Incentive misalignment under congestion-based pricing

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Background

- Analyze the future of pricing, shaping, and aggregation of Internet traffic
- Understand the incentives, risks and payoffs of different players
  - Consumers (human users, ISPs, overlay networks, network applications)
  - Providers

Outline

- Congestion pricing mechanisms for the Internet are ***not*** incentive compatible
  - myopic incentive compatible
  - not long-term incentive compatible
  - demonstrable under ***any one*** of a number of models of congestion pricing on the Internet
- Understanding the architectural and research implications

History of congestion pricing

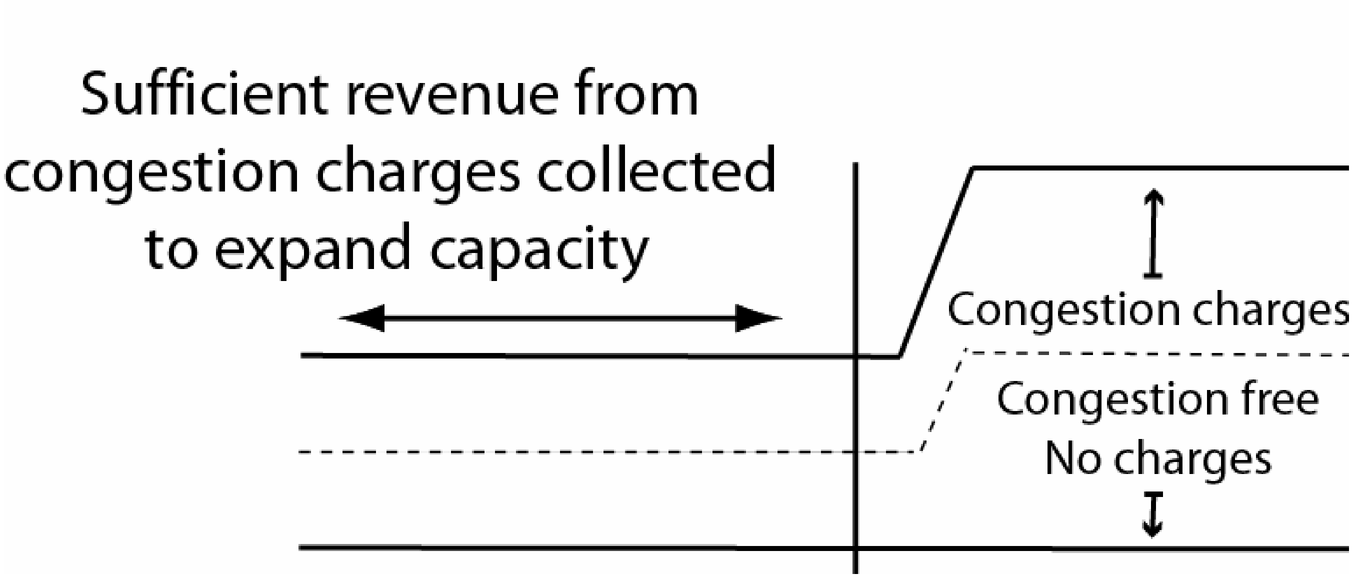
- Congestion price: variable price determined by the congestion level of the network
- Academically favored mechanisms for pricing traffic on the Internet
  - Congestion pricing is a form of marginal cost pricing implying that it is economically efficient
  - Creates the “right incentives”

Why hasn't congestion pricing been adopted?

- Over-provisioning is cheaper [Odlyzko]
- Other reasons:

Problems	Solutions
1. Perverse provider incentive to under provision	1. Competition will discipline the market
2. Large sunk cost recovery infeasible	2. Cost recover possible with two-part tariffs
3. Technically difficult to implement	3. Clever engineering solutions
4. Unacceptable in the real market	4. Only long-term sustainable approach

Capacity expansion assumption



- **Capacity expansion assumption:** revenues from congestion charges provide the financial basis for expanding a network
- Assumption underlying many related works on congestion pricing

Pricing actual congestion can lead to perverse incentives

Without providers' capacity expansion assumption	*With* providers' capacity expansion assumption
• **Providers** have perverse incentive to cause artificial congestion	• **Users** have perverse incentive to cause artificial congestion

Demonstration: in a repeated game model

Congestion pricing traffic game: Structure of the game

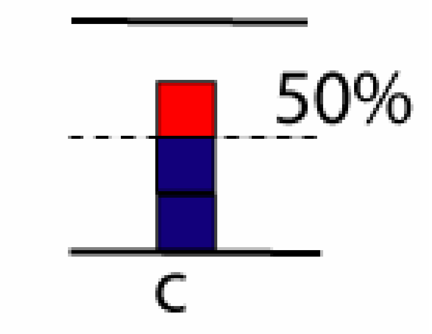
- Repeated game with complete information

- Provider
  1. The provider aims to operate its network at less than or equal to a congestion threshold **H** (50% in our examples).

Network

Congestion charging

2. The provider issues a congestion charge $\mathbf{C_t}$ to users if aggregate volume of network traffic exceeds the congestion threshold in time period t
3. The congestion charged to each user is proportional to the user's contribution to the volume of traffic during the congested period

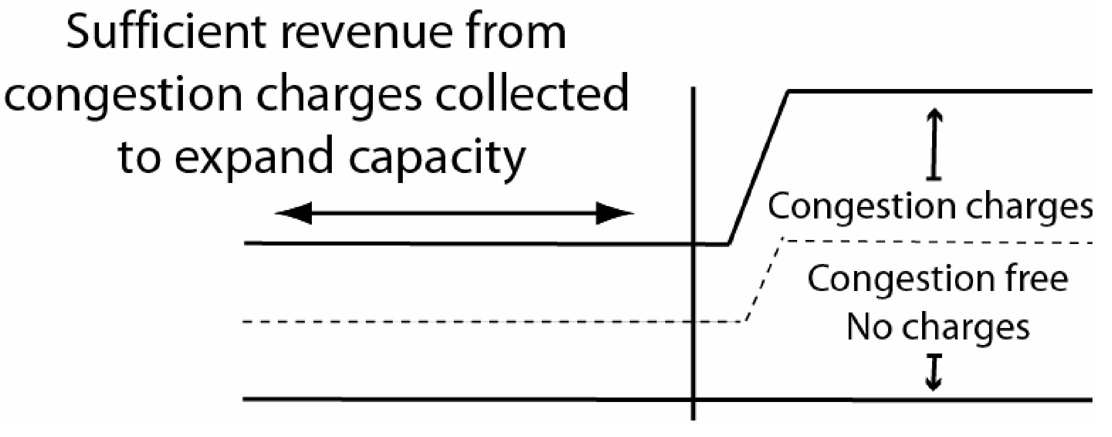


Red pays: $\frac{1}{3}$

Blue pays: $\frac{2}{3}$

Capacity expansion

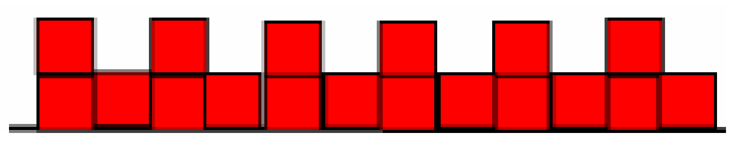
4. The provider will double the network capacity once $R_{capacity\text{-}expansion}$ revenue has been collected.

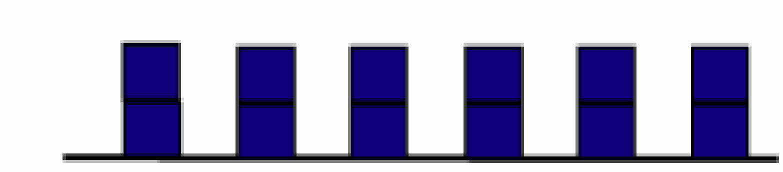


$$R_{CapacityExpansion} = \sum_{t=0}^{n} c_t$$

Structure of the game: Users

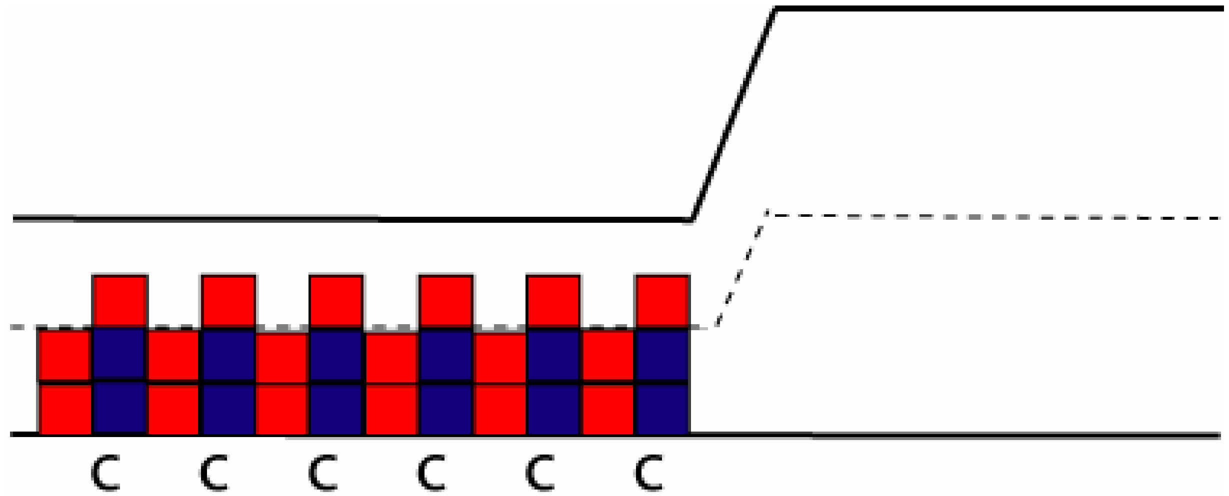
- User types:
  - Traffic generating functions: $f_i(t)$





- Action space:
  - *{send-artificial-traffic, no-artificial-traffic}*

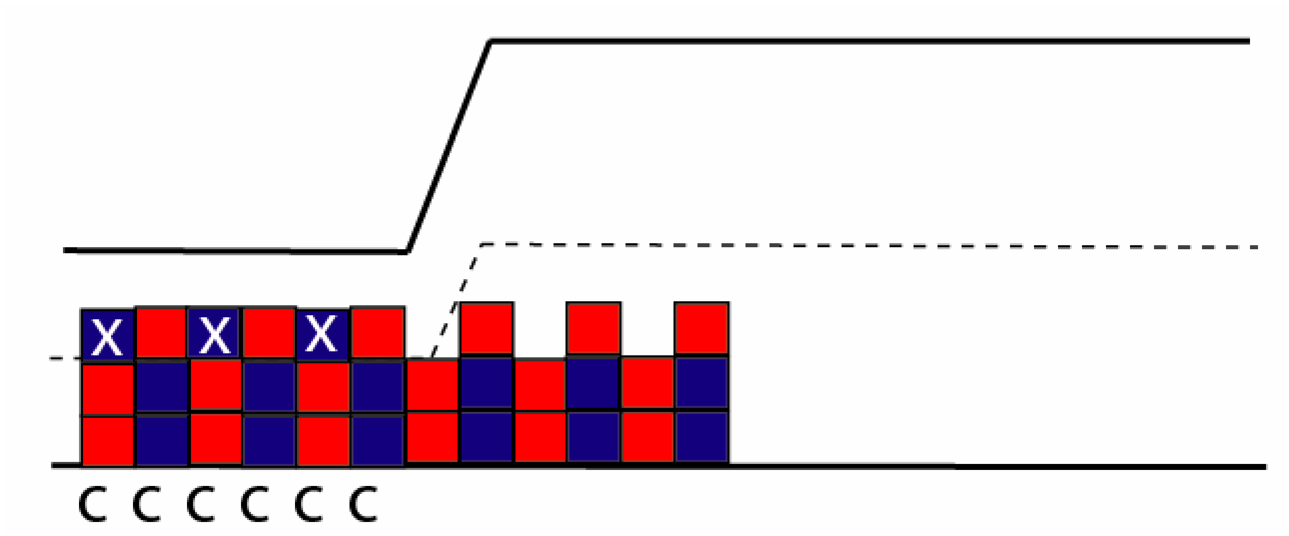
Intuitive example of perverse incentive



Red pays: $\frac{1}{3}$ of capacity expansion cost

Blue pays: $\frac{2}{3}$ of capacity expansion cost

Blue has a perverse incentive to cause congestion



Red pays: $\frac{1}{2}$ of capacity expansion cost

Blue pays: $\frac{1}{2}$ of capacity expansion cost

Subgame Perfect Equilibrium

- SPE is an appropriate equilibrium concept for repeated games with complete information
- A strategy is subgame perfect if
  - is a Nash equilibrium for the entire game and
  - is a Nash equilibrium for each subgame

Nash equilibrium

- Nash equilibrium: set of strategies such that no player wishes to change her strategy, given the strategy of the other players.

$$u_i(s_i, s_{-i}) \geq u(\hat{s}, s_{-i}) \forall \hat{s} \in \Omega$$

Achieving equilibrium

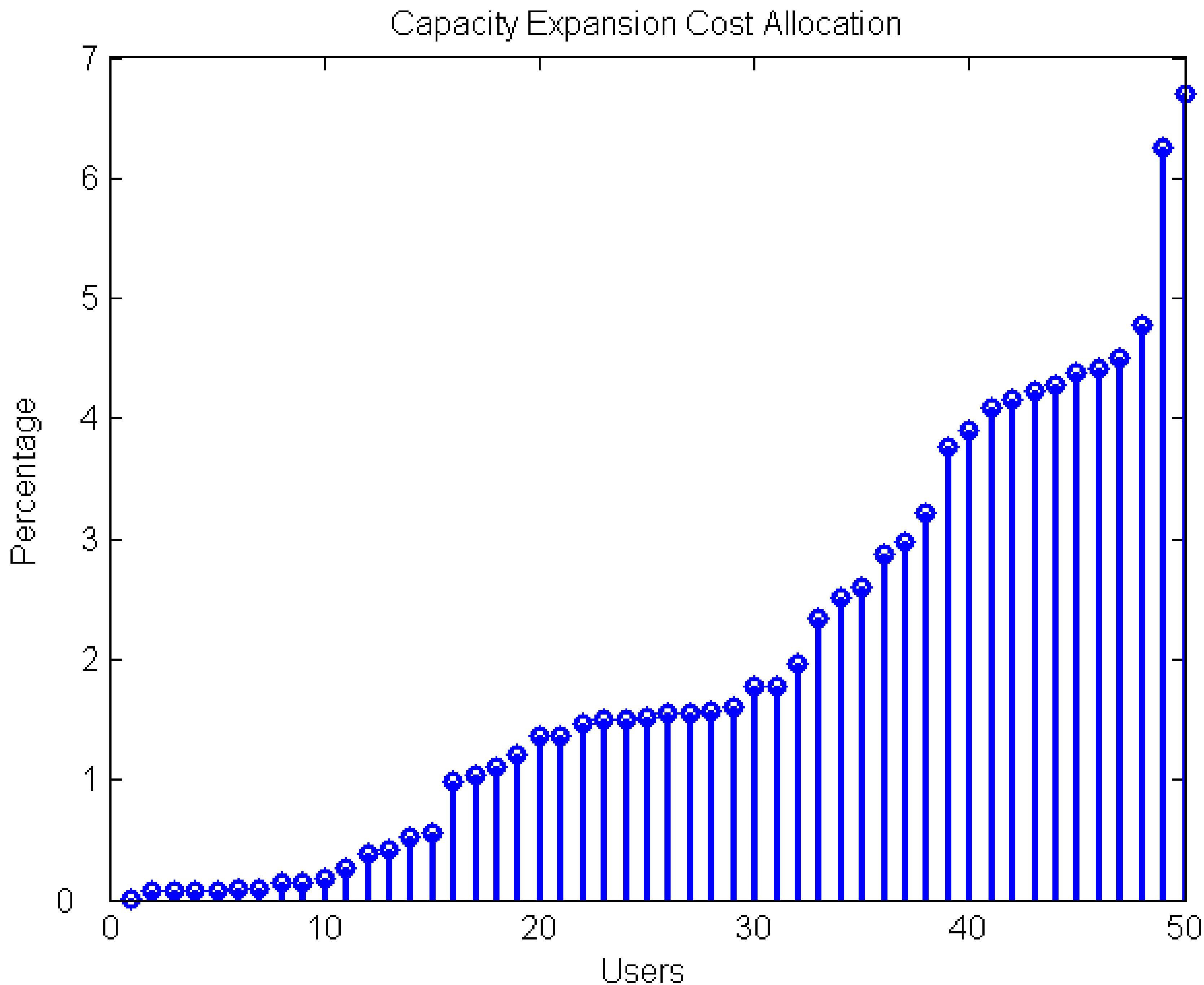
- SPE achieved through backward induction using a dynamic programming algorithm
  - Minimize contribution to $R_{capacity\text{-}expansion}$ by sending artificial traffic inducing an earlier expansion of capacity

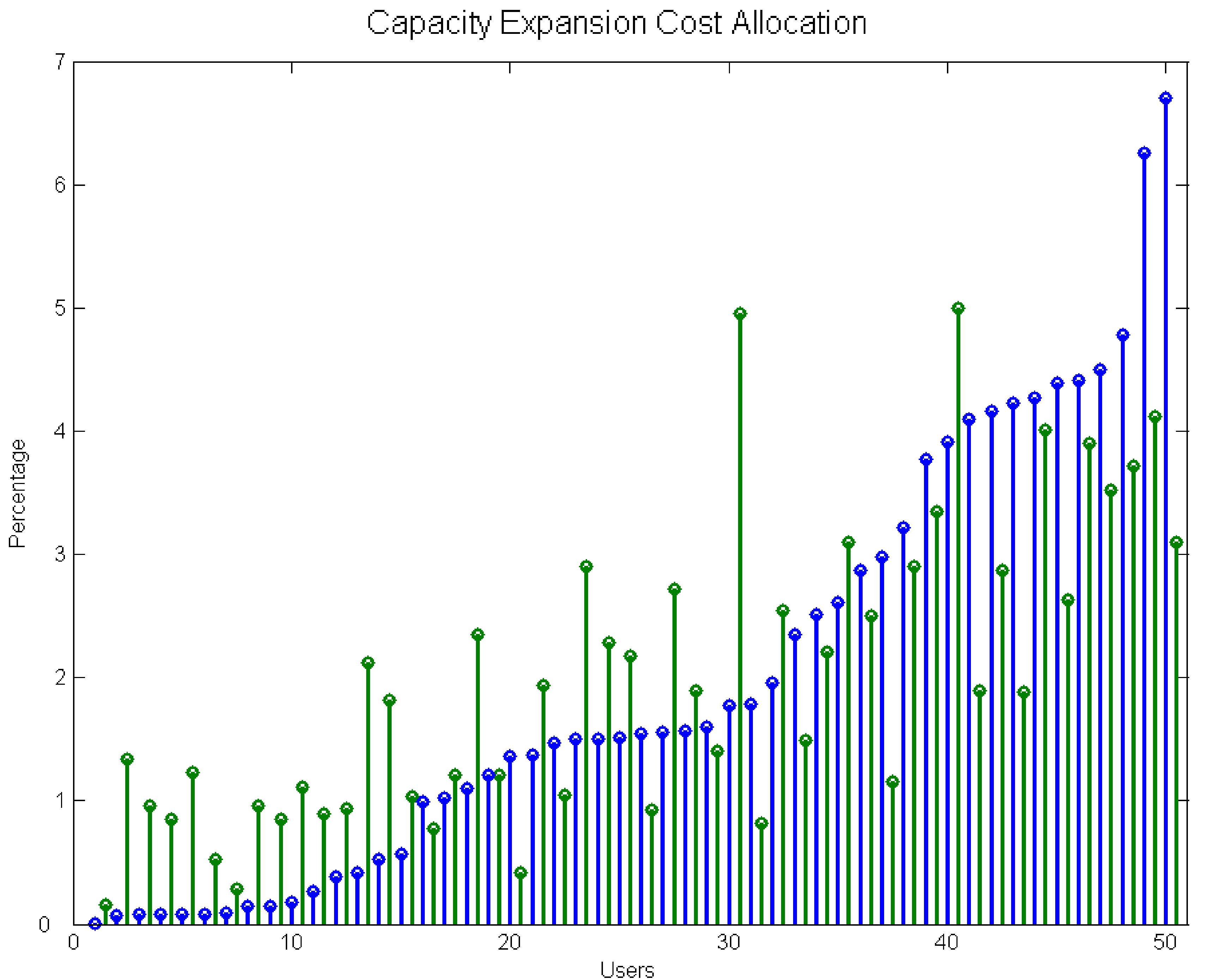
Analyzing the outcome of the equilibriums

- No analytic method for calculating the outcome of game
- Turn to simulation to understand:
  - what type of users benefit from strategic behavior
  - shifts in capacity expansion cost

Simulation

- Input:
  - Traffic matrix: users x time-periods
    - Traffic volumes
      - probabilistic model of being online
      - heavy tailed distribution of traffic volumes when online
  - Capacity expansion cost
  - Congestion threshold
- Backward induction algorithm
  - Factors in a discount factor for time value of money
  - Users minimize their contribution to capacity expansion cost by sending artificial traffic


Capacity Expansion Cost Allocation
Percentage
Users
0
1
2
3
4
5
6
7
0
10
20
30
40
50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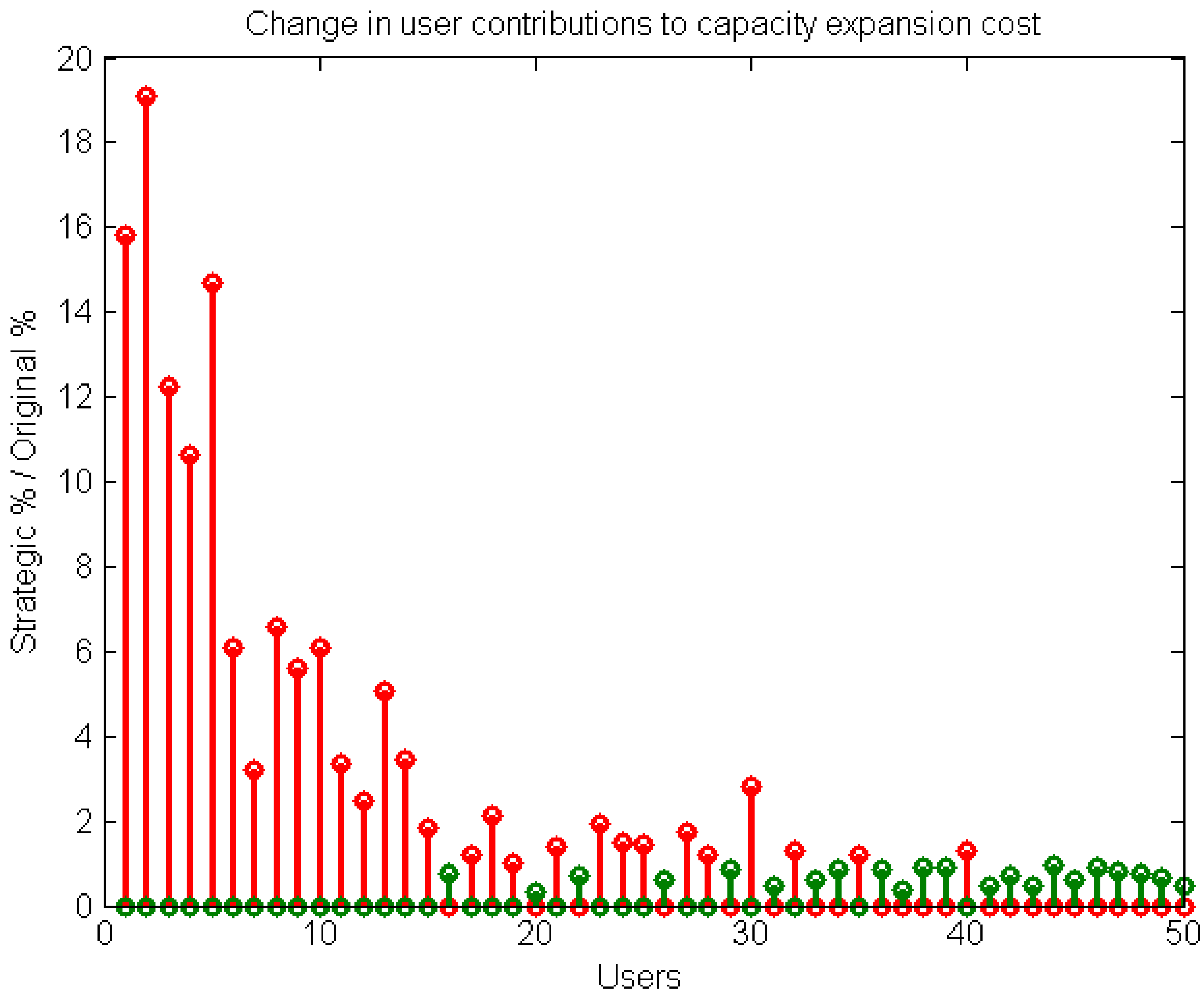

Change in user contributions to capacity expansion cost
Strategic % / Original %
Users
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50

Would strategic behavior be a ***practical*** problem under congestion pricing?

- Not likely for individual human users
- ***Congestion-strategic traffic behaviors*** would likely result from:
  - classes of applications
  - operating systems
  - overlay networks
  - companies with large volumes of traffic
  - competing ISPs with the same upstream

Implications

- Suggests congestion pricing can create perverse real world incentives
  - *Even if traditional objections to congestion pricing are conceded!*
- Contrary to conventional wisdom existing research on congestion pricing has not created incentive compatible mechanisms
- Conjectures:
  - Providers indifferent to incentive compatibility of pricing mechanism
  - Negative user reaction to any mechanism that creates incentives for “artificial congestion”

Perverse incentives of congestion pricing

- Demonstrable under a number of models of Internet congestion pricing
  - providers or users take a smaller short-term penalty for a larger long-term benefit
- Models
  1. Capacity expansion assumption
  2. Congestion budget constraints
  3. Competing ISPs with common congestible upstream

Future work

- Relax assumptions
  - Model as a repeated game with incomplete information
    - perfect Bayesian Nash equilibrium
- Explore evolutionary game theory as alterative to current deductive model
- Explore mechanism design problem of how to price in an incentive compatible manner

Conclusion

- Contributions:
  - Congestion pricing mechanisms on the Internet are not incentive compatible
  - A new model, the Congestion-Pricing Traffic Game (CPTG), for analyzing the incentives of congestion pricing
  - Demonstration of subgame perfect equilibrium of the CPTG game