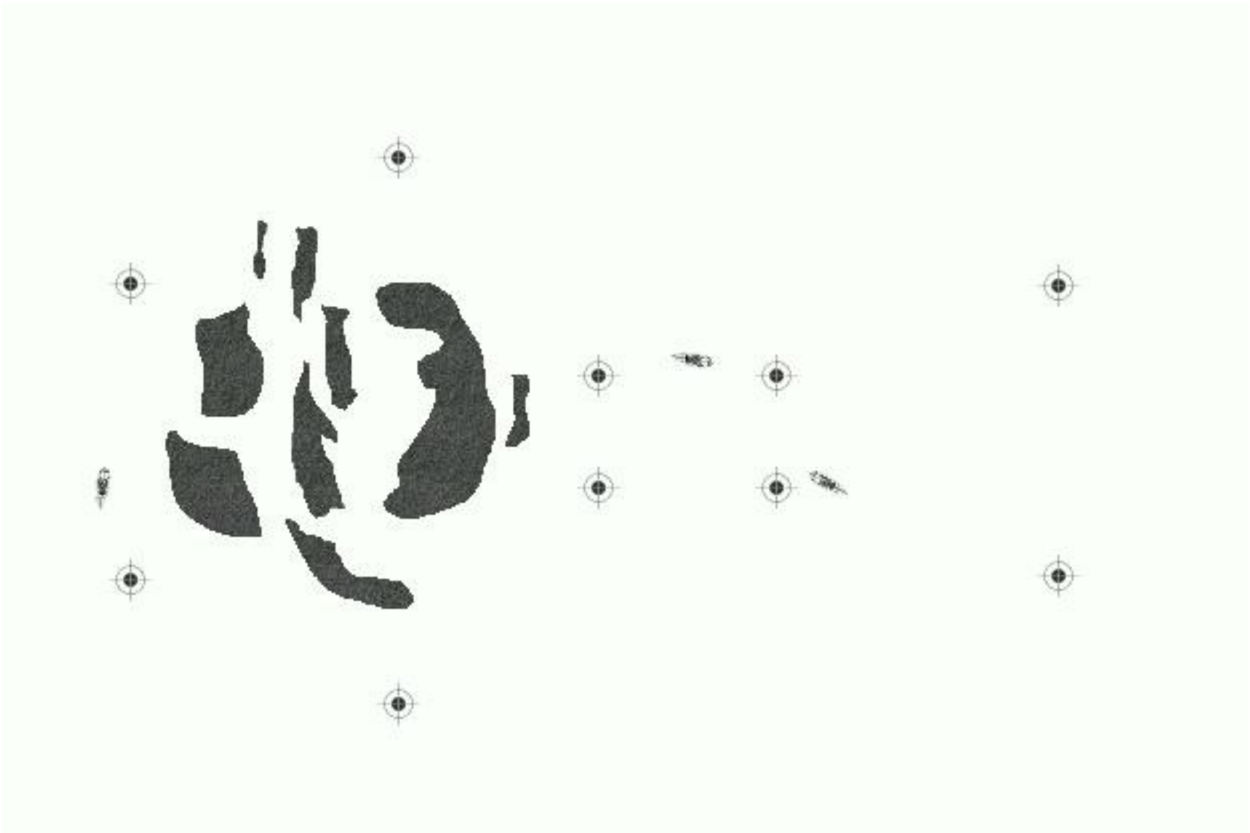
Ship Patrol: Multiagent Patrol under Complex Environmental Conditions

Noa Agmon, Daniel Urieli and Peter Stone
The University of Texas at Austin

Learning Agents Research Group
The University of Texas at Austin

Ship Patrol – How It All Began…



Outline

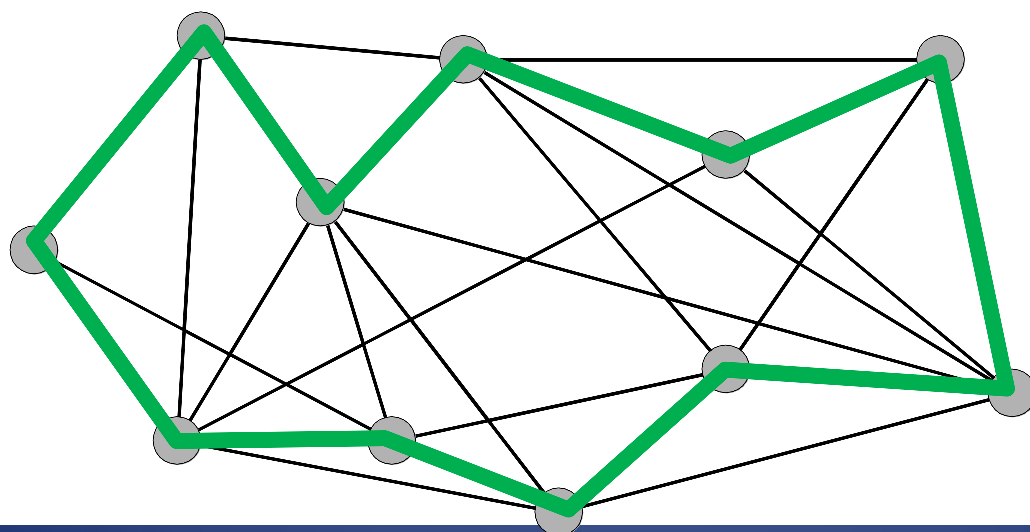
- Multiagent patrol
  - Current strategies, and motivation for a new strategy
- The generalized multiagent patrol problem on graphs
- Multiagent patrol on outerplanar graphs
  - Heuristic algorithm for solving the problem
- Empirical evaluation
  - Ship simulator

Multiagent Patrol

- Team of k agents repeatedly visit a target area to monitor change in state
  - Discrete graphs, continuous paths (linear, 2D, 3D)
- Different environments, different perspectives
  - Frequency-based patrol: Optimize frequency criteria
    e.g. [Chevaleyre 04, Machado et al. 03, Elmaliah et al. 09, Ahmadi&Stone 06]
  - Patrol in adversarial environments: Detect adversary
    e.g. [Basilico et al. 09, Agmon et al. 08]
- Here: Multiagent frequency based patrol on graphs
  - Goal: Minimize Idleness

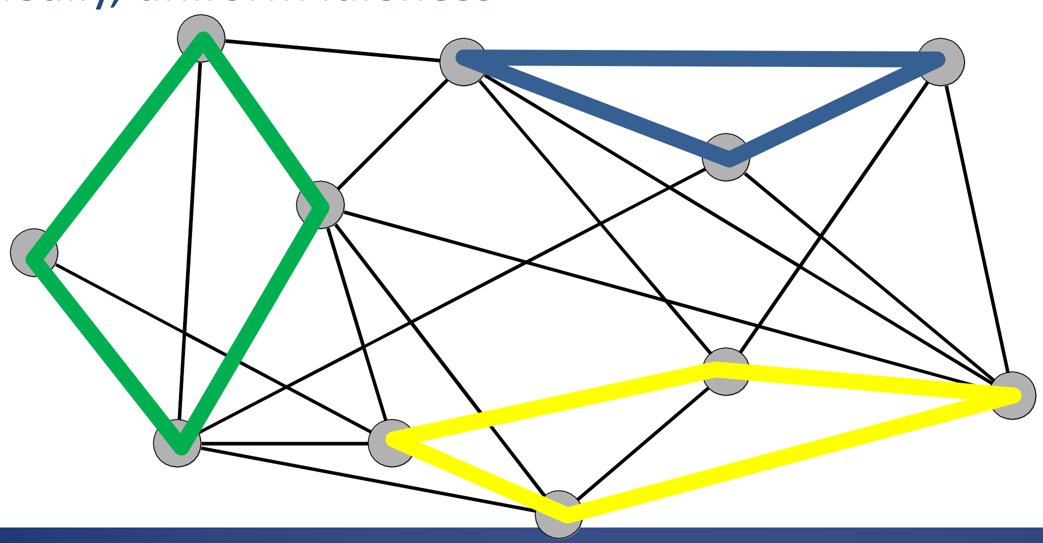
Multiagent Patrol Strategies

- SingleCycle:
  All agents travel along one (Hamiltonian) cycle
  - Travel time N, idleness is N/k (uniform)



Multiagent Patrol Strategies

- SingleCycle:
  All agents travel along one (Hamiltonian) cycle
  - Travel time N, idleness is N/k (uniform)
- UniPartition:
  Each agent patrols along a part of the graph
  - Ideally, uniform idleness



Multiagent Patrol Strategies

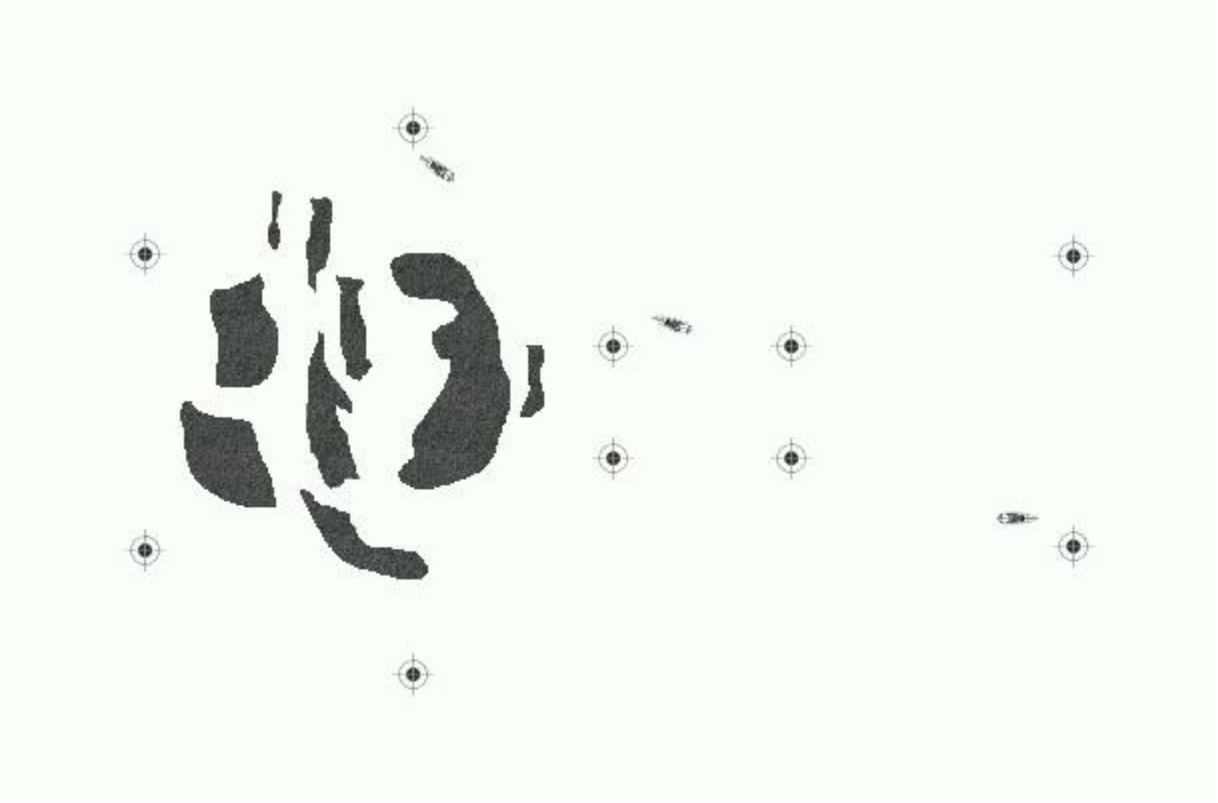
- SingleCycle:
  All agents travel along one (Hamiltonian) cycle
  - Travel time N, idleness is N/k (uniform)
- UniPartition:
  Each agent patrols along a part of the graph
  - Ideally, uniform idleness
- Generally, SingleCycle and UniPartition are intractable
  - Optimal solution under environment and agent sensing and movement assumptions [Elmaliah et al. 2008]

Complex Environments

- Example: Marine environments, rough terrains
- Travel time does not correspond to distance
- No triangle inequality
  - Cannot use trivial approximations for determining SingleCycle
  - UniPartition could also produce poor results

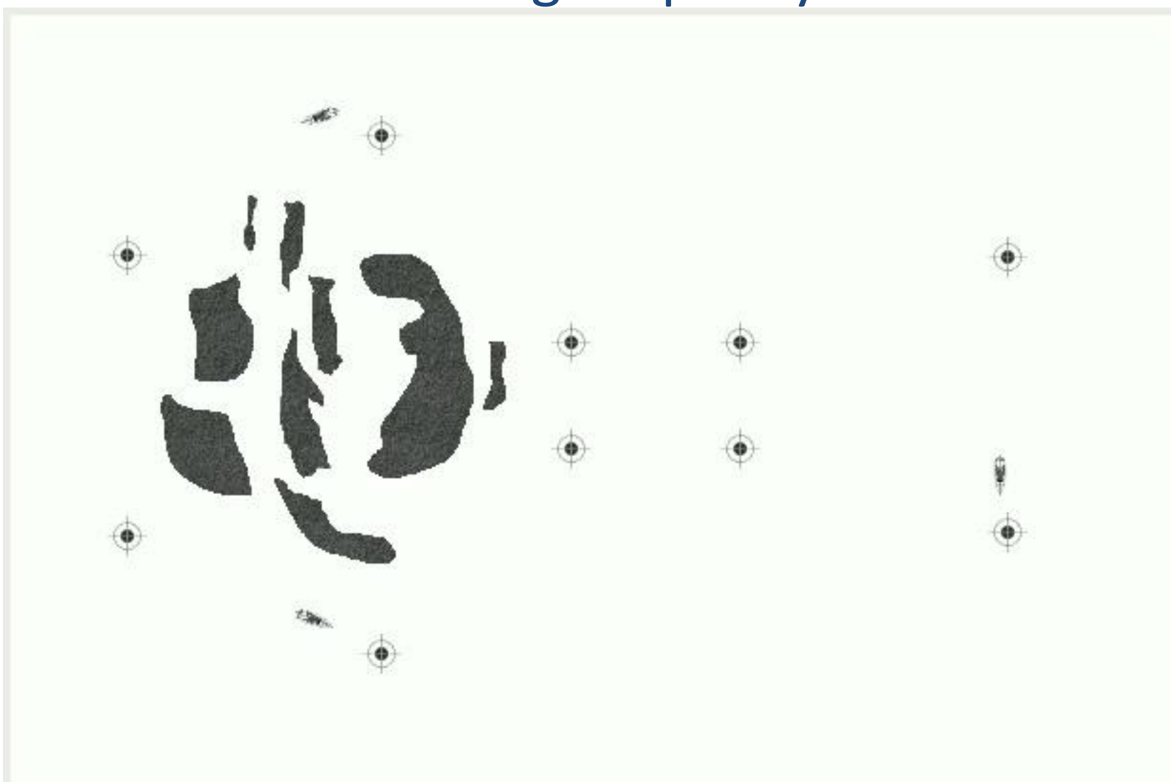
Ship Simulator

- Do the two strategies cover all interesting cases?



MultiPartition Strategy

- The agents are divided between cycles
- Can have more than one agent per cycle



ly…

Multiagent Graph Patrol Problem

- Given weighted graph G, k agents, desired worst idleness f
- Can G be divided into $m \leq k$ cyclic tours such that:
  - Each tour C_i is assigned k_i agents, $\sum_m k_i = k$
  - The worst idleness in each cycle is at most f

Multiagent Graph Patrol Problem

- Given weighted graph G, k agents, desired worst idleness f
- Can G be divided into $m \leq k$ cyclic tours such that:
  - Each tour C_i is assigned k_i agents, $\sum_m k_i = k$
  - The worst idleness in each cycle is at most f

Problem	Tours	Time Complexity
Multiagent Graph Patrol (MGP)	Each tour is cyclic	NP-Complete

Multiagent Graph Patrol Problem

- Given weighted graph G, k agents, desired worst idleness f
- Can G be divided into m ≤ k cyclic tours such that:
  - Each tour C_i is assigned k_i agents, $\sum_m k_i = k$
  - The worst idleness in each cycle is at most f

Problem	Tours	Time Complexity
Multiagent Graph Patrol (MGP)	Each tour is cyclic	NP-Complete

Practical requirement: Robots will never meet

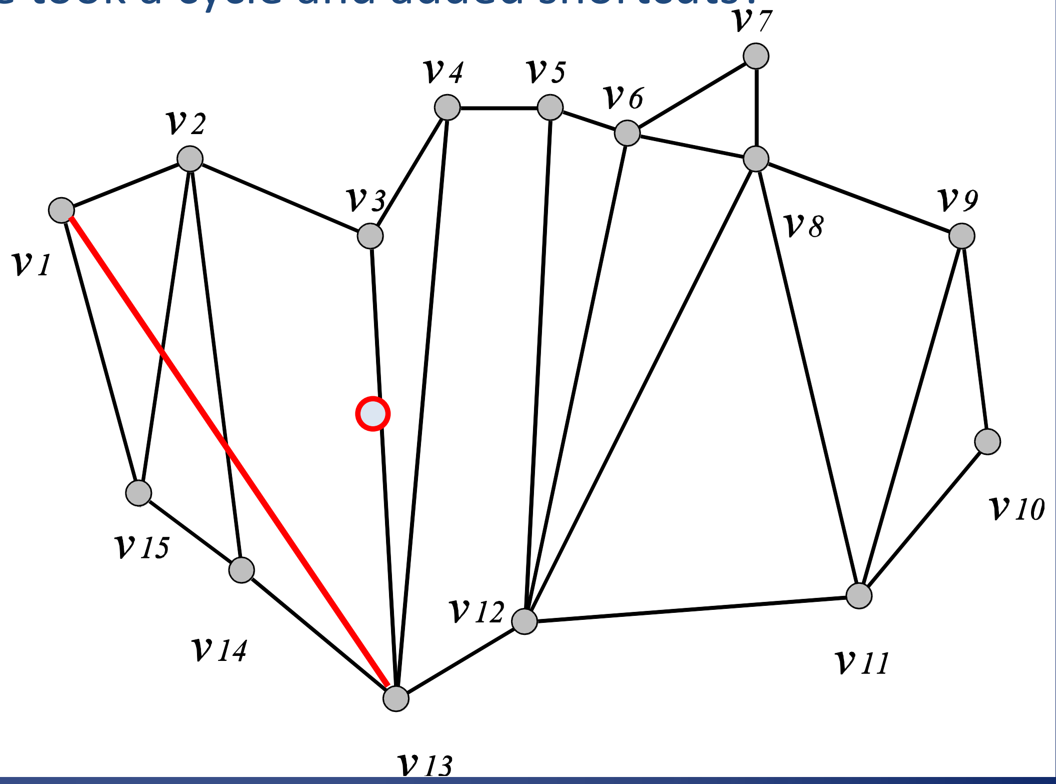
Multiagent Graph Patrol Problem

- Given weighted graph G, k agents, desired worst idleness f
- Can G be divided into m ≤ k cyclic tours such that:
  - Each tour C_i is assigned k_i agents, $\sum_m k_i = k$
  - The worst idleness in each cycle is at most f

Problem	Tours	Time Complexity
Multiagent Graph Patrol (MGP)	Each tour is cyclic	NP-Complete
Multiagent **Cyclic** Graph Patrol (MCGP)	Each tour is **a cycle** Tours are non intersecting	NP-Complete

Outerplanar Graphs

- Outerplanar graphs
  - Planar graphs, all nodes adjacent to one external face
  - Realistically: What if we took a cycle and added shortcuts? (biconnected)



Multiagent Patrol on Outerplanar Graphs

- Biconnected → Hamiltonian
- Subgraph of outerplanar is outerplanar

Multiagent Patrol on Outerplanar Graphs

- Biconnected → Hamiltonian
- Subgraph of outerplanar is outerplanar

Problem	Tours	Time Complexity
Multiagent Graph Patrol (MGP)	Each tour is cyclic	NP-Complete
Multiagent **Cyclic** Graph Patrol (MCGP)	Each tour is **a cycle** Tours are non intersecting	NP-Complete
Multiagent Patrol on Outerplanar Graphs	Each tour is **a cycle** Tours are non intersecting Graph is (biconnected) outerplanar	? (probably intractable)

Patrol Strategies in Outerplanar Graphs

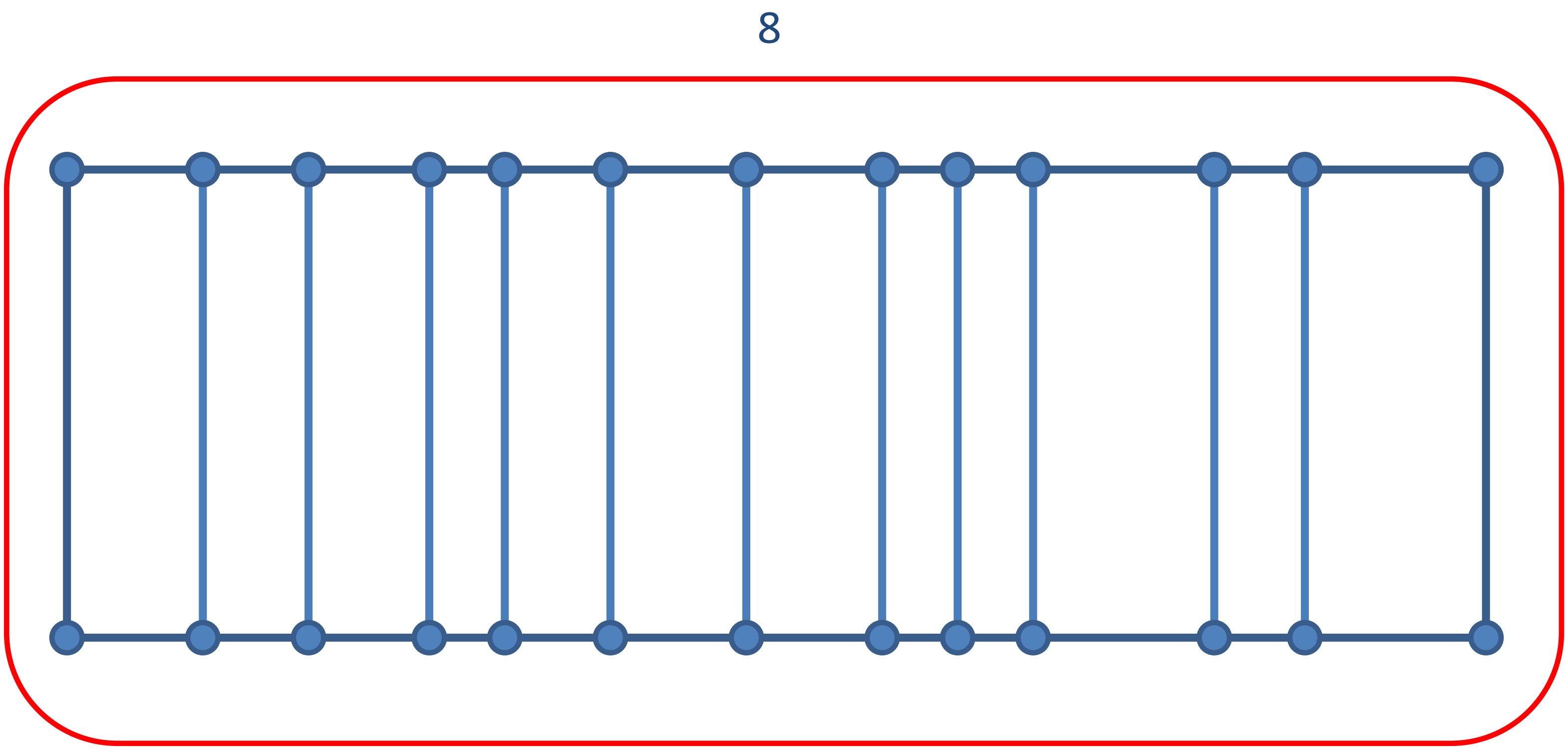
- SingleCycle found in linear time
- SinglePartition exponential
- MultiPartition probably still intractable

→ Use Heuristic algorithm

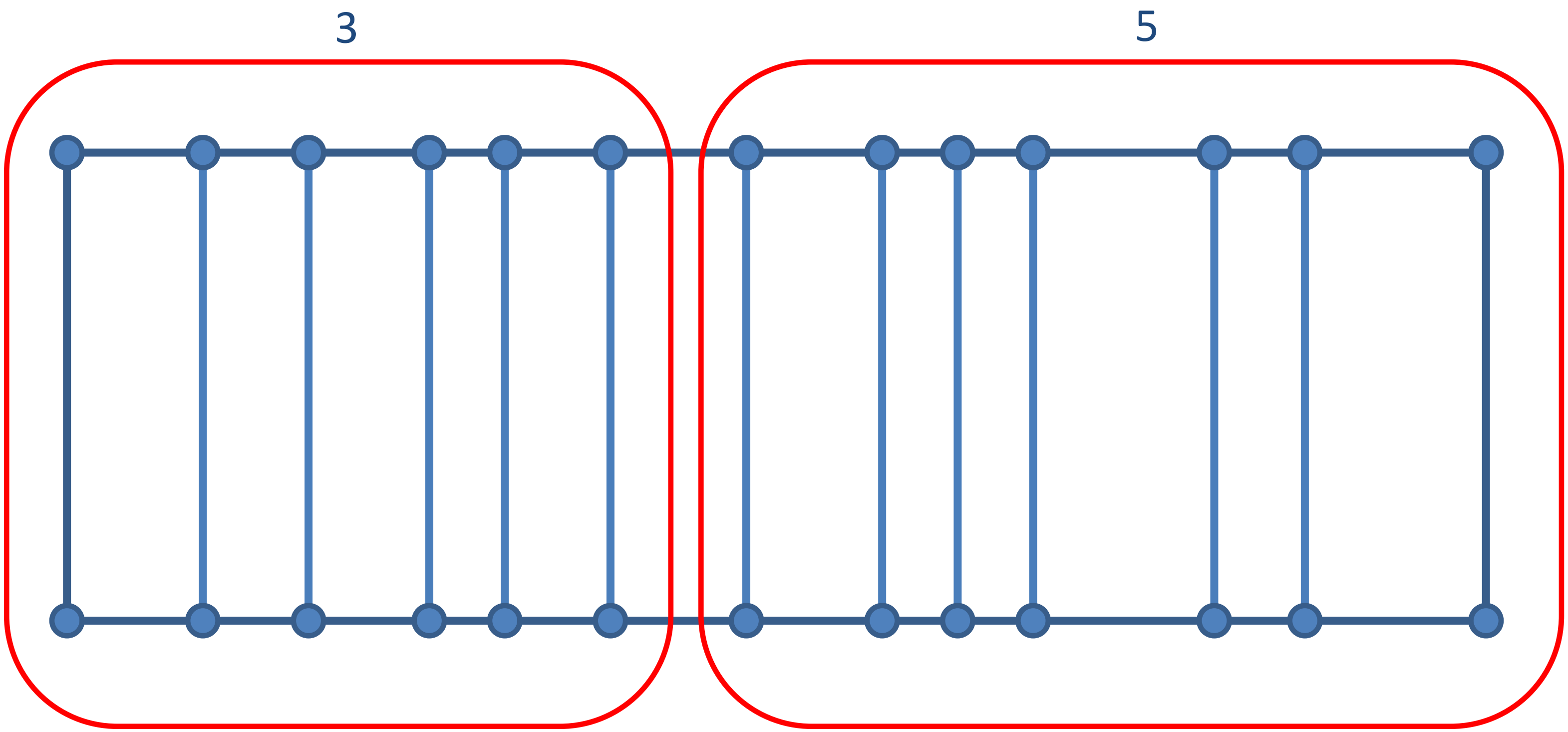
Algorithm HeuristicDivide

- Find all division of outerplanar graph into two disjoint components
  - Remove every pair of edges (proven: enough)
  - Check for disjoint biconnected components
  - Done in polynomial time
- Assign k_i agents to each of resulting cycles (optimally)
- Take division that improves and minimizes worst idleness
  - Clockwise/counterclockwise
- Take these divisions and continue recursively
- Depth of recursion: at most N
- Time complexity: $O(|E|^3)$

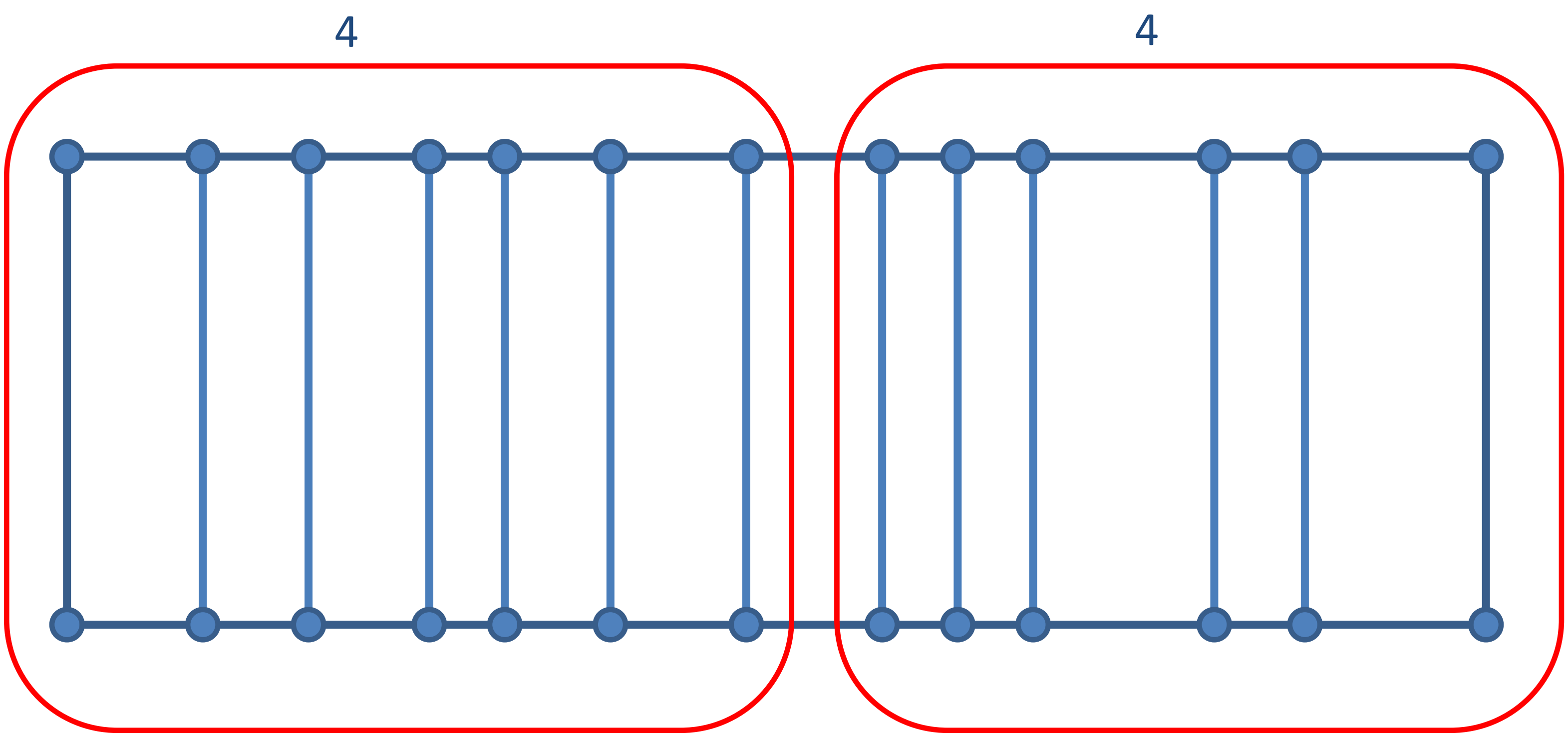
HeuristicDivide - Example



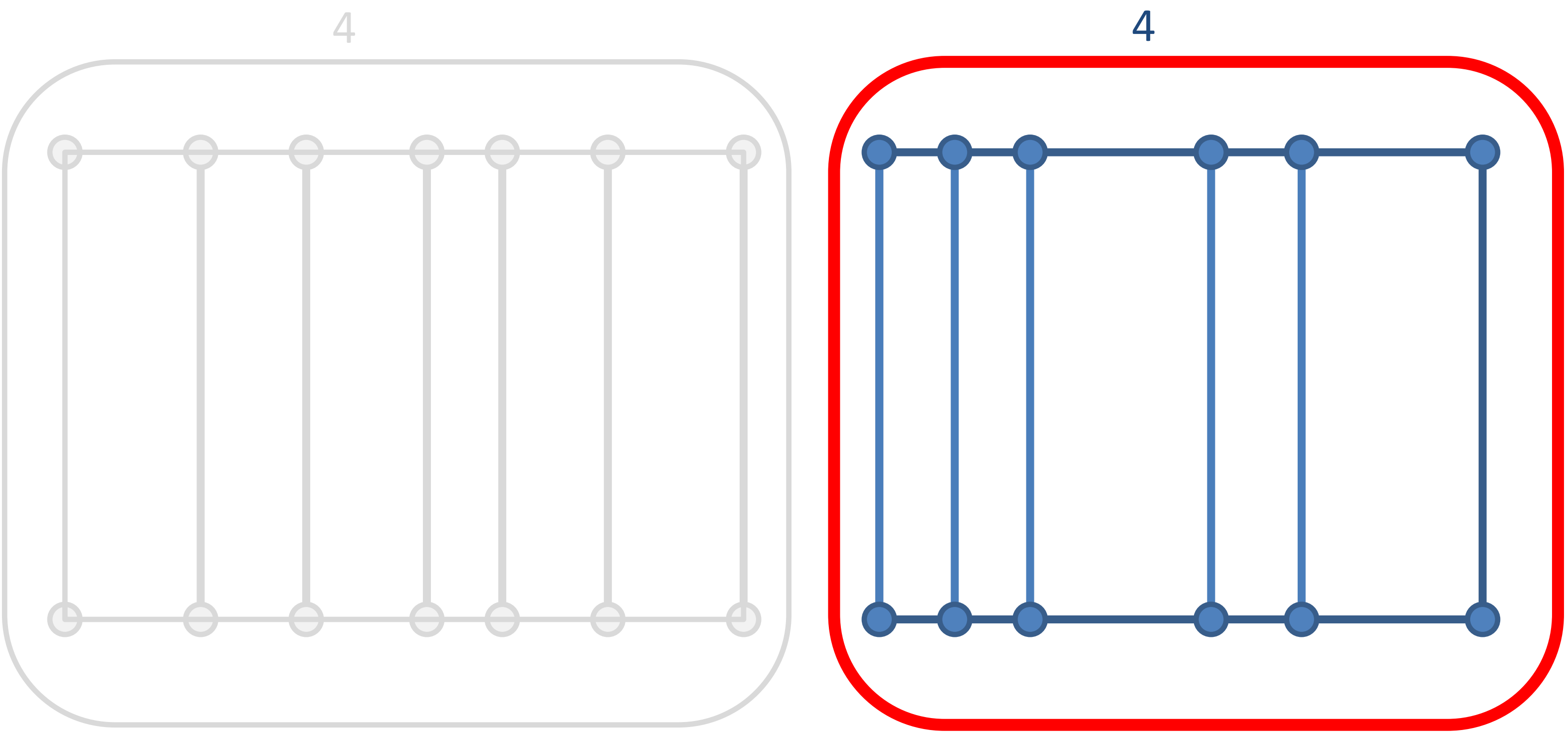
HeuristicDivide - Example



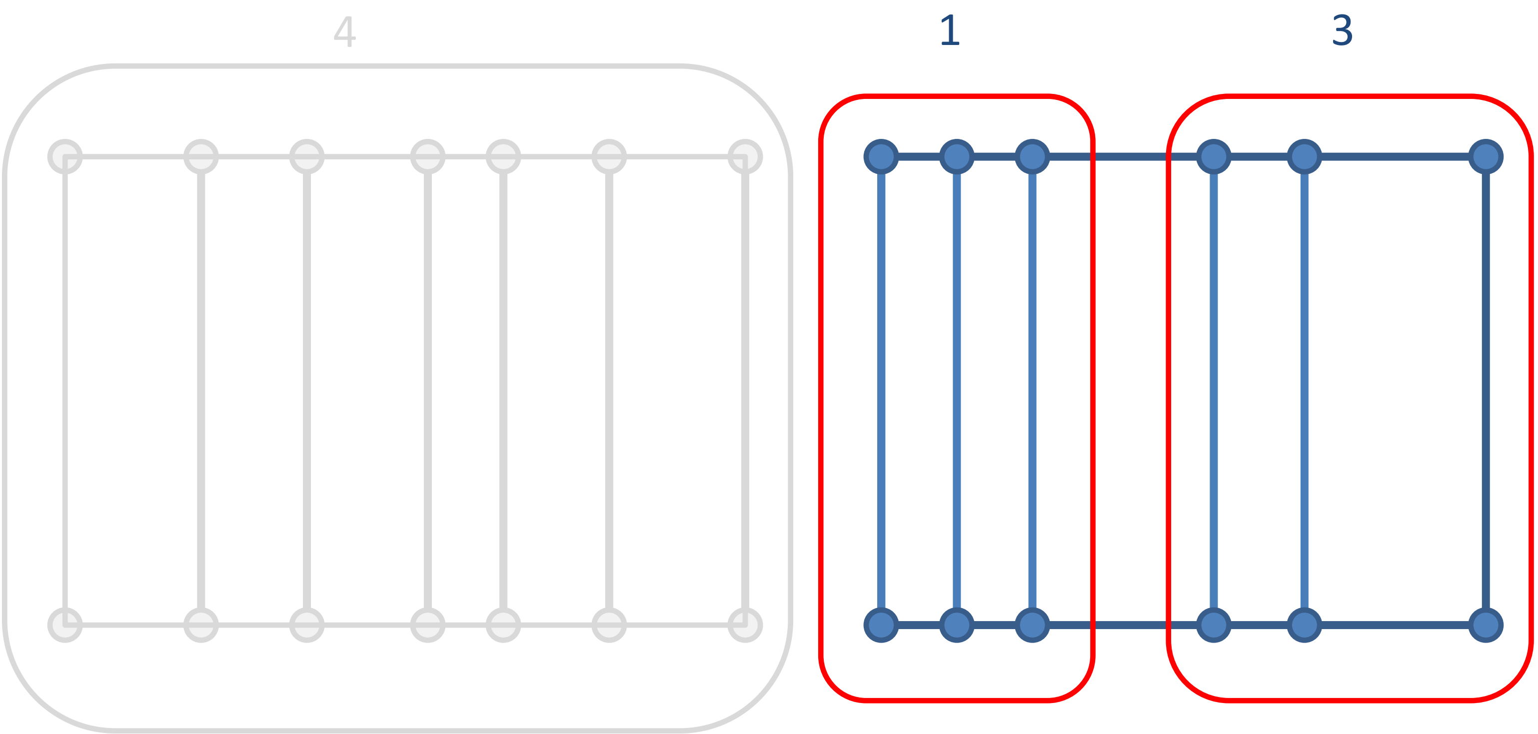
HeuristicDivide - Example



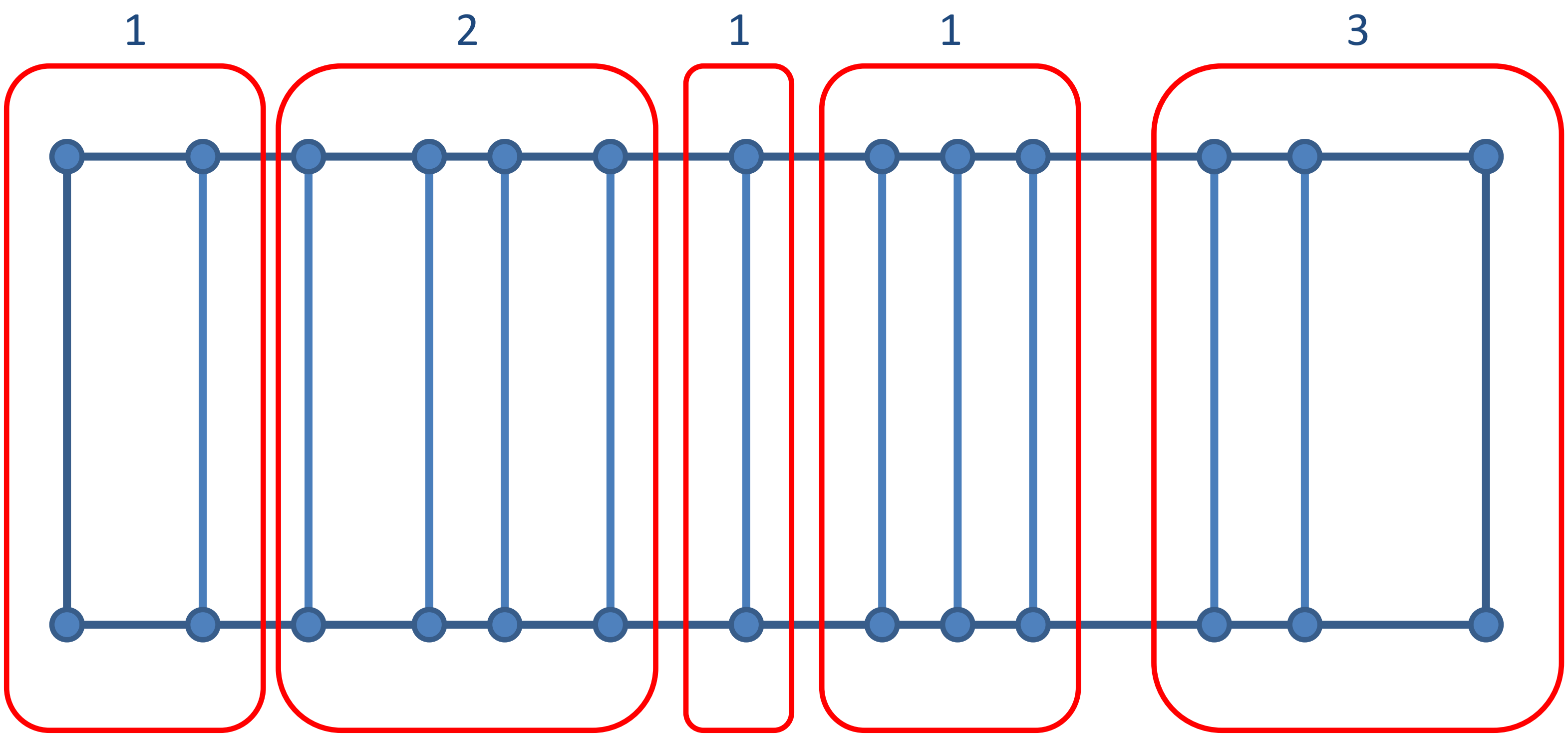
HeuristicDivide - Example



HeuristicDivide - Example



HeuristicDivide - Example

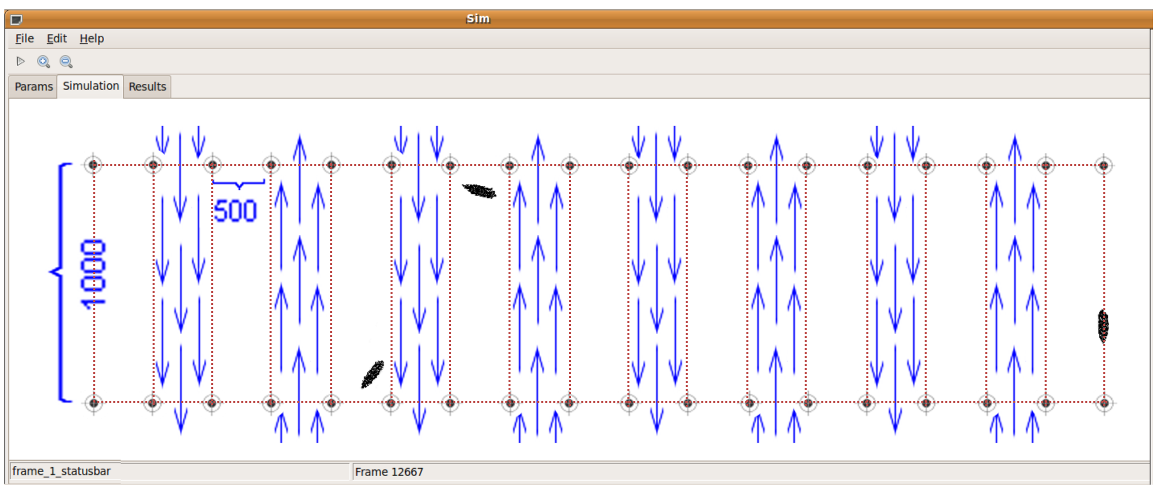


UTSeaSim

- Custom-designed naval surface navigation simulator
- Realistic *2D* physical models of marine environments and sea vessels
- Divided into three modules:
  - Sea Environment: Winds, water currents, waves and obstacles
  - Ship: Physical properties, sensing capabilities and actuators
  - Decision-Making: Autonomous agent that controls the ship

Empirical Evaluation – The Environment

- Environment with many combinations of subgraphs
- |V| = 36
- Four levels of strength of water currents and winds:
  - No winds or currents, weak, medium and strong
- Number of ships – from 1 to 30



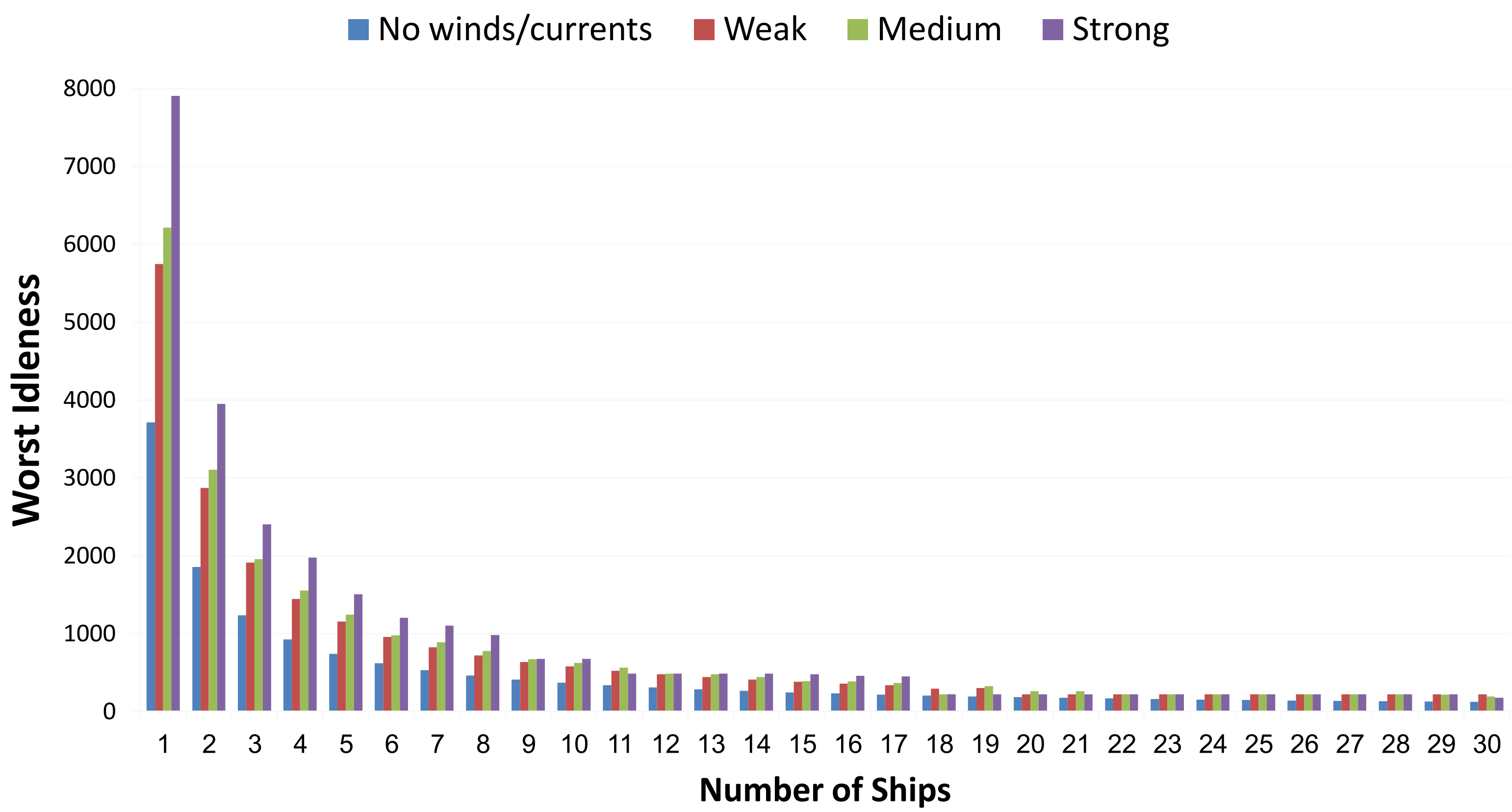
Empirical Evaluation – Evaluation Criteria

- Compared idleness from SingleCycle
  - Easily computable
- Performance of HeuristicDivide compared to trivial adjustment
  - Incremental change (k+1): new ship added to cycle with worst idleness
  - Decremental change (k-1): ship removed from cycle with best idleness

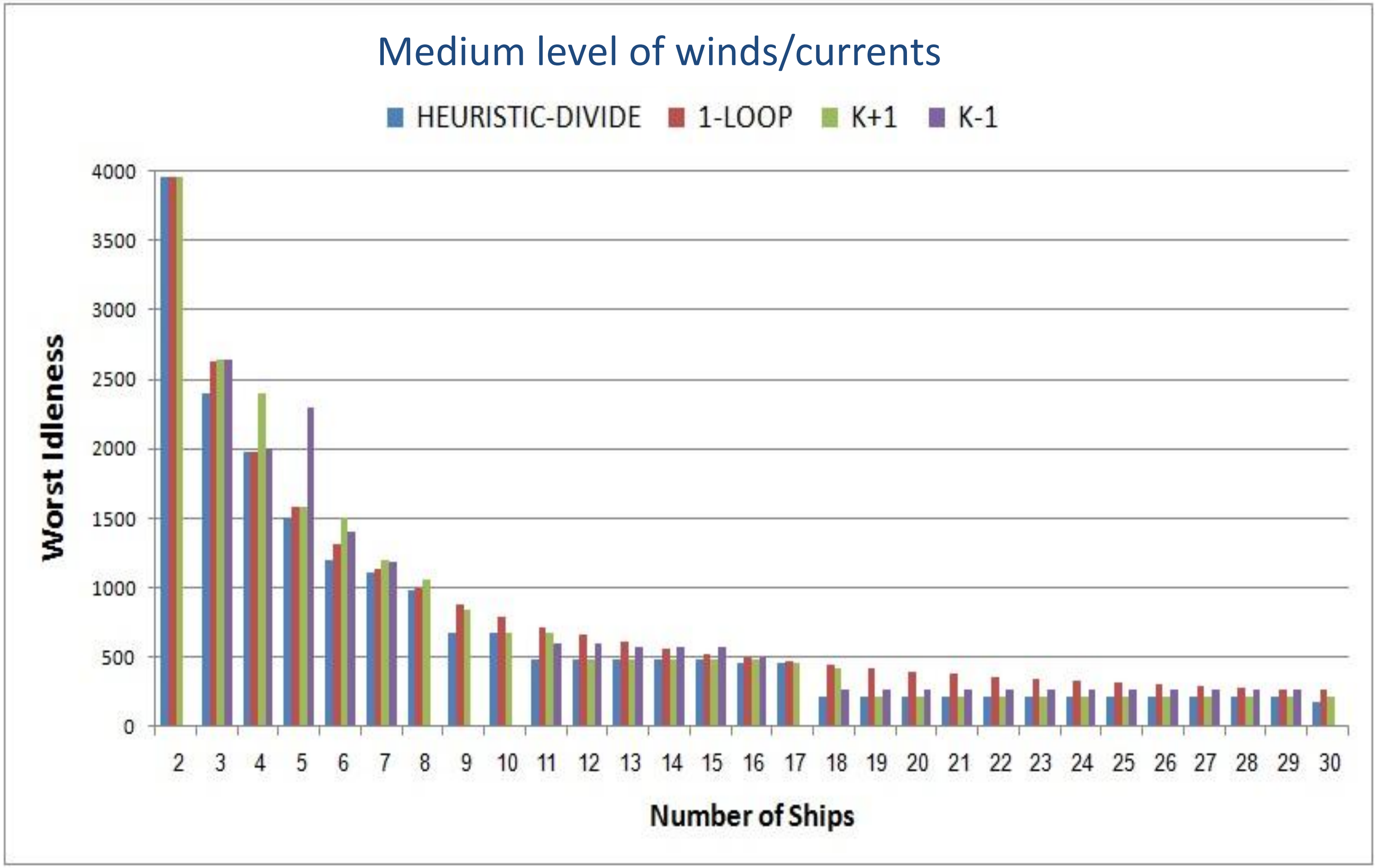
Empirical Evaluation – Results

- No winds/currents: HeuristicDivide always chose one cycle
- Medium/strong currents: HeuristicDivide significantly better
- Weak currents: Average better, no significance

Empirical Evaluation – HeuristicDivide Results



Empirical Evaluation – HeuristicDivide Comparison



Conclusions

- New strategy for multiagent patrol: MultiPartition
- Intractable in general graphs (as other strategies)
- Hard also in very simple (outerplanar) nonlinear environments
- Heuristic algorithm empirically outperforms previous strategies in complex (marine) environments
- Future work:
  - Realistic (movement) constraints incorporated in the algorithm
  - Examine local strategies for patrol based on MultiPartition
  - Learning in case of non uniform frequency constrains or of travel cost

Questions?

agmon@cs.utexas.edu