Coordinated Multi-Robot Real-Time Exploration With Connectivity and Bandwidth Awareness

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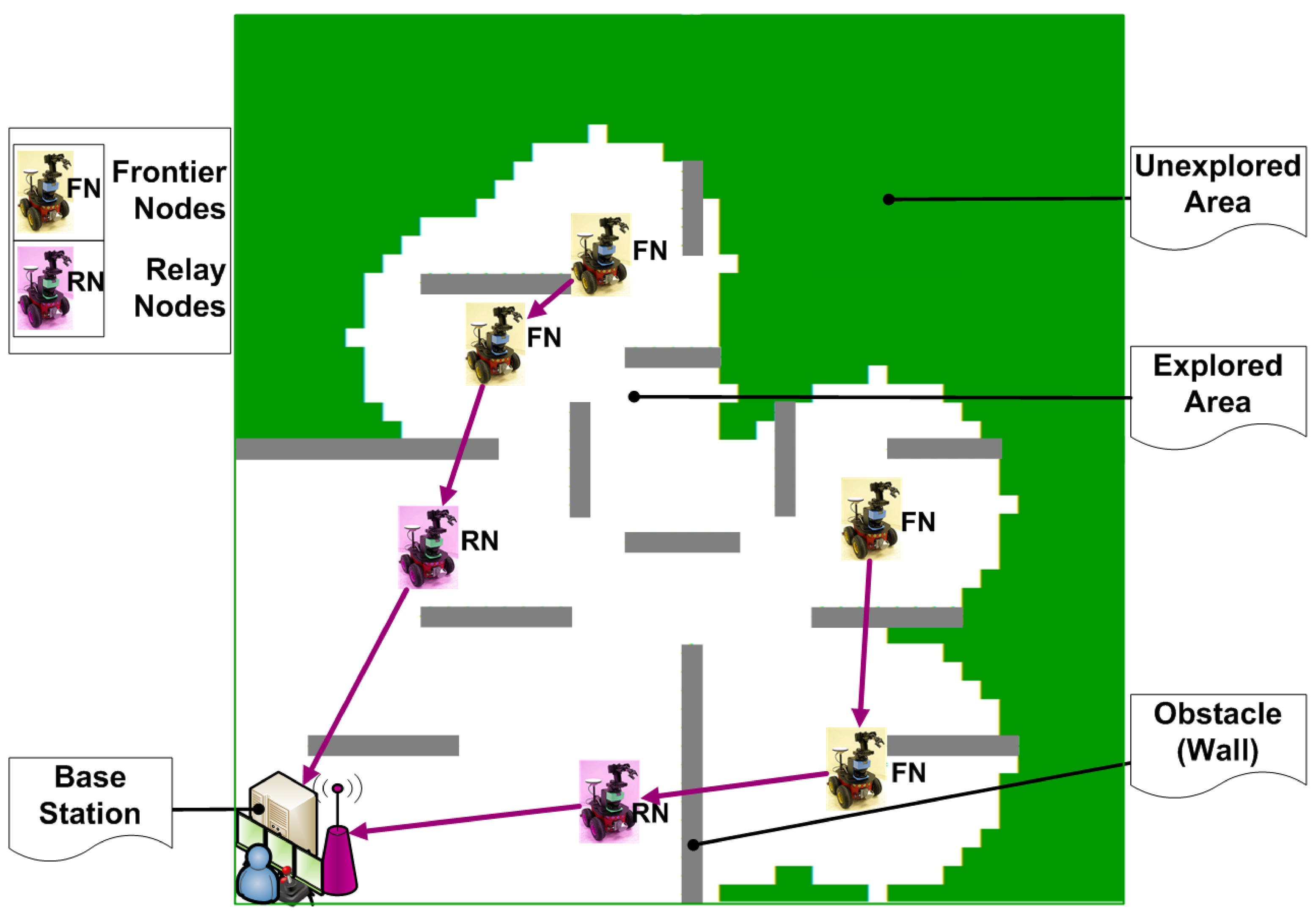
Introduction

- **Application of Multi-Robot *Real-time* Exploration**
  - Surveillance and reconnaissance.
  - Search and rescue missions in dangerous areas (such as earthquake, urban rescue for fire accident).
- **Problem: How to design an exploration strategy to:**
  - Let the robots efficiently search the unknown area..
  - Ensure bandwidth-consuming video/audio streams from newly-explored area to be reliably and safely transmitted to the BS as robots are moving forward.
- **Why interesting:**
  - Challenging to transmit quality real-time video/audio via mobile multi-hop wireless communication: Bandwidth constraint in coordinated mobile situation.
  - Human operators need to monitor robot team's action and obtain sensed information immediately.
  - Robotic sensing ability insufficient to accurately detect complex targets → Need human recognition.
  - Operators may need to teleoperate robots promptly after target discovery or under urgent conditions.



Exploration snapshot with 4 frontier nodes and 2 relay nodes.

Problem Formulation

How to design a coordinated exploration strategy for the robot team to explore the area in a minimum amount of time under the following ***two constraints***?

- ***Connectivity***: The network is always connected when data is transmitted.
- ***Bandwidth***: Aggregated consumed bandwidth of data flows from the frontier nodes cannot exceed link bandwidth when transmitting back to the BS.

Connectivity and Bandwidth Aware eXploration Overview (CBAX)

Leverage a heuristic to a subproblem: find a *local optimal configuration of* maximum total number of cells explored in unit migration time:

Iterative solution: Each iteration is decomposed as:

1) **Frontier node (FN) placement.**
2) **Relay node (RN) placement / routing path selection.**
3) **Position assignment and path generation.**

Frontier Robot Placement

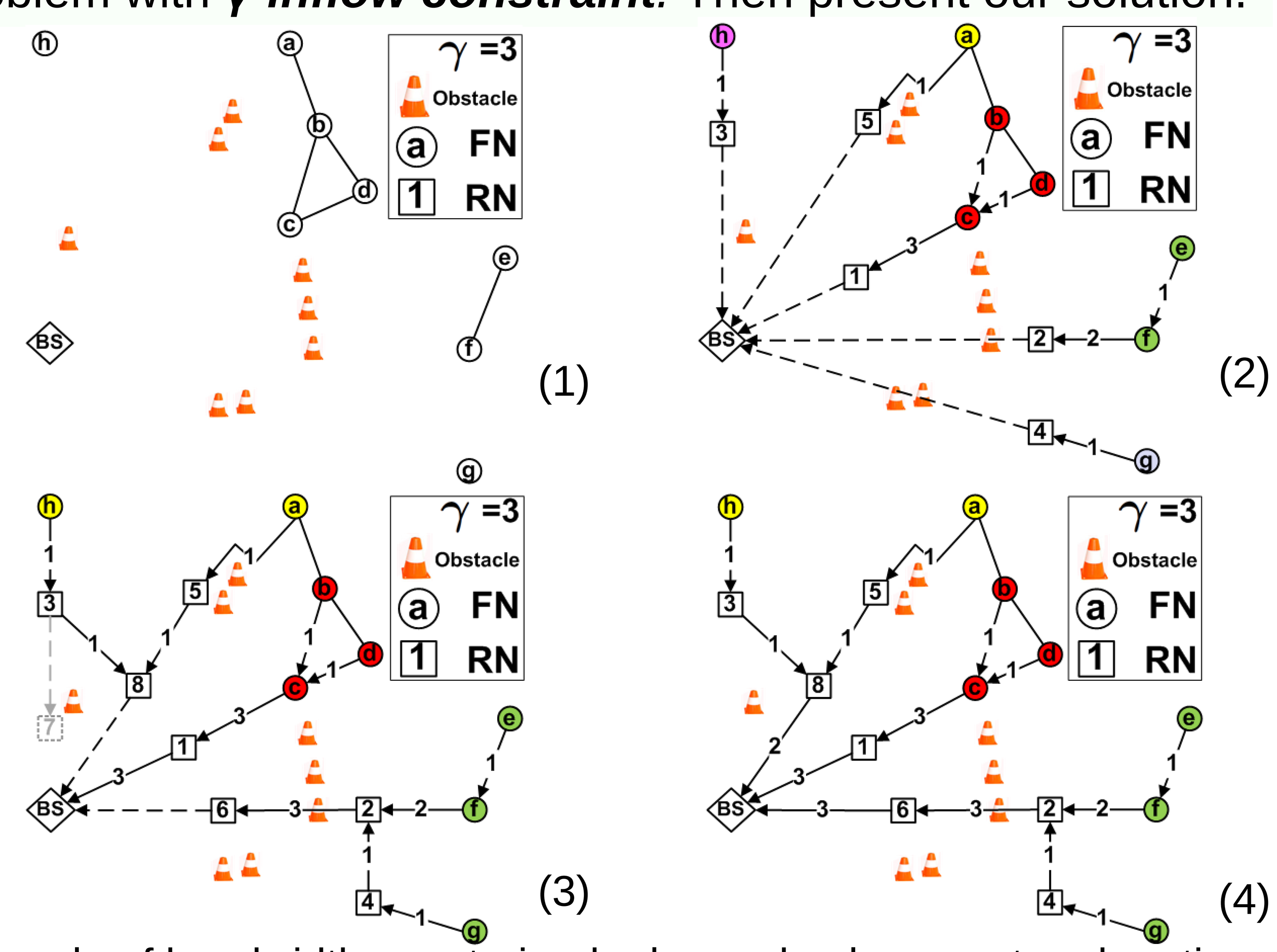
Where to place n_{fn} *number of* FNs in C_{frn} *to* cover maximum amount of unexplored area?

- Modeled by variant of **Set Cover.**
- Utility function considers distance from current positions to new ones: greedy approximation with dynamic cost model.

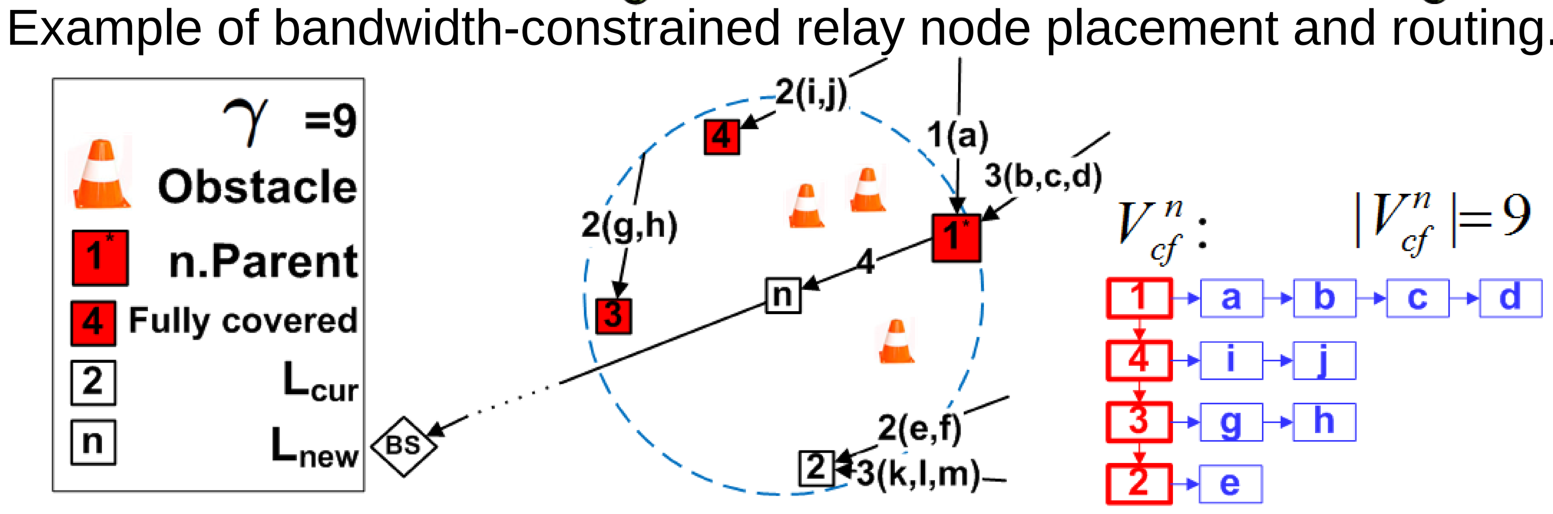
Relay Robot Placement

How to place minimum number relay nodes in explored area to satisfy the *two constraints* and select which paths to route flows from frontier nodes to base station?

- Modeled by new variation of **Steiner Minimum Tree** Problem with ***γ-inflow constraint***. Then present our solution.



Example of bandwidth-constrained relay node placement and routing.



Aggregate flows to nodes with maximal number of fully covered neighbors first to conserve relay nodes.

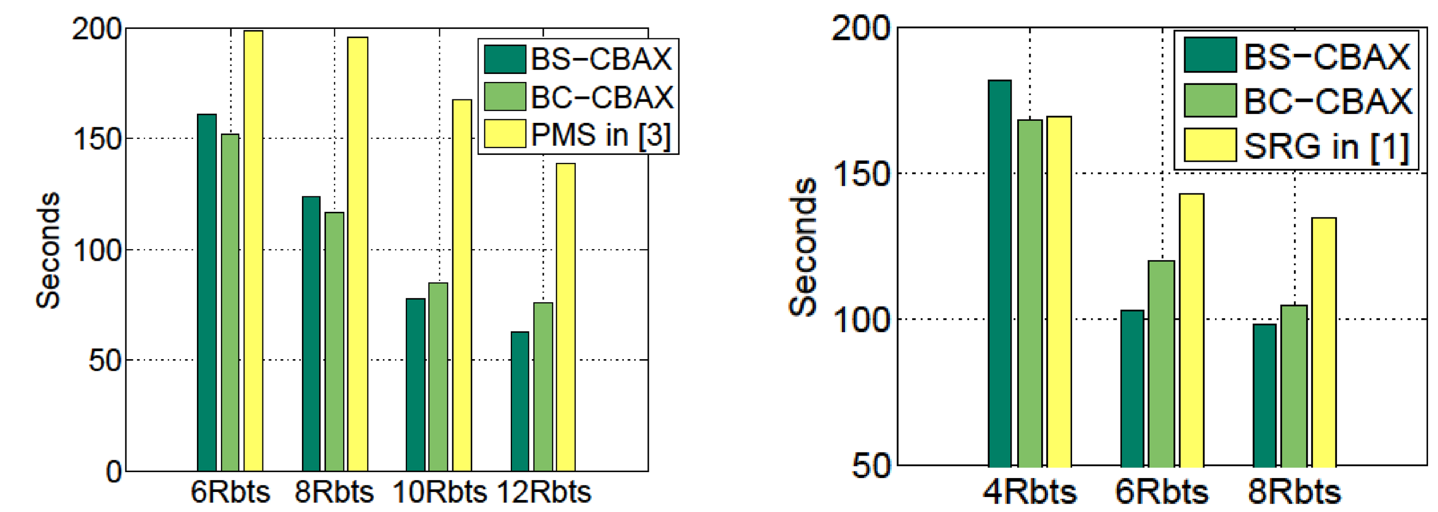
Path Generation

How to assign each robot with its target position and generate movement paths to minimize bottleneck time?

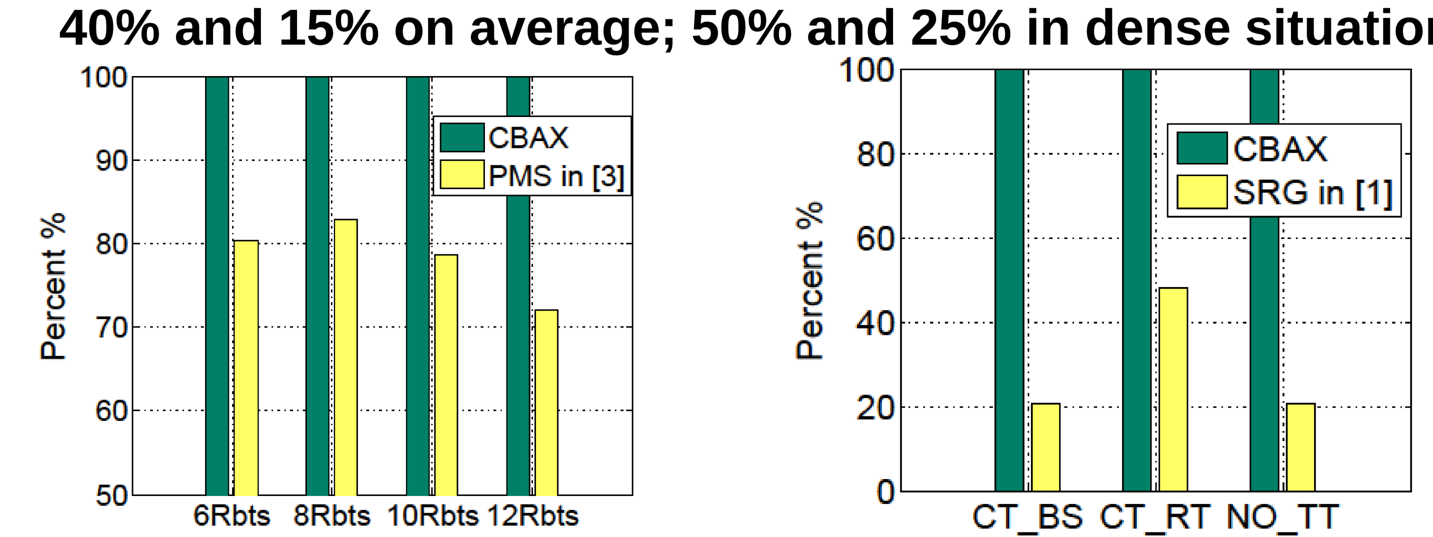
- Modeled: linear bottleneck assignment problem (**LBAP**).

Performance Evaluation

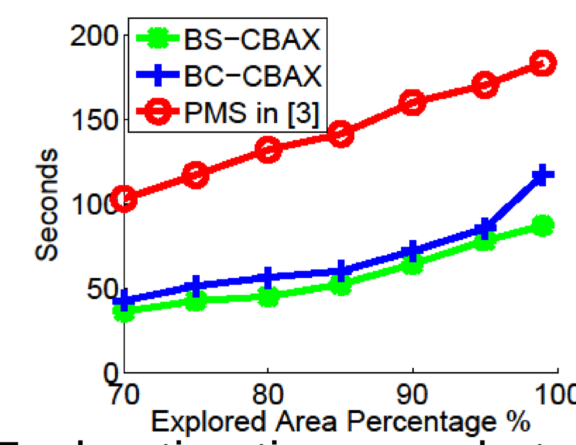
- Compared with 1) PMS: considering only connectivity; 2) SRG: considering neither connectivity nor bandwidth.
- BS/BC-CBAX: Bandwidth sufficient/constrained-CBAX.

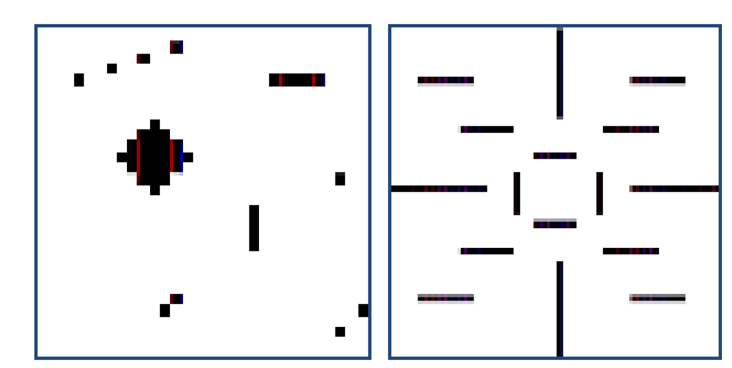


Exploration efficiency: compared with PMS and SRG: improves **40% and 15% on average; 50% and 25% in dense situations.**



Communication quality: reduce communication overflow by **22% and 79.3%** compared with PMS and SRG.





Exploration time as robots proceed (n=10). Environments.

Acknowledgement

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Contribution Highlights

- Modeled and considered **bandwidth** constraint.
  - Critical but not considered in previous work.
- Iteratively solved the problem with **algorithmic** and **graph-theoretic** tools: set cover, Steiner tree, LBAP.
- Modeled and solved relay node placement as a new variant of Steiner minimum tree problem.
- Achieves significant improved exploration efficiency and communication quality.