Schedule-Driven Coordination for Real-Time Traffic Control

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Outline of Talk

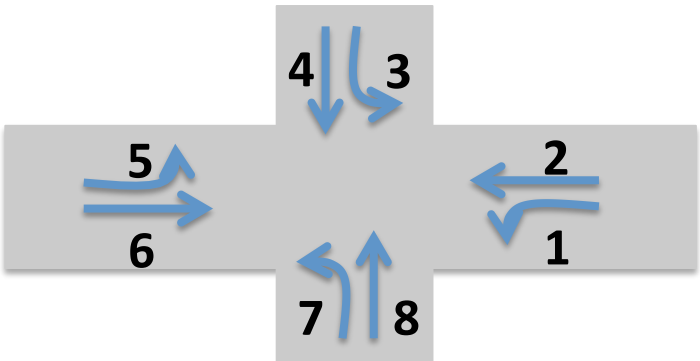
- Traffic Signal Control Problem
- Technical Approach: Schedule-Driven Coordination
- Experimental Results
- Pilot Implementation
- Conclusions

The Problem

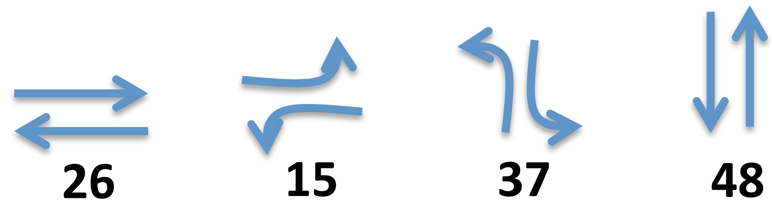
Better Traffic Signal Control Can Help

- Traffic signal control improvements generally provide the biggest payoff for reducing congestion on surface streets
- 10-20% reductions in travel times can be expected over basic non-interconnected signal systems
- Since 40% of time spent on surface streets is spent idling, significant further benefits in fuel consumption, carbon emissions and air pollution
- Although not yet in wide use, *adaptive traffic control systems* are generally believed to hold most promise for improvement

Traffic Signal Plans



Movement Phases:

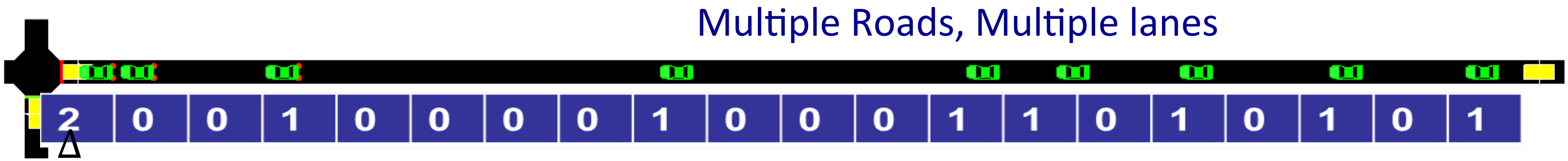


Signal Timing Plan:

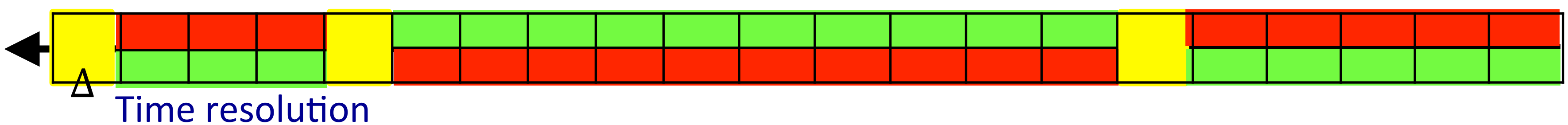
- Conventional signal systems use fixed, pre-programmed daily timing plans or simple actuation
- Adaptive signal systems sense current traffic flows and dynamically adjust timing plans in real-time

Real-Time Challenges

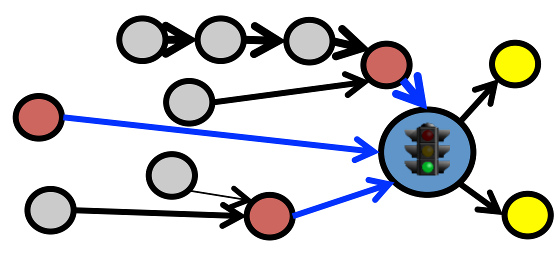
- **Planning Complexity**
  - State Space (Observations): Exponential in a prediction horizon



  - Action Space (Signal sequences): Exponential in a planning horizon



- **Sensing uncertainty**
- **Non-local impacts between intersections**
  - One nice property: networked problem structure



Current Approaches

- **Parametric (Split, Cycle, Offset) Adjustment:**
  - Use historical moving average data**;** Computationally cheap
  - **Limitation:** Requires some degree of stability in traffic flows over time; not sensitive to real-time variability of demands
- **Reinforcement Learning:**
  - Find policies for mapping local observations to signal actions
  - **Limitation:** Slow to converge and difficult to apply in dynamic traffic flow
- **Online Planning:**
  - Optimize in a planning search space using current observation
  - **Limitation:** Scalability **(**especially in a long planning horizon**)**

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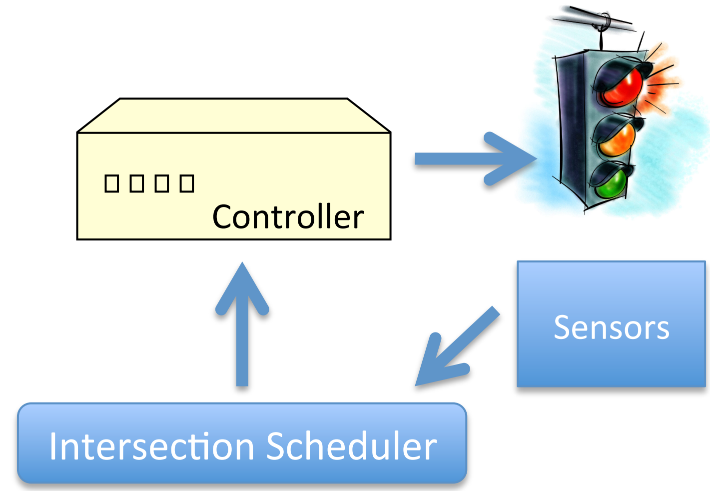
Schedule-Driven Coordination: Basic Approach

- D*ecentralized intersection control* (assume no interaction)
  - Construct schedules to optimize real-time traffic flow through each intersection independently
- *Optimistic, non-local coordination* (assume schedules will not change)
  - Provide schedules to downstream neighbors to increase visibility of future demand and open up "corridors"
- *Mechanisms for coping with Mis-coordination (*to account for fact that schedules might change)
  - Nervousness and Spillback prevention

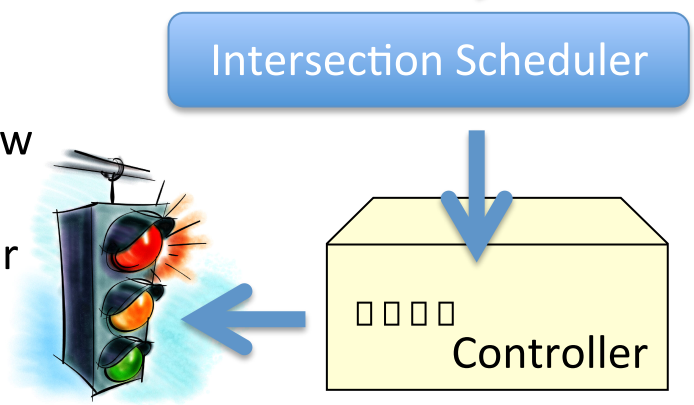
Concept of Operations



3. Schedule is communicated to downstream neighbors to indicate what is coming

1. Current traffic conditions are extracted from sensor data streams

2. System computes phase schedule that optimizes flow at intersection and sends commands to the controller when it is time to change phases



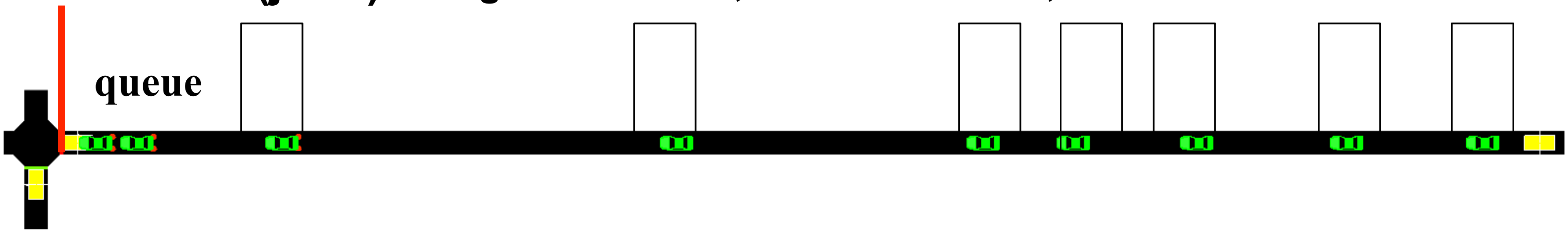
4. **Rolling Horizon:** Scheduling cycle is repeated every few seconds

Schedule-Driven Intersection Control (SchIC)

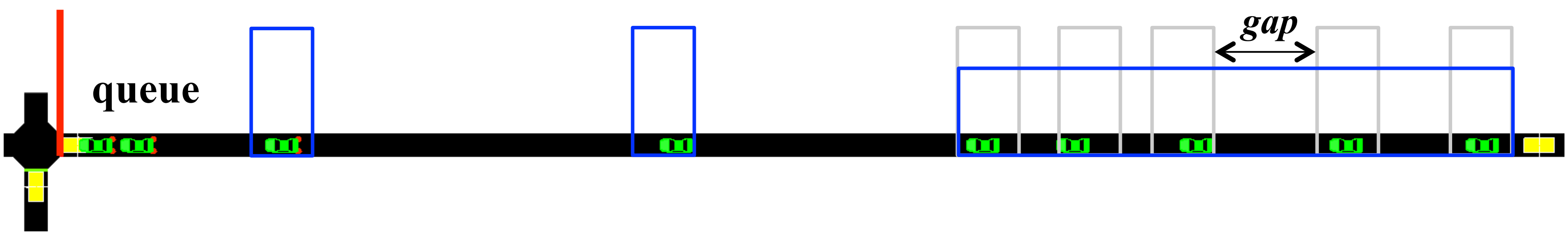
- Treat online planning as a *single machine* scheduling problem
- Exploit aggregate representation of traffic flows to identify input *jobs*
  - Captures non-uniform nature of real-time flows while providing more efficient search space
- Basic Approach:
  - Construct look-ahead schedule for current input flows
  - Use result to decide whether to extend or switch phases

Aggregate Flow Representation

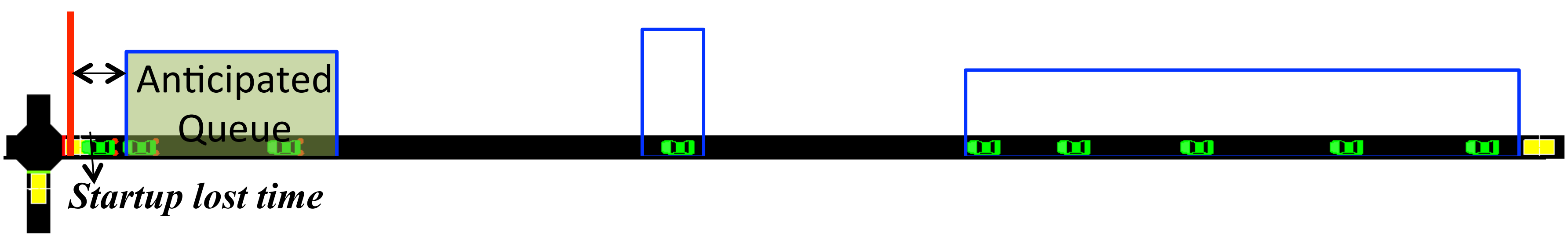
Clusters (jobs): **height = flow rate, width = duration, area = number of vehicles**



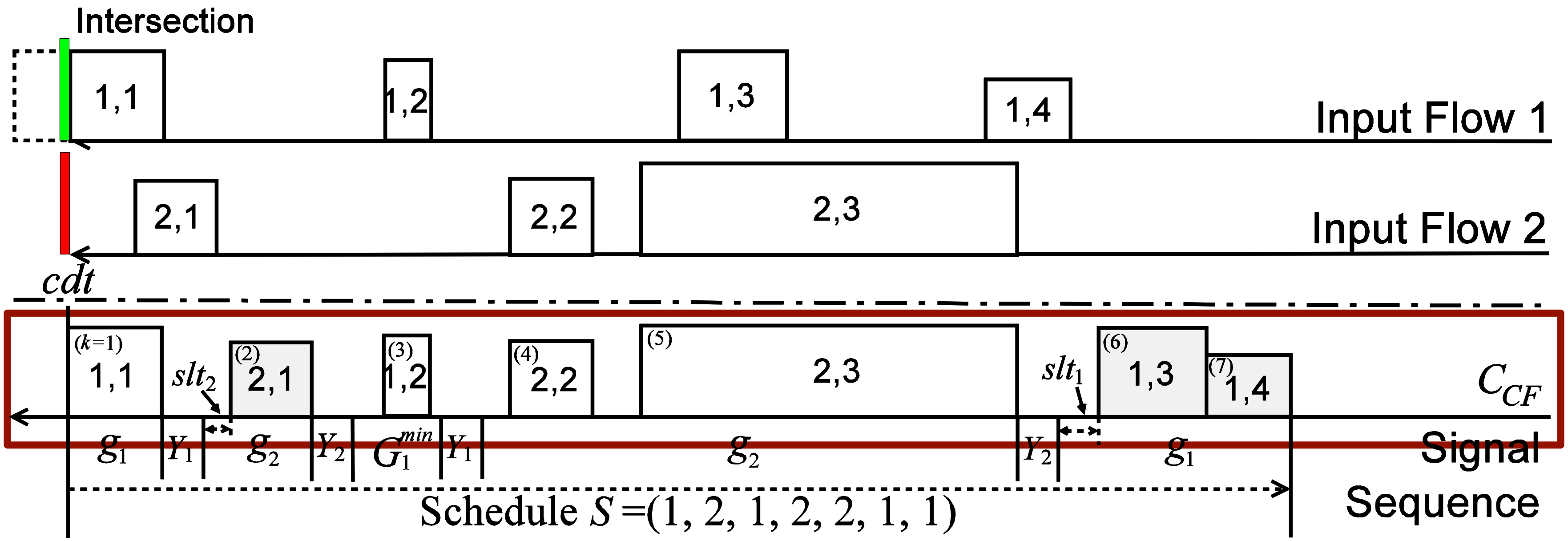
1. Threshold-based clustering: merge clusters with small gaps



2. Anticipated queue: Anticipate the number of vehicles that are either *presently in the queue* or *will join it before it clears* (Lämmer & Helbing, 2008)

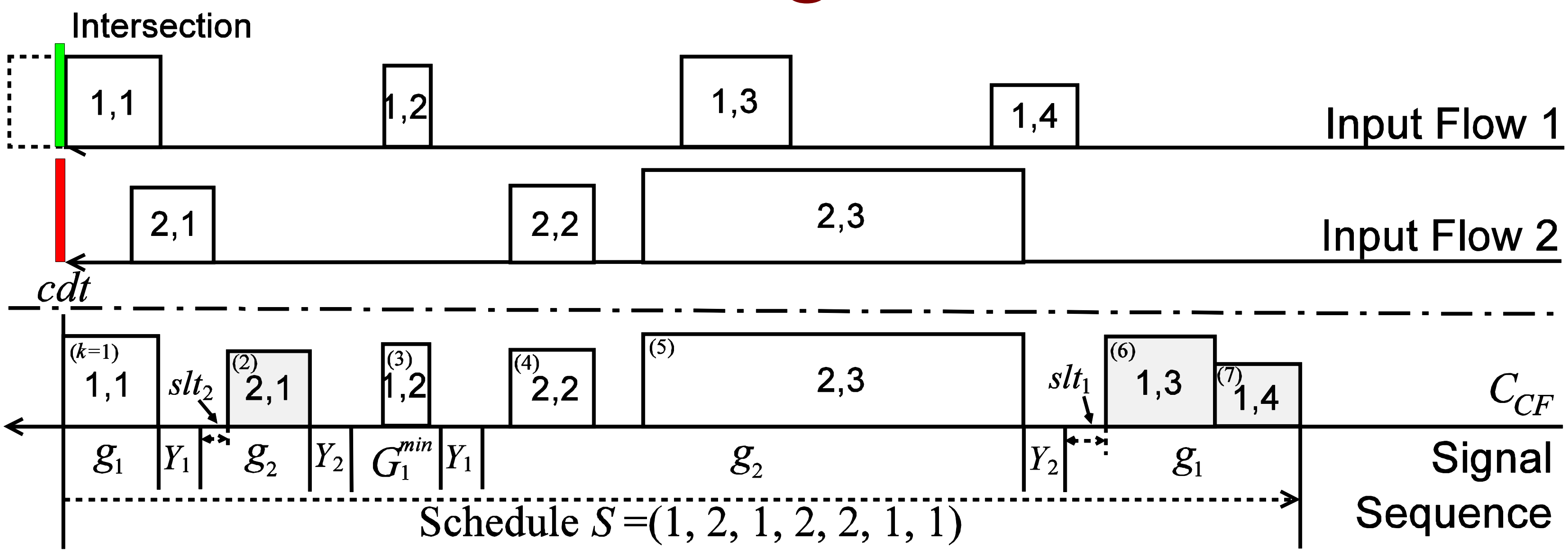


Scheduling Problem



- A **Schedule** = a sequence of all clusters (indivisible *jobs*)
- Schedule → **Planned Signal Sequence** (for traffic light)

Scheduling Problem



- A **Schedule** = a sequence of all clusters (indivisible *jobs*)
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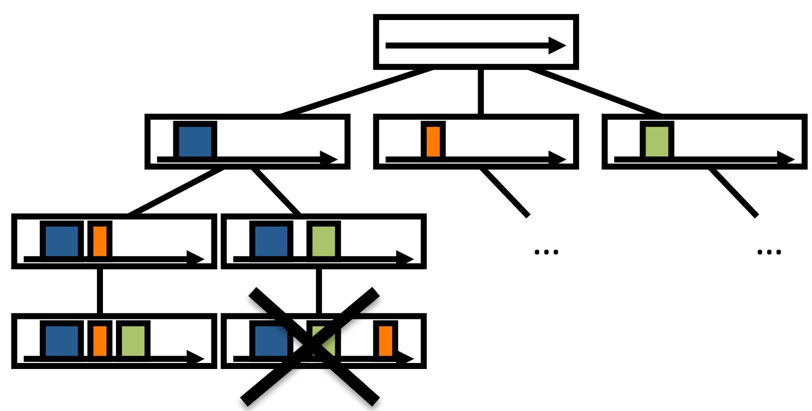
- **Problem:** Minimize the *cumulative delay* of all jobs, subject to
  - timing constraints for safety (yellow time) and fairness (G_i^{min} and G_i^{max} for each phase)

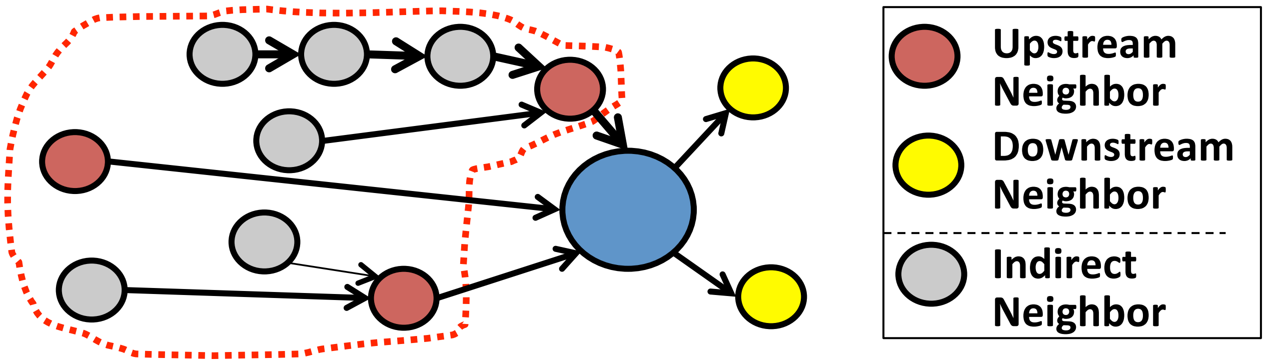
Scheduling Strategy

- Forward dynamic programming search
  - New job added to at each decision stage
  - Eliminate dominated solutions at each stage (same current phase, same jobs, *different orders*)
  - Only keep the state with minimum delay for each extension (greedy)
  - Time complexity: $|\text{phases}|^{2} * \Pi\ (|\text{clusters}_i|+1)$

In related work, SchIC has been shown to outperform other state-of-the-art approaches to intersection control [Xie et.al 2012b]



Optimistic Non-local Observation



- Optimistically assume that all neighbors follow their schedules and communicate planned output flows to amplify local views
  - Planned Output Flows (Int_i) => Predicted Input Flows for Int_i‘s downstream neighbors
  - Input Flows (Int_i) = Predicted (Local) Input Flows + Predicted (Non-local) Input Flows from Int_i’s upstream neighbors
- **Some Properties**
  - Scalable, since communication is only with direct neighbors
  - Incorporates impact from indirect neighbors with sufficiently large planning horizon

Coping with Mis-Coordination

- **Nervousness Prevention**
  - Since SchIC treats jobs as indivisible, it is possible that planned output flows may violate G_i^{max}
  - To avoid such mis-coordination with downstream neighbors, input clusters are split as necessary and SchIC is re-applied to ensure all G_i^{max} are satisfied
- **Spillback Prevention**
  - The queue size can exceed the physical capacity of a road segment in high load periods
  - If residue queue of next phase is expected to exceed capacity, then current phase is cut short
  - Sacrifice own interest for the sake of upstream neighbors

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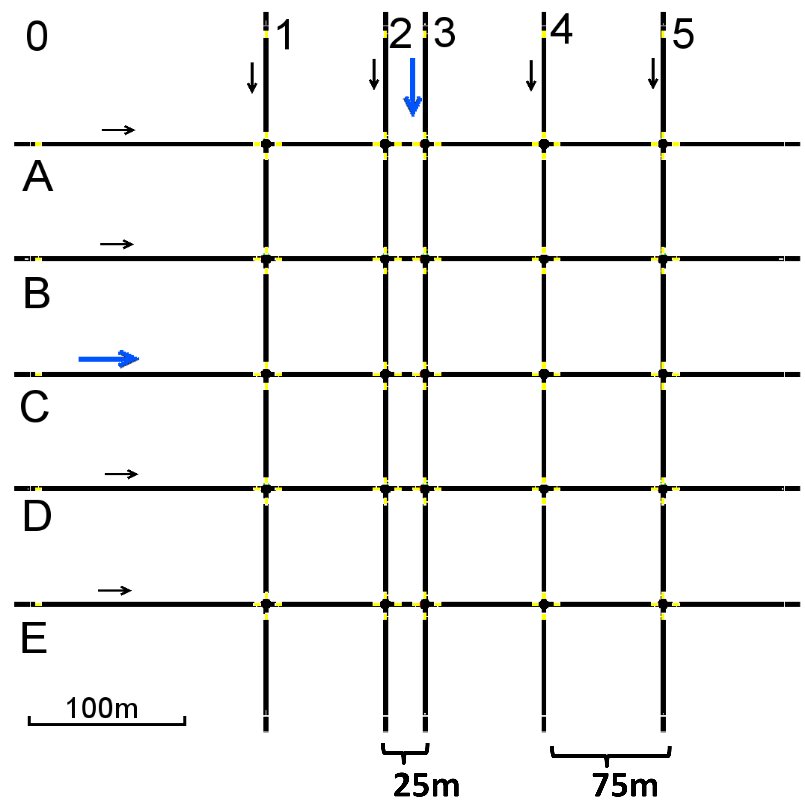
Synthetic Grid Network of 25 Intersections

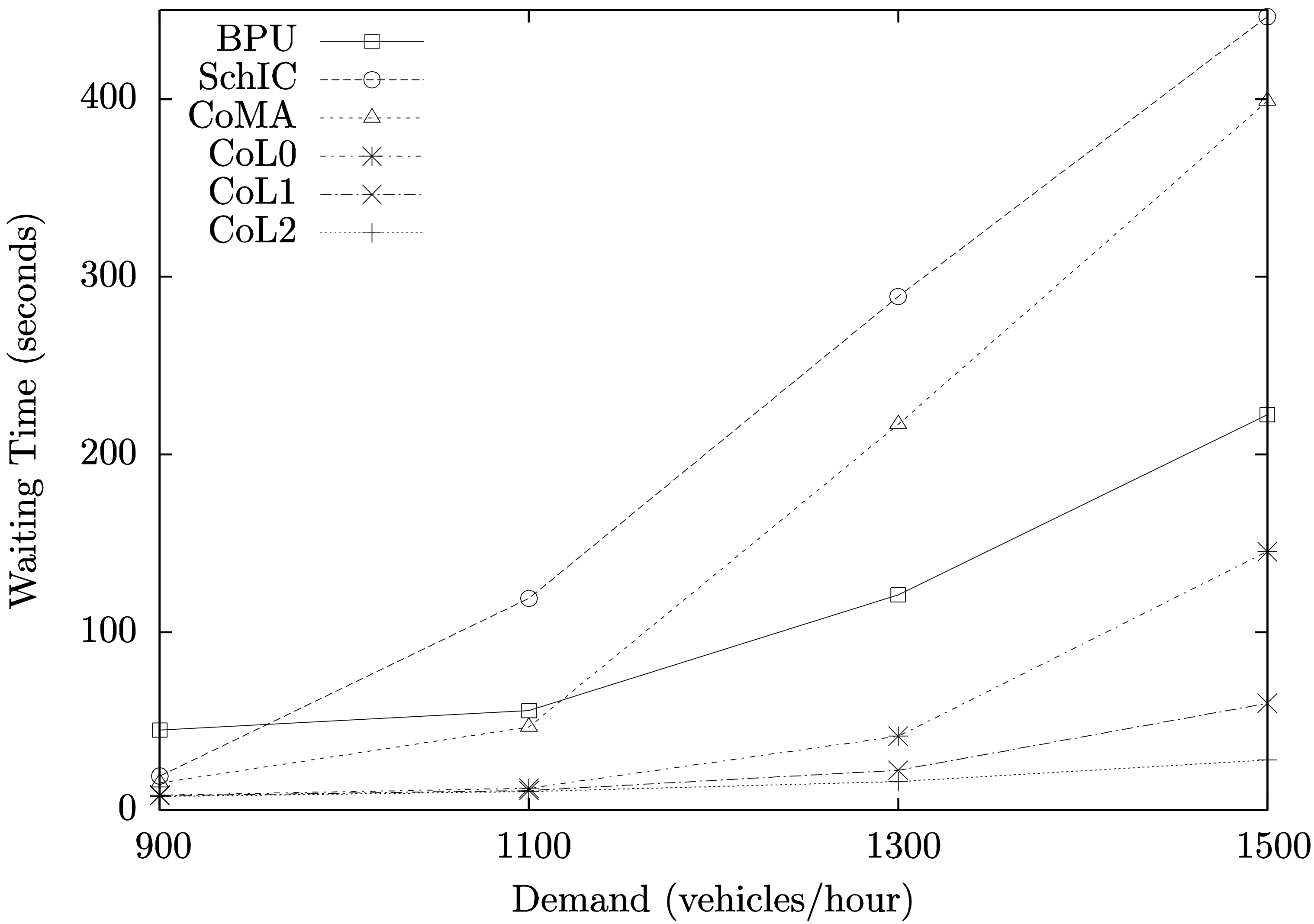
- **Overall Characteristics:** 0.5 second resolution; short intervening travel times; high congestion
- **Experiment Design**
  - All roads 1-way
  - 2 major flows (C, 3) that generate 3/5 of total traffic
  - All other routes: 1/20
- **Comparative Analysis**
  - Simulation control for 1 hour
  - Demand ratios on C and 3 shift every 20 minutes
  - Waiting time averaged over 100 runs



Control Strategies Tested

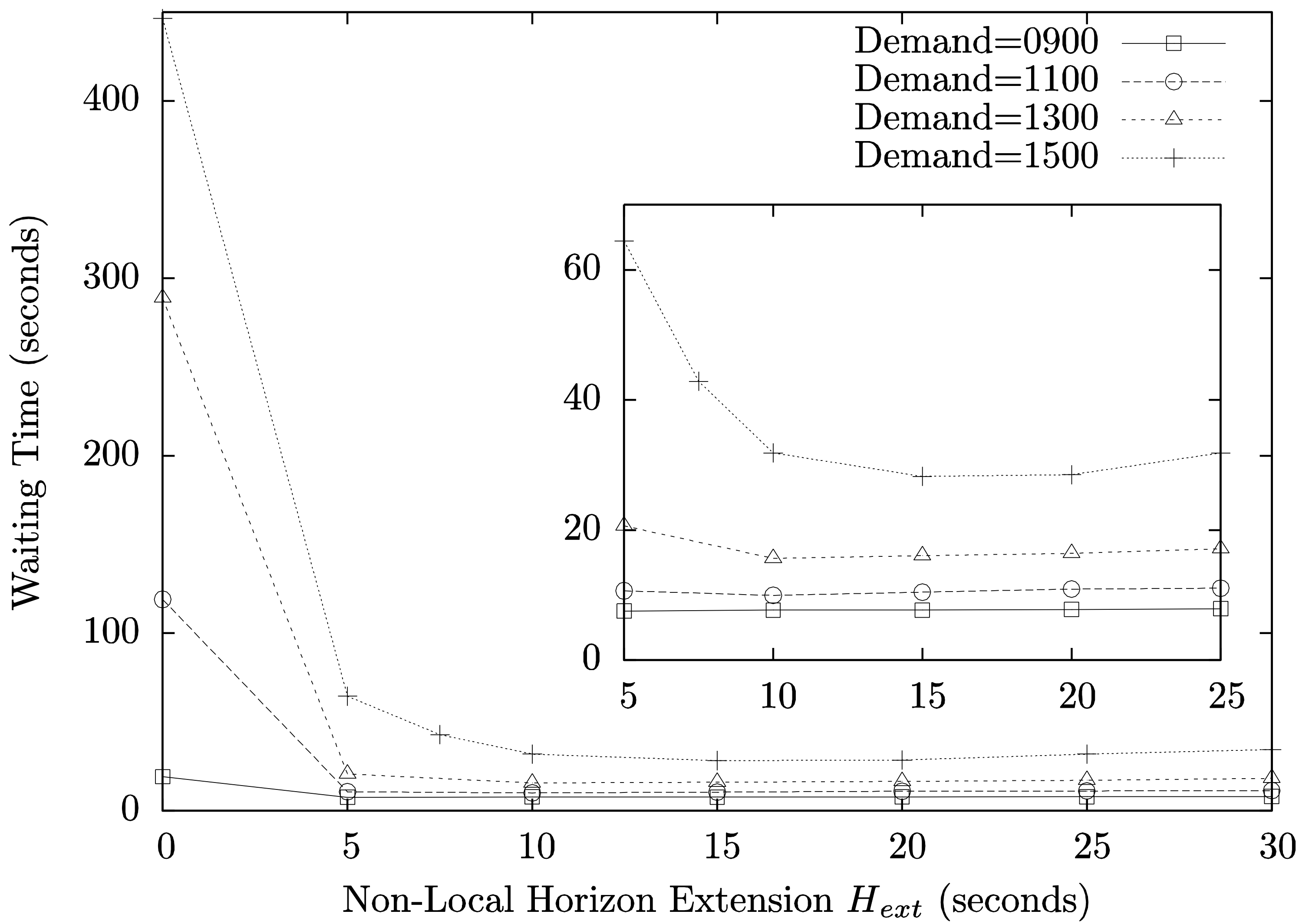
BPU	Balanced Phase Utilization • Coordination via cycle offset calculation
SchIC	Schedule-Driven Intersection Control • No Coordination
CoMA	SchIC + Moving average prediction
CoL0	SchIC + Optimistic non-local observation
CoL1	CoL0 + Nervousness prevention mechanism
CoL2	CoL1 + Spillover prevention mechanism

Results



BPU
SchIC
CoMA
CoL0
CoL1
CoL2
Waiting Time (seconds)
0
100
200
300
400
900
1100
1300
1500
Demand (vehicles/hour)

CoL2 with Different Planning Horizons



Penn Circle Pilot Study

Objective

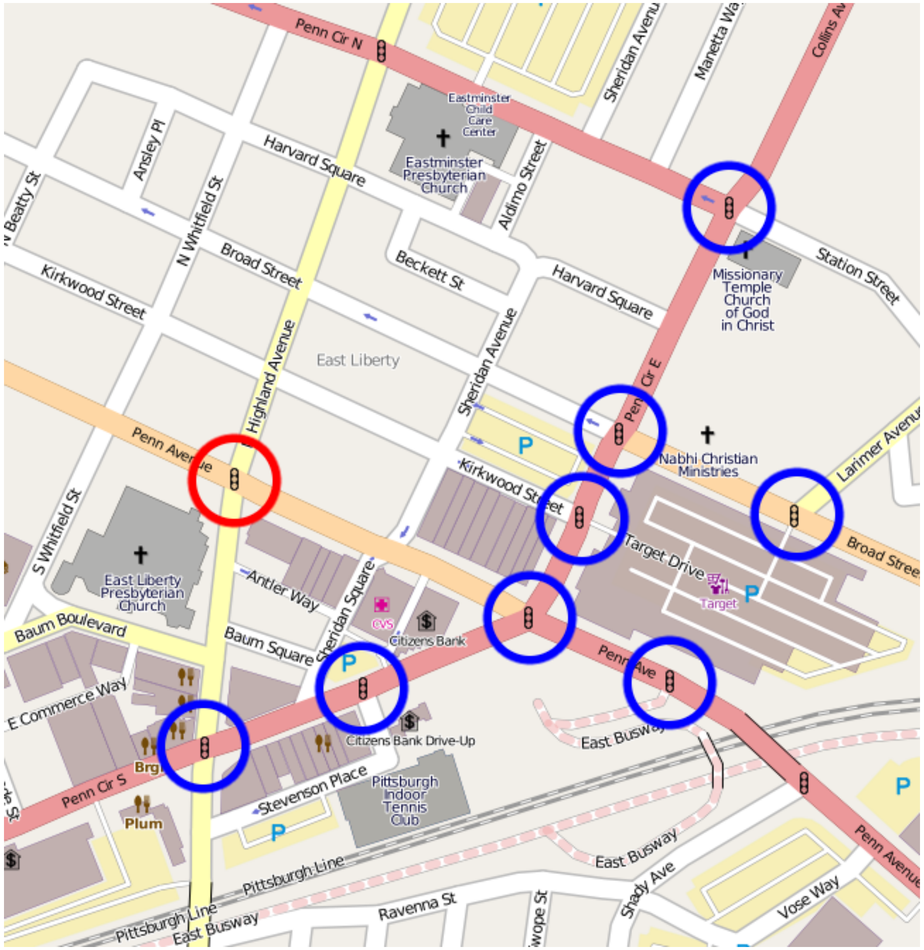
– Demonstrate ability of adaptive signal control to improve traffic flow and reduce air pollutants in urban road networks

Test Site

– Developing area of Pittsburgh with changing traffic patterns and volumes
– 8 recently upgraded intersections with camera detection
– 9th intersection upgraded for the pilot to create more grid-like road network

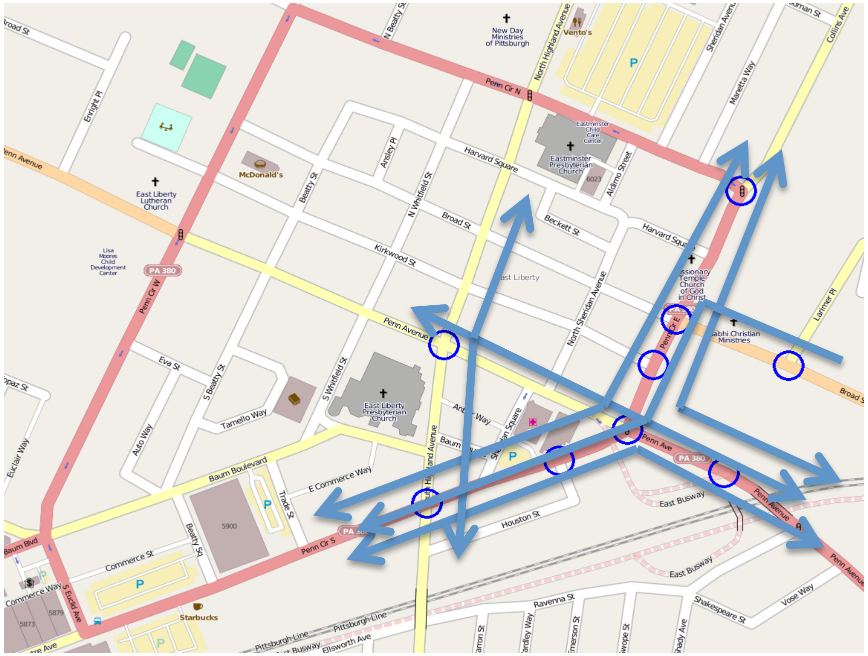
Sponsor and Partners

– Heinz Endowments (breathe.org)
– Traffic21
– City of Pittsburgh
– Traffic Control Products
– Traficon Traffic Video Detection



Pilot Test Evaluation

- **Performance comparison to current fixed timing plans**
  - Series of before and after drive-through runs over 12 routes at 4 different periods of the day
  - GPS tracking of travel times and number of stops
  - Traffic volume data used to combine data from different routes



- **Results:**

% Reduction	Travel Time	Wait Time	Emissions
AM rush	30.00%	48.33%	19.88%
PM rush	24.26%	40.%	18.82%

Conclusions

- Schedule-Driven Coordination can provide an effective, practical basis for real-time control of traffic networks
  - Aggregation of traffic flows enables efficient computation of near-optimal local schedules
  - Exchange of schedules extends local visibility of future demand
  - Nervousness and spillback prevention mechanisms compensate when neighbors change their schedules
- Asynchronous decentralized operation makes the approach inherently scalable

Future Directions

- Intersection scheduling extensions to incorporate “phase skipping”
  - View phase switching as a selection problem
- Better Coordination
- More principled tolerance of sensing uncertainty