UC SANTA BARBARA

Information *as* Control:
The Role of Communication in Distributed Systems

Bryce L. Ferguson

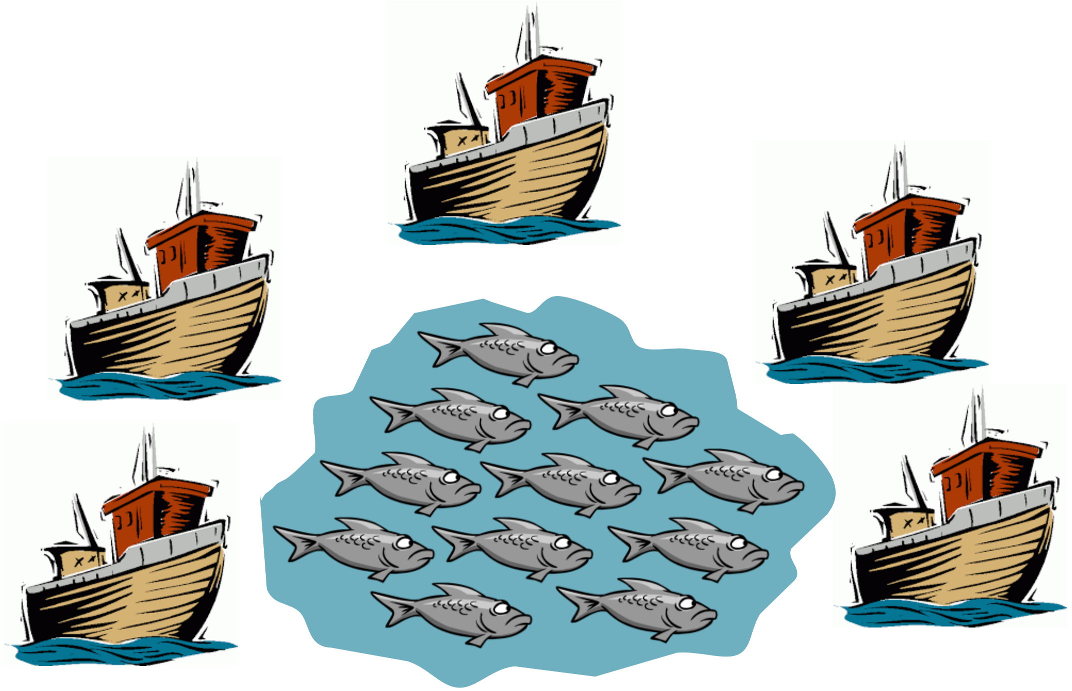
For the ECE Department at UC Santa Cruz

May 15th, 2023

Supported by NSF, ONR, AFOSR, and ARL

Tragedy of the Commons & Distributed Control

The Grand Banks Fishing Fiasco



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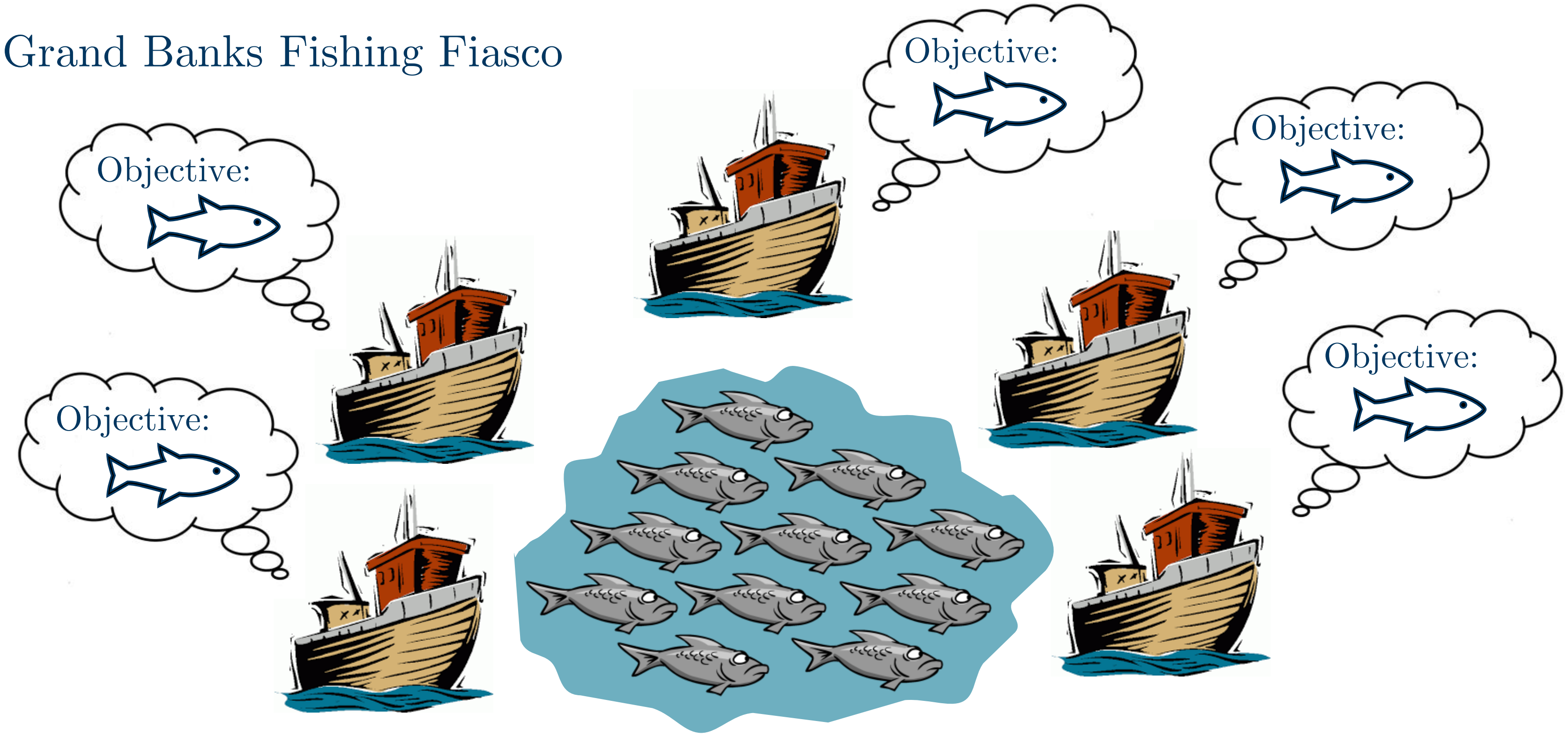

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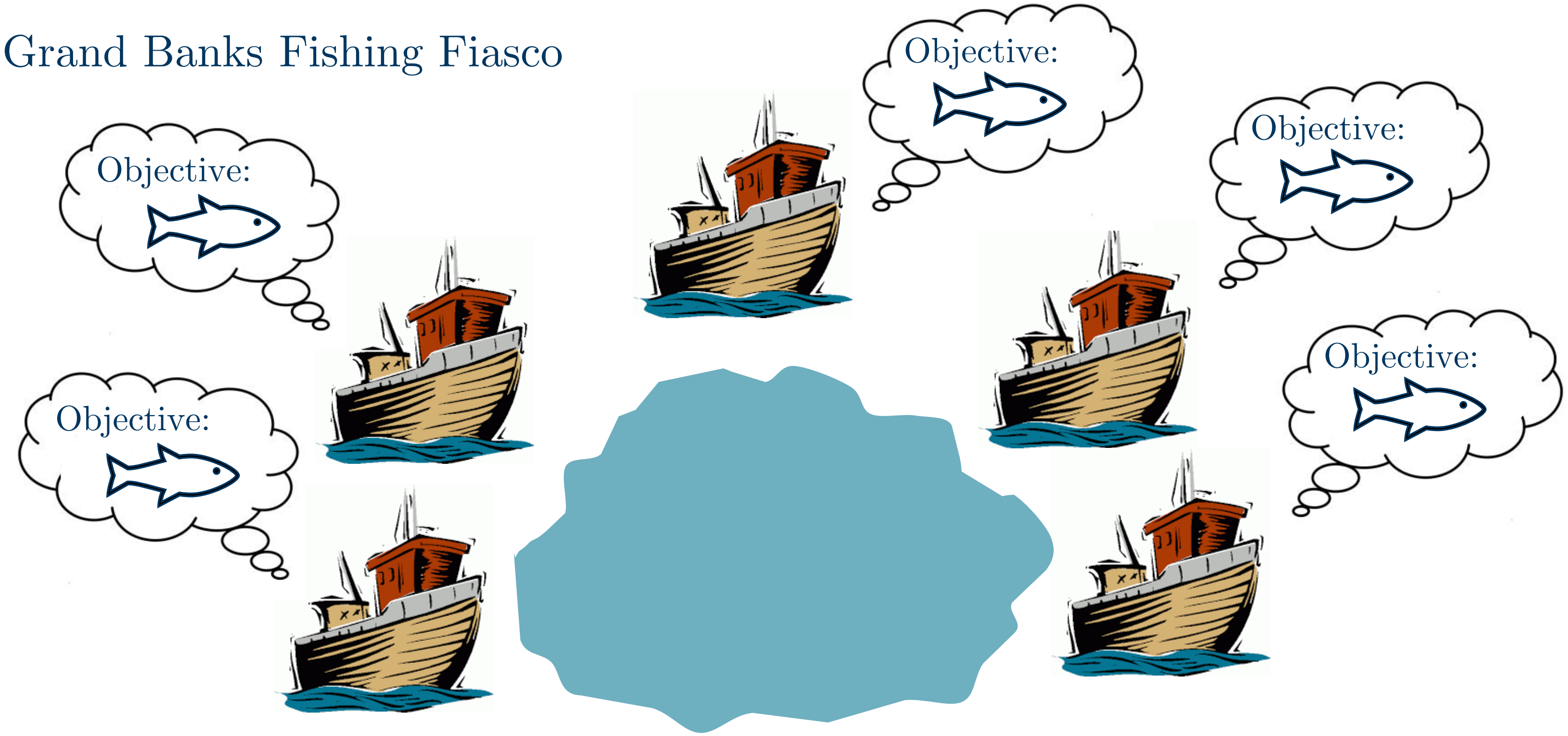

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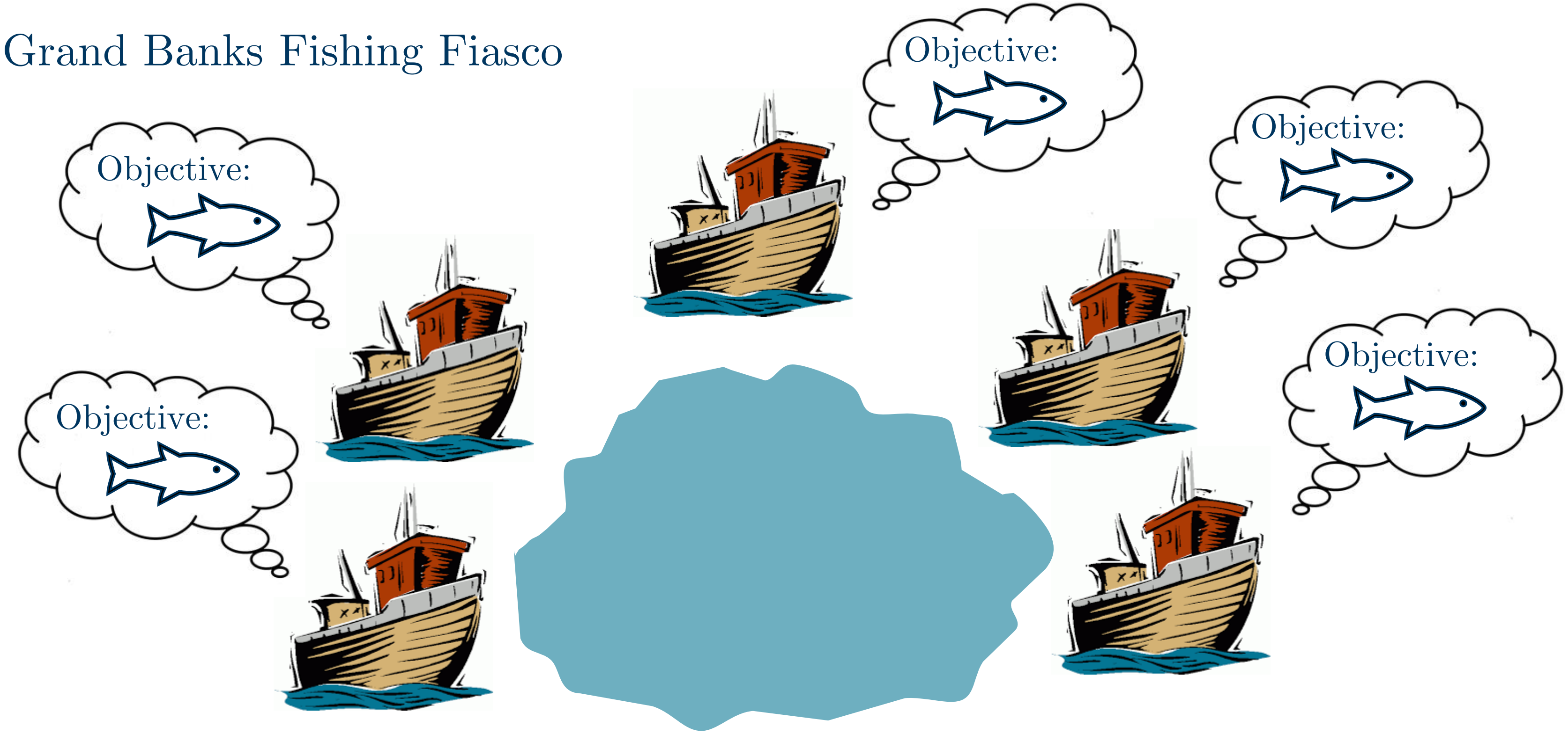

Local Decision Making → **Sub-optimal Global Behavior**

(catch many fish) (fish population disappears)

Tragedy of the Commons & Distributed Control

Environment

THE BALTIMORE SUN

Climate change and the "tragedy of the commons"

By Dylan Selterman
Baltimore Sun • Jan

CLIMATE

Deforestation in Brazilian Amazon hits tragic record in 2022

PUBLISHED WED, JUL 13 2022·9:36 AM EDT

Finance/Business

Gartner: Corporate Sustainability Suffers From Tragedy of the Commons

Emma Chervek | Reporter March 4, 2023 7:00 AM

FORBES

The Tragedy Of The Commons: How A Life Crisis Effects Family Wealth

Matthew Erskine Contributor

Traffic/Congestion

The New York Times

Data Driving New Approaches to Transportation

Analyzing digital streams of information from electric scooters and motor-assisted bicycles is helping solve travel congestion issues.

By Norman Mayersohn
Feb. 5, 2020

This article is part of
businesses evolve.

Five seconds after a
operated databank is
noting the location. In

Uber exemplifies the Tragedy of the Commons

FINANCIAL TIMES

From Tad Borek, San Francisco, CA, US — Wednesday's most read letter

Cloud Computing Services

DATA ECONOMY

ChatGPT is at capacity right now; yes, it is really annoying

Just like any oth

Lately, the "ChatGPT i
outstanding chatbot.
"ChatGPT is at capacit
when the chatbot ser
1020, network trouble, etc. Know that the chatbot's servers are overwhelmed by the volume of requests they're receiving when
you encounter any of these issues. However, a few simple steps can fix the widely used chatbot.

VentureBeat

3 ways data teams can avoid a tragedy of the cloud commons

Clinton Ford, Unravel Data

Tragedy of the Commons & Distributed Control

Internet Connected Devices

Local Decision Making → **Sub-optimal Global Behavior**

(device algorithms) (system errors/inefficiencies/privacy)

Tragedy of the Commons & Distributed Control

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Local Decision Making → **Sub-optimal Global Behavior**

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How do we elicit ***coordination*** among many ***decision-makers***?

Coordination in Distributed Systems

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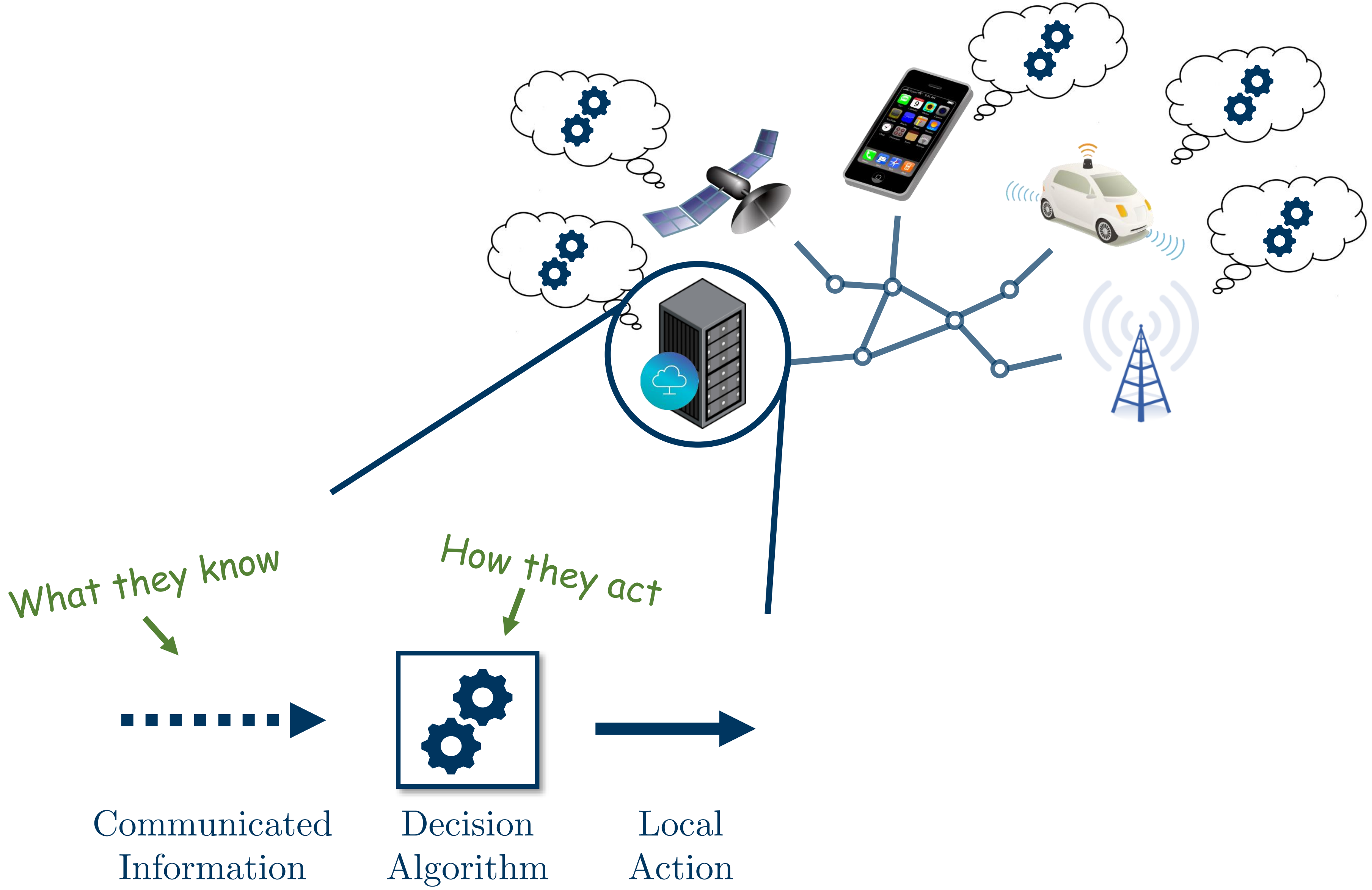

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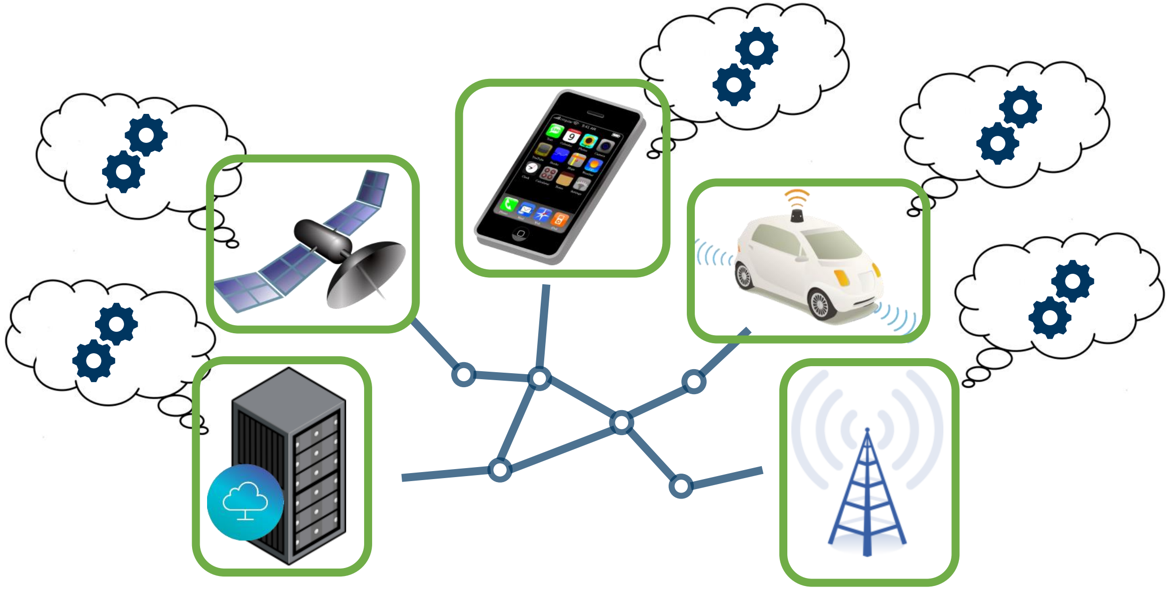
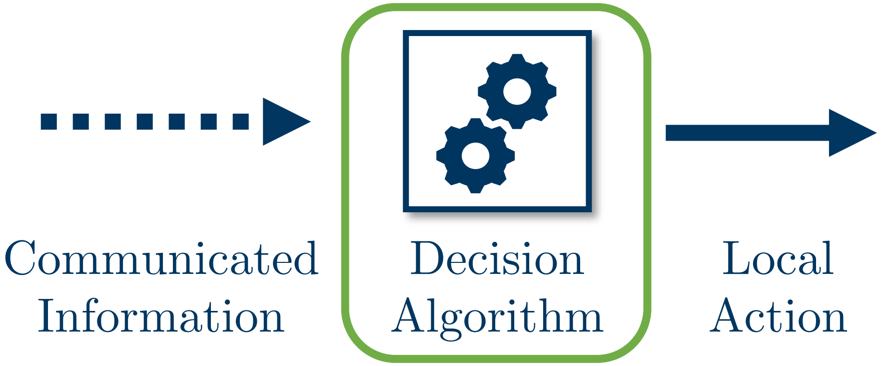


Objective Design

- Design local decision algorithm
- Utilize limited information



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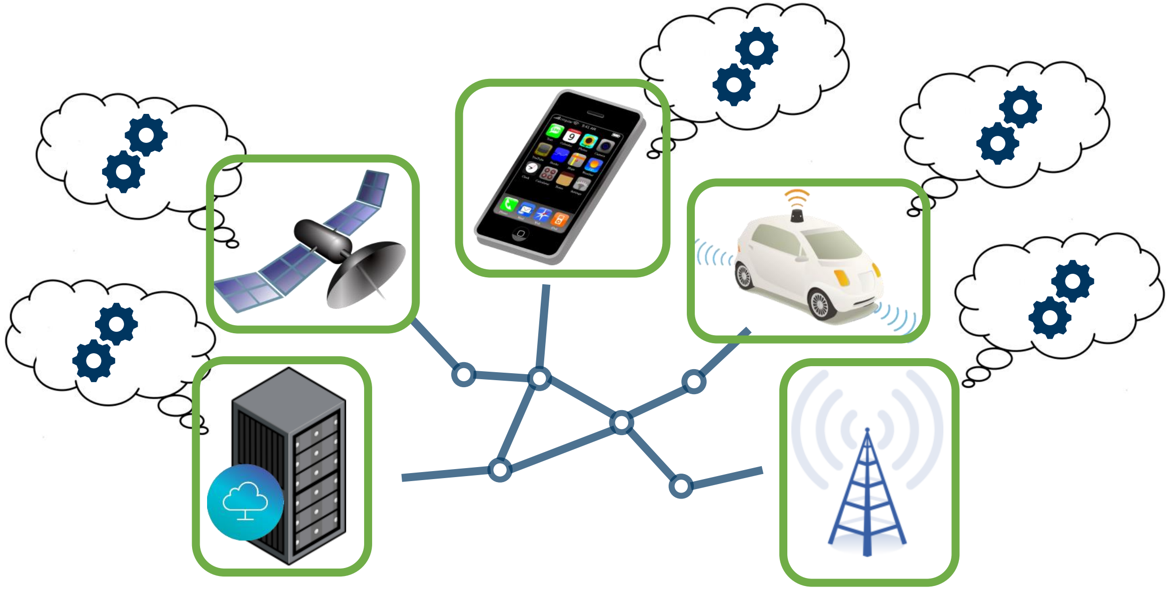

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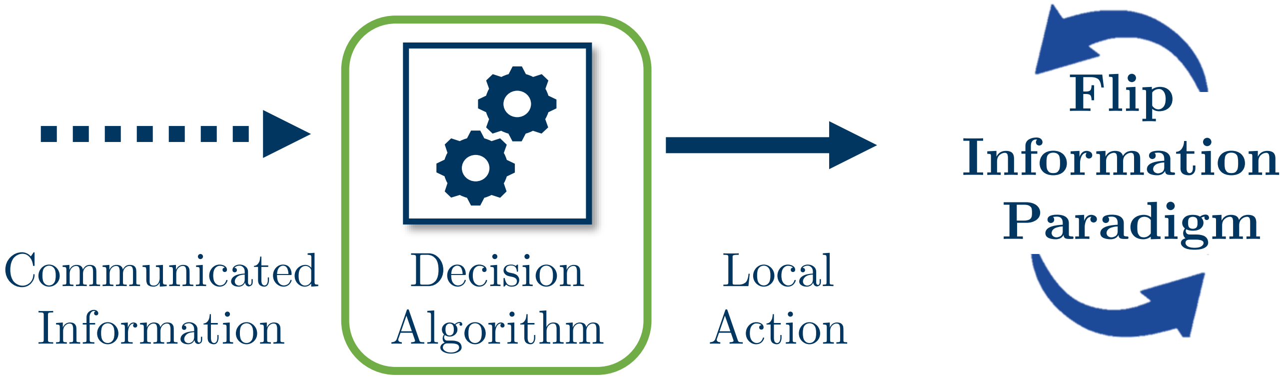


Coordination in Distributed Systems

Objective Design

- Design local decision algorithm
- Utilize limited information

Information Design

- Design communication structure
- Alter inputs to existing decision algorithms

Communicated Information → Decision Algorithm → Local Action

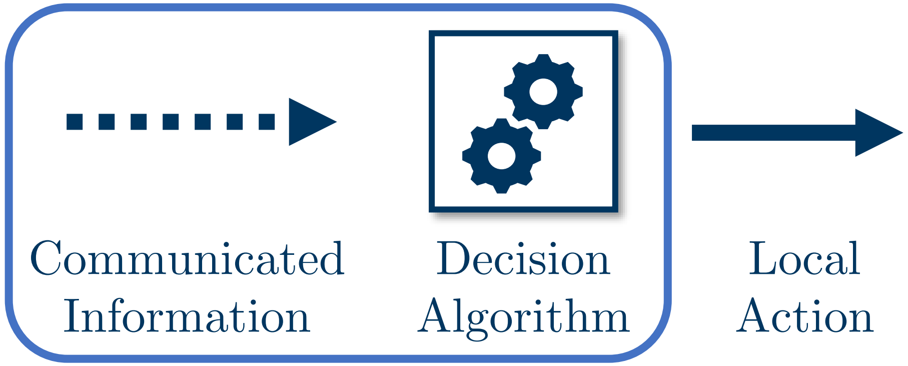
Flip Information Paradigm

Communicated Information → Decision Algorithm → Local Action

Coordination in Distributed Systems

Intelligent Information System Design

- Design communication and local algorithms together
- Improved performance at the cost of increased complexity



Types of Information-Communication

Information Sharing

Collaboratively exchange information

Information Provisioning

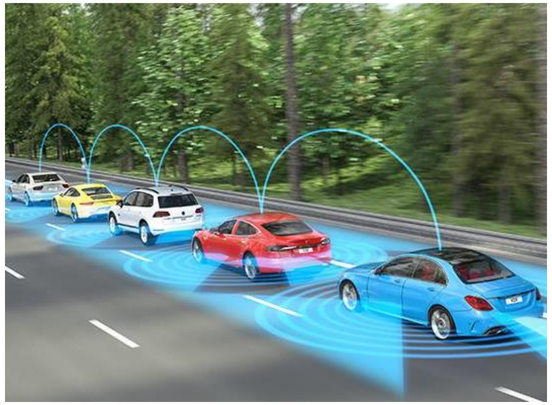
Strategically send out information

Types of Information-Communication

Information Sharing

Collaboratively exchange information

E.g., Autonomous Driving



Vehicle Platooning

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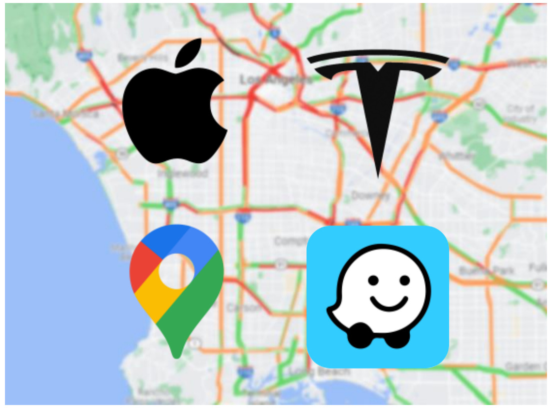

Traffic Signaling

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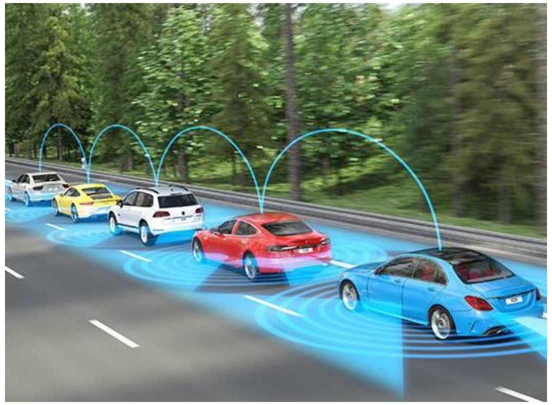

Vehicle Platooning

Traffic Signaling

Local information
Local decision

Local information
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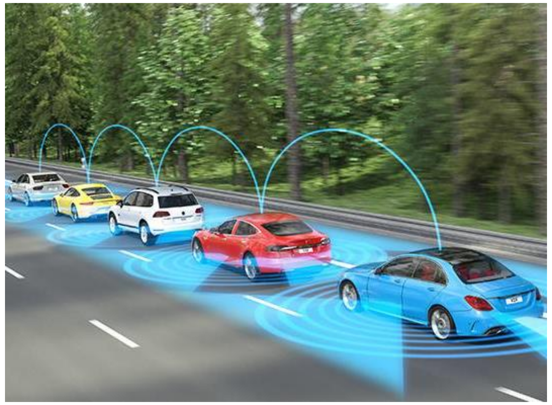

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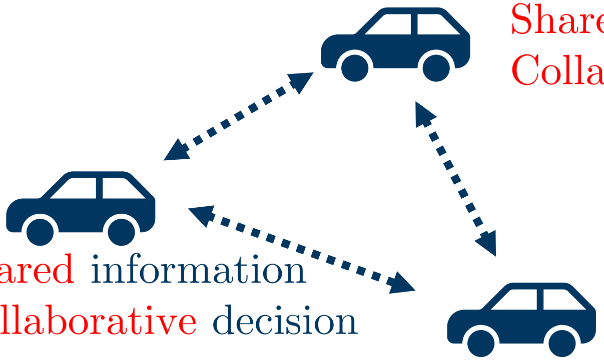

Shared information
Collaborative decision

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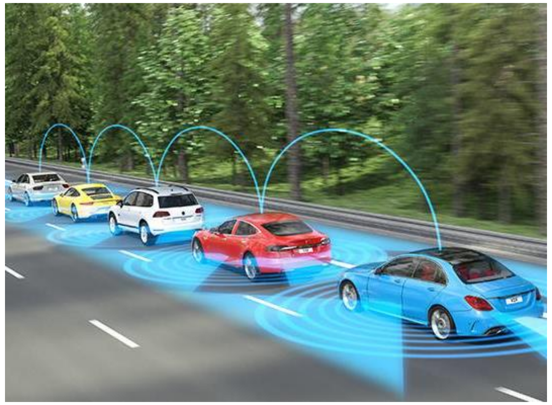

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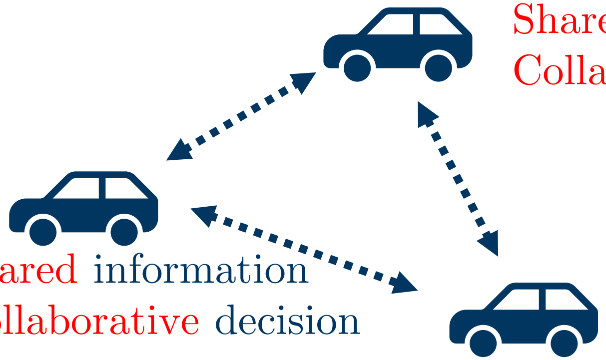

What information is shared?

How is information used?

Network Coordination [Jackson & Watts '02]
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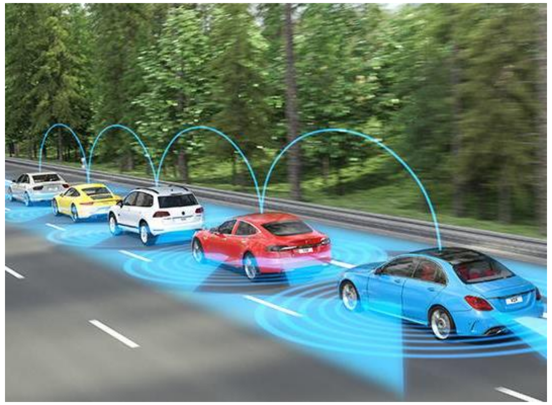

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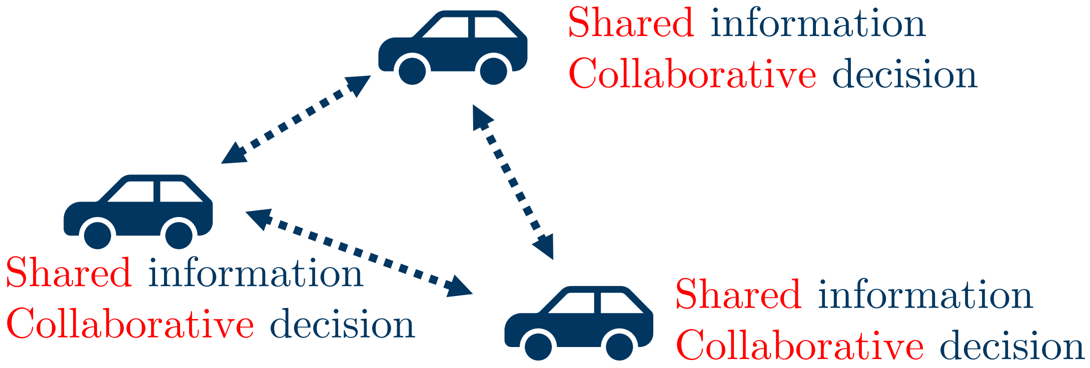

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$\underbrace{\hspace{10em}}$ Focus on convergence to equilibrium behavior

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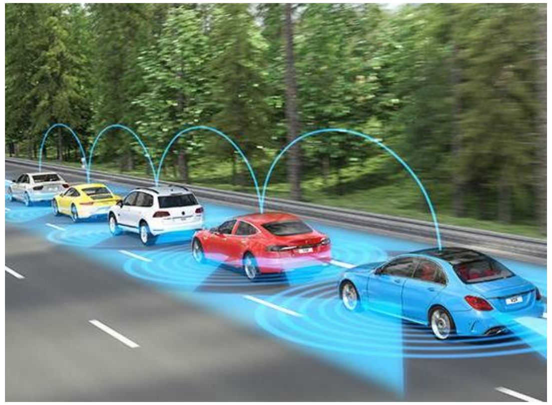

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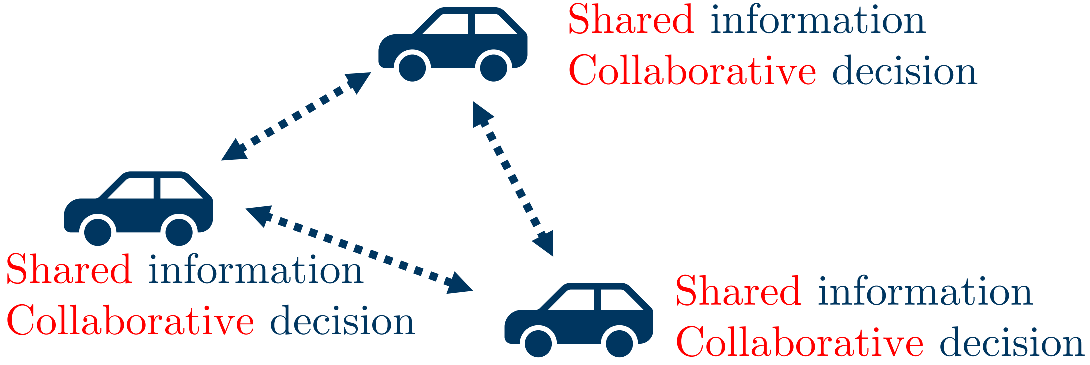

What information is shared?

How is information used?

My work:

Quantify the ***benefit*** of collaborative information sharing to system performance

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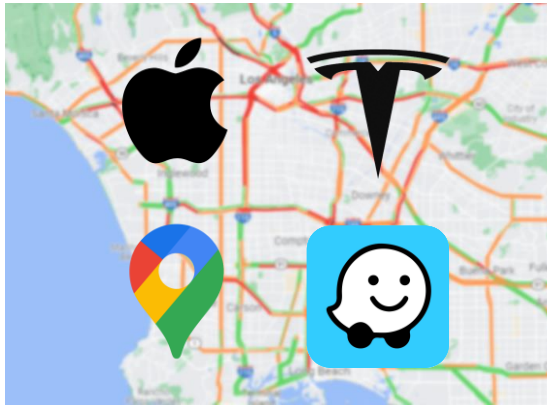

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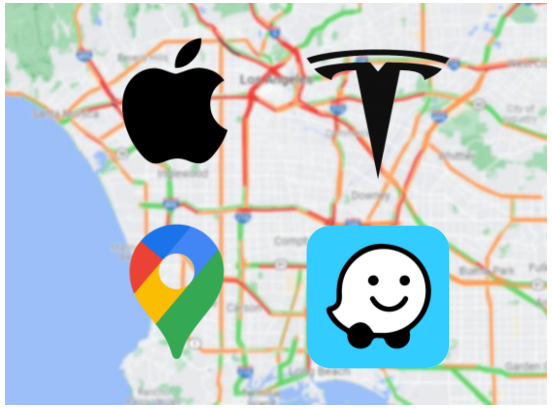


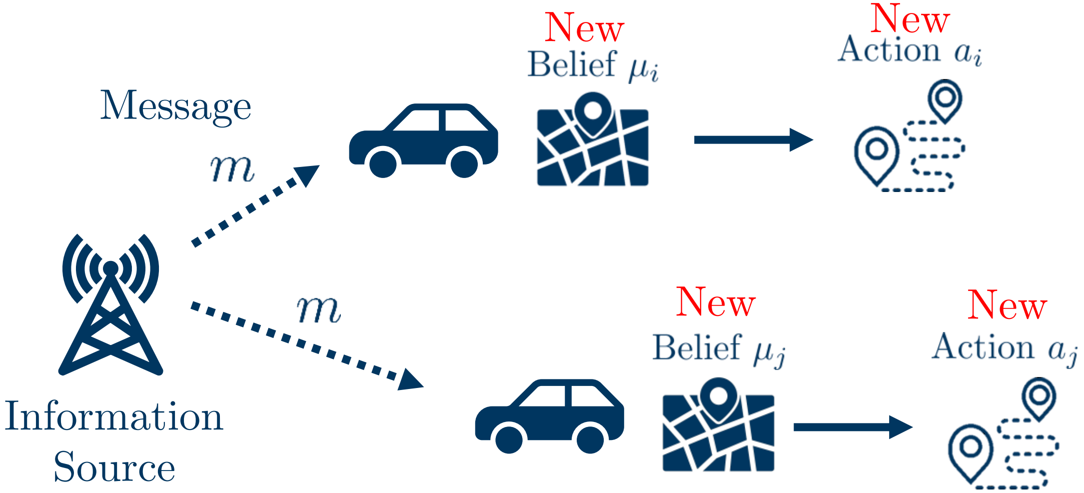
Traffic Signaling

Social Systems:

- Matching Markets [Ostrovsky et. al. ‘10]
- Social Media [Romero et. al. ‘11]
- Elections [Alonso et. al. ‘16]

Bayesian Persuasion: (more general framework)

- Public [Kamenica & Gentzkow ‘11]
- Private [Arieli & Babichenko ‘19]



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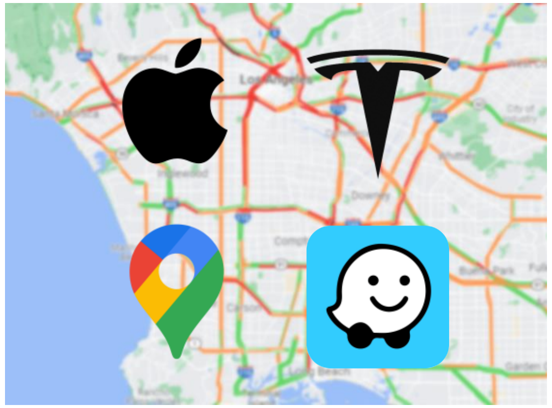

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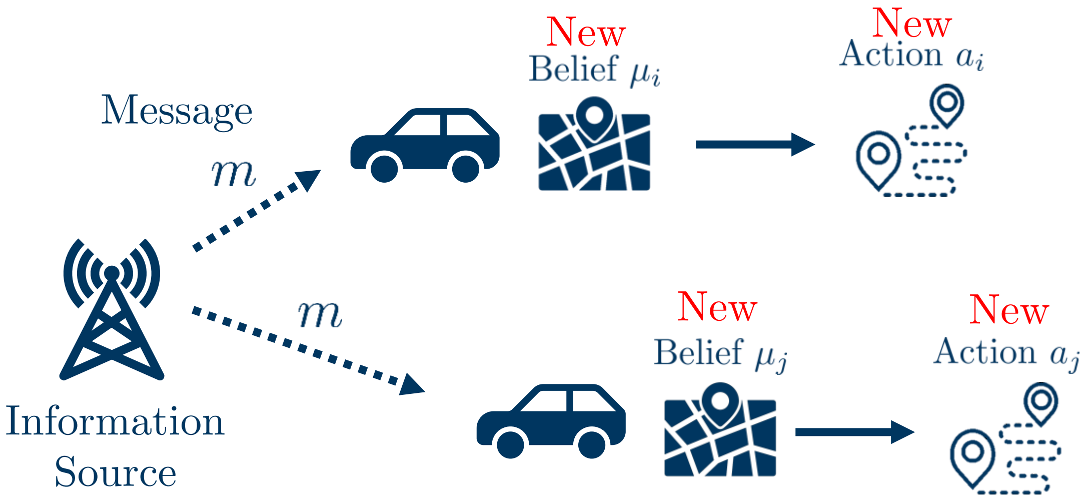
Identify scenarios where revealing info helps / hurts



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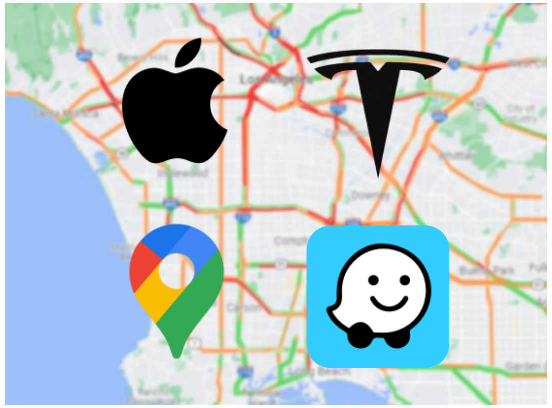

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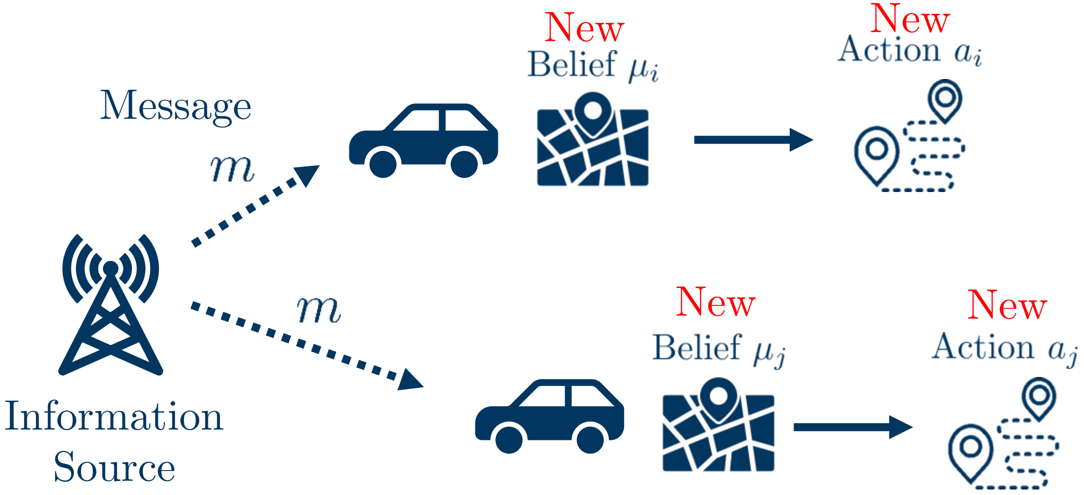

My work:

Quantify how information provisioning affects ***algorithmic guarantees*** of distributed systems

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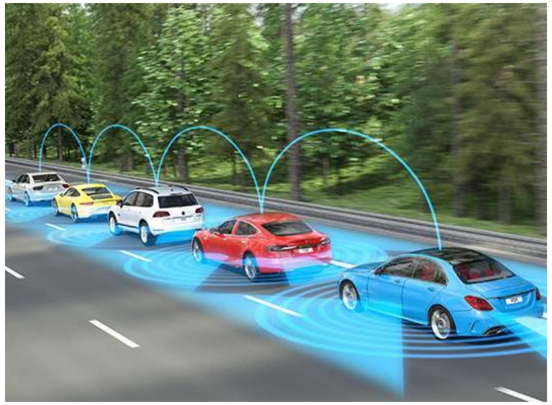

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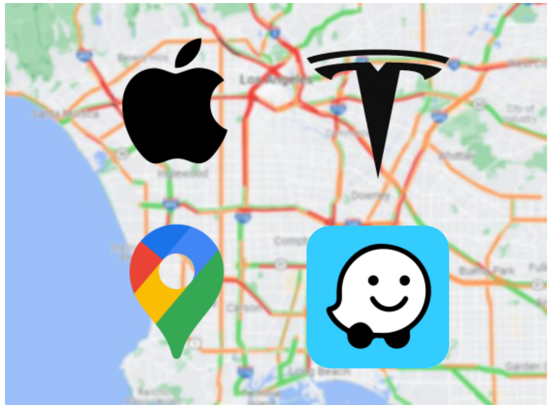

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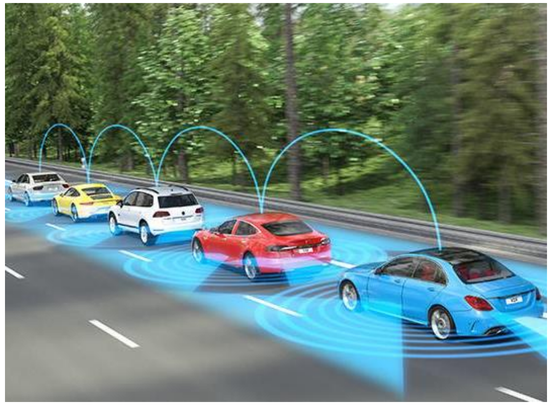

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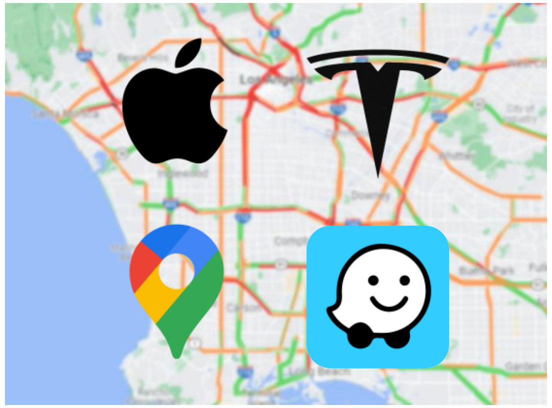

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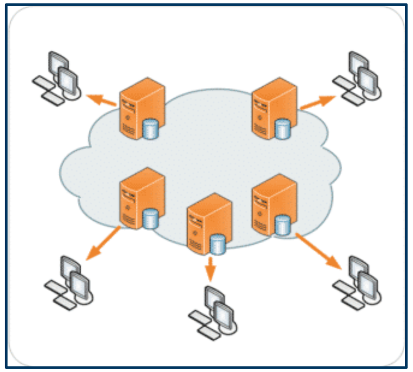

Cloud computing

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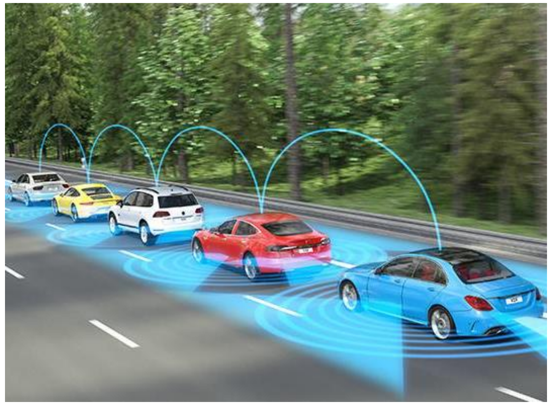

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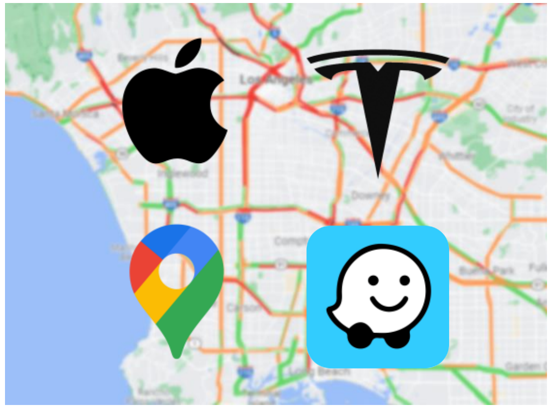

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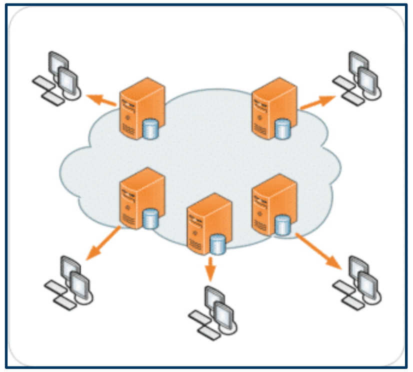

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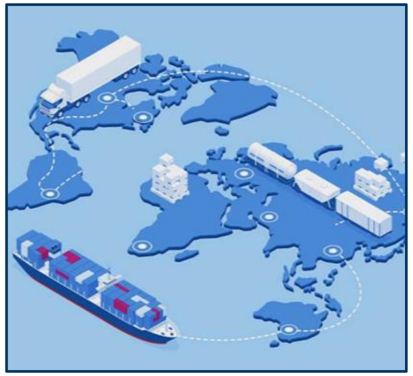

Supply-chain

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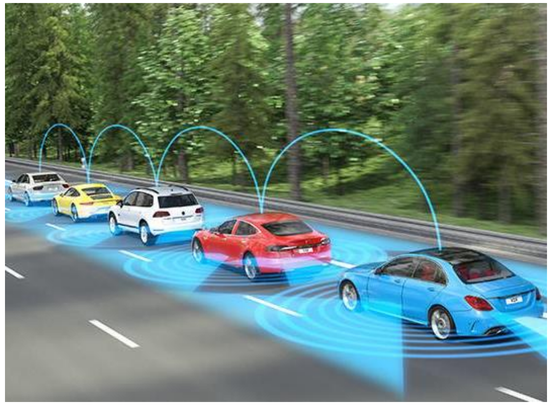

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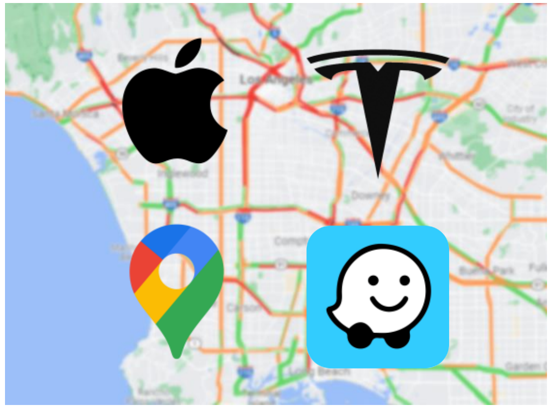

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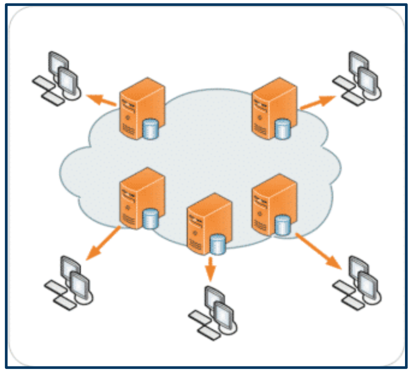

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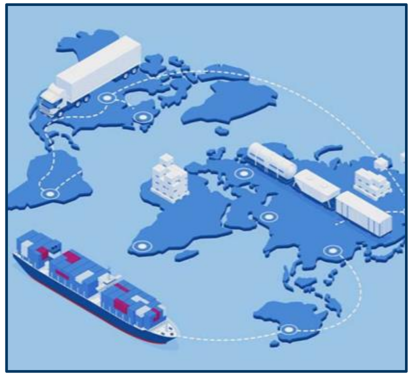

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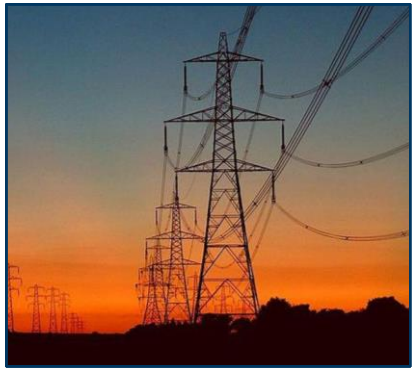

Power Grids

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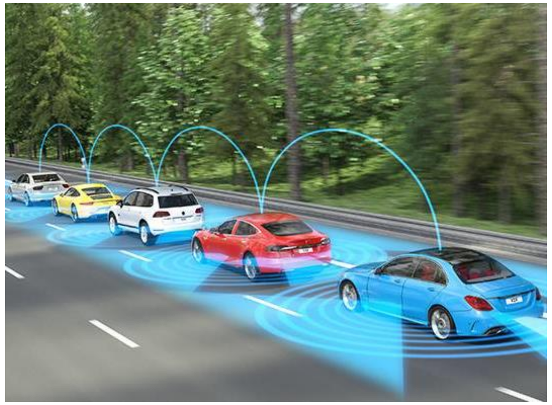
E.g., Autonomous Driving



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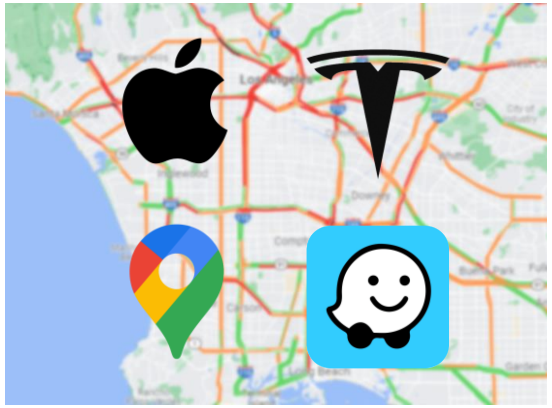

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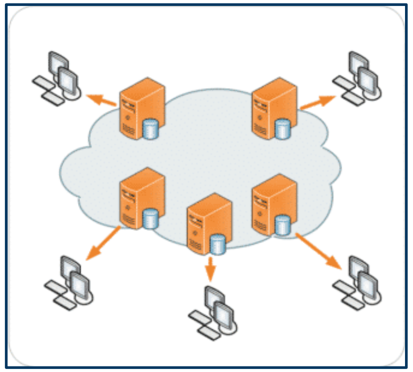

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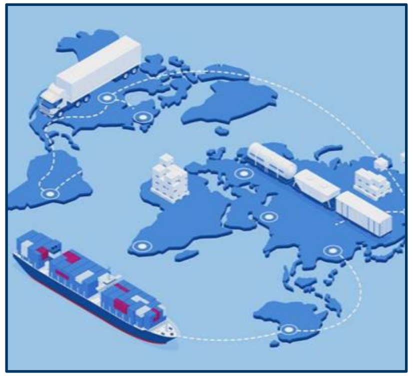

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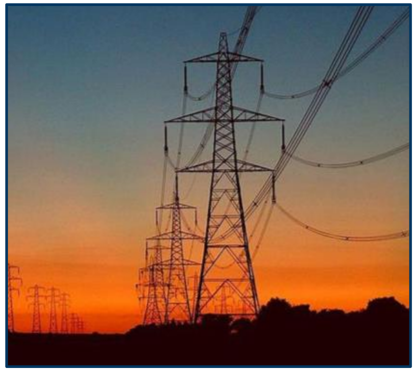

Power Grids

Fleet Robotics

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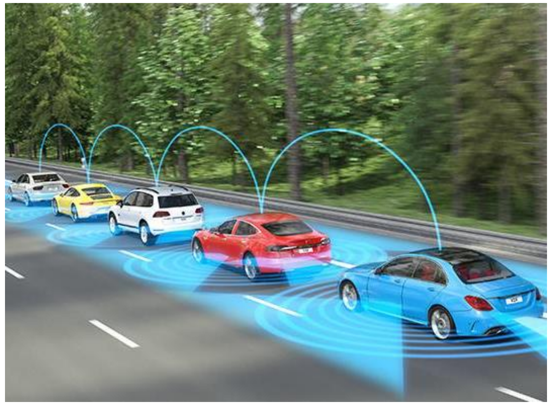

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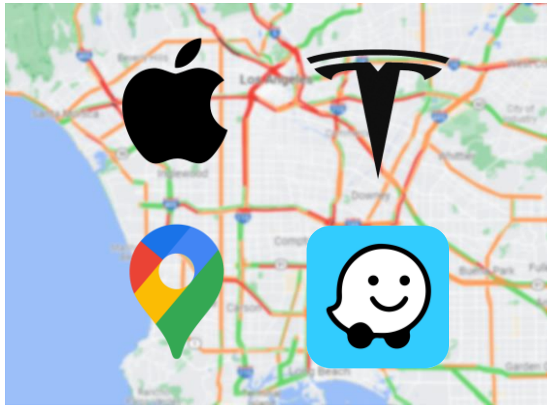

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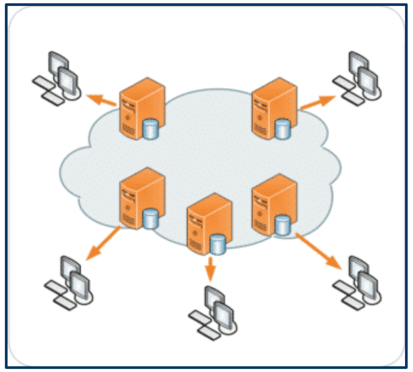

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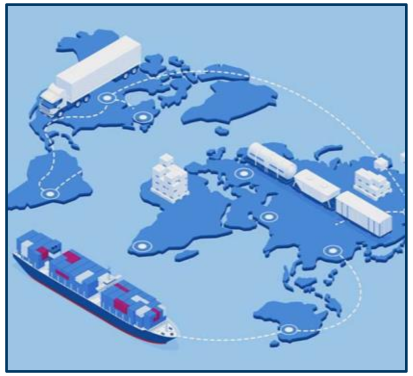

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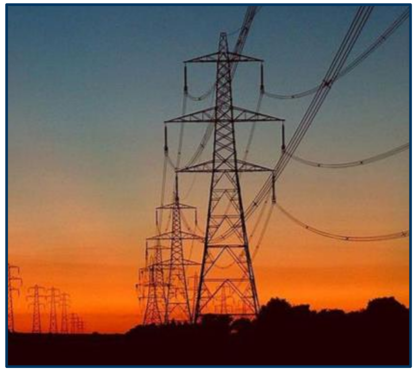

Power Grids

Fleet Robotics

Military Ops.

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The Effects of Information-Communication

Understand the ***benefits*** and ***costs*** of increasing the amount of communication in a distributed system

Benefit: improved system performance, better local decision making

Cost: physical/computational burdens, unexpected behavior can emerge

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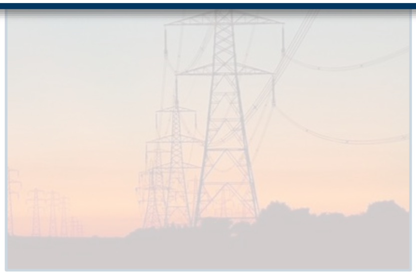

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Unreliable Communicators

Unreliable Information Sharing

Collaboratively exchange information

E.g., Autonomous Driving

Unreliable Information Provisioning

Strategically send out information

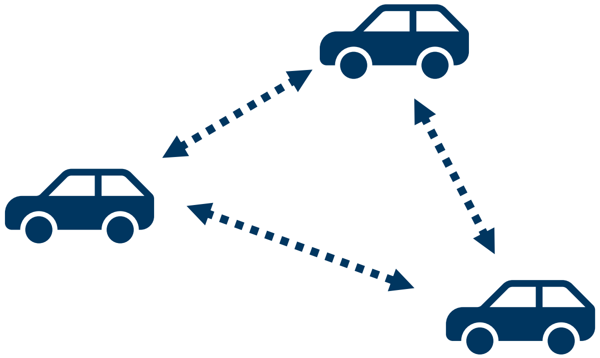
Simon Weckert

My work:

What are the effects of ***unreliable communicators*** and what can we do to mitigate them?

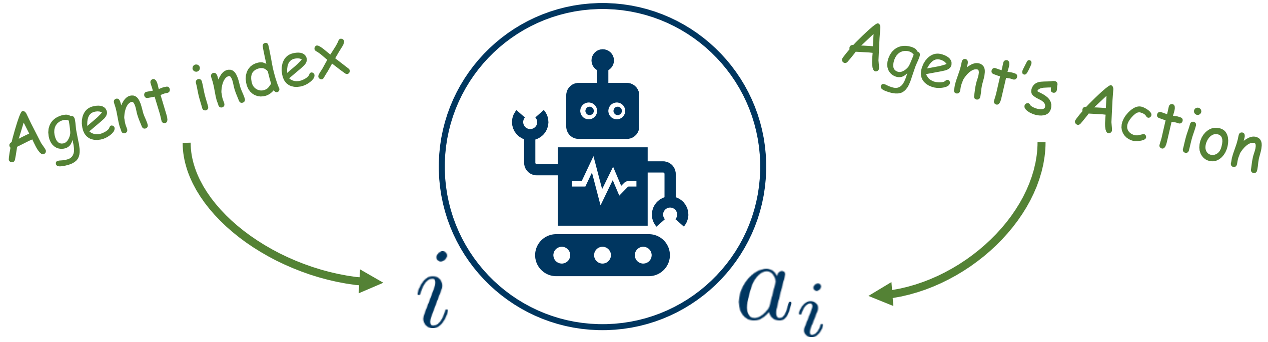
Outline

I. Information Sharing

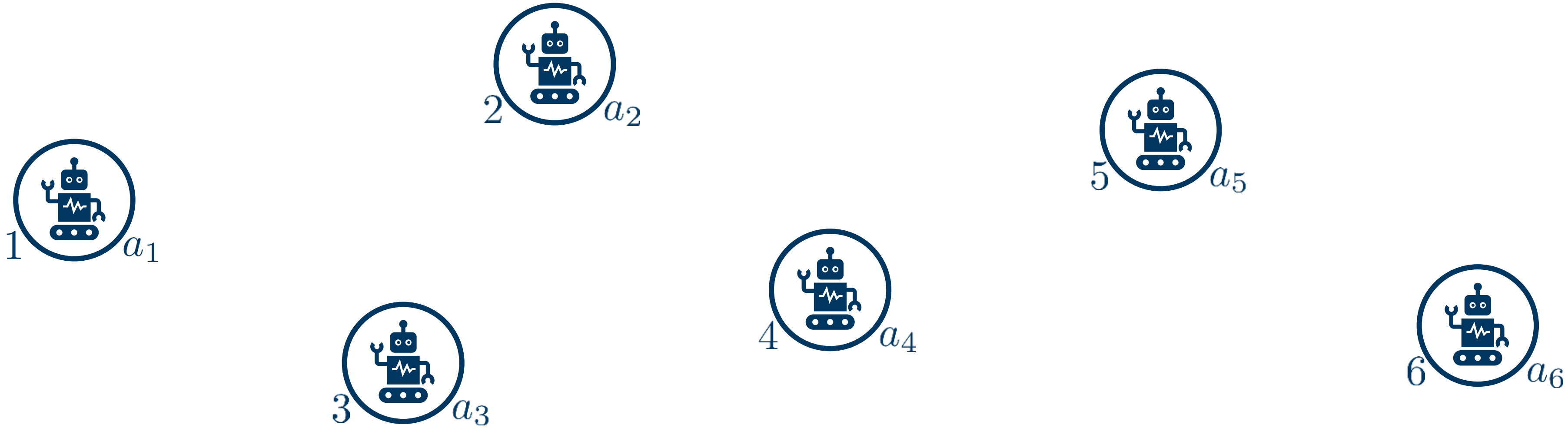


Communication Design in Engineered System

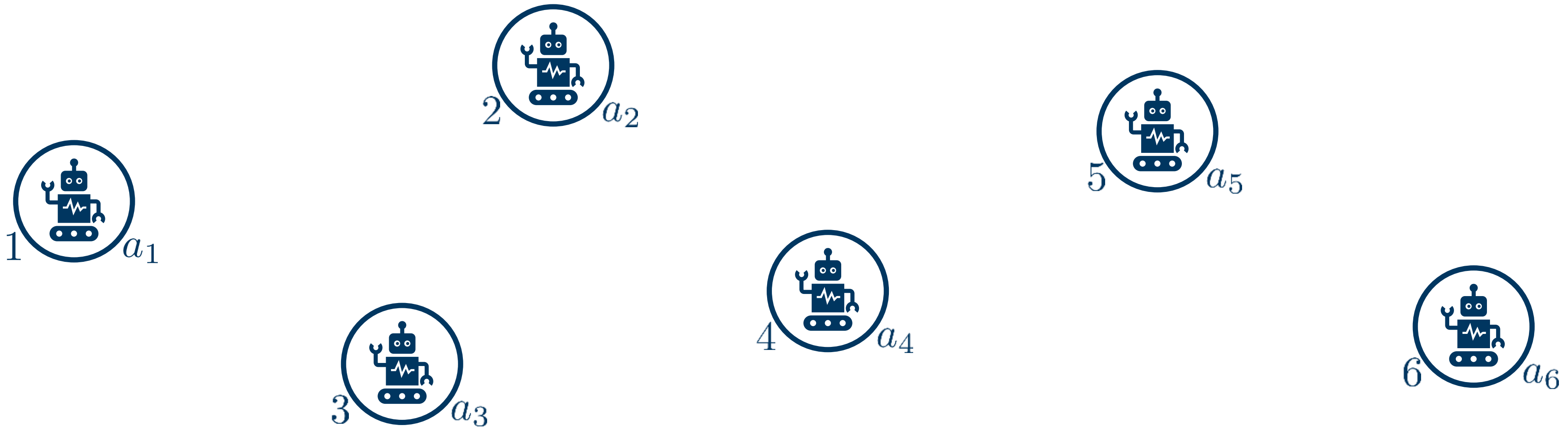
Engineered Agent



Communication Design in Engineered System

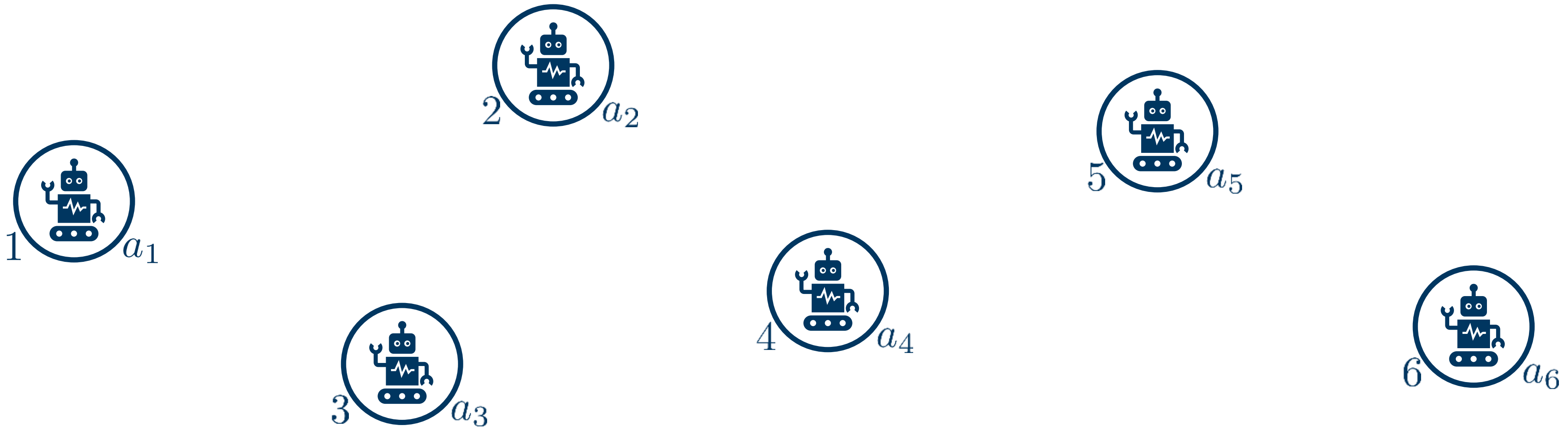


Communication Design in Engineered System



Information Communication $\longrightarrow$ Local Decision a_i $\longrightarrow$ System Behavior $a = (a_1, \ldots, a_n)$

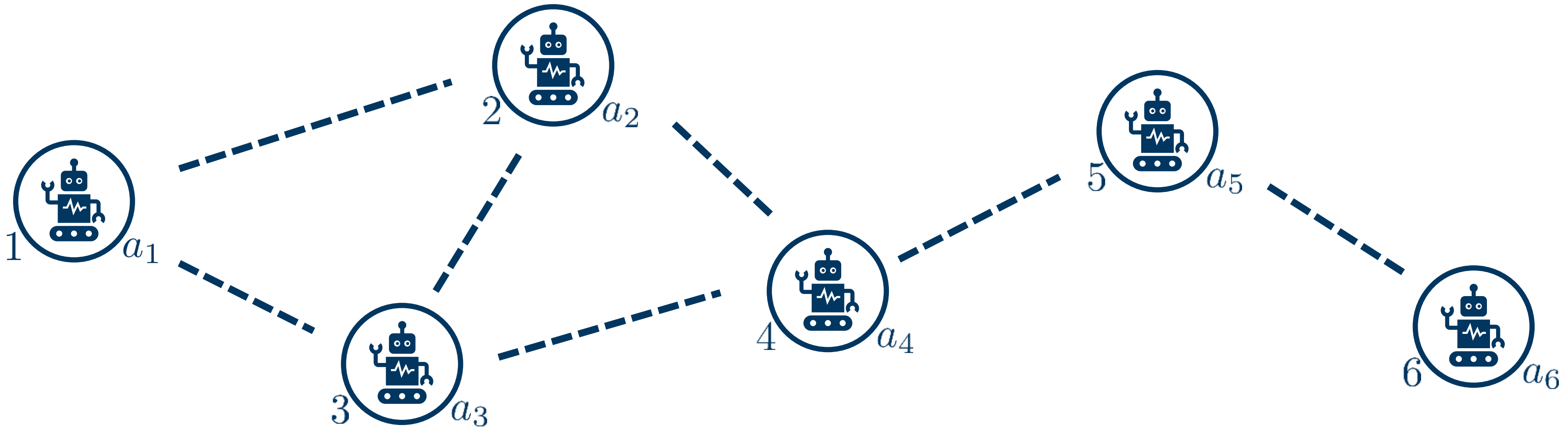
Communication Design in Engineered System



Information Communication → Local Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

How should agents communicate?

Communication Design in Engineered System

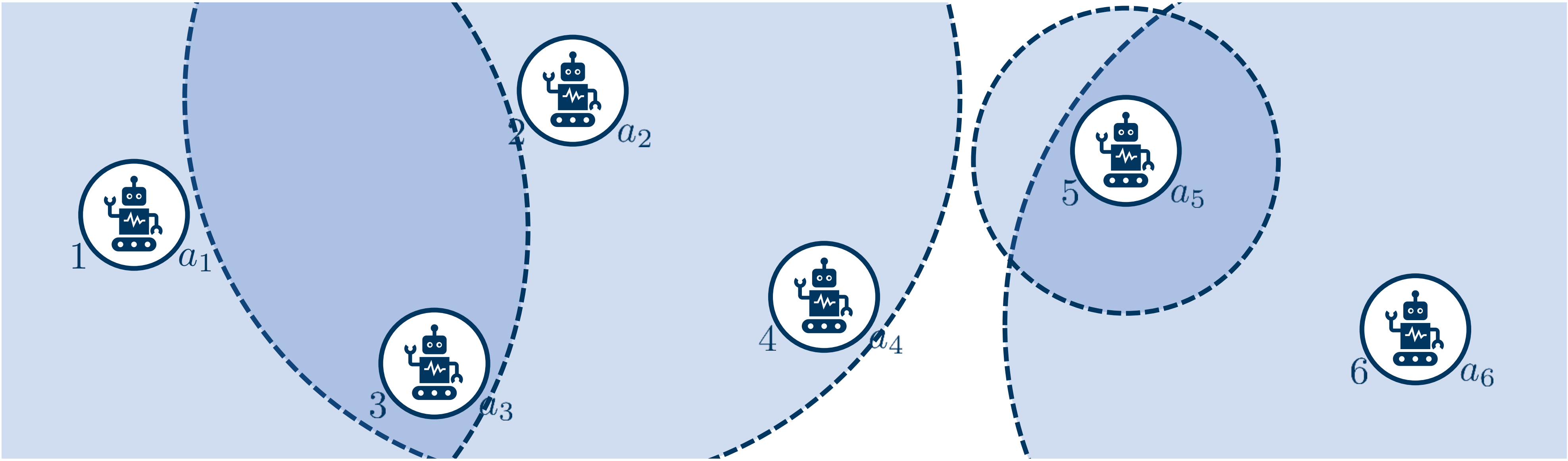


Information Communication → Local Decision a_i → System Behavior $a = (a_1, \dots, a_n)$

How should agents communicate?

- Networked communication?

Communication Design in Engineered System

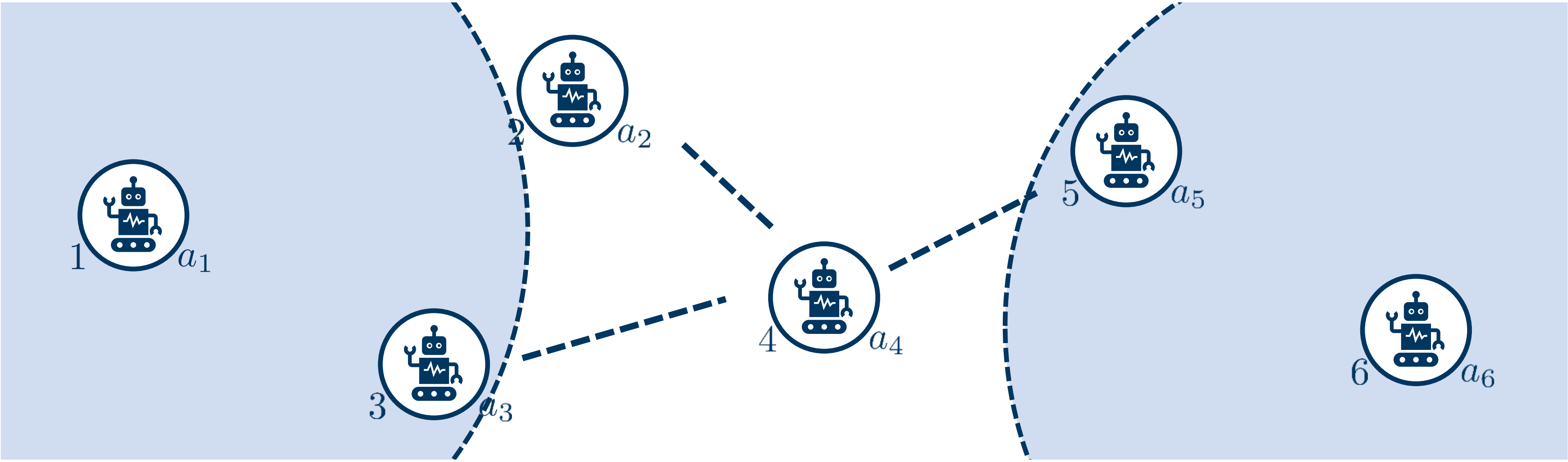


Information Communication → Local Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

How should agents communicate?

- Networked communication?
- Spatially Local communication?

Communication Design in Engineered System

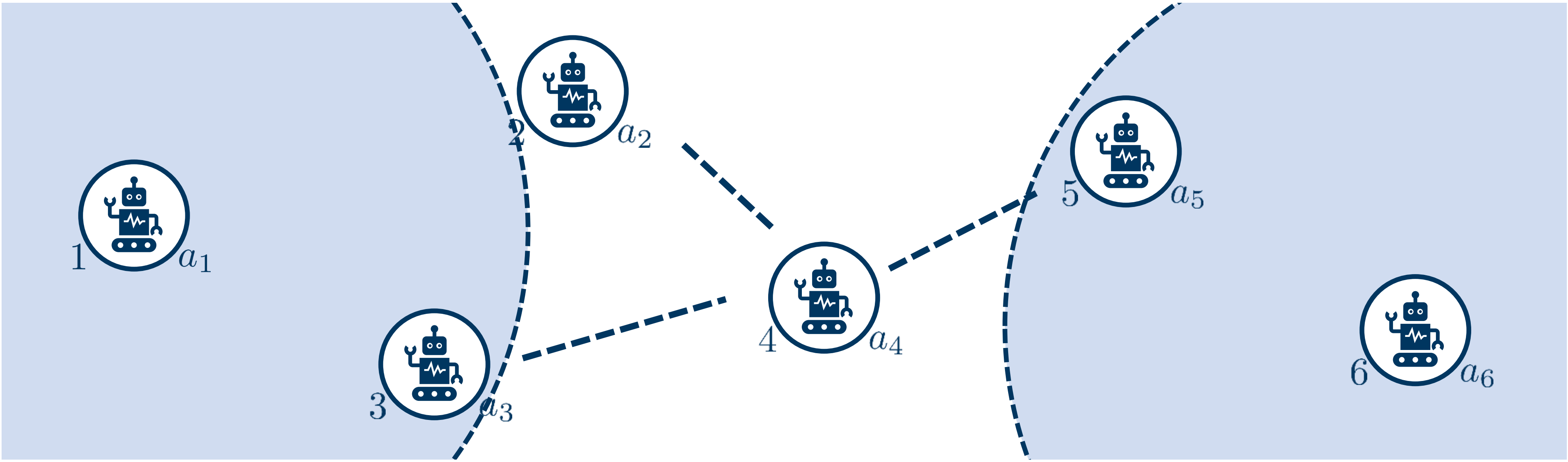


Information Communication → Local Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

How should agents communicate?

- Networked communication?
- Spatially Local communication?
- Pairwise communication?
- Etc.

Communication Design in Engineered System



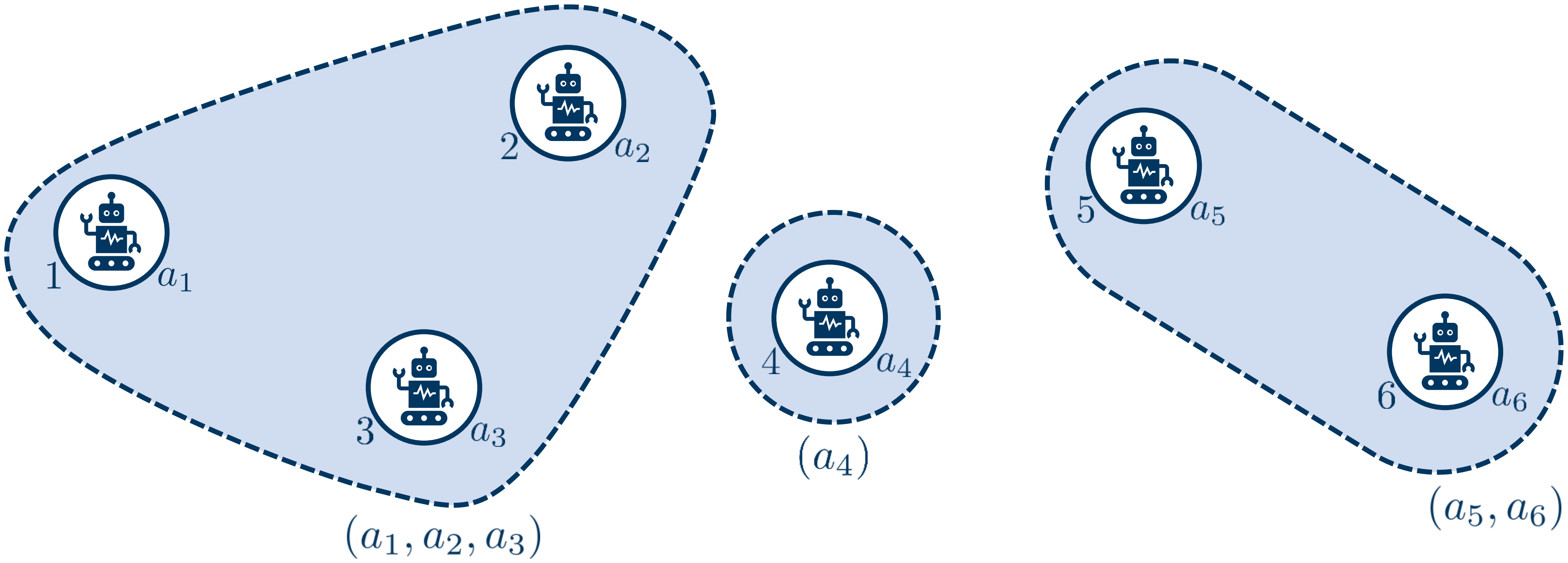
Information Communication → Local Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

How should agents communicate?

- Networked communication?
- Spatially Local communication?
- Pairwise communication?
- Etc.

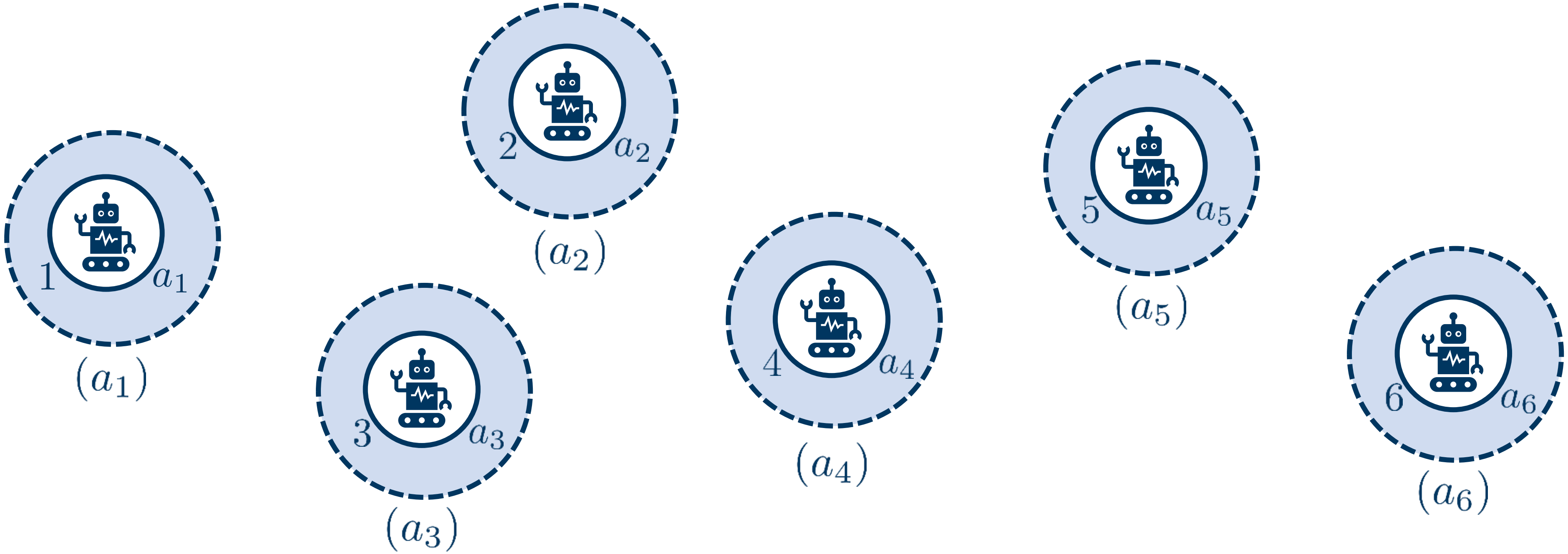
How does communication affect decision-making?

Collaborative Communication & Decision-Making



Collaborative Multi-Agent System: Defined groups of agents can communicate and collaborate in making their decision.

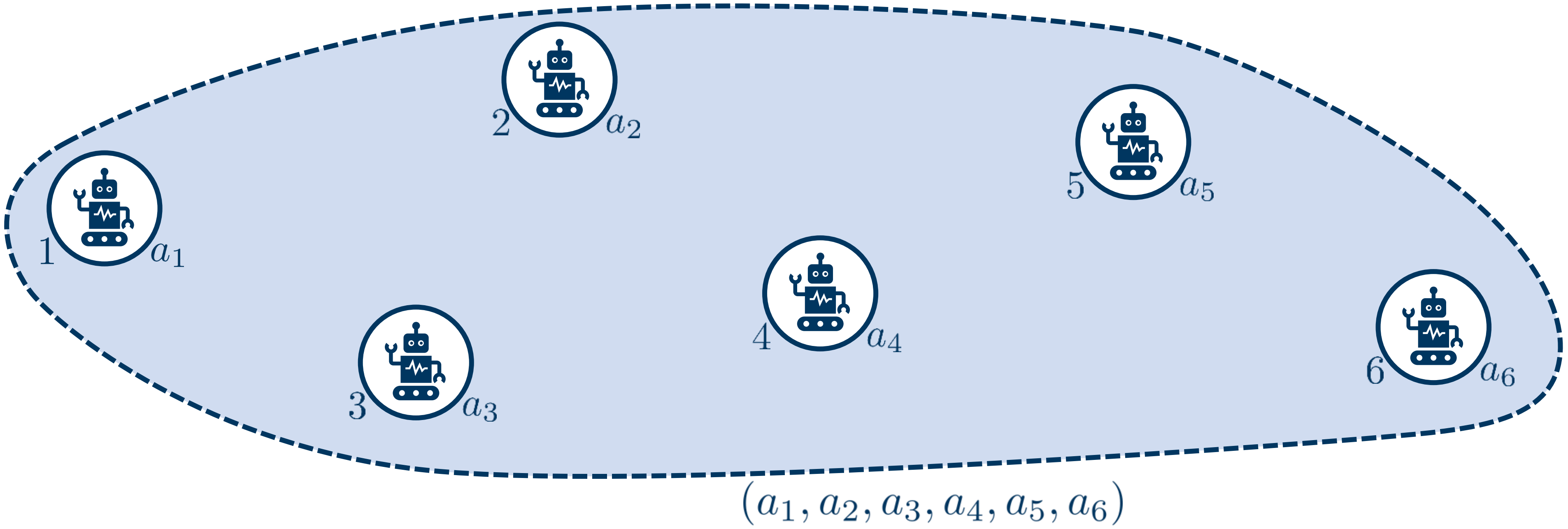
Collaborative Communication & Decision-Making



Collaborative Multi-Agent System: Defined groups of agents can communicate and collaborate in making their decision.

Distributed Decision-making
(Bad performance / low complexity)

Collaborative Communication & Decision-Making

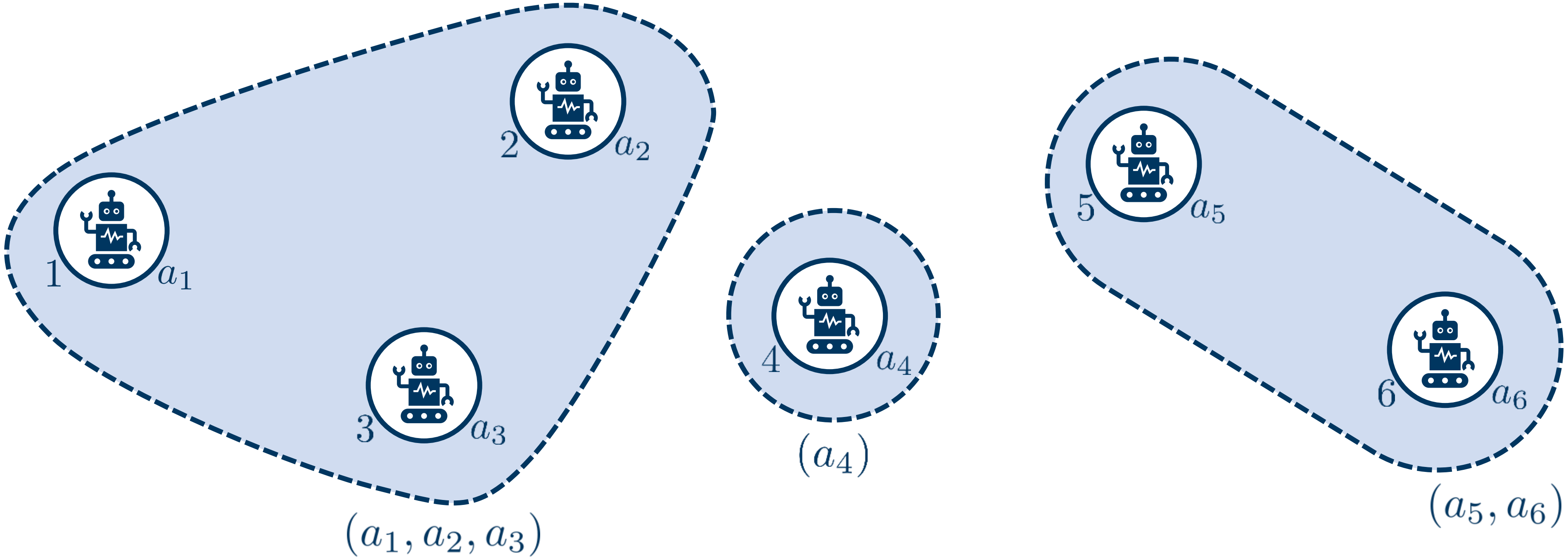


Collaborative Multi-Agent System: Defined groups of agents can communicate and collaborate in making their decision.

Distributed Decision-making
(Bad performance / low complexity)

Centralized Decision-making
(Best performance / high complexity)

Collaborative Communication & Decision-Making



Collaborative Multi-Agent System: Defined groups of agents can communicate and collaborate in making their decision.

Distributed Decision-making (Bad performance / low complexity)

Partially Collaborative Decision-making

Centralized Decision-making (Best performance / high complexity)

Study the ***benefits*** and ***costs*** of collaborative multi-agent systems

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$\max_{a_1,\ldots,a_n} \quad W(a_1,\ldots,a_n)$$

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$\max_{a_1,\ldots,a_n} \quad W(a_1,\ldots,a_n)$$

	Agent 1	Agent 2	Agent 3	$\ldots$	Agent n
Local Decision-Making:	Pick a_1	Pick a_2	Pick a_3		Pick a_n

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$\max_{a_1,\ldots,a_n} \quad W(a_1,\ldots,a_n)$$

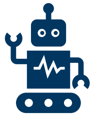
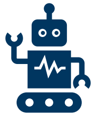
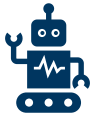
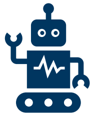
Agent 1   Agent 2   Agent 3   ...   Agent n

Local Decision-Making: $\max_{a_1} \; W(a_1, a_{-1})$ $\max_{a_2} \; W(a_2, a_{-2})$ $\max_{a_3} \; W(a_3, a_{-3})$ $\max_{a_n} \; W(a_n, a_{-n})$

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$\max_{a_1,\ldots,a_n} \quad W(a_1,\ldots,a_n)$$

Agent 1 | Agent 2 | Agent 3 | $\ldots$ | Agent n

Local Decision-Making: $\max_{a_1} W(a_1, a_{-1})$ $\max_{a_2} W(a_2, a_{-2})$ $\max_{a_3} W(a_3, a_{-3})$ $\max_{a_n} W(a_n, a_{-n})$

Dynamics: $$a(t+1) = \texttt{update}\,(a(t))$$

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$\max_{a_1,\ldots,a_n} \quad W(a_1,\ldots,a_n)$$

Agent 1   Agent 2   Agent 3 $\ldots$ Agent n

Local Decision-Making: $\max_{a_1} W(a_1, a_{-1})$ $\max_{a_2} W(a_2, a_{-2})$ $\max_{a_3} W(a_3, a_{-3})$ $\max_{a_n} W(a_n, a_{-n})$

Dynamics: $$a(t+1) = \texttt{update}\,(a(t))$$

Emergent Behavior: $\boxed{\textbf{Nash Equilibrium } (a^{\mathrm{NE}}): \quad W(a^{\mathrm{NE}}) \geq W(a_i', a_{-i}^{\mathrm{NE}}) \quad \forall a_i' \in \mathcal{A}_i,\ i \in \{1,\ldots,n\}}$

Distributed Decision-Making in Engineered Systems

Game Theoretic approach to Multi-Agent Control

System Objective: $$W^\star := \max_{a_1,\ldots,a_n} W(a_1,\ldots,a_n)$$

Agent 1 | Agent 2 | Agent 3 | … | Agent n

Local Decision-Making: $\max_{a_1} W(a_1, a_{-1})$ $\quad \max_{a_2} W(a_2, a_{-2})$ $\quad \max_{a_3} W(a_3, a_{-3})$ $\quad \max_{a_n} W(a_n, a_{-n})$

Dynamics: $$a(t+1) = \texttt{update}\,(a(t))$$

Emergent Behavior: $\boxed{\textbf{Nash Equilibrium } (a^{\mathrm{NE}}):\quad W(a^{\mathrm{NE}}) \geq W(a_i', a_{-i}^{\mathrm{NE}}) \quad \forall a_i' \in \mathcal{A}_i,\; i \in \{1,\ldots,n\}}$

System Performance: $$\texttt{Eff} = \min_{a^{\mathrm{NE}} \in \mathrm{NE}} \frac{W(a^{\mathrm{NE}})}{W^\star} \leq 1$$

(Price of Anarchy)

Focus of Existing Research

Dynamics

Reaching Nash Equilibria

Convergence Rate

- *Uncoupled dynamics do not lead to Nash equilibrium.* American Economic Review. Hart S, Mas-Colell A. 2003
- *The complexity of computing a Nash equilibrium.* SIAM Journal on Computing, Daskalakis C, Goldberg PW, Papadimitriou CH. 2009.

Asynchrony

- *Nash equilibrium seeking in noncooperative games.* IEEE Transactions on Automatic Control. Frihauf P, Krstic M, Basar T. 2011.
- *Learning efficient Nash equilibria in distributed systems.* Games and Economic behavior. Pradelski BS, Young HP. 2012.

Noise and Perturbations

- *Learning with Bandit Feedback in Potential Games.* Advances in Neural Information Processing Systems. Heliou A, Cohen J, Mertikopoulos P. 2017.
- *Learning in Games: Robustness of Fast Convergence.* Advances in Neural Information Processing Systems. Foster D, Li Z, Lykouris T, Sridharan K, Tardos E. 2016.

Performance

Efficiency of Nash Equilibria

Quantify the Price of Anarchy

- *Worst-case equilibria.* Computer science review. Koutsoupias E, Papadimitriou C. 2009.
- *Nash equilibria in competitive societies, with applications to facility location, traffic routing and auctions.* Symposium on Foundations of CS. Vetta A. 2002
- *The price of anarchy of finite congestion games.* In Proceedings of the thirty-seventh annual ACM symposium on Theory of computing. Christodoulou G, Koutsoupias E. 2005.
- *Intrinsic robustness of the price of anarchy.* Journal of the ACM (JACM). Roughgarden T. 2015.

Optimize the Price of Anarchy

- *Covering games: Approximation through non-cooperation.* In International Workshop on Internet and Network Economics. Gairing M. 2009.
- *A unifying tool for bounding the quality of non-cooperative solutions in weighted congestion games.* Theory of Computing Systems. Bilò V. 2018.
- *Utility design for distributed resource allocation—part I: Characterizing and optimizing the exact price of anarchy.* IEEE Transactions on Automatic Control. Paccagnan D, Chandan R, Marden JR. 2019.

Challenge existing ***informational*** and ***communication*** assumptions of Nash equilibria and associated efficiency guarantees

Collaborative Communication

Agent 1 $\qquad$ Agent 2 $\qquad$ Agent 3 $\qquad \cdots \qquad$ Agent n

$$\max_{a_1} W(a_1, a_{\text{-}1}) \qquad \max_{a_2} W(a_2, a_{\text{-}2}) \qquad \max_{a_3} W(a_3, a_{\text{-}3}) \qquad \max_{a_n} W(a_n, a_{\text{-}n})$$

No communication: unilateral deviations

Nash Equilibrium (a^{NE}):

$$W(a^{\mathrm{NE}}) \geq W(a_i', a_{\text{-}i}^{\mathrm{NE}})$$
$$\forall a_i' \in \mathcal{A}_i,$$
$$i \in N = \{1, \ldots, n\}$$

Collaborative Communication

Agent 1	Agent 2	Agent 3	$\cdots$	Agent n
$\max_{a_1} W(a_1, a_{\text{-}1})$	$\max_{a_2} W(a_2, a_{\text{-}2})$	$\max_{a_3} W(a_3, a_{\text{-}3})$		$\max_{a_n} W(a_n, a_{\text{-}n})$

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Nash Equilibrium (a^{NE}):

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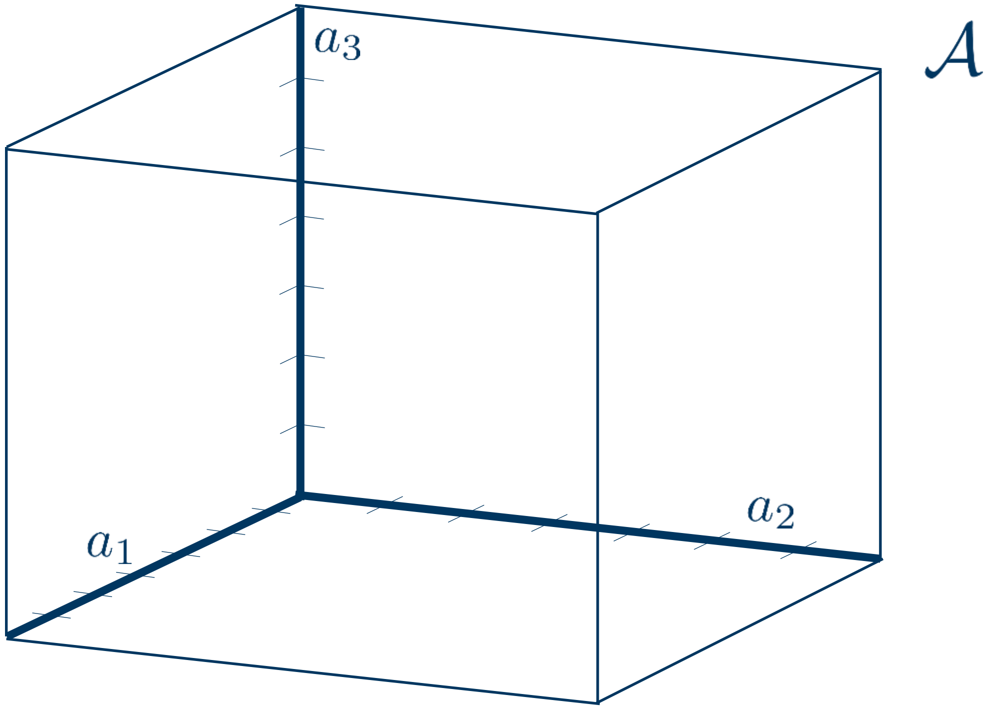
E.g.,



Collaborative Communication

Agent 1	Agent 2	Agent 3	…	Agent n
$\max\limits_{a_1} W(a_1, a_{\text{-}1})$	$\max\limits_{a_2} W(a_2, a_{\text{-}2})$	$\max\limits_{a_3} W(a_3, a_{\text{-}3})$		$\max\limits_{a_n} W(a_n, a_{\text{-}n})$

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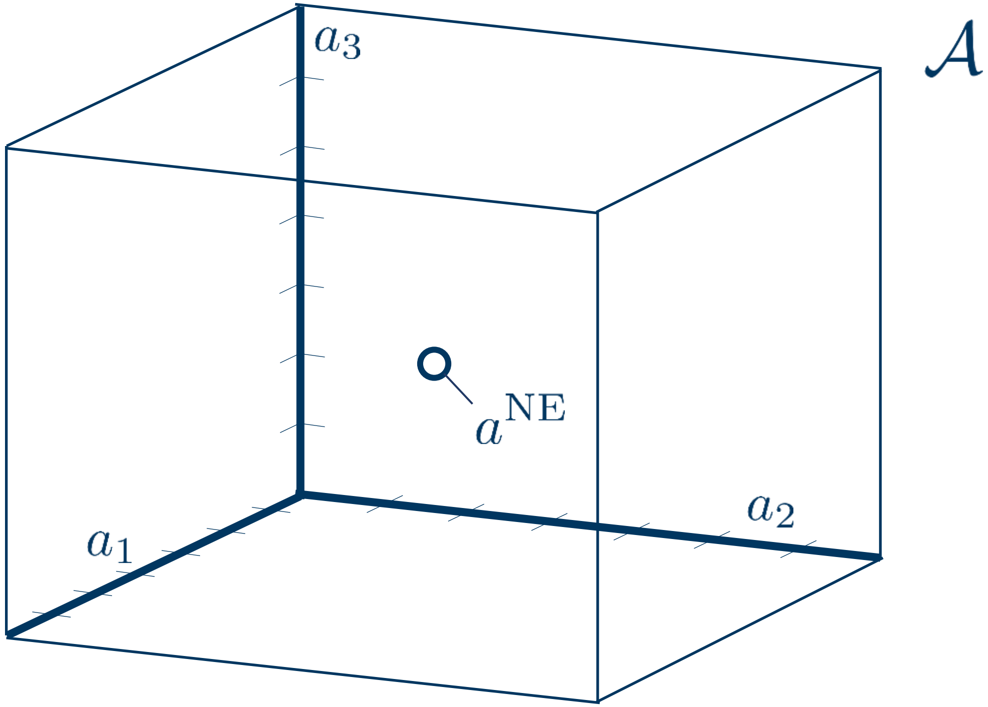

Collaborative Communication

Agent 1	Agent 2	Agent 3	$\cdots$	Agent n
$\max_{a_1} W(a_1, a_{\text{-}1})$	$\max_{a_2} W(a_2, a_{\text{-}2})$	$\max_{a_3} W(a_3, a_{\text{-}3})$		$\max_{a_n} W(a_n, a_{\text{-}n})$

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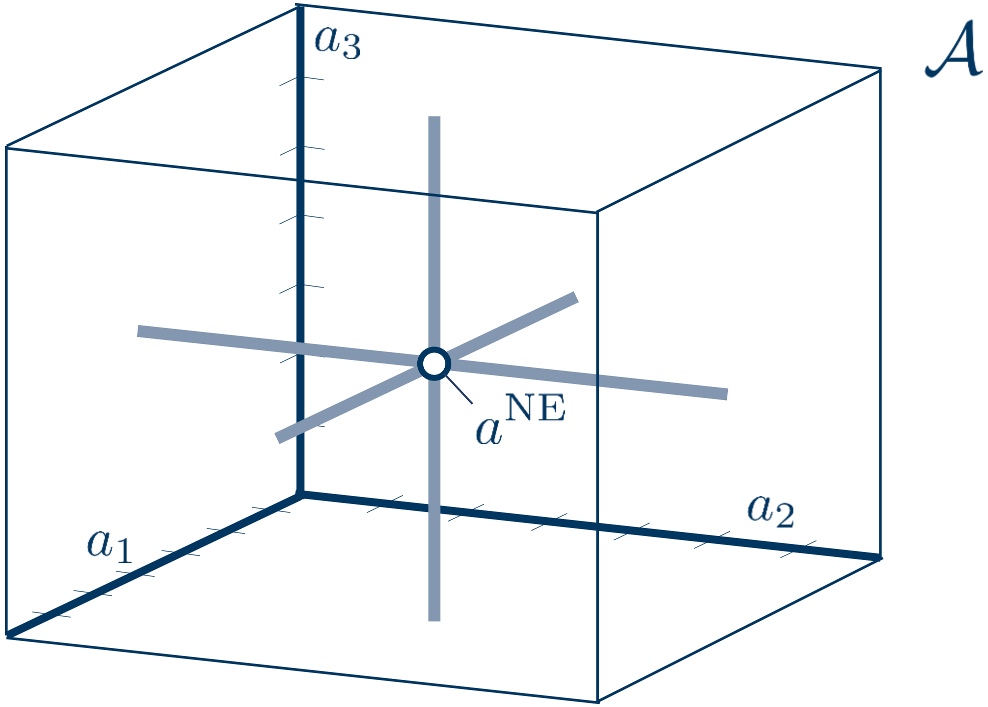
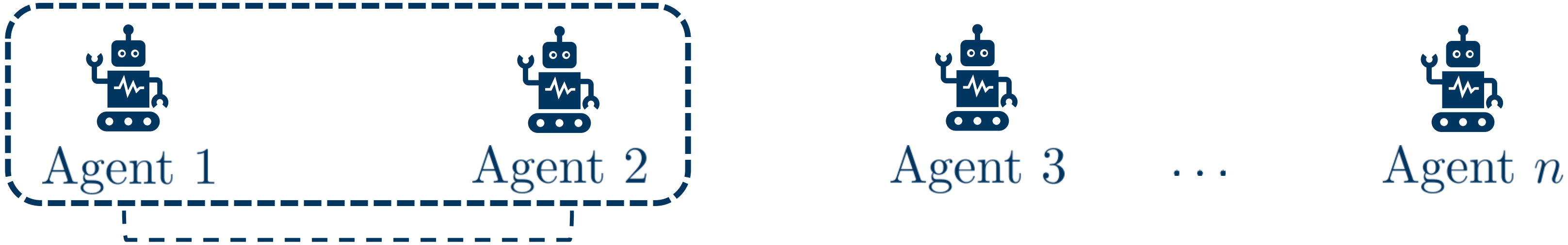


Collaborative Communication



$$\max_{a_1, a_2} W(a_1, a_2, a_{-12})$$

Nash Equilibrium (a^{NE}):

$$W(a^{\mathrm{NE}}) \geq W(a_i', a_{-i}^{\mathrm{NE}})$$
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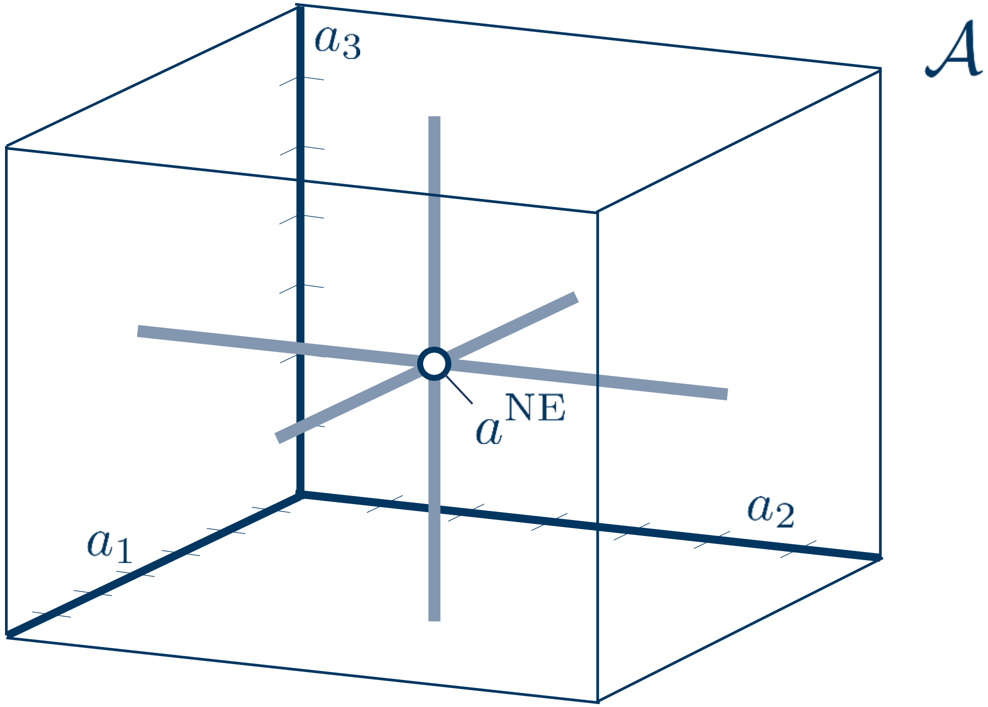
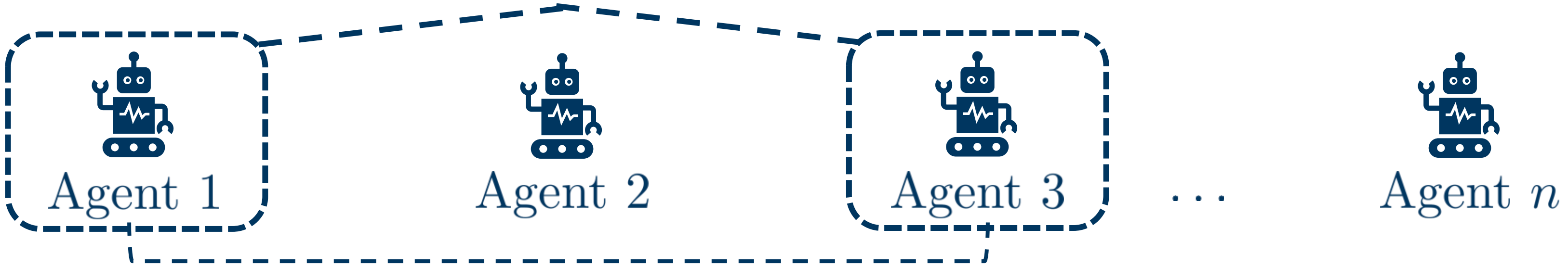


Collaborative Communication



$$\max_{a_1, a_3} W(a_1, a_3, a_{\text{-}13})$$

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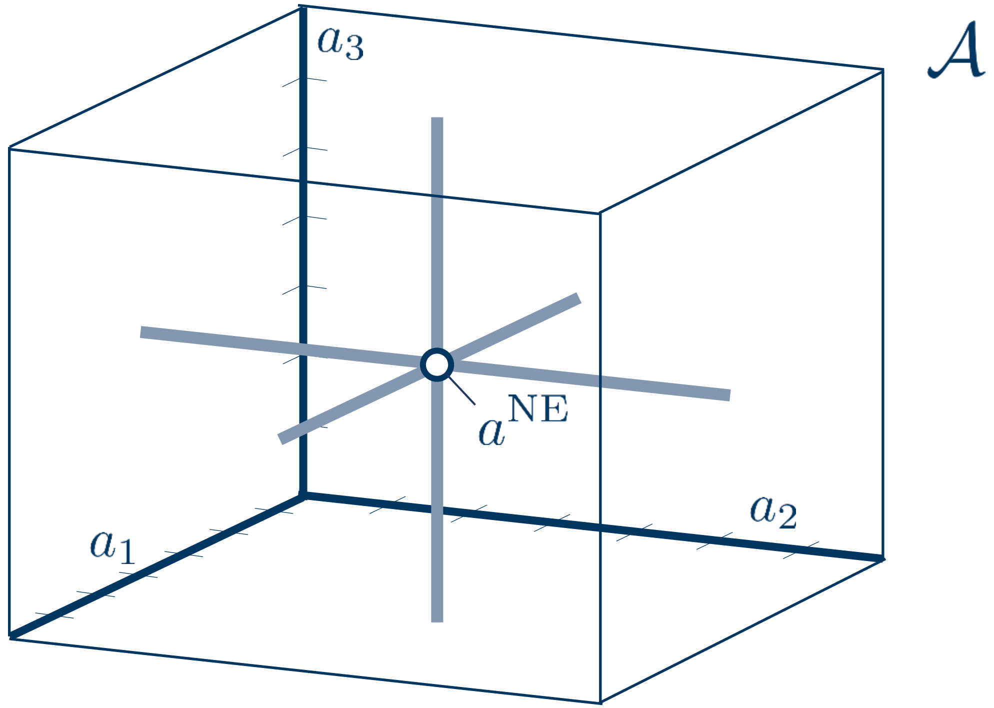
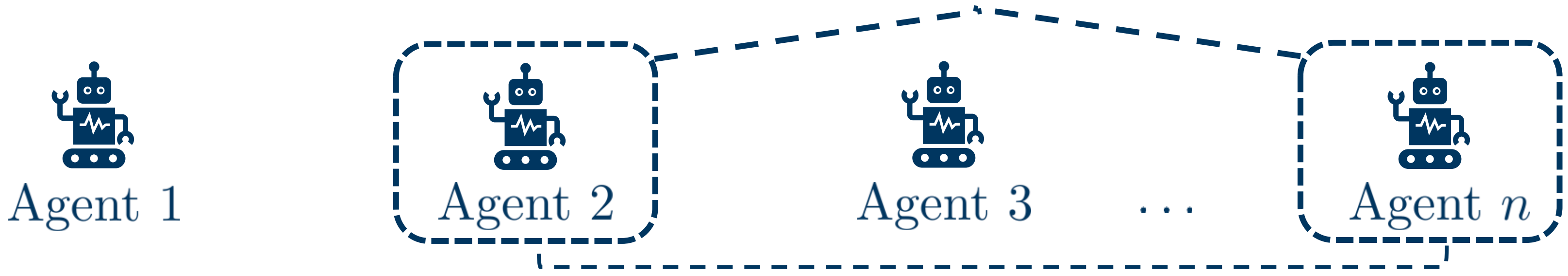


Collaborative Communication



$$\max_{a_2, a_n} W(a_2, a_n, a_{\text{-}2n})$$

Nash Equilibrium (a^{NE}):

$$W(a^{\mathrm{NE}}) \geq W(a'_i,\, a^{\mathrm{NE}}_{\text{-}i})$$
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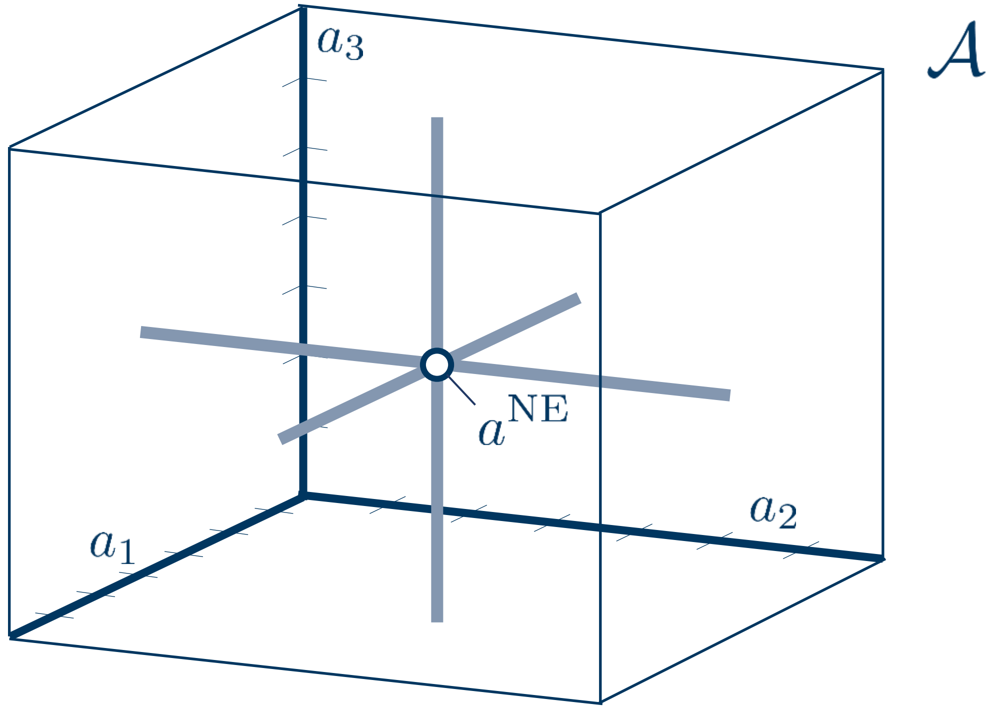
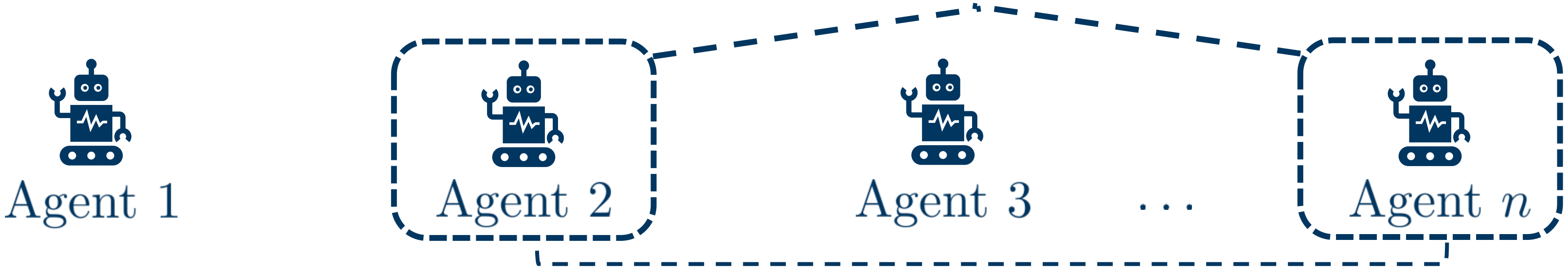


Collaborative Communication



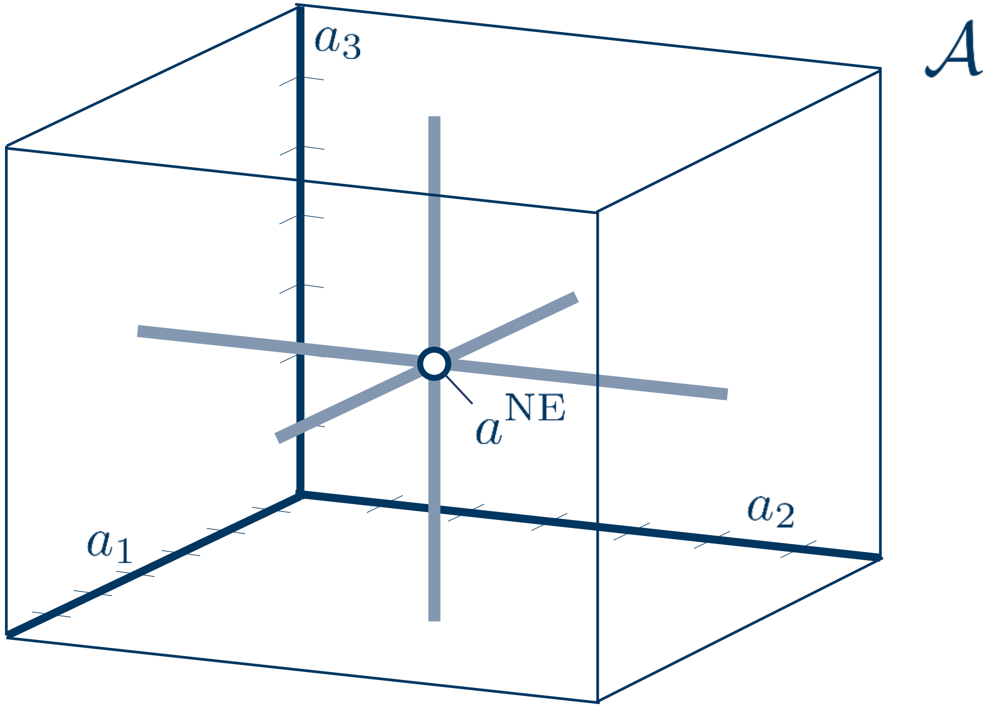
$$\max_{a_2, a_n} W(a_2, a_n, a_{\text{-}2n})$$

Pair-wise communication: bilateral deviations

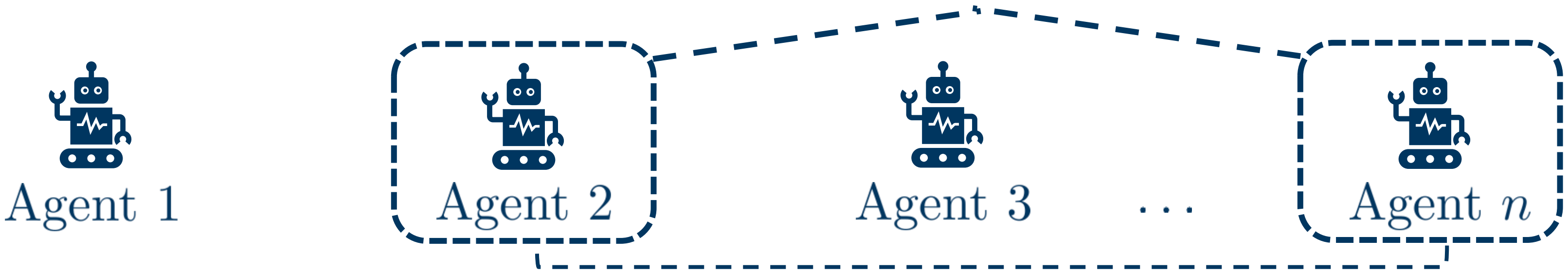
2-Strong Nash Equilibrium (a^{2SNE}):

$$W(a^{\text{2SNE}}) \geq W(a'_i,\, a'_j, a^{\text{2SNE}}_{\text{-}ij})$$
$$\forall a'_i \in \mathcal{A}_i,\ a'_j \in \mathcal{A}_j,$$
$$i, j \in N$$

E.g.,



Collaborative Communication



$$\max_{a_2, a_n} \; W(a_2, a_n, a_{\text{-}2n})$$

Pair-wise communication: bilateral deviations

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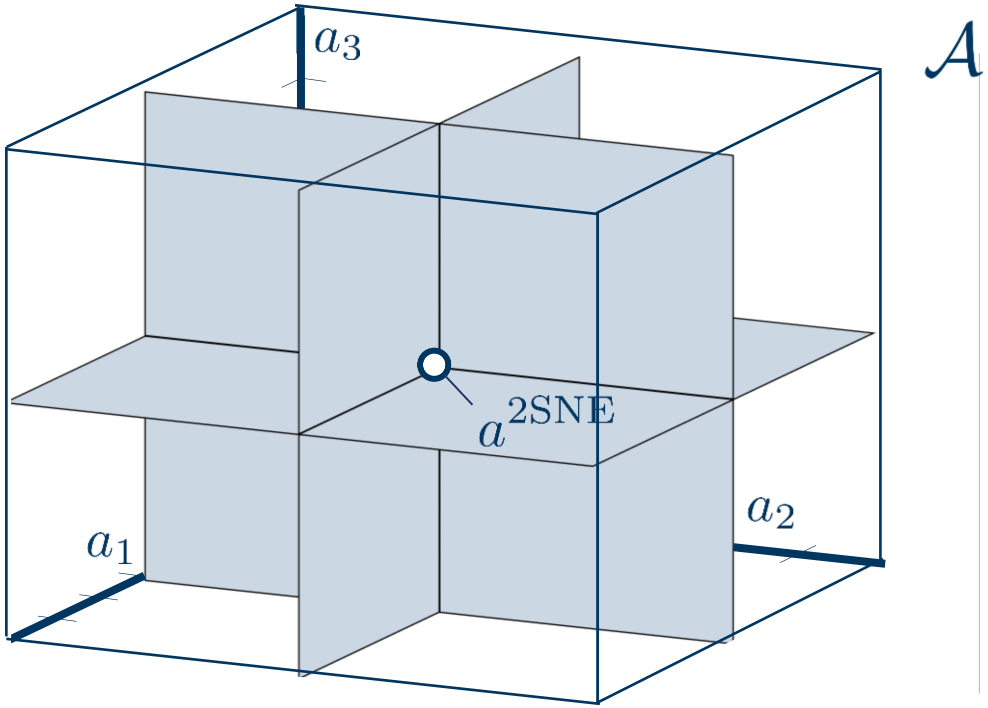

Collaborative Communication

Agent 1 Agent 2 Agent 3 $\cdots$ Agent n

$$\max_{a_\Gamma} \; W(a_\Gamma, a_{\text{-}\Gamma}), \quad \text{where } \Gamma \subseteq N$$

Multi-agent communication: group deviations

2-Strong Nash Equilibrium (a^{2SNE}):

$$W(a^{\text{2SNE}}) \geq W(a'_i,\, a'_j, a^{\text{2SNE}}_{\text{-}ij})$$

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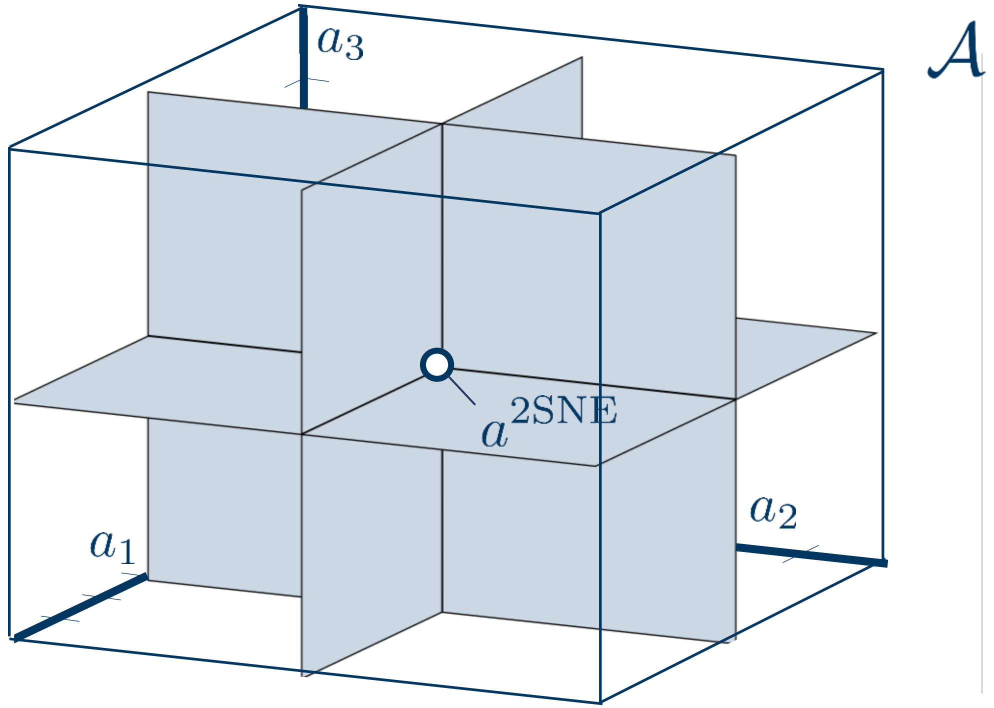


Collaborative Communication

Agent 1   Agent 2   Agent 3 $\cdots$ Agent n

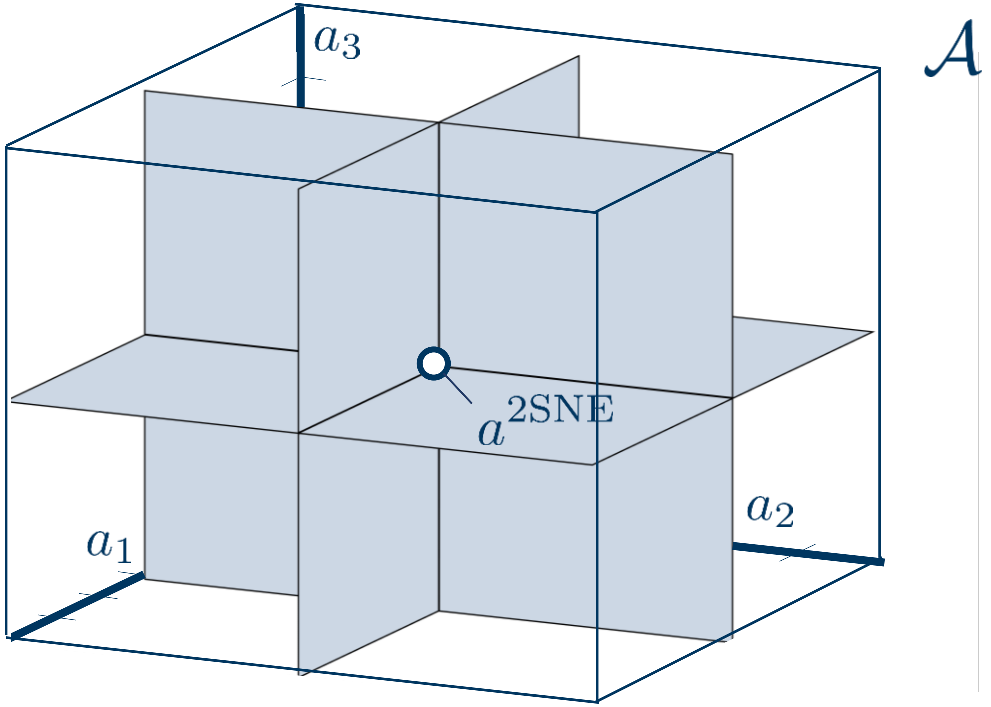
$$\max_{a_\Gamma} W(a_\Gamma, a_{\text{-}\Gamma}), \quad \text{where } \Gamma \subseteq N$$

Multi-agent communication: group deviations

k-Strong Nash Equilibrium $(a^{k\mathrm{SNE}})$:

$$W(a^{k\mathrm{SNE}}) \geq W(a'_\Gamma,\, a^{k\mathrm{SNE}}_{\text{-}\Gamma})$$
$$\forall a'_\Gamma \in \mathcal{A}_\Gamma = \prod_{i\in\Gamma} \mathcal{A}_i,$$
$$\Gamma \in \{Z \subseteq N : |Z| \leq k\}$$

E.g.,



Collaborative Communication

Agent 1 Agent 2 Agent 3 $\cdots$ Agent n

$$\max_{a_\Gamma} W(a_\Gamma, a_{\text{-}\Gamma}), \quad \text{where } \Gamma \subseteq N$$

Multi-agent communication: group deviations

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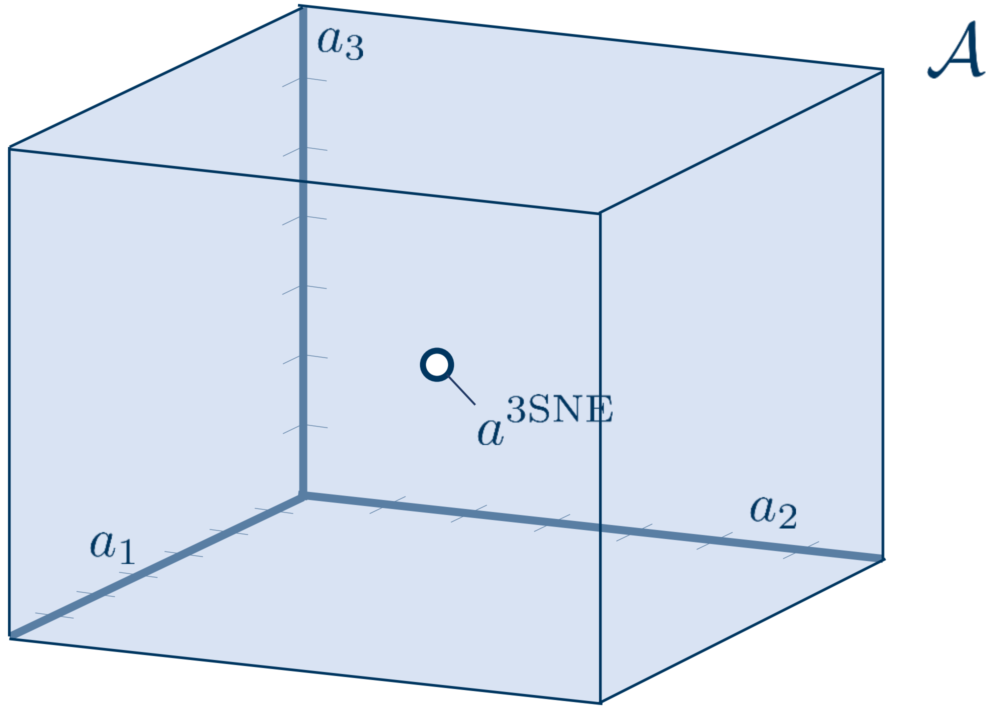

Collaborative Communication

Agent 1   Agent 2   Agent 3 $\cdots$ Agent n

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Multi-agent communication: group deviations

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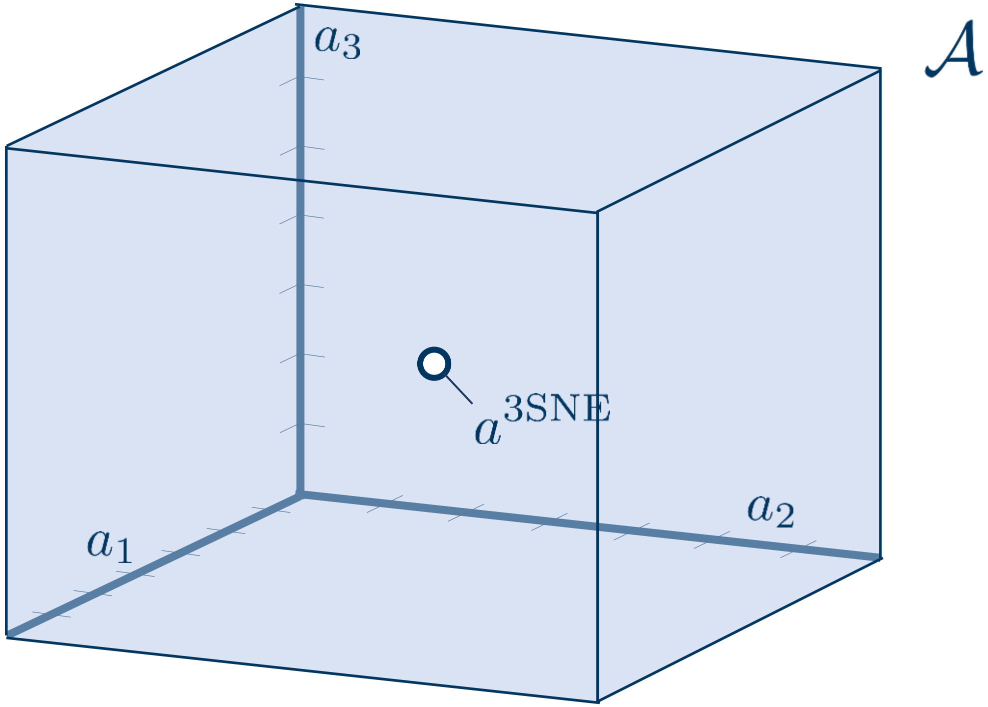


Use communication to ***improve efficiency*** and bridge gap between ***centralized*** and ***decentralized*** performance

k – Strong Nash Equilibria

In General:

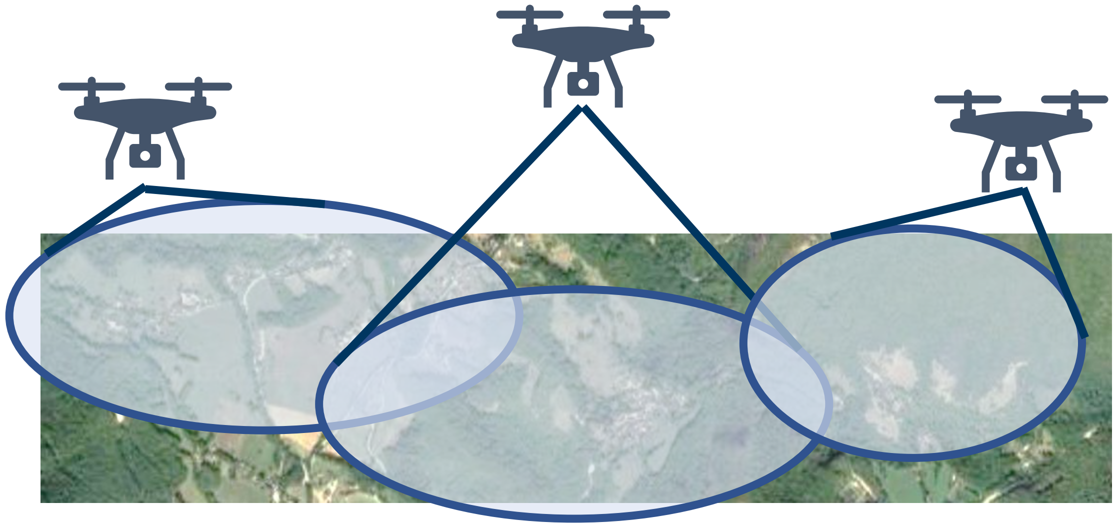
- Typically discussed in cooperative/cost-sharing games
- ***Need not exist*** (in general games)
- No guarantee of efficiency improvement (when such an equilibrium exists)

In Our Work:

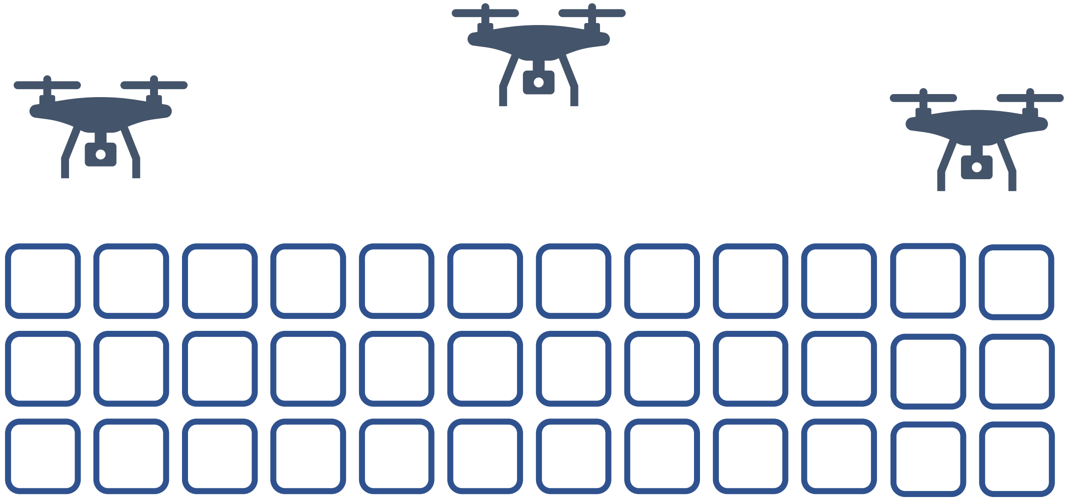
- Group of players collaborate to improve global (**common interest**) objective
- Existence guaranteed
- Optimal solution is a k-SNE
- Finite convergence time

Focus: 1. How does ***efficiency*** improve with communication (k)?
2. What additional ***complexity*** is incurred?

Resource Allocation Problems



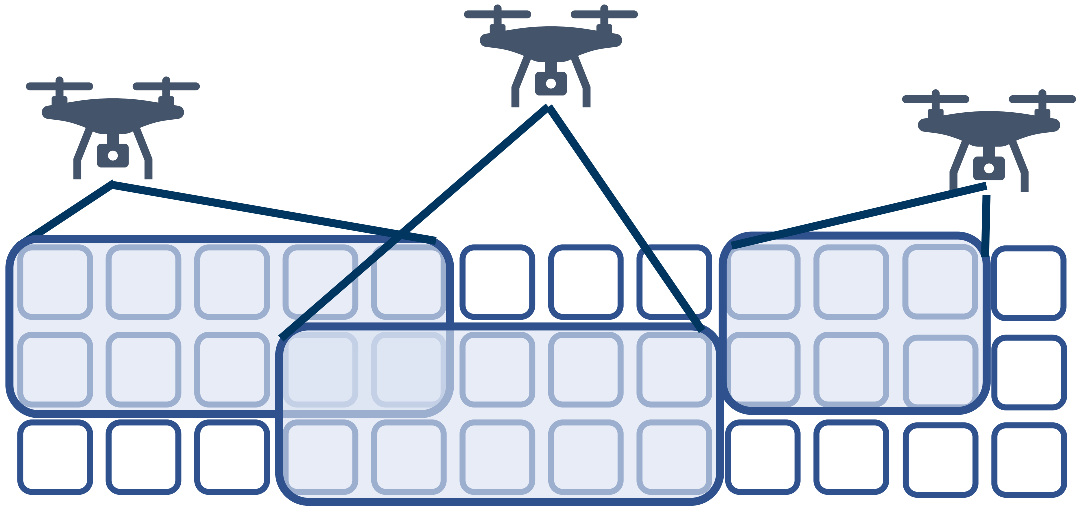
Resource Allocation Problems



Resources: $r \in \mathcal{R} = \{1, \ldots, R\}$

Agents: $i \in N = \{1, \ldots, n\}$

Resource Allocation Problems



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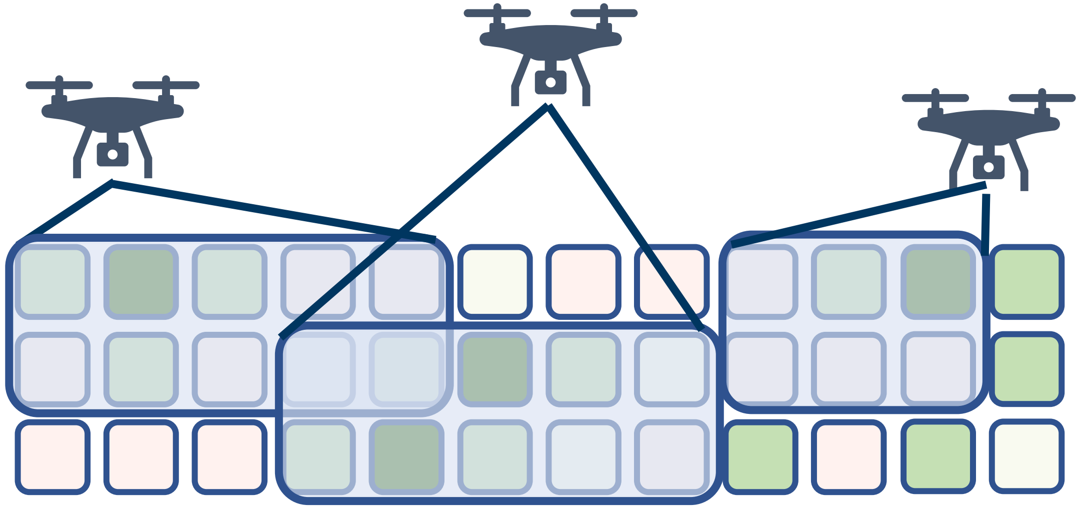
Resource Allocation Problems



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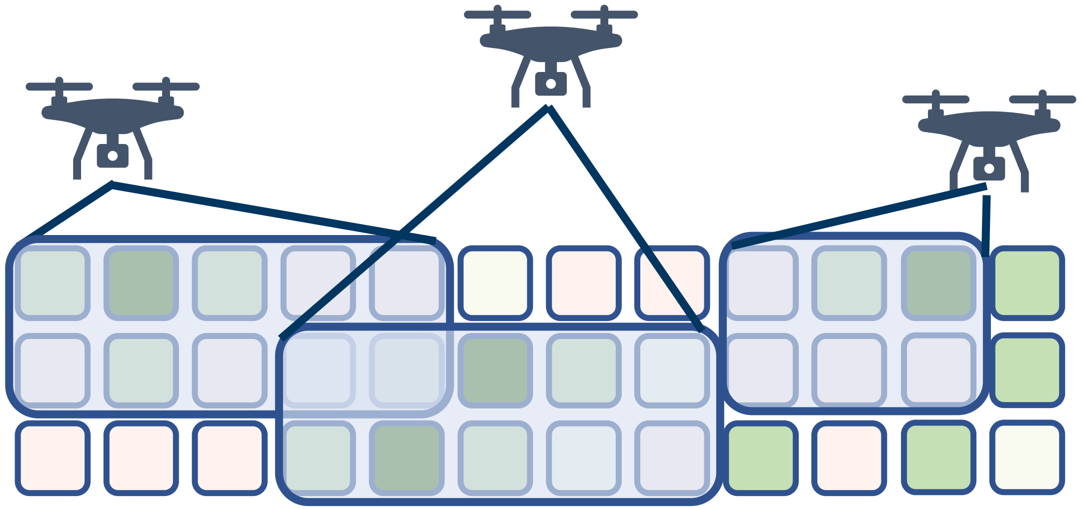
Agents: $i \in N = \{1, \ldots, n\}$

Actions: $a_i \subset \mathcal{R}, \quad \mathcal{A}_i \subseteq 2^{\mathcal{R}}$

System Welfare $$W(a) = \sum_{r \in \mathcal{R}} v_r w(|a|_r)$$

Resource Allocation Problems



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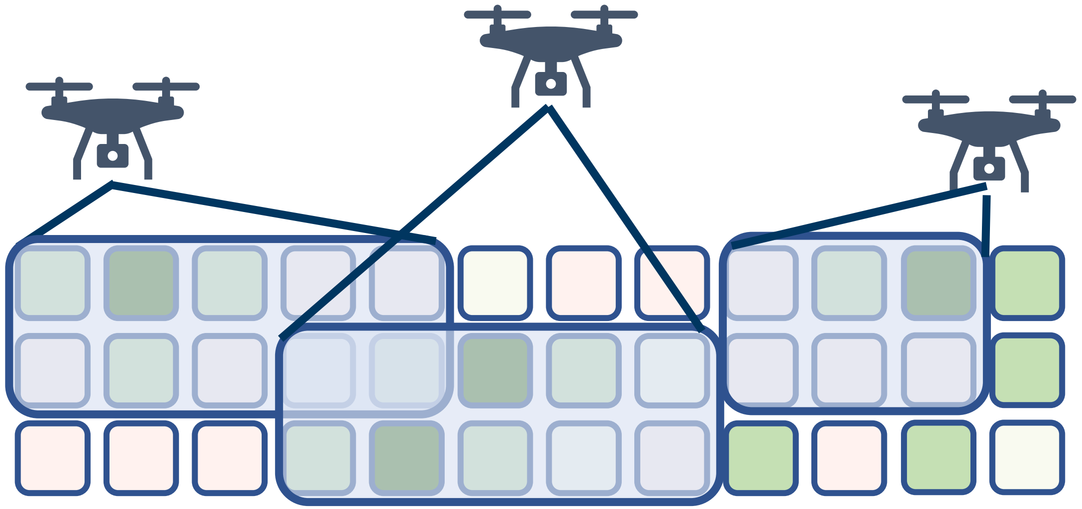
System Welfare $W(a) = \sum_{r \in \mathcal{R}} \underbrace{v_r w(|a|_r)}$

Value of having $|a|_r$ agents share resource r

Diminishing returns

Resource Allocation Problems



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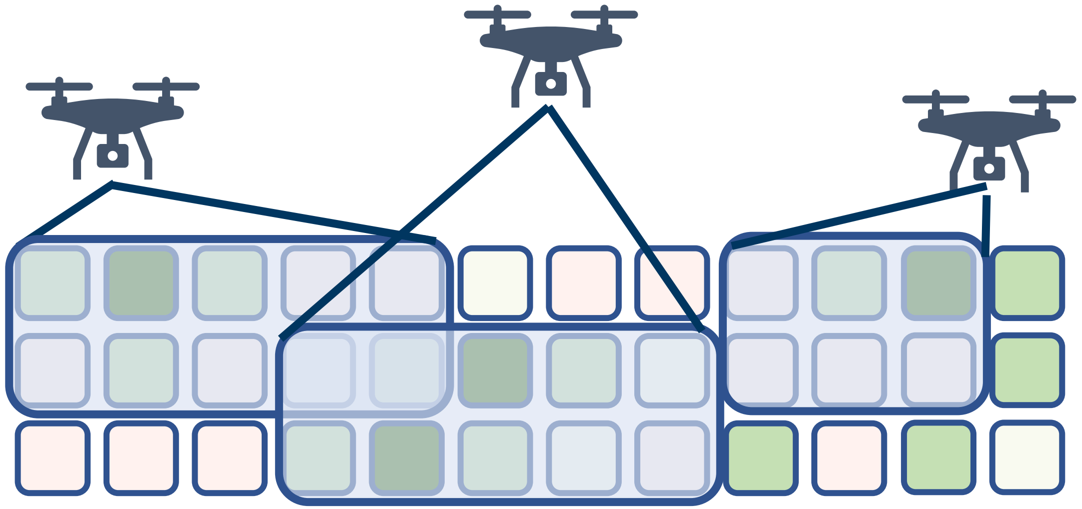
Optimal Solution: $a^{\text{opt}} \in \underset{a \in \mathcal{A}_1 \times \ldots \times \mathcal{A}_n}{\arg\max} \; W(a)$

Resource Allocation Problems



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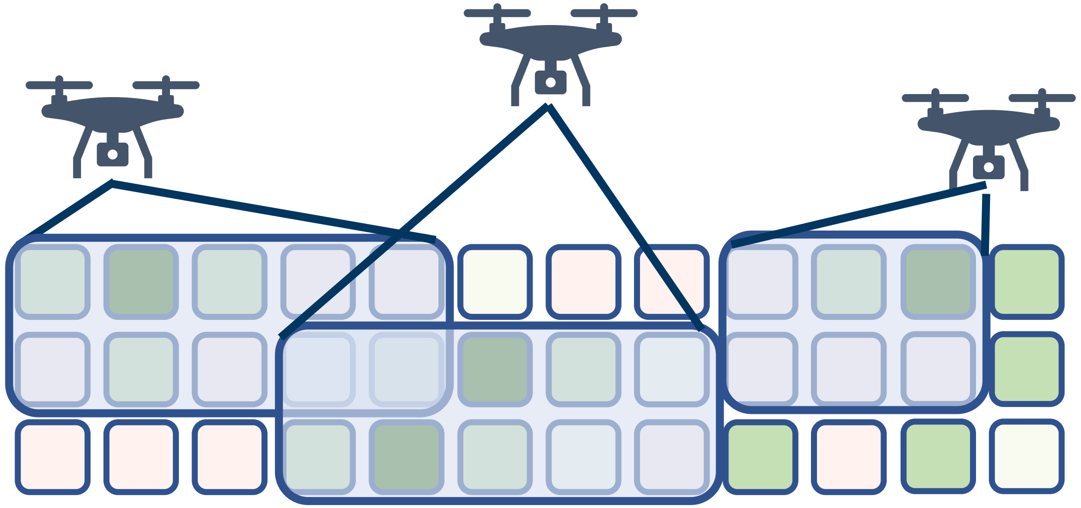
Combinatorial and NP-hard!

Resource Allocation Problems



Resources: $r \in \mathcal{R} = \{1, \ldots, R\}$

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Actions: $a_i \subset \mathcal{R}, \quad \mathcal{A}_i \subseteq 2^{\mathcal{R}}$

Utility: $U_i(a_i, a_{-i}) = W(a_i, a_{-i})$

System Welfare $W(a) = \sum_{r \in \mathcal{R}} \underbrace{v_r w(|a|_r)}$ Value of having $|a|_r$ agents share resource r

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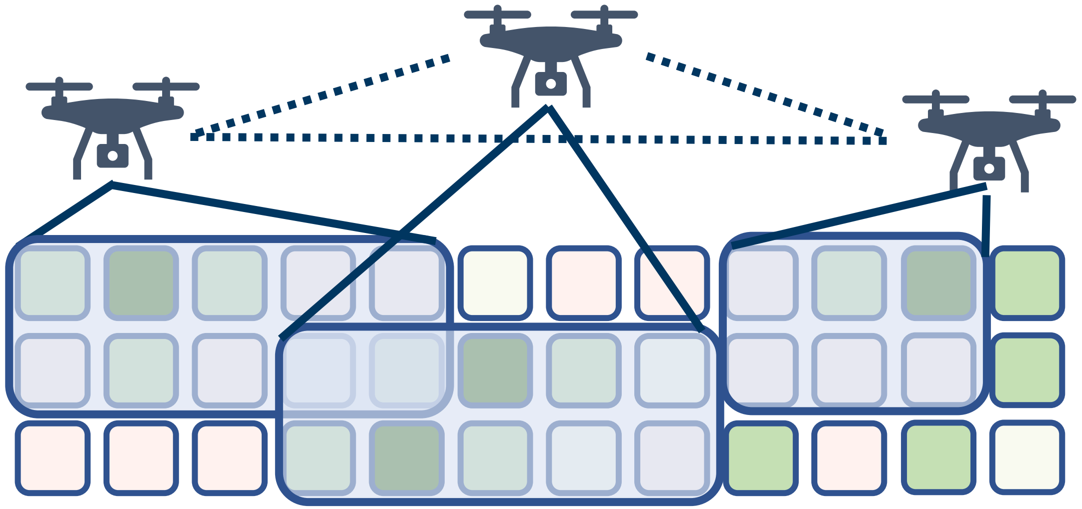

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Combinatorial and NP-hard!

Utility: $U_\Gamma(a_\Gamma, a_{-\Gamma}) = W(a_\Gamma, a_{-\Gamma}), \; \Gamma \subseteq N$

Emergent System Behavior:

k – Strong
Nash Equilibrium

Efficiency:

$$\mathtt{Eff}(k) = \min_{a^{k\text{SNE}} \in k\text{SNE}} \frac{W(a^{k\text{SNE}})}{W(a^{\text{opt}})}$$

Efficiency as a function of the level of communication between agents

Efficiency of k – Strong Nash Equilibria

How much does inter-agent communication ***improve efficiency***?

Theorem 1.1: [**BLF**, Paccagnan, Pradeslki, Marden CDC23*]

For a resource allocation problem $(\mathcal{R}, N, \mathcal{A}, \{v_r\}_{r\in\mathcal{R}}, w)$, a kSNE approximates the optimal solution with

$$\texttt{Eff}(k) \geq P^\star(n, w, k),$$

where $P^\star(n, w, k)$ is the solution to a linear program with $k+1$ decision variables and $\mathcal{O}(kn^3)$ constraints. Further, this bound is tight.

$$P^\star(n,w,k) = \max_{\theta\in\mathbb{R}^{|\mathcal{I}|}_{\geq 0}} \sum_{e,x,o} w(o+x)\theta(e,x,o)$$

$$\text{s.t.} \quad \sum_{e,x,o}\left(\frac{n!}{(n-\zeta)!}w(e+x) - \sum_{\substack{0\leq\alpha\leq\zeta\\0\leq\beta\leq\alpha}}\binom{\zeta}{\alpha}\binom{\zeta-\alpha}{\beta}e^{\underline{\alpha}}o^{\underline{\beta}}(n-e-o)^{\underline{\zeta\text{-}\alpha\text{-}\beta}}w(e+x+\beta-\alpha)\right)\theta(e,x,o) \geq 0 \quad \forall\zeta\in\{1,\ldots,k\}$$

$$\sum_{e,x,o} w(e+x)\theta(e,x,o) = 1$$

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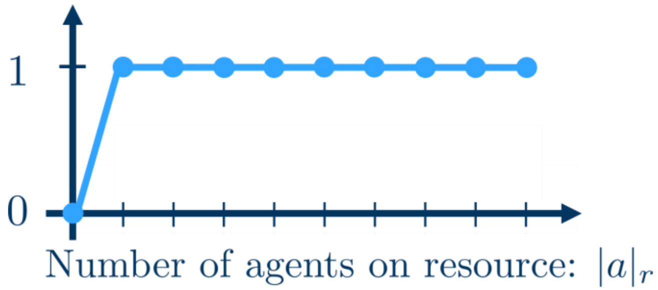
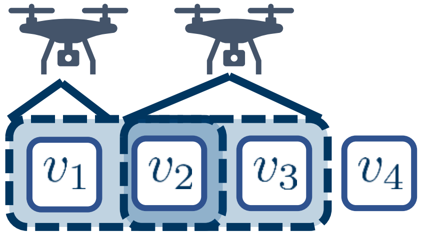
Example: Covering Problems

$$w(|a|_r) = \mathbb{1}\left[|a|_r \geq 1\right]$$





$$W(a) = v_1 + v_2 + v_3$$

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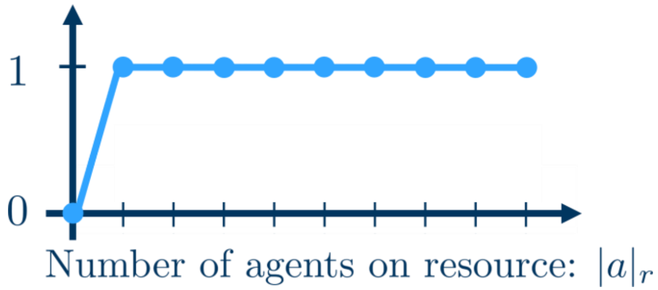
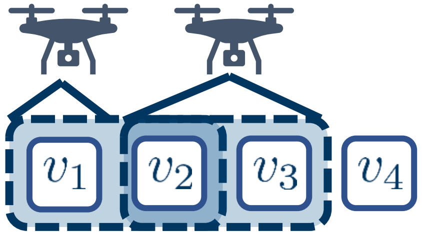
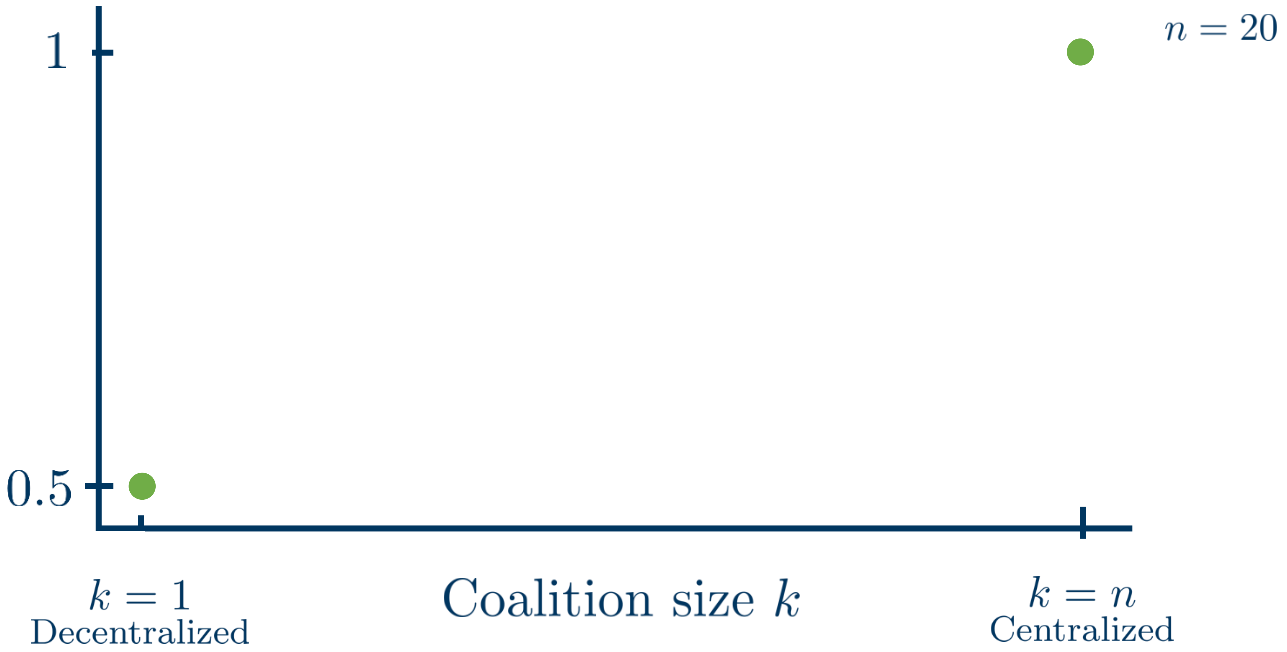




$W(a) = v_1 + v_2 + v_3$

$\texttt{Eff}(k)$ Lower-bound



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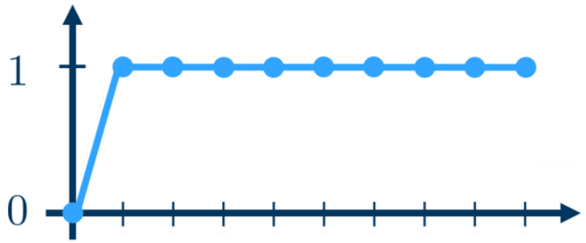

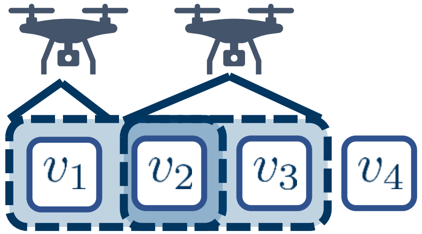

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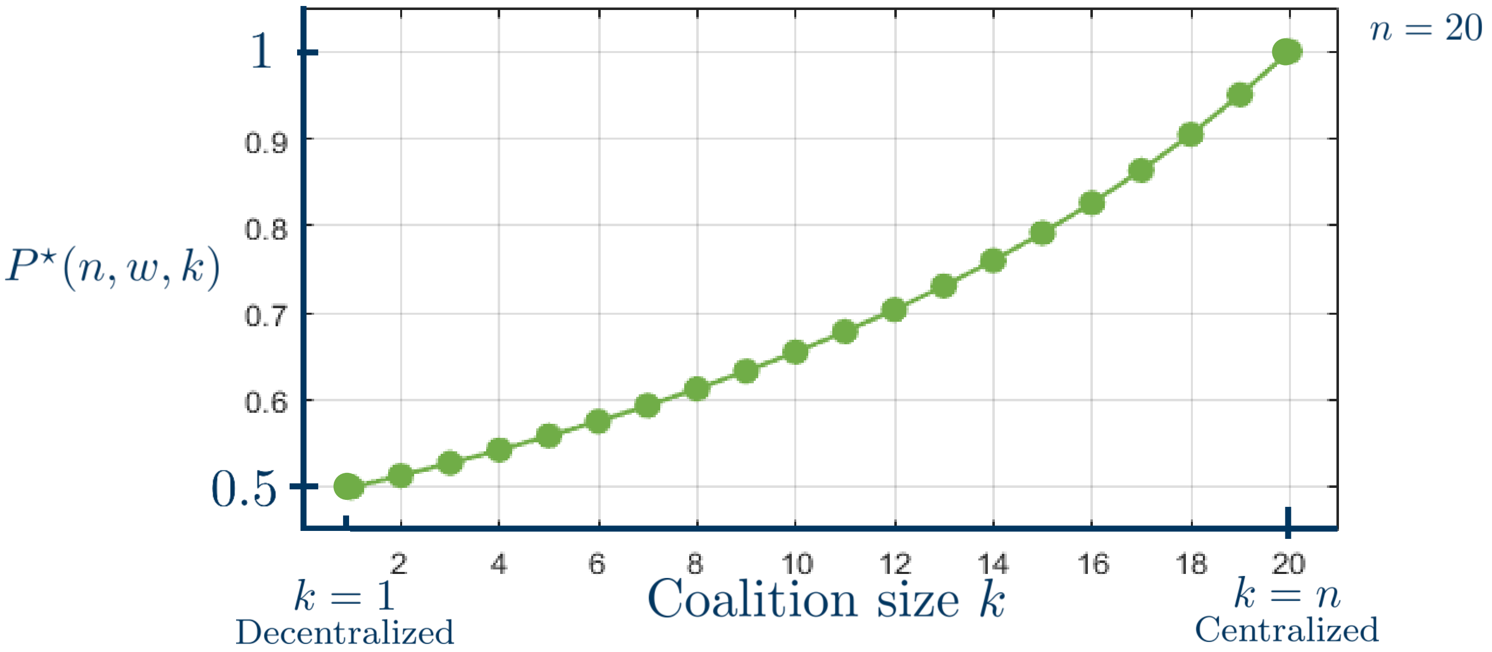

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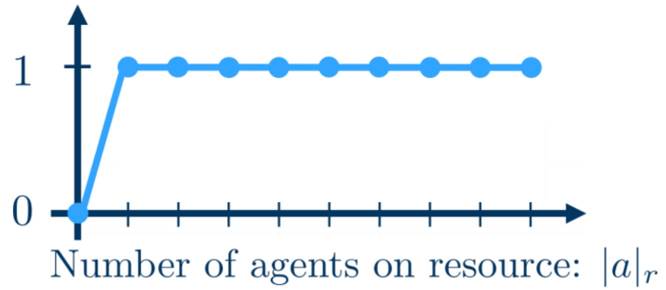

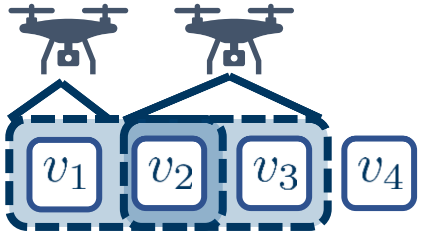

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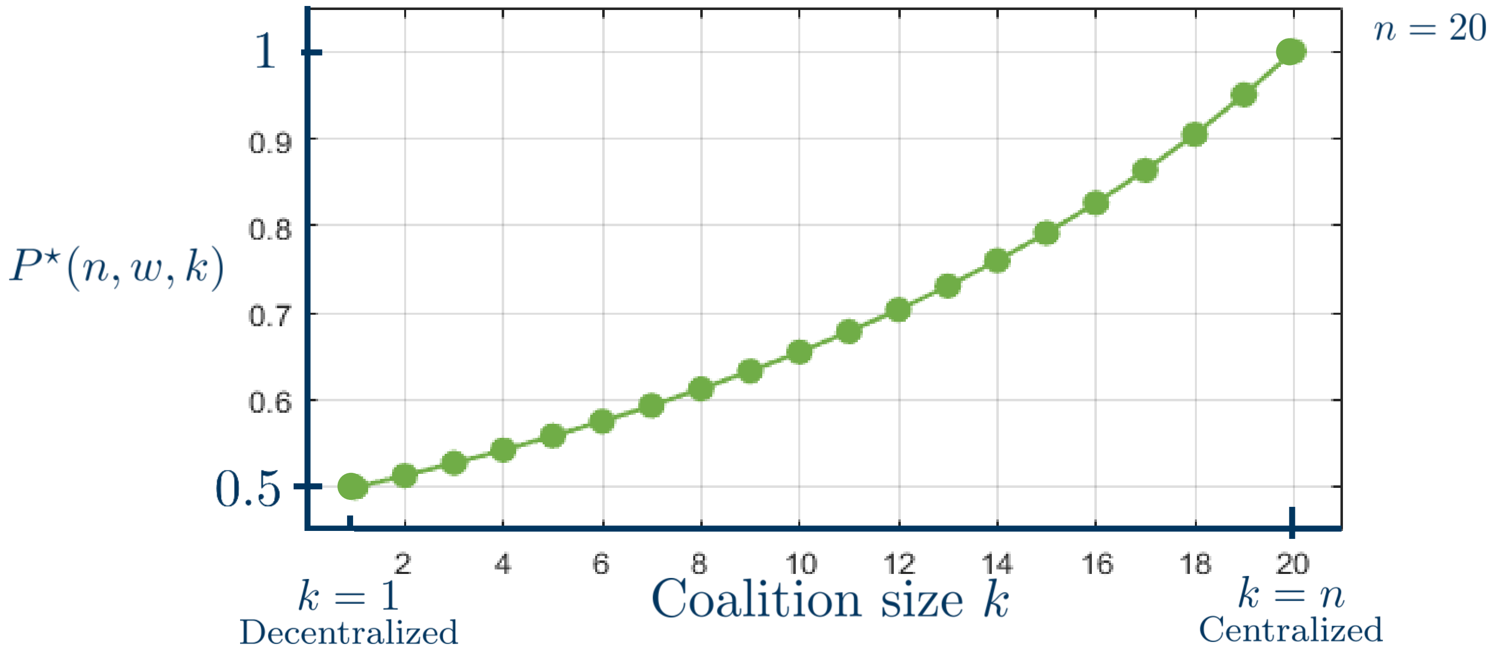
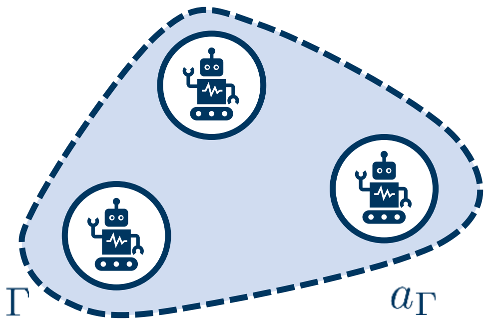


Thm1.1: Bridges gap between centralized and decentralized performance!

Coalitional Utility Design



Agent Group Decision

$$\max_{a_\Gamma} W(a_\Gamma, a_{-\Gamma})$$

System Objective

$$W(a)$$

Emergent Behavior

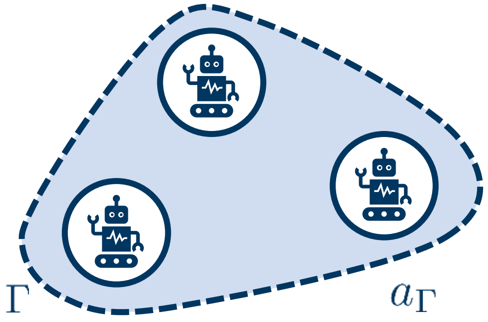
$$k\mathrm{SNE}$$

Efficiency

$$\texttt{Eff}(k) = \frac{\min_{a^{k\mathrm{SNE}} \in k\mathrm{SNE}} W(a^{\mathrm{NE}})}{\max_{a \in \mathcal{A}} W(a)} \leq 1$$

Design ***group*** objective to alter ***global*** behavior

Coalitional Utility Design



Agent Group Decision

$$\max_{a_\Gamma} U(a_\Gamma, a_{-\Gamma})$$

Redesign

New behavior

System Objective

$$W(a)$$

Emergent Behavior

$$k\mathrm{SNE}(U)$$

Efficiency

$$\mathtt{Eff}(k, U) = \frac{\min_{a^{k\mathrm{SNE}} \in k\mathrm{SNE}(U)} W(a^{\mathrm{NE}})}{\max_{a \in \mathcal{A}} W(a)} \leq 1$$

Design ***group*** objective to alter ***global*** behavior

Coalitional Utility Design

Agent Group Decision

$$\max_{a_\Gamma} U(a_\Gamma, a_{-\Gamma})$$

Redesign

New behavior

How much does ***designing utility*** help?

$W(a)$ $k\mathrm{SNE}(U)$

Efficiency

$$\mathtt{Eff}(k, U) = \frac{\min_{a^{k\mathrm{SNE}} \in k\mathrm{SNE}(U)} W(a^{\mathrm{NE}})}{\max_{a \in \mathcal{A}} W(a)} \leq 1$$

Design ***group*** objective to alter ***global*** behavior

Coalition Utility Design

Proposition 1.2: [**BLF**, Paccagnan, Pradeslki, Marden CDC23*]

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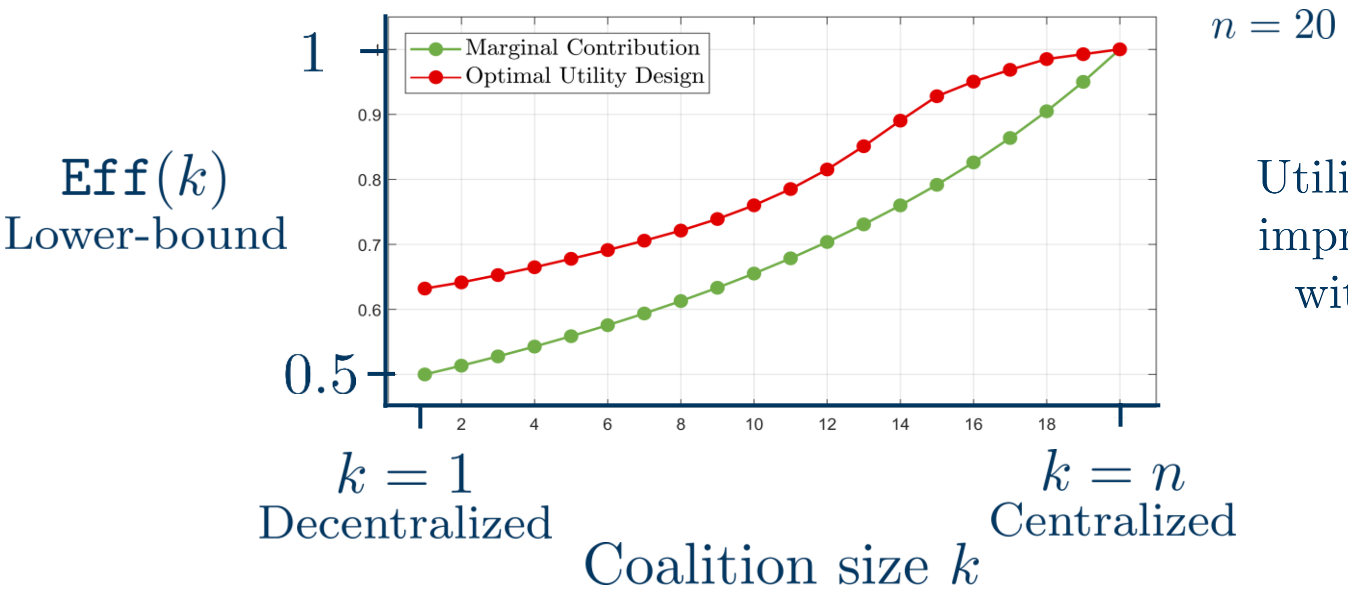

Utility Design can improve efficiency with coalitions

A Performance/Complexity Trade-off

Distributed Decision-making
(Bad performance / low complexity)

Partially Collaborative
Decision-making

Centralized Decision-making
(Best performance / high complexity)

A Performance/Complexity Trade-off

Distributed Decision-making
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Increasing Communication

Improve
Efficiency

Increase
Complexity

A Performance/Complexity Trade-off

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(Bad performance / low complexity)

Partially Collaborative
Decision-making

Centralized Decision-making
(Best performance / high complexity)

Increasing Communication

Improve
Efficiency

Increase
Complexity

We now have some understanding of performance,
What happens to complexity?

Complexity of kSNE

How does communication affect ***convergence rate***?

$n :=$ number of players $\quad m :=$ number of agent actions $\quad k :=$ size of coalitions

Complexity of kSNE

How does communication affect ***convergence rate***?

Nash Equilibrium	k-Strong Nash Equilibrium

Evaluating an equilibrium

$\mathcal{O}(nm)$	$\mathcal{O}\left(\frac{n!}{(n-k)!k!}m^k\right)$

$n :=$ number of players $\quad m :=$ number of agent actions $\quad k :=$ size of coalitions

Complexity of kSNE

How does communication affect ***convergence rate***?

	Nash Equilibrium	k-Strong Nash Equilibrium
Evaluating an equilibrium	$\mathcal{O}(nm)$	$\mathcal{O}\left(\frac{n!}{(n-k)!k!}m^k\right)$
Finding an equilibrium	$\mathcal{O}(m^n)$	?

As long or longer!

$n :=$ number of players $\quad m :=$ number of agent actions $\quad k :=$ size of coalitions

Complexity of kSNE

How does communication affect ***convergence rate***?

	Nash Equilibrium	k-Strong Nash Equilibrium
Evaluating an equilibrium	$\mathcal{O}(nm)$	$\mathcal{O}\left(\frac{n!}{(n-k)!k!}m^k\right)$
Finding an equilibrium	$\mathcal{O}(m^n)$	?

As long or longer!

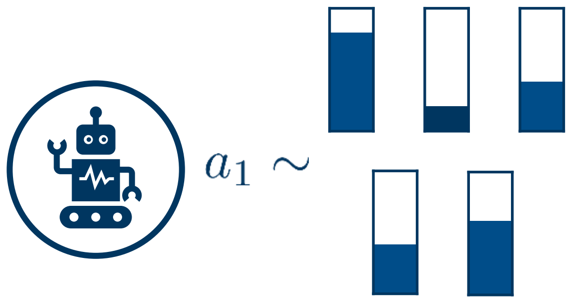
The relative value of faster convergence is context dependent!

What techniques can we employ to ***reduce complexity*** with the ***least sacrifice*** to performance?

$n :=$ number of players $\quad m :=$ number of agent actions $\quad k :=$ size of coalitions

Exploring the Trade-off

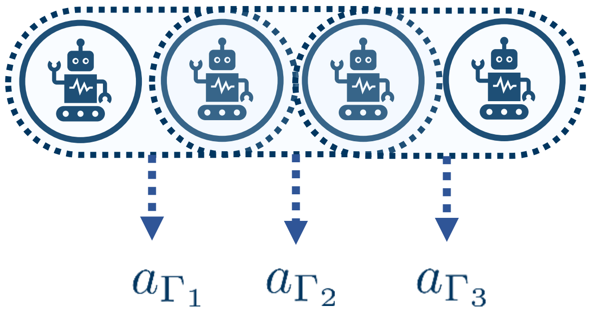
Non-Deterministic Algorithms



Group regret-based decision-making

- Stochastic decision making to non-pure equilibrium concepts
- Coarse-correlated equilibria and smoothness

Non-Equilibrium Algorithms

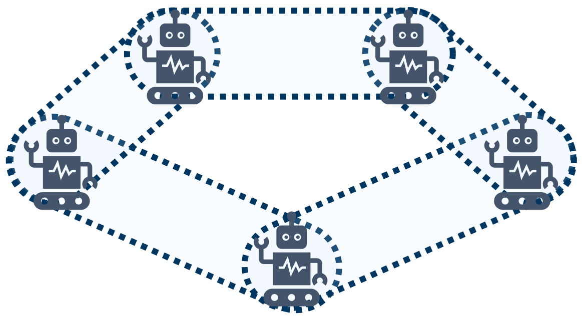


One-round walk & finite run time

- Each group revises their action finite times

$$\mathcal{O}\left(\frac{n!}{(n-k)!k!}m^k\right)$$

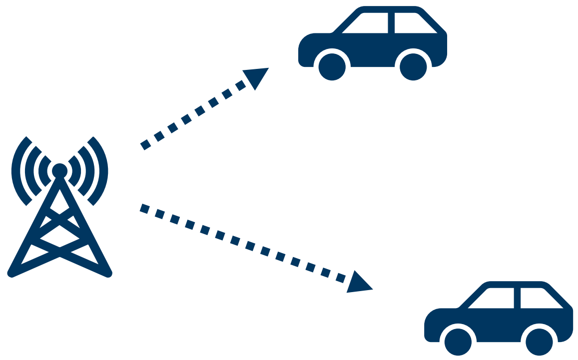
Weaker Communication Structures



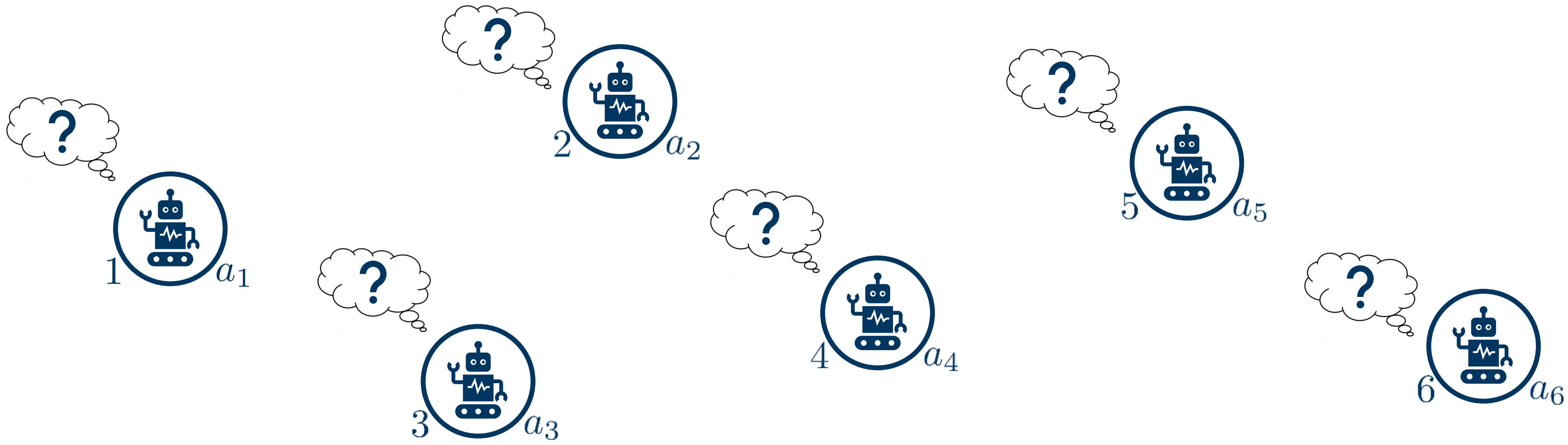
Not every subset communicates

- Lesser communication structure means worse performance guarantees
- Ideally, the reduction in complexity outweighs the loss in performance

II. Information Provisioning

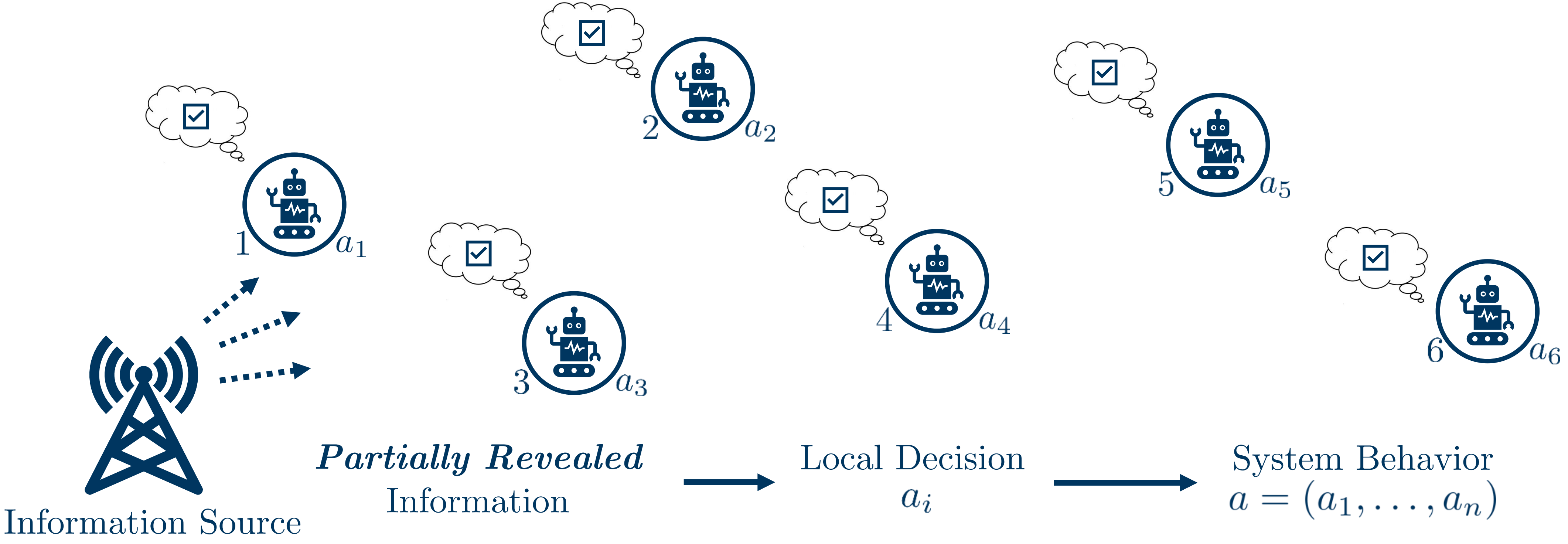


Information Provisioning



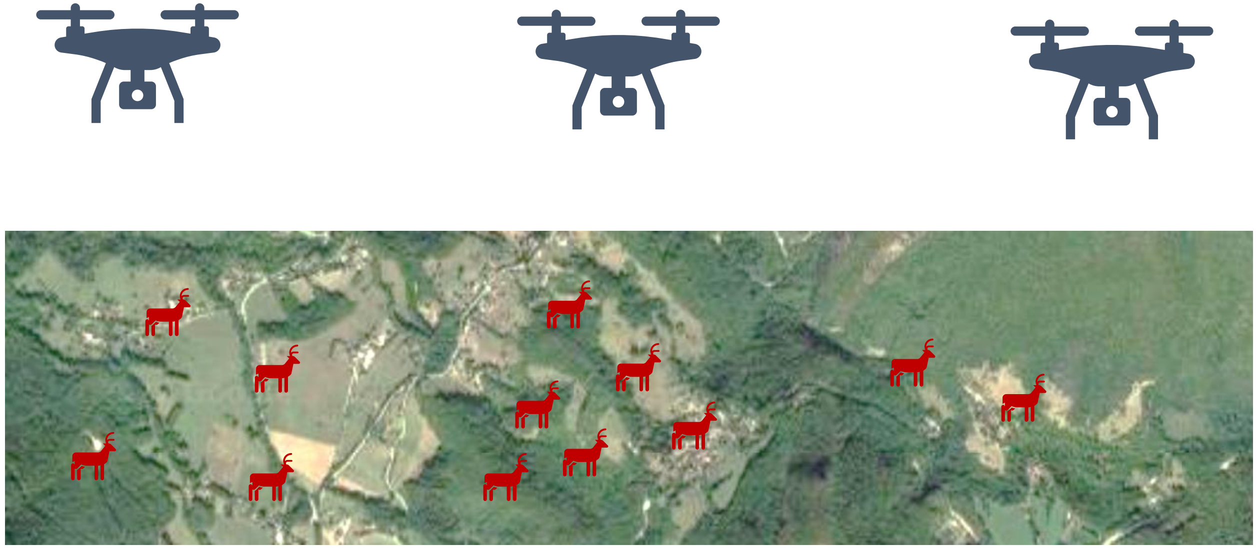
Missing Information → Local Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

Information Provisioning



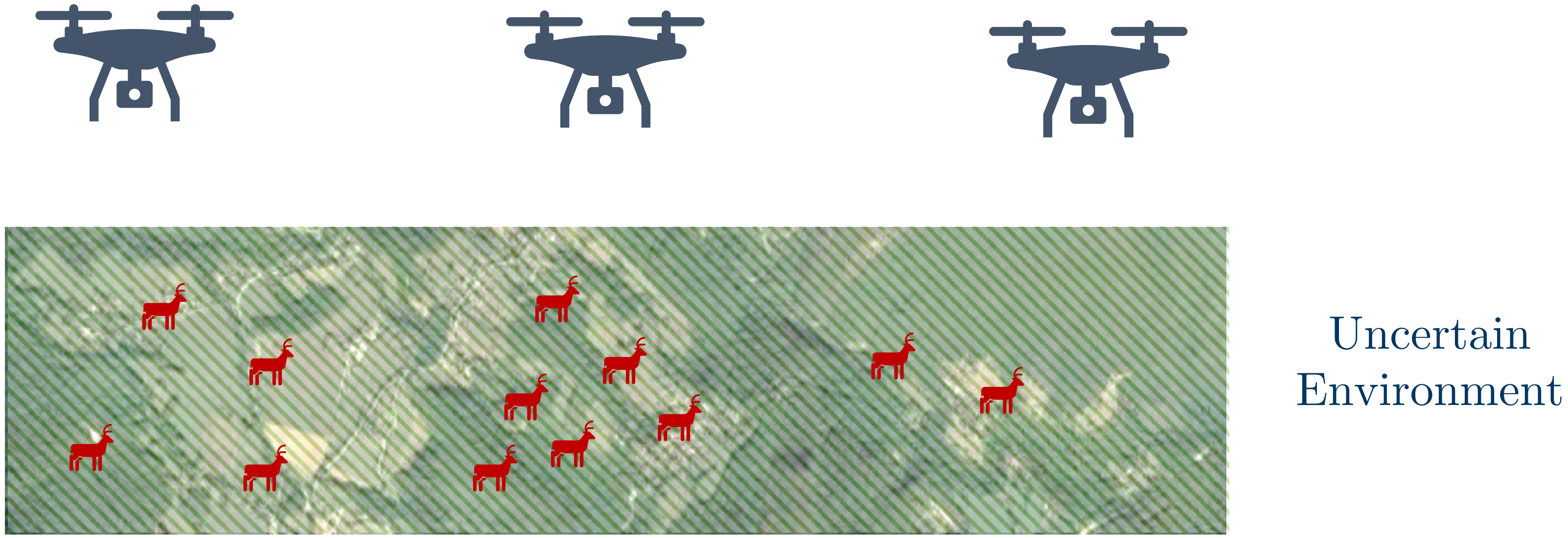
How does ***revealing information*** to local decision makers affect system performance?

Informing Decision-Makers



Goal: surveil number of deer with a distributed drone team

Informing Decision-Makers



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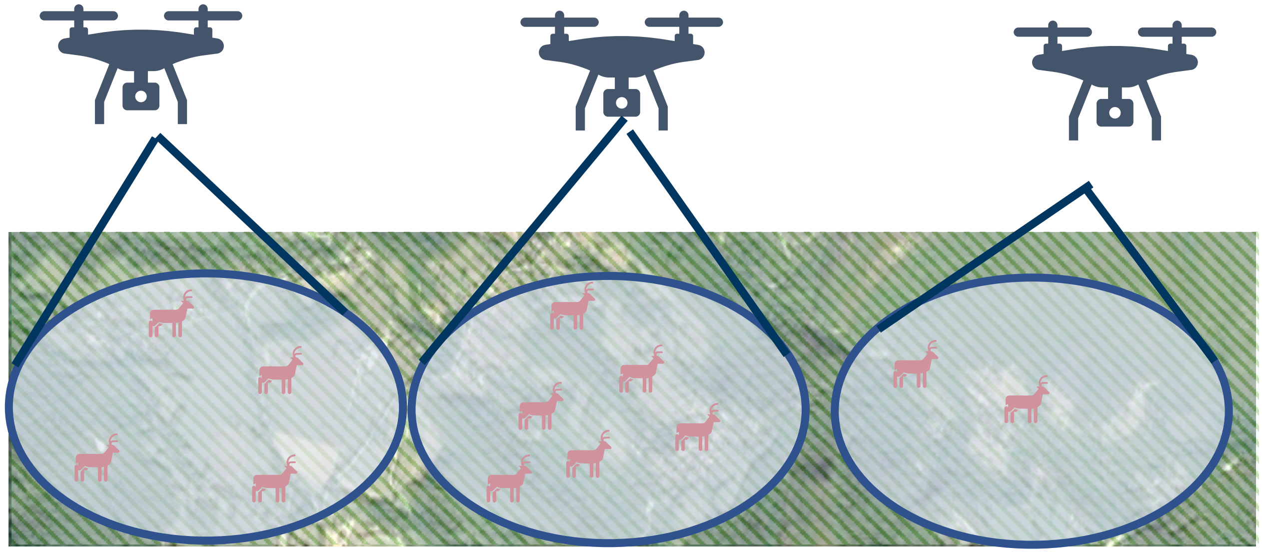

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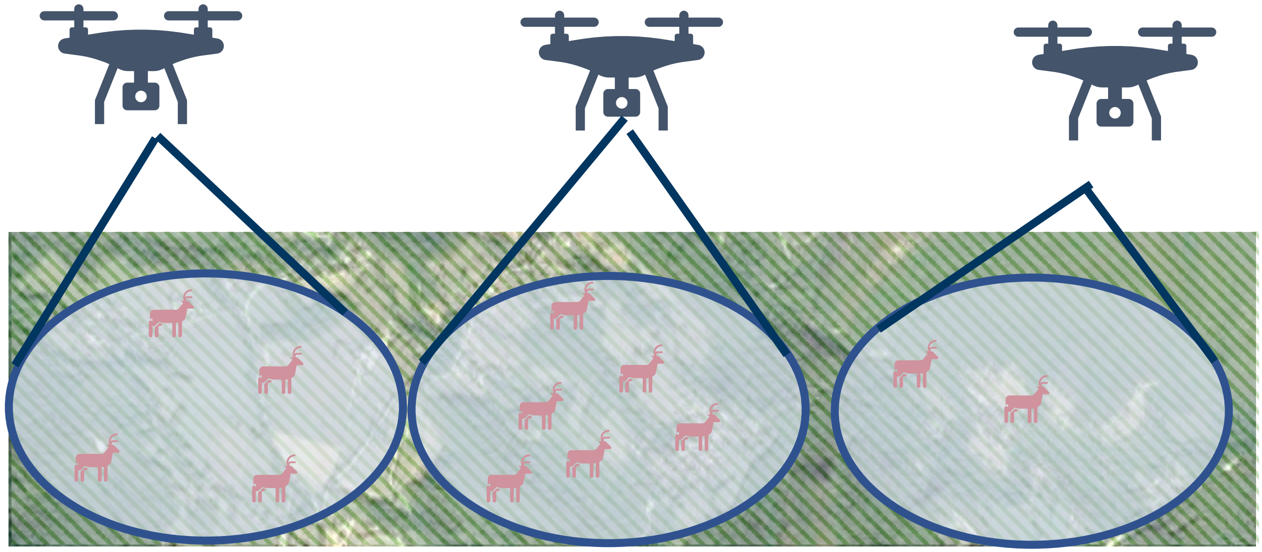
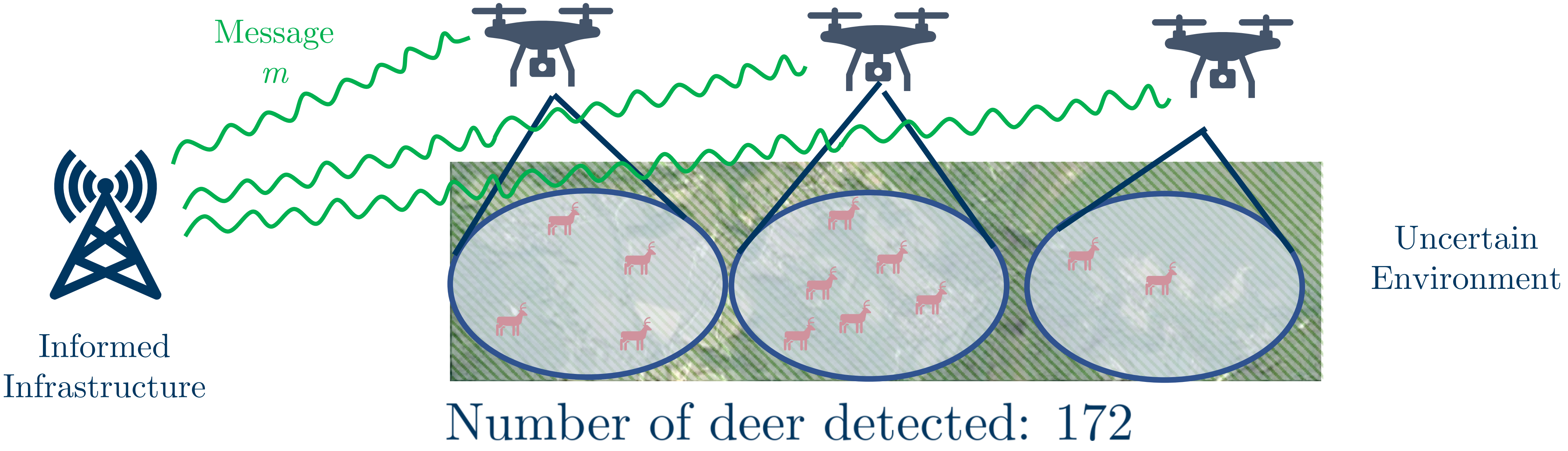


Number of deer detected: 172

Goal: surveil number of deer with a distributed drone team

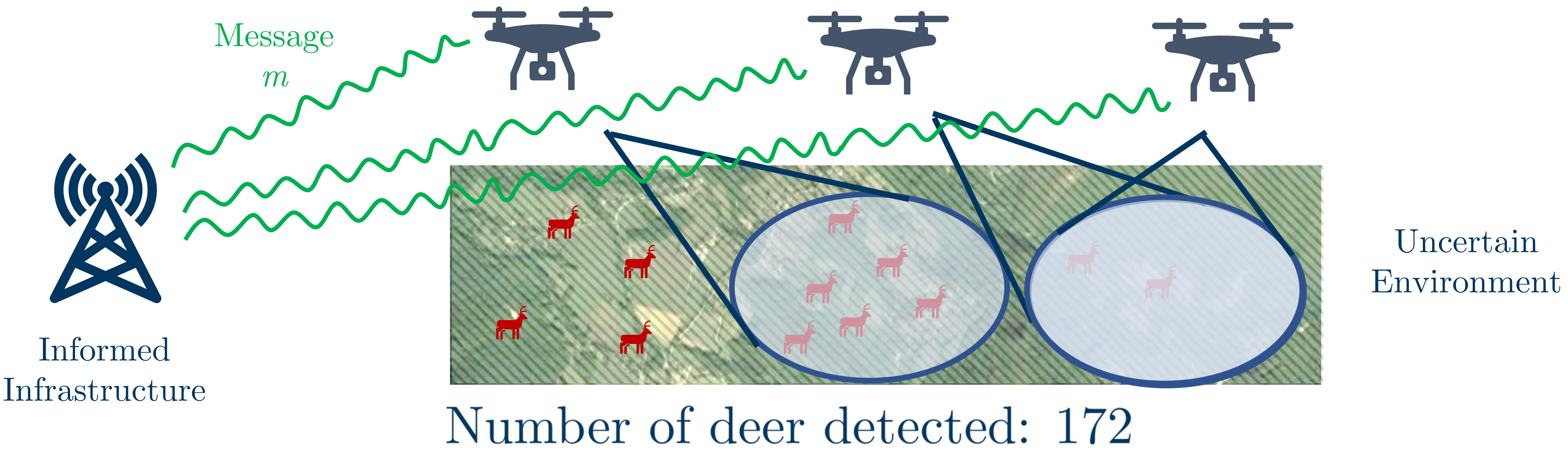
Informing Decision-Makers



Goal: surveil number of deer with a distributed drone team

Proposal: send **messages** to inform drones of areas with more deer throughout day

Informing Decision-Makers



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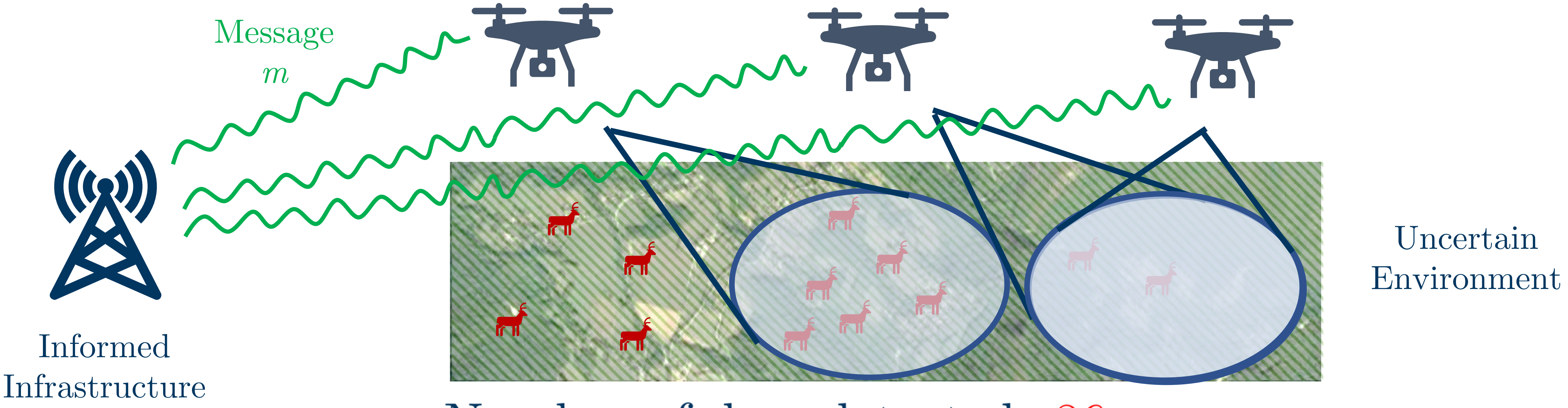


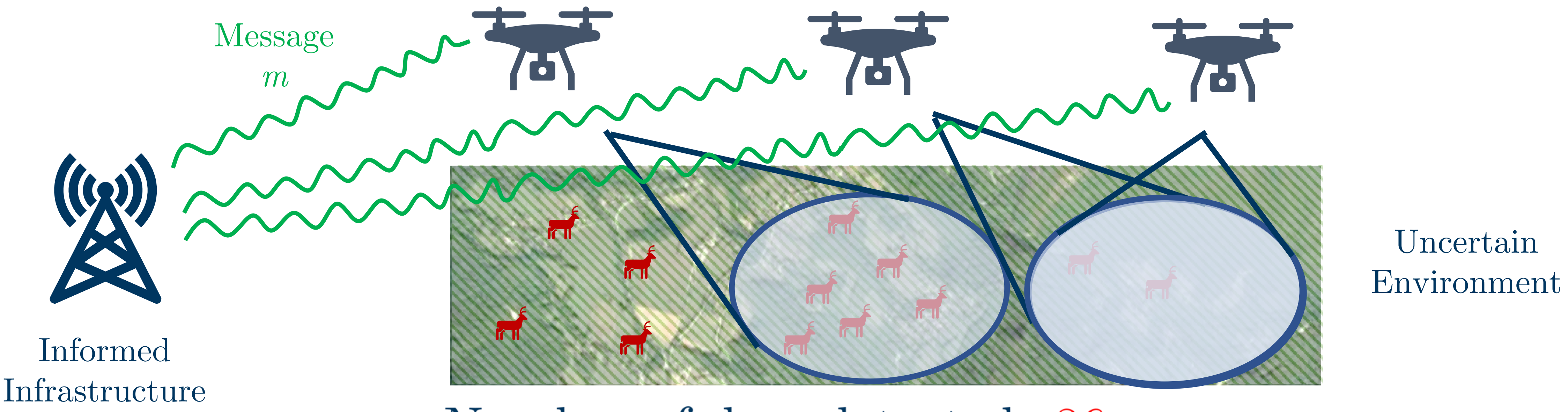
Number of deer detected: 86

Goal: surveil number of deer with a distributed drone team

Proposal: send **messages** to inform drones of areas with more deer throughout day

Result: far ***fewer*** deer were detected?

Informing Decision-Makers



Number of deer detected: 86

Goal: surveil number of deer with a distributed drone team

Proposal: send **messages** to inform drones of areas with more deer throughout day

Result: far ***fewer*** deer were detected?

Why did revealing information worsen system performance?

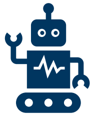
Information Signaling

Agent 1   Agent 2   Agent 3 $\ldots$ Agent n

$U_1(a; \alpha)$ $U_2(a; \alpha)$ $U_3(a; \alpha)$ $U_n(a; \alpha)$

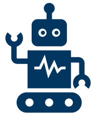
System state α affects agent costs

Information Signaling



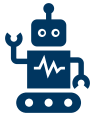
Agent 1

$U_1(a; \alpha)$



Agent 2

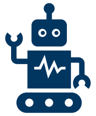
$U_2(a; \alpha)$



Agent 3

$U_3(a; \alpha)$

$\ldots$



Agent n

$U_n(a; \alpha)$

System state α affects agent costs

Player knowledge: full information on state

$$\alpha$$

Nash Equilibrium $(a^{\mathrm{NE}}, \alpha)$:

$$U_i(a^{\mathrm{NE}}; \alpha) \leq U_i(a_i', a_{\text{-}i}^{\mathrm{NE}}; \alpha)$$

$$\forall a_i' \in \mathcal{A}_i,$$

$$i \in N = \{1, \ldots, n\}$$

Information Signaling

Agent 1 $U_1(a; \alpha)$

Agent 2 $U_2(a; \alpha)$

Agent 3 $U_3(a; \alpha)$

$\dots$

Agent n $U_n(a; \alpha)$

System state α affects agent costs

Player knowledge: a prior belief

$$\mu_0(x) = \mathbb{P}[\alpha = x]$$

Nash Equilibrium $(a^{\mathrm{NE}}, \alpha)$:

$$U_i(a^{\mathrm{NE}}; \alpha) \leq U_i(a_i', a_{\text{-}i}^{\mathrm{NE}}; \alpha)$$
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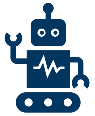
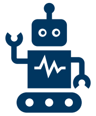
Information Signaling



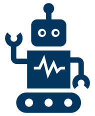
Agent 1

$$\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_1(a;\alpha)]$$



Agent 2

$$\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_2(a;\alpha)]$$



Agent 3

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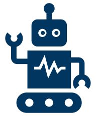

Agent n

$$\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_n(a;\alpha)]$$

System state α affects agent costs

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$$\mu_0(x) = \mathbb{P}[\alpha = x]$$

Uninformed Nash Equilibrium (a^{NE}, μ_0):

$$\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_i(a^{\mathrm{NE}};\alpha)] \leq \mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_i(a_i', a_{-i}^{\mathrm{NE}};\alpha)]$$

$$\forall a_i' \in \mathcal{A}_i,$$

$$i \in N = \{1, \dots, n\}$$

Information Signaling

Agent 1 $\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_1(a;\alpha)]$

Agent 2 $\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_2(a;\alpha)]$

Agent 3 $\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_3(a;\alpha)]$

...

Agent n $\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_n(a;\alpha)]$

System state α affects agent costs

Player knowledge: partial information via signals

$m = \pi(\alpha)$ Message

$\pi : \mathrm{supp}(\alpha) \to M$ Signaling policy

Uninformed Nash Equilibrium (a^{NE}, μ_0):

$$\mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_i(a^{\mathrm{NE}};\alpha)] \leq \mathop{\mathbb{E}}_{\alpha\sim\mu_0}[U_i(a_i', a_{-i}^{\mathrm{NE}};\alpha)]$$

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Information Signaling

Agent 1 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_1(a;\alpha)]$

Agent 2 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_2(a;\alpha)]$

Agent 3 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_3(a;\alpha)]$

...

Agent n $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_n(a;\alpha)]$

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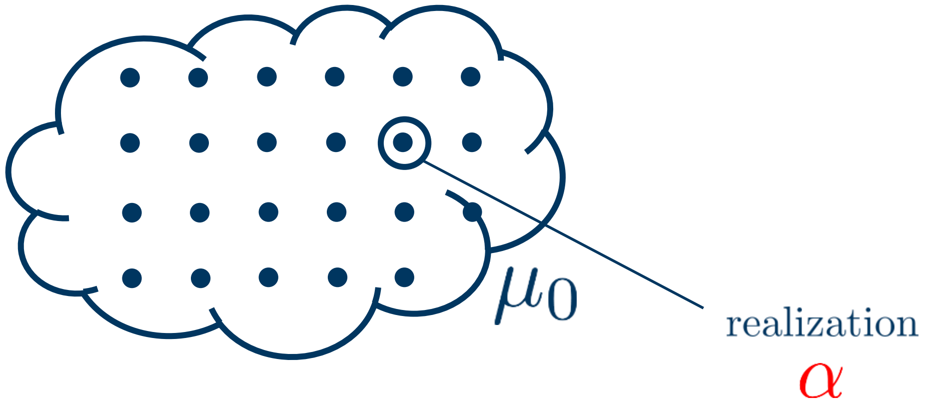
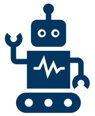
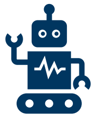
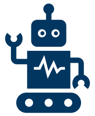
E.g.,



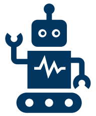
Information Signaling


Agent 1
$\mathbb{E}_{\alpha\sim\mu_0}[U_1(a;\alpha)]$


Agent 2
$\mathbb{E}_{\alpha\sim\mu_0}[U_2(a;\alpha)]$


Agent 3
$\mathbb{E}_{\alpha\sim\mu_0}[U_3(a;\alpha)]$

$\dots$


Agent n
$\mathbb{E}_{\alpha\sim\mu_0}[U_n(a;\alpha)]$

System state α affects agent costs

Player knowledge: partial information via signals

$m = \pi(\alpha)$ — Message

$\pi : \mathrm{supp}(\alpha) \to M$ — Signaling policy

Uninformed Nash Equilibrium (a^{NE}, μ_0):

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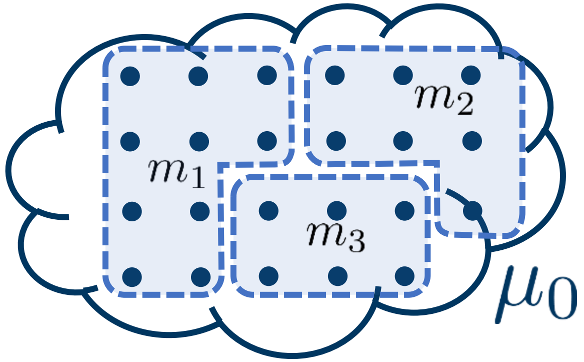


Posterior Belief
μ_m

$\to$ message
$m = \pi(\alpha)$

realization
α

Information Signaling

Agent 1 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_1(a;\alpha) \mid m]$

Agent 2 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_2(a;\alpha) \mid m]$

Agent 3 $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_3(a;\alpha) \mid m]$

…

Agent n $\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_n(a;\alpha) \mid m]$

System state α affects agent costs

Player knowledge: partial information via signals

$m = \pi(\alpha)$ Message

$\pi : \mathrm{supp}(\alpha) \to M$ Signaling policy

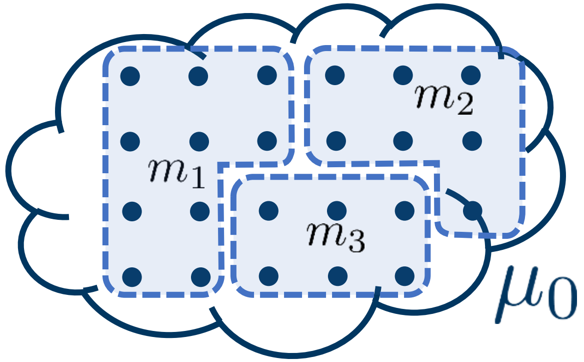
Bayes-Nash Equilibrium $(\{a^{\mathrm{NE}}(m)\}_{m\in M}, \mu_0, \pi)$:

$$\underset{\alpha\sim\mu_0}{\mathbb{E}}[U_i(a^{\mathrm{BNE}};\alpha) \mid m] \le \underset{\alpha\sim\mu_0}{\mathbb{E}}[U_i(a_i', a_{-i}^{\mathrm{BNE}};\alpha) \mid m]$$

$$\forall a_i' \in \mathcal{A}_i,\ m \in M$$

$$i \in N = \{1, \ldots, n\}$$

E.g.,



Posterior Belief μ_m

$\to$ message $m = \pi(\alpha)$

realization α

The Value of Informing

Informed System Performance: $W\left(a^{\mathrm{BNE}}(\pi)\right)$

Uninformed System Performance: $W\left(a^{\mathrm{NE}}(\mu_0)\right)$

The Value of Informing

$$\frac{\text{Informed System Performance:} \quad W\left(a^{\mathrm{BNE}}(\pi)\right)}{\text{Uninformed System Performance:} \quad W\left(a^{\mathrm{NE}}(\mu_0)\right)} =: \underset{\text{(value of informing)}}{\mathrm{VoI}(\pi)}$$

The Value of Informing

$$\frac{\text{Informed System Performance: } \quad W\left(a^{\mathrm{BNE}}(\pi)\right)}{\text{Uninformed System Performance: } \quad W\left(a^{\mathrm{NE}}(\mu_0)\right)} =: \underset{\text{(value of informing)}}{\mathrm{VoI}(\pi)}$$

Multiple Equilibria → Multiple Perspectives

Optimistic Perspective

$$\mathrm{VoI}^{+}(\pi) = \frac{\max_{a^{\mathrm{BNE}} \in \mathrm{BNE}(\pi)} \mathbb{E}\left[W\left(a^{\mathrm{BNE}}\right)\right]}{\max_{a^{\mathrm{NE}} \in \mathrm{NE}(\mu_0)} \mathbb{E}\left[W\left(a^{\mathrm{NE}}\right)\right]}$$

Gain of ***best-case*** equilibrium performance

Pessimistic Perspective

$$\mathrm{VoI}^{-}(\pi) = \frac{\min_{a^{\mathrm{BNE}} \in \mathrm{BNE}(\pi)} \mathbb{E}\left[W\left(a^{\mathrm{BNE}}\right)\right]}{\min_{a^{\mathrm{NE}} \in \mathrm{NE}(\mu_0)} \mathbb{E}\left[W\left(a^{\mathrm{NE}}\right)\right]}$$

Gain of ***worst-case*** equilibrium performance

Bounding the Value of Informing

Covering Problems $w_r(|a|_r) = \alpha_r \mathbb{1}\left[|a|_r \geq 1\right]$

System Objective

$U(a;\alpha) = W(a;\alpha) = \sum_{r \in \mathcal{R}} \alpha_r \mathbb{1}|a|_r > 0$

Thm 2.1 **[BLF**, D.Paccagnan, J.R.Marden LCSS*]

For a resource allocation game with the covering objective:

$$1 \leq \mathrm{VoI}^{+}(\pi) \leq |M|$$

$$1/2 \leq \mathrm{VoI}^{-}(\pi) \leq 2|M|$$

Bounding the Value of Informing

Covering Problems $w_r(|a|_r) = \alpha_r \mathbb{1}\left[|a|_r \geq 1\right]$

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Observations:

- Revealing information only helps best-case
- A richer message space leads to greater opportunities for improvement ($|M|$)
- Revealing information can ***worsen worst-case***

Bounding the Value of Informing

Covering Problems $w_r(|a|_r) = \alpha_r \mathbb{1}\left[|a|_r \geq 1\right]$

System Objective

$$U(a;\alpha) = W(a;\alpha) = \textstyle\sum_{r\in\mathcal{R}} \alpha_r \mathbb{1}|a|_r > 0$$

Optimal Pessimistic Utility Design

$$U(a;\alpha) = \textstyle\sum_{r\in\mathcal{R}} \alpha_r (|a|_r - 1)! \frac{\frac{1}{(n-1)(n-1)!} + \sum_{i=|a|_r}^{n-1} \frac{1}{i!}}{\frac{1}{(n-1)(n-1)!} + \sum_{i=1}^{n-1} \frac{1}{i!}}$$

Thm 2.1 [**BLF**, D.Paccagnan, J.R.Marden LCSS*]

For a resource allocation game with the covering objective:

$$1 \leq \mathrm{VoI}^+(\pi) \leq |M|$$

$$1/2 \leq \mathrm{VoI}^-(\pi) \leq 2|M|$$

Thm 2.2 [**BLF**, D.Paccagnan, J.R.Marden LCSS*]

For a resource allocation game with the covering objective and pessimistic design:

$$1 - \tfrac{1}{e} \leq \mathrm{VoI}^+(\pi) \leq \left(1 - \tfrac{1}{e}\right)^{-1} |M|$$

$$1 - \tfrac{1}{e} \leq \mathrm{VoI}^-(\pi) \leq \left(1 - \tfrac{1}{e}\right)^{-1} |M|$$

Observations:

- Revealing information only helps best-case
- A richer message space leads to greater opportunities for improvement ($|M|$)
- Revealing information can ***worsen worst-case***

Observation:

- Improving worst-case guarantee has negative consequences on best-case guarantee

Trade-off in Best-case/Worst-case Guarantees

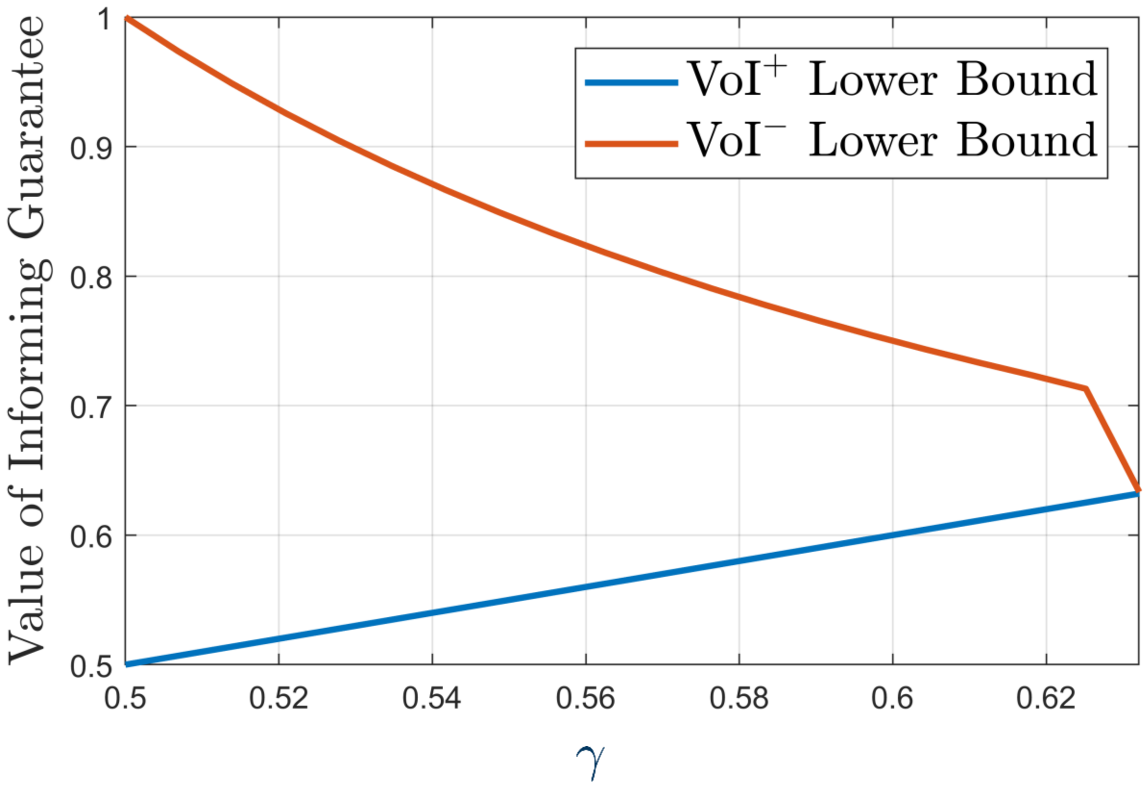
Prop. 2.3 **[BLF**, D.Paccagnan, J.R.Marden LCSS***]**

Given a desired VoI^- guarantee of $\gamma \in (1/2, 1-1/e]$ and $n \geq 2$, VoI^+ satisfies

$$\mathrm{VoI}^+ \geq Z(\gamma, n)$$

where $Z(\gamma, n)$ equals

$$\frac{1}{1+\max_{1\leq j\leq n-1} j j! \left(1-\left(\frac{1}{\gamma}-1\right)\sum_{i=1}^{j}\frac{1}{i!}\right)}.$$



Designing utilities for better pessimistic guarantees worsens the optimistic guarantees

Direction: Optimal Signaling Mechanism

$$\pi^\star \in \operatorname*{arg\,max}_{\pi:\mathrm{supp}(\alpha)\to M} W\left(a^{\mathrm{BNE}}(\pi)\right)$$

Direction: Optimal Signaling Mechanism

$$\pi^\star \in \underset{\pi:\mathrm{supp}(\alpha)\to M}{\arg\max} \; W\left(a^{\mathrm{BNE}}(\pi)\right)$$

Optimist Optimal

$$\pi^\star \in \underset{\pi:\mathrm{supp}(\alpha)\to M}{\arg\max} \; \max_{a^{\mathrm{BNE}}\in\mathrm{BNE}(\pi)} W\left(a^{\mathrm{BNE}}\right)$$

Reveal everything

Pessimist Optimal

$$\pi^\star \in \underset{\pi:\mathrm{supp}(\alpha)\to M}{\arg\max} \; \min_{a^{\mathrm{BNE}}\in\mathrm{BNE}(\pi)} W\left(a^{\mathrm{BNE}}\right)$$

Computationally intractable

Direction: Optimal Signaling Mechanism

$$\pi^\star \in \underset{\pi:\mathrm{supp}(\alpha)\to M}{\arg\max} \underset{a\in\mathrm{BNE}(\pi)}{\mathbb{E}} \left[W\left(a\right)\right]$$

Average Case Performance

Algorithm 1 Bandit Approach to Optimal Signals

1: Pick signaling policy π via UCB
2: Sample State α and initial allocation a_0
3: Find BNE via Best-Response $\texttt{BR}(a_0, \pi(\alpha))$
4: Record Equilibrium Reward

Direction: Optimal Signaling Mechanism

$$\pi^\star \in \underset{\pi:\mathrm{supp}(\alpha)\to M}{\arg\max} \ \underset{a\in \mathrm{BNE}(\pi)}{\mathbb{E}} [W(a)]$$

Algorithm 1 Bandit Approach to Optimal Signals

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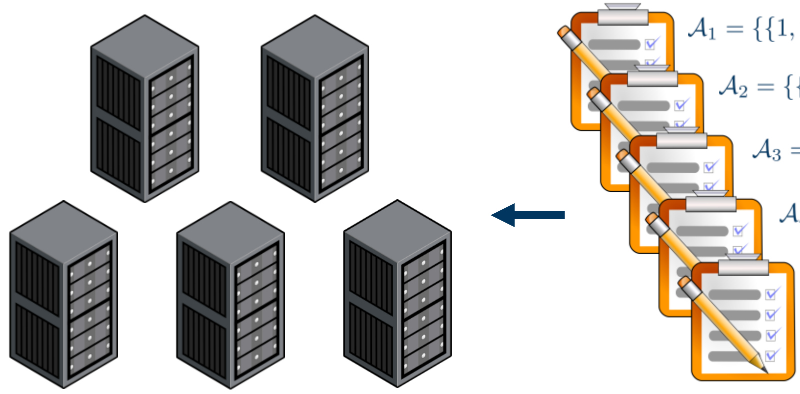
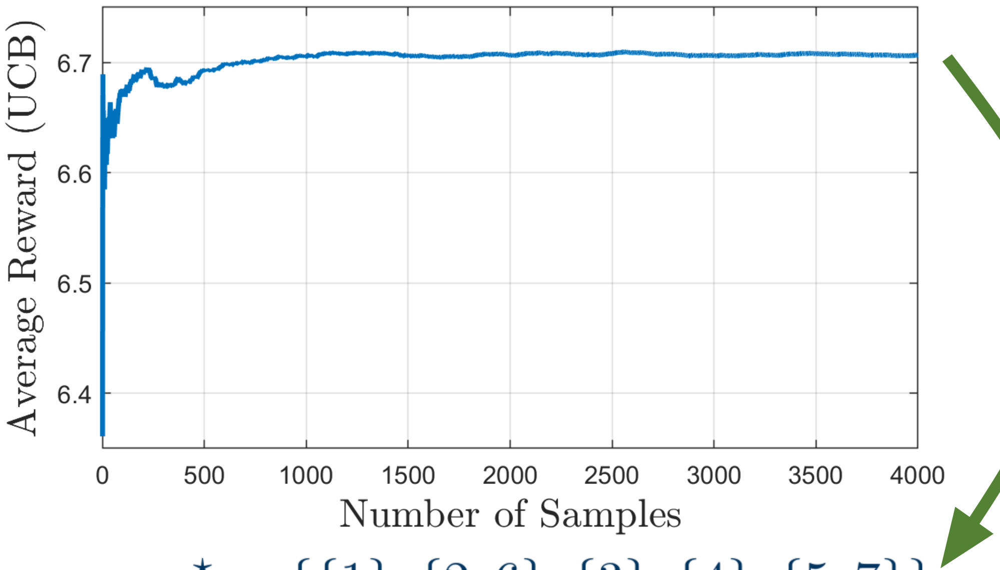
Average Case Performance



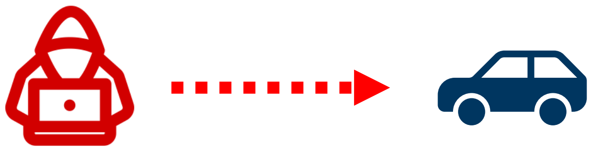
$\mathrm{supp}(\alpha) = \{\alpha_1, \ldots, \alpha_7\}$

$w_r(|a|_r) = \alpha_r |a|_r \texttt{exp}(-c|a|_r)$

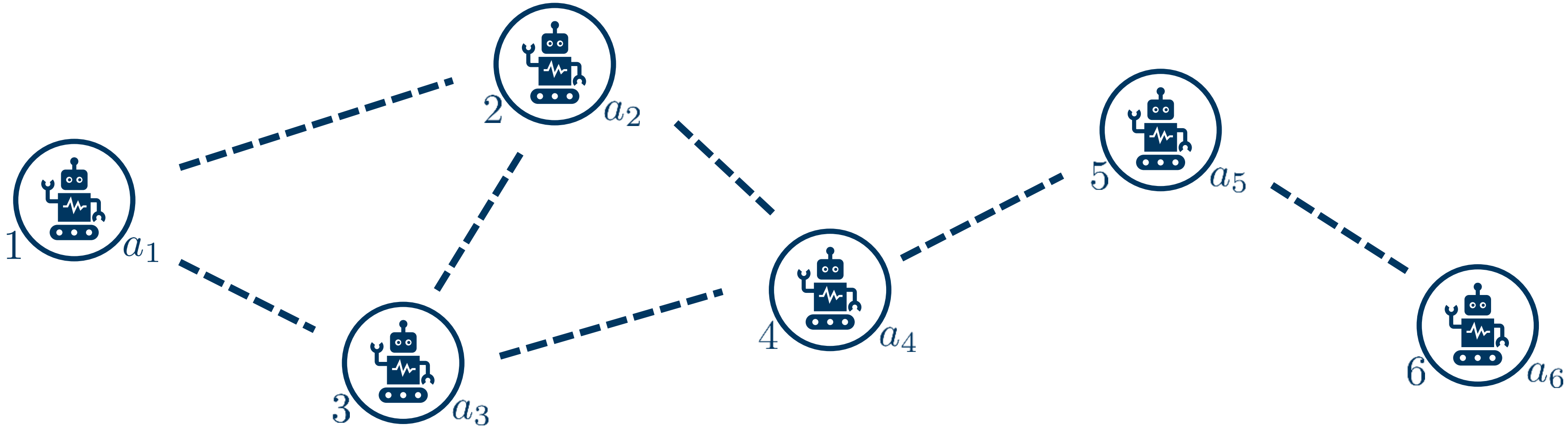


$\pi^\star = \{\{1\},\{2,6\},\{3\},\{4\},\{5,7\}\}$

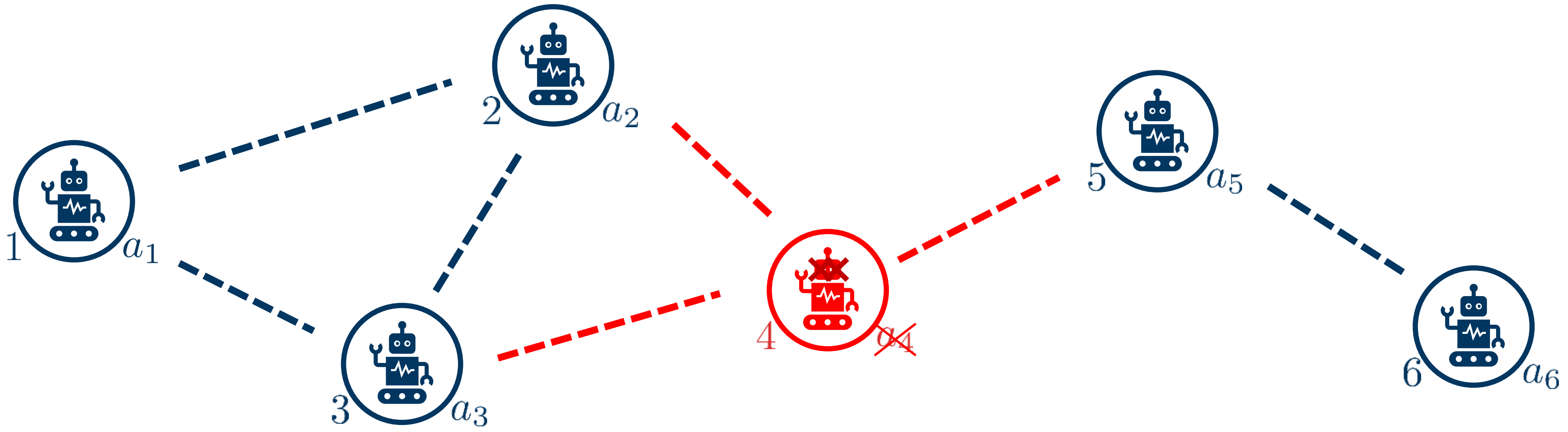
III. Unreliable Communicators

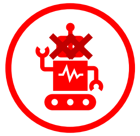


Sub-System Failures

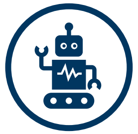


Sub-System Failures



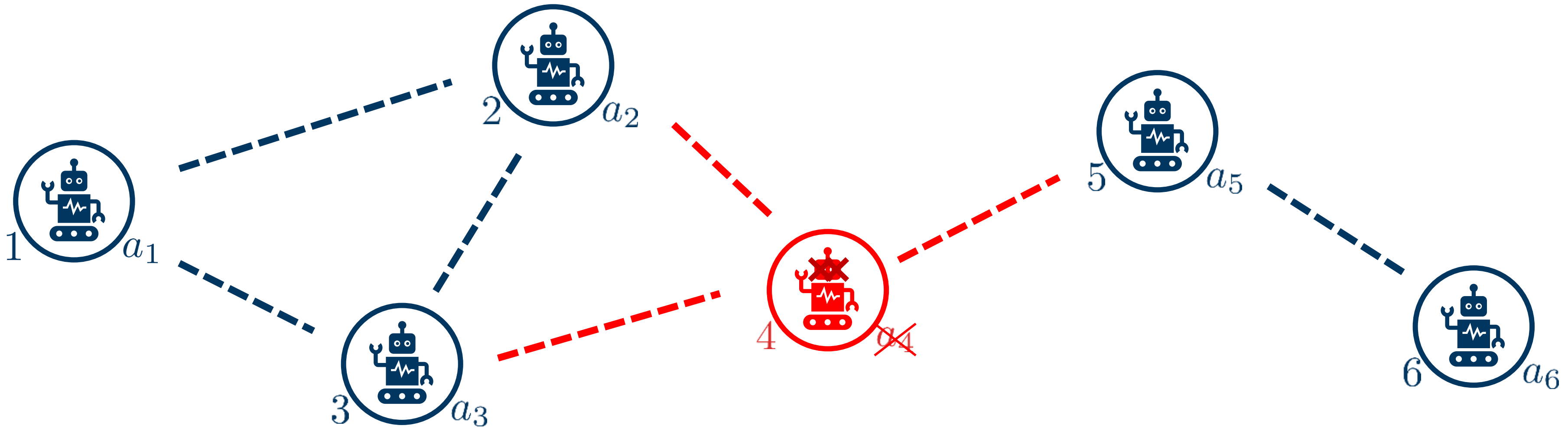


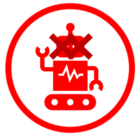
Defective Agent: Agent still communicates but does not contribute to the system objective



Nominal agents cannot determine which agents are defective. They must operate under the assumption some agents might be.

Sub-System Failures





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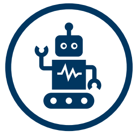
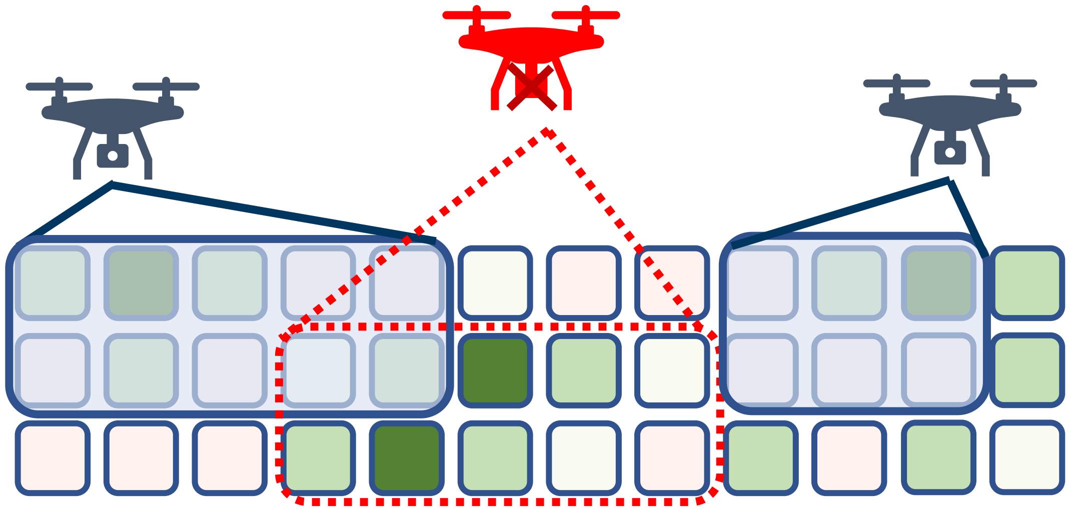


Nominal agents cannot determine which agents are defective.
They must operate under the assumption some agents might be.

How should agents be designed when others may be defective?

Sub-System Failures

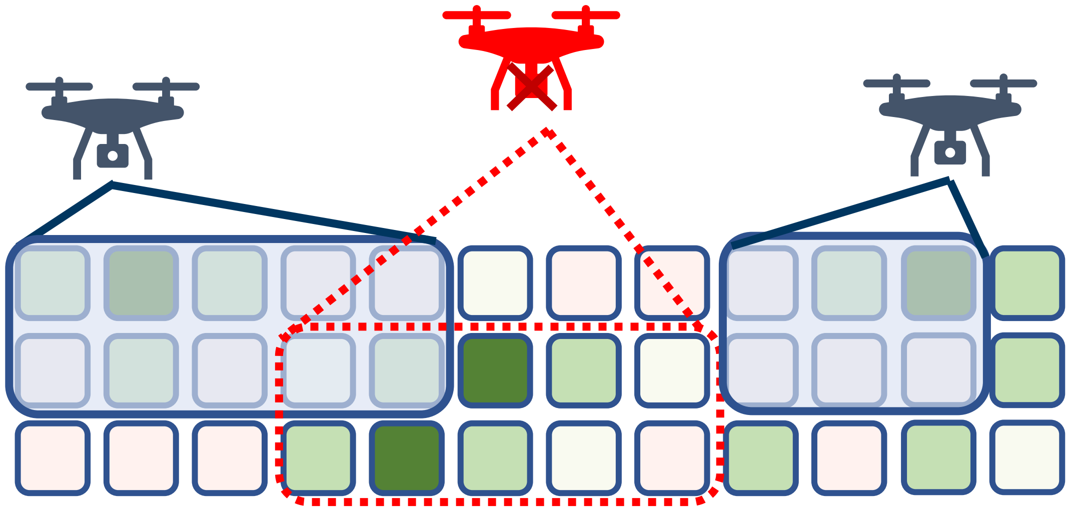


 Nominal Agents $i \in N$

 Defective Agents $j \in D$

with Fixed Action $z_j \in 2^{\mathcal{R}}$

Sub-System Failures



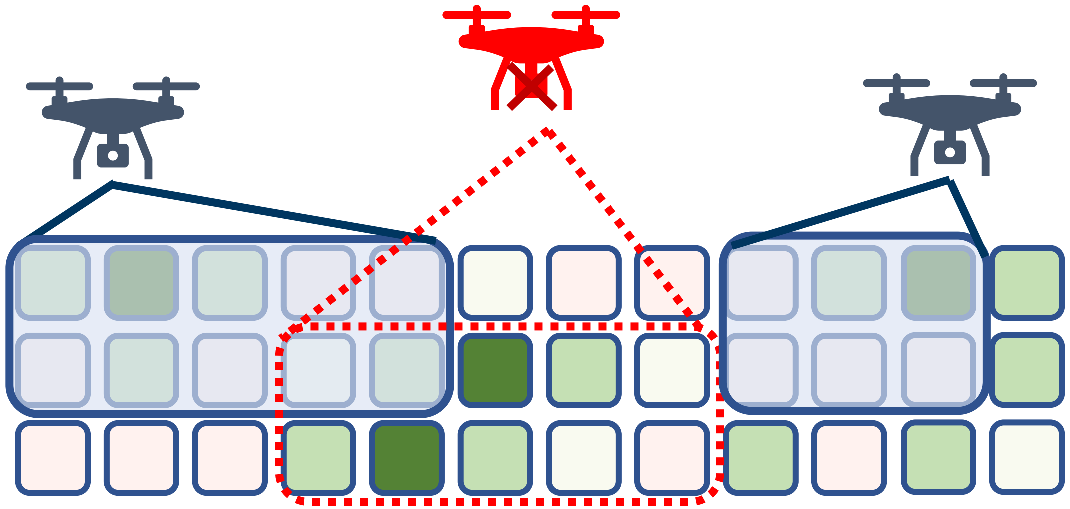
Nominal Agents $i \in N$

Defective Agents with Fixed Action $j \in D$ $\quad z_j \in 2^{\mathcal{R}}$

System Welfare $W(a) = \sum_{r \in \mathcal{R}} v_r w(\underbrace{|a|_r}_{\text{Only depends on regular agents}})$

Utility $U_i(a, z) = \sum_{r \in \mathcal{R}} v_r u(\underbrace{|a|_r + |z|_r}_{\text{Depends on regular } \textbf{\textit{and}} \text{ defective agents}})$

Sub-System Failures



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Utility $U_i(a, z) = \sum_{r \in \mathcal{R}} v_r u(\underbrace{|a|_r + |z|_r}_{\text{Depends on regular \textit{and} defective agents}})$

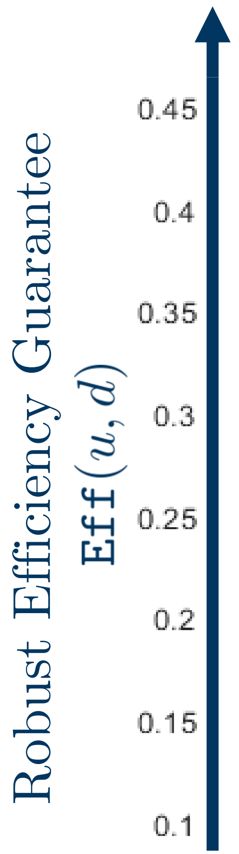
Defective agents can cause nominal agents to avoid high valued resources

Robust Design: choose utility functions to promote more overlap

Proposition 1.3: [CDC21,DGAA]

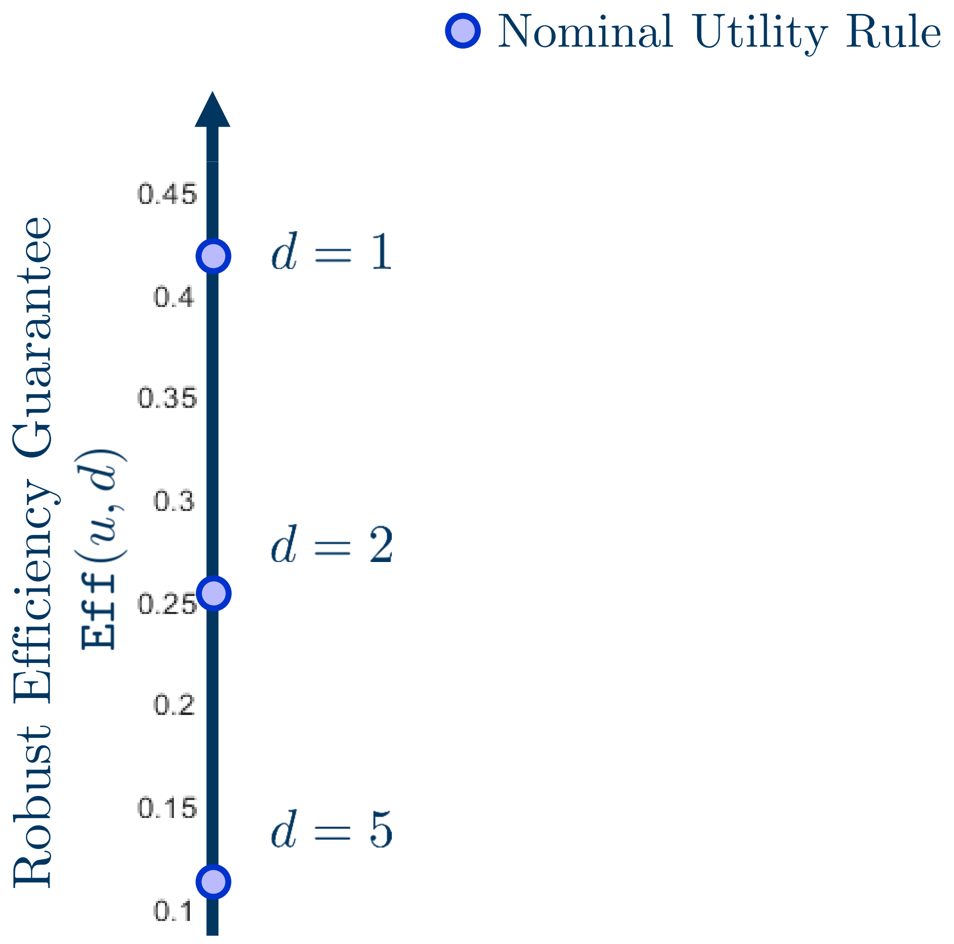
The optimal utility design and associated efficiency is the solution to a linear program.

Nominal/Robust Performance Trade-off



Nominal/Robust Performance Trade-off

In the class of covering games,



$d := \#$ defective agents

Nominal/Robust Performance Trade-off

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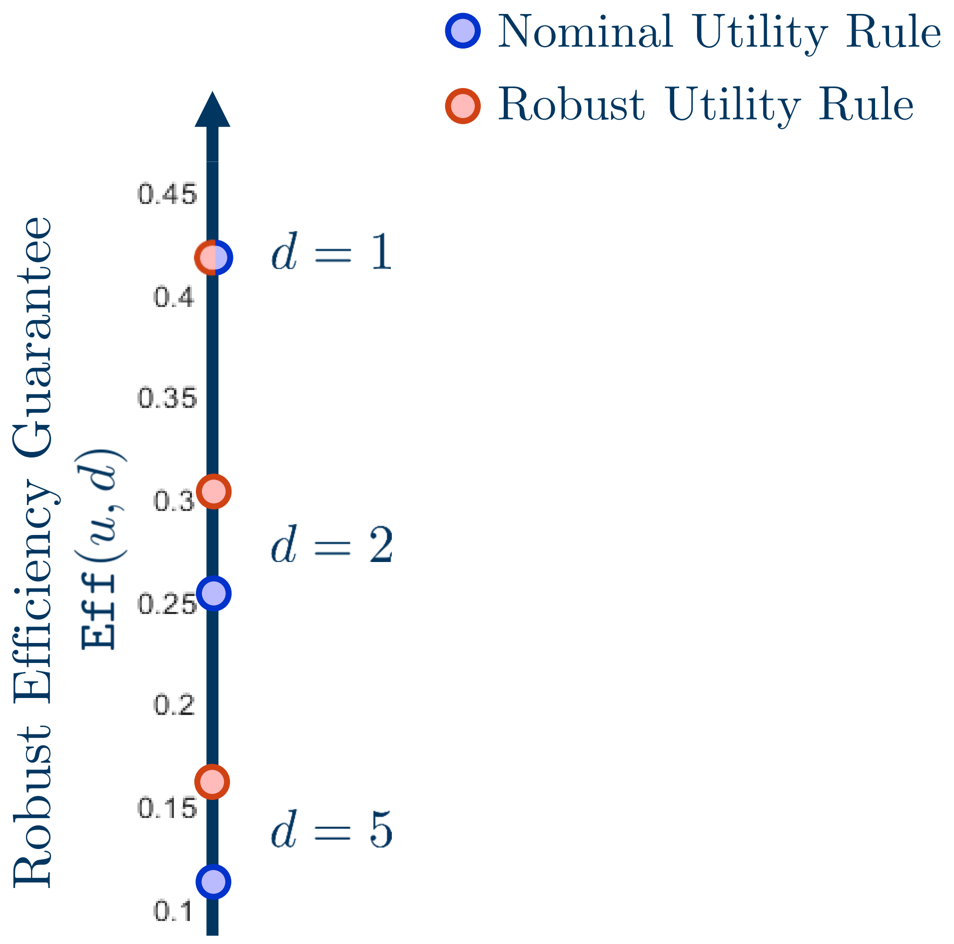


$d :=$ # defective agents

Nominal/Robust Performance Trade-off

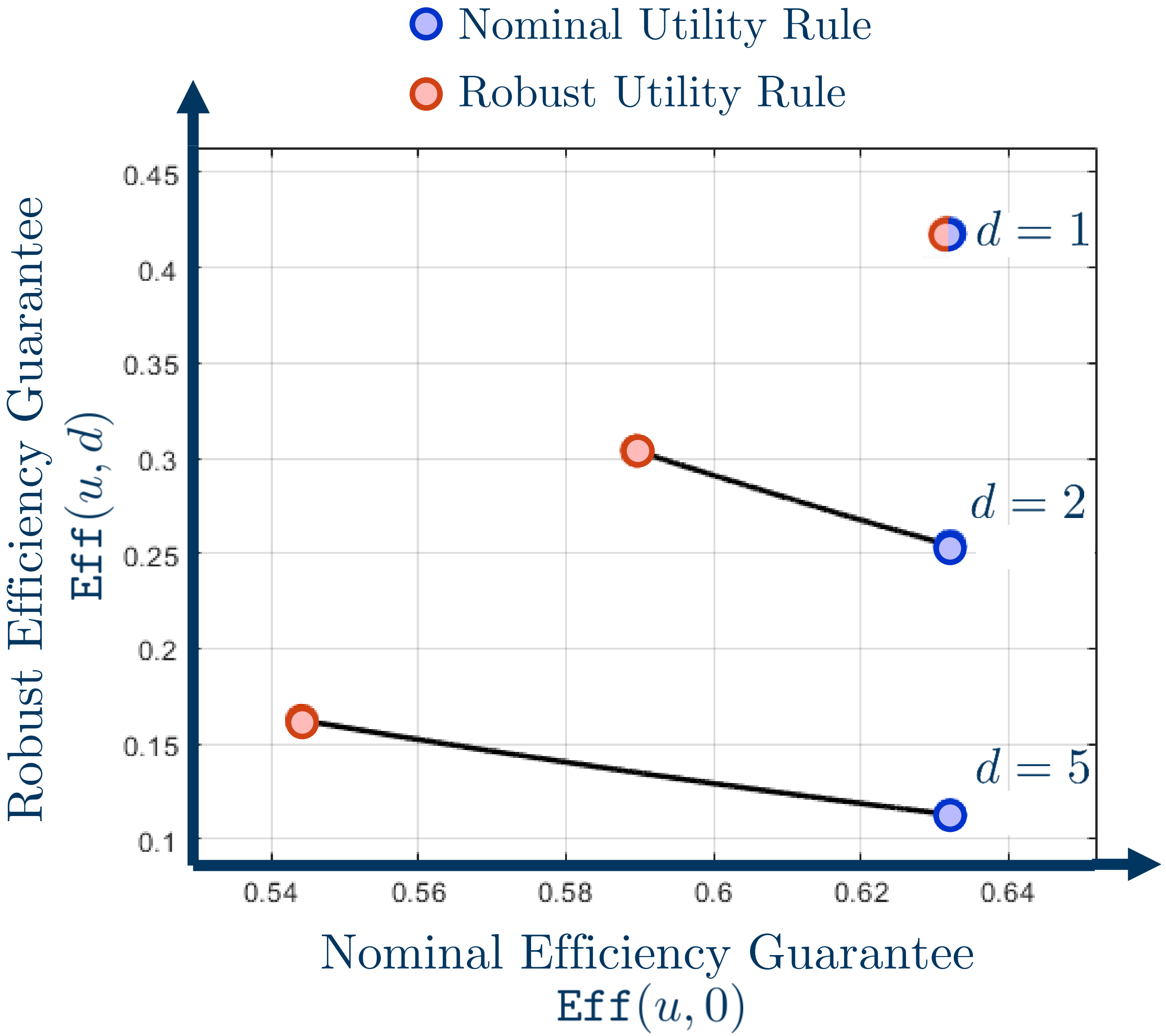
Theorem 1.4 [CDC21, DGAA]

In the class of covering games, if

$$\mathtt{Eff}(u,d) \geq \frac{Z_d + \frac{e}{e-1}}{1+tZ_d},$$

where $Z_d = d!\frac{e-\sum_{i=0}^{d-1}\frac{1}{i!}}{e-1} - 1$ and $t \in [0,1]$, then

$$\mathtt{Eff}(u,0) \leq \frac{(e-1)(1+tZ_d)}{1+(e-1)(1+tZ_d)}.$$



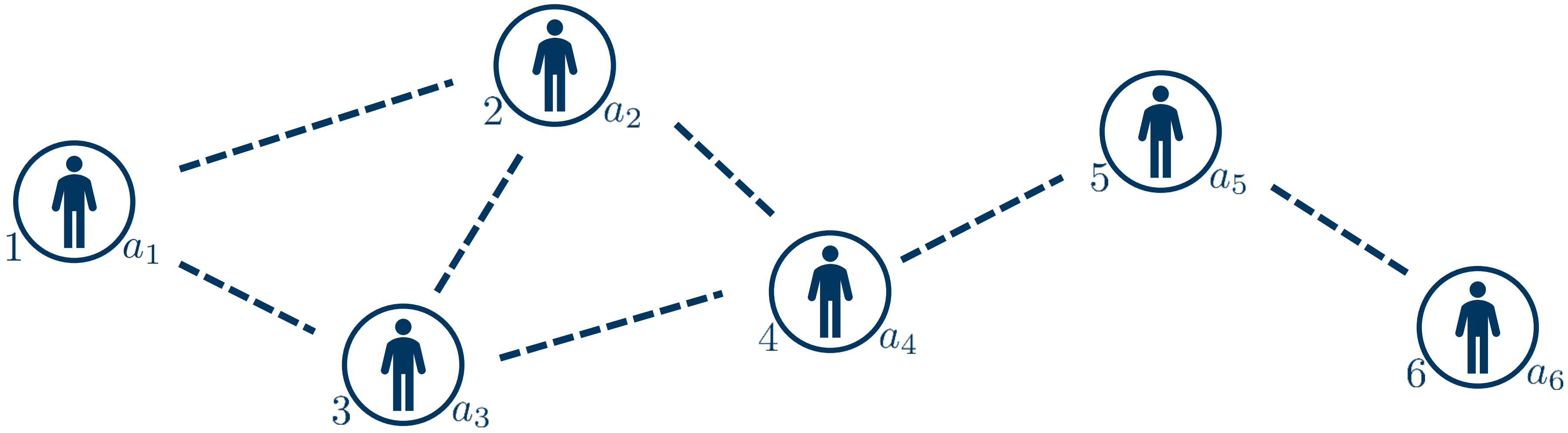
$d :=$ # defective agents

IV. Directions & Conclusions

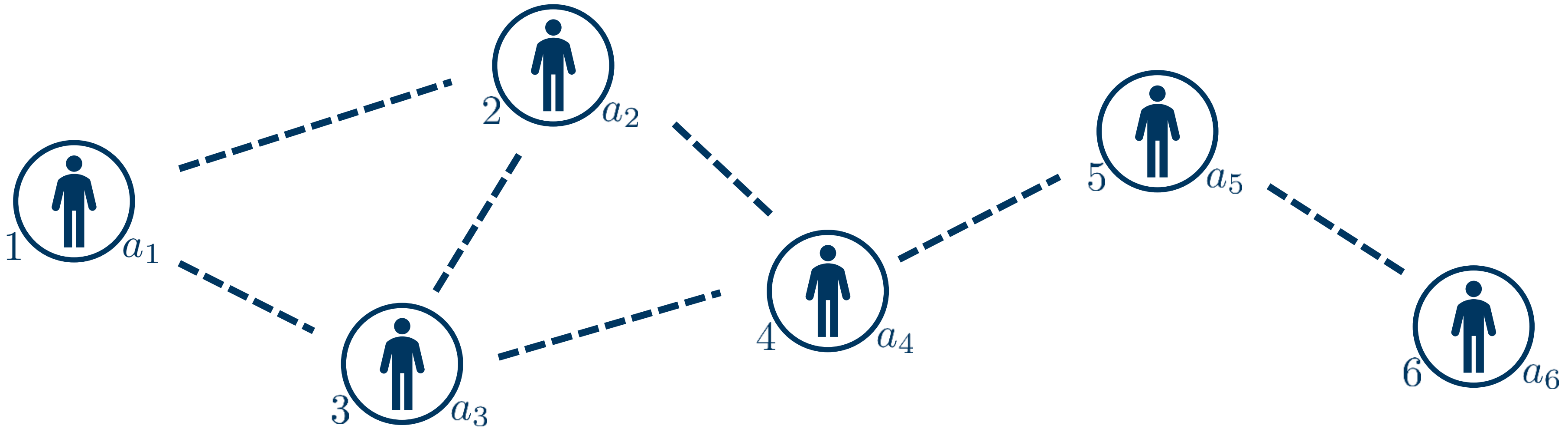
Human Users in Multi-Agent Systems

Human User Agent

Human Users in Multi-Agent Systems

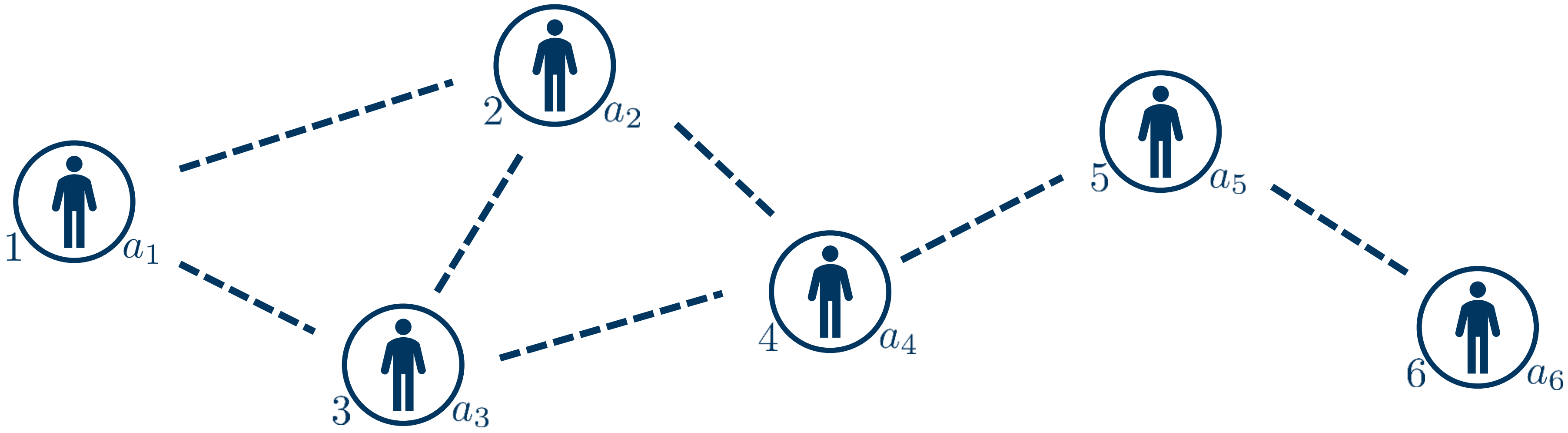


Human Users in Multi-Agent Systems



Preferences
Beliefs → Human Decision a_i → System Behavior $a = (a_1, \ldots, a_n)$

Human Users in Multi-Agent Systems



Preferences
Beliefs → Human Decision
a_i → System Behavior
$a = (a_1, \ldots, a_n)$

How can we influence human users?

Preferences ***Beliefs***

Types of Information Communication (Social Systems)

Agent-to-Agent

Social Networks and Viral Marketing

Agent-to-Infrastructure

Recommender Systems and Advertising

Unreliable Communicators

Belief Propagation and Fake News

Design communication mechanisms to alter ***users' beliefs*** and actions to ultimately guide system behavior

Directions in Socio-Technical Systems

Intersection of ***Engineered*** and ***Social*** systems

Smart services human demand

Autonomous mobility services

Human-robot interaction

Automation with human oversight

Human language AI interfaces

Conclusion

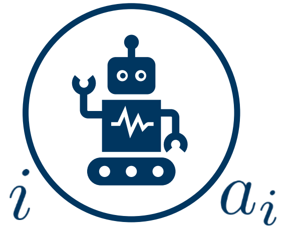
The Role of Communication in Distributed Systems

Share information to strategically alter system behavior

Benefits:
- Increase coordination
- Improve global objective
- Robustness to sub-system failures

Costs:
- Increased complexity
- Unexpected behavior

Understanding benefits/costs can help us design distributed systems more intelligently



References

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Information *as* Control:

The Role of Communication in Distributed Systems

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