Congestion aware multipath transport protocols in wired and wireless networks

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with

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Eg: Receiver Driven Multipath

- Eg, Kazaa, Skype, BitTorrent
- Routing: which routes /paths to take?
- Rate control: how much to send on each path?
Efficient Use of Resources

Multiple paths between src. and dst.
- Increase throughput
- Increase reliability
- Decrease packet loss rates

Wireless diversity

How to use exploit these efficiently?
- # of paths to use.
- Fair allocation of resources.
- Congestion control.

Ideas from network coding and multi-path congestion control help.
Resource sharing

Fixed Routing

- Capacity \( C \)
- Mean transfer time \( \frac{F}{C-\rho} \)

Dynamic Routing

- Transfer time \( \frac{1}{2} \frac{F}{C-\rho} \)

Fixed Proportions

- Transfer time \( F \left( \frac{p}{C-2\rho p} + \frac{1-p}{C-2\rho(1-p)} \right) \)

\[ \text{Stable} \iff C > 2\rho \max(p, 1-p) \]
Outline

• Multipath routing and congestion control
  – Coordinate vs. uncoordinated
• Path selection
  – Static
  – Dynamic
• Backpressure and wireless
Joint routing/congestion control

- Each session given a “set” of paths
- Let session balance load across routes
- How many paths?
- What is effect of RTT bias on controller?
- Coordinated or uncoordinated?
Example: TCP Rate model

- Rate of packet send, \( x \)

  \[ T = RTT \text{ (round trip time)}, p = \text{loss prob} \]

- As if user is trying to maximise net utility
  
  \[ \text{utility} - \text{cost} \]

  where

  \( \text{cost} = p \times x \)

\[ x = \frac{W}{T} = \text{window/RTT} \]

\[
\frac{dx}{dt} = \frac{1}{T} \frac{dW}{dt} = \frac{1}{T^2} - \frac{px^2}{2}
\]
Optimization framework

- Users of type $s$ have concave utility fn $U$
  - Number $n_s$,
  - Paths indexed by $r$, rate $x_r$,
  - Users $s$ can use paths $r \in R(s)$
  - Total rate sent on path $r$ is $\Lambda_r$
- Convex network cost function $\Gamma(\cdot)$
  - Network cost is $\Gamma(\{\Lambda_r\}_{r \in R})$
- Users selfishly maximise net utility
Link cost example

- Links \( \ell \) on path \( r \)
- Link load \( y_\ell = \sum_{r \in R: \ell \in r} n_r x_r \)
- Path price from link prices

\[
p_r = \sum_{\ell: \ell \in r} \pi_\ell (y_\ell) = \sum_{\ell: \ell \in r} \Gamma'_\ell (y)
\]
Link cost examples

- Links $\ell$ on path $S$
- Link load $y_\ell = \sum_{r \in R : \ell \in r} n_r x_r$
- Path price from link prices $p_r = \sum_{\ell : \ell \in r} \pi_\ell(y_\ell) = \sum_{\ell : \ell \in r} \Gamma'_\ell(y)$
- e.g. Packet loss (drop tail) $\pi_\ell(x) = \left(\frac{x}{C}\right)^B \frac{1-x/C}{1-(x/C)^{B+1}}$
Outline

• Modelling the Internet:
  – Utility maximization and fluid limits

• Multipath routing and congestion control
  – Coordinate vs uncoordinated
  – Path selection

• Generalised aggregation: series & parallel paths

• Pricing, control and real time

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Coordinated Congestion control

- User $s$, chooses paths $r$ from set $R(s)$ to

$$\text{Maximise } \sum_s N_s U_s \left( \sum_{r \in R(s)} x_r \right) - \Gamma(Nx)$$

over $x_r \geq 0$

- A utility *per user*, not per path: coordinates *across paths*

- Sends traffic on “least-cost” (lowest price, eg lowest loss) path, where price $p_r = \partial_r \Gamma(Nx)$

- Splits load to minimise network costs
Theorem: Flow control (Kelly)

- Distributed rate-adaptation schemes

\[ \frac{d}{dt} x_s(t) = \kappa_s \left[ U_s'(x_s) - p_s \right] \]

where path price

\[ p_s := \frac{\partial}{\partial z_s} \Gamma(z) \bigg|_{z=\{s, x_s}\} } \]

- Converge to welfare maximisation allocation
- While *Users selfishly maximise net benefit*
Uncoordinated (multipath) control

User $s$, chooses paths $r$ from set $R(s)$, eg each user chooses $b$ paths.  

\[ N_s = \sum_{r \in R(s)} N_r \]

- Maximises throughput

\[
\text{Maximise } \sum_{s} \sum_{r \in R(s)} N_r U_r(x_r) - \Gamma(Nx)
\]

over $x_r \geq 0$.

- Controller (utility) per path $r$: Uses paths in parallel (eg parallel TCP)
Coordinated vs uncoordinated

e.g. Two paths
Prices $p_1 < p_2$

• Coordinated sends all on path 1
  rate $U^{-1}(p_1)$

• Uncoordinated sends on both:
  – Rates $U^{-1}(p_1), U^{-1}(p_2)$
Eg: Selecting relay or access points

- $N$ resources, each unit capacity
- $aN$ users, each selects $b$ resources at random
- Performance measure: worst user rate
Scaling Results:

- In the Uncoordinated & Uncoordinated case, for the example
  - Optimal allocation independent of Utilities

- Uncoordinated: Worst case user
  - Scales as $\log \log (N) / \log (N)$
Scaling Results:

- **Coordinated** (worst case allocation)
  - Bounded away from zero (strictly better than uncoord)
  - Minimises expected download rate
  - Load balances – (max-min across allocations)
  - Need $b = \mathcal{O}(\log N)$ for “perfect” allocation
Outline

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Route choices

• Allow users to (selfishly) choose paths:
  – To maximise throughput eg, for unncord

\[
\frac{\Lambda_r}{N_r} = \max_{r' \in R(s)} \frac{\Lambda_{r'}}{N_{r'}}
\]

– Allocations are a Nash equilibrium if achieved
Uncoordinated: RTT bias and inefficiency

- Uncoordinated controllers with *RTT bias* can reach inefficient equilibria
- Eg, choice of short –thin or long-fat routes
  - Each user chooses b routes
  - Symmetric sources
  - Can reach inefficient Nash equil. if
    \[
    \frac{\sqrt{2} \frac{T + 2\tau}{2T + \tau}}{< 1}
    \]
  - Half the throughput

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Congestion Aware Multipath
**Dynamic Route Selection**

- What if there are a large number of route choices available?
- Suppose user $s$ using a set of routes $c, c \subseteq R(s)$
  - $N_c = N_s$
  - Offered a new set $c'(at random time intervals)$
  - Switch to new set if higher net benefit
  - Equivalently: *if receive a higher rate on $c'$*
- *Eg, just use 2 paths and resample*
How many paths to choose?

- For coordinated control
  - $n=2 \rightarrow 50\%$ improvement
  - $n=3 \rightarrow$ extra $15\%$ improvement
  - Any $n$ with resampling gives full utilisation

But have to remove RTT bias for TCP
Generalised aggregation route choice: series parallel and backpressure
Using paths in parallel and series

- Elementary combinations: parallel & series
Maximization framework

Data buffered:

\[ W_i \]

\[ \sum_{j} f_{ij} x_{ij} \]

\[ \text{price} \quad p_{ij} = \frac{\partial}{\partial y_{ij}} \gamma(y) \]

\[ x^f = \sum_{j} x^f_{sj} \]

Max

\[ \sum_{f} U_f (x^f) - \Gamma(y) \]

over \( x_{ij} \geq 0, \quad (ij) \in \text{path set } \mathcal{P}(f) \)

s.t. node flow constraints

where \( y_{ij} = \sum_{f} x^f_{ij} \)
Rate adaptation with backpressure

• For each valid path \((ij)\)

\[
\dot{x}^f_{ij} = \kappa^f_{ij} \left[ \prod_{i=0}^{s(f)} U'_f(x_f) - p_{ij} + \varphi(W^f_i) - \varphi(W^f_j) \right]
\]

where \(\varphi(\cdot)\) is continuous strictly increasing, with \(\varphi(0) = 0\)

Then: equilibrium solves utility maximization
Rate adaptation with backpressure

- For each valid path \((ij)\)

where \(\phi(\cdot)\) is continuous strictly increasing, with \(\phi(0)=0\)

Then: equilibrium solves utility maximization

i.e.

\[
U'(x) = p_{si} + \phi(W_i)
\]

\[
\Rightarrow U'(x) = p_{si} + p_{ij} + p_{jd}
\]
Wireless: How Much Traffic on a Route?

- We propose adaptive credit-based scheme for traffic control
- Based on Back-pressure
Parting remarks

• Routing and congestion control should be combined
  – Control at RTT timescales
• Utility maximization and fluid models for modelling: “Welfare” maximization achievable
• Uncoordinated controls can be inefficient/unfair
  – RTT bias (of TCP) a problem...
• Coordinated controls preferable
• Two paths and randomisation give load balancing
  – Add in reselection for efficiency
References

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Questions?