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Resource Allocation in Contention-Based WiFi Networks

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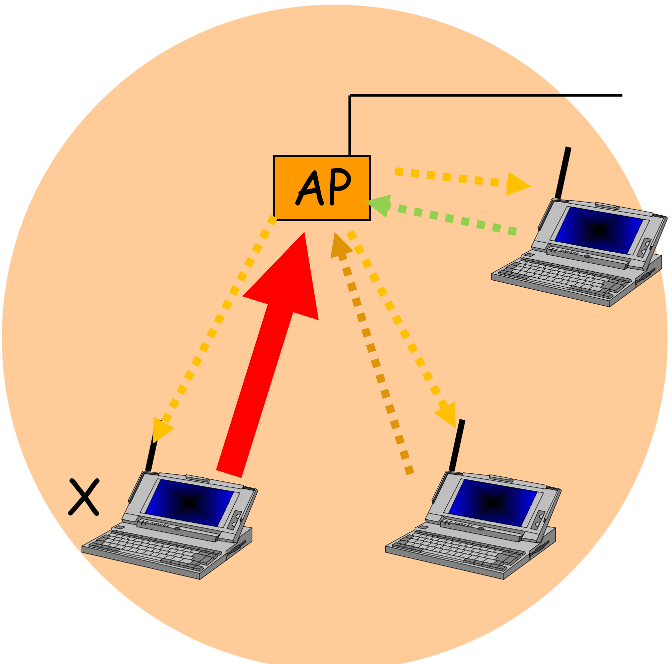
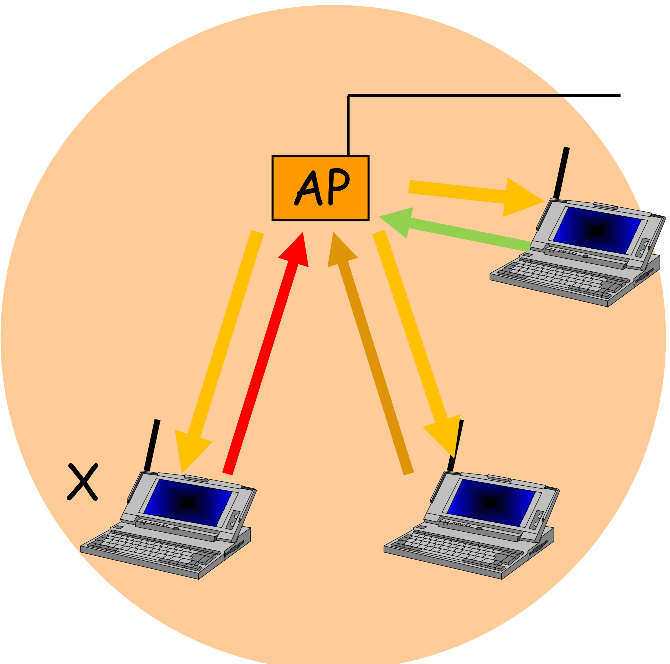
Resource allocation in Contention-based networks

- Analysis with rational nodes:
  - Infrastructured IEEE 802.11 Networks
    - Achieving distributed fair bandwith among nodes in non homogeneous bidirectional traffic to optimize throughput
    - Game theoretical analysis and design
- Schemes for multi-hop topologies
  - Wireless Ad-Hoc Networks
    - Grouping contending nodes (TDMA approach) in combination with Carrier Sense to access the channel (CSMA/CA)
    - Graph coloring solution to assign slots

Infrastructured Networks



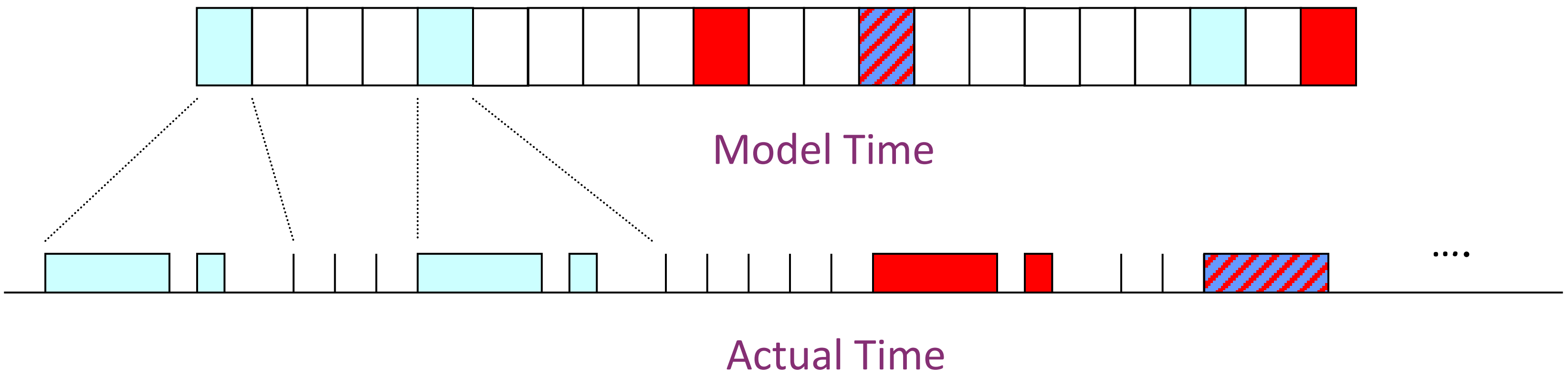


If station X tries to get all wireless resources ⟹ no space for the other stations, including the AP!

If station X leaves spaces to the AP ⟹ also the other stations able to transmit. ki - desired up/down ratio for each station

IEEE 802.11 DCF as a Slotted Access protocol

- **D**istributed **C**oordination **F**unction (**DCF**) regulates access to the shared medium:
  - dynamic adaptation of the contention windows (short term unfairness)
  - use of **homogeneous** contention parameters among the contending nodes
- Protocol operations summarized in terms of **average access probability** in a slotted channel (with uneven or even slot size)
- In each system slot, each station accesses with probability τ (and does not access with probability $\mathbf{1-\tau}$).
- Most protocols make τ depending on the collision probability p, $\boldsymbol{\tau = f(p)}$, as a tradeoff between channel wastes due to collisions and idle slots.



Game Theoretic Approach

- Thanks to open source drivers and programmable cards, we propose a **dynamic tuning** of the contention parameters used by the nodes via a **game-theoretic** approach.
- **AIM:** To guarantee a fair resource sharing among the nodes, while **optimizing** the per-node uploading and downloading bandwidth.
- **SOLUTION:**
  - Some DCF protocol EXTENSIONS able to cope with current resource sharing problems.
  - A non cooperative game where the contending stations act as the players
  - The stations works in saturated conditions and DCF can be modeled as a slotted access protocol while the station behavior is summarized in terms of per slot access probability

Contention-based access as a non-cooperative game

-Contending stations = players

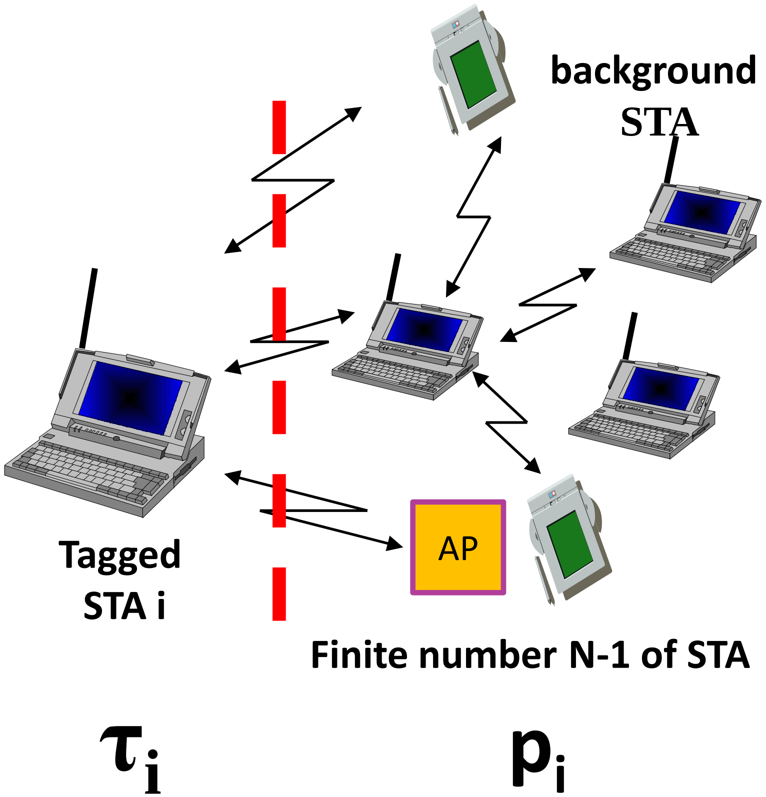
-Channel access probability **τ** = player strategy

Game definition:

N players, $[0,1]^N$ set of strategies, node payoff (J1, J2, …, JN)

-Payoff perceived by each station depends on the whole set of probability $(\tau_1, \tau_2, \ldots \tau_n)$ chosen by all the stations

$(\tau_1, \tau_2, \ldots \tau_n)$->**$(\tau_i, p_i)$** with pi = $1-\prod_{j\neq i}(1-\tau_j)$



Node Payoff with Bidirectional Traffic

- Assumption: AP is a legacy station $\tau_{AP}=f(p_{AP})$ equally sharing the downlink throughput among the stations.
- For the i-station:
  - Uplink throughput:
    $$S^{i}{}_{u}(\tau_i, p_i) = \frac{\tau_i(1-p_i)(1-\tau_{AP})P}{E[slot]} \qquad \uparrow \tau_i$$
  - Downlink throughput:
    $$S^{i}{}_{d}(\tau_i, p_i) = x_i \frac{\tau_{AP}(1-p_{AP})P}{E[slot]} \qquad \downarrow \tau_i$$
  - The utility function

    with ki in (0, ∞)
    $$J^{i}(\tau_i, p_i) = \min(S^{i}{}_{u}, k_i S^{i}{}_{d})$$

Main Results

- Determination of Nash Equilibria and Pareto Optimality
- Mechanism design -> using of the AP to force desired equilibria
- Implementation of new DCF operations with best response strategy
- Implementation of Channel Monitoring functionalities (estimation of number of nodes and load conditions)
- Analysis of NE convergence and stability

References

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- I.Tinnirello, L. Giarré, G. Neglia. “ MAC design for WiFi infrastructure networks: a game theoretic approach**. IEEE Transaction on Wireless Communication**, in print, 2011.
- I. Tinnirello, L. Giarré, G. Neglia, “The role of the Access Point in Wi-Fi networks with selfish nodes”, **IEEE GAMENETS,** 2009.
- L. Giarré, G. Neglia, I. Tinnirello, “Performance Analysis of Selfish Access Strategies on WiFi Infrastructure Networks”, **IEEE Globecom** 2009
- L. Giarré, G. Neglia, I. Tinnirello, “Resource Sharing Optimality in WiFi infrastructure networks”, **IEEE CDC,** 2009
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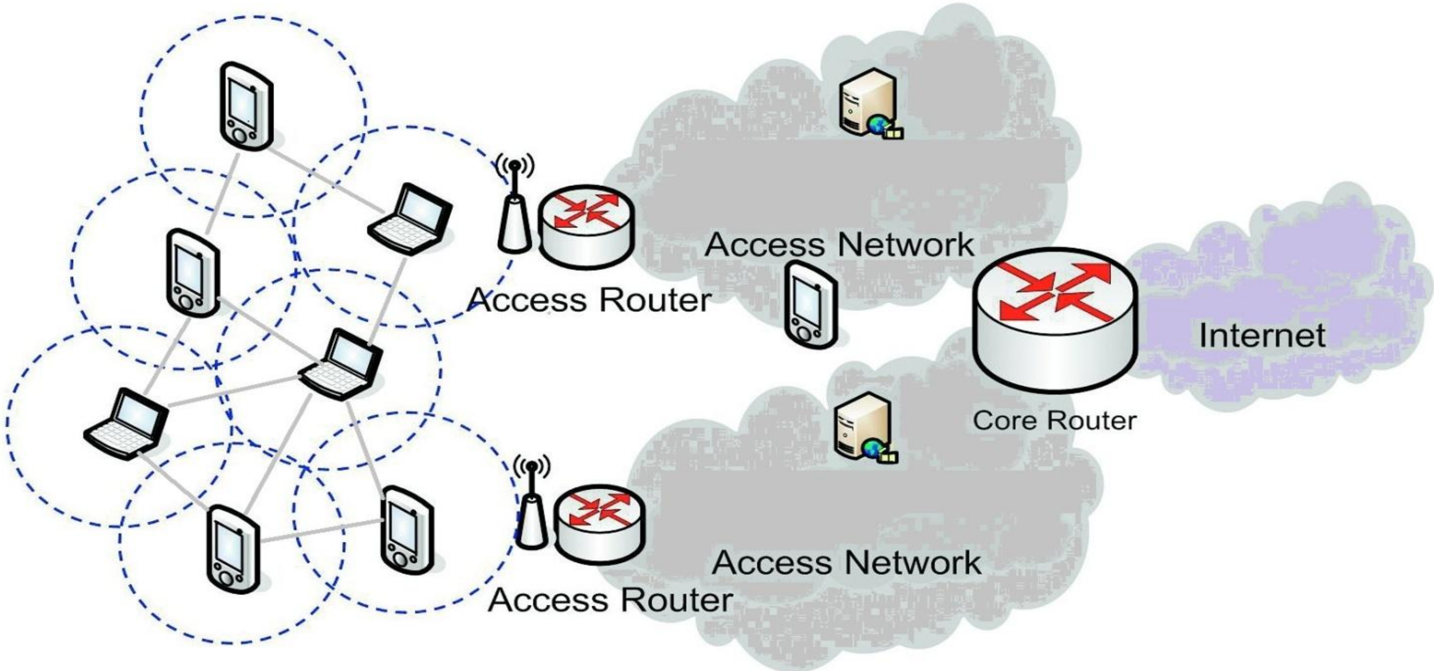
Ad-hoc networks



- Suitable for a large number of applications:
  - from **low-range** sensor networks targeted to distributed monitoring
  - to **high-range** mesh networks targeted to build infrastructure-less transport networks.

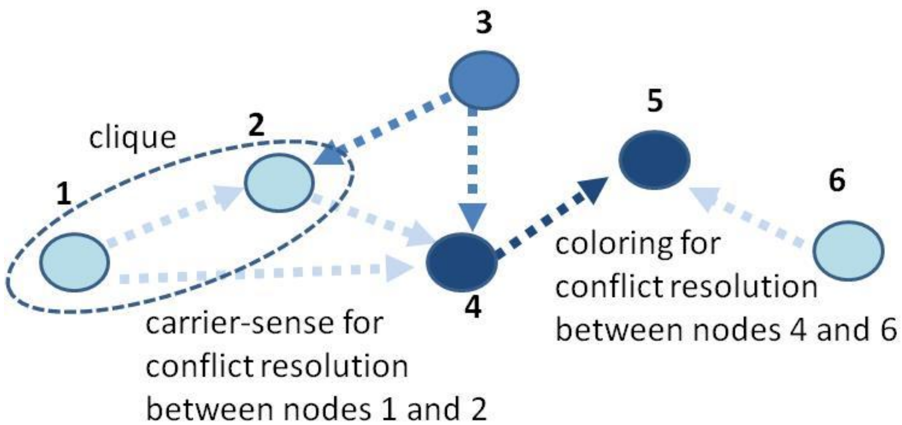
Ad-hoc Networks

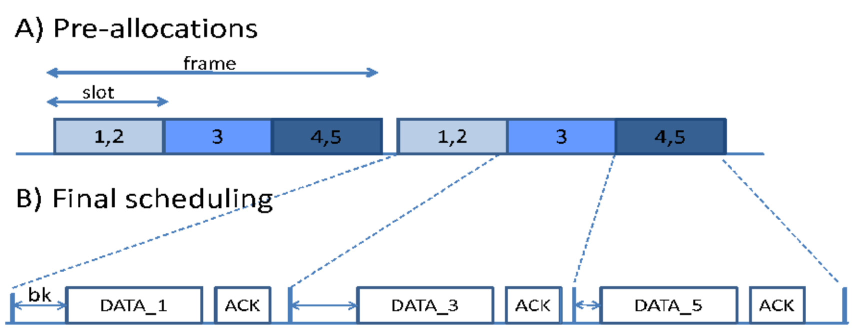
- Most ad-hoc networks rely on contention-based medium access protocols,
- regardless to the specific physical layer technology

(IEEE 802.15.4 PHY or 802.11a/b/g/n PHY, defining available bandwidth, transmission power, modulation coding scheme..)

- The use of carrier sense and random backoff mechanisms is a simple and well-established solution to manage multiple access over a shared channel bandwidth.
- CSMA/CA protocols exhibit very poor performance for **multi-hop** transmissions (inter-link interference due to imperfect carrier sensing).

Ad hoc Networks





Ad-Hoc networks

- **Aim:** Distributed resource allocation problems for multi-hop wireless networks.
- **Main idea:** Combining the TDMA approach for grouping the contending nodes in non-interfering sets) with the CSMA/CA approach (for managing the final access to the shared channel).
- **Solution:** determining the best number of slots in a frame and the best assignment of slots to different in terms of a map coloring problem, by trying to identify the most effective trade-offs between complexity, signaling overheads and performance gain.

Main Results

- **Problem:** Determine a distributed protocol setting the number x of slots in a frame and the slots allocations, in order to maximize **the per-node throughput** in saturation conditions
- Network transport capacity is critically affected by the number of slots x!
- **Incompatibility constraints**:
  - all neighbors and hidden nodes on different colors
  - only hidden nodes on different colors

References
(Ad hoc networks)

- I. Tinnirello, L.Giarrè and R. Pesenti. Decentralized Synchronization for Zigbee Sensor Networks in Multi-hop topology. **Necsys** 2010.
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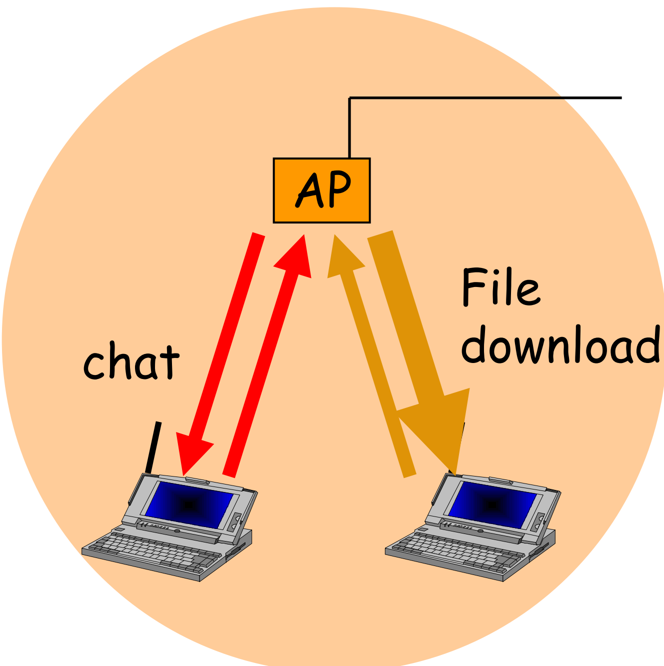
Infrastructure Networks with heterogeneous applications



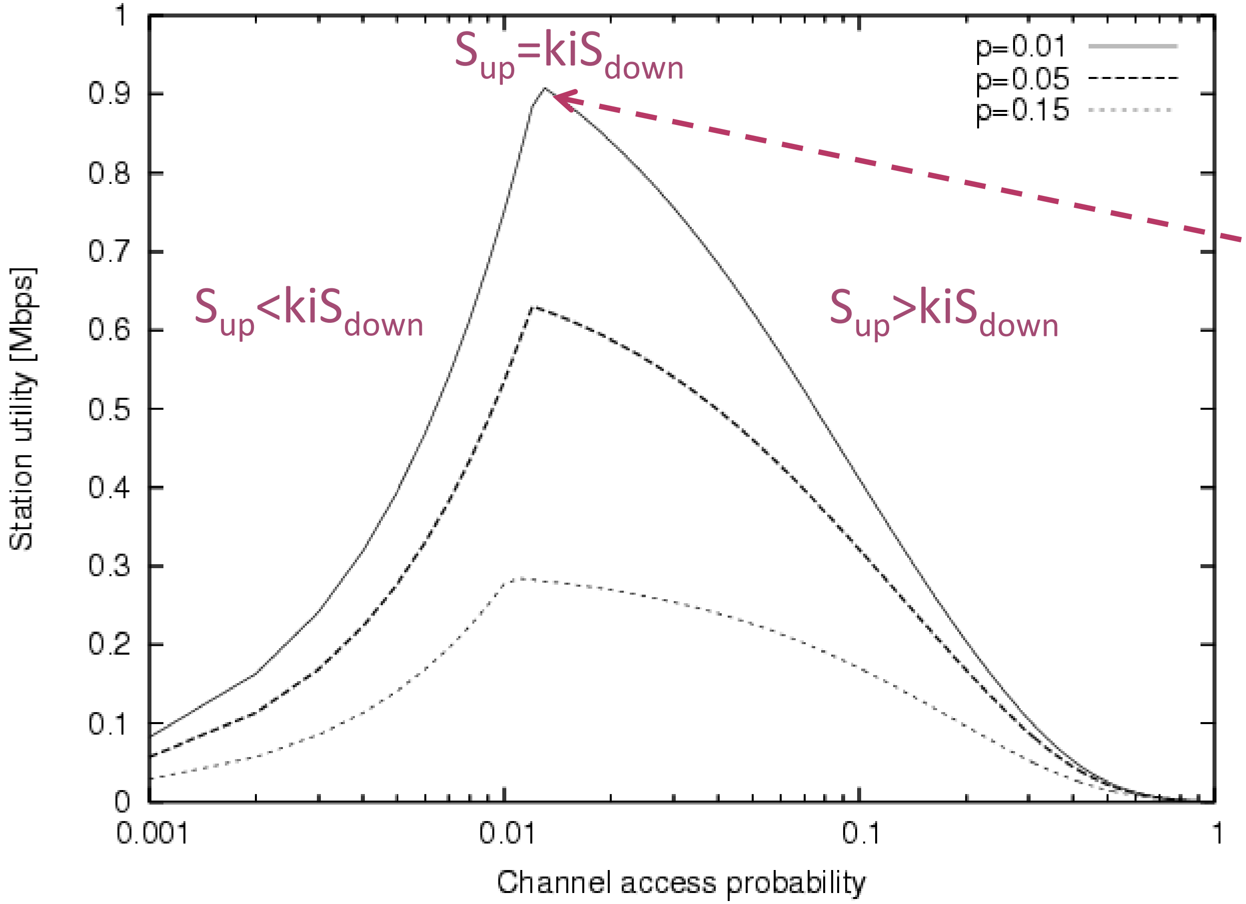
It might happen that k1 != k2

$J_i(\tau_i,p)=\min(S_u{}^i,\mathbf{k_i}\, S_d{}^i)$

1. Does a best response policy lead to a NE?

2. How should the AP share the downlink throughput ?
(choice of **xi**)

Node Best Response



ki=k=1, xi=1/n

(τ, p) outcome

$$\tau_{br} = \frac{k_i x_i \tau_{AP}}{1-(1-k_i x_i)\tau_{AP}}$$

where:

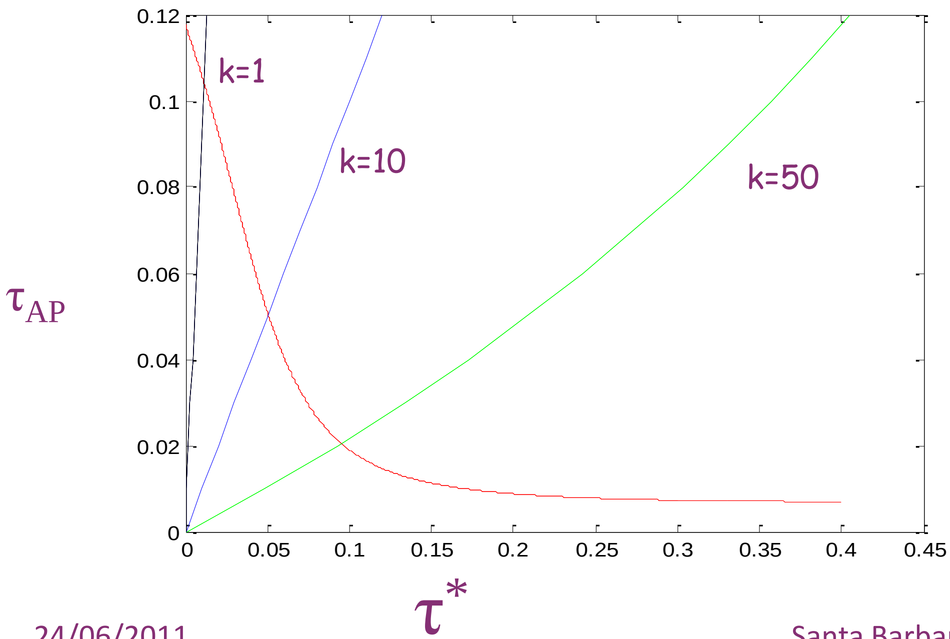
$\tau_{AP}=f(p_{AP})$ is function of the strategy set (τ,p)

Nash Equilibrium (ki=k=cost,xi=1/n)

Proposition: The homogeneous strategy vector (τ^*, τ^*,…τ^*) such that

$$\tau^* = \frac{kf(1-(1-\tau^*)^n)}{n-(n-k)f(1-(1-\tau^*)^n)}$$

is the only Nash equilibrium in $[0,1)^n$ of the game with non-null utility.



Proof sketch:

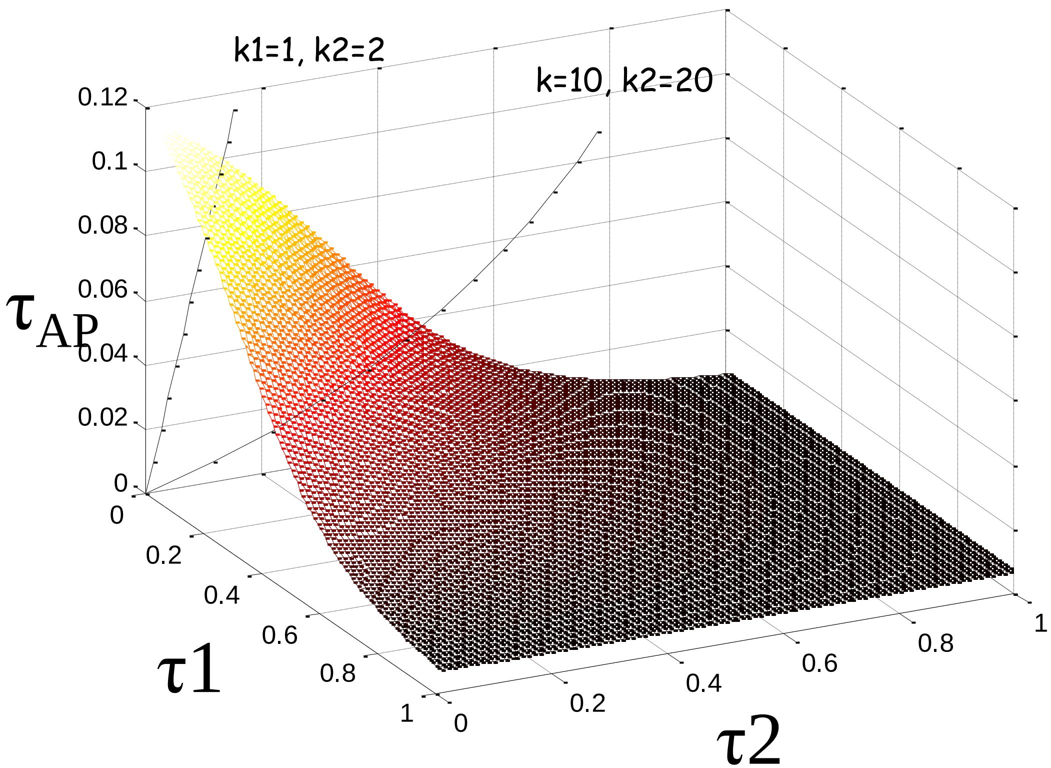
At the NE point, two conditions simultaneously hold:

$$\begin{cases} \tau^* = \dfrac{k\tau_{AP}}{n-(n-k)\tau_{AP}} = g(\tau_{AP}) \\ \tau_{AP} = f(1-(1-\tau^*)^N) \end{cases}$$

being f() decreasing in τ^* starting from 0, and g() increasing in τ_{AP}, a single intersection exists

Nash Equilibrium (ki, xi=1/n)

Proposition: For a given vector **k=**(k_1,k_2, ..k_n) of application requirements, by equally sharing the downlink throughput, it exists a unique NE with non-null utility.



Proof sketch:

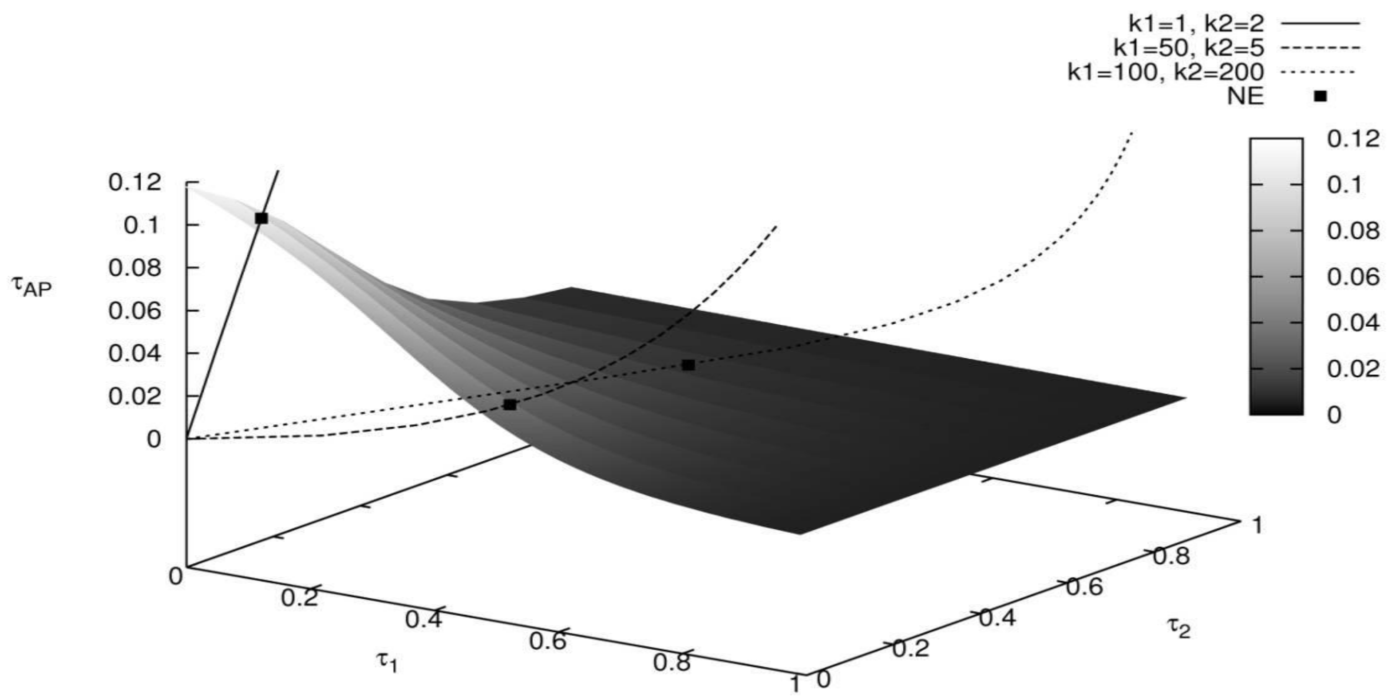
At the NE point, N+1 conditions simultaneously hold:

$$\begin{cases} \begin{cases} \tau_1 = \dfrac{k_1 \tau_{AP}}{n-(n-k_1)\tau_{AP}} \\ \tau_2 = \dfrac{k_2 \tau_{AP}}{n-(n-k_2)\tau_{AP}} \\ \dots \\ \tau_n = \dfrac{k_n \tau_{AP}}{n-(n-k_n)\tau_{AP}} \end{cases} \\ \tau_{AP} = f(1-\Pi(1-\tau_i)) \end{cases}$$

The first N conditions represent a 1-dim curve in a N+1 space; the last one a surface..

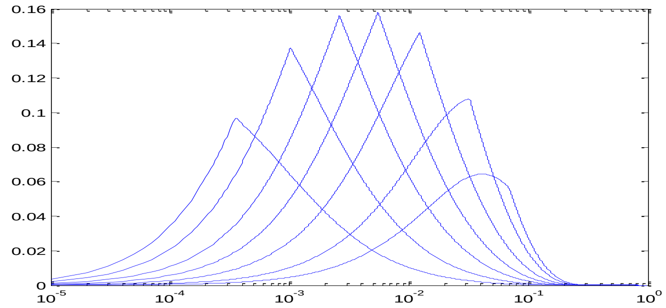
Nash Equilibrium (ki, xi)

Proposition: For a given vector **k**=(k_1,k_2, ..k_n) of application requirements, and a given vector of downlink throughput coefficeints (x1,x2..,xn), it exists a unique NE with non-null utility.



Mechanism design

- Can the AP play the role of arbitrator in order to improve the performance of its access network?
  1. Using τ_{AP} as a configuration parameter (rather than $f(p_{AP})$)

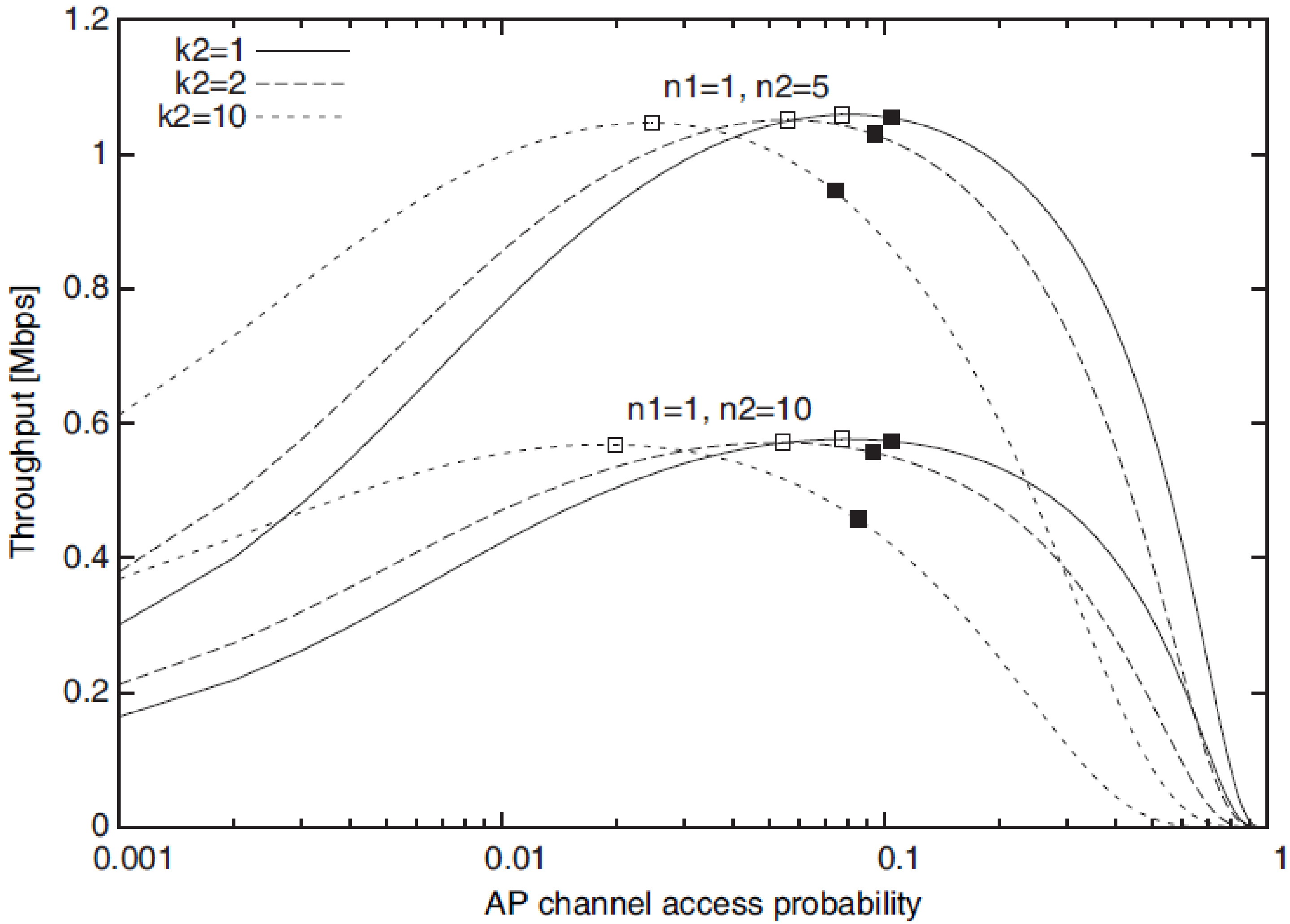


  2. Employing a downlink scheduling according to the application requirement **k**=(k1,k2,k2,..,kn)

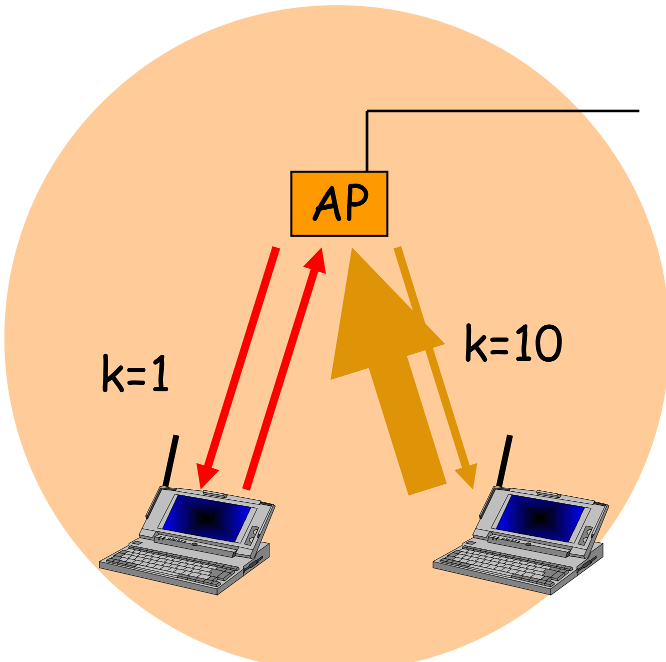
Tuning the AP channel access probability

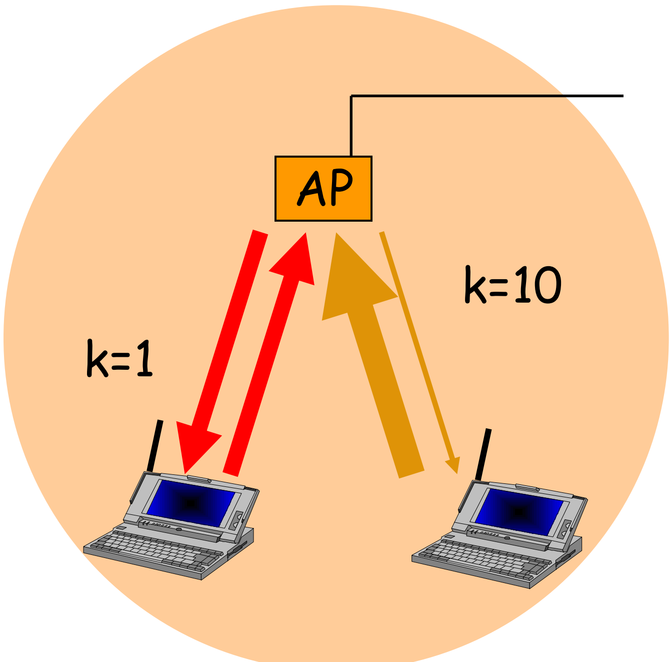
- The best response is $$\tau_i^+ = \frac{k_i x_i \cdot c}{1 - (1 - k_i x_i)c}$$
- The NE becomes the intersection between an hyperplane T_{AP}=c and the parametric curve identified by the best response equations

Per-station total bandwidth



Downlink Scheduling





By equally sharing the downlink, stations with higher **k** get an higher total up-down capacity

A fairer criterion could be an equal repartition of the per-station up+down capacity!

$S_d^i = x_i S_{AP}$ with $x_i = \frac{\frac{1}{k_i+1}}{\sum_{j=1}^{n} \frac{1}{k_j+1}}$

The unique NE still exists

Scheduling policies

- AA: Application Agnostic

  The AP is **not aware** of the per station application requirements (Ki). AP equally shares the downlink throughput among the stations ($S_d=S_{AP}/n$).

  - At NE each station perceives a throughput of $(1+k_i)S_d$

- AW: Application aWare

  The AP is **aware** of Ki. AP can allocate and heterogeneous downlink throughput $S^i_d = x_i S_{AP}$

with $$x_i = \frac{\frac{1}{k_i+1}}{\sum_{j=1}^{n} \frac{1}{k_j+1}}$$

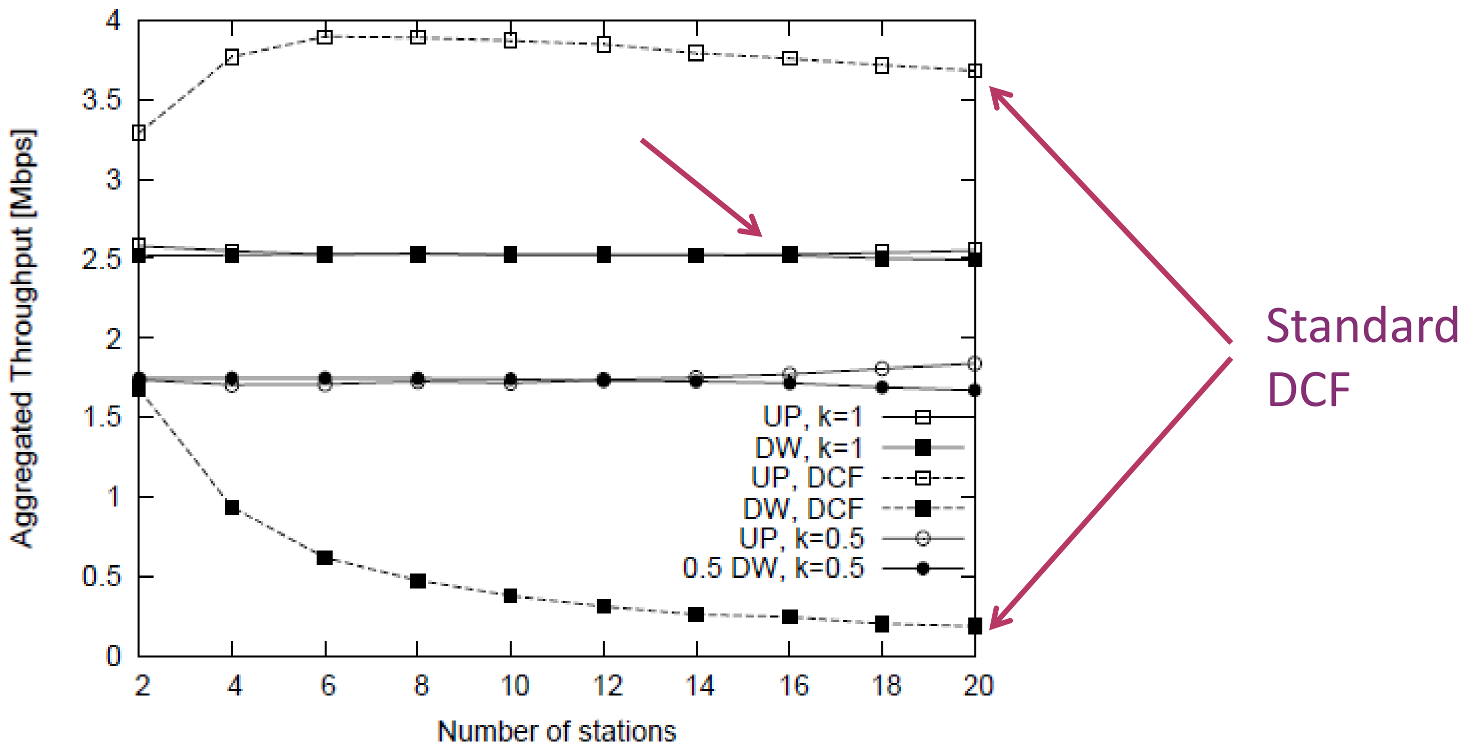
Game-based MAC Scheme implementation and evaluation

- Each station has an two estimators for probing uplink and downlink load conditions
- The station best response depends not only on the application requirements (Ki) but also on the uplink load (n) and downlink load (Tap)
- Cases
  - 1) AP as a legacy
  - 2) AP implementing the adaptive tuning mechanism of the channel access probability
- Algorithms: AA (Application Agnostic scheduling) and AW (Application aWare scheduling)

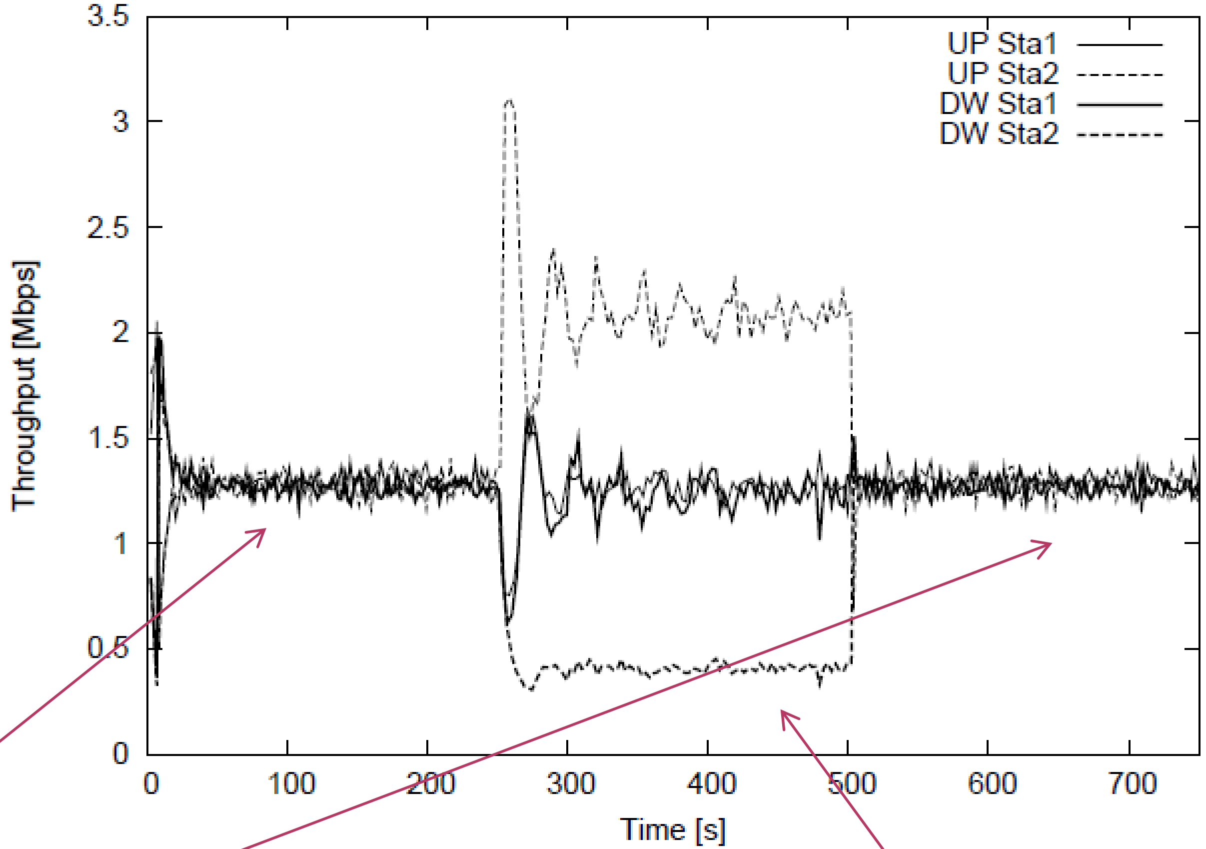
Numerical Example:

Resource Repartition

-Custom-made simulation platform;
-Interval update:0.5 seconds; 802.11b; P=1500 bytes



Effects of best response strategy
(Time-varying Application requirements)



k1=k2=1

k2=5, k1=1

Final Remarks on Infrastructure Networks

- **Contention-based access protocols can be defined in terms of non-cooperative games**
  - Standards are somehow limited with the proliferation of open-source drivers
- In infrastructure networks, the node strategies converge to Nash equilibria with non-zero payoff, by considering both uplink and downlink bandwidth requirements of user applications
- AP can be used for mechanism design, in order to force desired equilibrium conditions
  - by tuning its channel access probability
  - by employing scheduling policies for improving the network fairness

Ad-hoc Networks
Minimum Graph Coloring

- **Minimum Graph Coloring (MGC)** problem on an incompatibility graph, built on the basis of network topology G = (V,E) V: nodes i of the network, E: pairs of nodes
- He is the **Incompatibility graph type I** (V, Fe), where for each $e \in 2^E$: $F_e = \{(j,k): \exists\, i \in V$ s.t. $(j,i),(i,k) \in E\}$
  - (j,k) frame may collide if transmitted simultaneously
  - *$H_e=G^2$: all nodes have non-interfering allocations and we can guarantee a collision-free throughput proportional to r/x*
- H0 is the **Incompatibility graph type II** (V, F0), where for each $e \in 2^E$: $F_0 = \{(j,k): \exists\, i \in V$ s.t. $(j,i),(i,k) \in E$, but $(j.k) \notin E\}$
  - (j,k) collide and reciprocally hidden
  - *$H_{\emptyset}=G^2$-G: visible nodes share the same allocations*

Coloring Algorithms

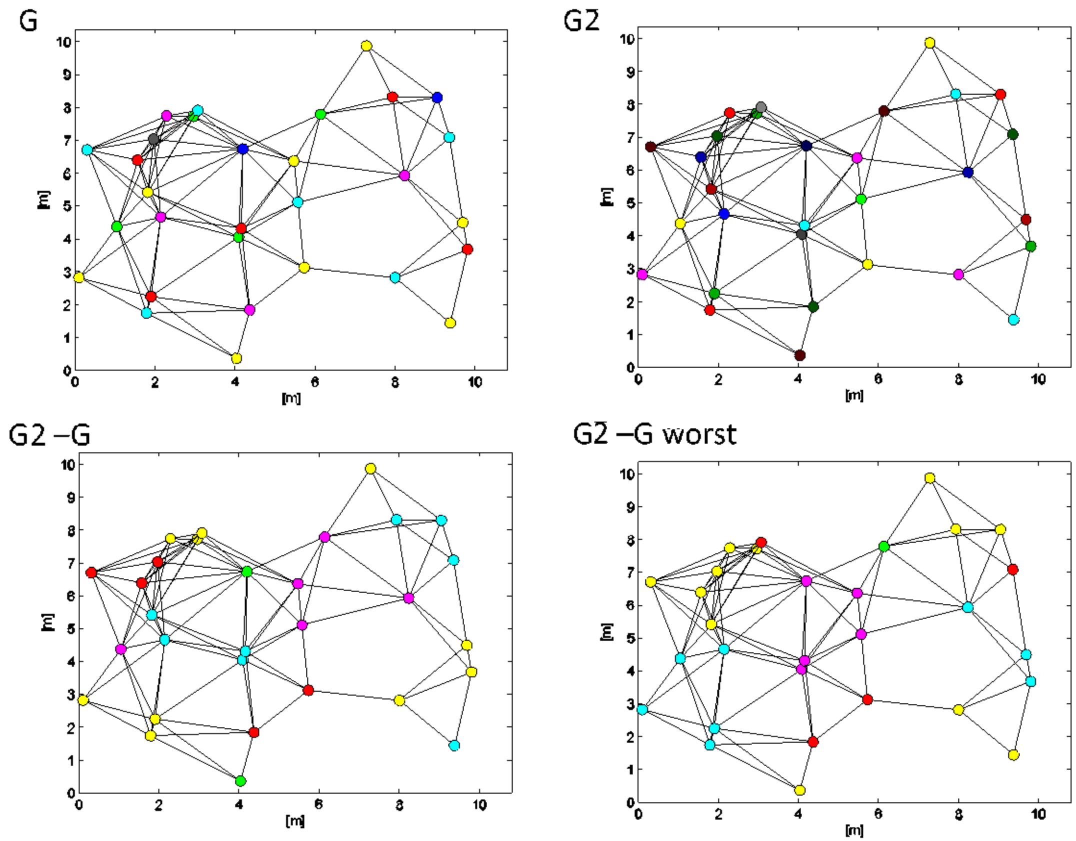
- ## Select and Compare (SC):

1. **First coloring** Randomly pick a color from a list of available colors.
2. **Conflict Resolution** If none of your (1-hop or 2-hop) neighboring nodes has chosen the same color, keep it as definitive color, otherwise remove it form the list and try again the next step.
3. **List update** If the color list is empty, add new colors. The list is updated starting from min(c+1, xmax) color, where c=max(neighboring node colors)

- ## Choose the First Available color (CFA) :

Instead of randomly picking a color from the available ones, each node first updates the list of available colors and then selects the color with the lowest index

Example of colored network



A network topology colored with different CFA maps for the incompatibility graphs G,G^2, G^2-G

Performance Evaluation

- Given a graph He, the maximum number of needed colors is upper bounded by **Δ_e+1**, where **Δ_e** is the maximum node degree of the graph.
- Let x_e the number of colors required in H_e and c_e the number of cliques. After coloring, the throughput sum perceived by all the nodes belonging to each clique is obviously **r/x_e**, thus resulting in a total throughput equal to: $\rho^e_{tot} = \frac{r}{x^e} c^e$
- Average per-node throughput as $\rho_{tot}/n = r / x_e E[d_e]$

  ($E[d_e] = n/c_e$ represents the average after coloring clique size).

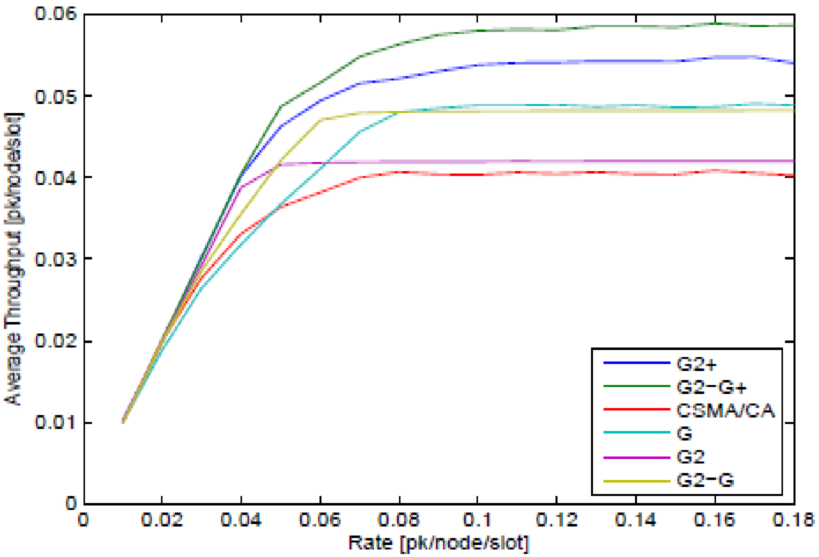
Performance Evaluation

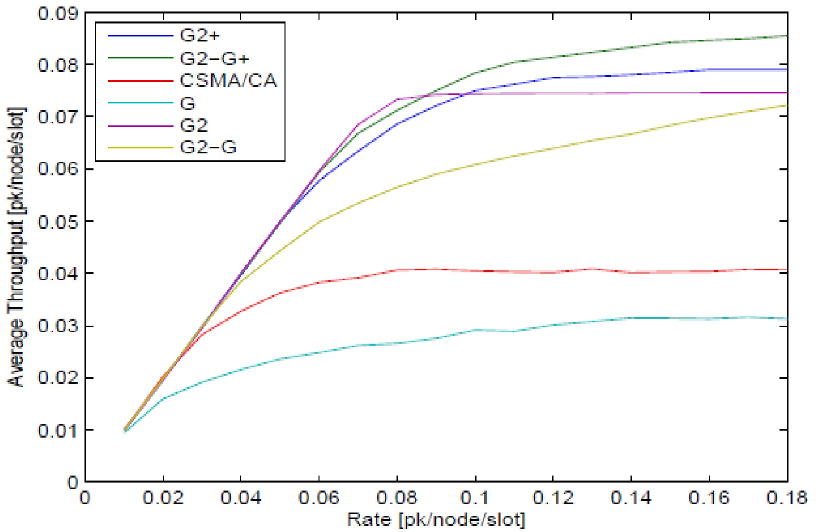
Topology	H_e	x_e	c^e	$\ddot{\rho}^e/\mathrm{r}$	$E[\rho^e]/\mathrm{r}$
1	G^2	16	30	0.0624	0.0625
1	$G^2 - G$	5	12	0.0792	0.0800
2	G^2	13	30	0.0768	0.0769
2	$G^2 - G$	5	11	0.0730	0.0733
3	G^2	15	30	0.0666	0.0667
3	$G^2 - G$	5	13	0.0863	0.0867

TABLE I

MEASUREMENTS AND ESTIMATES OF THROUGHPUT.

Performance Evaluation





Average throughput under the SC coloring scheme

Average throughput under the CFA coloring scheme

Some Observations

1. **Coloring G** can be useless, because the carrier sense functionality is already able to avoid interference among adjacent nodes. For the CFA case, the performance obtained under the G coloring are even worse than the ones obtained with the CSMA/CA protocol, because the slot allocations may synchronize hidden nodes for lower packet generation rates.
2. **Coloring G2** can be more efficient (CFA case) or less efficient (SC case) than coloring G2-G, according to the network topology and to the effectiveness of the coloring scheme in selecting a limited number of colors and/or leaving a limited number of bottlenecks.
3. **If we allow node i** to transmit during the slots associated to its color and to colors different form the ones of its adjacent nodes (schemes G2+ and G2-G+), we can further improve the network performance

From PALERMO to SANTA BARBARA

THANKS!