Intermittently Connected Robot Networks

Michael M. Zavlanos
Mechanical Engineering & Materials Science
Electrical & Computer Engineering
Computer Science
Duke University

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Networked Systems & Connectivity

Many different (mobile) sensors collecting data that are connected to each other and the infrastructure through dedicated wireless networks.

Goal: Real-time availability of information, which requires connectivity.

Connectivity & Distributed Control

Distributed Optimization Over
Time-Varying Directed Graphs

Angelia Nedić and Alex Olshevsky

Coordination of Groups of Mobile Autonomous
Agents Using Nearest Neighbor Rules

Ali Jadbabaie, Jie Lin, and A. Stephen Morse, *Fellow, IEEE*

Online Distributed Convex Optimization
on Dynamic Networks

Saghar Hosseini, Airlie Chapman, and Mehran Mesbahi

Α Σαδδλε Ποιντ Αλγοριτημ φορ Νετωορκεδ
Ονλινε Χονϖεξ Οπτιμιζατιον

Αλεξ Κοππελ, Φελιχια Ψ. Θακυβιεχ, ανδ Αλεϕανδρο Ριβειρο

Distributed Random Projection Algorithm
for Convex Optimization

Soomin Lee and Angelia Nedić

**Distributed Continuous-Time Convex Optimization
on Weight-Balanced Digraphs**

Bahman Gharesifard and Jorge Cortés

Distributed Constrained Optimization by
Consensus-Based Primal-Dual Perturbation Method

Tsung-Hui Chang, *Member, IEEE*, Angelia Nedić, *Member, IEEE*, and Anna Scaglione, *Fellow, IEEE*

Multi-Agent Distributed Optimization
via Inexact Consensus ADMM

Tsung-Hui Chang, *Member, IEEE*, Mingyi Hong, and Xiangfeng Wang

A Distributed Newton Method for Network
Utility Maximization–I: Algorithm

Ermin Wei, *Student Member, IEEE*, Asuman Ozdaglar, *Member, IEEE*, and Ali Jadbabaie, *Senior M*

**Proximal Alternating Direction Method of Multipliers for Distribut
Optimization on Weighted Graphs**

De Meng, Maryam Fazel and Mehran Mesbahi

Every distributed control and
optimization algorithm **assumes** some
form of connectivity of the underlying
communication graph

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From Connectivity Control to Intermittent Communication

Connectivity Control

- Graph theoretic methods
  [Kim, TAC, 2006], [Ji, TRO, 2007], [Zavlanos, TRO, 2008], [Savla, SICON, 2009], [Z
  [Franceschelli, Aut, 2013], [Sabattini, IJRR, 2013], and many more…
- Realistic communication models
  [Lindhe, CDC, 2010], [Ghaffarkhah, TAC, 2011], [Fink, IEEE, 2012], [Yan, TRO, 2012], [Zavlanos, TAC, 2013]

…but due to uncertainty in the wireless channel it is impossible to ensure all-time connectivity in practice

Intermittent Communication Frameworks

- Consensus and Coverage Control
  [Wen, IJRNC, 2014], [Wang, TAC, 2010]
- Delay Tolerant Networks
  [Jones, TMC, 2007], [Costa, JSAC, 2008]
- Event-based Network Control
  [Tabuada, TAC, 2007], [Wang, TAC, 2011], [Dimarogonas et al, TAC, 2012], [Seyboth, Aut, 2013]

Assume connectivity infinitely often

Intermittent Communication Applications

Communications-Limited Environments

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Outline

Distributed Intermittent Communication Control

Distributed Intermittent Communication Control with Independent Temporal Tasks

Distributed Intermittent Communication Control for Collaborative State Estimation

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Problem Formulation

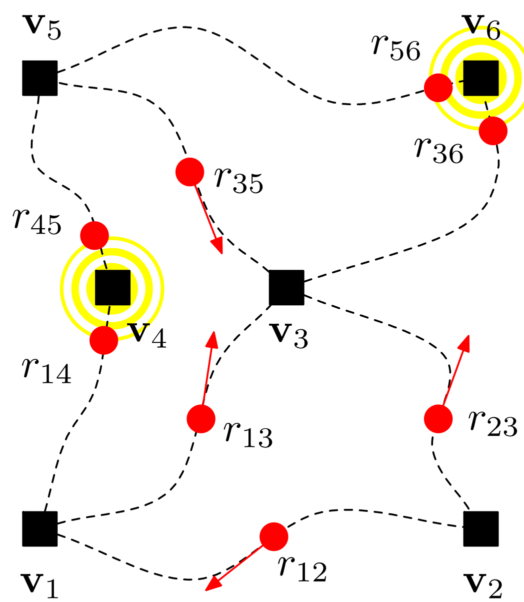
Assume R communication points positioned at $\mathbf{v}_i \in \mathbb{R}^n$

Paths $\gamma_{ij} : [0,1] \to \mathbb{R}^n$ that connect nodes i and j.

N mobile robots r_{ij} move back and forth between nodes i and j along the path.

Communication at node i occurs if

$$\|\mathbf{x}_{ij} - \mathbf{v}_i\| \leq \epsilon, \ \ \forall\, r_{ij} \in \mathcal{N}_i$$



The communication network is ***connected over time*** if communication at every node occurs infinitely often. In disconnect mode, the robots can accomplish other tasks.

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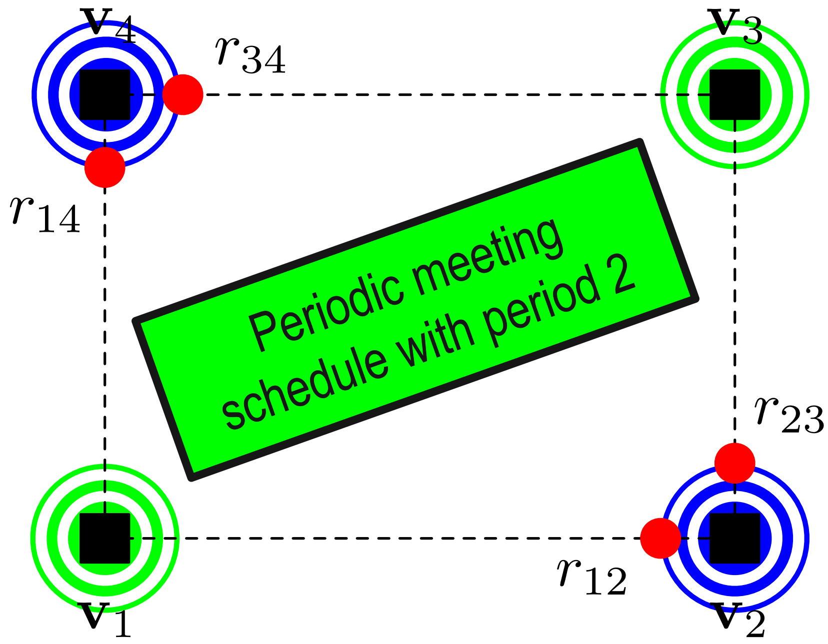
Lets build some intuition…



Policy: Move to a meeting point and stay there forever or until the other robots arrive

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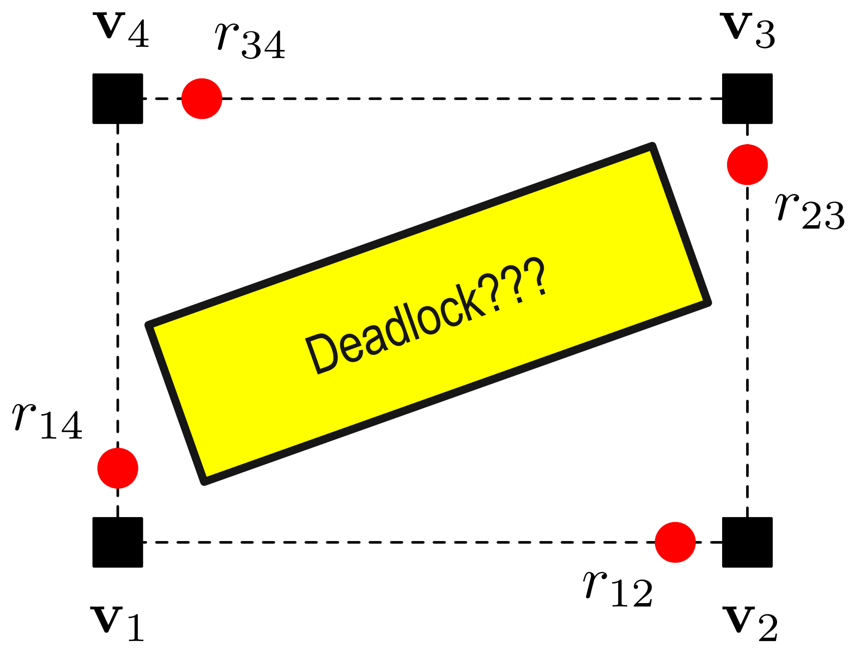
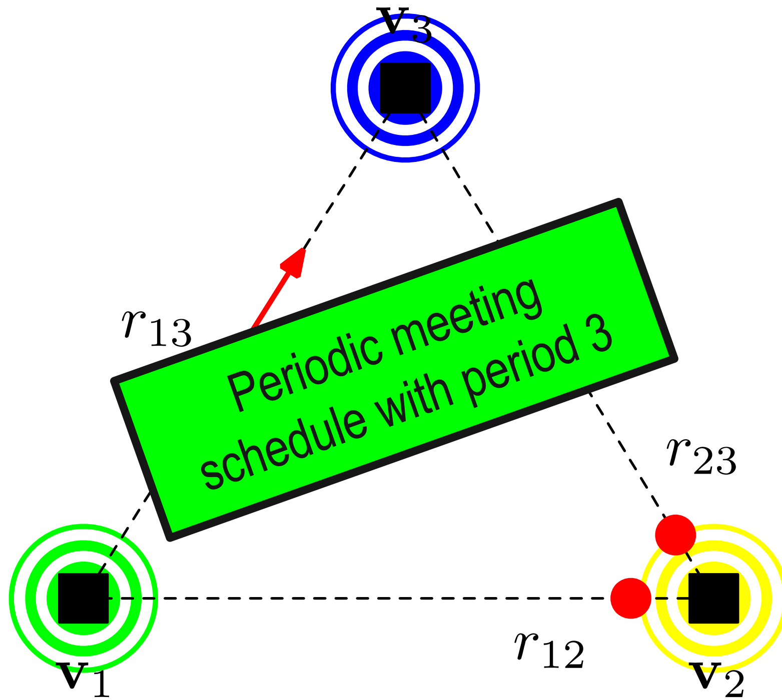
What if we change the initial condition?



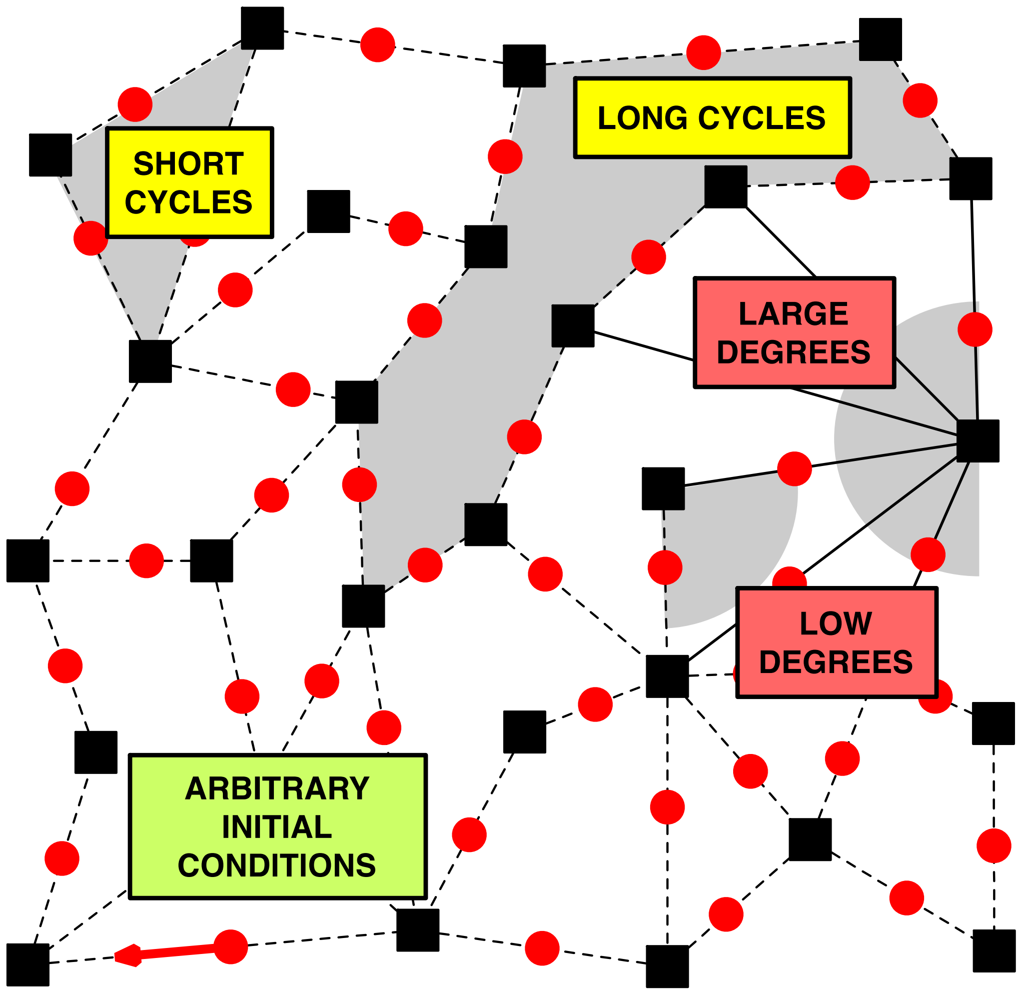
Policy: Move to a meeting point and stay there forever or until the other robots arrive

What if we change the mobility graph?

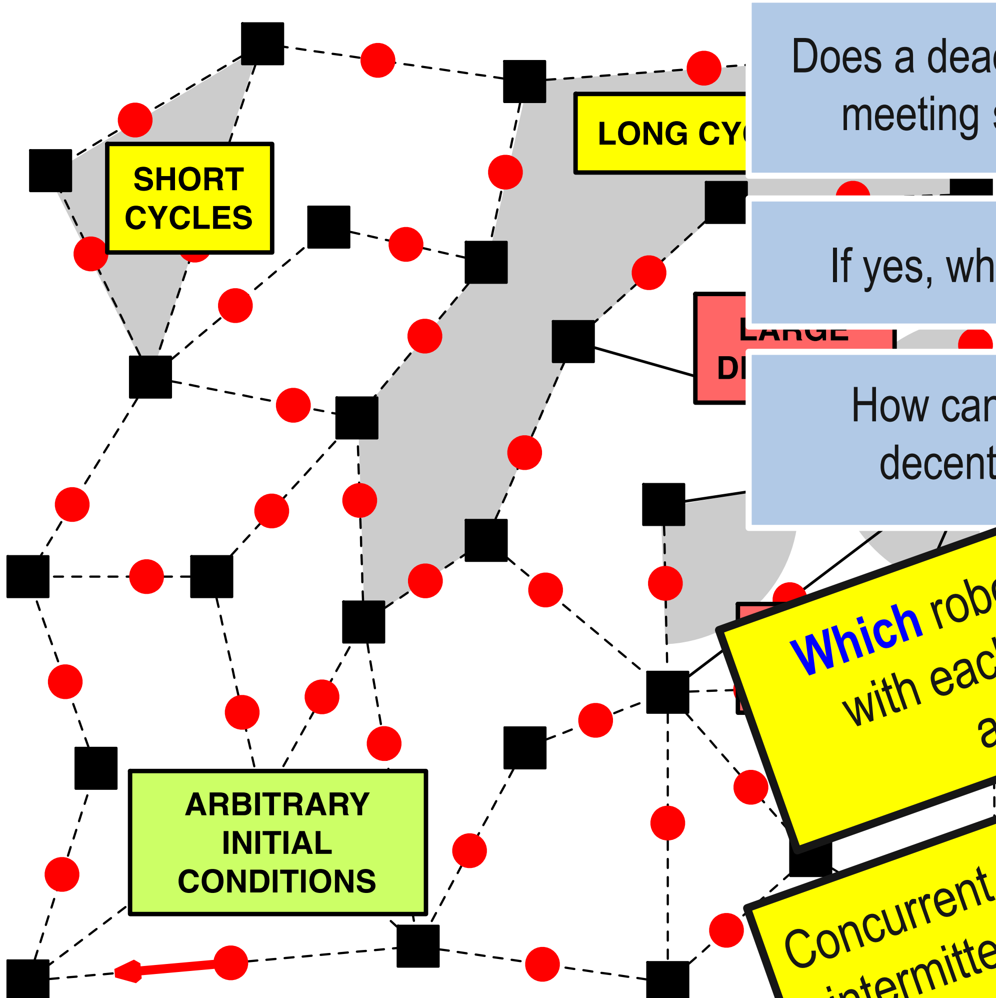


Policy: Move to a meeting point and stay there forever or until the other robots arrive

Intermittent communication over arbitrary graphs?



Challenges



Does a deadlock-free periodic meeting schedule exist?

If yes, what is the period?

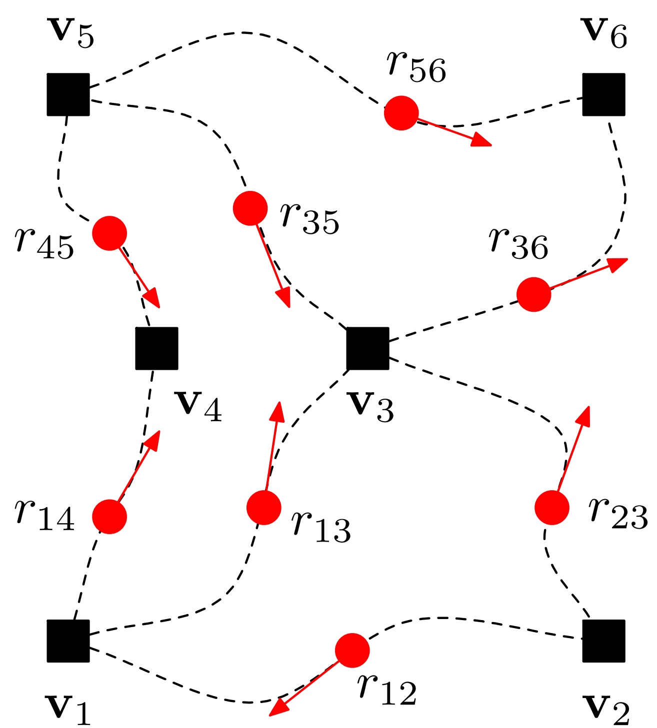
How can we find it in a decentralized way?

Which robots should meet with each other, **where**, and **when**?

Concurrent **task planning** and intermittent communication?

Problem Formulation

Given any initial configuration of the robots in the mobility graph $\mathcal{G}$ determine distributed controllers for all robots such that connectivity of the communication graph is guaranteed over time, infinitely often.



Linear Temporal Logic (LTL)

LTL is a formal type of logic that consists of Boolean and temporal operators defined over a set of atomic propositions/predicates.

Syntax: $\phi ::= \text{true} \mid \pi \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid \bigcirc \phi \mid \phi_1 \mathcal{U} \phi_2$

Set $\mathcal{AP}$ of Atomic Propositions (Boolean variables).

Example: $\pi_{ij}^{\mathbf{v}_i} = \begin{cases} 1 & \text{if robot } r_{ij} \text{ is in location } \mathbf{v}_i \\ 0 & \text{otherwise} \end{cases}$

Other useful temporal operators:

- Always $\Box$
- Eventually $\Diamond$
- Infinitely often $\Box\Diamond$

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Mathematical Formulation

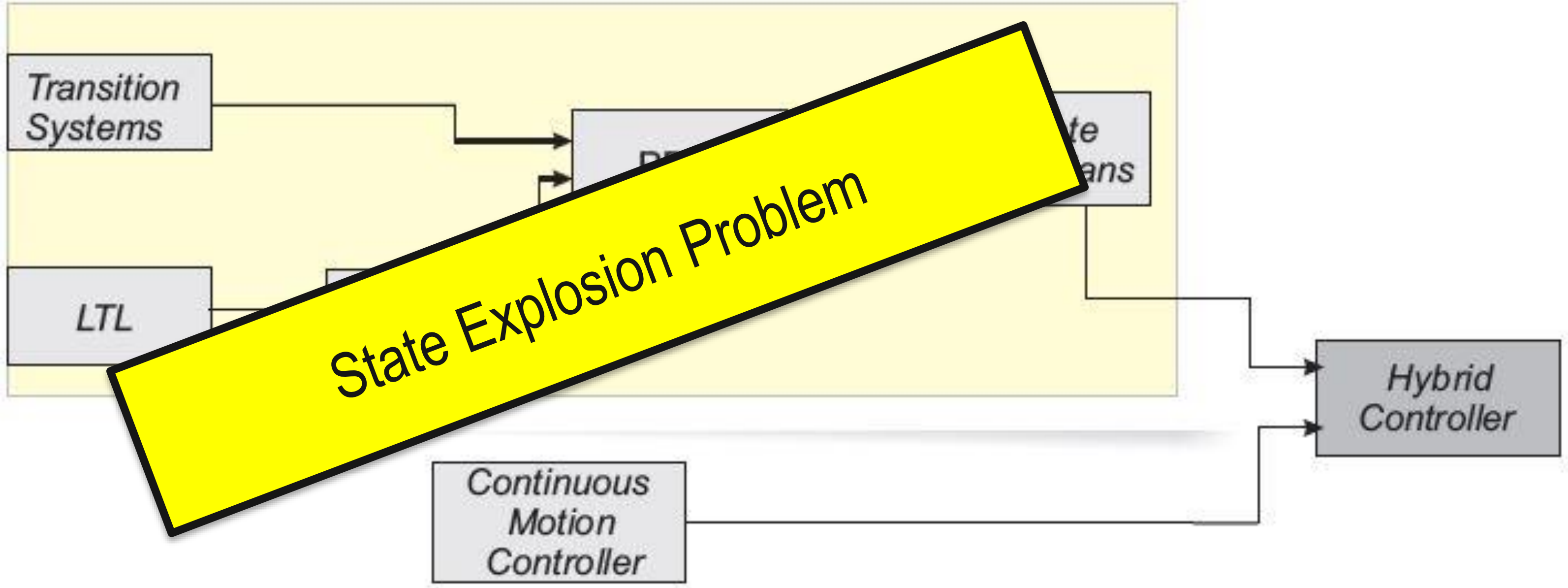
All robots adjacent to every meeting point should meet at their assigned meeting point infinitely often, i.e.,

$$\phi = \bigwedge_{i=1}^{R} \left(\Box \Diamond \bigwedge_{j \in \mathcal{N}_i} \pi_{ij}^{\mathbf{v}_i} \right)$$

where $\pi_{ij}^{\mathbf{v}_i} = \begin{cases} 1 & \text{if } \|\mathbf{x}_{ij} - \mathbf{v}_i\| \leq \epsilon \\ 0 & \text{otherwise} \end{cases}$

for a sufficiently small $\epsilon > 0$.

Automata-based Plan Synthesis



Robot Mobility Abstraction

Motion is abstracted by a Transition System (TS): $TS_{ij} = \{\mathcal{Q}_{ij}, q_{ij}^0, \rightarrow_{ij}, \mathcal{A}_{ij}, \mathcal{AP}, L_{ij}\}$

State-Space: $\mathcal{Q}_{ij} = \{q_{ij}^{\mathbf{v}_i}, q_{ij}^{\mathbf{v}_j}\}$

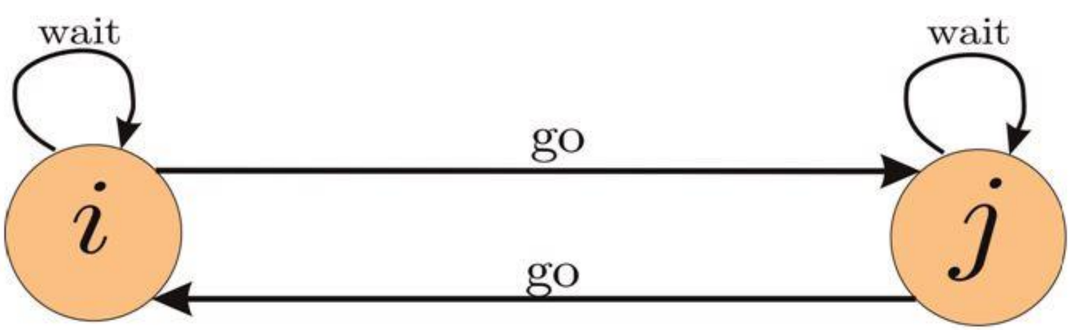
Initial state: q_{ij}^0

Transition relation: $\rightarrow_{ij} \subseteq \mathcal{Q}_{ij} \times \mathcal{A}_{ij} \times \mathcal{Q}_{ij}$

Action set: $\mathcal{A}_{ij}$

Atomic propositions: $\mathcal{AP}$

Labeling function: $L_{ij} : \mathcal{Q}_{ij} \rightarrow 2^{\mathcal{AP}}$



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Decomposition of Global LTL Specification

Global LTL specification: $\phi = \bigwedge_{i=1}^{R} \left(\Box\Diamond \bigwedge_{j \in \mathcal{N}_i} \pi_{ij}^{\mathbf{v}_i} \right)$

Decomposition of ϕ into local LTL specification: $\phi_{\mathbf{v}_i}$

such that $\phi = \bigwedge_{i=1}^{R} \phi_{\mathbf{v}_i}$ and $\phi_{\mathbf{v}_i} = \Box\Diamond \left(\bigwedge_{j \in \mathcal{N}_i} \pi_{ij}^{\mathbf{v}_i} \right)$

Discrete motion plans $\tau_{\mathbf{v}_i} \models \phi_{\mathbf{v}_i}$ such that

$$\tau_{\mathbf{v}_i} = \underbrace{\left[\underbrace{(q_{ij_1}^{0}, q_{ij_2}^{0}, \ldots, q_{ij_{|\mathcal{N}_i|}}^{0})}_{\text{Initial robot states}}, \underbrace{(q_{ij_1}^{\mathbf{v}_i}, q_{ij_2}^{\mathbf{v}_i}, \ldots, q_{ij_{|\mathcal{N}_i|}}^{\mathbf{v}_i})}_{\text{Robots move to node i}} \right]}_{\text{Plan Prefix}} \underbrace{\left[\underbrace{(q_{ij_1}^{\mathbf{v}_i}, q_{ij_2}^{\mathbf{v}_i}, \ldots, q_{ij_{|\mathcal{N}_i|}}^{\mathbf{v}_i})}_{\text{Robots wait indefinitely at node i}} \right]^{\omega}}_{\text{Plan Suffix}}$$

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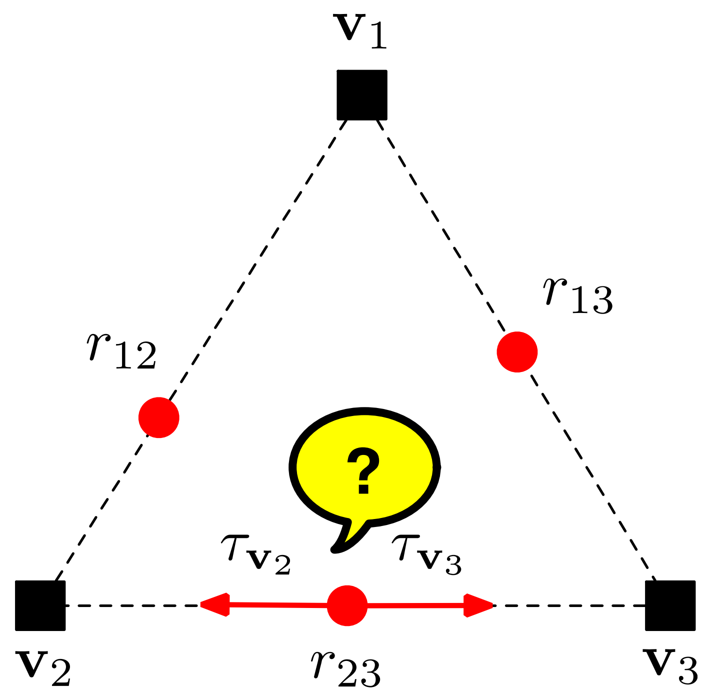
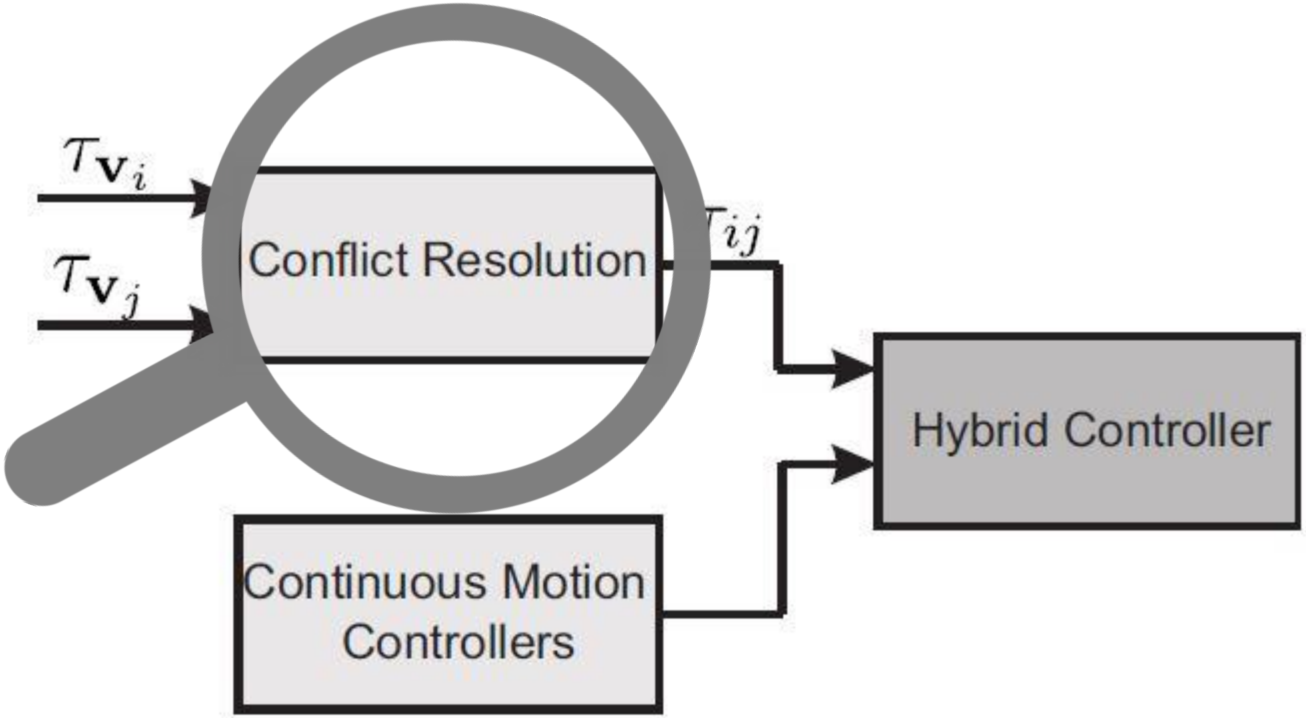
Conflicting Robot Behaviors



Distributed Control Synthesis



Conflict Resolution

General structure of motion plan τ_{ij} as an infinite sequence of states

$$\tau_{ij} = \tau_{ij}(1)\tau_{ij}(2)\cdots = [\tau_{ij}(m)]_{m=1}^{\infty}$$

Rewrite motion plan τ_{ij} as an infinite sequence of finite paths p_{ij}^k as $\tau_{ij} = [p_{ij}^k]_{k=1}^{\infty}$

where

$$p_{ij}^k = \overbrace{X \ldots X \; \Pi|_{TS_{ij}}\tau_{\mathbf{v}_i}(k) \; X \ldots X \; \Pi|_{TS_{ij}}\tau_{\mathbf{v}_j}(k) \; X \ldots X}^{\text{length } \ell = \max\{d_{\mathbf{v}_i}\}_{i=1}^{R} + 1}$$

Robot waits at the previous state

Projection of the k-th state of plan $\tau_{\mathbf{v}_i}$ onto TS_{ij}

Projection of the k-th state of plan $\tau_{\mathbf{v}_j}$ onto TS_{ij}

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Correctness

Proposition: The proposed algorithm can always construct finite paths p_{ij}^{k} with length at most equal to $\ell = \max\{d_{\mathbf{v}_i}\}_{i=1}^{R} + 1$.

Proposition: The proposed algorithm generates admissible discrete motion plans τ_{ij} , i.e., motion plans that are free of conflicts and satisfy the transition rule $\rightarrow_{ij}$.

Proposition: The composition of motion plans τ_{ij} generated by the proposed algorithm satisfies the global LTL expression, i.e., connectivity of the robot network is ensured over time, infinitely often.

Proposition: The proposed algorithm generates discrete motion pl prefix-suffix structure, i.e., $\tau_{ij} = \tau_{ij}^{\text{pre}}[\tau_{ij}^{\text{suf}}]^{\omega}$.

The motion plans can also be executed in an **asynchronous** way

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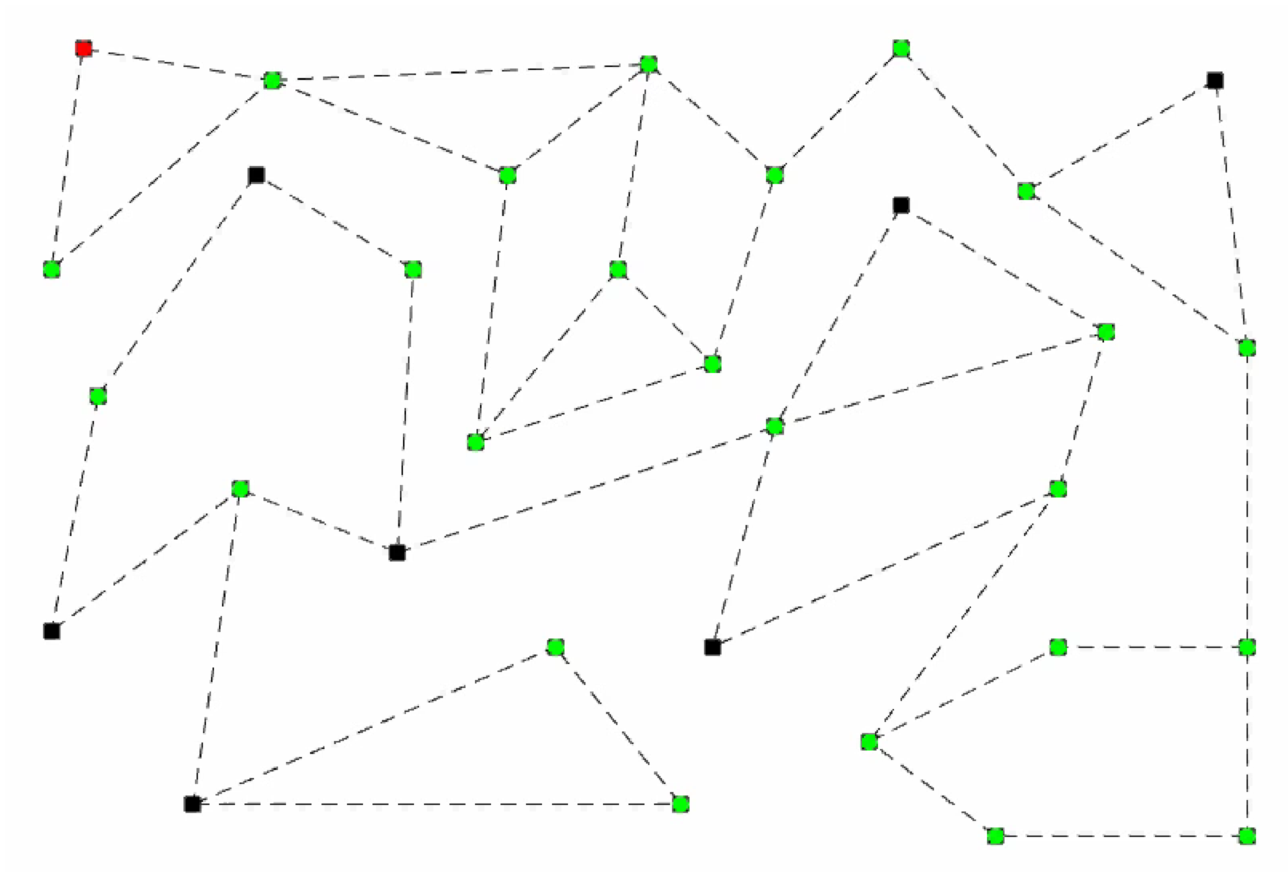
Numerical Experiments

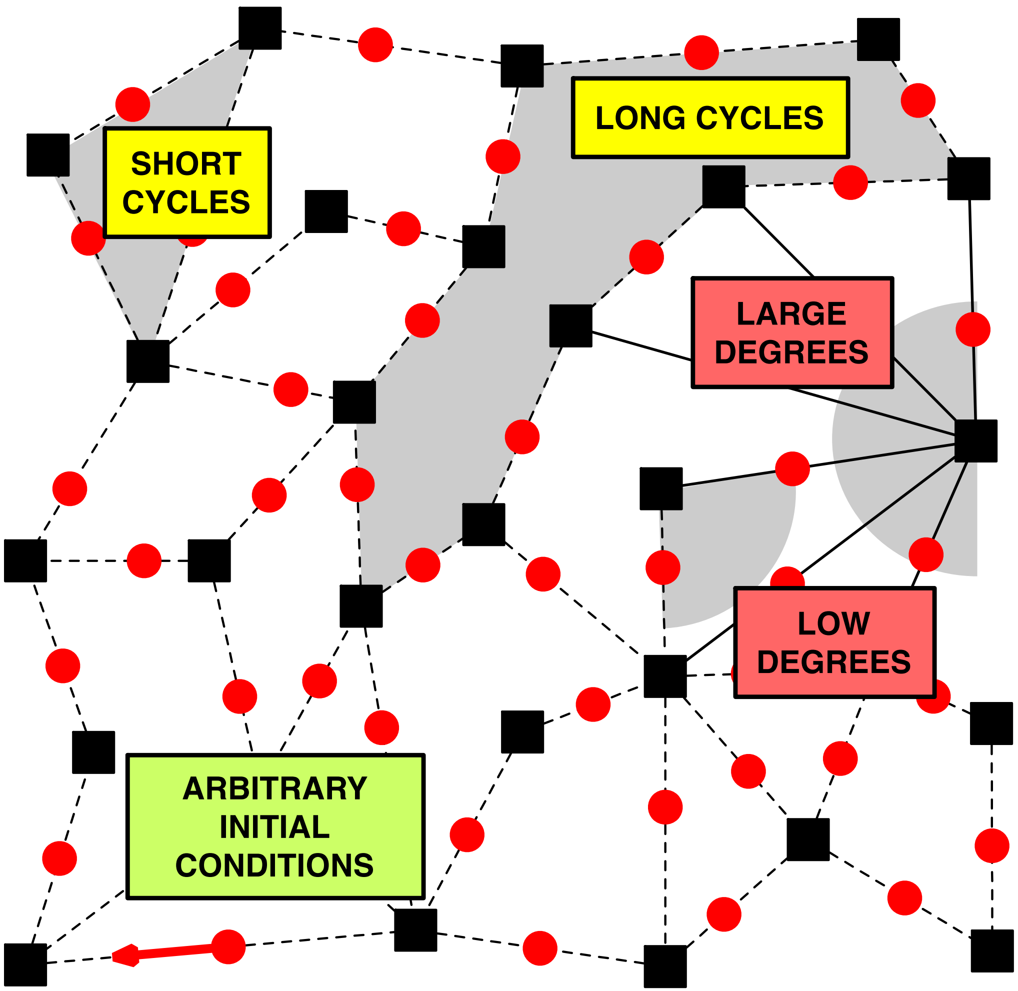


$$|\mathcal{Q}_{PBA}| = |\mathcal{Q}_{PTS}| \cdot |\mathcal{Q}_B|$$

$$2^{42} = 4,398,046,511,104$$

Impossible to use available model checking methods to solve this problem

Challenges



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Distributed Intermittent Communication Control

Distributed Intermittent Communication Control with Independent Temporal Tasks

Distributed Intermittent Communication Control for Collaborative State Estimation

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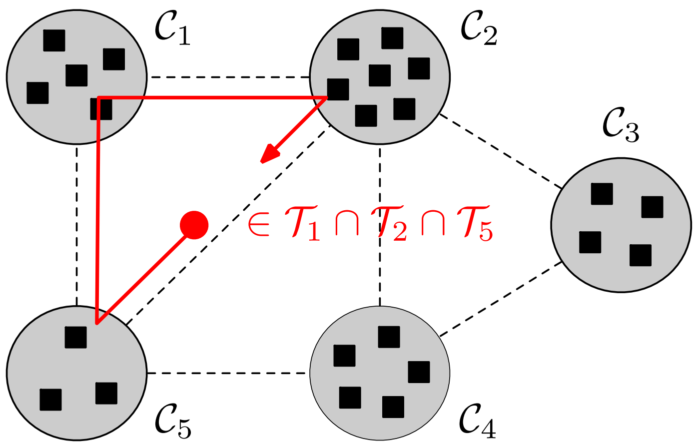
Incorporating Temporal Tasks

Robots are divided in M teams $\{\mathcal{T}_m\}_{m=1}^{M}$

Multiple possible communication points for team $\mathcal{T}_m$ in the set $\mathcal{C}_m$

Every robot can belong to **more than two** teams



Intermittent connectivity requirement

$$\phi_{\text{comm}} = \bigwedge_{m=1}^{M} \left(\square \lozenge \left(\bigvee_{\mathbf{v}_j \in \mathcal{C}_m} \left(\wedge_{i \in \mathcal{T}_m} \pi_i^{\mathbf{v}_j} \right) \right) \right)$$

Every robot also has independent tasks modeled by LTL formulas ϕ_i

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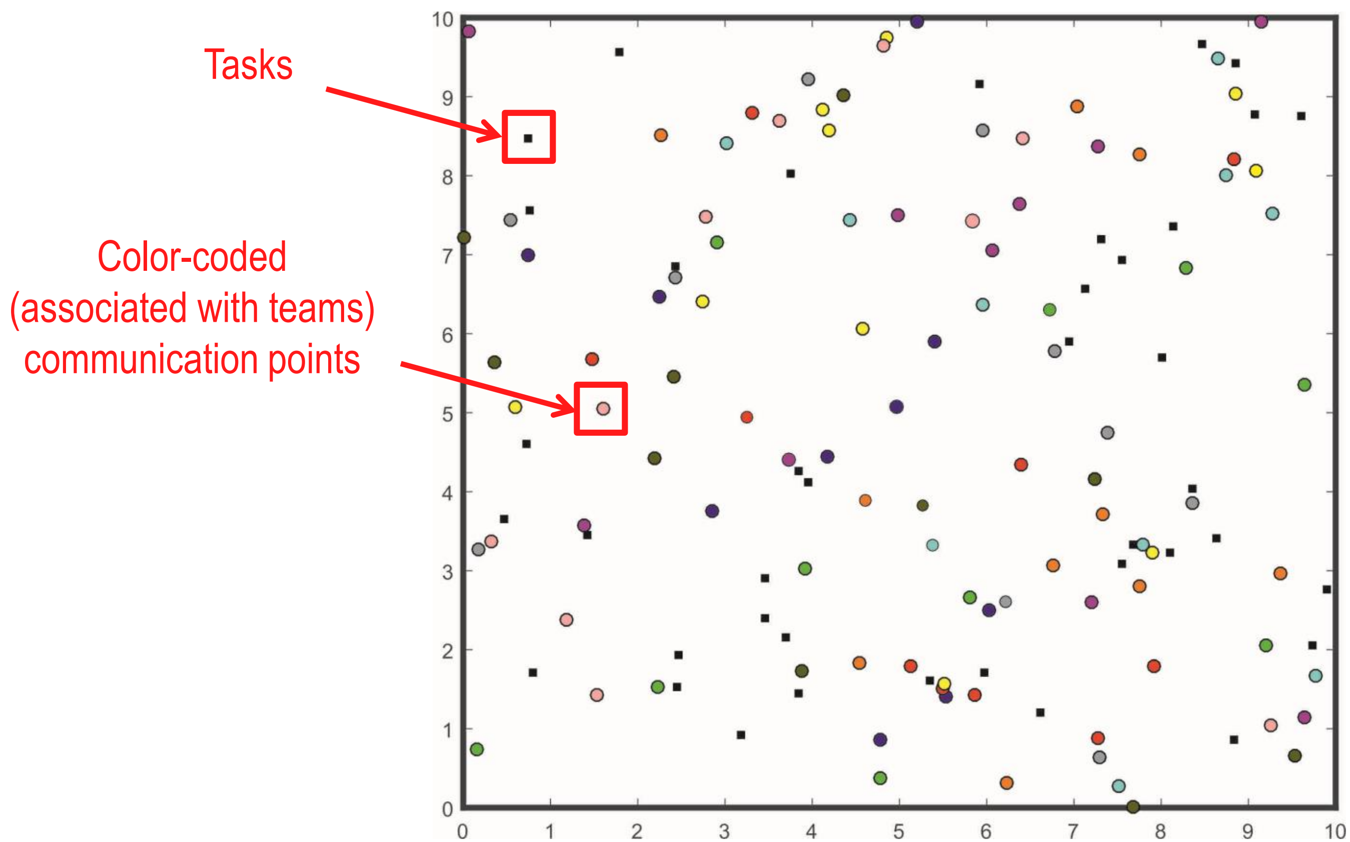
Example Temporal Tasks

Visit locations 8, 10, 12, 19, 24, and 34 infinitely often.

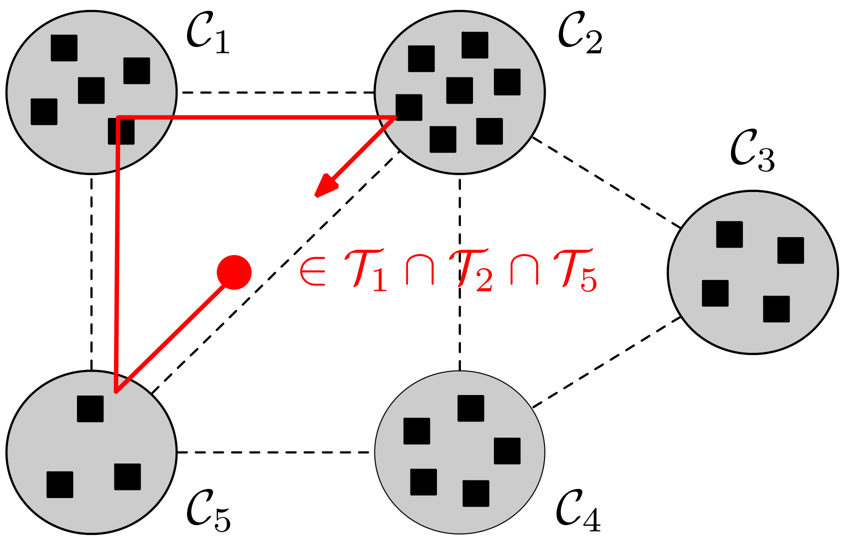
$$\phi_7 = (\square\lozenge\pi_7^{\mathbf{v}_8}) \wedge (\square\lozenge\pi_7^{\mathbf{v}_{10}}) \wedge (\square\lozenge\pi_7^{\mathbf{v}_{12}}) \wedge (\square\lozenge\pi_7^{\mathbf{v}_{24}}) \wedge (\square\lozenge\pi_7^{\mathbf{v}_{34}}) \wedge (\square\lozenge\pi_7^{\mathbf{v}_{19}})$$



Temporal Task Planning under Intermittent Communication

Determine minimum cost discrete motion plans τ_{ij} whose composition satisfies the global LTL statement

$$\phi = (\wedge_i \phi_i) \wedge \phi_{\text{comm}}$$



Meeting locations are **not pre-determined** so the resulting motion plans determine a **sequence meeting times (not locations)** for all robots in every team.

How can we embed these meeting schedules in space?

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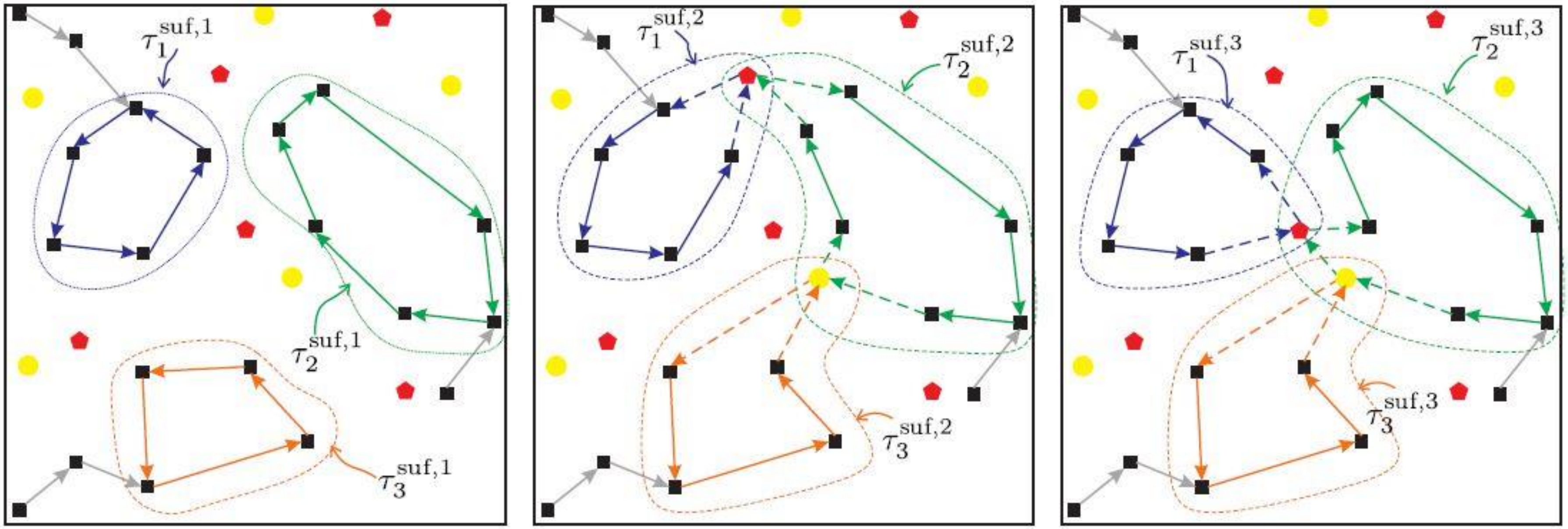
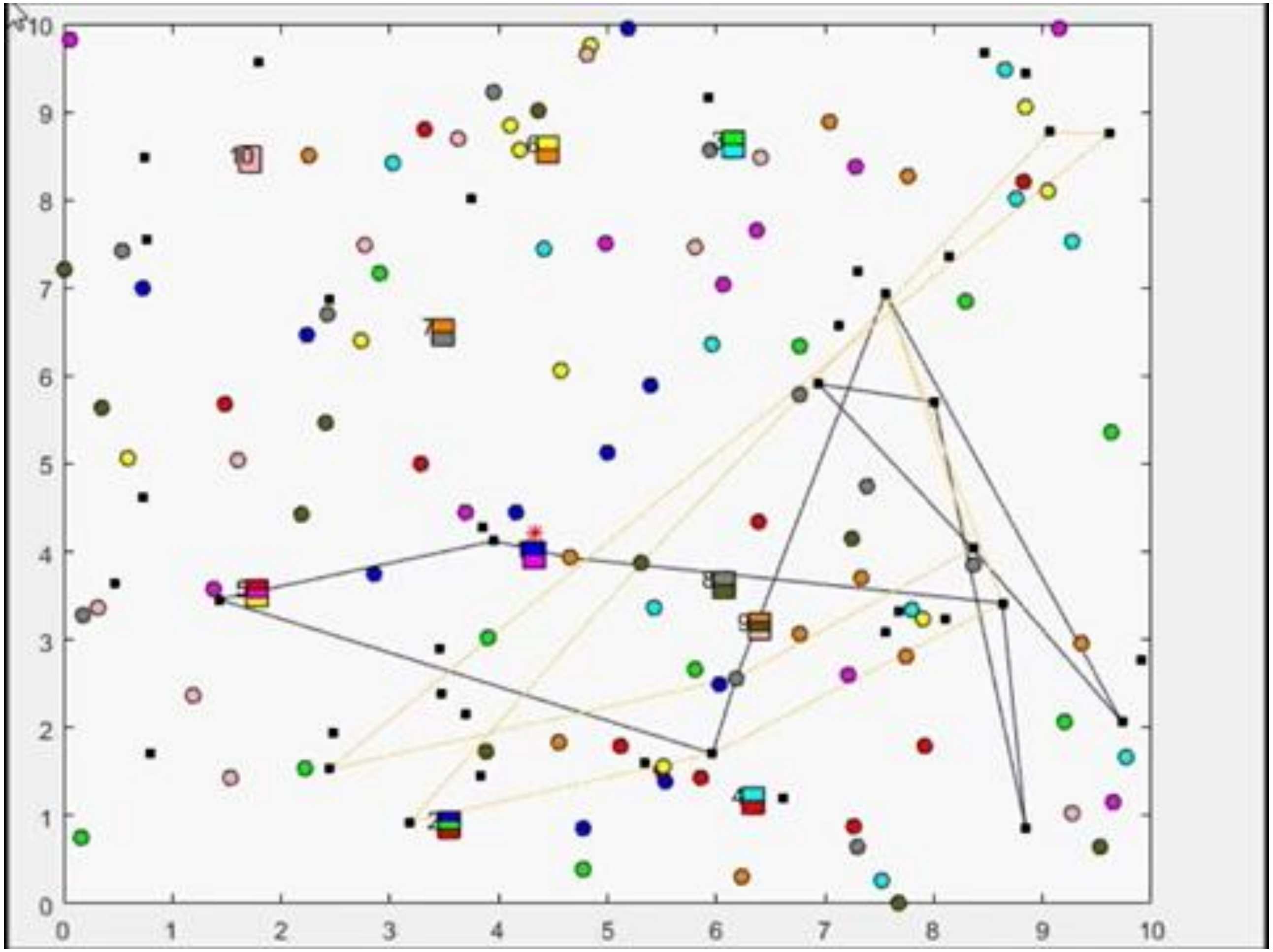
Distributed Control Synthesis

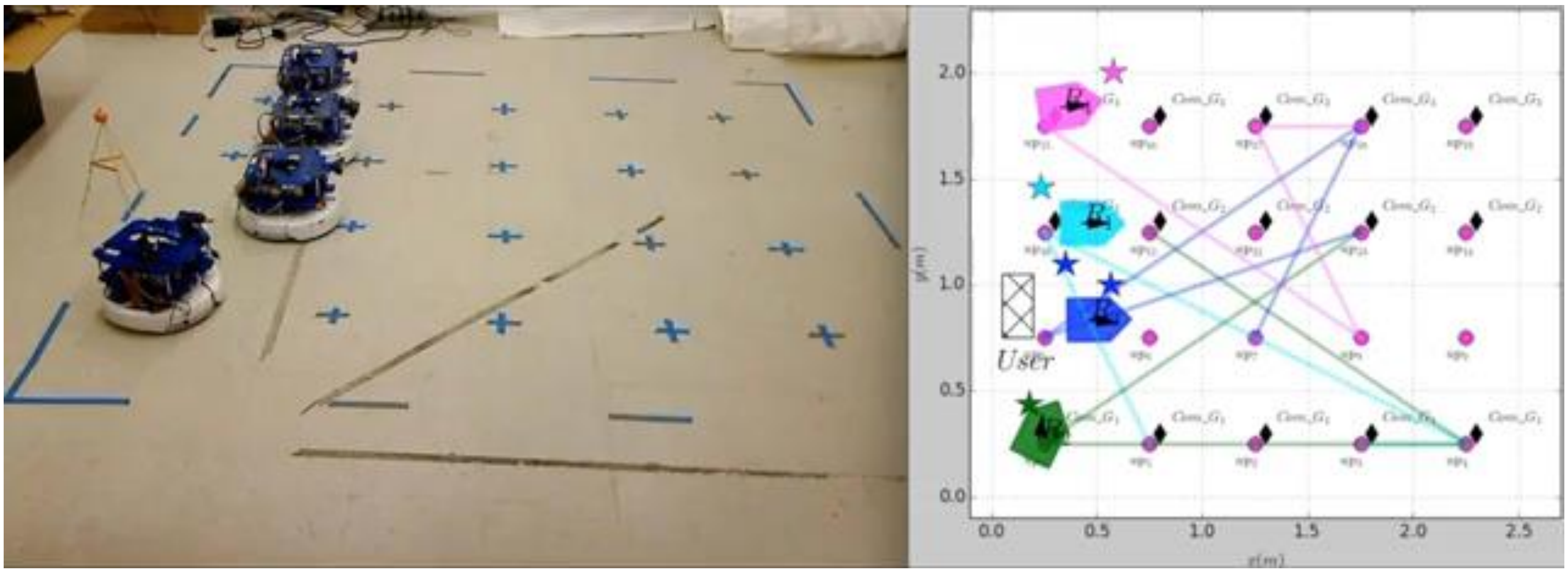


- Construct motion plans that satisfy the LTL-based tasks.
- Revise their suffix parts so that common communication points for all robots within a team are selected and incorporated into the suffix structures in an optimal way.

Numerical Experiments



Experimental Validation



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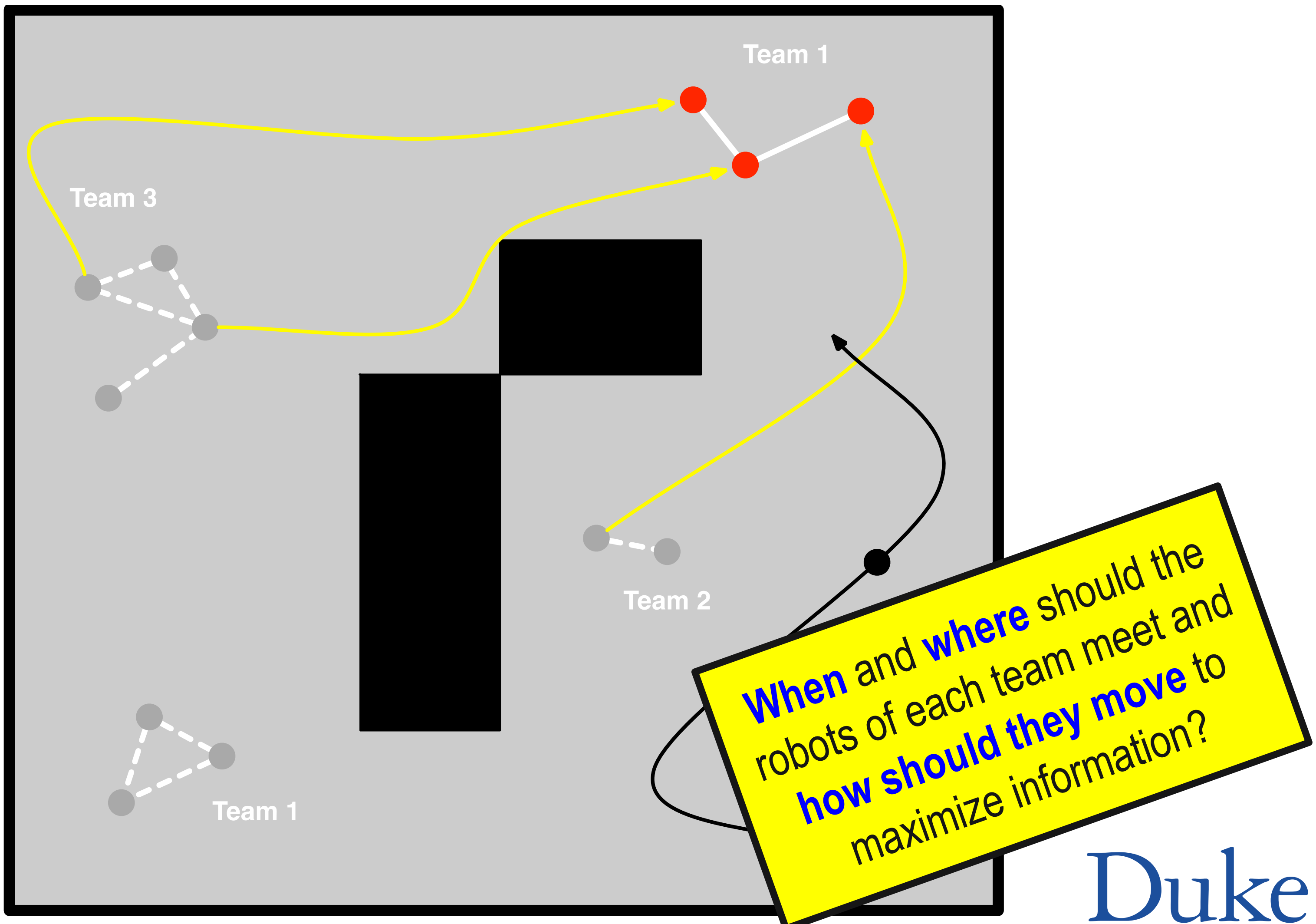
Information-Driven Intermittent Communication Control



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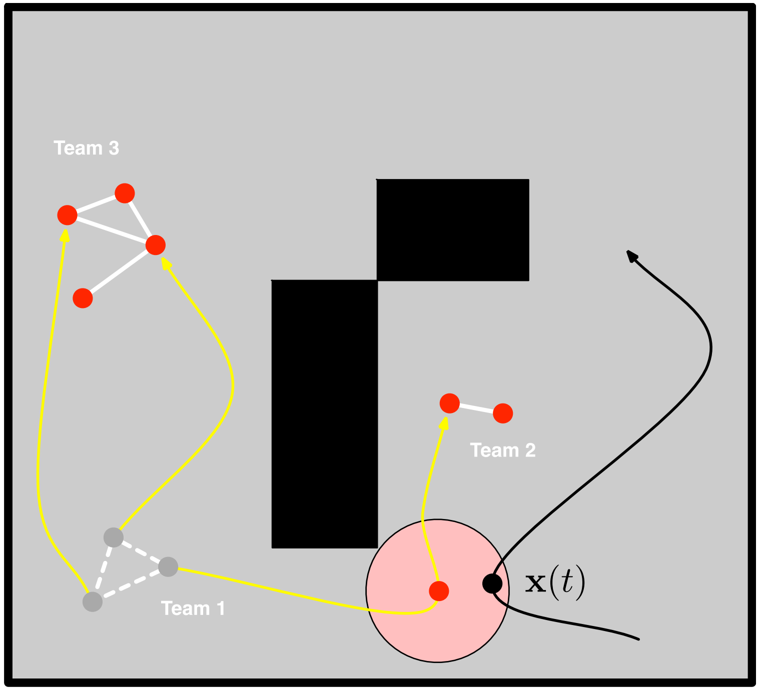
Information-Driven Intermittent Communication Control



Unknown state: $\mathbf{x}(t+1) = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t), \mathbf{w}(t))$

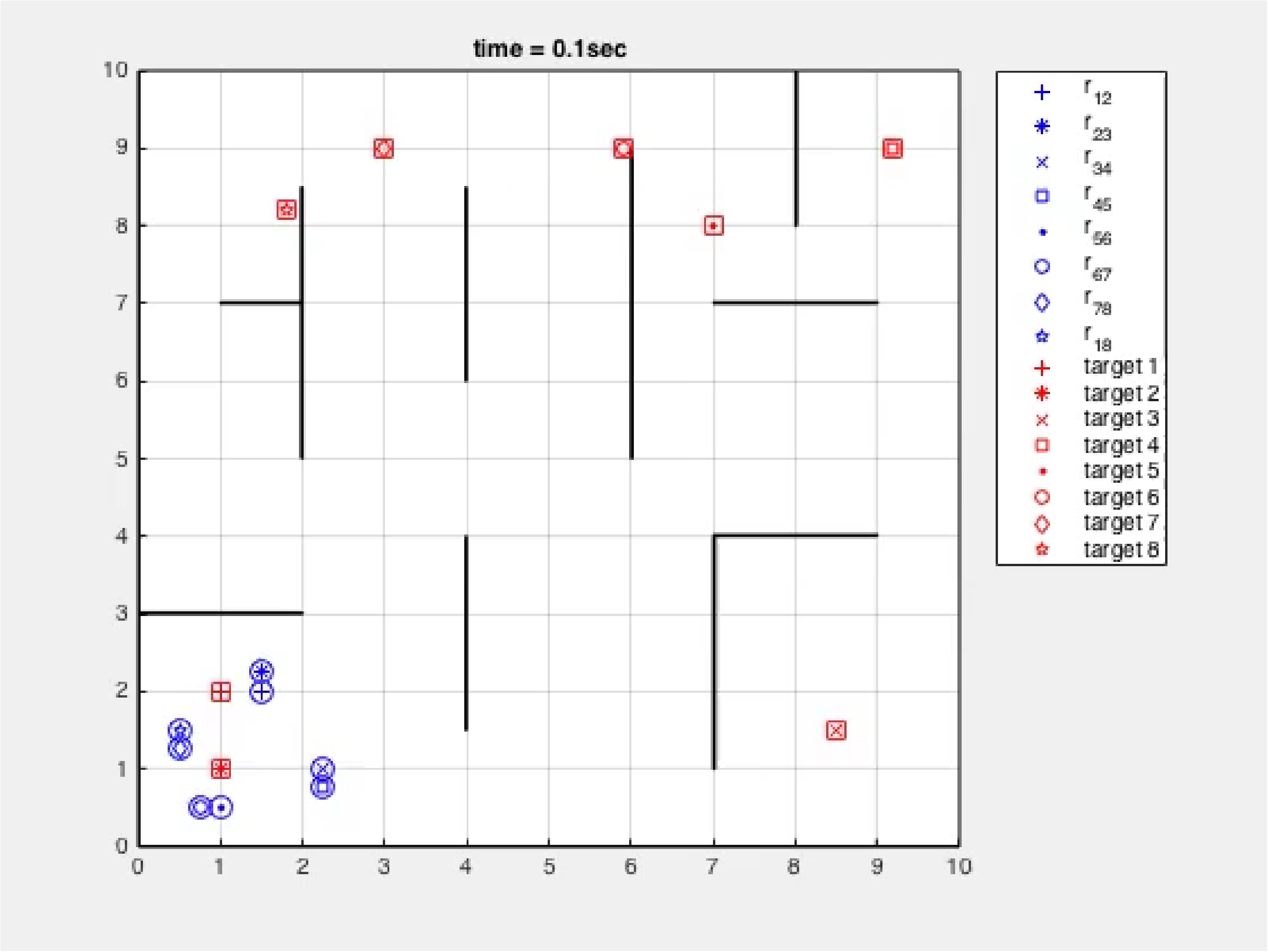
Measurement model: $\mathbf{y}(t, \mathbf{q}) = \mathbf{h}(\mathbf{x}(t), \mathbf{q}, \mathbf{v}(t))$

N robots divided into *M* teams $\{\mathcal{T}_m\}_{m=1}^{M}$

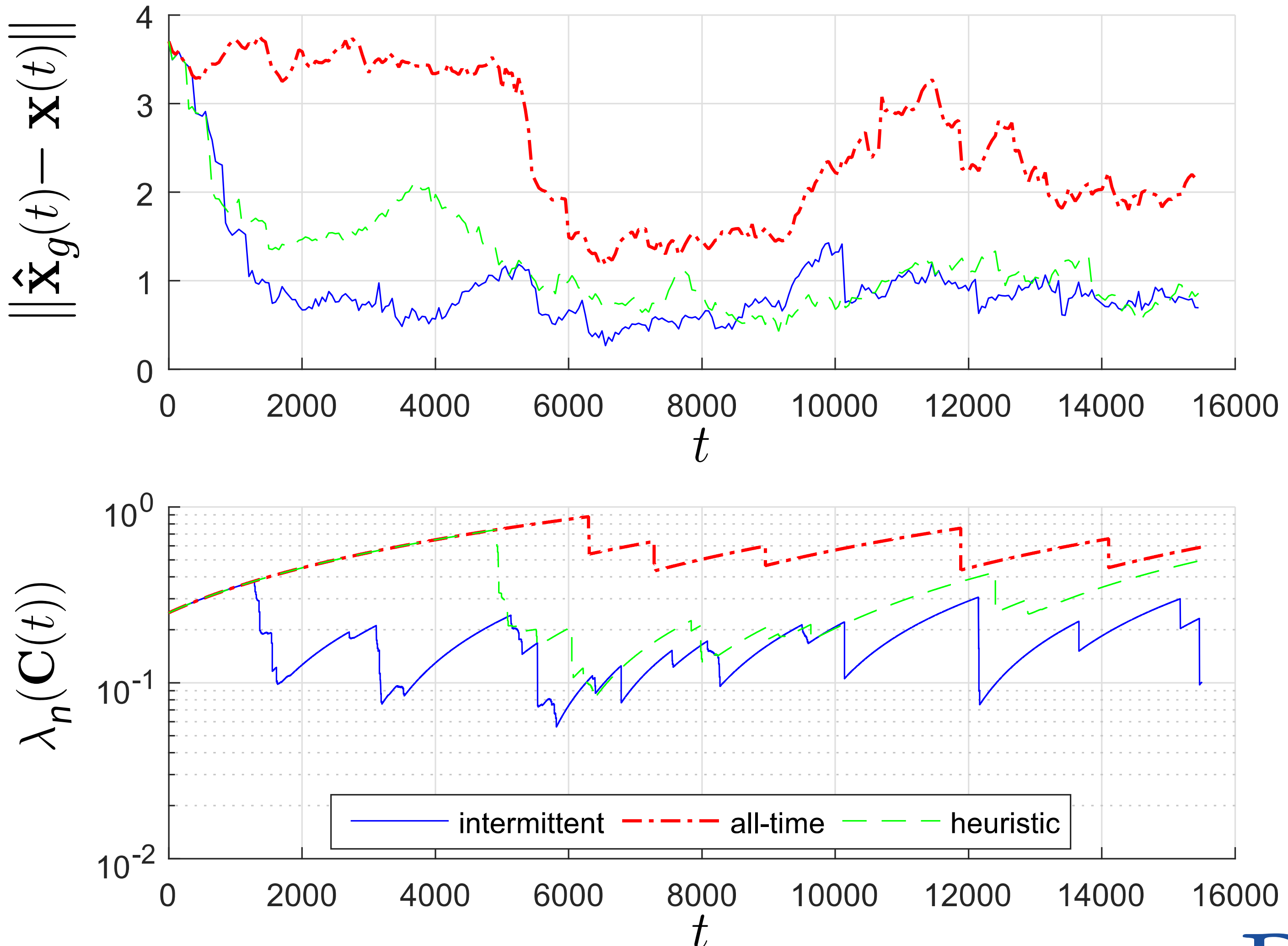
Robots in team $\mathcal{T}_m$ can communicate if they construct a connected communication network

Determine motion plans for the robots that minimize estimation uncertainty of the state x(t) while ensuring intermittent communication infinitely often.

Numerical Experiments



Numerical Experiments



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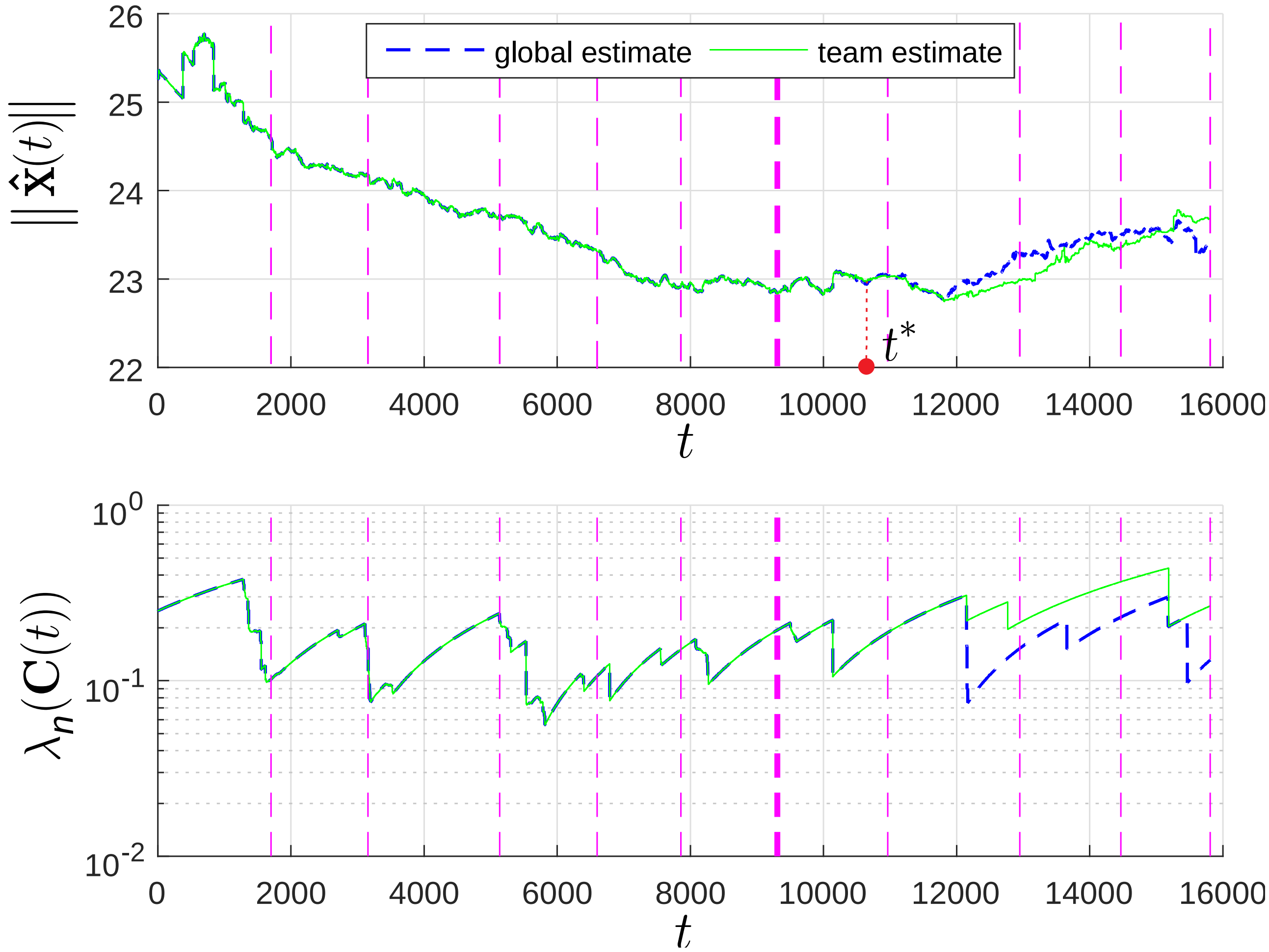
Numerical Experiments



Summary

Connectivity is necessary for real-time availability of information and distributed control.
In practice, it is not possible to ensure all-to-all connectivity for all time.

Intermittent communication control frameworks can provide an efficient solution while allowing the robots to accomplish other tasks free of communication constraints.

But also…

Thank You

Distributed Intermittent Connectivity Control

- Y. Kantaros and M. M. Zavlanos, “Distributed Intermittent Connectivity Control of Mobile Robot Networks,” IEEE Transactions on Automatic Control, Jul. 2017.

Task Planning and Distributed Intermittent Connectivity Control

- Y. Kantaros, M. Guo, and M. M. Zavlanos, “Temporal Logic Task Planning and Intermittent Connectivity Control of Mobile Robot Networks,” IEEE Transactions on Automatic Control, Oct. 2019.
- R. Khodayi-mehr, Y. Kantaros, and M. M. Zavlanos, “Distributed State Estimation using Intermittently Connected Robot Networks,” IEEE Transactions on Robotics, Jun. 2019.
- M. Guo and M. M. Zavlanos, “Multi-Robot Data Gathering under Buffer Constraints and Intermittent Communication,” IEEE Transactions on Robotics, Aug. 2018.
- Y. Kantaros and M. M. Zavlanos, “Distributed Intermittent Communication Control of Mobile Robot Networks under Time-Critical Dynamic Tasks,” in Proc. 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, Australia, May 2018.