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A Two-Layer Coalitional Game among Rational Cognitive Radio Users

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Yuan Lu
ylu8@ncsu.edu

Alexandra Duel-Hallen
sasha@ncsu.edu

Department of Electrical and Computer Engineering
North Carolina State University

Introduction: Hardware Constrained CR

Overlay Cognitive Radio (CR) Structure

- Secondary users (**SU**s) are required to **sense before accessing** the spectrum licensed to primary users (**PU**s).

Hardware Constraints

- Each SU has **limited sensing capability**.
- Sensing outcomes are **prone to errors**:
  - Miss detection (**MD**) ➔ Collision with PUs,
  - False alarm (**FA**) ➔ Missed spectrum opportunities.
- No central control unit ➔ **Distributed** CR access ➔ **SU collision**.

Approach: SU Cooperation

Observations and Related Work

Observations

- Traditionally, cooperative sensing is studied assuming
  - a **fixed** number of SUs & a **single channel**;
  - all participating SUs are **fully cooperative**.

In practice, there are many possible channels!

- How to make **rational sensing & cooperation decisions**?
- How to **share** the detected spectrum resources **fairly**?

Related Work:

- **Game theory** has been utilized recently for SU cooperation:
  - **cognitive access** is ignored in [1-3];
  - **sensing decision** is not studied in [4];
  - only [5] **jointly** considers **sensing & access** – but is **not fair**.

[1] B. Wang, et al., *IEEE Trans Commun.* 10
[2] W. Saad et al., *IEEE Trans. Veh. Technol.* 11
[3] W. Wang et al., *GLOBECOM* 10
[4] J. Rajasekharan et al., *Asilomar* 10
[5] X. Hao et al., *IEEE Trans. Wireless Commun.* 12

Definition and Assumption

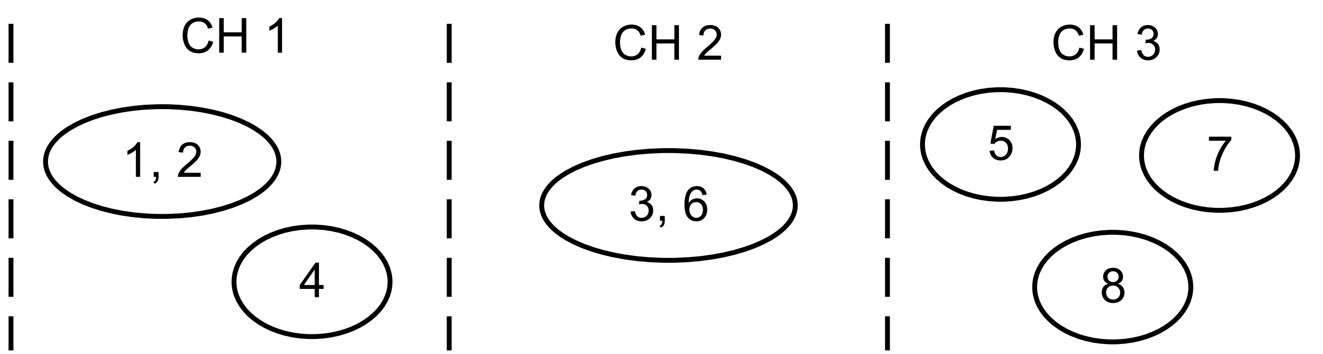
- **Set of all SUs** $\mathcal{M} = \{1, \dots, M\}$; **Set of all channels** $\mathcal{N} = \{1, \dots, N\}$.
- **Top-layer coalition** $C = (S, n)$: a set of SUs S sensing channel n;
  ➔ **Top-layer partition** $\mathcal{P} = \{C^1, C^2, \dots, C^N\}$.
- **Bottom-layer coalition** $\eta \subseteq S$: a set of cooperating SUs;
  ➔ **Bottom-layer partition** ρ.

$$\mathcal{M} = \{1, \dots, 8\}; \mathcal{N} = \{1, 2, 3\}$$

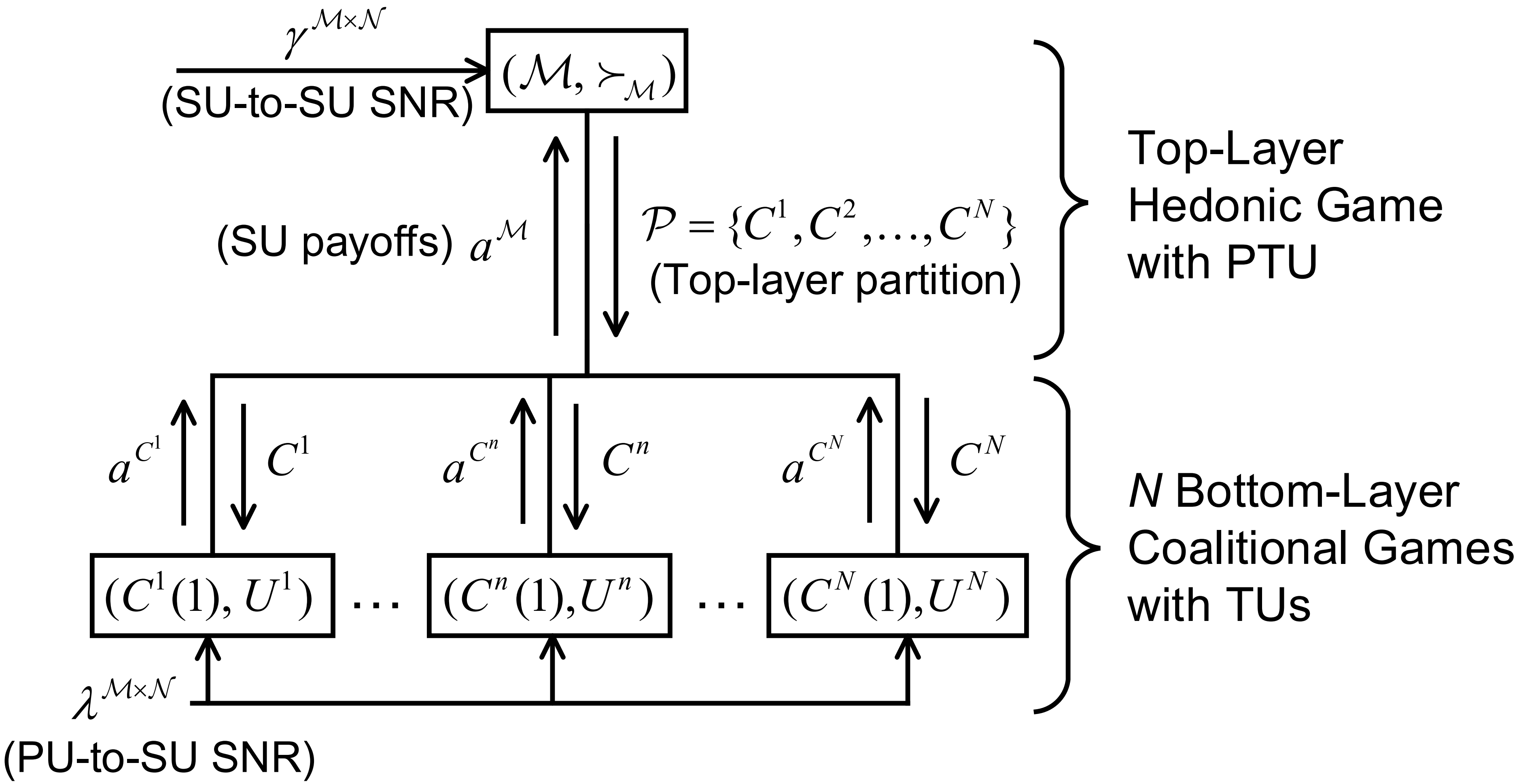
$$\mathcal{P} = \{\underbrace{(\{1,2,4\}, 1)}_{C^1}, \underbrace{(\{3,6\}, 2)}_{C^2}, \underbrace{(\{5,7,8\}, 3)}_{C^3}\}$$

(1) Cooperative sensing
➔ Improved successful tx prob.
(2) Coordinated access
➔ Reduced SU collisions

$$\rho = \{\underbrace{\{1, 2\}}_{\eta}, \{4\}\}$$



Two-Layer Game Formulation

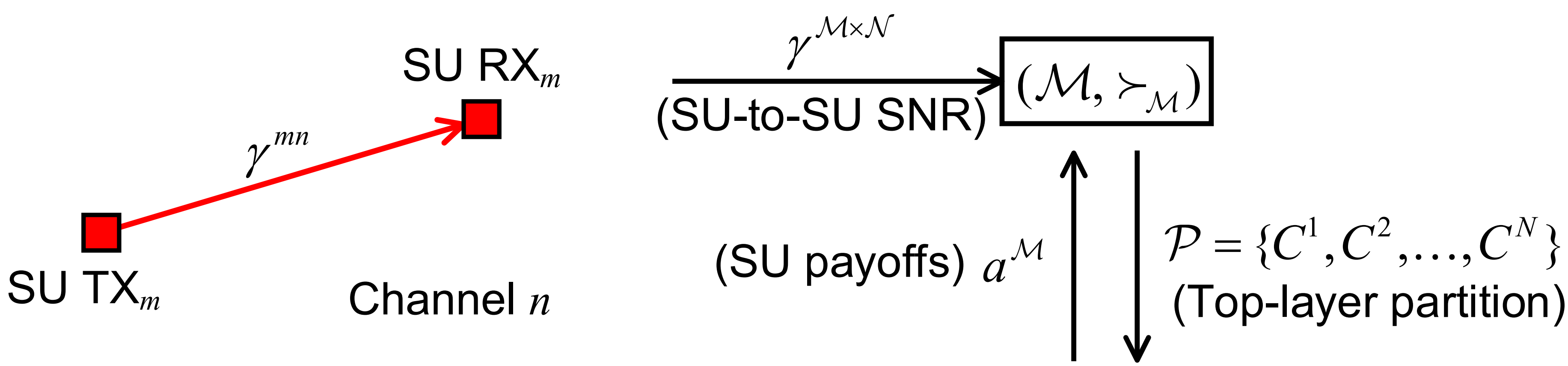


Top-Layer Game Formulation

- Each SU $m \in C$ obtains a **partially transferable utility** (**PTU**) given by the **expected data rate**:

$$x^{mC} = a^{mC} R^{mn}$$

  - **measures** the worth of top-layer coalition C to SU $m \in C$ (1);
  - **data rate** R^{mn} is a non-transferable utility (**NTU**);
  - **probability of successful transmission** a^{mC} is a transferable utility (**TU**) given by the payoff generated by the bottom-layer game.
- A **top-layer partition** $\mathcal{P}$ determines SUs' **sensing decisions**.



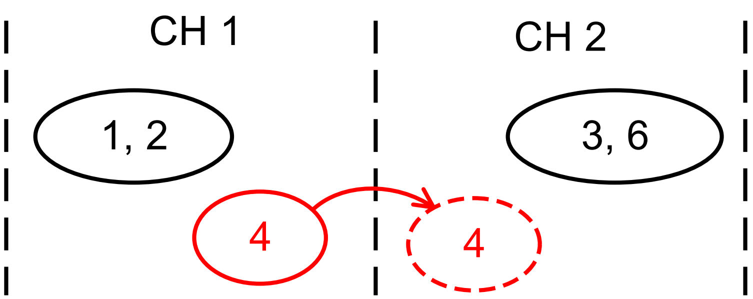
Top-Layer Game Formulation

- An SU m **prefers** to move from channel n to $\tilde{n}$ if

$$\underset{②}{C_r^{\tilde{n}}} \succ_m \underset{③}{C^n} \Leftrightarrow \begin{cases} x^{mC_r^{\tilde{n}}} > x^{mC^n} & \text{(i)} \\ \underbrace{\sum_{i\in C_r^n(1)} a^{iC_r^n}\ ① + \sum_{i\in C_r^{\tilde{n}}(1)} a^{iC_r^{\tilde{n}}}\ ②}_{\text{After the move}} > \underbrace{\sum_{i\in C^n(1)} a^{iC^n}\ ③ + \sum_{i\in C^{\tilde{n}}(1)} a^{iC^{\tilde{n}}}\ ④}_{\text{Before the move}} & \text{(ii)} \end{cases}$$

  - **expected data rate of SU m** improves (i);
  - **sum** of the **successful tx probabilities** on both channels increases (ii).
  - **preference relation** $\succ_m$ combines **individual** & **social** objectives.

- **Hedonic game** $(\mathcal{M}, \succ_{\mathcal{M}})$ (A. Bogomolnaia & M. O. Jackson, *Game Econ. Behav.* 02)



$m = 4, n = 1, \tilde{n} = 2$

$$\left.\begin{array}{l} ①\ C_r^n = (\{1,2\}, 1) \\ ②\ C_r^{\tilde{n}} = (\{3,6,4\}, 2) \end{array}\right\} \text{After}$$

$$\left.\begin{array}{l} ③\ C^n = (\{1,2,4\}, 1) \\ ④\ C^{\tilde{n}} = (\{3,6\}, 2) \end{array}\right\} \text{Before}$$

Bottom-Layer Game Formulation

- N **coalitional games** (S, U^n) are played on different channels
  - a set of SUs $S = C(1)$ on channel $n = C(2)$ for some $C \in \mathcal{P}$.
- Medium access control (**MAC**) is needed when multiple bottom-layer coalitions **compete for detected spectrum opportunity**:
  - **0/X-model**: All competing SUs fail to transmit successfully.
  - **1/X-model**: All competing SUs gain equal probability for access.
- Define the **value** U^n of any **bottom-layer coalition** $\eta \subseteq S$ as the **overall successful transmission probability** of η on channel n:

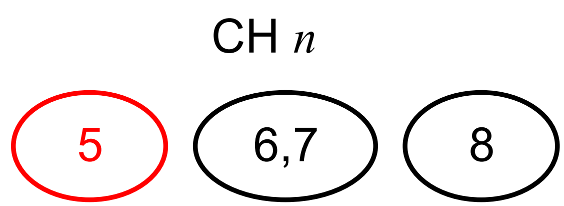
$$U^n_{0/\mathrm{X}}(\eta; \rho) = \beta^n \cdot (1 - P^n_{\mathrm{FA}}(\eta)) \cdot \prod_{\xi \in \rho \backslash \{\eta\}} P^n_{\mathrm{FA}}(\xi)$$

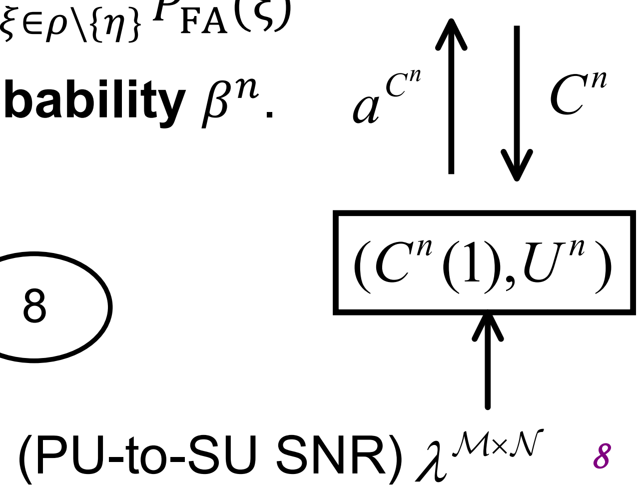
  - Bernoulli i.i.d. PU traffic with **availability probability** β^n.

$\eta = \{5\}$

$\rho = \{\{5\}, \{6,7\}, \{8\}\}$

$\rho \backslash \{\eta\} = \{\{6,7\}, \{8\}\}$





Bottom-Layer Game Formulation

- **Transmission opportunity** can be **transferred** within a bottom-layer coalition (if **all member SUs agree**):
  - **Coalition value** $U^n(\eta) = \Pr[\text{some SU in } \eta \text{ transmits successfully}]$ is a transferable utility (**TU)**;
  - **Allocated payoff probability** $a^{mC} = \Pr[\text{SU } m \text{ transmits successfully}]$;
- How to **implement**?
  - If a slot is sensed idle ➔ SU m transmits with probability $a^{mC}/U^n(\eta)$;
  - The resulting $\Pr[\text{SU } m \text{ transmits successfully}] = a^{mC}$.
- Example: $U^n(\eta) = U^n(\{1,2\}) = 0.8$ for a 2-SU bottom-layer coalition.

	Allocated payoff prob.	**Transmission prob. given a slot is sensed idle by η**
SU 1	$a^1 = 0.2$	$a^1/U(\eta) = 0.25$
SU 2	$a^2 = 0.6$	$a^2/U(\eta) = 0.75$

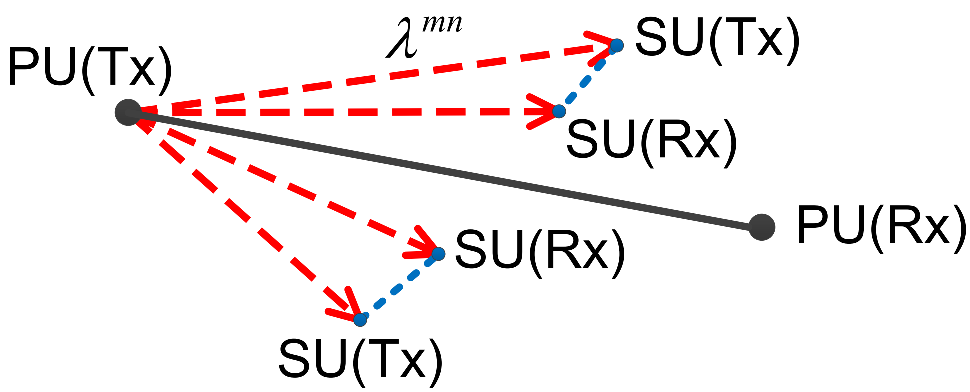
Cooperative Sensing

- We regulate $\boldsymbol{P_{\mathrm{MD}}^{n}(m)}$ and adjust τ^{mn} to guarantee **PU protection**.
- **Individual** MD & FA probabilities for SU m on channel n are [1]:

$$P_{\mathrm{MD}}^{n}(m) = 1 - Q\left((\tau^{mn}/2\nu - \lambda^{mn} - 1)\sqrt{\nu/(2\lambda^{mn}+1)}\right)$$

$$P_{\mathrm{FA}}^{n}(m) = Q((\tau^{mn}/2\nu - 1)\sqrt{\nu})$$

  - τ^{mn} is the detection threshold and ν is the number of samples;
  - Adaptive threshold control: $P_{\mathrm{FA}}^{n}(m)$ decreases with PU-to-SU SNR λ^{mn}.
- Tight $P_{\mathrm{MD}}^{n}(m)$ constraint ➔ low τ^{mn} ➔ large $P_{\mathrm{FA}}^{n}(m)$.



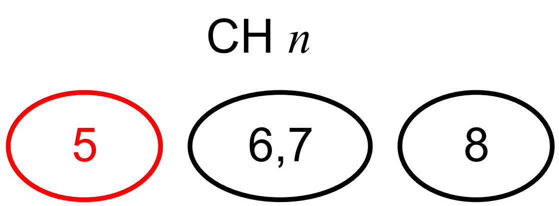
[1] Y. C. Liang et al., *IEEE Trans. Wireless Commun.* 08

Cooperative Sensing

- We assume the **AND-rule hard decision combining** [1].
- SUs in bottom-layer coalition $\eta \in \rho$ **cooperate** to sense channel n:

$$P_{\mathrm{MD}}^{n}(\eta) = 1 - \prod_{m\in\eta}\left(1 - P_{\mathrm{MD}}^{n}(m)\right), \quad P_{\mathrm{FA}}^{n}(\eta) = \prod_{m\in\eta}\left(P_{\mathrm{FA}}^{n}(m)\right).$$

- **Integrated** MD probability is $P_{\mathrm{MD}}^{n}(\rho) = 1 - \prod_{\eta\in\rho}\left(1 - P_{\mathrm{MD}}^{n}(\eta)\right)$.



$\eta = \{5\}$
$\rho = \{\{5\}, \{6,7\}, \{8\}\}$

- Require: (i) $P_{\mathrm{MD}}^{n}(\rho) = P_{\mathrm{MD}}^{\mathrm{Ch}}$ (MD constraint on each channel) (ii) Any 2 equal-sized bottom-layer coalitions maintain the same MD rate.

$$P_{\mathrm{MD}}^{n}(m) = 1 - \left(1 - P_{\mathrm{MD}}^{n}(\eta)\right)^{\frac{1}{|\eta|}} = 1 - \left(1 - P_{\mathrm{MD}}^{\mathrm{Ch}}\right)^{\frac{1}{|S|}}.$$

  - Large SU population $|S|$ ➔ tight $P_{\mathrm{MD}}^{n}(m)$ constraint ➔ increased $P_{\mathrm{FA}}^{n}(m)$ ➔ reduced coalition value.

[1] Y. C. Liang et al., *IEEE Trans. Wireless Commun.* 08

Bottom-Layer: Coalition Formation

- **0/X-model:** $(S, U^n_{0/\mathrm{X}})$ reduces to a **superadditive** coalitional game in **characteristic form** [1]:
  - The **value** of any bottom-layer coalition η is **independent of** $\boldsymbol{\rho}\backslash\{\boldsymbol{\eta}\}$.
  - SUs obtain **larger coalition values** from **forming larger coalitions**.
- **1/X-model:** $(S, U^n_{1/\mathrm{X}})$ exhibits **nonpositive externalities** and all bottom-layer partitions of S are **equally efficient**:
  - A **merger** between two coalitions **cannot benefit** the other coalitions.
  - For any partitions ρ and $\tilde{\rho}$ of S, $\sum_{\boldsymbol{\eta}\in\boldsymbol{\rho}} \boldsymbol{U}^{\boldsymbol{n}}_{\mathbf{1}/\mathrm{X}}(\boldsymbol{\eta};\boldsymbol{\rho}) = \sum_{\boldsymbol{\eta}\in\widetilde{\boldsymbol{\rho}}} \boldsymbol{U}^{\boldsymbol{n}}_{\mathbf{1}/\mathrm{X}}(\boldsymbol{\eta};\widetilde{\boldsymbol{\rho}})$.
- **Grand coalition $\boldsymbol{\rho} = \{\boldsymbol{S}\}$ forms** for both 0/X & 1/X models [2,3].
  - All SUs in S are **willing to cooperate**.
  - **Successful transmission probability** for some SU on channel n = **grand coalition value** $U^n(S)$.

[1] W. Saad et al., *IEEE Signal Process. Mag.* 09
[2] E. Maskin, *Presidential Address to the Econometric Society* 03
[2] I. E. Hafalir, *Games Econ.Behav.* 07

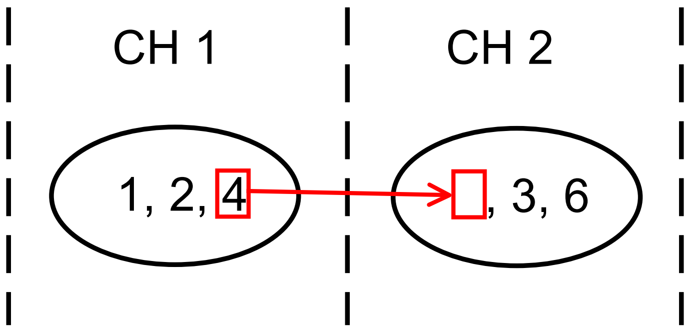
Bottom-Layer: Payoff Allocation

- How to **allocate** the **value** $\boldsymbol{U^n(S)}$ to every SU in S?
  - **Individual payoff** that an SU **could have obtained** by leaving $U^n(S)$ (**disagreement point**) ➔ **Nash Bargaining Solution (NBS)** [1,2].
- 0/X-model: $a^{mC}_{\mathrm{NBS},0/\mathrm{X}} = U^n_{0/\mathrm{X}}(\{m\}) + \frac{1}{|S|}\left[U^n_{0/\mathrm{X}}(S) - \sum_{i\in S} U^n_{0/X}(\{i\})\right]$
  - ≥ **hypothetical individual payoff** (guaranteed);
  - the 2nd term allocates the **surplus due to cooperation** equally to all SUs on channel n.
- 1/X-model: $a^{mC}_{f\mathrm{NBS},1/\mathrm{X}} = U^n_{1/\mathrm{X}}(\{m\}; \{\{j\}_{j\in S}\})$
  - **= hypothetical individual payoff** (assume other SUs are also **alone**);
  - **≠>** SUs should **deviate from the grand coalition** ➔ may end up with a **much worse payoff** if other SUs **collude**.

[1] K. Avrachenkov et al., *Networking* 11
[2] T. Kawamori & T. Miyakawa, *Osaka Univ. Econ. Work. Paper Series* 12
[3] W. Saad et al., *IEEE Signal Process. Mag.* 09

Top-Layer: Coalition Formation

- SUs evolve to different top-layer coalitions in a **distributed** manner.
- An SU m **switches** to another channel if the newly formed coalition is **strictly preferable** ($\succ_m$) to its current coalition.



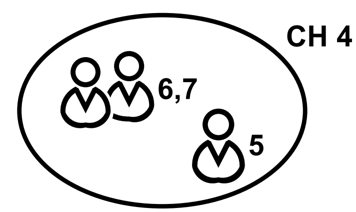
$m = 4, n = 1, \tilde{n} = 2$

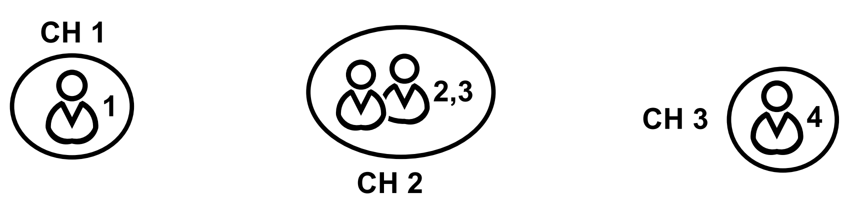
Current coalition $= (\{1,2,4\}, 1)$

New coalition $= (\{4,3,6\}, 2)$

$(\{4,3,6\}, 2) \succ_4 (\{1,2,4\}, 1)$?

- We prove **convergence to a final top-layer partition** $\mathcal{P}^*$:
  - **Overall successful tx prob.** of the CR network **increases** in each transition;
  - SUs **cannot revisit** the same top-layer partition;
  - Only a **finite number** of N^M possible **top-layer partitions**.

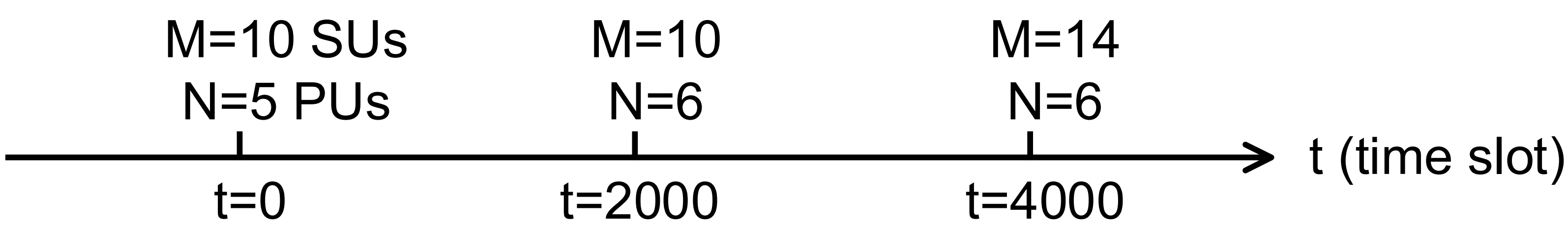




Simulation Setup

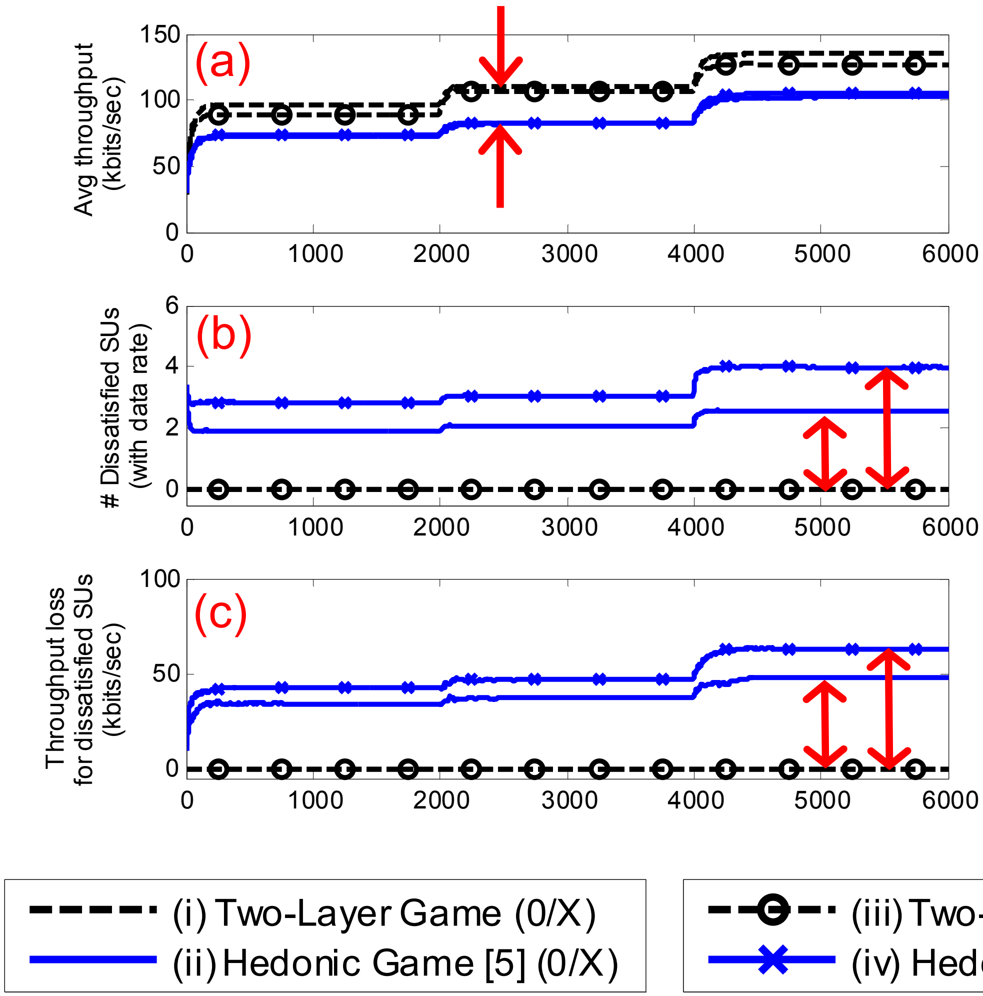
- Only consider the pass loss effects with the path loss exponent = 2.
- All users randomly placed in a square region of $100\text{m} \times 100\text{m}$.
- Each PU uses one channel with bandwidth = $10\ \text{MHz}$ exclusively.

Parameter	Value
Sensing/Slot duration	$5\ \text{ms}/100\text{ms}$
Sensing/Noise power	$10\text{mW}/0.1\text{mW}$
PU/SU transmission power	$100\text{mW}/10\text{mW}$
Number of samples ν	5
Channel availability probability β^n	0.2



Simulation Result: Throughput

- **Better network throughput** under both 0/X and 1/X models
- **All SUs are satisfied** with their individual throughputs.



(a) Average network throughput

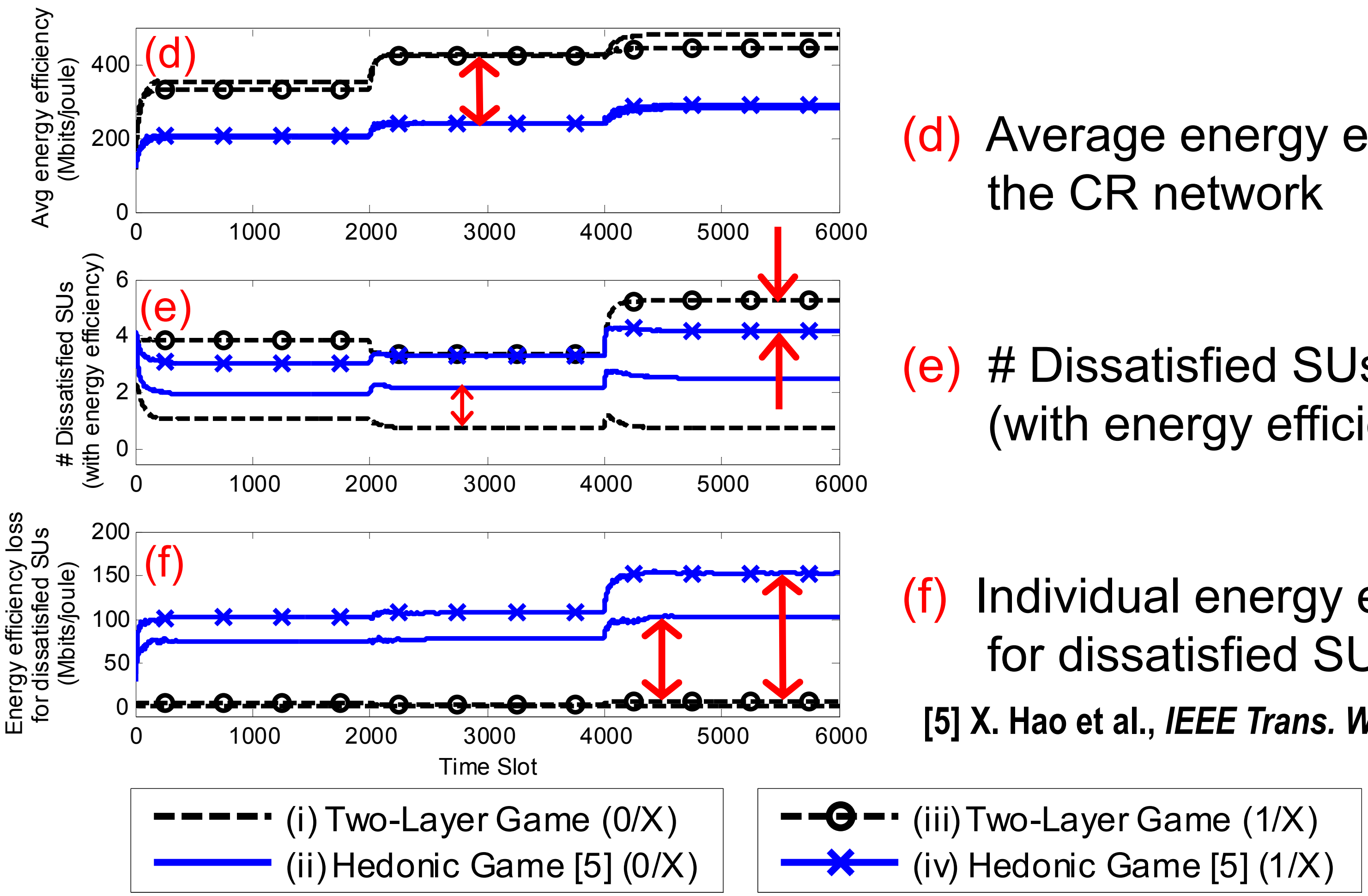
(b) # Dissatisfied SUs (with throughput)

(c) Individual throughput loss (for dissatisfied SUs)

[5] X. Hao et al., *IEEE Trans. Wireless Commun.* 12

Simulation Result: Energy Efficiency

- **One exception:** more dissatisfied SUs under the 1/X-model (d).
  - **Negligible** energy efficiency **loss** for these individuals in (e).
  - **Significantly improved** overall energy efficiency (f).



(d) Average energy efficiency of the CR network

(e) # Dissatisfied SUs (with energy efficiency)

(f) Individual energy efficiency loss for dissatisfied SUs

[5] X. Hao et al., *IEEE Trans. Wireless Commun.* 12

Conclusion

- A **comprehensive** two-layer coalitional game framework for **SU cooperation** in **multichannel multi-SU** CR networks.
- An **efficient**, **stable**, and **distributed** coalition formation algorithm that improves the SU throughput.
- A **fair** payoff allocation scheme to promote **individual incentives** for cooperation.
- A novel **distributed threshold adaptation** approach for cooperative sensing with **guaranteed PU protection**.

Thank you!