On Selfish Behavior in CSMA/CA Networks

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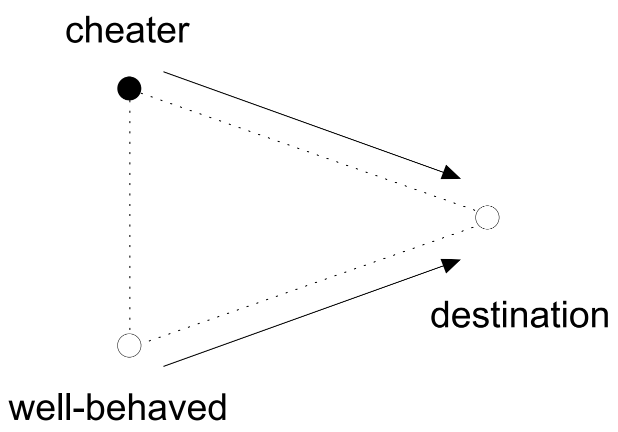
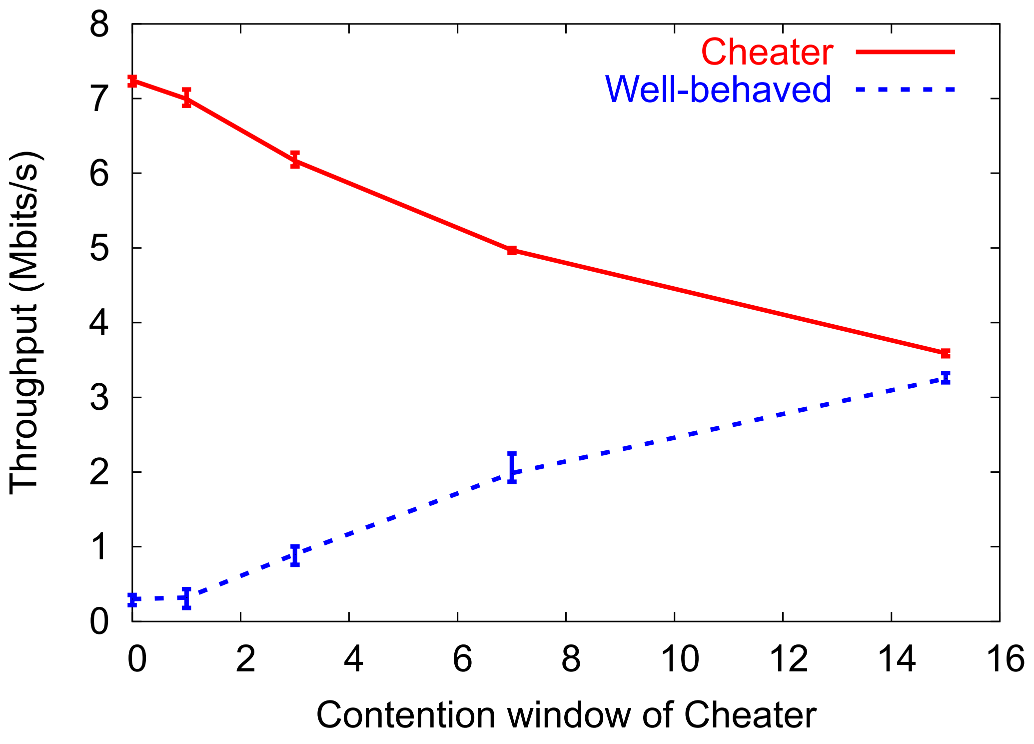
Introduction

- CSMA/CA is the most popular MAC paradigm for wireless networks
- CSMA/CA protocols rely on a (fair) random deferment of packet transmission
  - where nodes control their own random delays
- CSMA/CA is efficient if nodes follow predefined rules, however, nodes have a **rational motive to cheat**

Cheating pays well





Our goal

- Study the coexistence of a population of greedy stations

- Derive the conditions for the stable and optimal functioning of a population of greedy stations

Model and assumptions

- Network of N nodes (transmitters) out of which C are cheaters
  - IEEE 802.11 protocol
  - MAC layer authentication (no Sybil attack)
  - single collision domain (no hidden terminals)
  - nodes always have packets (of the same size) to transmit
- **Contention window size**-based cheating
  - fix $W_i = W_{\min} = W_{\max}$ (no exponential backoff)
  - delay transmissions for $d_i \in_U \{1, 2, \ldots, W_i\}$
- Cheaters are rational (maximize their throughput r_i)

Cheaters utility function U_i

- Derived from Bianchi's model of IEEE 802.11
  - each cheater i controls its **access probability**

$$\tau_i = \frac{2}{W_i + 1}$$

  - cheater i receives the following throughput:

$$U_i(\tau_i, \tau_{-i}) \equiv r_i(\tau_i, \tau_{-i}) = \frac{\tau_i c_1^i(\tau_{-i})}{\tau_i c_2^i(\tau_{-i}) + c_3^i(\tau_{-i})} \ ,$$

where $\tau_{-i} \equiv (\tau_1, \ldots, \tau_{i-1}, \tau_{i+1}, \ldots, \tau_N)$.

Static CSMA/CA game

- Static games
  - **players** make their **moves** independently of other players
  - players play the same move forever

- A move in the CSMA/CA game corresponds to setting the value of the cheater's contention window W_i (that is, τ_i)

- Solution concept - **Nash equilibrium** (NE)
  - $\mathbf{W} = (W_1, W_2, \ldots, W_C)$ is a NE point if $\forall i = 1, \ldots, C$, we have: $U_i(W_i, W_{-i}) \geq U_i(\hat{W}_i, W_{-i})$, $\forall \hat{W}_i \in \{1, 2, \ldots, W_{\max}\}$

Nash equilibria of the static game

Proposition 1. *A vector* $\mathbf{W} = (W_1, \ldots, W_C)$ *is a Nash equilibrium if and only if* $\exists i \in \{1, 2, \ldots, C\}$ *s.t.* $W_i = 1$.

Proposition 2. *The static CSMA/CA game admits exactly* $W_{\max}^C - (W_{\max} - 1)^C$ *Nash equilibria.*

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- Two families of Nash equilibria
  - define $\mathcal{D} \equiv \{i : W_i = 1,\ i = 1, 2, \ldots, C\}$
  - 1st family, $|\mathcal{D}| = 1$, implying that only one cheater receives a non-null throughput (**some allocations are Pareto-optimal!**)
  - 2nd family, $|\mathcal{D}| > 1$, implying $r_i = 0$, for $i = 1, \ldots, C$ (known as **the tragedy of the commons**)

How to avoid undesirable equilibria?

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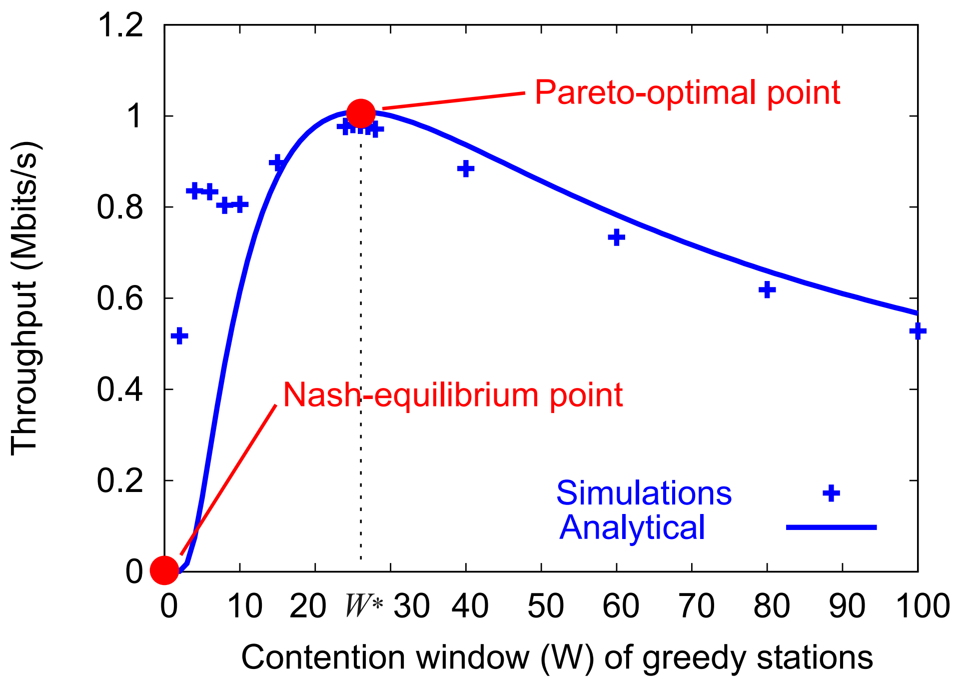
- To derive a better solution we use **Nash bargaining framework**
  - solve the following problem

$$\mathbf{\Pi_1}: \quad \text{s.t.} \quad \begin{array}{l} \max \prod_{i=1}^{C} (r_i - r_i^0) \\ \mathbf{r} \in R \\ \mathbf{r} \geq \mathbf{r}^0 \ . \end{array}$$

  - where R is a finite set of feasible solutions, and $r_i^0 \equiv \max_i \min_{-i} r_i, \ i = 1, 2, \ldots, C$ is the disagreement point

Uniqueness, fairness and optimality

- $\mathbf{\Pi_1}$ admits a **unique**, **fair** and **Pareto-optimal solution** W^* (**Nash bargaining solution**)



Dynamic CSMA/CA game

- W^* is a desirable solution, but is not a Nash equilibrium
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- In the model of dynamic games
  - cheaters' utility function changes to $J_i = r_i - P_i$, where P_i is a **penalty function**
  - cheaters are reactive

Penalty function P_i

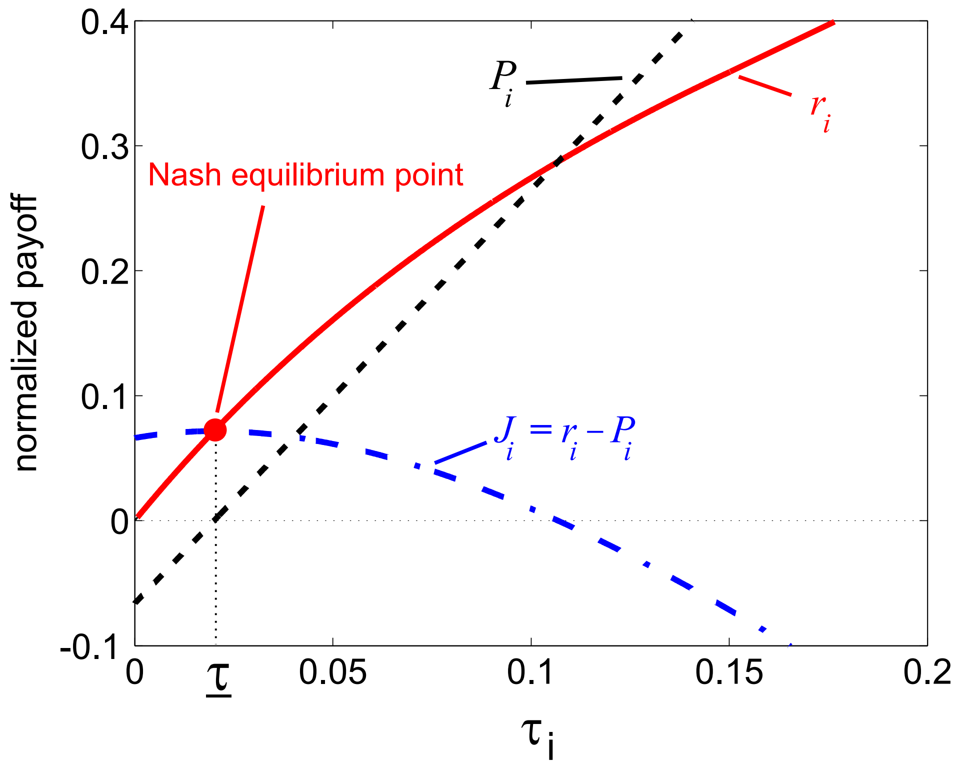
Proposition 3. *Define:*

$$P_i = \begin{cases} p_i, & \textit{if } \tau_i > \underline{\tau} \\ 0, & \textit{otherwise} \end{cases},$$

where $\partial p_i / \partial \tau_i > \partial r_i / \partial \tau_i$ *and* $\tau_i < 1,\ i = 1, 2, \ldots, C$. *Then,* $J_i = r_i - P_i$ *has a unique maximizer* $\underline{\tau}$.

Graphical interpretation

- Example: $P_i = k_i(\tau_i - \underline{\tau})$, with $k_i > \partial r_i / \partial \tau_i$



Making W^* a Nash equilibrium point

- Let

$$\underline{\tau} = \min_{i=1,\ldots,C} \tau_i, \text{ (i.e., } \underline{W} = \max_{i=1,\ldots,C} W_i)$$

- Each player j calculates a penalty p_i^j to be inflicted on player $i \neq j$, given that $r_i > r_j$, as follows:
  - $p_i^j = r_i - r_j$
  - note, $\partial r_i / \partial \tau_i > 0$ and $\partial r_j / \partial \tau_i < 0 \Rightarrow \partial p_i^j / \partial \tau_i > \partial r_i / \partial \tau_i$
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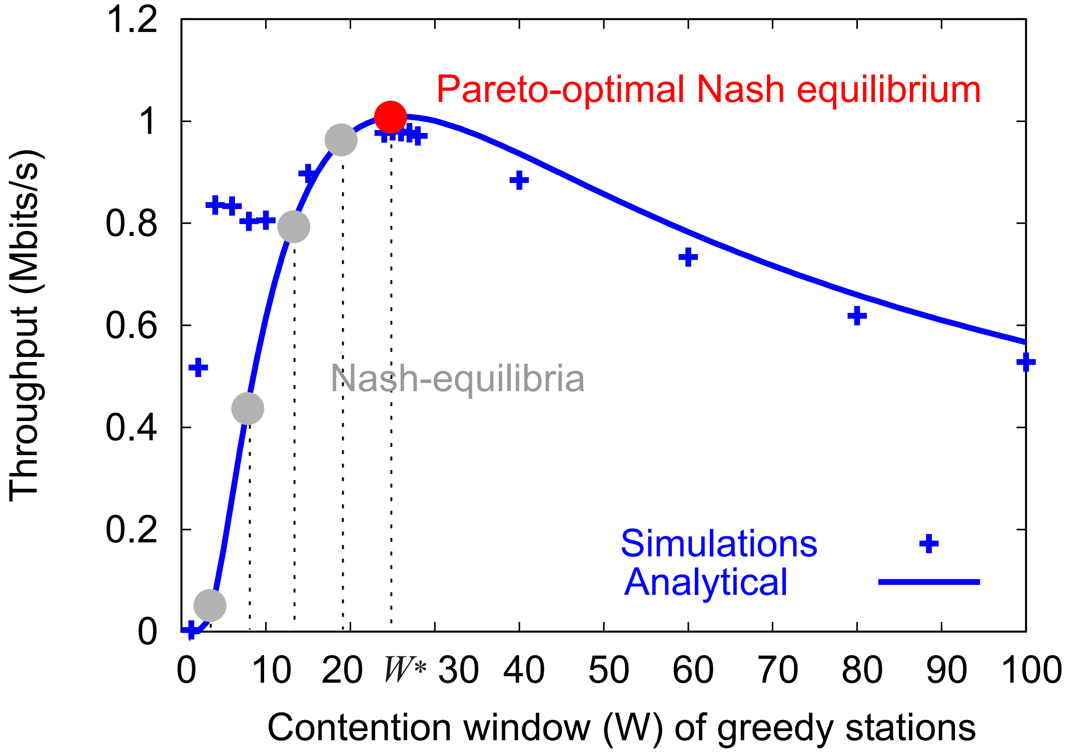
Then, $\tau_i = \underline{\tau}$ (i.e., $W_i = \underline{W}$), $i = 1, \ldots, C$, is a unique Nash equilibrium.

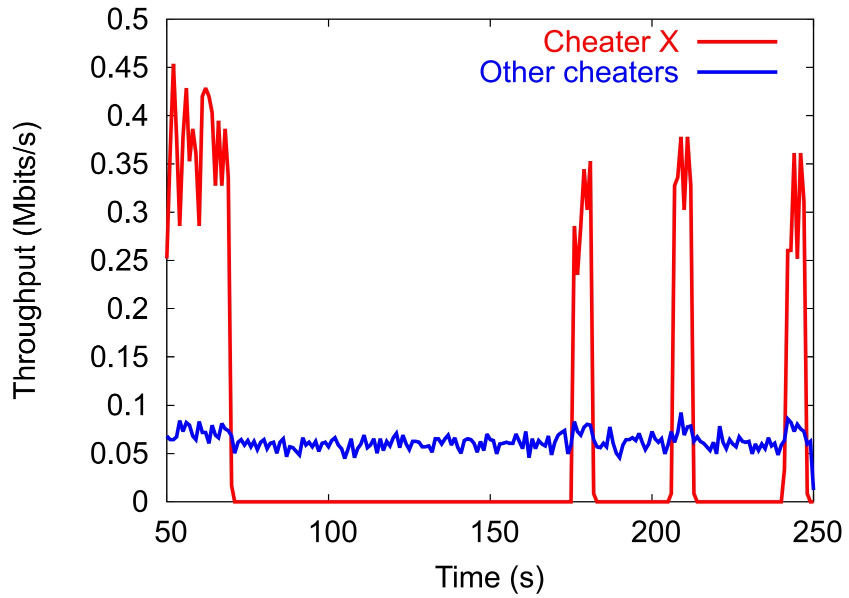
Making W^* a Nash equilibrium point (cont.)

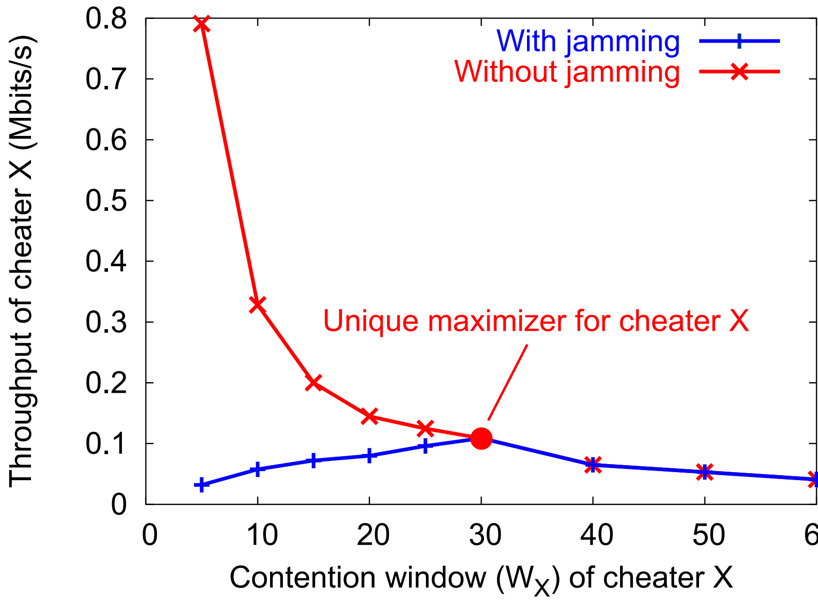
- **Moving Nash Equilibrium**



Implementation of the penalty function

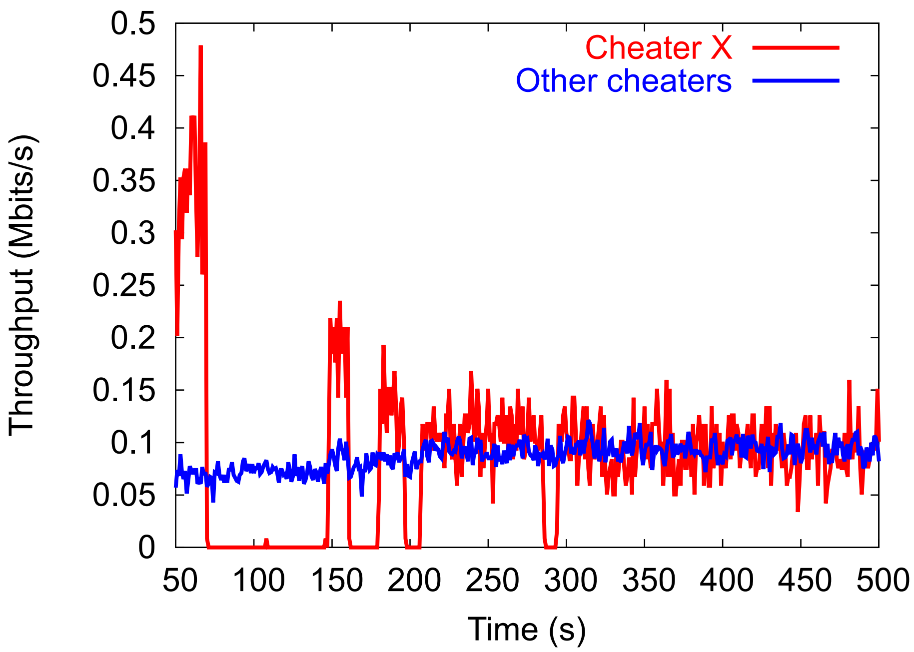
- Achieved by **selective jamming**
- Penalty should result in $r_i = r_j$, therefore $T_{\text{jam}} = (r_i/r_j - 1)T_{\text{obs}}$

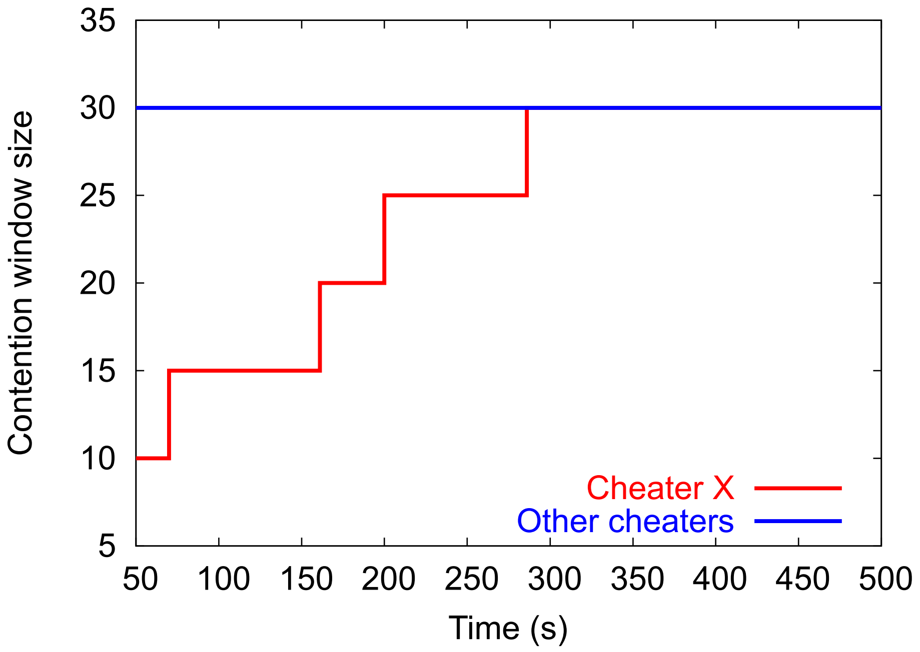




Adaptive strategy

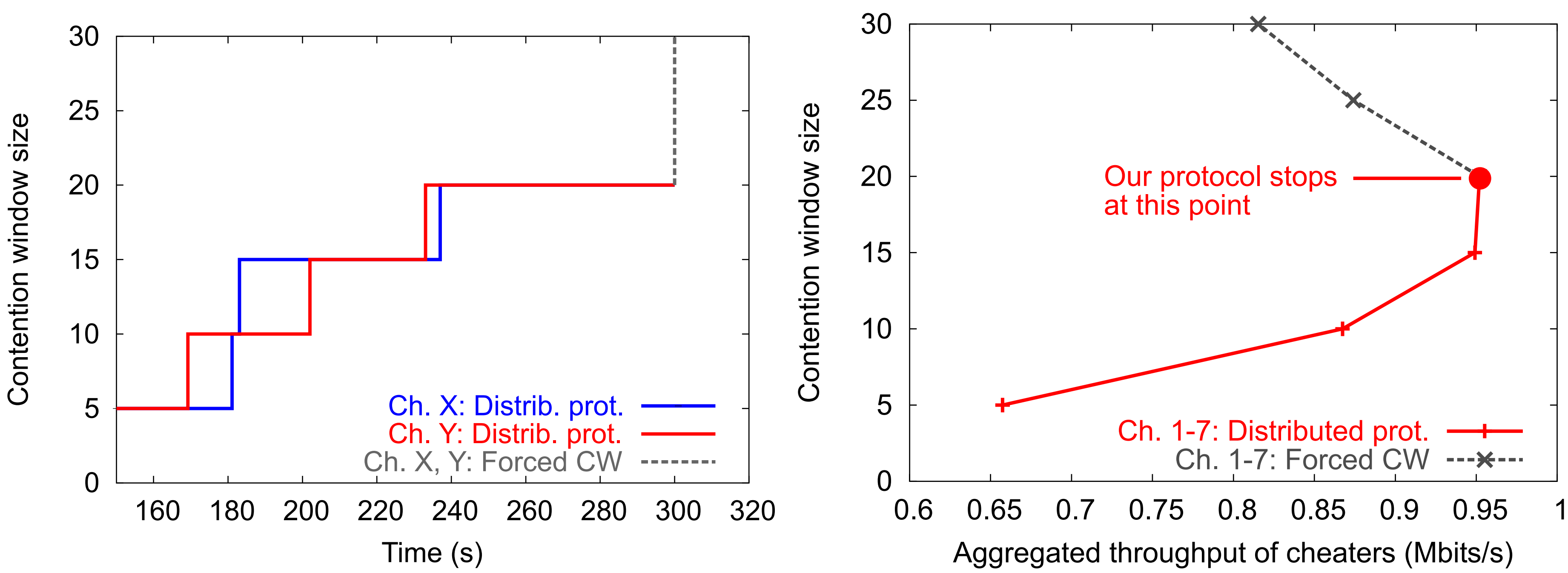
- Prescribes to a player what to do when the player is penalized (jammed)





Fully distributed algorithm

- Evolution of the contention windows and the aggregated cheaters' throughput for $N = 20,\ C = 7$, the step size $\gamma = 5$



Conclusions

- Static CSMA/CA game admits two families of Nash equilibria
  - one family includes equilibria that are also Pareto-optimal
- Nash bargaining framework is appropriate to study fairness at the MAC layer
  - using this framework we have identified the unique Pareto-optimal point exhibiting efficiency and fairness
- We have shown how to make this Pareto-optimal point a Nash equilibrium point, by
  - providing a fully distributed algorithm that leads a population of greedy stations to the efficient Paret-optimal Nash equilibrium

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- **CSMA/CA game has a high educational value**