Traffic Engineering vs. Content Distribution

A Game-Theoretic Perspective

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Overview

- **Traffic Engineering** is the optimal assignment of users to routes in a network.

- **Content Distribution** involves users selecting content from various servers.

- These two may be in conflict!
  - The Traffic Engineer does not anticipate that users may change behavior in response to his decisions!
The Traffic Engineer

- Sees current traffic between users and servers
- Assigns routes to each user-server pair
  - Routes may involve overlapping resources (e.g. links)
  - Flows through resources generate congestion

- Given traffic $\vec{e}$ the engineer chooses a routing policy $\vec{\pi}$
  - He wants to minimize the total congestion at the resources:
    \[
    \sum_{j \in J} L_j(f_j(\vec{e}, \vec{\pi}))
    \]

- Flows:
  \[
  f_j(\vec{e}, \vec{\pi}) = \sum_{ms} \sum_{r: j \in r, r \in R_{ms}} \pi_{mr} e_{ms}
  \]
The Traffic Engineer

Splits determined by routing policy

The User

Route 1

Route 2

Route 3

Server 1

Server 2

Server 3

Total traffic for Server 1

Total traffic for Server 3
The Users

- See current routing assignment

- Choose how much traffic to request from each server

- Given routing policy $\vec{\pi}$ the users select servers and generate traffic $\vec{e}$
  - They want to minimize the price they pay to access servers
**Users** determine how much traffic to send to each **server**

The Users

Users determine how much traffic to send to each server.
Prices and Latency

- Users of distributed content often use *signals* when choosing servers.
- Example of a signal: *delay* or *latency* to the server.
- Abstraction: flow-dependent *price* $p_j(f_j)$ on each link $j$.
  - Price may simply be the *delay* $l_j(f_j)$ of link $j$.
  - Or some more complicated function:
    \[ p_j(f_j) = l_j(f_j) + f_j l'_j(f_j) \]
- Price of a *route* is the sum of prices of its links.
- Price to a *server* is the average price of its routes, as determined by the Traffic Engineer’s *routing policy*.
Prices and Wardrop Equilibria

• We assume users are **infinitesimal**
  • Individually, their decisions do not greatly impact the flows

• Collectively, in **equilibrium**, they only communicate with servers that have the minimum prices

• The resulting traffic implicitly minimizes an **objective function**:
  \[ \sum_j \int_0^{f_j} p_j(t) \, dt \]

• This is the **implicit objective function** of the users
The Importance of Optimism

Zero traffic for Server 1

Important to have good routing policies even to unused servers (just in case users want to switch)

Total traffic for Server 2
Pigovian Taxes

• Suppose the delay on a link is \( l_j(f_j) \)
• Then the total delay on that link is \( f_j l_j(f_j) \)

• Problem: Users do not account for the delay they impose on others through their decision!

• Solution: Charge them a **Pigovian tax**
  • Have them act as if delay (price) is \( l_j(f_j) + f_j l_j'(f_j) \)
  • The extra term forces them to **internalize** the effect they have on others
Unified Objectives

- When the Traffic Engineer’s congestion function is total delay: \( L_j(f_j) = f_j l_j(f_j) \)
- And the Users’ price function has a Pigovian tax:
  \[
  p_j(f_j) = l_j(f_j) + f_j l'_j(f_j)
  \]
- Then both parties have the same objective function
- There is only one equilibrium, and it is the best possible outcome (i.e. total delay is minimized over all server choices and routing policies)
Dynamics

- Traffic Engineering is typically done on a **slow timescale**, e.g. a few times a day
- Users of distributed content may change their servers **very quickly**
  - So between changes by the Traffic Engineer, the users have time to converge to the **Wardrop Equilibrium**

- Under Unified Objectives, these dynamics converge to the **best possible outcome**
- With different objectives, the dynamics may be unstable and suboptimal
Extensions

• The results extend gracefully to:
  • Multiple classes of users
  • Multiple types of content
  • General overlay networks
  • Delays at the servers

• With some additional assumptions, we can also extend to:
  • Multiple ISPs (and multiple Traffic Engineers)
    • Requires that users are the ones who control inter-domain routing
Conclusion

- Traffic Engineering and Content Distribution may result in conflicting and unanticipated decisions by the relevant parties.

- With the use of Pigovian taxes, the objectives of the users and the Traffic Engineer may be aligned:
  - When objectives are aligned, the equilibrium outcome is predictable and optimal.

- These considerations may aid in the design of content distribution systems.
Related Work


