Evolution of the Internet Economic Ecosystem

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Special topics in Network Algorithms

Overview

- Introduction
- Macroscopic AP-TP Model
- Market Equilibrium
- Price Dynamics in Equilibrium
- Internet’s Economic Evolution
- Summary

Little bit of background

- Macroeconomics
  - The branch of economics concerned with large-scale or general economic factors, such as interest rates and national productivity
- AP
  - Application Provider - Netflix, Youtube, Google etc.,
- TP
  - Transport Provider - ISPs + CDNs
- Net Neutrality
- Flattening Phenomenon
  - Not related to the subject, but interesting to know about it

Introduction

- The evolution of the Internet has manifested itself in many ways: the traffic characteristics, the interconnection topologies, and the business relationships among the autonomous components
- Business -> Money -> Economics -> Macroeconomics -> Model capturing most of the features
- The driving forces and the dynamics of the market equilibrium will help us
- Projecting the likely future evolutions, our model can help application and network providers to make informed business decisions so as to succeed in this competitive ecosystem (?)

Macroscopic AP-TP Model

- Macroscopic model of the Internet ecosystem that consists a set of APs and TPs.
- The TPs differ by their service qualities and the prices they charge
- Model and analyze the APs' choice of TP based on their own characteristics:
  - How profitable the AP is ?
  - How sensitive the AP traffic is to the obtained level of service quality?
- Model to help us to understand the decision process of these players in the Internet ecosystem
- How these decisions may influence their business relationships?

Macroscopic AP-TP Model

- (***M***, ***N***) - Model having a set ***M*** of TPs and a set ***N*** of APs
- Each TP $\boldsymbol{l} \in \boldsymbol{M}$ is denoted by a triple (p_l, q_l, v_l)
  - Per-unit traffic charge for the APs to use TP ***l***
  - Service quality of TP ***l***, e.g., queueing delay or packet loss probability.
    - Lower the value -> Better the QoS
  - Bandwidth capacity of TP ***l***
- Each AP $\boldsymbol{i} \in \boldsymbol{N}$ is characterised by its utility function $\boldsymbol{u_i(p_l\,, q_l)}$ when it uses TP ***l***
- $\boldsymbol{N_l \subseteq N}$ is set of all APs with use TP ***l***

Macroscopic AP-TP Model

Assumption 1: $u_i(\cdot,\cdot)$ is nonincreasing in both arguments.

Assumption 2: For any set $\mathcal{M}$ of TPs, each AP $i \in \mathcal{N}$ chooses to use a TP, denoted as $I_i \in \mathcal{M}$, that satisfies

$$u_i\left(p_{I_i}, q_{I_i}\right) \geq u_i(p_I, q_I) \qquad \forall I \in \mathcal{M}.$$

Interpretation:

- AP tries to maximise Utility by choosing the best TP
- If two TPs have the same quality, then they have to price equally, otherwise, the one with higher price will not obtain any market share

Multiple TPs with same amount of utility for the AP -> AP has certain preference to break the tie
and choose one of the TPs.

Macroscopic AP-TP Model

- $\boldsymbol{\lambda_i}(\boldsymbol{q_I})$ - defines the aggregate throughput of AP ***i*** toward its consumers under a quality level $\boldsymbol{q_I}$
- $\boldsymbol{v_i}$ per-unit traffic revenue for AP ***i***
- We model any AP ***i***'s utility as its total profit (profit margin multiplied by the total throughput rate), defined by $u_i(p_I, q_I) = (v_i - p_I)\lambda_i(q_I)$

Assumption 3: For any AP $i \in \mathcal{N}$, $\lambda_i(\cdot)$ is a nonincreasing function with $\alpha_i = \lim_{q_i \to 0} \lambda_i(q_i)$ and $\lim_{q_i \to \infty} \lambda_i(q_i) = 0$.

Interpretation:

Throughput will not decrease if an AP uses a better service. $\boldsymbol{\lambda_i}$ reaches a maximum value of α_i when it receives the best quality , and decreases to zero if the quality deteriorates infinitely.

Macroscopic AP-TP Model

- Canonical form of the throughput function $\lambda_i(q_I) = \alpha_i e^{-\beta_i q_I}$
- β_i captures the sensitivity of AP to the received quality $\boldsymbol{q_I}$
- We capture entire user demand in $\boldsymbol{\alpha_i}$ as we are only dealing with AP and TP
- Throughput elasticity of quality ϵ_i ,

$$\epsilon_i = (d\lambda_i(q_I)/dq_I)(q_I/\lambda_i(q_I)) = -\beta_i q_I$$

- The throughput elasticity captures the ratio of the percentage change in throughput caused by the percentage change in the quality

Macroscopic AP-TP Model

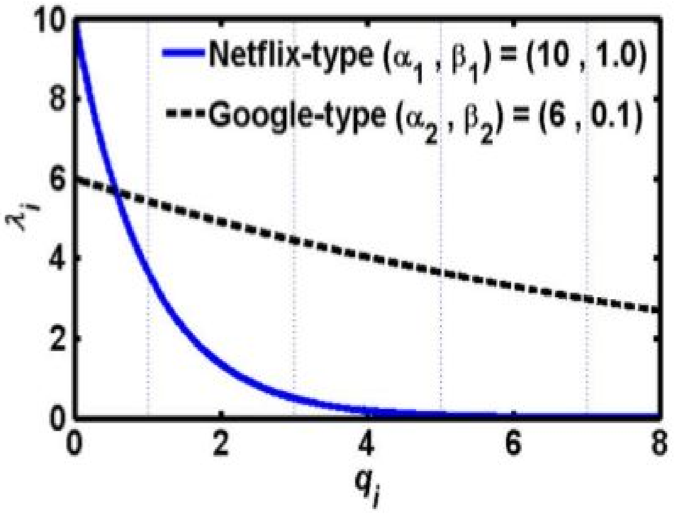

Fig. 1. Throughput of different types of APs.

- Netflix type of application is more sensitive to delay and has a high maximum rate
- Google type of query application that is less sensitive to delay
- We observe that when delay increases, the throughput of delay-sensitive application decreases sharply, while the delay-insensitive application decreases only mildly

Macroscopic AP-TP Model

$$u_i(p_I, q_I) = (v_i - p_I)\lambda_i(q_I) = \alpha_i(v_i - p_I)e^{-\beta_i q_I}$$

So each AP ***i*** can be denoted as a triple (α_i, β_i, v_i)

When facing a set $\mathcal{M}$ of TPs, each AP i's best choice I_i depends on the price–quality pairs $\{(p_I, q_I) : I \in \mathcal{M}\}$ and its own characteristics (β_i, v_i). The APs' choices satisfy the following results.

Theorem 1 (Monotonicity of AP Choices): For a fixed set $\mathcal{M}$ and any two APs i and j with $\beta_j \geq \beta_i, v_j \geq v_i$ and $(\beta_j, v_j) \neq (\beta_i, v_i)$, their chosen service qualities satisfy $q_{I_i} \geq q_{I_j}$.

Theorem 1 says that if an AP j is more profitable and more sensitive to service quality than another AP i, then the chosen quality of AP j will be at least as good as that of AP i. This property holds regardless of how the services are priced.

Macroscopic AP-TP Model

Theorem 2: For any $\kappa_1, \kappa_2, \kappa_3 > 0$, and system $(\mathcal{M}, \mathcal{N})$, we define a scaled system $(\mathcal{M}', \mathcal{N}')$ as $\mathcal{M}' = \{(\kappa_1 p_I + \kappa_2, q_I/\kappa_3, \nu_I) : I \in \mathcal{M}\}$ and $\mathcal{N}' = \{(\alpha_i, \kappa_3 \beta_i, \kappa_1 v_i + \kappa_2) : i \in \mathcal{N}\}$, then system $(\mathcal{M}', \mathcal{N}')$ satisfies $\mathcal{N}_I(\mathcal{M}', \mathcal{N}') = \mathcal{N}_I(\mathcal{M}, \mathcal{N})$ for all $I \in \mathcal{M}$.

Theorem 2 says that if: 1) the AP profitability v_i and the TP price p_I are linearly scaled in the same way; and/or 2) the quality q_I of the TPs and the sensitivity β_i of the APs scale inversely at the same rate, then the APs' choices of TP will not change. The intuition is that the above-mentioned scaling in v_i and p_I does not change the APs' optimal choices of TPs, and the scaling in β_i and q_I does not change the throughput. This result will help us normalize different systems and make a fair comparison of various solutions.

Macroscopic AP-TP Model

Theorem 3: For any $\kappa > 0$ and a fixed set $\mathcal{N}$ of APs, let $\mathcal{M}' = \{(p_I, \kappa q_I, \nu_I) : I \in \mathcal{M}\}$, then for all $i \in \mathcal{N}$: 1) $q_{I_i'} \leq \kappa q_{I_i}$ if $\kappa > 1$; and 2) $q_{I_i'} \geq \kappa q_{I_i}$ if $\kappa < 1$.

Theorem 3 says that if all the qualities in the market deteriorate ($\kappa > 1$) linearly at the same rate, APs will not use worse-quality TPs than before. The opposite is also true: When qualities improve linearly, APs will not use better-quality TPs than before. Intuitively, this result captures the fact that quality becomes a more (less) important concern when all the TPs provide worse (better) of it.

Macroscopic AP-TP Model

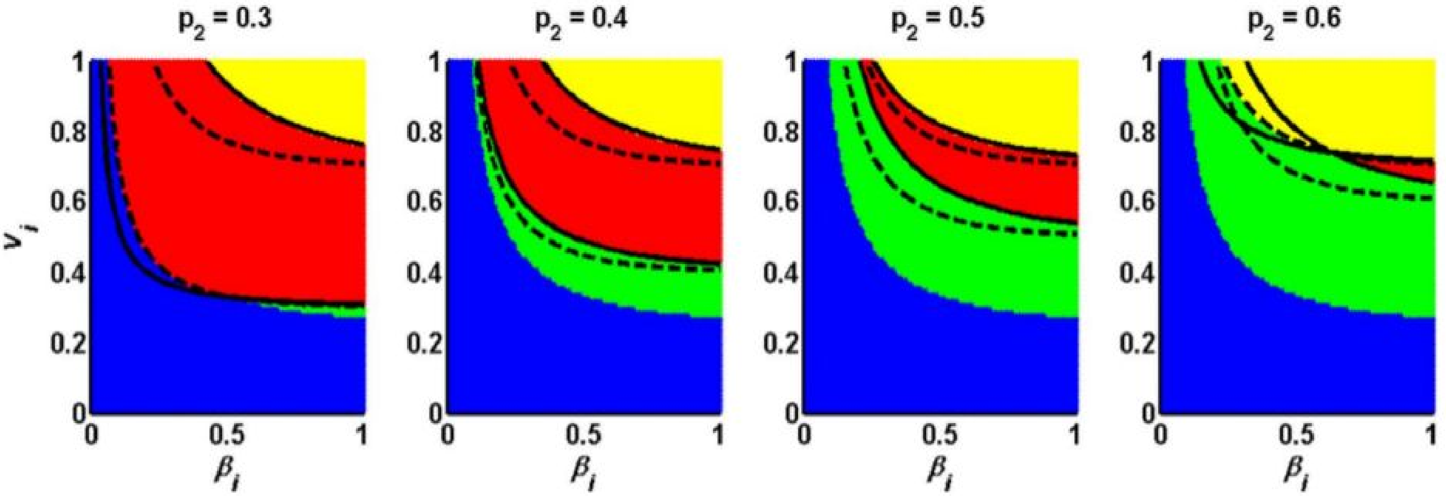

Fig. 2. Shift of market share for four TPs under $(q_1, q_2, q_3, q_4) = (1, 3, 5, 7)$ and $(p_1, p_3, p_4) = (0.7, 0.25, 0.1)$.

1 -> Yellow, 2 -> Red, 3 -> Green, 4 -> Blue

Macroscopic AP-TP Model

For any $I, J \in \mathcal{M}$, we define $\mathcal{N}_{IJ} = \{(\beta_i, v_i) : u_i(p_I, q_I) = u_i(p_J, q_J)\}$ to be the set of APs that obtain equal utility from I and J. In each subfigure, we plot $\mathcal{N}_{12}$ and $\mathcal{N}_{23}$ in solid lines and $\mathcal{N}_{13}$ and $\mathcal{N}_{24}$ in dashed lines. Thus, Fig. 2 illustrates the *shift of market shares* for these four TPs when we vary the price p_2 of TP 2.

Definition 1 (Convexity): The pricing of $\mathcal{M}$ is *convex* if for any TPs $I, J, K \in \mathcal{M}$ with $q_I < q_K < q_J$, we have $p_K \leq \eta p_I + (1-\eta) p_J$, where $\eta = (q_J - q_K)/(q_J - q_I)$.

The above definition is a discrete version of a continuous convex pricing function. Convex pricing often reflects the underlying convex cost structure where the marginal cost monotonically increases with the level of quality.

Macroscopic AP-TP Model

Definition 2 (Quasi-Concavity): The utility function u_i is *quasi-concave* if the upper contour sets $\{(p_i, q_i) \in \mathbb{R}^2_+ : u_i(p_i, q_i) \geq u\}$ are convex for all $u \in \mathbb{R}$.

- The quasi-concavity of the utility function implies that if two choices provide at least ***u*** amount of utility then any linear combination of the choices will induce at least that amount of utility
- In practice, an AP often prefers better-quality services until a certain level at which the price becomes a concern. Combined with a convex pricing, a quasi-concave utility function implies this kind of single-peak preference of the AP as follows

Macroscopic AP-TP Model

Lemma 1 (Single-Peak Preference): When the pricing of $\mathcal{M}$ is convex and u_i is quasi-concave, for any TPs $I, J \in \mathcal{M}$ with $u_i(p_I, q_I) > u_i(p_J, q_J)$, then $u_i(p_J, q_J) \geq u_i(p_K, q_K)$ if $q_I < q_J < q_K$ or $q_I > q_J > q_K$.

Lemma 1 gives a condition under which if an AP prefers a higher- (lower-) quality TP I over a lower- (higher-) quality TP J, then it prefers I over any TP whose quality is inferior (superior) to that of J

Lemma 2: The utility function $u_i(p_I, q_I) = (v_i - p_I)\lambda_i(q_I)$ is quasi-concave in the domain $(v_i, \infty) \times \mathbb{R}_+$ if $\lambda_i(\cdot)$ is in the form of $\lambda_i(q_I) = \alpha_i e^{-\beta_i q_I}$.

Summary of the model

This is hectic, I know.

A framework to help us to analyze (and understand) the APs' decision on choosing TPs based on TP's quality and price, and AP's profitability and sensitivity to the quality

In reality, the prices of the TPs fluctuate due to competition. Next, we will study what affects the market prices and characterize the equilibrium market prices, which also depend on the traffic intensity of the APs and the capacity of the TPs

Market Equilibrium

- As we already know no TP can continue to provide the service quality $\boldsymbol{q_I}$, if it is overwhelmed in terms of capacity
- So another mathematical model for achieved quality $\boldsymbol{Q_I(\lambda_I, v_I)}$ ie., a function of throughput and capacity
- *Assumption 4:* The achieved quality $Q_I(\lambda_I, \nu_I)$ for any TP $I \in \mathcal{M}$ is nondecreasing in λ_I and nonincreasing in ν_I.

  Definition 3: A set $\mathcal{X} \subseteq \mathcal{N}$ of APs is *feasible* for TP I with quality q_I, if $Q_I(\lambda_I(\mathcal{X}), \nu_I) \leq q_I$, where $\lambda_I(\mathcal{X}) = \sum_{i \in \mathcal{X}} \lambda_i(q_I)$ defines the induced throughput of the set $\mathcal{X}$ of APs under quality q_I.

Market Equilibrium

- In a market of TPs, each TP would adjust its strategies to accommodate its customer APs' traffic demand and keep its service quality promise
- For example, if the current capacity of TP cannot support quality , it might:
  - expend its capacity
  - increase price ; or
  - reduce the quality level .
- We define a market equilibrium where the APs' demand are feasible and the TPs' strategies are stable.

Market Equilibrium

Definition 4: Let $p_I^{\min}$ be the cost (or minimum price) of TP I. Let $\mathcal{M}'$ be identical to $\mathcal{M}$ except for $p'_I \neq p_I$ for some $I \in \mathcal{M}$ and $\mathcal{N}'_I$ be the set of APs choosing TP I under $\mathcal{M}'$. A system $(\mathcal{M}, \mathcal{N})$ forms a *market equilibrium* if: 1) all APs' aggregate demands are feasible, i.e., $Q_I(\lambda_I(\mathcal{N}_I), \nu_I) \leq q_I$, for all $I \in \mathcal{M}$; and 2) each price p_I maximizes the utilization of capacity for acceptable throughput at TP I, i.e., for any $p'_I \geq p_I^{\min}$ with the corresponding $\mathcal{N}'_I$ satisfying $Q_I(\lambda_I(\mathcal{N}'_I), \nu_I) \leq q_I$, we have $\lambda_I(\mathcal{N}'_I) \leq \lambda_I(\mathcal{N}_I)$.

Market Equilibrium

- Real life:
  - Capacity of TPs is not sufficient -> price rise
  - But every AP needs a TP

Assumption 5: There always exists a dummy TP $D \in \mathcal{M}$ with quality $q_D = \infty$ and price $p_D = 0$.

By Assumption 5, quality q_D always induces zero throughput for any AP, and therefore the dummy TP guarantees a zero utility and can accommodate as many APs as possible in equilibrium. Effectively, the set $\mathcal{N}_D$ models the APs that cannot afford to use any TP in the market in reality.

Market Equilibrium

Theorem 4: For any fixed set $\mathcal{N}$ of APs and any set $\mathcal{M}$ of TPs with fixed values of $p_I^{\min}$, q_I and ν_I for all $I \in \mathcal{M}$, there exists a set $\{p_I : I \in \mathcal{M}\}$ of prices that makes $(\mathcal{M}, \mathcal{N})$ a market equilibrium.

- TPs might be able to adopt new technologies to improve or differentiate their services, the quality that they can provide is often physically constrained by the nature of the TP
- TPs might execute a long-term capacity planning, the supply of capacity does not change in a small timescale
- Compared to service quality and capacity, market prices change more frequently and easily. Theorem 4 says that even in a small timescale where prices adapt to market conditions, prices might still converge to an equilibrium, which reflects the short-term market structure of the Internet ecosystem.

Market Equilibrium

- In theory, one might find multiple sets of prices that make a market equilibrium
- For example, from any existing equilibrium, one might find a TP such that with only a small change in pricing, no APs will change their choices
- This new price also constitutes a market equilibrium. In practice, these price differences can happen by two reasons.
    - First, even without a monopoly in a market segment, oligopolistic providers might implicitly collude on the price so that they keep a relatively high price simultaneously. When one of them starts to reduce price, the price of that segment will converge to a lower price.
    - Second, the preferences of the APs are quite different so that the price change in one segment might not affect the demand choices of the APs.

Market Equilibrium

Definition 5: A market equilibrium $(\mathcal{M}, \mathcal{N})$ is *competitive* if there does not exist any $p_I^{\min} \leq p'_I < p_I$ with the corresponding $\mathcal{N}'_I$ satisfying $Q_I(\lambda_I(\mathcal{N}'_I), \nu_I) \leq q_I$.

- Technically, a competitive market equilibrium might not exist since the minimum price might not exist when all the feasible equilibrium prices form an open set
- However, prices in practice have a minimum unit, e.g., one cent, and we can always find such a competitive market equilibrium.

Market Equilibrium

Theorem 5: Let $\mathcal{N}' = \{(\kappa\alpha_i, \beta_i, v_i) : i \in \mathcal{N}\}$ and $\mathcal{M}' = \{(p_I, q_I, \kappa\nu_I) : I \in \mathcal{M}\}$ for some $\kappa > 0$. If $(\mathcal{M}, \mathcal{N})$ is a market equilibrium and the quality function $Q_I(\cdot, \cdot)$'s are homogeneous of degree 0, i.e., $Q_I(\lambda_I, \nu_I) = Q_I(\kappa\lambda_I, \kappa\nu_I), \forall\kappa > 0, I \in \mathcal{M}$, then $(\mathcal{M}', \mathcal{N}')$ is a market equilibrium too.

- Theorem 5 says that if the quality only depends on the ratio of the incoming traffic rate and the capacity, then when the number of APs (and their traffic intensity) and the capacities scale at the same speed, the original market equilibrium prices will remain in equilibrium.

Market Equilibrium

- μ_I is the maximum throughput that TP ***I*** can accept when it still can fulfill the quality q_I

$$\mu_I = \arg\max_{\lambda_I} Q_I(\lambda_I, \nu_I) \leq q_I.$$

Definition 6: A system $(\mathcal{M}, \mathcal{N})$ forms a *market equilibrium* if for all TP I: 1) $\lambda_I(\mathcal{N}_I) \leq \mu_I$; and 2) there does not exist $p'_I \geq p_I^{\min}$ with the corresponding $\mathcal{N}'_I$ satisfying $\lambda_I(\mathcal{N}_I) < \lambda_I(\mathcal{N}'_I) \leq \mu_I$.

- The alternate definition of market equilibrium helps us calculate competitive equilibrium prices without repeated evaluation of Q_I

Market Equilibrium

Calculate Price Equilibrium $(\mathcal{N}, \{p_I^{\min}, q_I, \nu_I : I \in \mathcal{M}\})$

1. *Set* $p_I = \infty$ *for all TP* $I \in \mathcal{M}$;
2. *Calculate* μ_I *for all TP* $I \in \mathcal{M}$ based on q_I and Q_I;
3. **while** *there exists* $p'_I \in [p_I^{\min}, p_I)$ *such that* $\lambda_I(\mathcal{N}_I) \leq \lambda_I(\mathcal{N}'_I) \leq \mu_I$
4. **set** $p_I = p'_I$;
5. **return** $\{p_I : I \in \mathcal{M}\}$;

Based on Theorems 2 and 5, we have the following result.

Corollary 1: Let $\mathcal{N}' = \{(\kappa\alpha_i, \kappa_3\beta_i, \kappa_1 v_i + \kappa_2) : i \in \mathcal{N}\}$ and $\mathcal{M}' = \{(\kappa_1 p_I + \kappa_2, q_I/\kappa_3, \nu'_I) : I \in \mathcal{M}\}$ for positive $\kappa, \kappa_1, \kappa_2, \kappa_3$ with $\mu'_I = \kappa\mu_I$ for all $I \in \mathcal{M}$. If $(\mathcal{M}, \mathcal{N})$ is a market equilibrium, then $(\mathcal{M}', \mathcal{N}')$ is a market equilibrium.

Summary of the Market Equilibrium

Although the prices of the TPs influence the APs' choices, which further affect the capacity utilization of the TPs, equilibrium prices are the fixed points in which both the APs' choices and the TPs' prices do not change. However, external factors could move the resulting equilibrium. In next Section, we will study these fundamental driving forces for the evolution of the Internet economic ecosystem. By understanding these factors, we will know why the market prices change and why certain evolutions happen.

Price Dynamics in Equilibrium

- Qualitative dynamics of the equilibrium market prices
- Explore how the different characteristics of the APs and the TPs can affect the market prices in equilibrium
- First step:
  - Normalize the system parameters

We define $v_{\max} = \max\{v_i : i \in \mathcal{N}\}$, $\beta_{\max} = \max\{\beta_i : i \in \mathcal{N}\}$, and $p_{\min} = \min\{p_I^{\min} : I \in \mathcal{M}\}$. Based on Theorem 2, we normalize any system $(\mathcal{M}, \mathcal{N})$ by factors $\kappa_1 = 1/(v_{\max} - p_{\min})$, $\kappa_2 = p_{\min}/(v_{\max} - p_{\min})$, and $\kappa_3 = 1/\beta_{\max}$

$$p_I = (v_{\max} - p_{\min}) p_I^{scaled} + p_{\min}$$

Price Dynamics in Equilibrium

$\alpha = \sum_{i \in \mathcal{N}} \alpha_i$ $\mu = \sum_{I \in \mathcal{M}} \mu_I$ $\rho = \mu / \alpha$

$\sigma_I = \mu_I / \mu$ $\mu_I = \sigma_I \rho$

After the above normalization, we can describe any system by the following four parameters:

1) a set of qualities $\{q_I : I \in \mathcal{M}\}$;
2) the normalized aggregate capacity ρ;
3) the distribution of α_i over the domain $[0,1]^2$ of (β_i, v_i);
4) the capacity distribution $\{\sigma_I : I \in \mathcal{M}\}$.

Price Dynamics in Equilibrium

- Three different qualities
  - The highest quality for real-time content delivery
  - Medium quality, mostly for Web applications
  - The best-effort quality, mostly for elastic traffic
- Let us take 1 : 5 : 25 for the sake of simplicity
- APs profitability and sensitivity follow certain pdfs
- Alpha follows the joint distribution of the above pdfs

Price Dynamics in Equilibrium

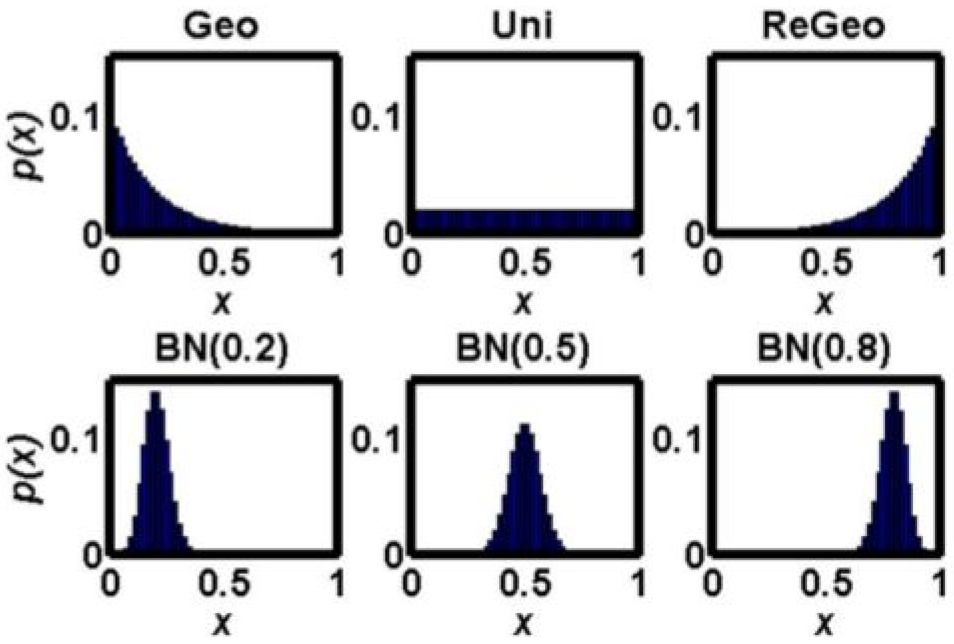

Fig. 4. Common distributions: geometric, uniform, reversed geometric, binomial with $p = 0.2, 0.5$, and 0.8.

Geo is used to model sensitivity where AP traffic is elastic and the amount of quality-sensitive traffic decreases exponentially with its sensitivity level.

BN to denote approx normal distribution of profitability or sensitivity where ***p*** is the mean value

Price Dynamics in Equilibrium

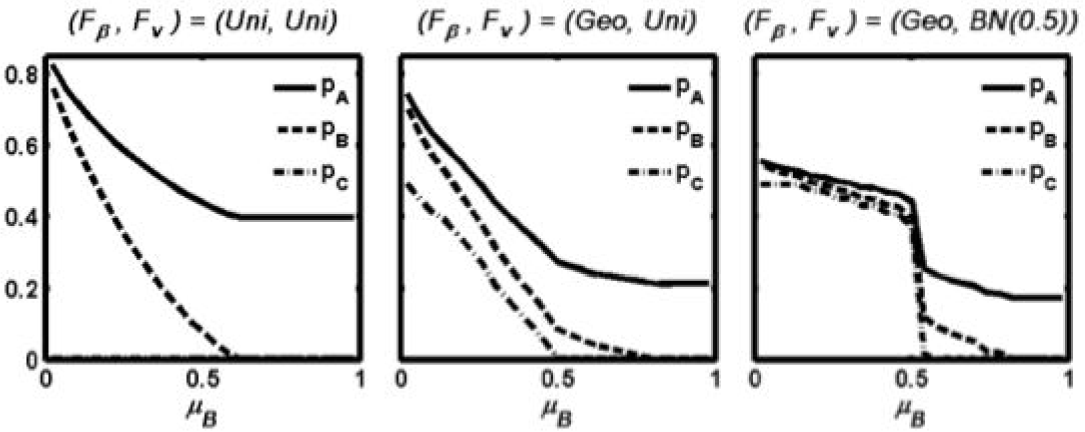

Fig. 5. Shift in market prices as μ_B varies: with $(q_A, q_B, q_C) = (0.2, 1, 5)$, $\mu_A = 0.05$, and $\mu_C = 0.25$.

Price Dynamics in Equilibrium

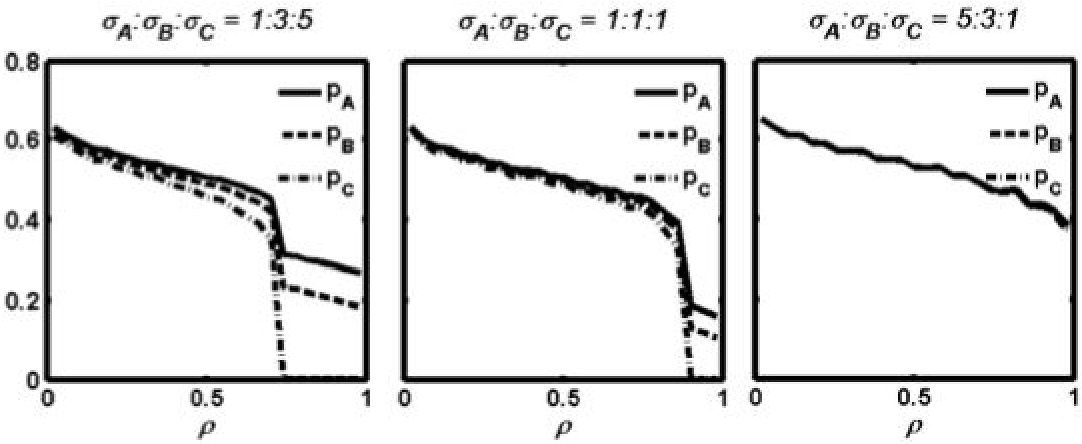

Fig. 6. Shift in market prices as ρ varies: with $(q_A, q_B, q_C) = (0.2, 1, 5)$ and $(F_\beta, F_v) = (Geo, Uni)$.

Price Dynamics in Equilibrium

Lessons (The TP Capacity Effects on Prices) Learned:

- Capacity expansion drives market prices down.
- The capacity expansion of a particular TP I would affect not only its own price p_I, but also other TPs' prices, due to the substitution effect of TP I to other TPs.
- When TP I's capacity share σ_I is small (big), its price p_I is close to that of its next higher- (lower-) class TP.

Price Dynamics in Equilibrium

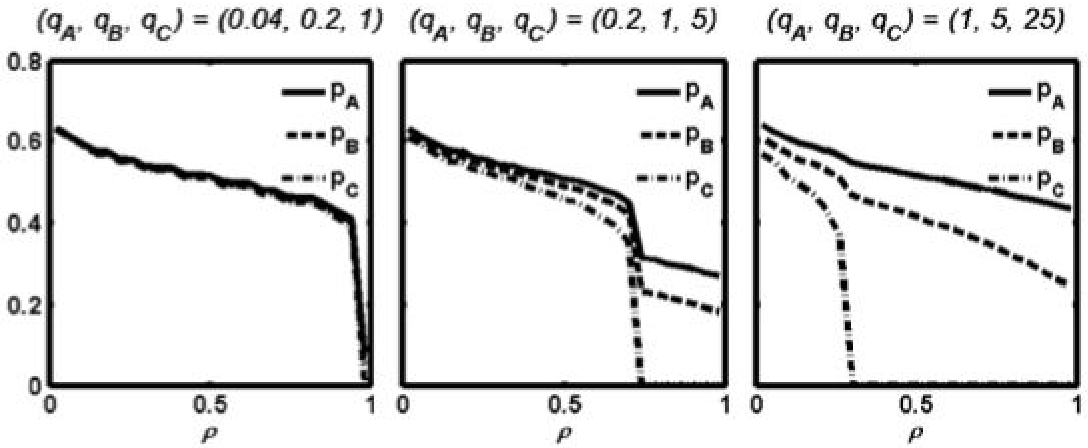

Fig. 7. Shift in market prices as ρ varies: with $(q_A, q_B, q_C) = \kappa(0.2, 1, 5)$ where $\kappa = 0.2$, 1, and 5.

Price Dynamics in Equilibrium

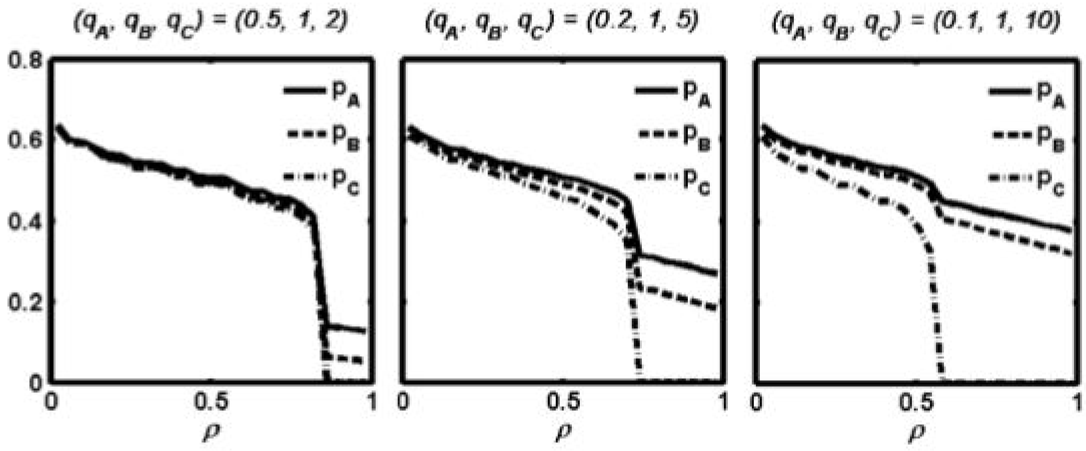

Fig. 8. Shift in market prices as ρ varies: with $q_B = 1, q_A : q_B = q_B : q_C = 1 : \kappa$ where $\kappa = 2, 5, 100$.

Price Dynamics in Equilibrium

Lessons (The TP Quality Effects on Prices) Learned:

- The market prices of the TPs would be close to (far from) one another if the quality ratio is small (big) or/and the overall qualities of the market are high (low).
- In reality, the qualities provided by the TPs are becoming better and better, which implies that market prices for different services might converge.
- High-end market segments can still maintain a price difference if they can differentiate their quality from the lower-class TPs substantially.

Price Dynamics in Equilibrium

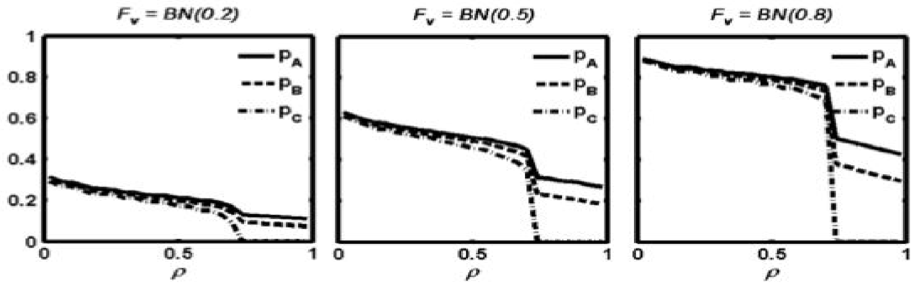

Fig. 9. Shift in market prices as ρ varies: $(q_A, q_B, q_C) = (0.2, 1, 5)$, $\sigma_A : \sigma_B : \sigma_C = 1 : 3 : 5$, $F_\beta = Geo$.

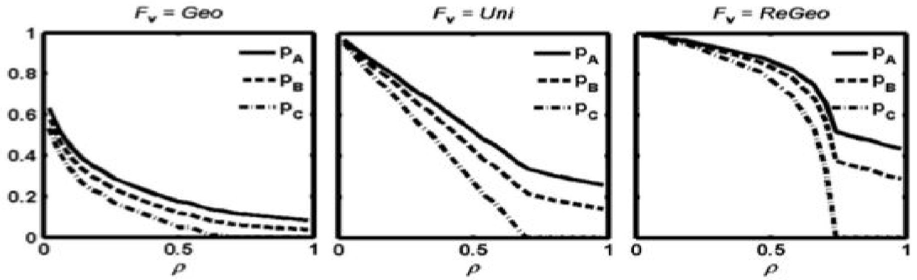

Fig. 10. Shift in market prices as ρ varies: $(q_A, q_B, q_C) = (0.2, 1, 5)$, $\sigma_A : \sigma_B : \sigma_C = 1 : 3 : 5$, $F_\beta = Geo$.

Price Dynamics in Equilibrium

Lessons (The AP Wealth Effects on Prices) Learned:

- The market prices of the TPs are positively correlated with the mean profitability of the APs.
- At a certain price range where the density of the APs is high (low), more (less) competition among the APs drives the prices close to (far below) their profitability.

Price Dynamics in Equilibrium

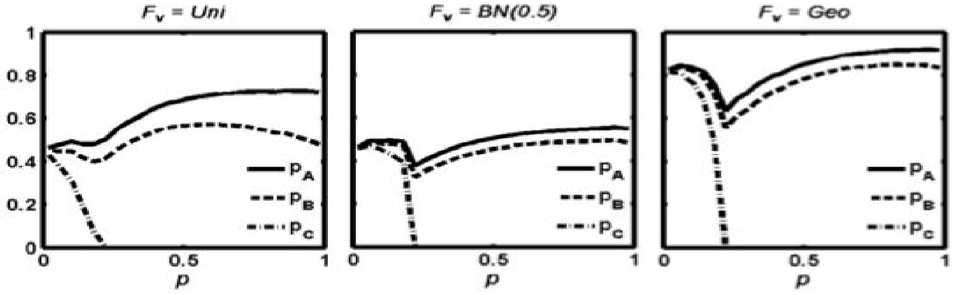

Fig. 11. Shift of market prices when we vary AP's sensitivity to quality: with $\sigma_A : \sigma_B : \sigma_C = 1 : 3 : 5$, $\rho = 0.5$, $(q_A, q_B, q_C) = (0.2, 1, 5)$, and $F_\beta = BN(p)$.

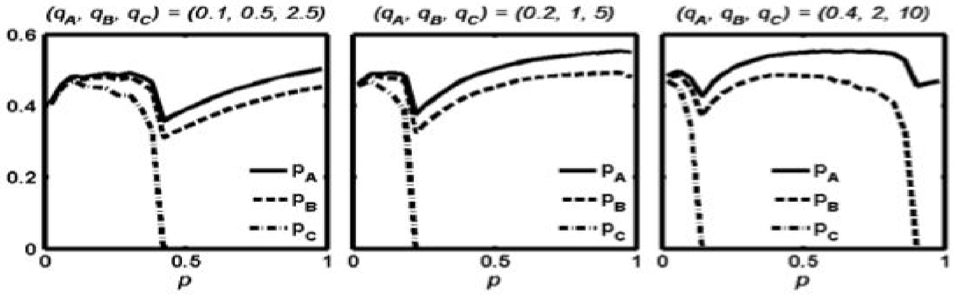

Fig. 12. Shift of market prices when we vary AP's sensitivity to quality: with $\sigma_A : \sigma_B : \sigma_C = 1 : 3 : 5$, $\rho = 0.5$, $F_v = BN(0.5)$, and $F_\beta = BN(p)$.

Price Dynamics in Equilibrium

Lessons (The AP Quality-Sensitivity Effects) Learned:

- When the APs become more sensitive to the service quality, the price of lower-class TPs will drop quickly.
- When the price of the lowest-quality TP goes down to its cost, the prices of higher-quality TPs might increase due to their relatively cheap prices and high demand.

Price Dynamics in Equilibrium

- Why Have the IP Transit Prices Been Dropping?
  - The price drop can be a consequence of the capacity expansion of the transit providers (capacity effect)
  - Reduction in CDN prices -> reduction in transit prices
  - CDN has great quality -> curves diverge
  - The wealth effect tells that since the majority of the elastic APs might not be very profitable, transit providers cannot fully utilize its capacity and charge a high price at the same time -> Differential and value added services
  - Inelastic traffic hate lower quality thus price falls
- Why Have the CDNs Emerged in the Ecosystem?
  - Exact opposite of the bad quality providers

Price Dynamics in Equilibrium

- Why has the Pricing Power Shifted to the Access ISPs?
  - Similar to CDN but Access ISPs are closer to end users
- Why Are the Large Content Providers Building Their Own Wide-Area Networks Toward Users?
  - Flattening phenomenon
  - Avoid the pricing of ISPs
  - Future plans

Internet's Economic Evolution

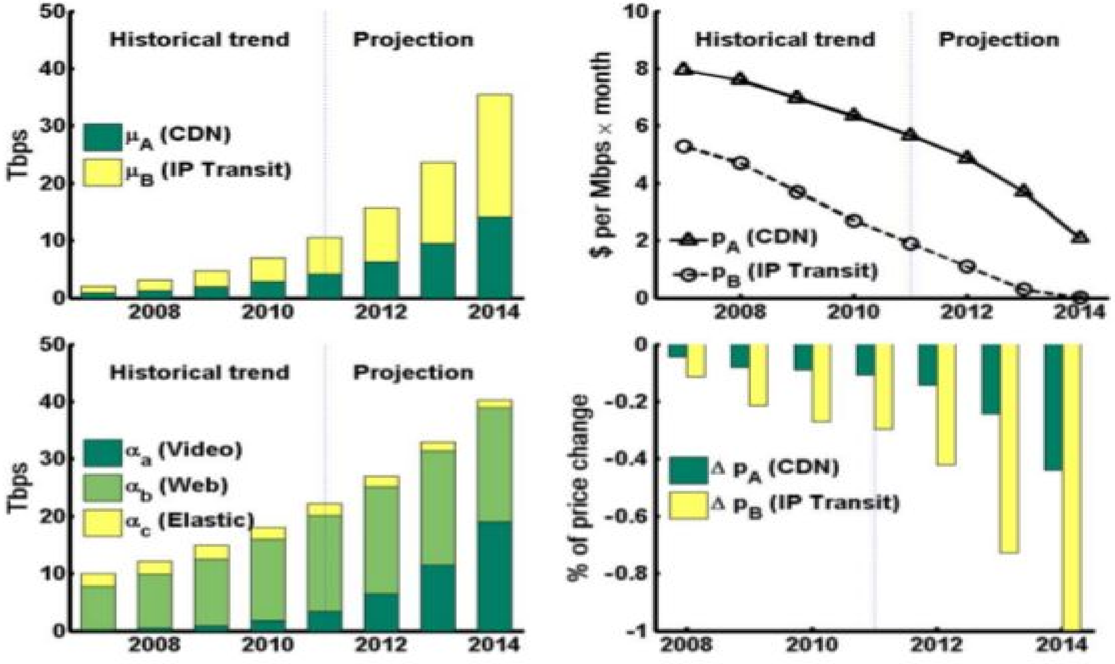

Fig. 13. Historical price and future price projection.

Internet's Economic Evolution

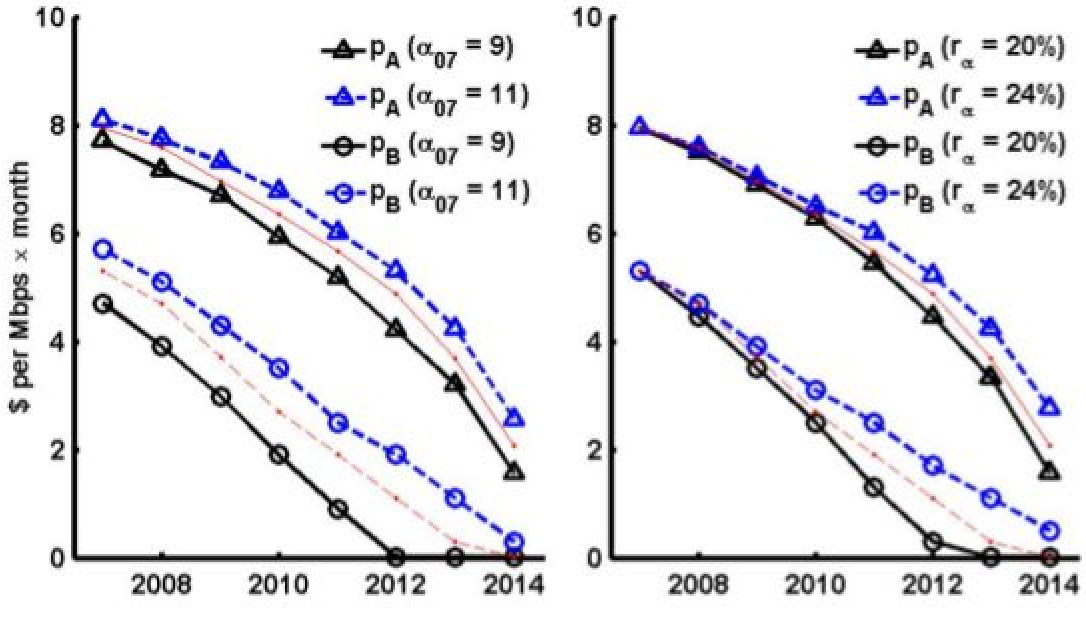

Fig. 14. Sensitivity to initial demand α_{07} and rate r_α.

Internet’s Economic Evolution

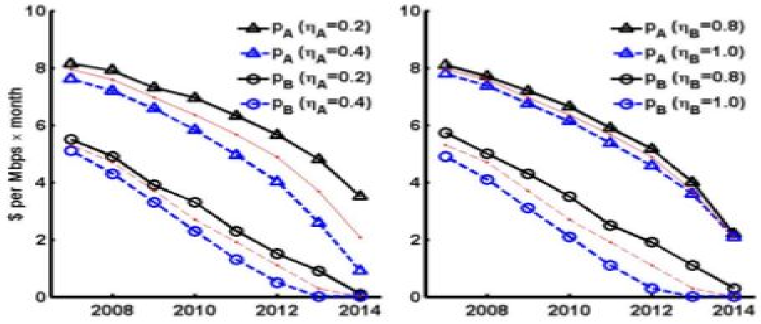

Fig. 15. Sensitivity to capacity utilization η_A and η_B.

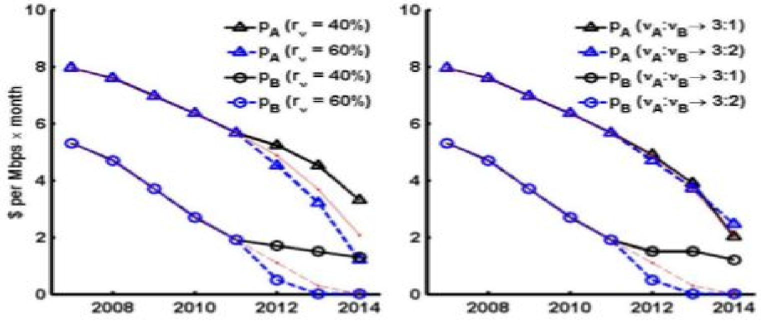

Fig. 16. Price projection under various capacity ratios ν_A : ν_B and capacity expansion rate r_ν.

Internet’s Economic Evolution

- We can help the TPs to make business decisions on:
  - How aggressive the TPs should expand their capacity
  - Whether the TPs should/would tend toward Open or Selective peering policies
- Observations tell us that the ISPs providing IP transit services might want to slow down their investment in capacity expansion
- However, CDN providers and ISPs that sell private-peering and QoS might want to continue to expand their capacity when their profit margins are still above zero
- As the price of IP transit drops, we believe that the investment in the transit capacity will slow down, which will also stabilize the price of the IP transit services

Internet’s Economic Evolution

- We observe that if more ISPs are going to use an Open peering policy, the IP transit price will drop to its cost quickly; other- wise, it will get closer to the CDN price and be stable
- This observation implies that ISPs would have strong incentives to move toward Selective peering policies if possible, which coincides with the reality that the access ISP, Comcast, started to use private peering exclusively

Summary of Internet's Economic Evolution

We predict that although the CDN price will still be dropping, the price of IP transit will be more stable. Furthermore, the capacity expansion will slow down and more ISPs will tend to use Selective rather than Open peering policies in the near future

Limitations

- Market segment could be lack of competition and form a monopolistic or oligopolistic market structure
- Not capture the off-equilibrium and transit dynamics that could happen in practice
- Microscopic details are avoided like peering, topology etc.,
- Model does not intend to capture the end-user market aspects
- The qualitative reasons provided are not exhaustive

Thank You