Graph-Based Modeling, Scheduling, and Verification for Intersection Management of Intelligent Vehicles

CS637A: Embedded and Cyber Physical Systems

Fall 2020: Project Presentation

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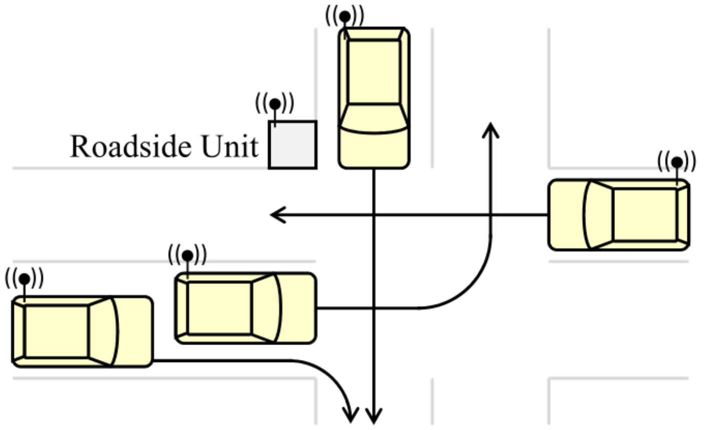
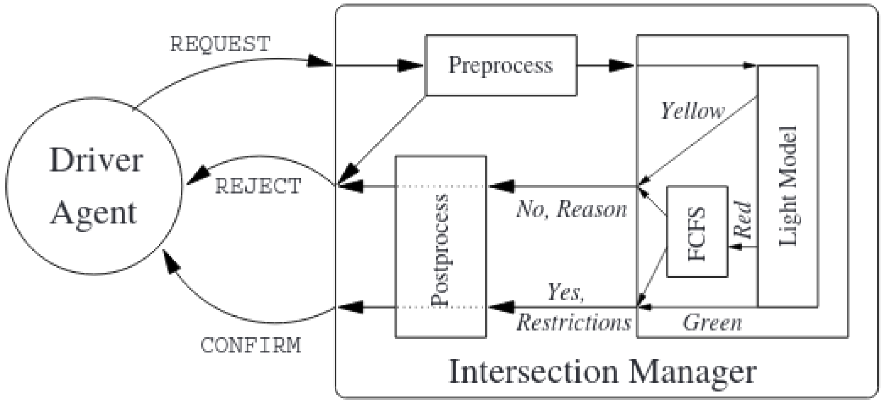
Intersection Management

- Management of vehicles and their passing order, at intersections
- Crucial for efficient traffic management and safety, especially with the advent of autonomous vehicles
- Optimizing passing time, preventing deadlock and ensuring no collisions – some of the prime objectives
- Position of each vehicle and commands communicated amongst themselves, or to a roadside unit – the intersection manager

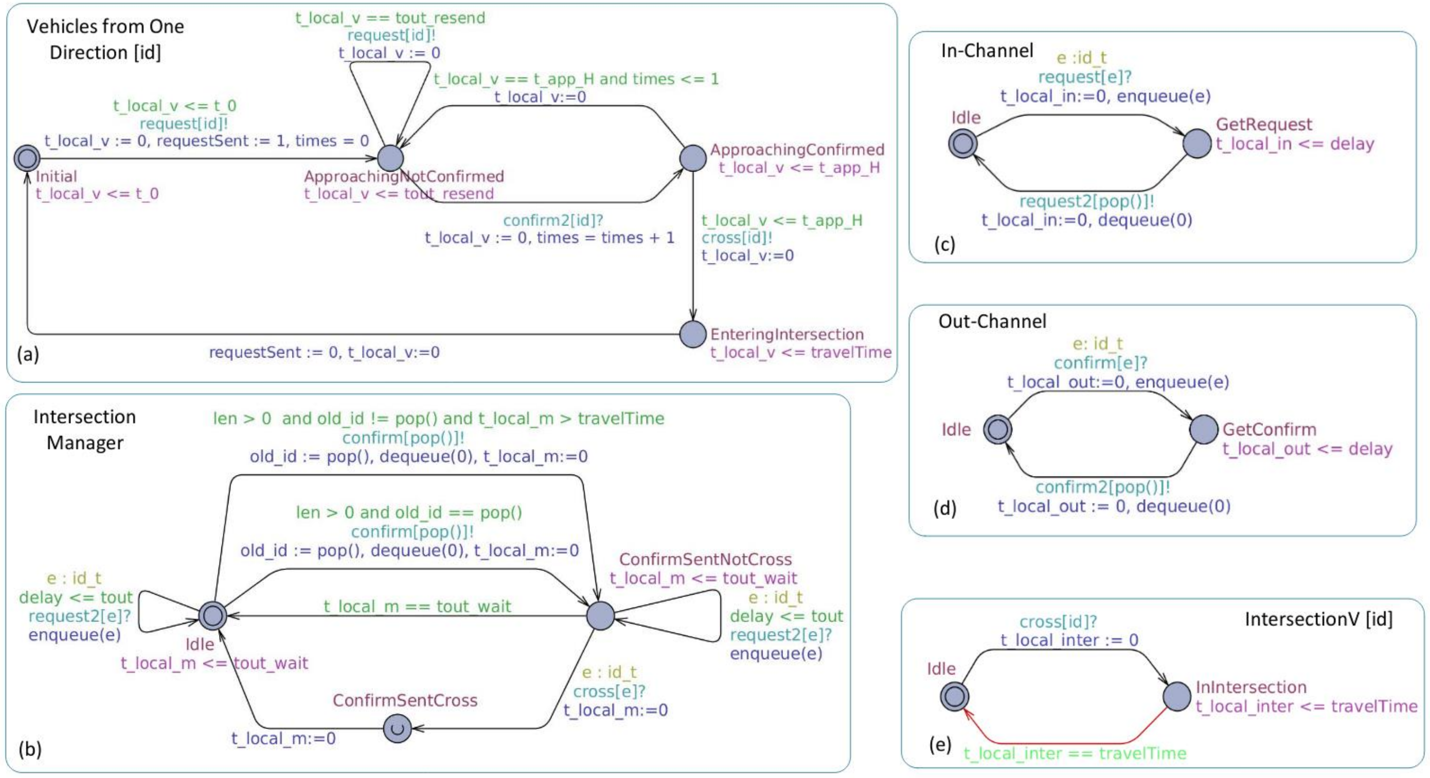


Related Work

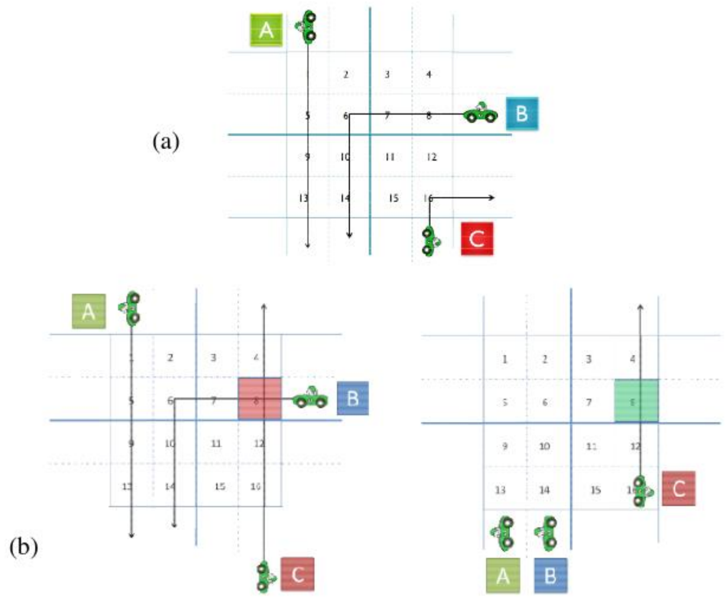
- Protocols between vehicles and a centralized intersection manager



Multi-Agent Reservation-based Scheduler [12]



Delay-aware centralized intersection manager [26]



STIP: V2V Intersection Protocols [4]

Related Work

- Discrete-event control and conflict resolution in a centralized setting

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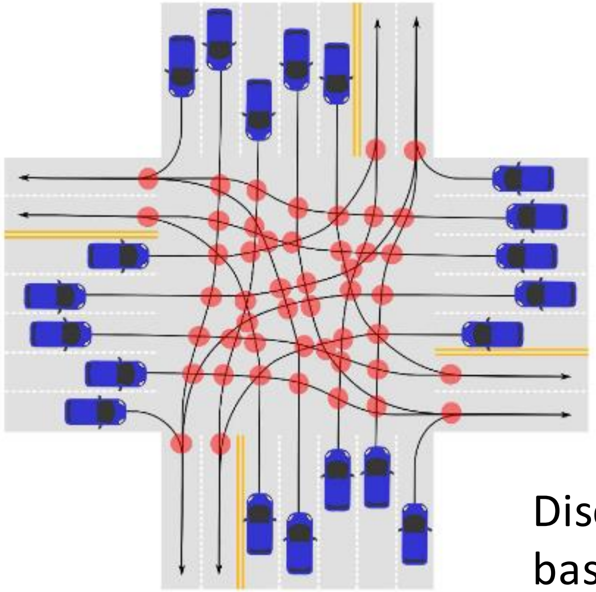
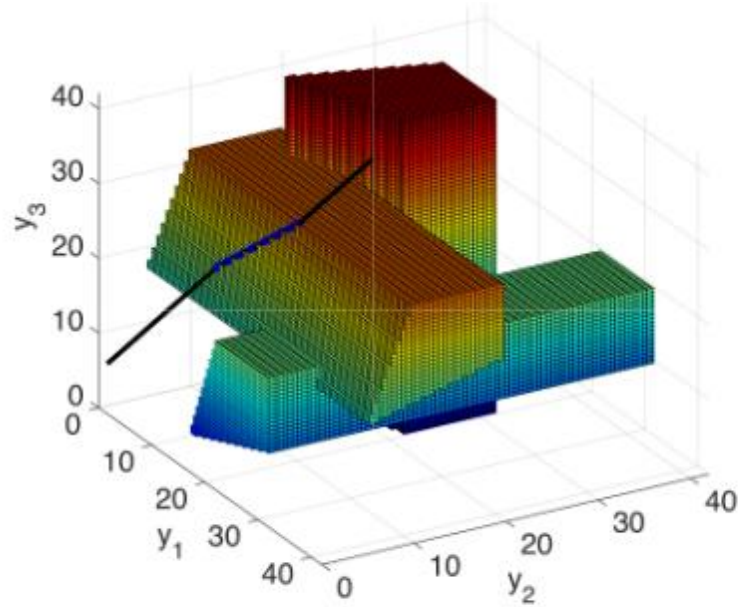
Algorithm 1 Supervisor$(\mathbf{x}(k\tau), \mathbf{u}^k_{driver})$

$\{\mathbf{T}_1, \mathbf{p}_1, answer_1\} = \text{Jobshop}(\hat{\mathbf{x}}(\mathbf{u}^k_{driver}), \Theta)$
if $answer_1 = yes$ **then**
    $\mathbf{u}^{k+1,\infty} \leftarrow \sigma(\hat{\mathbf{x}}(\mathbf{u}^k_{driver}), \mathbf{T}_1, \mathbf{p}_1)$
    $\mathbf{u}^{k+1}_{safe} \leftarrow \mathbf{u}^{k+1,\infty}(t)$ for $t \in [(k+1)\tau, (k+2)\tau)$
    return $\mathbf{u}^k_{driver}$
else
    $\{\mathbf{T}_2, \mathbf{p}_2, answer_2\} = \text{Jobshop}(\hat{\mathbf{x}}(\mathbf{u}^k_{safe}), \Theta)$
    $\mathbf{u}^{k+1,\infty} \leftarrow \sigma(\hat{\mathbf{x}}(\mathbf{u}^k_{safe}), \mathbf{T}_2, \mathbf{p}_2)$
    $\mathbf{u}^{k+1}_{safe} \leftarrow \mathbf{u}^{k+1,\infty}(t)$ for $t \in [(k+1)\tau, (k+2)\tau)$
    return $\mathbf{u}^k_{safe}$
end if

Job scheduling-based semi-autonomous supervisory control



Discrete-event conflict-based modelling

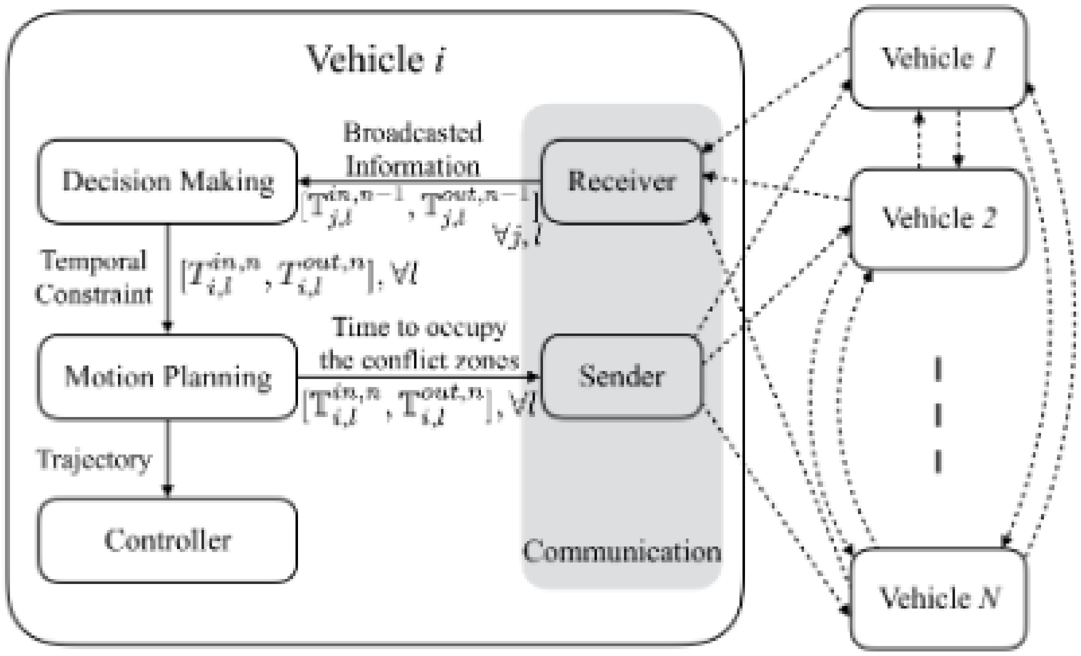


Reactive supervisory control

Refs: [2,7,9,22]

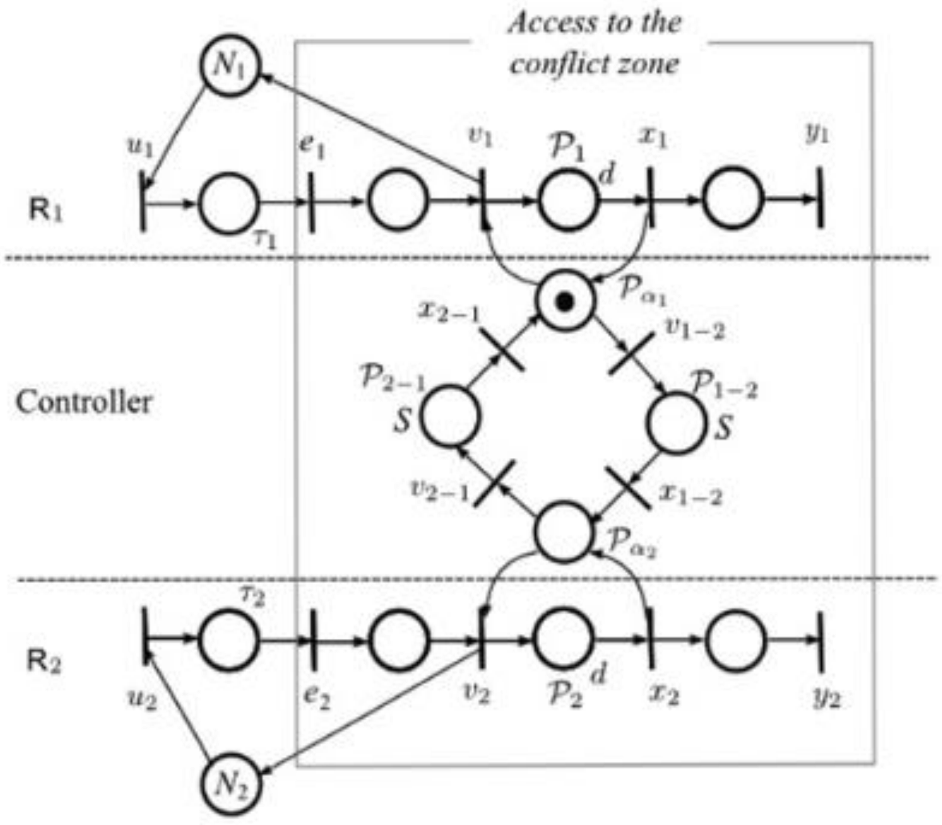
Related Work

- Distributed inter-vehicle communication-based scheduling



Vehicle model for distributed scheduling [18]

- Petri net-based modelling for cooperative vehicles

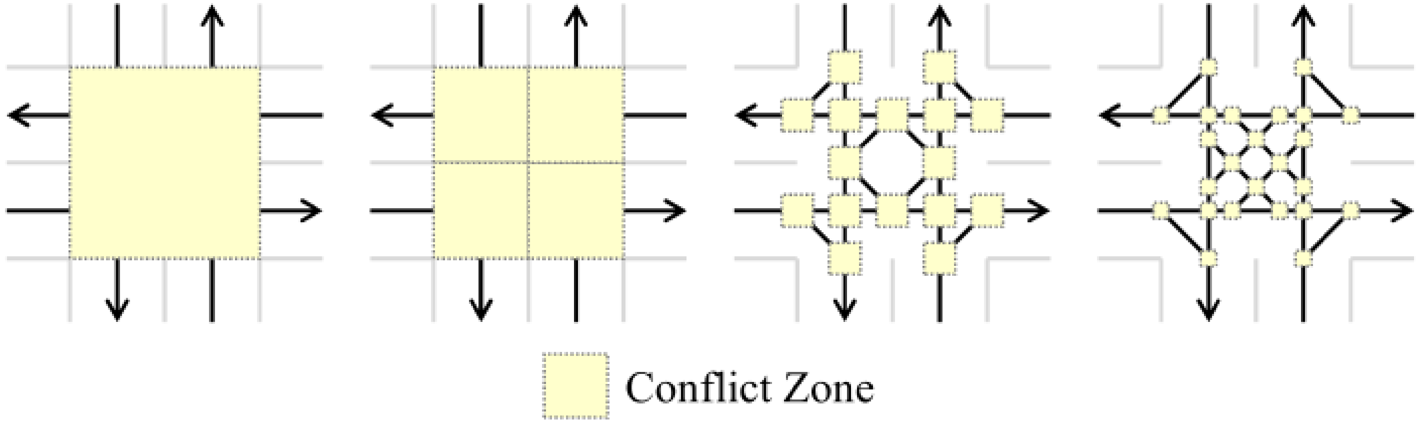


Timed petri-net model for two-lane intersection [24]

Paper Contributions

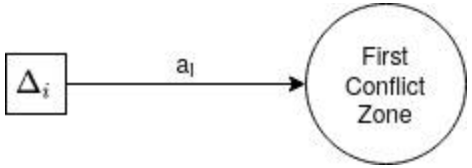
- Graph based model – can deal with various granularities of intersections, highly expressive
- Centralized cycle removal for efficient, safe and deadlock free crossing of vehicle
- Efficiently scalable in response to increasing number of vehicles and conflict zone complexity
- Formal verification techniques to guarantee deadlock-freeness in all scenarios

Terminology

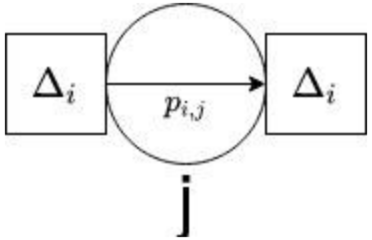


- Intersection
- Conflict Zone (j)
- Vehicle (Δ_i)
- Intersection Manager

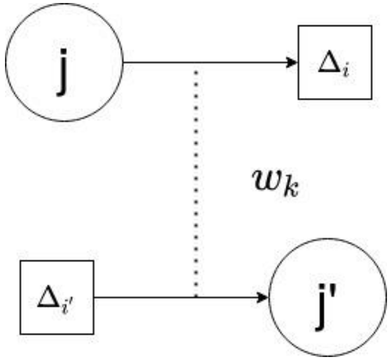
- Earliest Arrival Time(a_i)



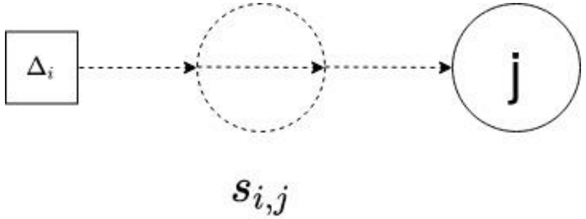
- Vertex Passing Time ($p_{i,j}$)



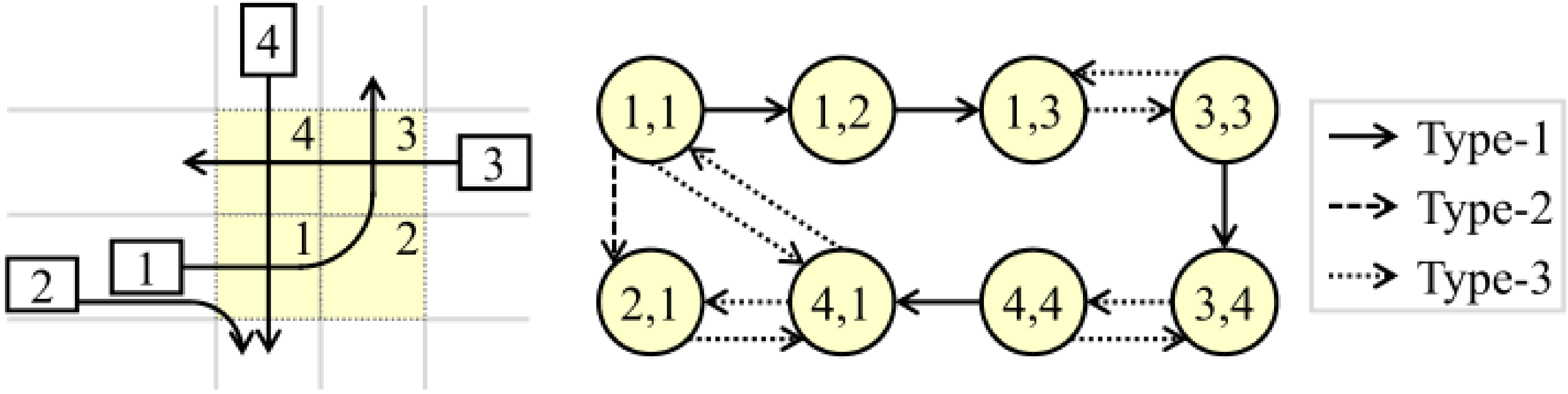
- Edge Waiting Time(w_k)



- Vertex Entering Time($s_{i,j}$)



Timing Conflict Graph (TCG)



(a) (b)

- Type-1: Vehicle Δ_i goes from j to j'
- Type-2: Vehicles Δ_i and $\Delta_{i'}$ (in the same starting lane) go through j
- Type-3: Vehicles Δ_i and $\Delta_{i'}$ (in different starting lanes) go through j
    - Always in pairs

Problem Modelling

- Given a TCG G, earliest arrival times, edge waiting and passing times

1. Compute an acyclic subgraph G'
   - With all the vertices, Type-1 and Type-2 edges
   - Only one out of each pair of Type-3 edges
2. Guarantee no deadlock in G'
3. Assign an entering time to each vertex in G'
4. Minimize the maximum leaving time $t_{max} = max_{G'}(s_{i,j} + p_{i,j})$

1. Collision Freeness
2. Liveness/Feasibility
3. Scheduling
4. Optimality of Schedule

Assumptions

- Perfect, no-delay communication among vehicles and intersection managers.
  - Can model delay by increasing edge wait times, or adding noise in inputs.
- Problem solved in discrete chunks, no dynamic addition of vehicles
  - Vehicles coming in before the current graph is processed will be scheduled in the next chunk
- Dynamics of the vehicles aren't modelled – speed is constant or zero
  - No overtaking allowed

Verification

- Collision-freeness is guaranteed by the scheduler

- Need to ensure deadlock-freeness through verification
  - Graph-based verification
  - Petri net-based verification

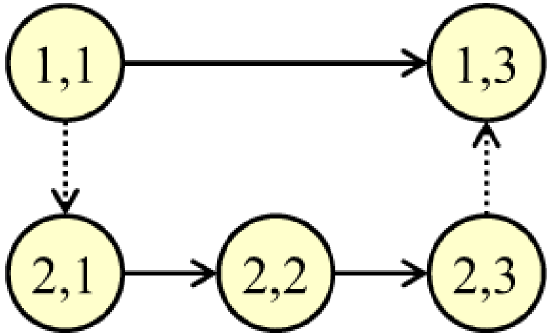
- Either method can be used as a sub-routine to verify liveness of candidate schedules during scheduling

Graph-based Verification

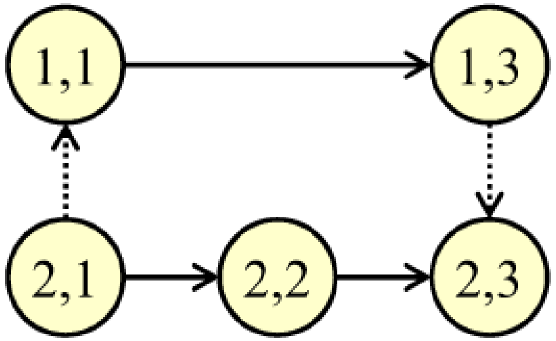
- One would expect deadlock to occur when there is a cycle in the timing conflict graph. But:

  <u>Having no cycle in G' or G does not guarantee deadlock-freeness</u>

- Deadlock can occur due to two parallel paths between same start and end vertices.
- Create an alternative graph to model deadlocks as cycles based on the timing conflict graph.



Ex. 1: V2 waits for V1 to pass Z1
V1 waits for V2 to pass Z3
Deadlock, no cycle



Ex. 2: V1 waits for V2 to pass Z1
V2 waits for V1 to pass Z3
No deadlock, V2 can move to Z2

Resource Conflict Graph (RCG)

- The basic idea is to combine edges of the conflict graph into vertices
- All Type-1 and Type-2 edges absorbed into vertices
- Each edge in the resource conflict graph is a Type-3 edge in the timing conflict graph
- At least one of the j-indices are equal across an edge

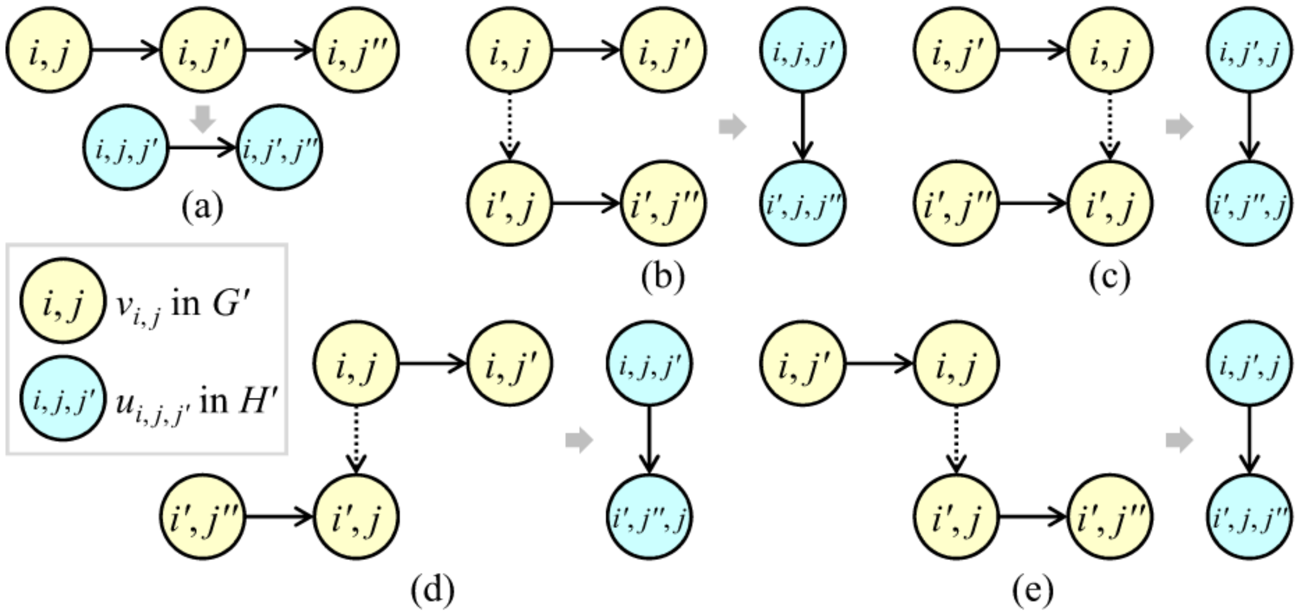
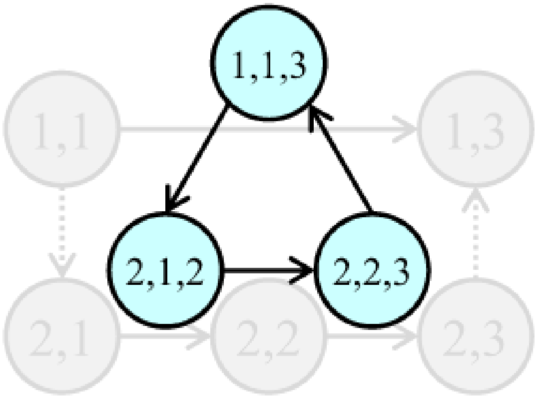


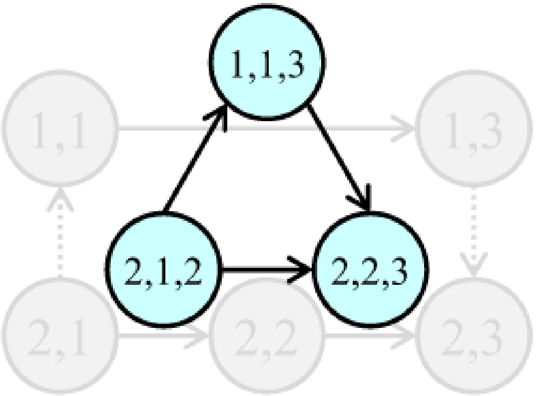
Fig. 6. The construction rules of resource conflict graphs.

Verifying Liveness

- An edge $(i_k, j_k, j'_k) \rightarrow (i_{k+1}, j_{k+1}, j'_{k+1})$ in RCG implies i_k must free up the common conflict zone before i_{k+1} arrives.
  - If there is a cycle in RCG, then there is a deadlock.
- If there is a deadlock, say i can't move from j to j', then there must be an edge to (i, j, j') in RCG
  - Can show using one of the construction rules
  - Repeatedly apply above statement to all vehicles in deadlock
  - Ultimately forms a cycle in RCG, since vehicles and zones are finite.



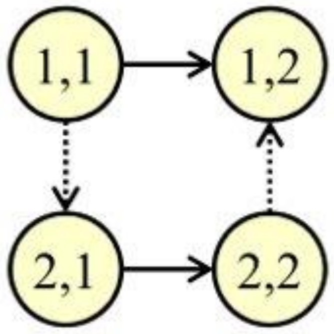
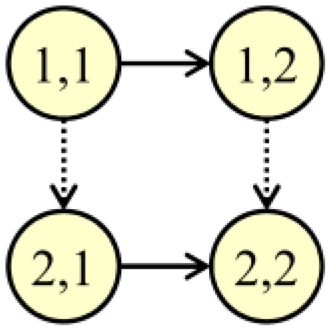
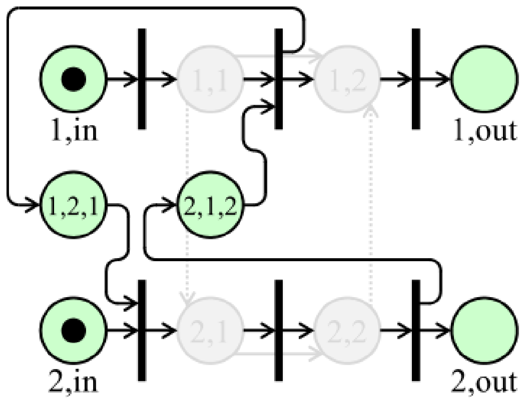
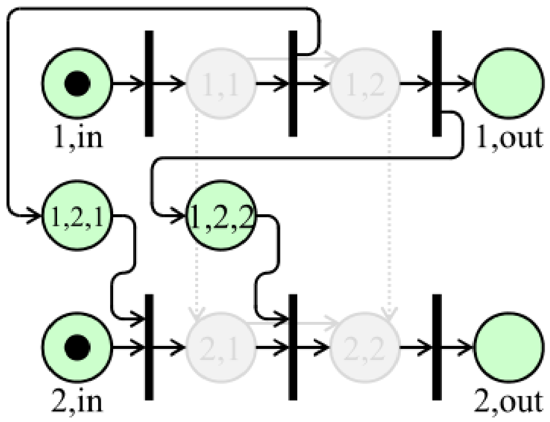
Ex. 1: Deadlock, cycle exists



Ex. 2: No deadlock, no cycle

- So, to verify that acyclic subgraph has no deadlock – construct its resource conflict graph and check for cycles in it.

Petri Net Construction

	With Deadlock	Without Deadlock
Acyclic TCG G'		
Equivalent Petri-Net Π		

Petri Net Verification

<u>The Petri net Π has a deadlock if and only if G' has a deadlock</u>

- If Π has a deadlock, at least one place $q_{i,i',j}$ never receives a token, which implies that Δ_i cannot leave j before $\Delta_{i'}$ enters j (so deadlock in G')
- If deadlock occurs in G' (suppose that some Δ_i can't go from j to j') it implies that $q_{i',i,j}$ will never receive a token (so deadlock in Π)
- So, to verify that acyclic subgraph has no deadlock – construct equivalent Petri Net and check it for deadlocks

Scheduling

- Naïve approach: first-come first-serve schedule
  - Ignores key interactions between vehicles and conflict zones
  - Introduces extra delays in many cases

- Generate a passing order for vehicles by constructing acyclic subgraph G' from conflict graph G with minimum total passing time.
  - Subgraph generated through cycle removal

- Naïve cycle removal: DFS traversal of the graph
  - May not always remove "good" edges to optimize objective
  - Can't remove some types of edges due to safety constraints

Cycle Removal-Based Scheduling

- We need to remove cycles while minimizing total passing time
  - Min. Spanning Tree – acyclic subgraph with minimum sum of edge weights
  - Iteratively remove max-cost edge whose removal doesn't disconnect graph

- Proposed algorithm is based on the above idea
  - Iteratively remove max-cost Type-3 edges without violating constraints
  - Ensuring liveness complicates the problem – deadlocks exist even in acyclic graphs, as shown earlier
  - Need to efficiently handle cases where max-cost edge cannot be removed
    - Backtracking and redoing is computationally expensive.

Edge and Vertex States

Edge State: For an edge e,

ON - e is included in G'

OFF – e has been removed from G'

UNDECIDED – Will decide ON/OFF in current subproblem

DONTCARE – e not included in current subproblem

- All Type-1 and Type-2 edges always ON

Vertex State: For a vertex v,

BLACK – Entering time scheduled

GRAY – Entering time depends on Type-3 edges only

WHITE – Entering time can depend on any type of edges

- If any outgoing edge is ON, v is BLACK
- If v is BLACK, all edges through it must be ON/OFF
- If v is GRAY, v' must be BLACK if (v', v) is not a Type-3 edge

Vertex Entering Time

- Δ_i can't enter j before all earlier vehicles $\Delta_{i'}$ have passed

$$\max\{s_{i',j} + p_{i',j} + w_k\}$$

- Additionally, need to wait for $\Delta_{i'}$ to move to next zone j'

$$\max\{s_{i',j'} - w_{k'} + w_k\}$$

- Entering time is max of above two quantities – need to fulfill both
- For the first conflict zone on Δ_i's path, also depends on arrival time a_i
- For v, depends on the earlier vertices u where (u,v) is an edge of G'
  - Since G' is acyclic, compute in topological order

Vertex Slack

- Maximum delay that can be added at vertex without changing the maximum leaving time t_{max} (i.e. the optimization objective)
- For the last vertex on the path of the last vehicle $v_{i,j'}$

$$t_{max} – (s_{i,j'} + p_{i,j'})$$

- For other vertices u, it is minimum of slack of all reachable vertices v where (u,v) edge in G'
- Compute reverse topologically for acyclic graph

Defining the Cost of an Edge

Edge Cost: Delay incurred in t_{max} due to adding this edge in G'

Only need to look at cost of Type-3 edges, $e_k = (v_{i,j}, v_{i',j})$

$$cost[e_k] = (s_{i,j} + p_{i,j} + w_k) - s_{i',j} - slack[v_{i',j}]$$

$(s_{i,j} + p_{i,j} + w_k)$ and $s_{i',j}$ are start times for $v_{i',j}$ with & without e_k

Compare with slack at $v_{i',j}$ to determine effect of e_k on t_{max}

If the cost is positive, t_{max} will increase.

But if cost is negative, t_{max} won't change.

Removal of Type-3 Edges

- Initialization
  - Include Type-1 and Type-2 edges in G', set their states to ON
  - Compute vertex entering times on G', leaving time of last vehicle as t_{max}
  - Set Type-3 states to UNDECIDED, compute vertex slacks.

- Identify candidate edges for removal
  - Leader vertex – $v_{i,j}$ where i is first vehicle on source lane, j is first conflict zone
  - Candidate edges – UNDECIDED Type-3 edges with one vertex as a leader vertex
  - Compute cost of these edges, and try to remove in decreasing order of cost

Ensuring Deadlock-Freeness

- Type-3 edges always in pairs – exactly one of two must be included
- Remove one and verify deadlock-freeness - if it fails, swap the edges
  - Use edge state variables to temporarily remove an edge
- If G' is deadlock-free, recompute vertex entering times and slacks
  - Identify newly set GRAY vertices as leader vertices, and repeat
- If G' is not deadlock-free, need to re-evaluate entire assignment till e_k
  - Backtracking is expensive – divide into subproblems
  - Schedule the first half of the vehicles arranged in increasing arrival time
    - For Type-3 edges between the two halves, assume first half passes before second half
    - Use the schedule of the first half while solving the second subproblem

Proof of Correctness and Time Complexity

- Type-1 and Type-2 edges included in G' by default.
- Exactly one Type-3 edge is selected out of every pair
- Deadlock-freeness is verified on removing each Type-3 edge
- For the solution obtained by recursively dividing into subproblems
  - No deadlock while merging both halves – we assume first passes before second
  - Each subproblem is essentially applying the same algorithm on a smaller set
  - Base case – only one vehicle: no Type-3 edges, so G' is feasible here
- Hence algorithm provably generates acyclic and deadlock-free G'.
- Time complexity of scheduling algorithm: $O(E^2 \log V)$

Results

For maximum a_i equal to 60 seconds

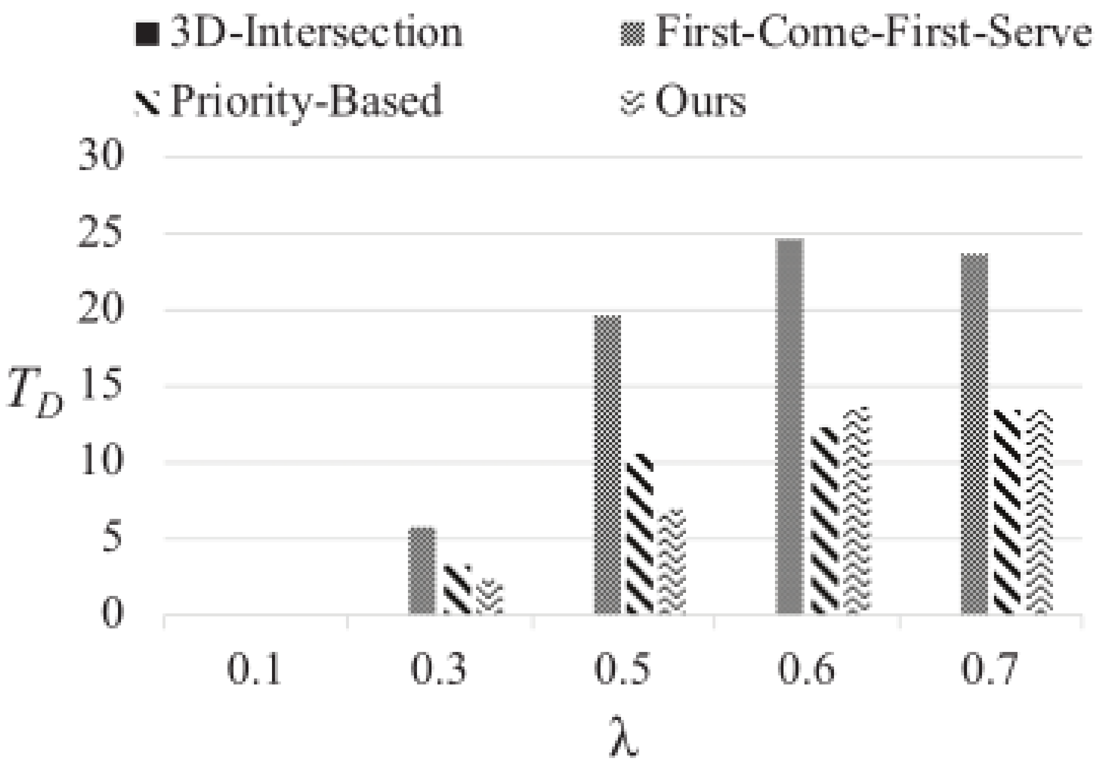
λ	m	3D-Intersection			First-Come-First-Serve			Priority-Based			Ours		
		T_L	T_D	RT	T_L	T_D	RT	T_L	T_D	RT	T_L	T_D	RT
0.1	25	66.30	0	0.002	68.80	0.48	0.005	68.80	0.48	0.008	66.90	0.32	0.006
0.3	66	68.80	0	0.009	89.19	10.84	0.013	73.50	2.36	0.015	71.10	1.78	0.070
0.5	104	74.00	0	0.015	131.10	26.75	0.020	105.30	12.30	0.052	98.40	11.80	0.229
0.6	129	71.50	0	0.026	149.20	37.62	0.033	133.00	27.64	0.091	116.90	20.77	0.626
0.7	157	72.90	0	0.039	176.50	54.67	0.049	157.80	38.49	0.157	139.50	34.22	1.825

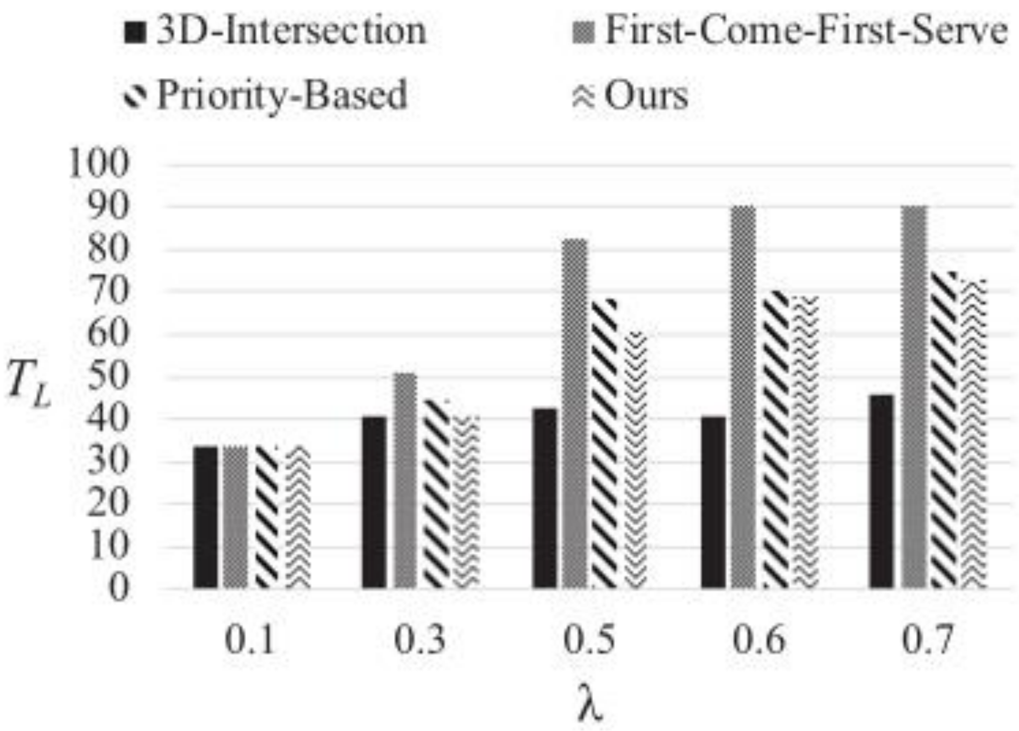
For maximum a_i equal to 30 seconds

λ	m	3D-Intersection			First-Come-First-Serve			Priority-Based			Ours		
		T_L	T_D	RT	T_L	T_D	RT	T_L	T_D	RT	T_L	T_D	RT
0.1	11	33.40	0	0.001	33.40	0.00	0.003	33.40	0.00	0.009	33.40	0.00	0.002
0.3	34	40.70	0	0.003	50.70	5.85	0.005	44.50	3.17	0.007	40.80	2.23	0.015
0.5	58	42.40	0	0.006	82.40	19.58	0.009	68.20	10.62	0.013	60.40	6.91	0.057
0.6	66	40.50	0	0.009	90.39	24.65	0.011	70.10	12.31	0.020	68.70	13.65	0.119
0.7	77	46.10	0	0.010	90.20	23.68	0.013	74.90	13.44	0.024	72.80	13.46	0.174

Results

- Graph of T_D and T_L for various algorithms, with maximum a_i = 30 seconds





Experiments were run by the authors on a macOS Mojave notebook with 2.3 GHz Intel CPU and 8 GB memory.

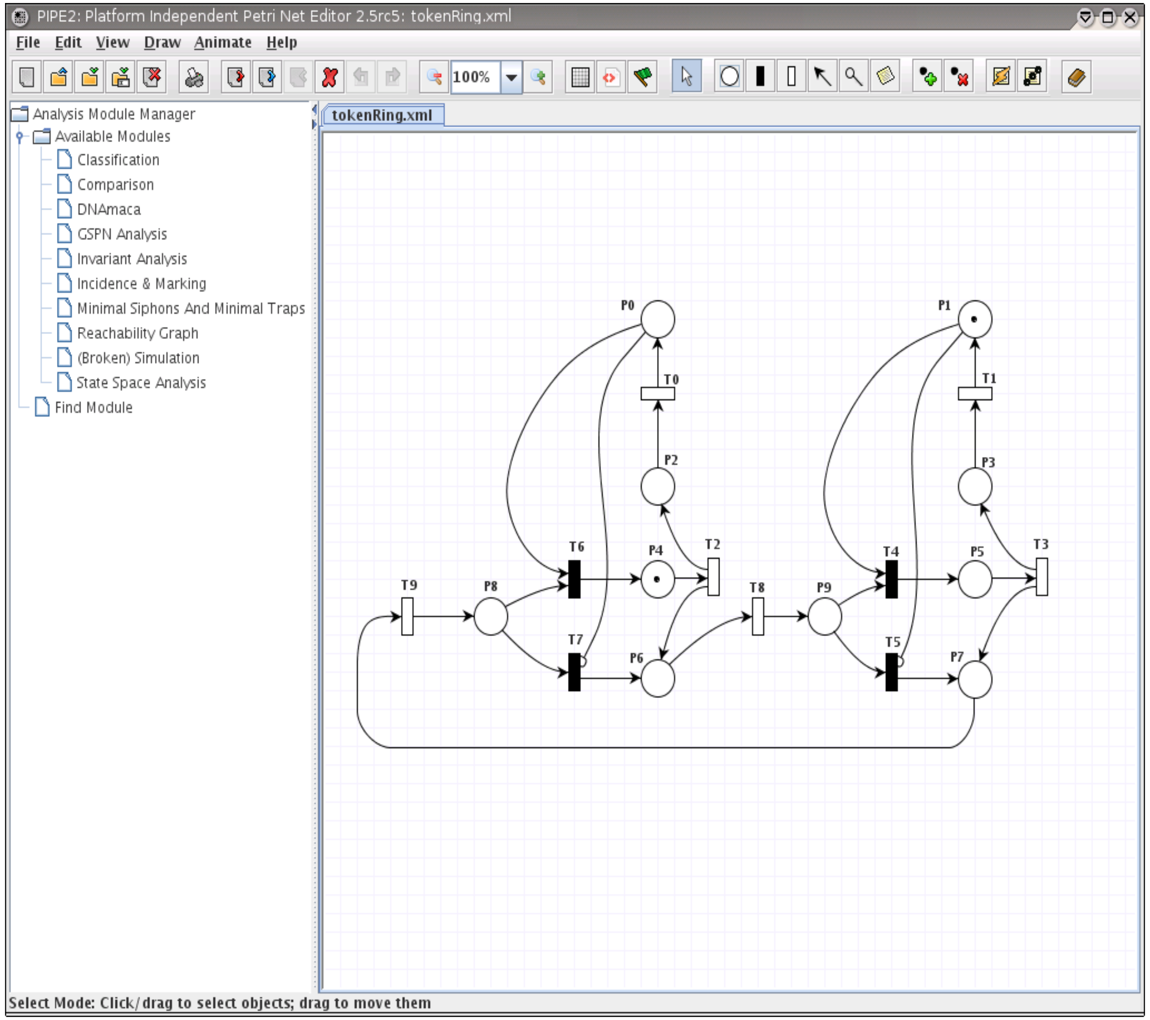
Our Implementation

https://github.com/ashwin2802/CS637
(Debugging in progress)

- Have implemented the algorithm as well as the simulation aspect of it, using C/C++
- Random traffic generator, intersections with 1-16 conflict zones, TCG graph generator, scheduler and deadlock checker (using RCG and Petri-Net).
- Traffic and Intersection generator, TCG graph generator and deadlock checking work, runtime errors in the scheduler.
- Also can visualize the order of vehicle passing using SUMO simulator

http://pipe2.sourceforge.net/

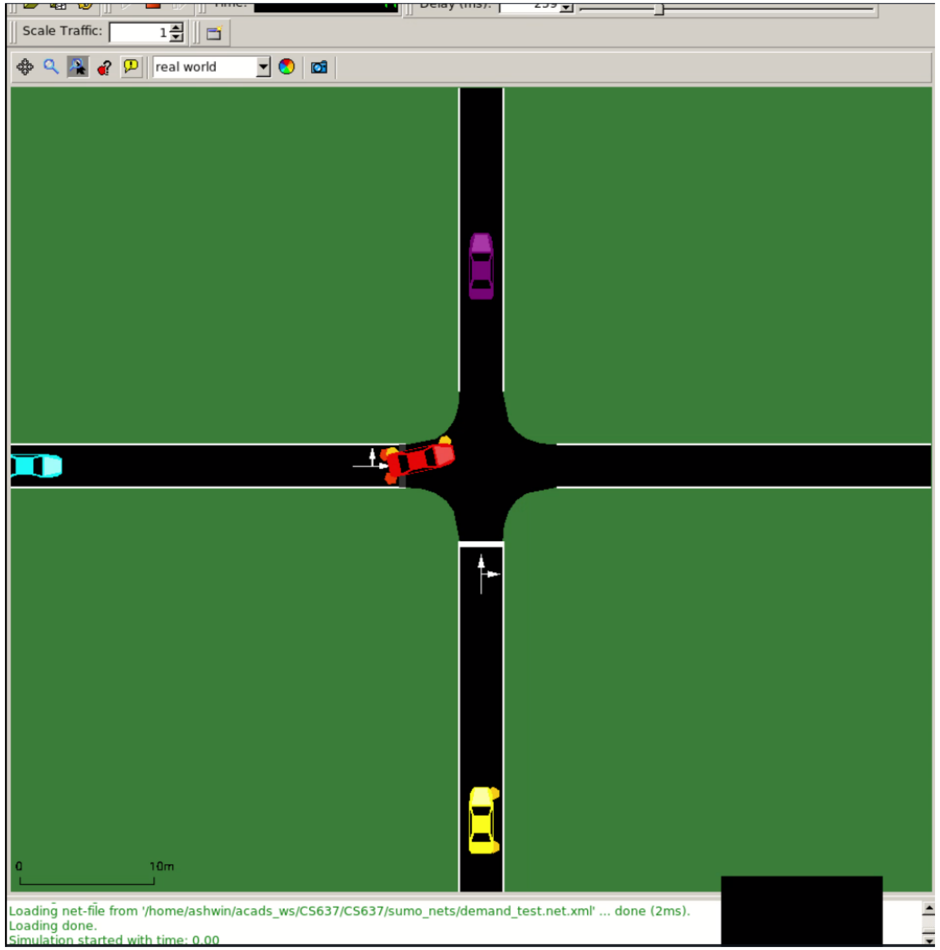
- Paper authors have suggested using Platform Independent Petri-net Editor (PIPE2)
- A GUI tool for easily modelling and visualizing Petri-nets and doing reachability analysis
- However, documentation is scarce and no way to interface it with code



SUMO Simulation of Urban Mobility

- Continuous traffic simulation package
- Completely open-source, highly portable
- Some features
  - Simulation of public transport
  - Simulation of logistics, individual people, trip chains
  - Optimal Path Routing, pedestrian traffic modeling
  - Bicycle, waterway and railway simulations

https://www.eclipse.org/sumo/



Conclusions

- Presents a very general graph-based model for intersection management
- Can be applied to other types of intersections as well – the core concept is modelling the conflict zones discretely
- Presents an effective realtime scheduling algorithm based on cycle removal
- Pretty lightweight once the requisite data is available to the code
- Presents formal verification approaches for deadlock-freeness
- Challenges faced in implementation on an embedded system aren't taken into account

References

Yi-Ting Lin, Hsiang Hsu, Shang-Chien Lin, Chung-Wei Lin, Iris Hui-Ru Jiang, and Changliu Liu. 2019. Graph-Based Modeling, Scheduling, and Verification for Intersection Management of Intelligent Vehicles. ACM Trans. Embed. Comput. Syst. 18, 5s, Article 95 (October 2019), 21 pages. DOI:https://doi.org/10.1145/3358221

References in Recent Works section of the presentation refer to accordingly numbered citations of the above paper.