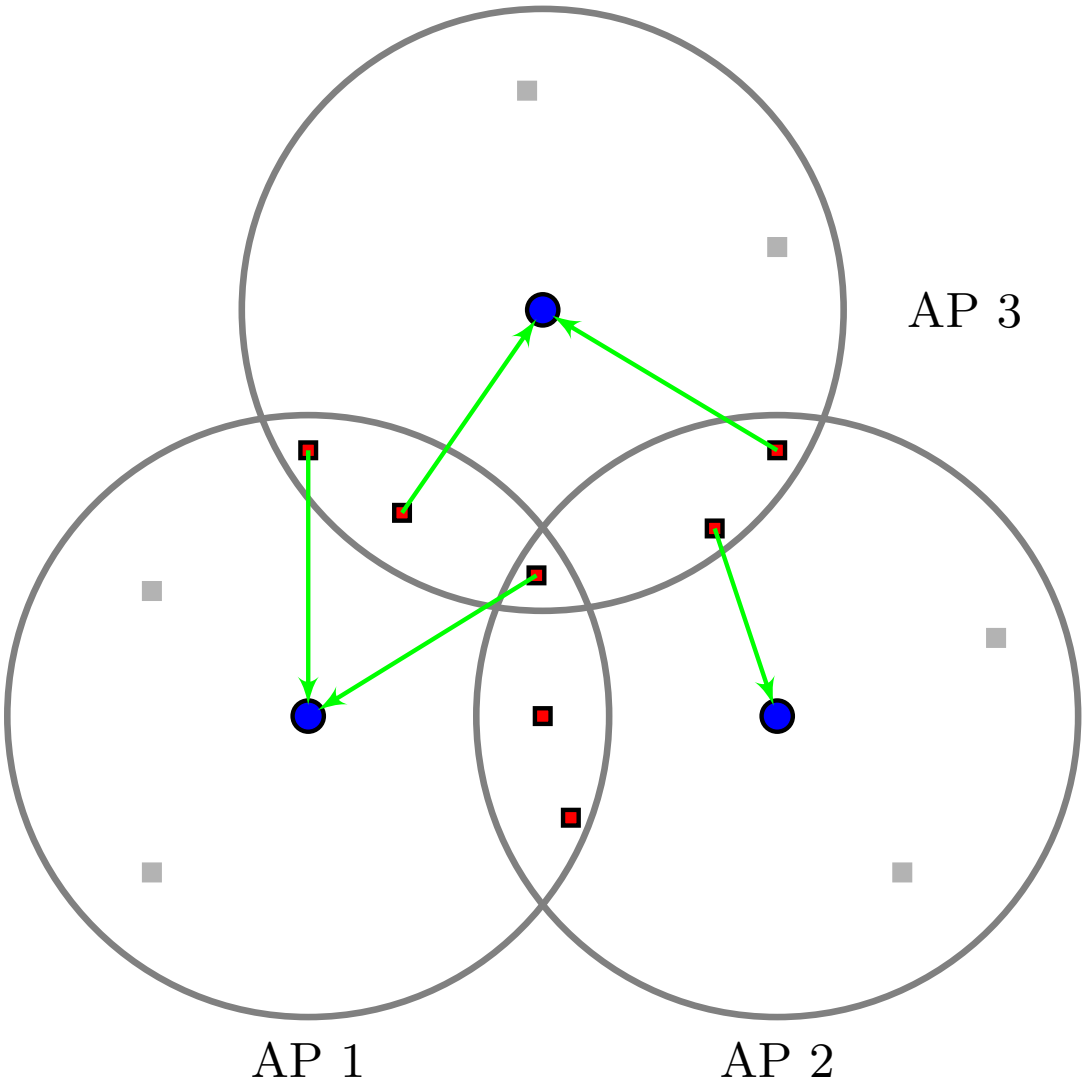

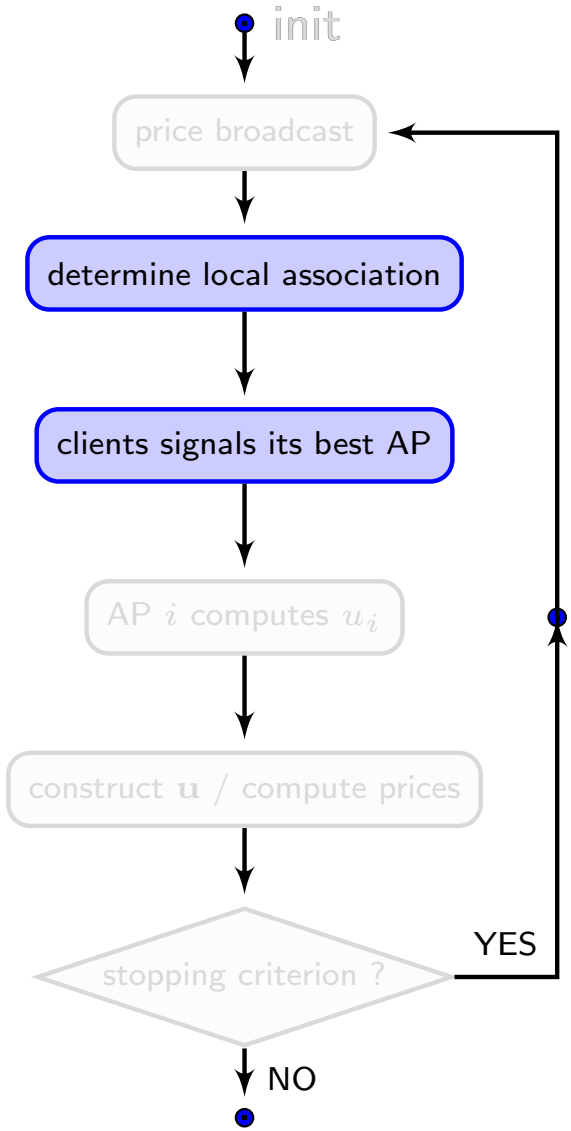

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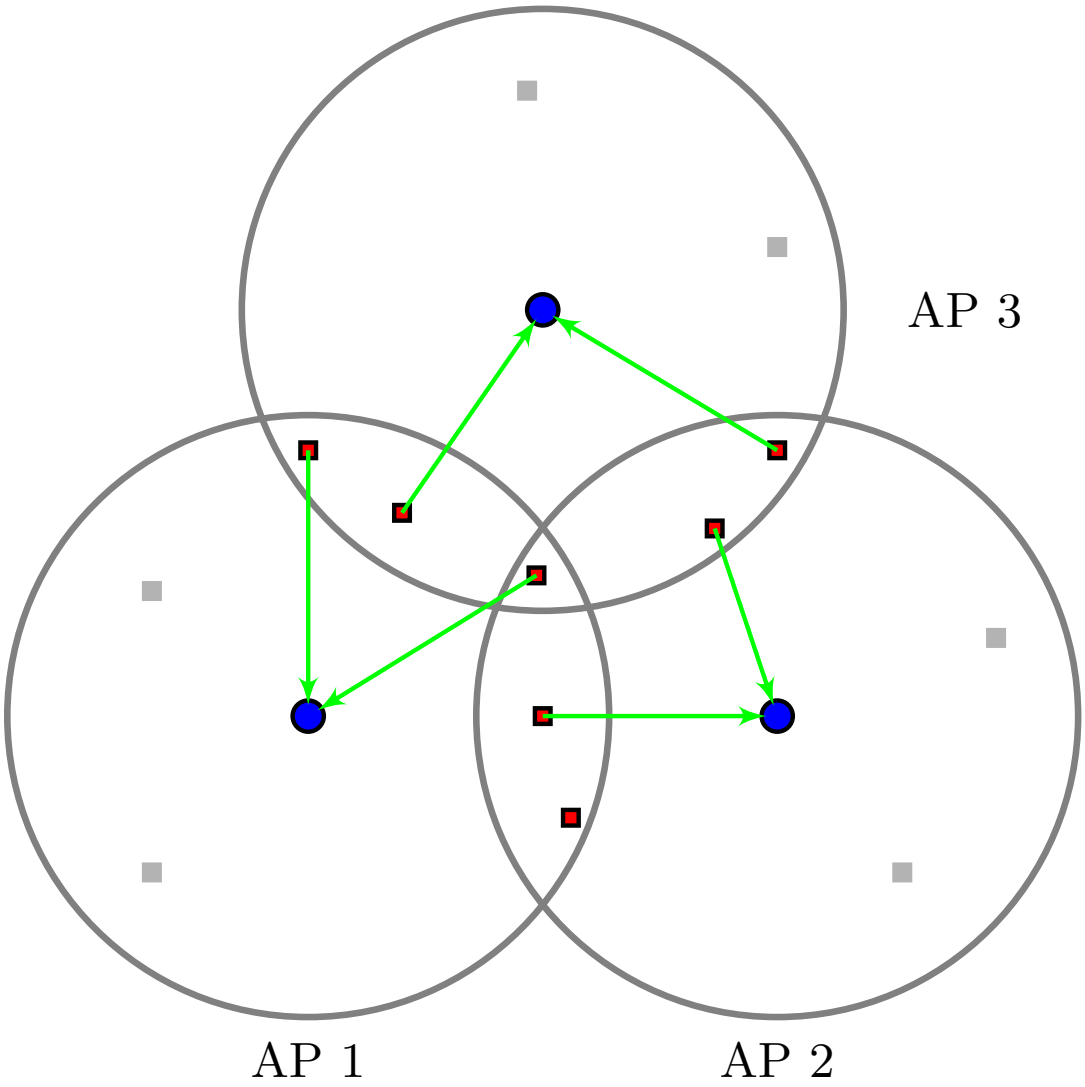

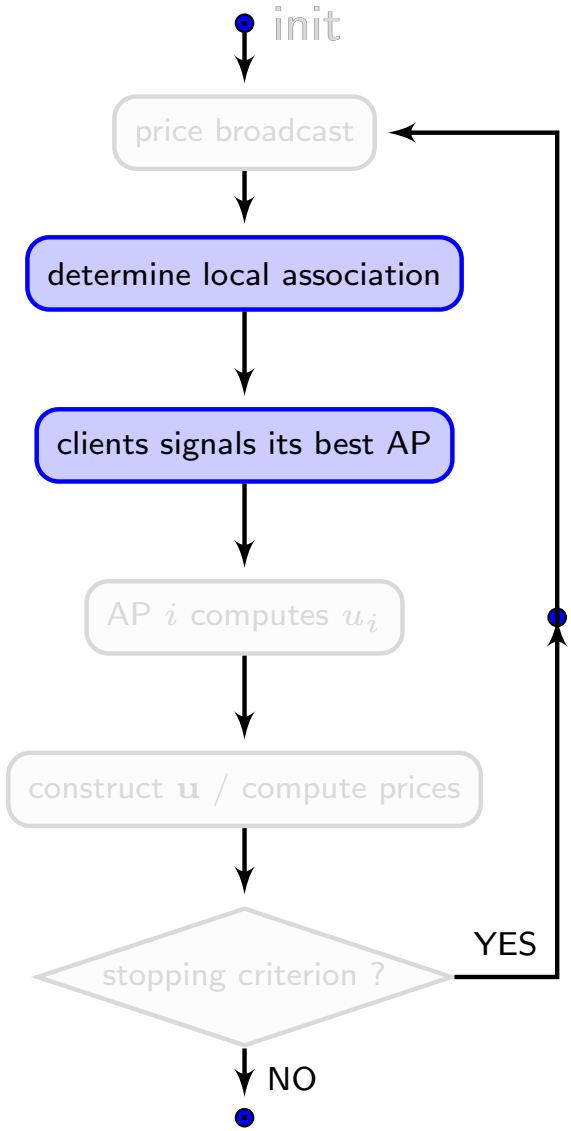

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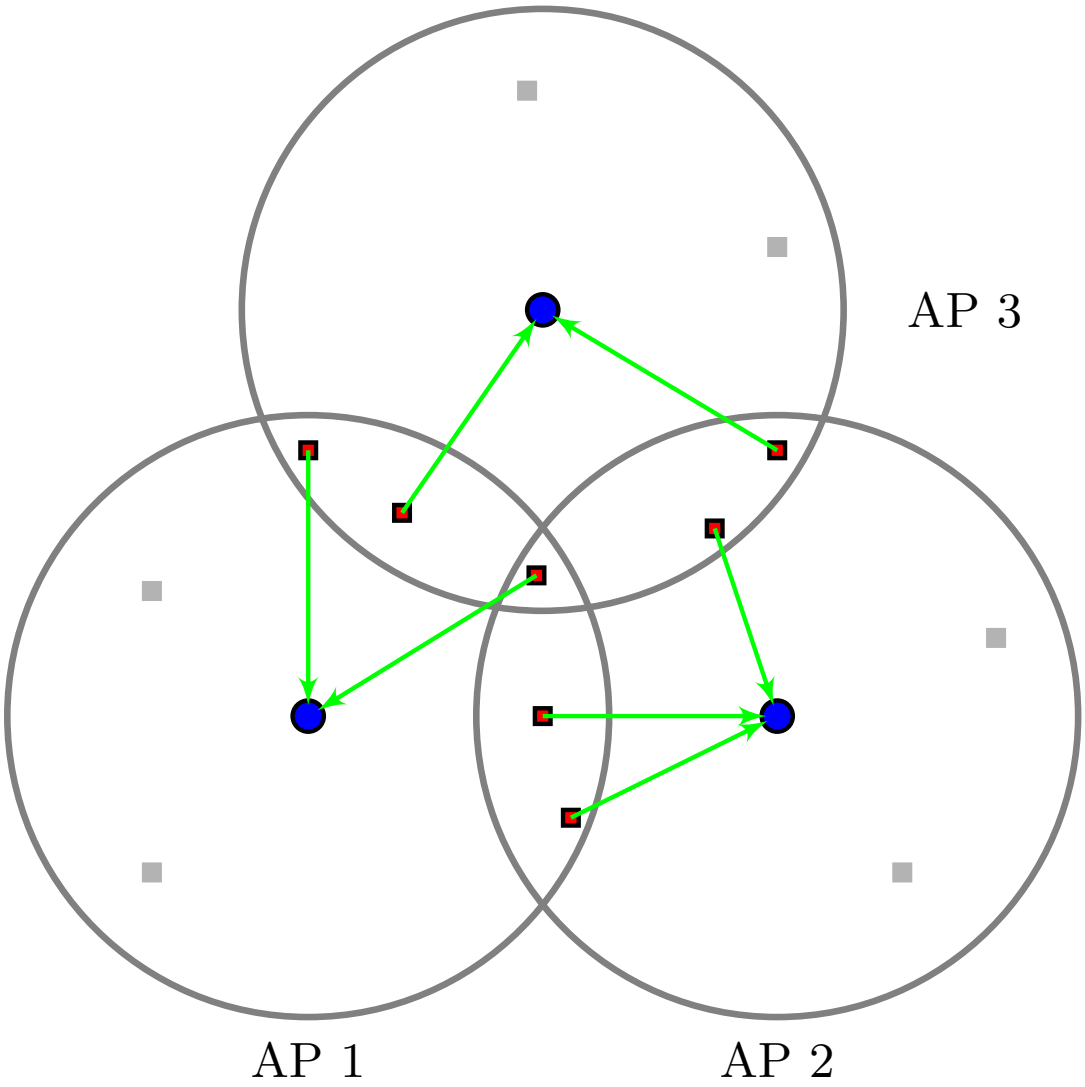

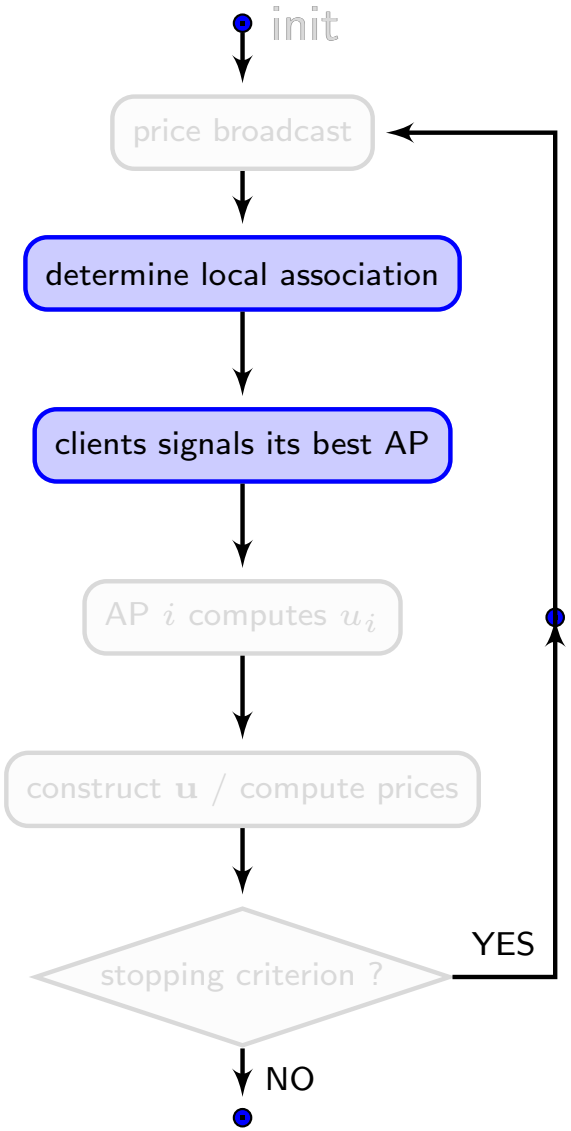

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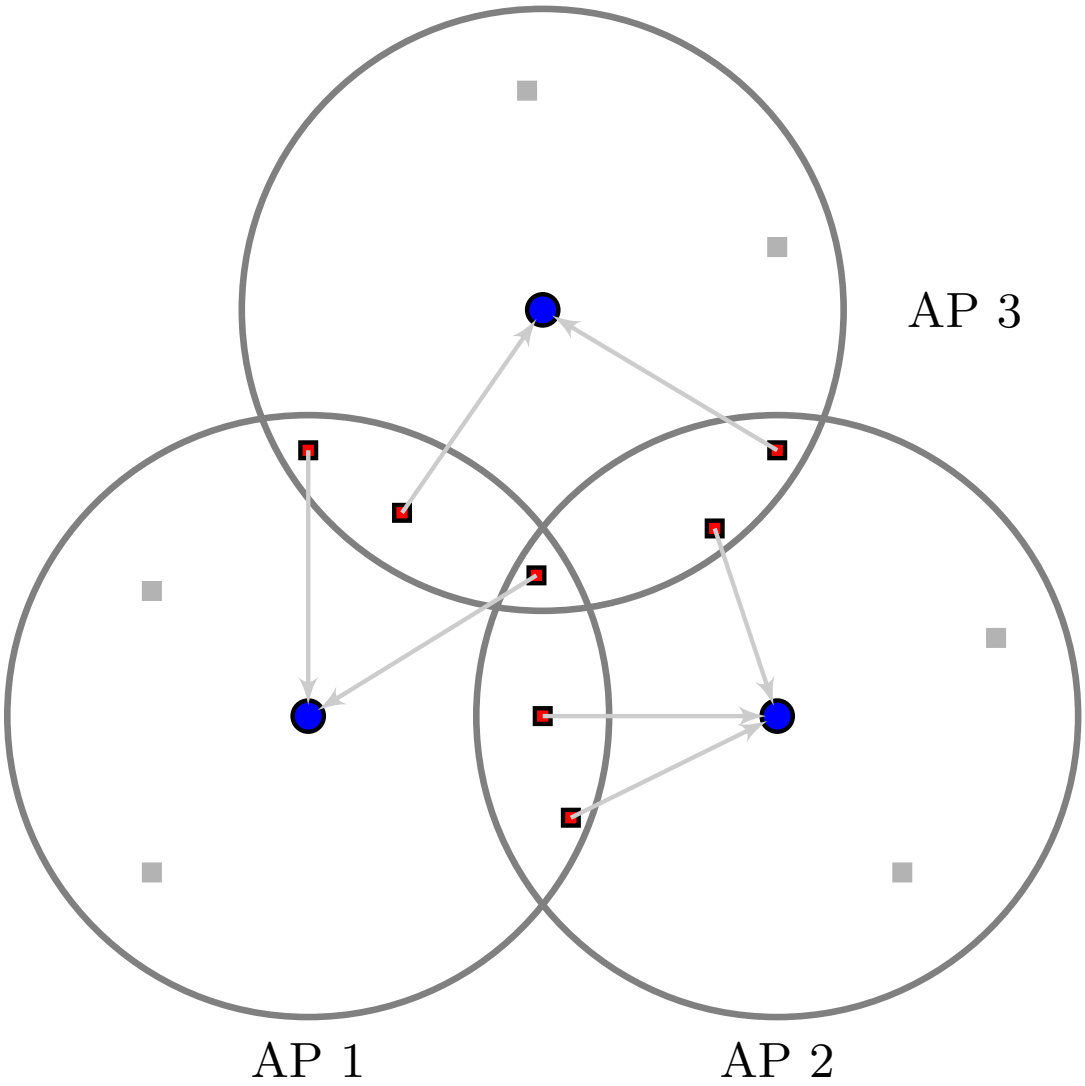

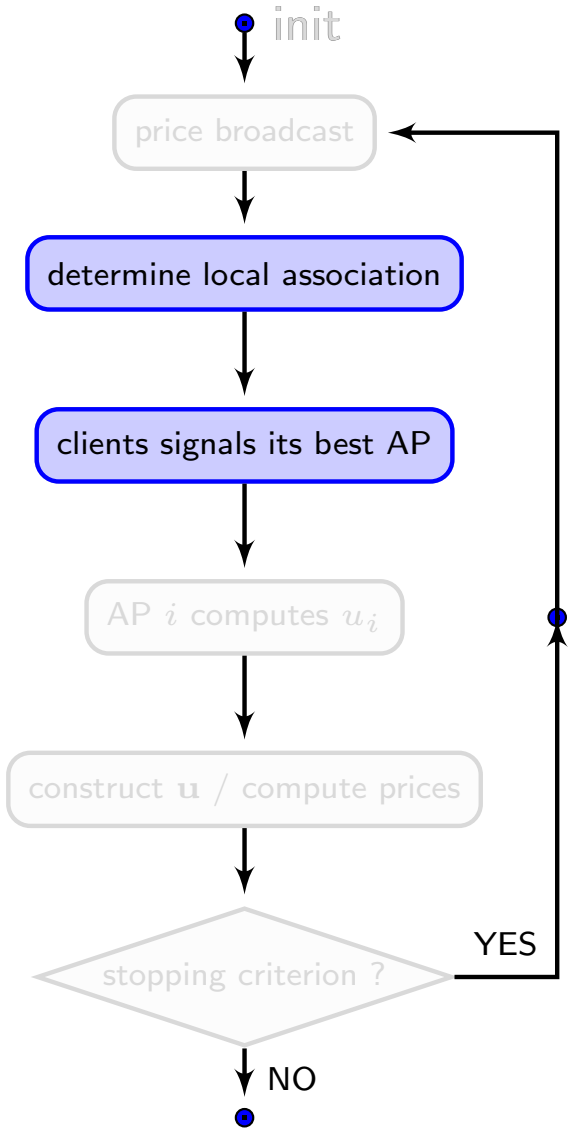

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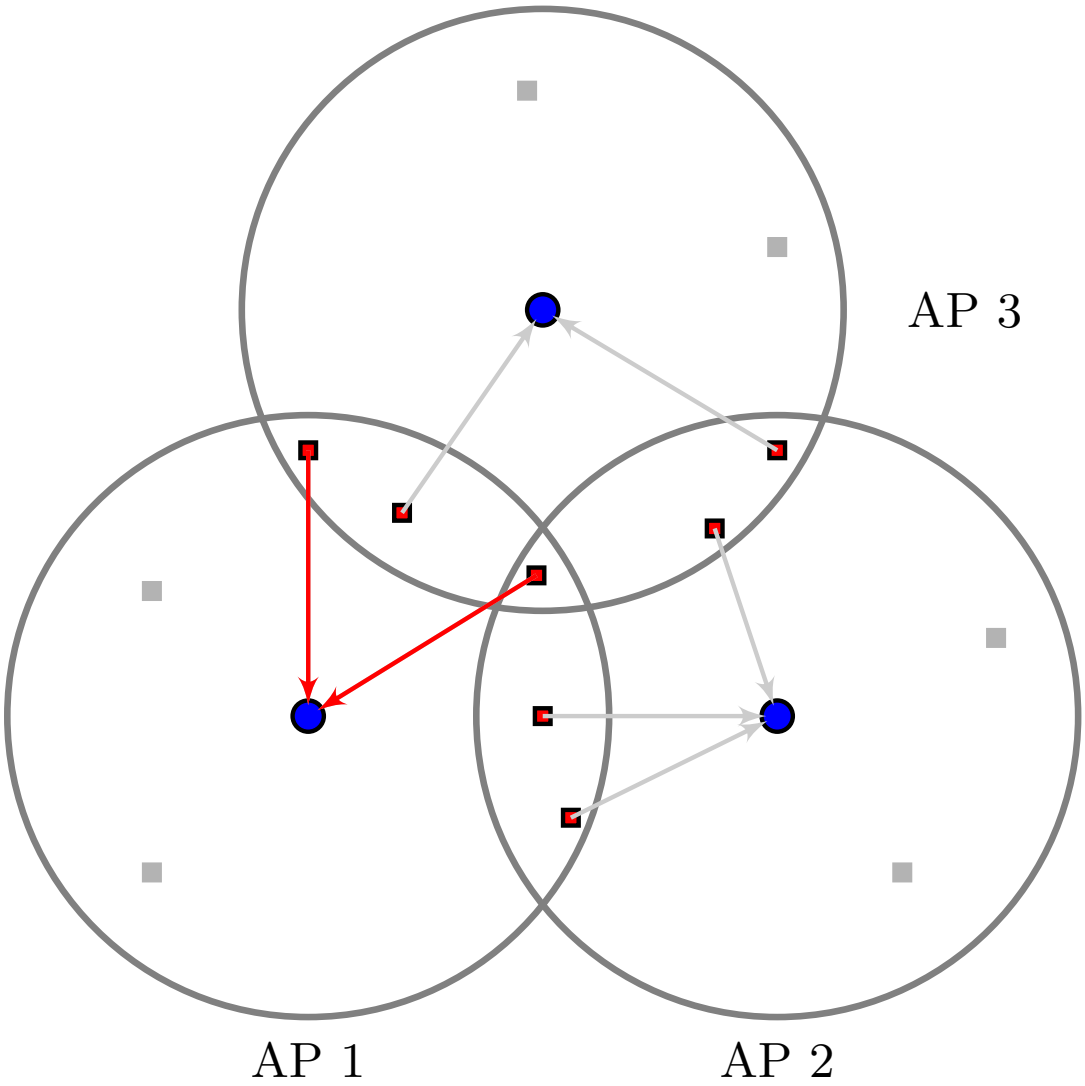

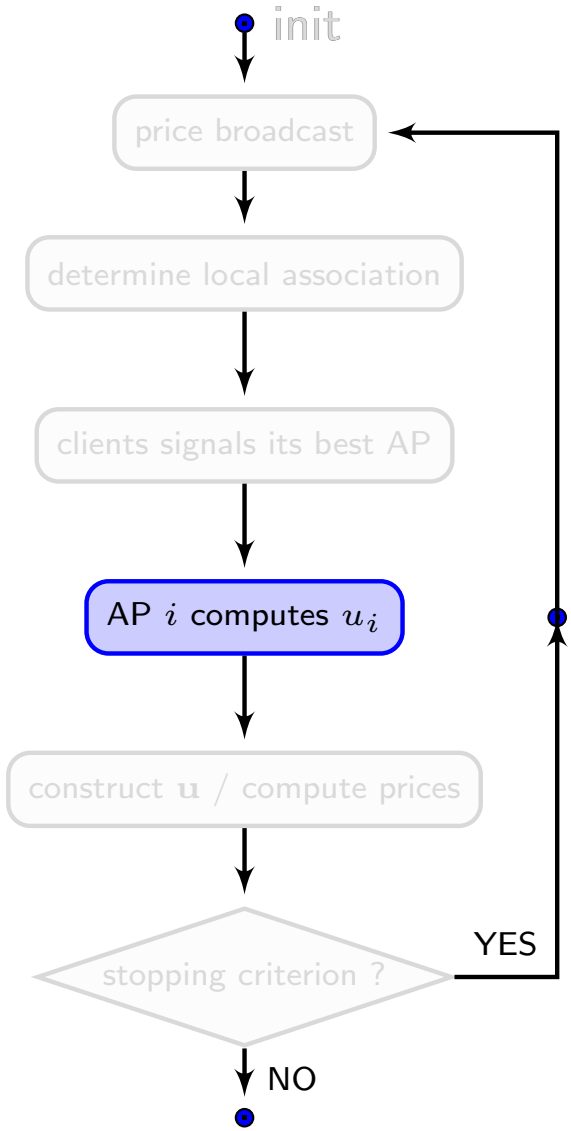

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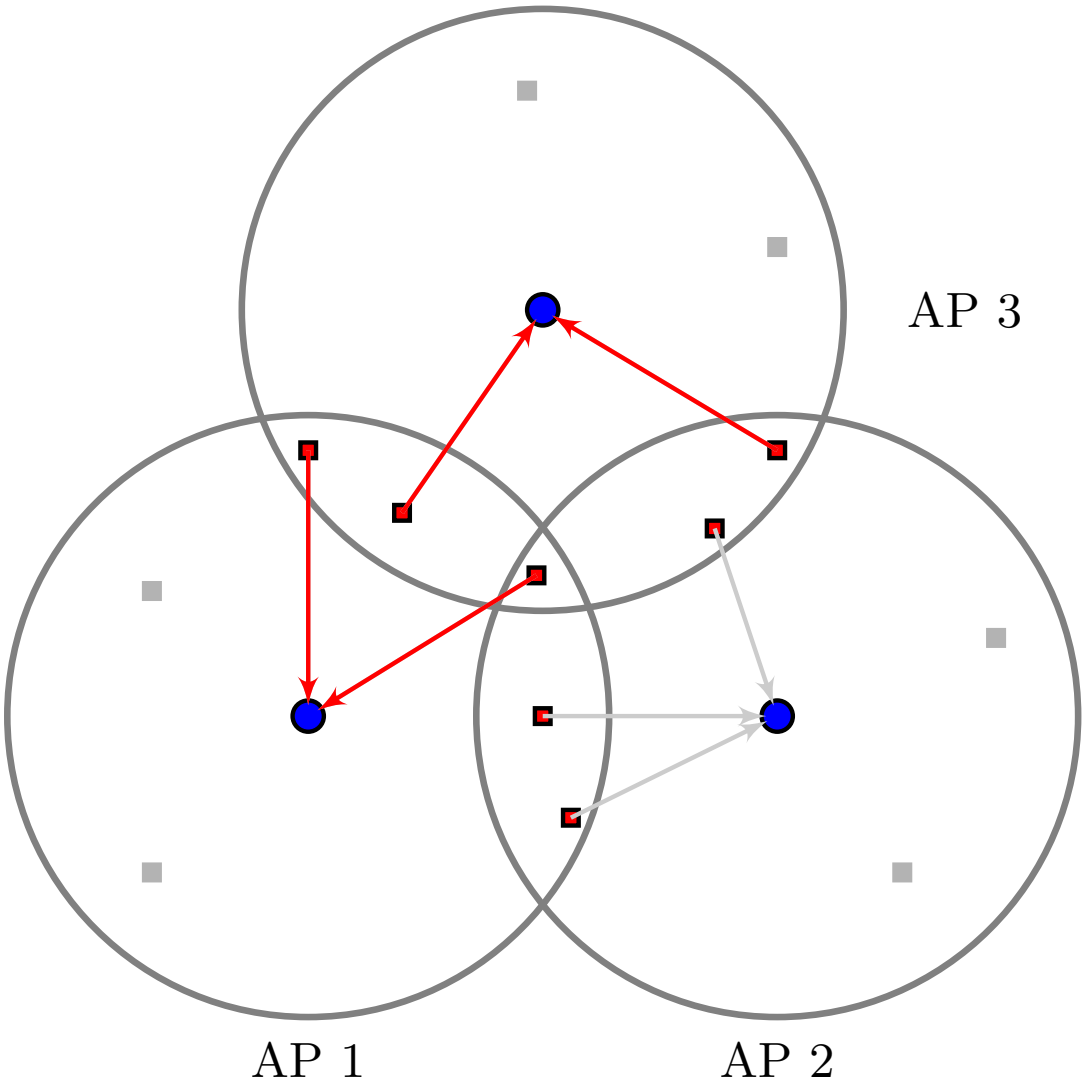

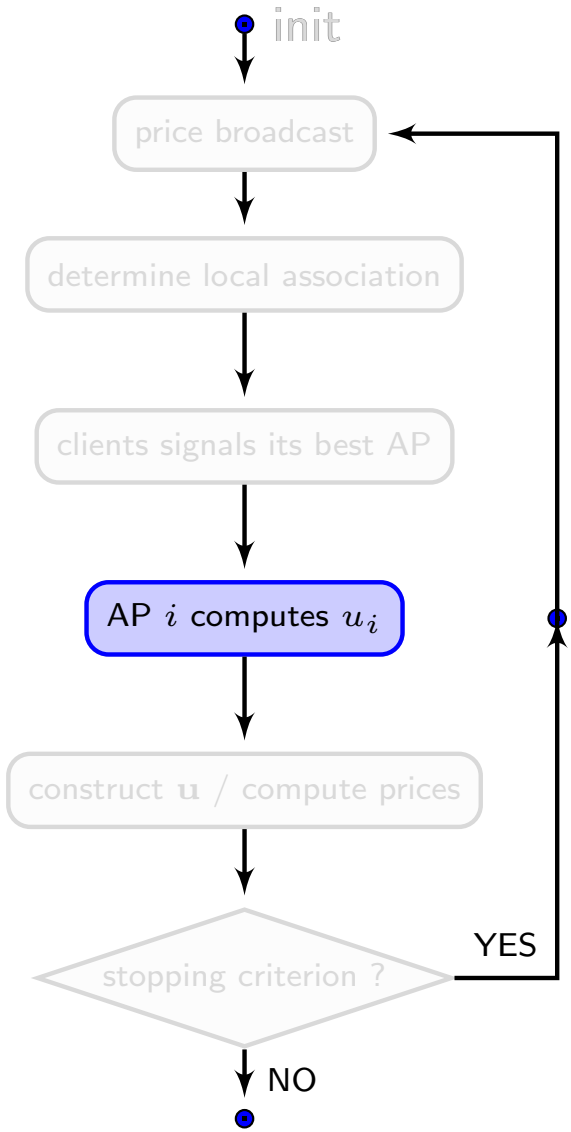

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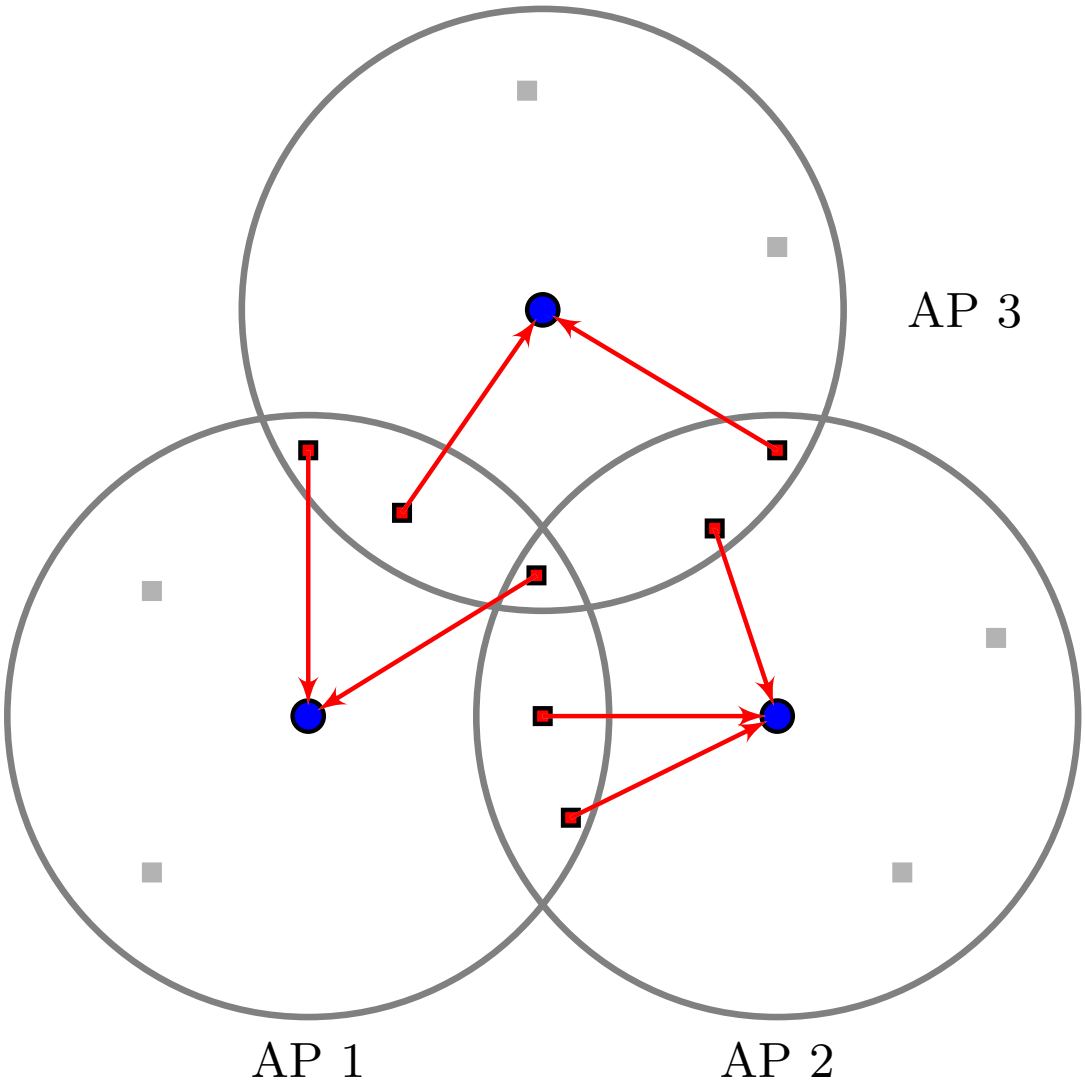

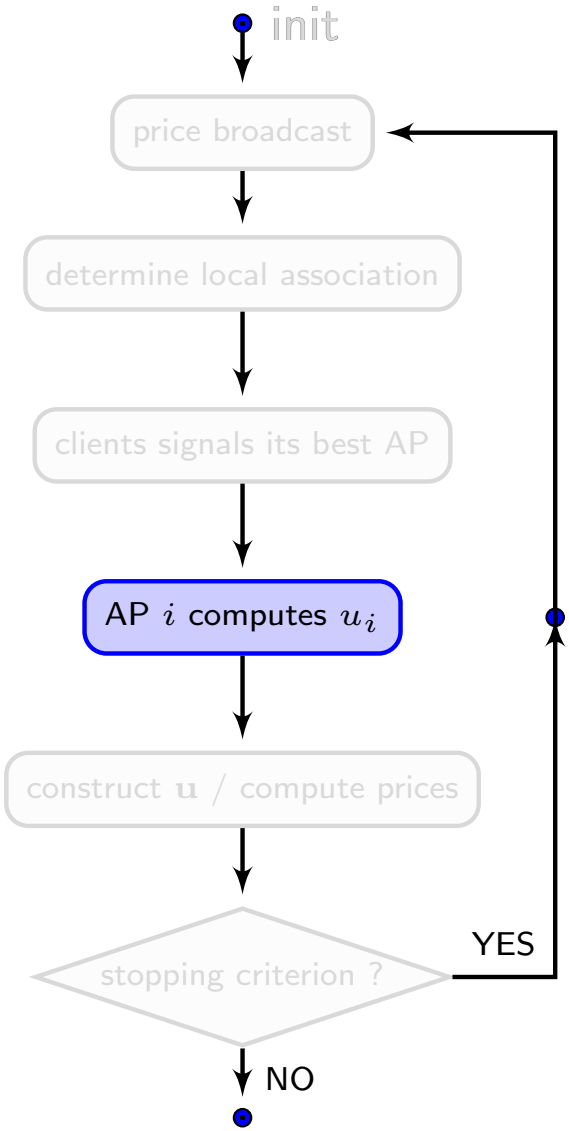

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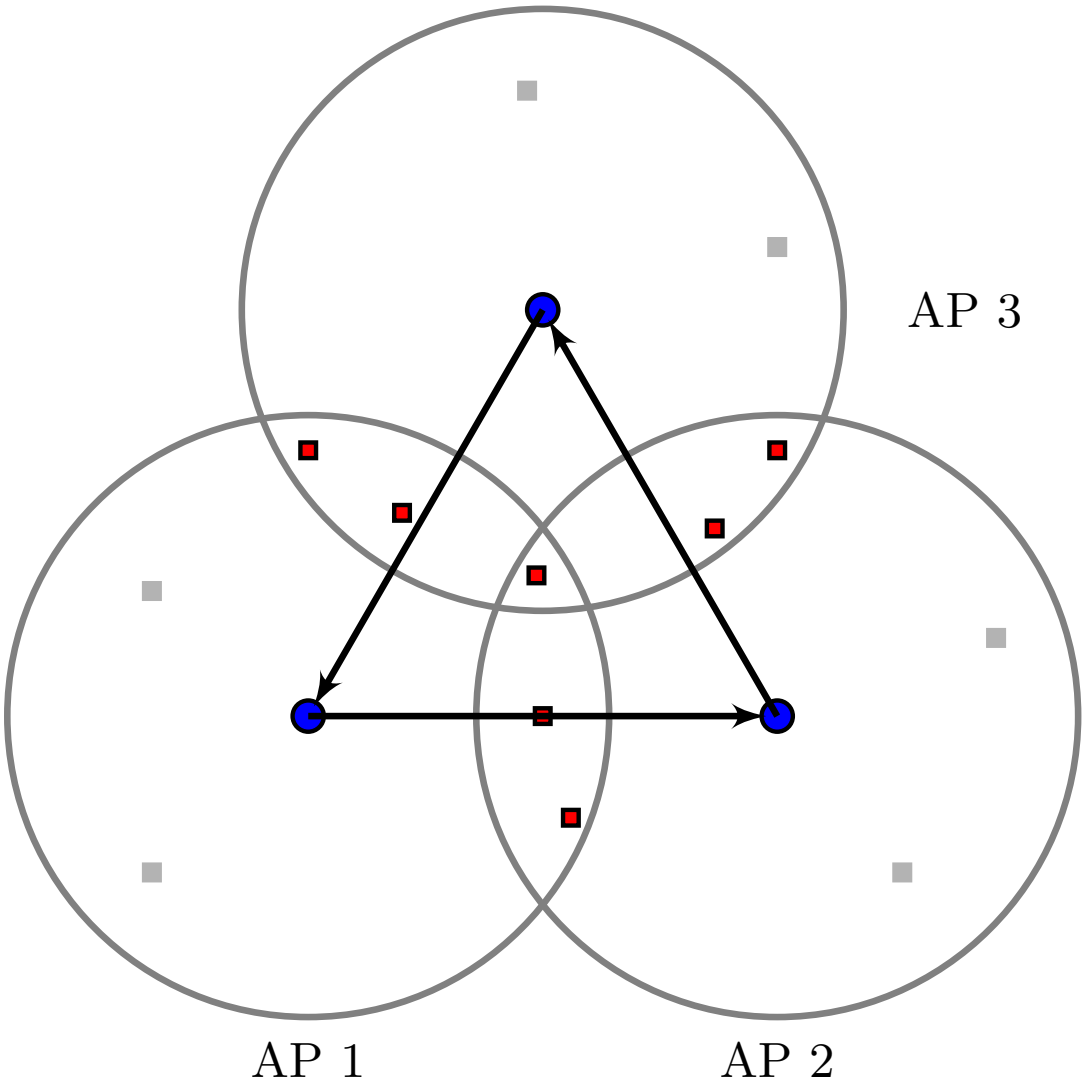

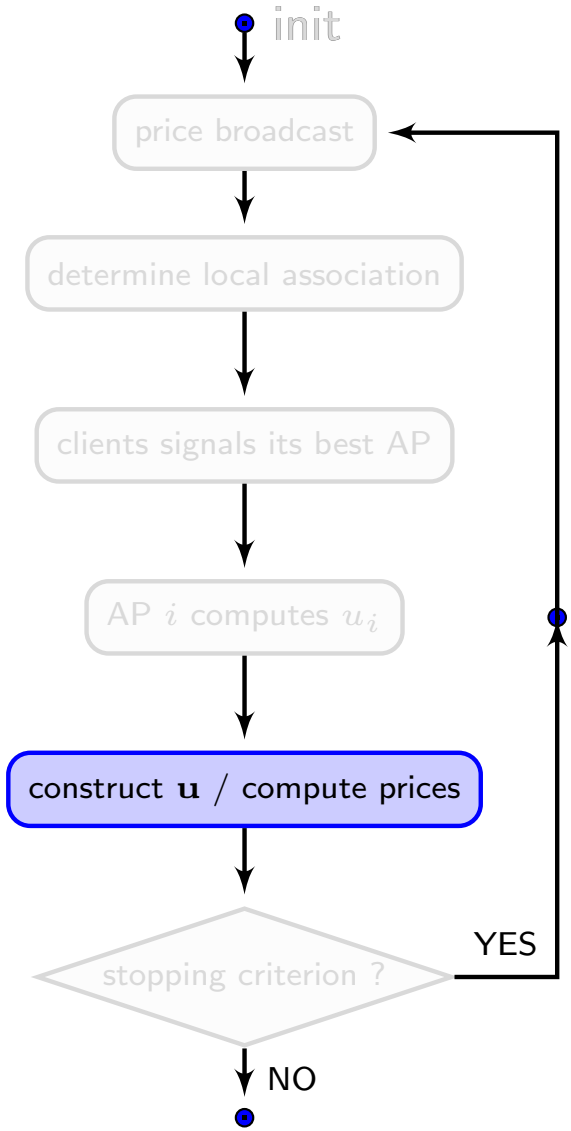

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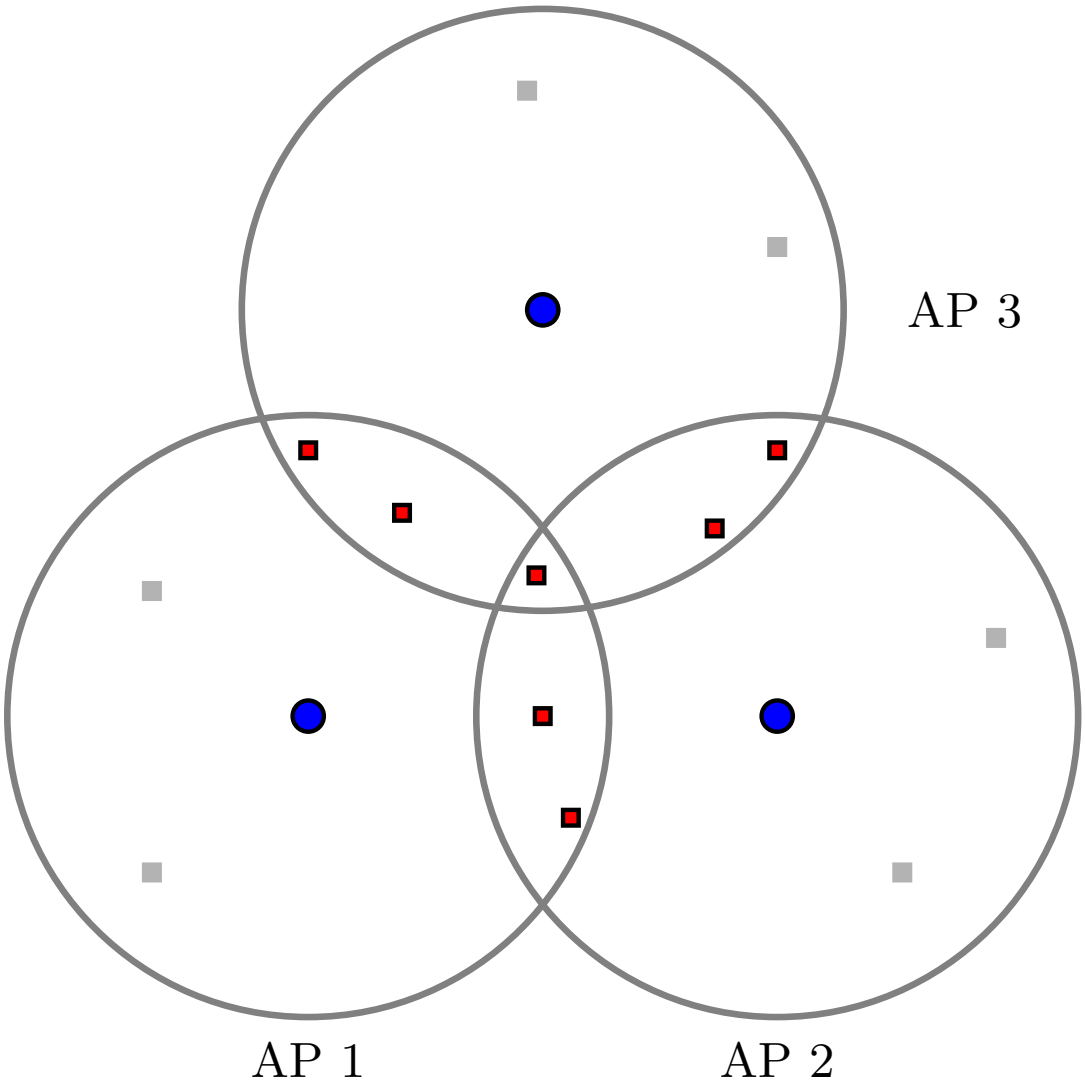

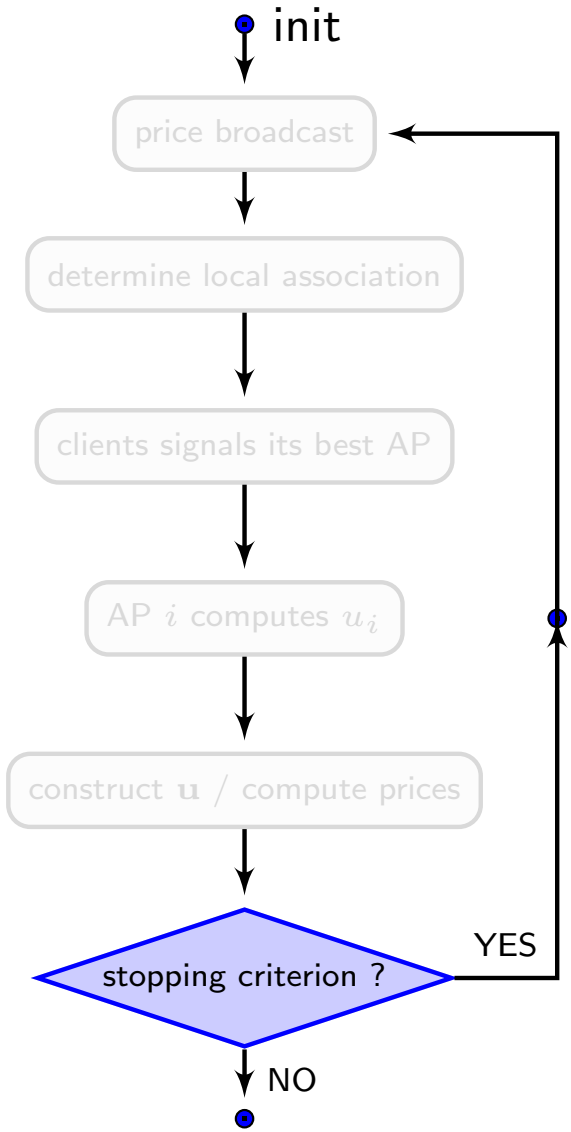

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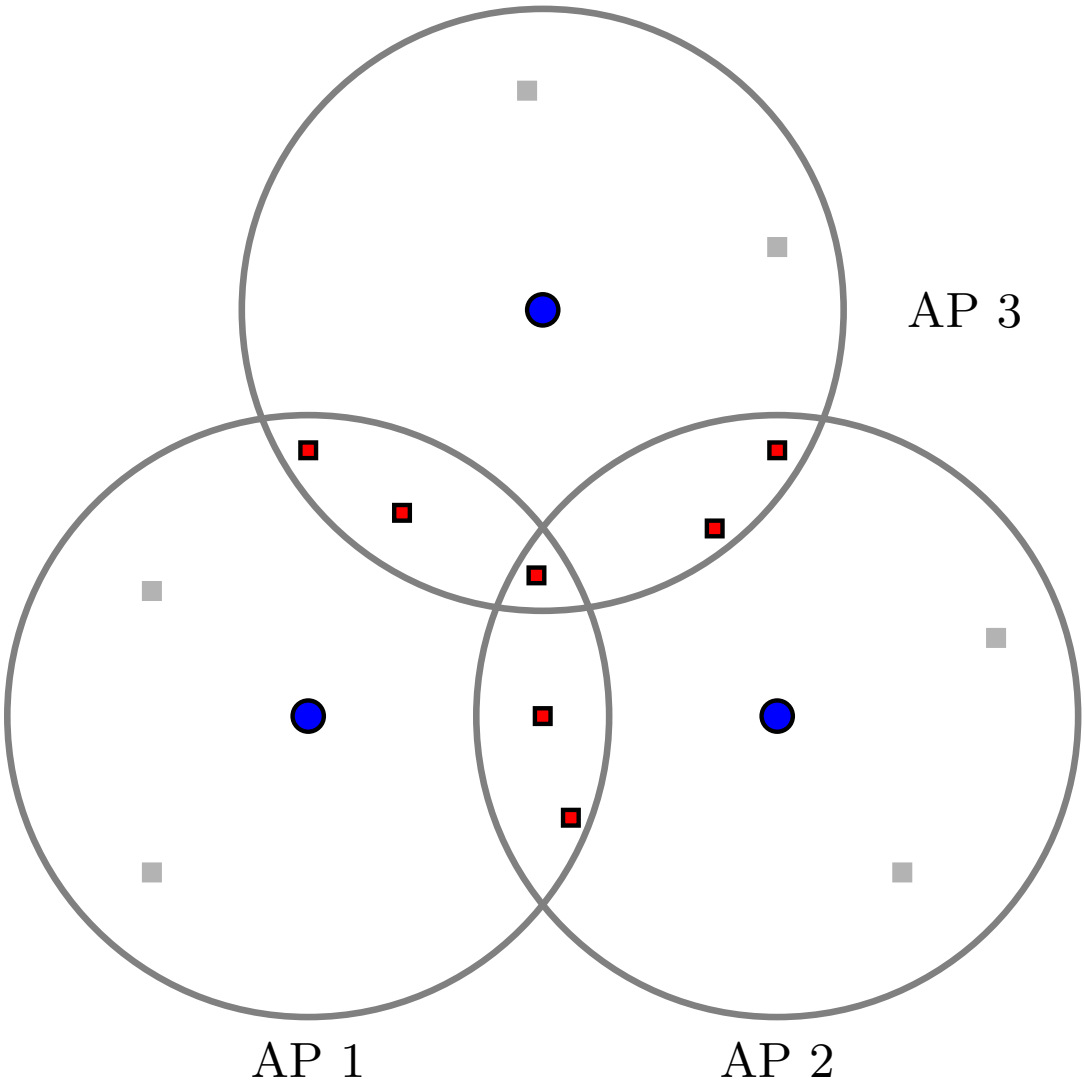
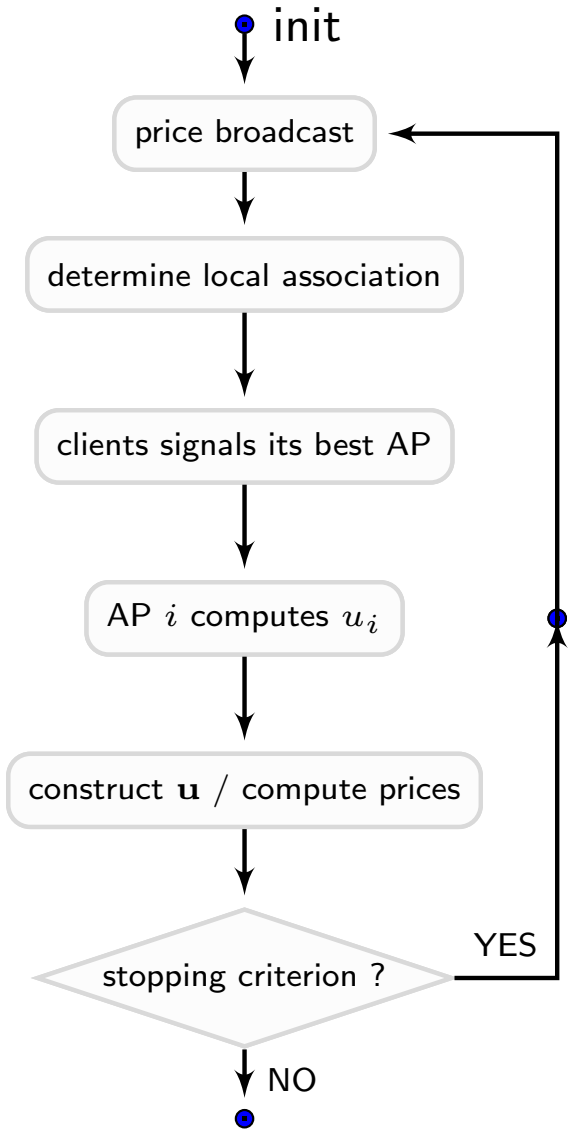




DAA Properties

Proposition

Let $g_{\text{best}}^{(k)}$ *denote the best dual objective value found after* k *subgradient iterations, i.e.,* $g_{\text{best}}^{(k)} = \max\{g(\boldsymbol{\lambda}^{(1)}), \ldots, g(\boldsymbol{\lambda}^{(k)})\}$. *Then,* $\forall \epsilon > 0$ $\exists n \geq 1$ *such that* $\forall k \; k \geq n \Rightarrow \left(d^\star - g_{\text{best}}^{(k)}\right) < \epsilon$.

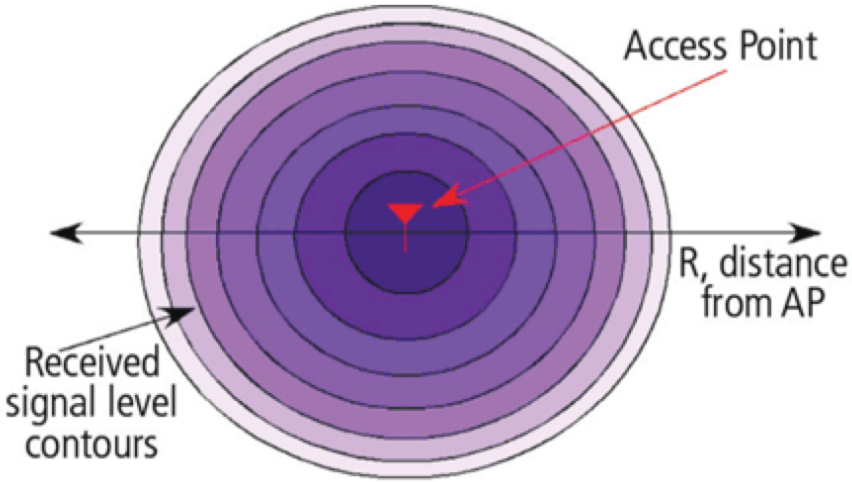
Theorem

The optimal duality gap of the mixed integer linear program is bounded as follows:

$$p^\star - d^\star \leq (N+1)(\varrho + \max_{j \in \mathcal{M}} \varrho_j) \ ,$$

where $\varrho = \max_{i \in \mathcal{N}, j \in \mathcal{M}_i} \beta_{ij}$ *and* $\varrho_j = \min_{i \in \mathcal{N}_j} \beta_{ij}$. *Moreover, the relative duality gap* $(p^\star - d^\star)/p^\star$ *diminishes to* 0 *as* $M \to \infty$.

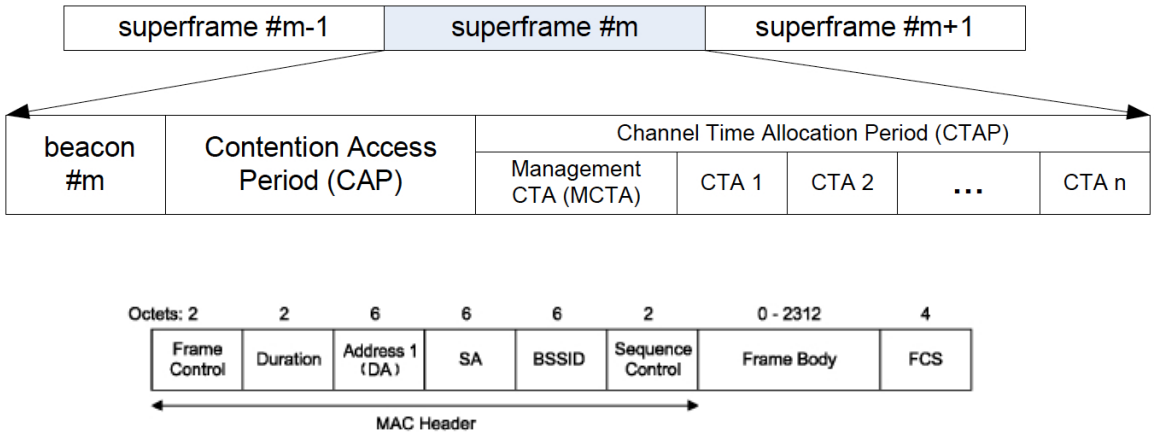
Implementation Over Existing Standards



- Initially the clients follow the RSSI-based association policy that IEEE 802.11ad and IEEE 802.15.3c define

- **DAA** is periodically executed to correct possible suboptimal client associations by reallocating the available resources

Implementation Over Existing Standards



- APs trigger the initialization of **DAA** by setting a special bit into the beacon frame
- Information exchange is performed through the control frames or piggy-backing the data frames

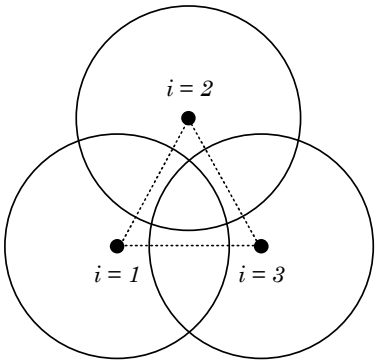
Outline

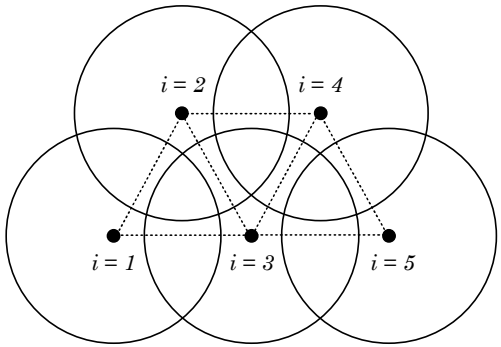
- Past, Present and Future in wireless communications
- 60 GHz millimeterWave wireless technology
- Optimizing resource allocation
- Distributed client association (DAA)
- **Numerical analysis of DAA**
- Conclusions and open research topics

Numerical Analysis

- Consider a multi-user multi-cell environment
- Compare **DAA** to
  - Random association
  - RSSI-based association (IEEE 802.11)
  - Optimal association (IBM CPLEX)
- Measure
  - Convergence
  - Scalability
  - Time efficiency
  - Fairness

Topologies





λ	Wavelength
d_0	Far field reference distance
η	Path loss exponent

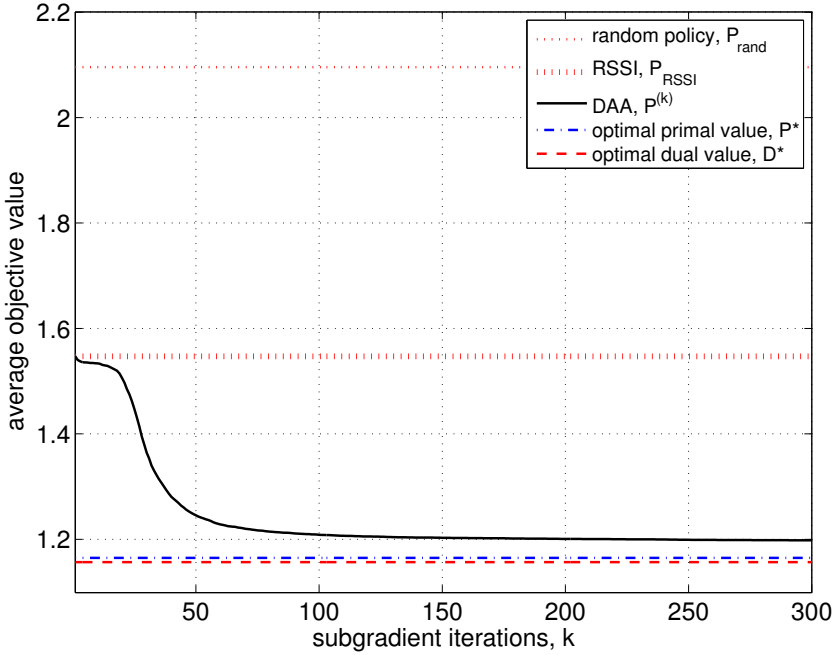
- SNR operating point at a distance d from any AP

$$\texttt{SNR}(d) = \begin{cases} P_0\lambda^2/(16\pi^2 N_0 W) & d \leq d_0 \\ P_0\lambda^2/(16\pi^2 N_0 W) \cdot (d/d_0)^{-\eta} & \text{otherwise} \end{cases}$$

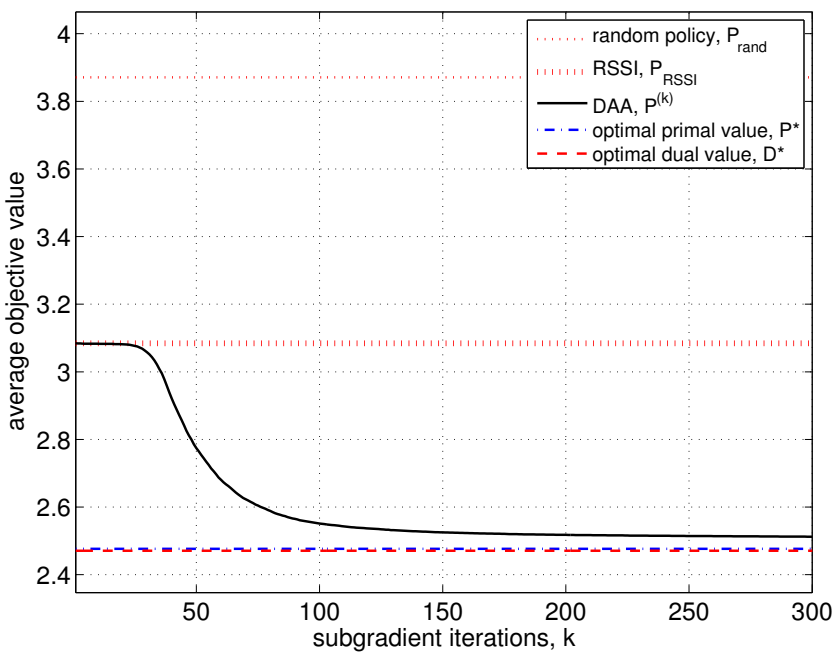
- Radius of each cell r is chosen such that $\texttt{SNR}(r) = 10$ dB
- Clients are uniformly distributed at random, among the circular cells

Convergence of DAA

5 APs, 100 clients



5 APs, 200 clients

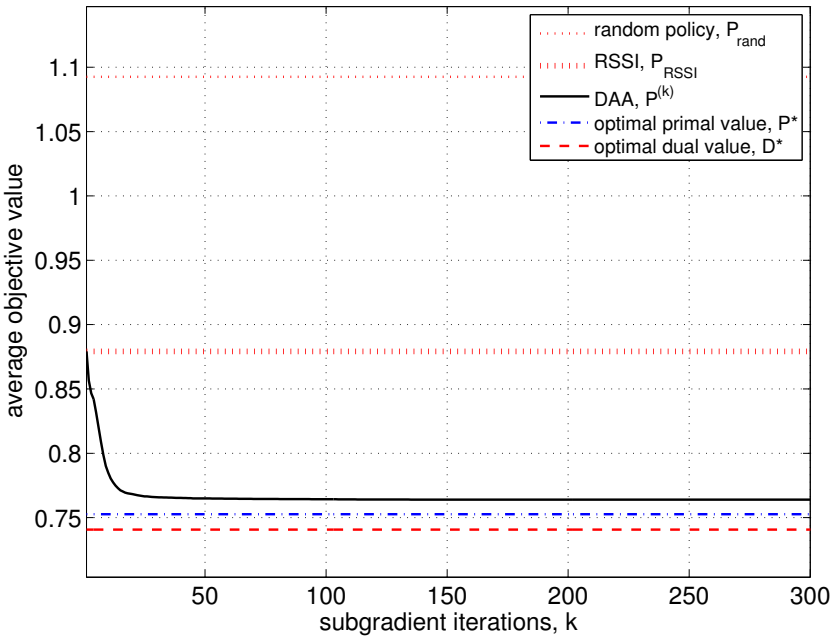


- Average primal objective value from **DAA** after k subgradient iterations: $\mathtt{P}^{(k)} = (1/\bar{T}) \sum_{T=1}^{\bar{T}} p_{\text{best}}^{(k)}(T)$

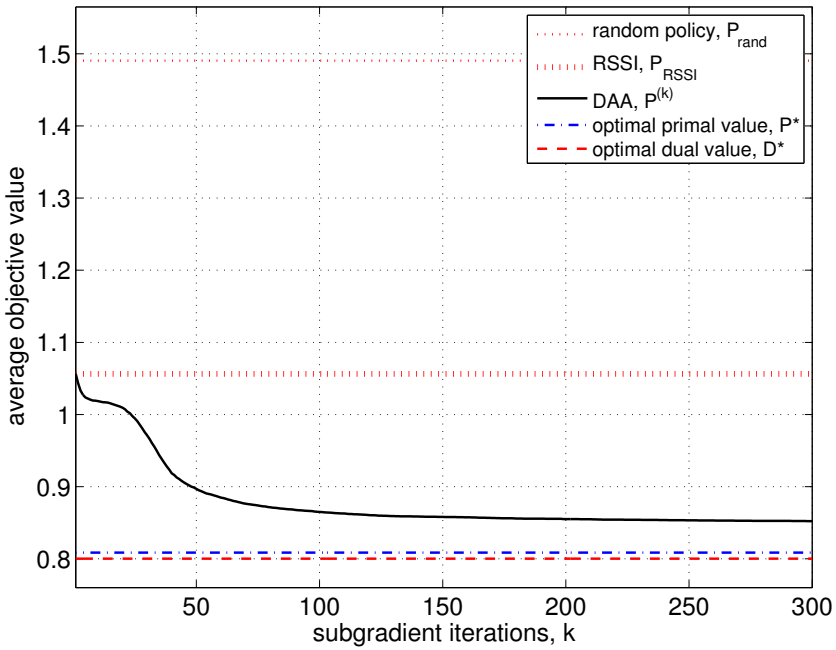
- Average dual optimal value by **DAA**: $\mathtt{D}^{\star} = (1/\bar{T}) \sum_{T=1}^{\bar{T}} d^{\star}(T)$

Convergence of DAA

3 APs, 30 clients

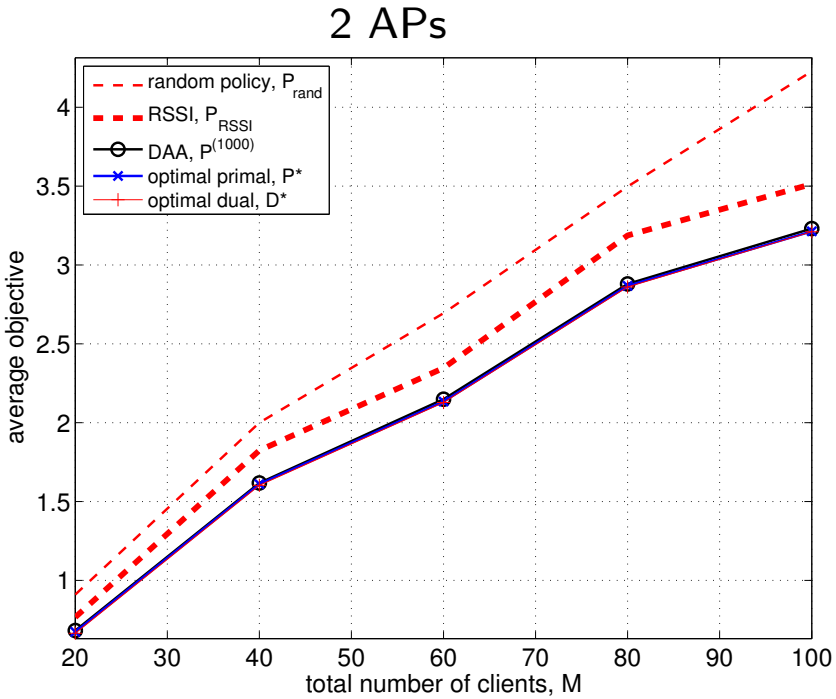


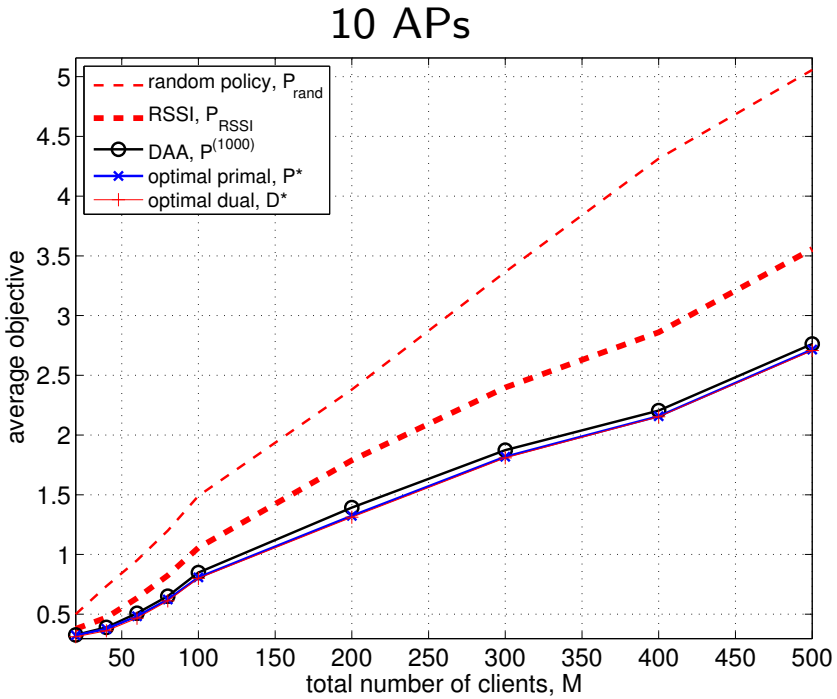
10 APs, 100 clients



- Convergence time is affected by the number of APs and clients: The smaller the network, the faster **DAA** converges

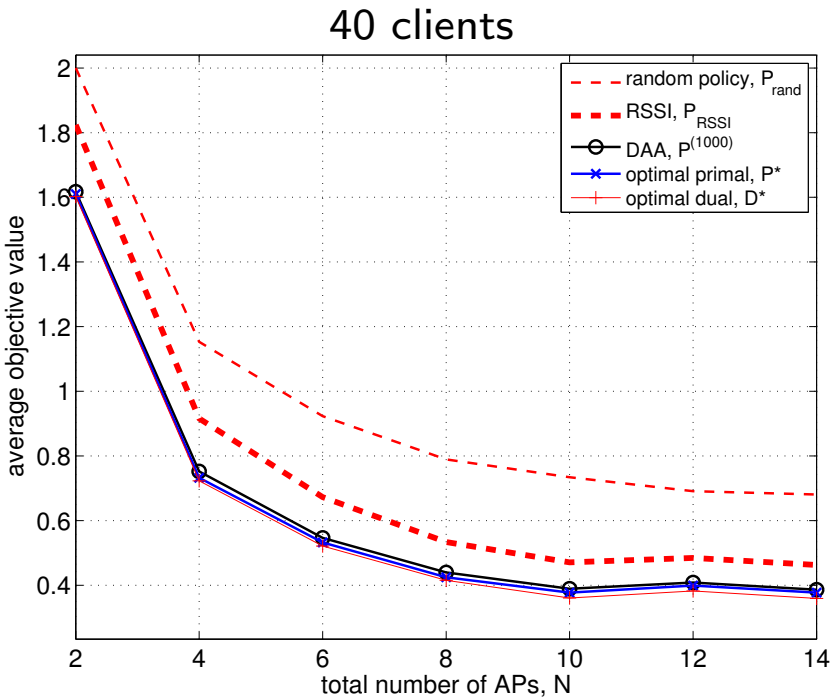
Scalability of DAA

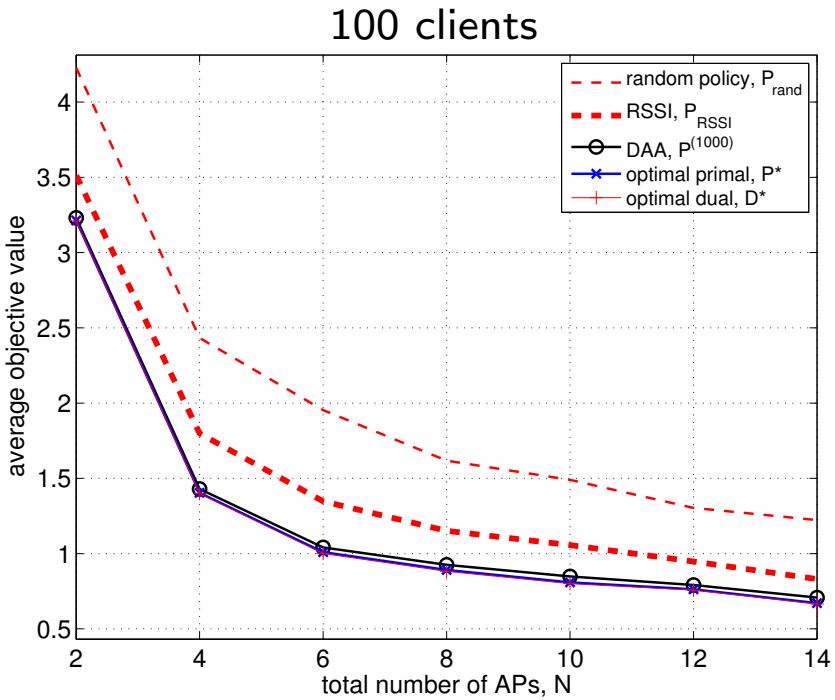




- Performance improvement increases while the network becomes bigger and more loaded
- **DAA** performs close to optimal

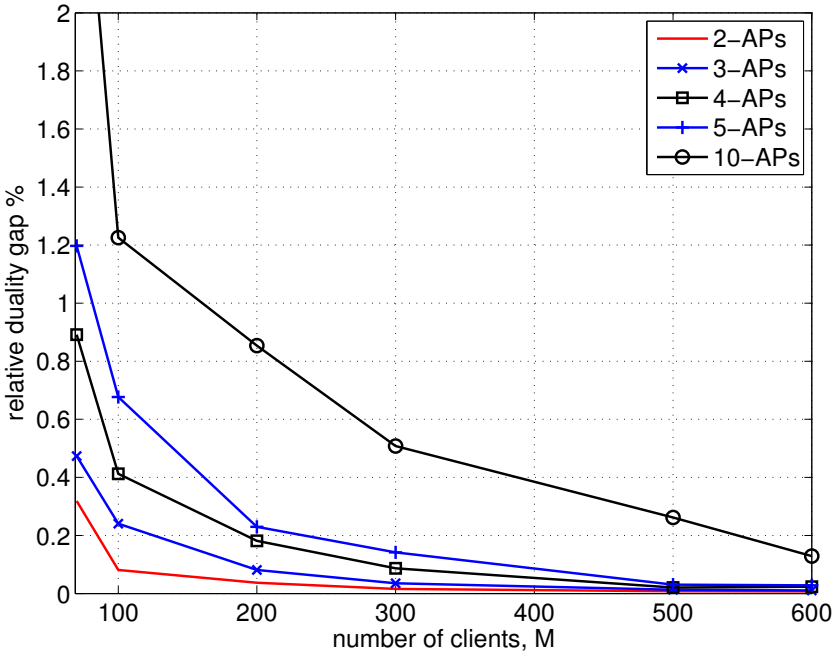
Scalability of DAA

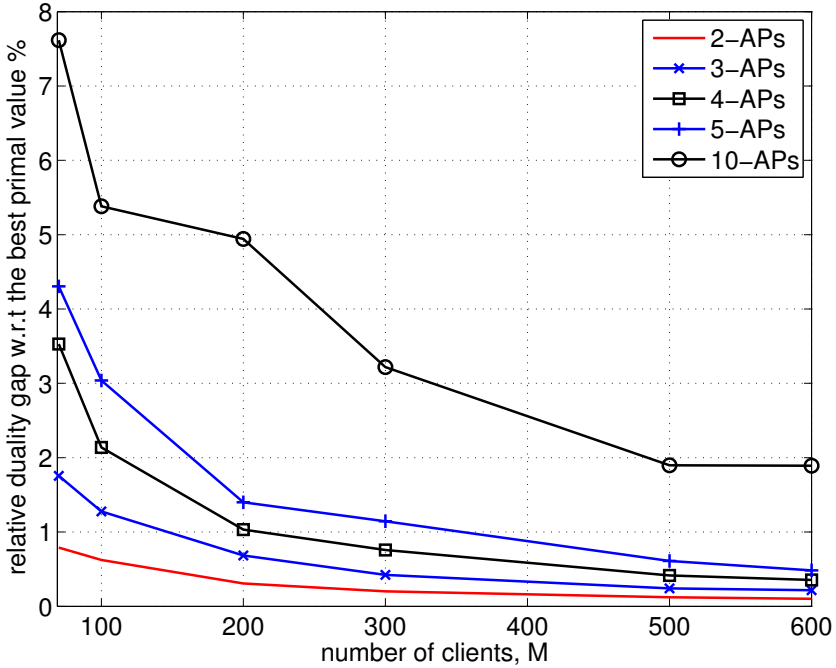




- Considering constant load, the average objective value decreases while the number of APs increases
- **DAA** performs close to optimal

Optimality of DAA

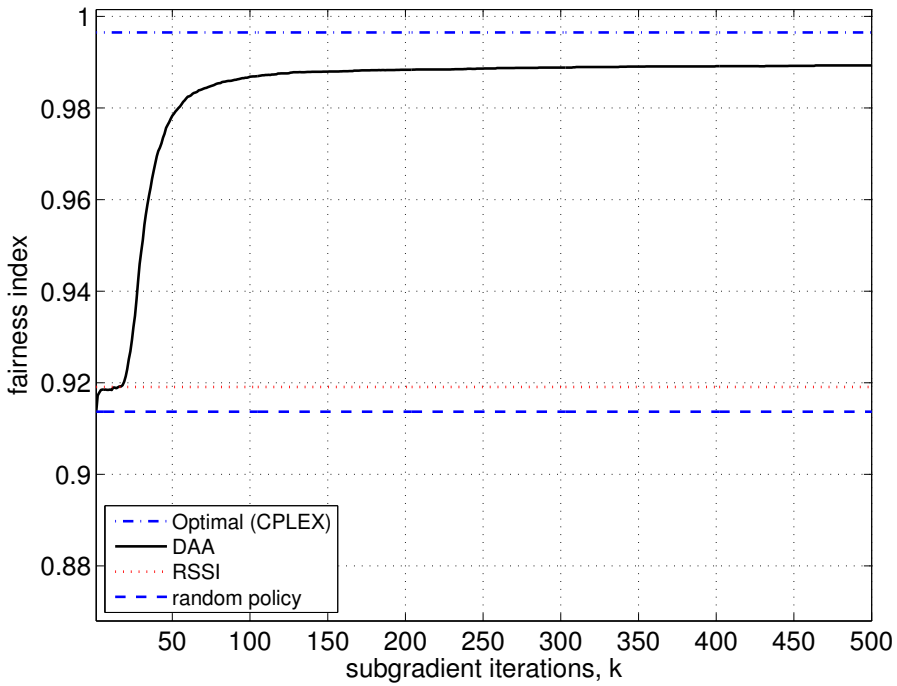




- Average relative duality gap:
  $\texttt{Ave-RDG} = (1/\bar{T}) \sum_{T=1}^{\bar{T}} (p^\star(T) - d^\star(T))/p^\star(T)$

- Average relative duality gap taking into account the best primal feasible objective value from **DAA** after K iterations at time slot T:
  $\texttt{Ave-RDG-best-achieved} = (1/\bar{T}) \sum_{T=1}^{\bar{T}} (p_{\text{best}}^{(K)}(T) - d^\star(T))/p_{\text{best}}^{(K)}(T)$

Fairness Achieved by DAA

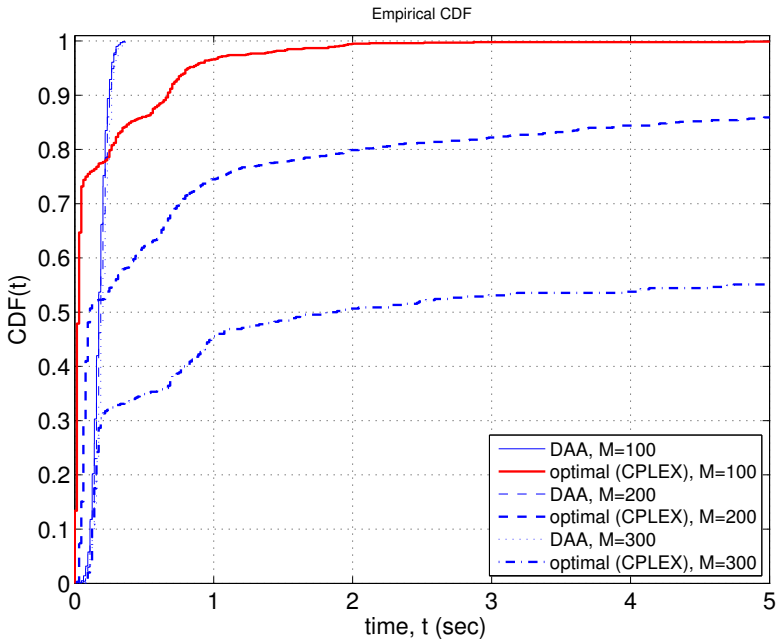


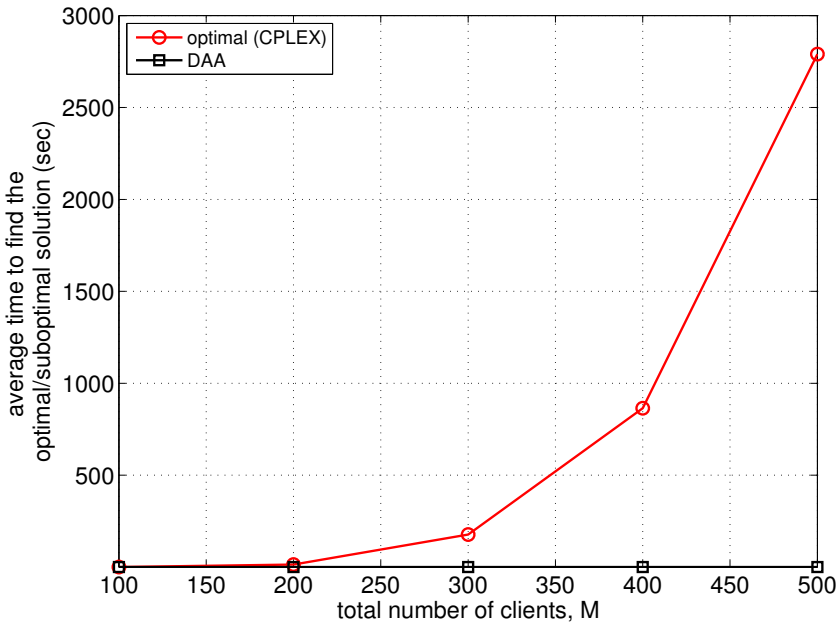
- Jain's fairness index:

$$J^{(k)}(T) = \Big(\sum_{i\in\mathcal{N}} Y_i^{(k)}(T)\Big)^2 / (N \sum_{i\in\mathcal{N}} Y_i^{(k)}(T)^2),$$

$Y_i^{(k)}(T) = \sum_{j\in\mathcal{M}_i} \beta_{ij} x_{ij}^{(k)}(T)$ and $x_{ij}^{(k)}(T)$ is the solution (best feasible) resulted from **DAA** at time slot T after k iterations

Speed and Resources Used by DAA





- Empirical CDF plots of the number of iterations for $M = 100, 200, 300$ clients, with $N = 10$ APs
- Trade-off between optimality and complexity

Outline

- Past, Present and Future in wireless communications
- 60 GHz millimeterWave wireless technology
- Optimizing resource allocation
- Distributed client association (DAA)
- Numerical analysis of DAA
- **Conclusions and open research topics**

Conclusions

- 60 GHz wireless technology: characteristics, benefits, challenges, applications
- Distributed association algorithm (**DAA**) for optimizing resource allocation in 60 GHz wireless access networks
- Performance evaluation of **DAA**: Asymptotically optimal, convergence, time efficiency and fairness
- Integration of **DAA** into current standards

Open Research Topics

- 60 GHz channel modeling
- Medium Access Control (MAC)
- Connectivity maintenance, blockage and directivity
- Coexistence and cooperation with existing wireless technologies
- Multi-hop communications
- ...

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Thank you

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Optimizing Resource Allocation in 60 GHz Wireless Access Networks

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