From traffic estimation to macroscopic traffic control via multi-commodity back-pressure

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*Joint work with Balazs Kulcsar, Ali Zaidi, Hamed Farhadi, and Themistoklis Charalambous
Motivation

Urban traffic predicted to increase
- Limited possibility to build more roads
- Non-invasive methods needed
- Leverage communication capabilities
- Future-proof in combination with autonomous drive
Outline

• Scheduling and routing: problem solved?
• From communication networks to transportation networks
• Traffic flow optimization
• Dealing with uncertainty
• Future work
• Conclusions
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Single hop communication: max-weight scheduling

- Ad-hoc network, link $l$ has queue $Q_l(t)$ and arrival $A_l(t)$ with rate $\lambda_l$
- $S =$ set of feasible schedules (e.g., $S=$\{1,2,3,4,(3,4)\}) with associated link rates $r_l(s)$
  \[ Q_l(t+1) = \max(Q_l(t) - r_l(s), 0) + A_l(t) \]
- Max-weight scheduling decision: $s^*(t) \in \arg \max_{s \in S} \sum_l r_l(s)Q_l(t)$
- Stabilizes the network for any $\lambda$ in capacity region

Global knowledge 🎉

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Max-weight scheduling: performance in noisy conditions

\[ \lambda_1 = 0.37 \text{ and } \lambda_2 = 0.86 \]

**Diagram:**
- Node 1 with service rate \( \lambda_1 \)
- Node 2 with service rate \( \lambda_2 \)
- Node 3
- Noise: \( U[+0,+0] \)
- Noise: \( U[+10,+10] \)
- Noise: \( U[+50,+50] \)

**Figure:**
- Time series of \( Q_1 + Q_2 \) with varying noise levels.
Multi-hop communication: backpressure routing

- Packets arrive at source nodes with rate $\lambda_i$
- Flows with same destination: commodity c (destination $d(c)$)
- Each node keeps queue per commodity $Q_i^{(c)}(t)$ with $Q_{d(c)}^{(c)}(t) = 0$
- Control actions $I(t) \in \mathcal{I}$ with resulting rates $\mu_{ij}(I(t))$
- Queue dynamics:
  \[ Q_n^{(c)}(t + 1) = \max(Q_n^{(c)}(t) - \sum_j \mu_{n,j}^{(c)}(t), 0) + \sum_i \mu_{in}^{(c)}(t) + \sum_{m \in \mathcal{M}_n^{(c)}} A_m(t) \]
- Links that are allowed to transmit commodity c can be predetermined (e.g., to limit delay)
- **Backpressure**: control policy that stabilizes the network within the capacity region
Multi-hop communication: backpressure routing

- Determine optimal control action:
  1. find optimal commodity for each link (ij): $c_{ij}^*(t) = \arg \max_c (Q_i^{(c)}(t) - Q_j^{(c)}(t))$
  2. find optimal weight for each link (ij): $W_{ij}^*(t) = \max(Q_i^{(c_{ij}^*(t))}(t) - Q_j^{(c_{ij}^*(t))}(t), 0)$
  3. find optimal control action: $I^*(t) = \arg \max_{I \in \mathcal{I}} \sum_{ij} W_{ij}^*(t) \mu_{ij}(I)$

- Routing: for each link (ij) send $\mu_{ij}(I^*(t))$ of commodity $c_{ij}^*(t)$
Backpressure routing: example

- **Control:** \( \mathcal{I} = \{I_{\text{clock}}, I_{\text{c-clock}}\} \)
- **Rates:** 1 for each link, except 5 for \((1 \rightarrow 2)\) and \((2 \rightarrow 1)\)
- **Optimal commodity:**
  \( c_{12}^* = 1, c_{21}^* = 2, c_{13}^* = 2, c_{31}^* = 1, c_{23}^* = 2, c_{32}^* = 1 \)
- **Optimal weights:**
  \( W_{12}^* = 3, W_{21}^* = 2, W_{13}^* = 1, W_{31}^* = 1, W_{23}^* = 3, W_{32}^* = 4 \)
- **Optimal control:** \textit{clockwise}
  - Clockwise: \(5 \times 3 + 3 + 1 = 19\)
  - Counter clockwise: \(5 \times 2 + 1 + 4 = 15\)

\[ I^*(t) = \arg \max_{I \in \mathcal{I}} \sum_{ij} W_{ij}^*(t)\mu_{ij}(I) \]
Backpressure routing: example

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  - Counter clockwise: $5 \times 2 + 1 + 4 = 15$
- If node 2 is destination for commodity 1:
  green queue will be empty again
Outline

- Scheduling and routing: problem solved?
- From communication networks to transportation networks
- Traffic flow optimization
- Dealing with uncertainty
- Future work
- Conclusions
From communication to transport networks

- **Communication**: packets, buffers, links, rates, schedules, routes
- **Transport**: vehicles, roads, junction lanes, flow, junctions phases, routes
References


• A. Zaidi, B. Kulcsar, and H. Wymeersch, “Decentralized Traffic Signal Control with Fixed and Adaptive Routing of Vehicles in Urban Road Networks,” in *IEEE Transactions on Intelligent Transportation Systems*, Provisionally accepted 2015. (also see ECC, 2015)

### Detailed comparison

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Control actions do not need to be coordinated
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Real queues and logical queues must be decoupled

- Can be ignored by backpressure (so no routing)
- Or can be modeled through shadow queues* (so adaptive routing)
- Routing requires *explicit* information from vehicles

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Computing the pressure and control

- Rate: vehicles that can leave a lane during green light
- Queue size: number of cars on lane (free flow + congested)
- Does not consider TWR or fundamental diagram
- Turns out to not be critical for performance

$$\begin{align*}
\rho &\geq \rho_{\text{crit}} \\
\rho &< \rho_{\text{max}}
\end{align*}$$
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Different sources of uncertainty

- People may not follow decisions/suggestions
- Queues based on sensor data may be incorrect

floating car data  cameras, loop detectors
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Roads are buffers

- Roads are finite (especially short ones), leading to non-work conserving behavior and gridlock
- Use admission control or normalized queue (e.g., $f(\text{queue/length})$) with fairness constraint

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Scenario: Stockholm network

- **Parameters:** 24 intersections, 84 links, 16 flows (origin destination pairs), max speed 70 kph, signal phase lasts 15 sec. Simulation using PTV VISSIM.
- **Methods:** fixed, single-commodity BP with fixed routing, multi-commodity BP with fixed routing, multi-commodity BP active routing
Backpressure stabilizes queues (@ 350 veh/hour arrival)

- fixed signaling
- single commodity, no routing BP
- multi-commodity, no routing BP
- active routing BP
Adaptive routing can lead to excessive delays

- Fig. 6: Average queue lengths over a 2 hours long simulation time period for different methods.
- Fig. 7: Average travel times computed over a 2 hours simulation time period for different methods.

- MC-BP is significantly better over both simulation time and number of vehicles in the case of queue length and rates.
- AR-BP yields the smallest queue length followed by MC-BP, SC-BP, and FT respectively.
- An additional observation is that the multi-commodity scheme is optimized over a set of fixed signal schedules.
- SC-BP outperforms SCATS, and active routing BP, with respectively small queue lengths and average travel times.
- AR-BP offers considerable improvement over single commodity back-pressure schemes.
- In a saturated network, although vehicles may follow a longer route on average under AR-BP, the travel time is significantly lower on average compared to the fixed routing methods.
- In order to study the effects of traffic volume, we plot average travel time and average queue lengths under the modified AR-BP scheme with different values of the parameter $\alpha$ (equal to 1.5) for the given network that provides good performance in low traffic volumes.
- Normally, one expects that a larger queue length should lead to a higher travel time. However, it is this adaptive routing that forces the vehicles to follow shorter paths, which is good for low load situations but may not be good in a high load situation. According to Fig. 9 and Fig. 10, there exists a value $\alpha = 0$ for the given network that provides good performance.

**Graph:**
- X-axis: Arrival rate [vehicles/hour]
- Y-axis: Average travel time [min]
- Legend:
  - Red dotted line: Fixed signaling
  - Blue dashed line: Single commodity, no routing BP
  - Black solid line: Multi-commodity, no routing BP
  - Green dashed line: Active routing BP

**Key points:**
- Gap can be closed
- Average travel time [min]
- Vehicles/hour
Backpressure delays can be mitigated in many ways

![Graph showing average travel time versus arrival rate](image)

- Green line: \( \alpha = 0 \)
- Black dashed line: \( \alpha = 1.5 \)
- Red dotted line: \( \alpha = 3 \)
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Imperfect queue state information

\[ \hat{Q}^{(c)}_i(t) = \max(Q^{(c)}_i(t) + n_i(t), 0), n_i(t) \sim U(-W, +W) \]
Noisy queue information leads to longer queues

- No uncertainty
- [-5,+5] vehicles uncertainty
- [-10,+10] vehicles uncertainty

![Graph showing queue length over time with different uncertainty levels](image)
Noisy queue information leads to reduced speed, longer travel time

- Filtering would help to reduce uncertainty
- What are suitable models for uncertainty?
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Future work

- Backpressure operates only on queues, ignores fundamental diagram. Can we address this?
- How much queue uncertainty is tolerable? Relation to real sensors?
- Performance in the presence of adversarial cars, trying to game the system?
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Conclusions

- Scheduling and routing of vehicles can alleviate traffic problems
- Backpressure-style algorithms have rich history in communication networks
- Many changes needed in vehicular context, but algorithms appear robust against model mismatch and uncertainty
- Impact of traffic sensing is important and not fully understood
- Connection with road flow dynamics is unclear