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SAFE MAPF WITH TIME UNCERTAINTY

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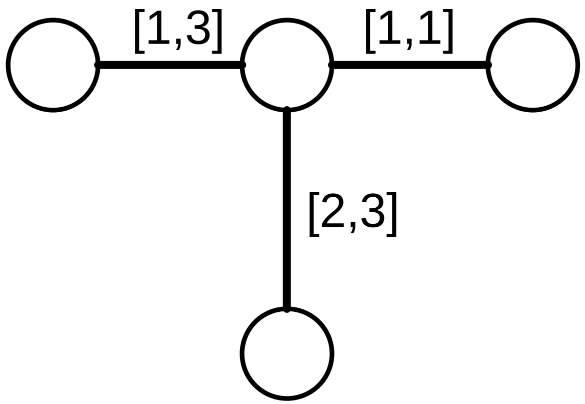
OUTLINE

- Introduction
- MAPF-TU
- Algorithms
  - $A^* + OD_{TU}$
  - CBS_{TU}
- Experiments
- Online Replanning
- Conclusion

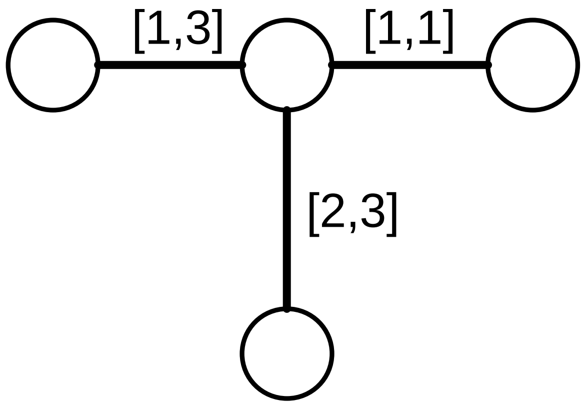
INTRODUCTION, RELATED WORK

- Delays
- Existing approaches
  - k-robustness
  - p-robustness
- New approach
  - Bounds on edge travel time
  - Looking for *safe* solution



MAPF-TU

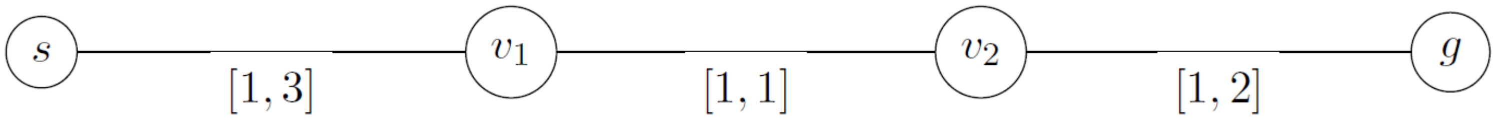
- Classical MAPF
  - Graph $G = (V, E)$
  - Start and target for each agent
  - Discrete time
- $w^{-}(e), w^{+}(e)$ - lower and upper bound on time to traverse edge e
- Solution:
  - vector of single-agent plans
    - $\pi_a = \big((v_0, v_1), (v_1, v_2), \dots, (v_{n-1}, v_n)\big)$ where $v_0 = s(a), v_n = t(a)$
  - *Safe* solution



POTENTIAL PRESENCE

- Uncertainty in agent's actual position
- Potential presence $\tau(\pi, v)$
  - set of time intervals when agent may be at v when following single-agent plan π

$$\pi = \big((s, v_1), (v_1, v_2),\ (v_2, g)\big)$$



$\tau(\pi, s) = [0, 0]$ $\quad$ $\tau(\pi, v_1) = [1, 3]$ $\quad$ $\tau(\pi, v_2) = [2, 4]$ $\quad$ $\tau(\pi, g) = [3, 6]$

- Potential presence for an edge similarly

POTENTIAL CONFLICT

- Potential conflict = non-empty intersection of potential presence
- *Safe* solution = no potential conflicts

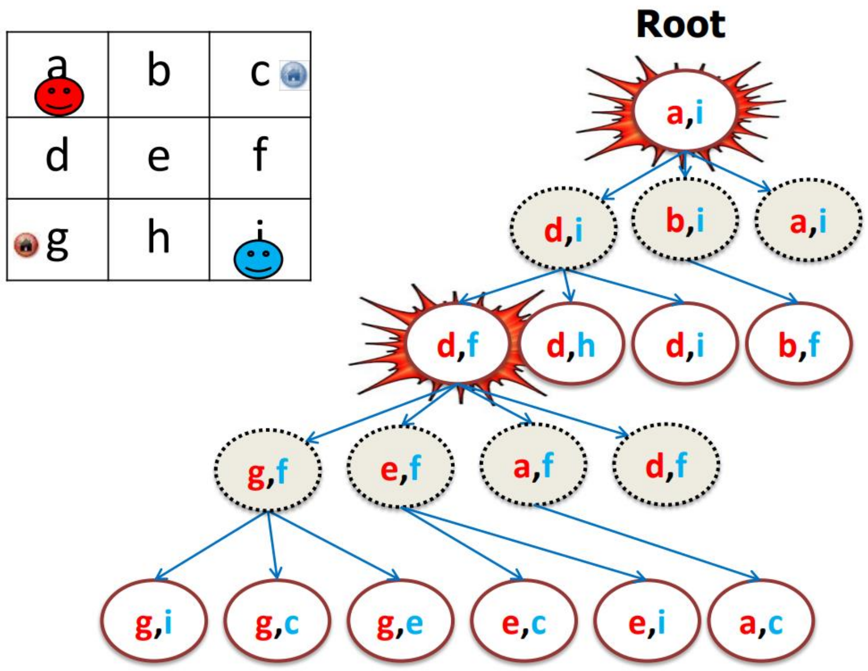
$$\bigcup_{1\leq i<j\leq k}\Bigg[\bigcup_{v\in\mathcal{V}}\tau(\pi_i,v)\cap\tau(\pi_j,v)$$
$$\cup\bigcup_{u,v\in\mathcal{V}}\tau(\pi_i,u,v)\cap\tau(\pi_j,u,v)$$
$$\cup\bigcup_{u,v\in\mathcal{V}}\tau(\pi_i,u,v)\cap\tau(\pi_j,v,u)\Bigg]=\emptyset$$

SOLUTION COST

- Uncertainty over edge durations
- SOC*opt* – sum of lower bound durations of all actions
- SOC*pes* – sum of upper bound durations of all actions

A* + OD

- A* for MAPF
  - State: vector of individual positions
  - Action: vector of individual actions
  - Legal actions only
- Operator Decomposition
  - Expanding only one agent
  - Fixed order of agents



A* + OD_{TU}

- Non-unit edge lengths
  - State: $(\langle a_1, v_1, T_1 \rangle, \ldots, \langle a_k, v_k, T_k \rangle)$
  - Expanding with agent having minimal optimistic bound instead of round-robin
  - Needs to check predecessor states for conflict
- Heuristic
  - SIC – sum of "shortest" paths

CBS_{TU}

- Lower level
  - A* over states (v, T) where T is potential presence
- Higher level
  - Potential conflicts
  - Improvement: Prioritized Conflicts (PC)
    - Cardinal
    - Semi-cardinal
    - Non-cardinal

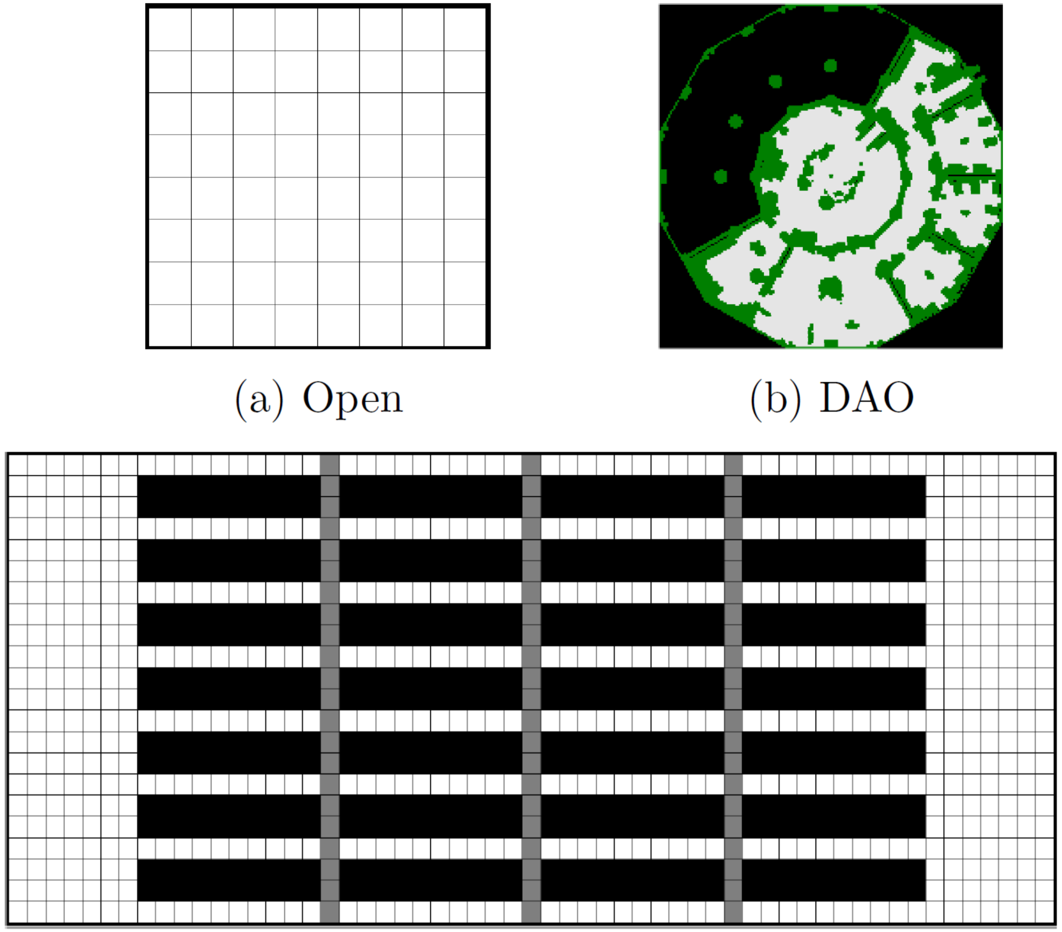
Algorithm 1: The CBS_{TU} Algorithm.

Input: A MAPF-TU instance with k agents; An optimization criteria, f
Output: A set of collision-free single-agent plans

$root.constraints = \emptyset$
$root.solution \leftarrow$ individual *single-agent plans* returned by *low-level*() approach
$root.cost \leftarrow SOC(root.solution)$
Add *root* to OPEN
while *OPEN not empty* **do**
    $N \leftarrow$ the best node from OPEN   // based on some objective function
    Validate *single-agent plans* in N until the first conflict occurs
    if *no conflict found* **then**
        return $N.solution$
    $conflict \leftarrow FindConflict(N.solution)$
    for *agent* a_i belongs to the conflict **do**
        $N_i \leftarrow$ *Create* a new CT node
        if *vertex-conflict*(*conflict*) **then**
            $N_i.constraints \leftarrow N.constraints \cup (a_i, v, t)$
        else
            $N_i.constraints \leftarrow N.constraints \cup (a_i, e, t)$
        $N_i.solution \leftarrow N.solution$
        Update $N_i.solution$ with a *single-agent plan* returned by $low\text{-}level(N_i)$ for a_i
        $N_i.cost = SOC(N_i.solution)$
        Add node N_i to OPEN
return No solution found

EXPERIMENTAL SETUP

- Edge traversal time
  - Uncertainty parameter U
  - $w^-(e)$ from $[1, U+1]$
  - $w^+(e)$ from $[w^-(e), U+1]$
    - Uniformly at random
- Timeout: 5 min
- Optimizing SOC*pes*



(a) Open (b) DAO

(c) Warehouse

EXPERIMENTS – RESULTS

- Success rates for Open grid 8 x 8

k	$U=0$		$U=1$		$U=2$		$U=4$	
	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$
3	100%	100%	100%	100%	100%	100%	100%	100%
7	100%	100%	100%	88%	94%	72%	58%	46%
10	100%	87%	80%	43%	54%	13%	12%	0%
15	100%	13%	18%	3%	0%	0%	0%	0%

- $k = \#$ agents
- Edge traversal time bounds … randomly from $[1, U+1]$

EXPERIMENTS – RESULTS

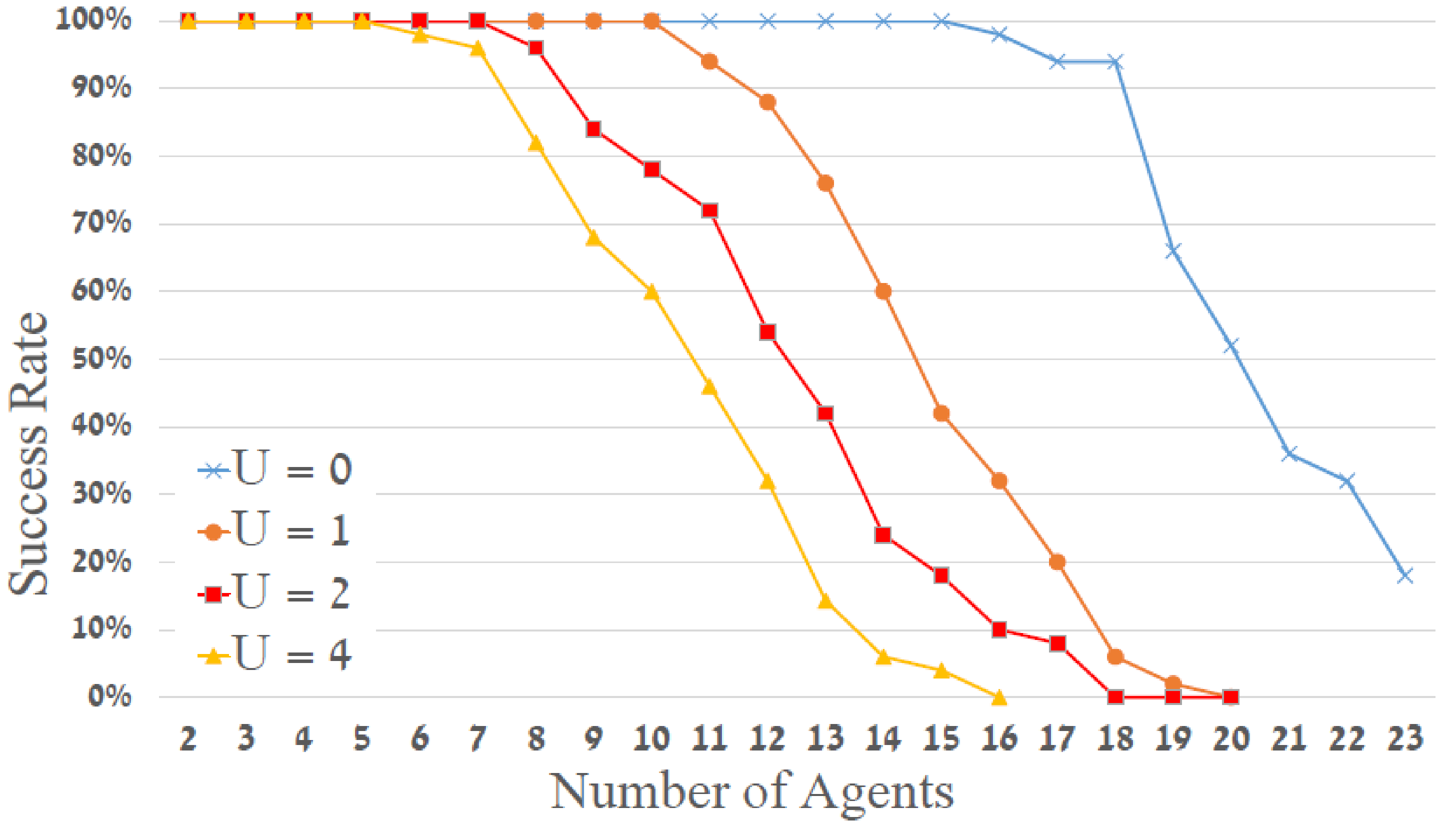
- Success rates for DAO map

k	$U = 0$		$U = 1$		$U = 2$		$U = 4$	
	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$	CBS_{TU}	$\mathrm{A}^* + \mathrm{OD}_{\mathrm{TU}}$
4	100%	100%	52%	17%	44%	23%	22%	13%
7	92%	93%	14%	0%	2%	0%	0%	0%
10	80%	70%	4%	0%	3%	0%	0%	0%
13	70%	27%	0%	0%	0%	0%	0%	0%

- $k = \#$ agents
- Edge traversal time bounds … randomly from $[1, U + 1]$

EXPERIMENTS – RESULTS

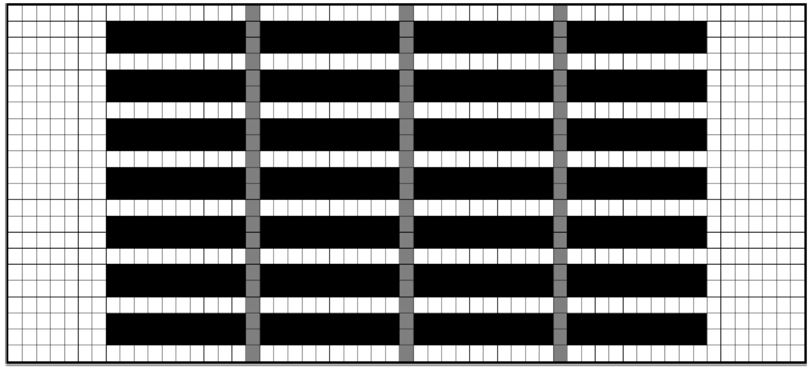
- Open grid 8x8, CBS_{TU}



EXPERIMENTS – RESULTS

- Success rates for Warehouse map

k	$U=0$		$U=1$		$U=2$		$U=4$	
	CU	PU	CU	PU	CU	PU	CU	PU
4	100%	100%	96%	100%	92%	98%	86%	96%
7	98%	98%	84%	96%	68%	92%	48%	80%
10	94%	94%	48%	76%	34%	68%	10%	56%
13	82%	82%	18%	42%	6%	28%	0%	18%



(c) Warehouse

- k = # agents
- Edge traversal time bounds … randomly from $[1, U+1]$
- Complete (CU) and Partial (PU) Uncertainty

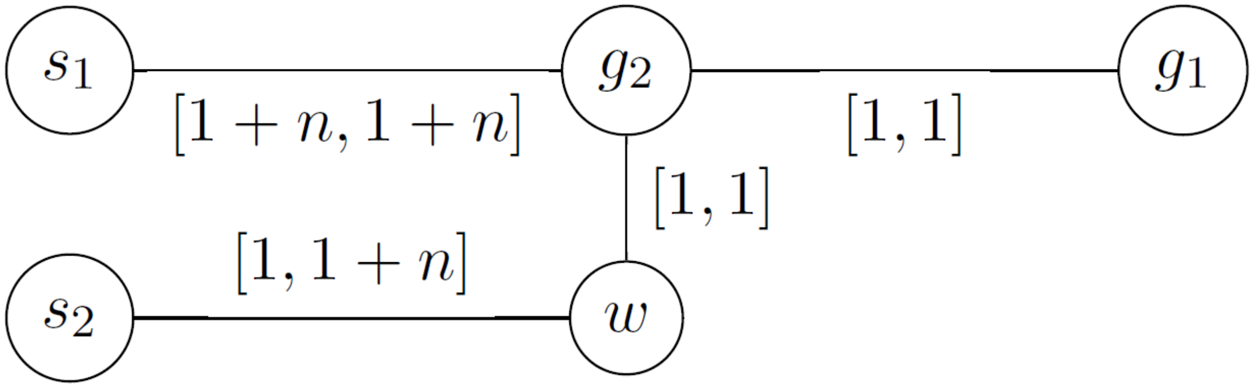
EXPERIMENTS – RESULTS

- Open grid 8x8, 9 agents, CBS_{TU}

U	*Sum of Cost (SOC)*			*Time*	*Success*
	Opt.	*Pes.*	*Range*		
0	47.7	47.7	0.0	0.04	100%
1	59.5	70.3	10.8	2.59	100%
2	73.6	96.9	23.3	5.59	98%
3	86.4	122.2	35.8	20.2	84%
4	104.0	146.7	42.7	19.4	70%
5	107.3	166.0	58.7	34.3	67%
6	122.5	179.4	56.0	30.1	69%
7	137.3	205.2	67.9	23.9	69%
8	145.9	232.8	86.9	32.6	53%
9	171.5	286.5	115.0	42.0	50%

ONLINE REPLANNING

- Agent can sense current time when arrives at a vertex



- SOC*pes*: $4+3n$ vs. $4+2n$

SENSE SETTING

- No communication
- Agent improves its plan individually
- $\tau(\pi_i',*) \subset \tau(\pi_i,*)$ to ensure safety

SENSE+COM

- Agents share sensed information
- Centralized replanning
  - Run CBS_{TU} for *replanning agents*
  - Initialized with constraints covering potential presence of not-replanning agents

REPLANNING – EXPERIMENTS

- Open grid map, 8 agents

SOC*opt*

U	$Initial\ SOC$	$Final\ SOC$ $SENSE$	$Final\ SOC$ $S{+}C$
0	43.06	43.06	43.06
1	59.32	58.22	58.05
2	72.89	72.61	72.96
3	93.45	90.79	91.10
4	111.09	109.10	107.64
5	115.60	118.67	111.07
6	129.53	137.96	127.33
7	155.57	150.10	148.57
8	166.89	163.47	159.22

SOC*pes*

U	$Initial\ SOC$	$Final\ SOC$ $SENSE$	$Final\ SOC$ $S{+}C$
0	43.06	43.06	43.06
1	58.58	58.16	58.63
2	74.44	75.70	73.56
3	93.76	92.74	91.88
4	116.04	116.41	114.13
5	124.07	125.02	120.04
6	137.63	138.90	134.60
7	163.10	158.98	160.68
8	176.07	173.42	173.81

REPLANNING – EXPERIMENTS

- Warehouse map, 8 agents

SOC*opt*

U	Initial SOC	Final SOC: SENSE	Final SOC: S+C
0	240.00	240.00	240.00
1	265.31	265.11	255.83
2	283.29	282.79	257.88
3	305.43	305.10	260.95
4	316.17	315.39	254.78
5	338.43	337.57	264.29
6	346.46	345.85	264.46
7	368.38	367.62	267.15
8	423.10	421.91	280.60

SOC*pes*

U	Initial SOC	Final SOC: SENSE	Final SOC: S+C
0	240.00	240.00	240.00
1	248.70	251.07	248.50
2	262.55	266.12	262.05
3	264.44	272.18	264.56
4	268.30	268.30	268.47
5	270.45	270.45	270.66
6	272.97	272.97	273.84
7	276.68	276.68	276.54
8	285.80	285.80	284.39

CONCLUSION

- MAPF with uncertainty in time to traverse an edge
- CBS_{TU} is better
- Online replanning
  - Theoretically always advantageous
  - Experimentally: significant benefit only in SENSE+COM optimizing for optimistic SOC