# Economic Issues for Information-Centric Networking

George Kesidis

CSE and EE Depts
The Pennsylvania State University,
CSE & EE Depts, University Park, PA, 16802, USA.
kesidis@engr.psu.edu

In collaboration with:
E. Altman *et al.*, S. Caron, S. Fdida, F. Kocak, T.-M. Pham, S. Sarkar

This work supported by the National Science Foundation of the USA.

RESCOM, Porquerolles, France, May 17, 2013

# Outline

- Overview of issues for the current Internet: neutrality, access and transit pricing
- The ICN case - reversing side-payment polarity (ISP to CP)
- A simple game model with one access and one content-provider player
- Competition - multiple players of each type
- Convex demand response to price
- Two-player game with ISP caching
- Discussion: advertising, security, DRM

## Simple games modeling Internet economics

- There are enormous financial stakes in the Internet's on-going network neutrality debate.

- Economic forces are important when considering architectural evolution of the Internet.

- In the following, we will employ simple game-theoretic models to concretely illustrate some of the current and future Internet's economic issues.

- ISPs (access or transit/backbone providers), application-service/content providers (CPs), name resolvers/rendezvous entities, advertisers, *etc.*, can be taken to be players on a platform of end-user demand.

- On a platform of end-user demand, the following games will be variations of the classical Bertrand price-competition model:
  - studied at their Bertrand-Nash equilibrium,
  - also considering bandwidth constraints (as in classical Cournot "quantity" competitions).

## Economic Internet games (cont)

- For simplicity, we will herein consider
  - only two-sided models, *i.e.*, at most two *types* of players (ISP and CP), or
  - two like players (each both an ISP and CP).
- In particular, we will not make simple extensions to consider side-payments to separate content resolvers of proposed future information-centric networking (ICN) architectures.
- If resolvers are assumed to be part of some of the ISP and/or CP players of some future Internet game model, Shapley values could be used to determine resolver component revenues.
- Note that other researchers have considered variations, *e.g.*, end-users and CPs playing on an ISP platform (*e.g.*, Musacchio *et al.* '09), and three-sided models of end-users, CPs and ISPs (*e.g.*, Hande *et al.* '09).

## Internet end-user access pricing

- Originally, asymmetrically bandwidth-limited flat-rate subscription tiers, no overages.
- Today also coarse volume-based subscription tiers (*i.e.*, volume overages), especially for cellular wireless access.
- In the following we will assume service-class (or by application type) based pricing, with
  - a flat-rate best-effort basic service, and
  - usage priced premium service, where
  - our focus will be on the latter.
- Premium service could require reservation fees for a quantity.
- Time-of-day variations in usage-based prices to deter use during peak loads and incent use during off-peak hours.
- See recent survey Sen *et al.* '12 comparing such mechanisms.

# Application neutrality of current Internet

- Network neutrality requires providing network access without unfair discrimination among applications, content, nor the specific source of traffic.

- In the context of the service agreement with the end-user and their ISP, what constitutes (unfair) discrimination?

- If there are two applications that "require the same network resources" and one is offered better quality of service (shorter delays, higher transmission capacity, *etc.*) then there is discrimination.

- When is a discrimination fair? A preferential treatment of traffic is considered fair as long as the preference is left to the user.

# Network Neutrality and side-payments of current Internet

- NN "usually means that broadband service providers charge consumers only once for Internet access, do not favor one content provider over another, and do not charge content providers for sending information over broadband lines to end users." (Hahn & Wallsten '06)

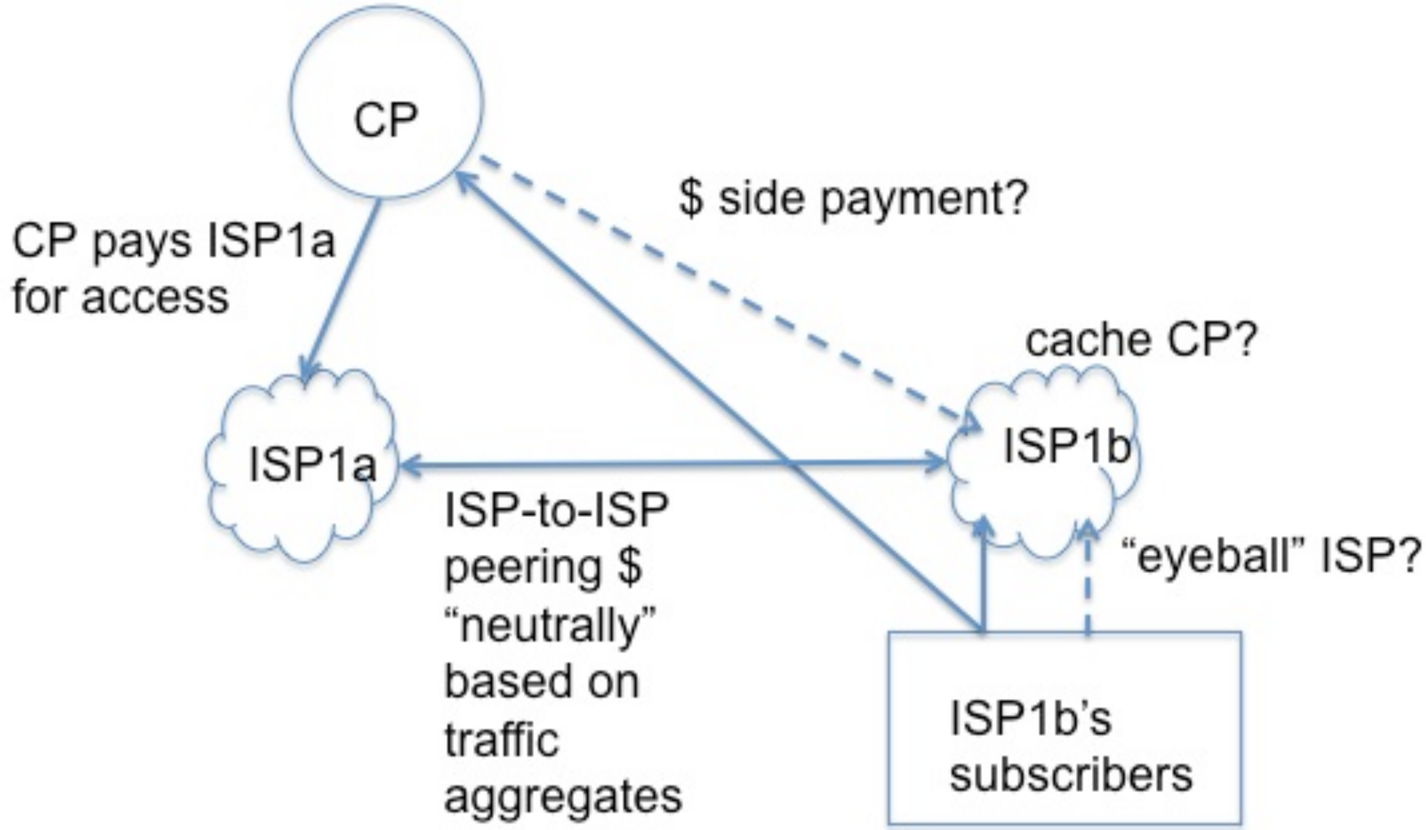
- Here, "charging once" disavows side payments between remote CPs and the ISPs of end-users.

- In the past, peering between ISPs often did not involve costs associated with asymmetric traffic volumes at the peering point(s); but today, side-payments between ISPs and CPs may manifest indirectly through peering SLAs between a CP's ISP and a residential ISP that is remote to the CP.

- Such SLAs target traffic asymmetries wherein the ISP receiving the net packet-flow load applies a charge to the net-sending ISP based on
  - average (or "sustainable") packet rate (equivalently a quota over a fixed time period), possibly tiered to allow for graduated bulk discounting, and
  - a type of peak-rate penalty, e.g., an additional charge per packet-volume over a short time-interval that is above a threshold (peak overages), or based on a "percentile peak" measure.

- In the following, we will model content-caching of two eyeball ISPs using a simple fixed-rate per unit volume (single pricing tier) of net packet-flow.

# Network neutrality and side-payments (cont)




Asymmetry in peering may mean more $ for ISP1b, so its best interest may be *not* to cache content.
However, the lack of local content caching may result in poor responsiveness from the end-user's perspective, hence lower end-user demand (and possible loss of end-user customers).

## Simple two-player game with ISP and CP

- Consider a model with three actors:
  - the Internauts (end-users) collectively,
  - a network access provider for the Internauts, called ISP1, and
  - a content provider and its ISP, collectively called CP2.
- Users pay $p_i \geq 0$ per unit consumption to provider $i \in \{1, 2\}$.

## Common, linear demand response to price

- Users are modeled through a common (to both ISP1 and CP2), linear demand function:

$$D = D_{\mathsf{max}} - pd,$$

  where

$$p = p_1 + p_2, \quad p_1, p_2, D \geq 0,$$

  $D_{\mathsf{max}}$ is the maximal demand, and
  $d > 0$ is the demand sensitivity to price.

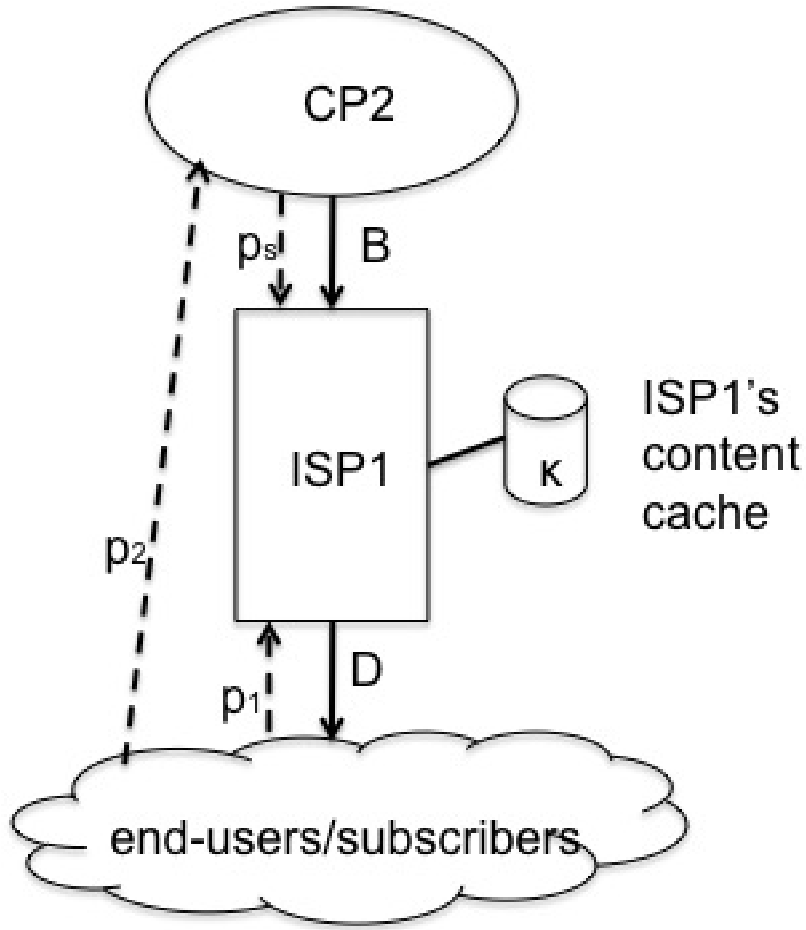
- So, provider $i$'s revenues are

$$U_i = p_i D, \quad i = 1, 2.$$

- Subsequently, we will consider demand functions that are nonlinear in price.

- Different demand sensitivities $d$ for access and price, though not considered in this talk, are motivated by, *e.g.*, a scenario where
  - the CP charges the same for two instances of content which
  - are of very different sizes, so they are different from the ISP's point-of-view.

# ISP and CP game on a platform of end-user demand-response



## Cooperative pricing

- Suppose the objective of *both* ISP1 and CP2 is to maximize $U_1 + U_2$, *i.e.*, solve

$$\frac{\partial(U_1 + U_2)}{\partial p_i} = D_{\mathsf{max}} - 2pd = 0, \; i = 1, 2.$$

- So, the total price $p = p_1 + p_2 = D_{\mathsf{max}}/(2d)$, maximizes $U_1 + U_2$ to give

$$(U_1 + U_2)_{\mathsf{max}} \quad = \quad D^2_{\mathsf{max}}/(4d).$$

- Shapley values, measures of appropriate division of communal revenue, have been used to advocate for such side payments in past work (Ma *et al.* '08).

- Here, they evenly divide total revenue among CP and ISP, *i.e.*,

$$U_i^* \quad = \quad D^2_{\mathsf{max}}/(8d), \quad \text{for } i \in \{1, 2\}.$$

# Competitive pricing

- In a noncooperative game, each player has their own objective (net utility) depending on their own and other players' play actions.
- A Nash equilibrium point (NEP) is a kind of multi-objective stalemate at which any unilateral action by any player, assuming the plays of the others are fixed, results in lower net utility for that player.
- In this talk, we do not focus the iterative play-action dynamics arriving at a NEP.
- If the providers do not cooperate then the utility of provider $i$ is obtained by computing the interior NEP.
- Owing to utility concavity, this is equivalent to solving the first-order conditions

$$\frac{\partial U_i}{\partial p_i} = D - p_i d = 0, \; i \in \{1, 2\}.$$

- This gives NEP $p_1^* = p_2^* = D_{\mathsf{max}}/(3d)$ at which the utilities for each provider $i \in \{1, 2\}$,

$$U_i^* = \frac{D_{\mathsf{max}}^2}{9d} \quad < \quad \frac{D_{\mathsf{max}}^2}{8d},$$

*i.e.*, less than the optimal utilities under cooperative pricing.

## Competitive pricing with side payments

- Next consider the competitive model with *side payments* per unit demand, $p_s$.

- Assume CP2 is requested to pay $p_s$ to ISP1 per unit of "transit" flow (recall assumption of common demand response).

- The revenues of the providers are now:

$$\begin{aligned} U_1 &= [D_{\max} - d\,(p_1 + p_2)]\,(p_1 + p_s) \\ U_2 &= [D_{\max} - d(p_1 + p_2)]\,(p_2 - p_s) \end{aligned}$$

- Note that negative side-payment ($p_s < 0$) would simply mean net payment to CP2 from ISP1.

# Fixed/regulated side payment

- Since the CP and ISP utilities are linear in $p_s$, if either player optimizes over $p_s$, then it will set $p_s$ at an extreme value, *i.e.*, 0 or

$$p_{\max} \quad := \quad D_{\max}/d.$$

- So it's possible that a regulator will limit the control of any one player over the side payment amount, particularly in the absence of competition among like providers.

- Note that the first-order condition for equilibrium, $\partial U_i/\partial p_s \;\; = 0$ corresponds to zero demand, for either player $i \in \{1, 2\}$.

- So, in the following we will typically assume that $p_s$ is not a decision (play) variable of the game, rather a fixed parameter.

- We will consider equilibrium performance for different cases of side payment.

## Fixed side payment - interior NEP for $|p_s| \leq p_{\max}/3$

- When $|p_s| < p_{\max}/3$, jointly maximizing utilities $U_i$ over $p_i$ leads to the interior NEP:

$$p_1^* = -p_s + p_{\max}/3 \quad \text{and} \quad p_2^* = p_s + p_{\max}/3.$$

- So, the equilibrium utilities are

$$U_i^* = D_{\max}^2/(9d), \quad i \in \{1, 2\}.$$

- Thus, the side-payment does not affect revenues.

# Fixed side payment - boundary NEP with $p_s > p_{\text{max}}/3$

- Recall $p_s > 0$ if net side payment from CP2 to ISP1.
- When $p_s \geq p_{\text{max}}/3$, there is a boundary NEP at
$$p_1^* = 0 \quad \text{and} \quad p_2^* = (p_s + p_{\text{max}})/2,$$
*i.e.*, the ISP has no direct usage-priced revenue (only flat-rate monthly access fees for best-effort service).
- So, the Nash equilibrium utilities are
$$U_1^* = (D_{\text{max}} - dp_s)p_s/2 \quad \text{and} \quad U_2^* = (D_{\text{max}} - dp_s)^2/(4d).$$
- Note that $p_s \geq p_{\text{max}}/3 \Leftrightarrow U_1^* \geq U_2^*$.
- Also, if $p_{\text{max}}/3 < p_s \leq 2p_{\text{max}}/3$, then $U_1^* > D_{\text{max}}^2/(9d)$, *i.e.*, increasing $p_s$ to this range results in improved revenue for ISP1 compared to that when $p_s \in [0, p_{\text{max}}/3)$.
- However, if $p_s > 2p_{\text{max}}/3$, then $U_1^* < D_{\text{max}}^2/(9d)$, *i.e.*, increasing the side payment to this range results in *less* revenue for the ISP1.
- Of course, at $p_s = p_{\text{max}}$, $D = 0 \Rightarrow U_1 = 0 = U_2$.

# Excess side-payments may lead to less revenue for all

- Generally, a player (CP2) making a large (net) side payment will try to recover those costs by increasing prices to the consumers, in turn that will cause consumer demand to fall, thereby tending to reduce revenue to the player receiving the side payment (ISP1).

- So, excess side payments (as $p_s \to p_{\max}$), will cause demand $D \to 0$ as the side-payment payer $i$ increases their price $p_i$ so that $p_i > p_k$ (*i.e.*, its revenue $U_i > 0$).

## Present Internet vs ICN: side-payment polarity

- In the present-day Internet, consumers request content/services from specific content providers,
  - *i.e.*, those user-requested CPs *push* content to the ISP,
  - so it may be reasonable to expect that if a side-payment is in play it will tend to be from CP to ISP; also, the CP could pay the ISP to cache its content (*e.g.*, Agyopong & Sirbu '11).
  - Again note that a direct side-payment would be equivalent to an indirect provision in a SLA between CP2's ISP and the residential-serving, last-mile ISP1, favoring ISP1 due to aggregate traffic load asymmetry at the peering points.
- In a future information-centric network where the consumers make an anycast request for content to the ISP:
  - the ISP selects a CP and *pulls* the content in,
  - and so it may be reasonable to expect that the ISP may need to pay the CP for its content (royalties) and networking costs,
  - i.e., $p_s < 0$ (Trossen & Kostopoulos '12).

## Fixed side payment - boundary NEP with $p_s < -p_{\max}/3$ (ICN)

- Recall how the interior NEP covered the case where $p_s \in [-p_{\max}/3, 0]$, *i.e.*, $p_s < 0$ as in the ICN scenario.

- As for the complementary Internet case, when $p_s < -p_{\max}/3$, the boundary NEP is

$$p_2^* = 0 \quad \text{and} \quad p_1^* = -p_s + p_{\max}/2.$$

- Note that $p_s \in [-p_{\max}/3, 0] \Leftrightarrow U_2^* \geq U_1^*$ (the Nash equilibrium utilities).

- Also note that for $p_s \in [-2p_{\max}/3, -p_{\max}/3)$, $U_2^* > D_{\max}^2/(9d)$, *i.e.*, decreasing (increasing the magnitude of) the side payment to this range results in improved revenue for CP2 compared to that when $p_s \in [-p_{\max}/3, 0]$.

- However, if $p_s < -2p_{\max}/3$, then $U_2^* < D_{\max}^2/(9d)$, *i.e.*, increasing the side payment to this range results in *less* revenue for CP2.

# Stackelberg equilibrium

- Stackelberg games involve a leader leader player and one or more follower players.

- Play actions are no longer taken simultaneously: first the leader takes an action, and then the followers react to this action.

- Assume that the ISP1 is the leader and has set $p_1$ <u>and</u> $p_s$.

- Now CP2 is given $p_1$ and $p_s$, and is to set $p_2$ to maximize concave

$$U_2 = (D_{\max} - d(p_1 + p_2))(p_2 - p_s).$$

- So, the first-order conditions are necessary and sufficient to maximize $U_2$ over $p_2 \geq 0$,

$$\frac{\partial U_2}{\partial p_2} = D_{\max} - d(p_1 + p_2) - d(p_2 - p_s) = 0.$$

- Thus to maximize $U_2$ at an interior point, CP2 will take $p_2$ as

$$p_2^* = \frac{1}{2}\Big(\frac{D_{\max}}{d} + p_s - p_1\Big).$$

# Boundary Stackelberg equilibrium for the ICN case

- Substituting $p_2^*$ in $U_1$, we obtain:

$$\begin{aligned} U_1 &= (D_{\mathsf{max}} - d(p_1 + p_2))\,(p_1 + p_s) \\ &= \frac{1}{2}(D_{\mathsf{max}} - 3p_1 d - p_s d)\,(p_1 + p_s) \end{aligned}$$

- Now ISP1 will reselect $p_1$ and $p_s$ to maximize $U_1$ which is concave in $(p_1, p_s)$.
- The first-order conditions (FOCs) for an interior NEP are:

$$\begin{aligned} \frac{\partial U_1}{\partial p_1} &= \frac{D_{\mathsf{max}} - 4dp_s - 6dp_1}{2} = 0 \\ \frac{\partial U_1}{\partial p_s} &= \frac{D_{\mathsf{max}} - 2dp_s - 4dp_1}{2} = 0 \end{aligned}$$

- Subtracting these FOCs gives

$$-p_s^* = p_1^* = \frac{D_{\mathsf{max}}}{2d} > 0,$$

*i.e.*, $p_s^* < 0$ (the ICN case).

# Boundary Stackelberg equilibrium for the ICN case (cont)

- But this implies $p_2^* = 0$, *i.e.*, the boundary NEP is

$$(p_1^*, p_2^*, p_s^*) \quad = \quad (\frac{D_{\mathsf{max}}}{2d}, 0, -\frac{D_{\mathsf{max}}}{2d}).$$

- Note that in this case, the CP has zero revenue directly from end-users.

# Boundary Stackelberg equilibrium for the Internet case

- Now assume that

$$p_1 \quad = \quad 0.$$

- If $p_s > 0$ (the Internet case), then the above FOC $\partial U_1/\partial p_s = 0$, gives that $U_1$ is maximized at

$$p_s \quad = \quad \frac{D_{\mathsf{max}}}{2d},$$

which is consistent with the assumption that $p_s > 0$.

- Substituting back into the optimal CP2 price, we get

$$p_2 \quad = \quad \frac{3D_{\mathsf{max}}}{4d} > 0.$$

- So, the above three displays give a boundary Stackelberg equilibrium for the Internet case,

$$(p_1^*, p_2^*, p_s^*) \quad = \quad (0, \frac{3D_{\mathsf{max}}}{4d}, \frac{D_{\mathsf{max}}}{2d}).$$

# Multiple providers of each type

- Again, Internauts (end users, consumers) are modeled collectively by their demand response.
- Now suppose $n_1 \geq 1$ last-mile ISPs, and $n_2 \geq 1$ CPs.
- Consumers pay one ISP and one CP usage-dependent fees for access and content.
- Providers then compete in a game to settle on their usage-based prices, which may turn out to be 0$/byte, *i.e.*, only flat-rate subscription fees would apply.
- Let $p_{1i} \geq 0$ (resp. $p_{2j} \geq 0$) the usage-based price of the $i^{\text{th}}$ ISP (resp. $j^{\text{th}}$ CP).
- Common user demand response is assumed linear

  $$D(p_{1i}, p_{2j}) = D_{\text{max}} - d_1 p_{1i} - d_2 p_{2j},$$

  where $d_k$ is the demand sensitivity to price paid to provider of type $k$ (here possibly provider dependent where, again, subscript $k = 1$ for ISP, 2 for CP).
- Assuming a *common* demand response for different types of providers, consistent with assuming $d_1 = d_2 = d$.

# Customer stickiness

- As we suppose all providers of a given type propose the *same* type/quality of content/service, user decisions are only based on price considerations.
- If an ISP charges a price significantly lower than the other ISPs, eventually all customers will choose it and the other ISPs will have no choice but to align their prices or opt out of the game.
- Therefore, our homogeneity hypothesis means all $n_1$ ISPs (and similarly all $n_2$ CPs) have roughly the same prices: $p_{ki} \approx p_{kj}\ \forall k, i, j$.
- As providers play the usage-based pricing game, first-order differences between these prices may appear (*e.g.*, the $i^{\text{th}}$ ISP reducing his price by $\delta p_{1i}$ to attract new end users).
- Consumers are then more likely to go to the cheapest providers of each type, but price differences may be too small to convince all of them to move and some will stay with their current provider.
- Rather than modeling customers as separate players, simply let $\sigma_{ki} \equiv \sigma(i, \mathbf{p}_k)$ be the fraction of users with provider $i$ of type $k$ (charging $p_{ki}$).

# Customer Stickiness: Properties

(a) $\sigma(i, \mathbf{p}_k) \geq 0$ and $\sum_{j=1}^{n_k} \sigma(j, \mathbf{p}_k) = 1$;

(b) if $\mathbf{p}_k = (p, p, \ldots, p)$, then $\forall i \in \{1, ..., n_k\}$, $\sigma(i, \mathbf{p}_k) = 1/n_k$; and

(c) $p_{ki} < p_{kj} \Rightarrow \sigma(i, \mathbf{p}_k) > \sigma(j, \mathbf{p}_k)$.

- So, uniform distr'n if all providers of a given type charge exactly the same price, otherwise that cheaper providers attract more consumers.

- We chose

$$\sigma(i, \mathbf{p}_k) \;=\; \frac{1/p_{ki}}{\sum_{j=1}^{n_k} 1/p_{kj}} \;=:\; \sigma_{ki}$$

- The average usage-based price charged by a type-$k$ provider to a customer is $p_k := \sum_i \sigma_{ki} p_{ki}$, *i.e.*, the harmonic mean of $\{p_{ki}\}_i$.

# Without side payments

- With no side payments nor application discrimination, the $i^{\text{th}}$ ISP's expected usage-based revenue is the quadratic form:

$$\begin{aligned} U_{1i} &= \sum_{j=1}^{n_2} \sigma_{1i}\, \sigma_{2j}\, D(p_{1i}, p_{2j})\, p_{1i} \\ &= \sigma_{1i}\, D(p_{1i}, \overline{p}_2)\, p_{1i}, \end{aligned}$$

  and similarly $U_{2j}$ for the $j^{\text{th}}$ CP.

- Necessary conditions for an interior Nash Equilibrium Point (NEP) are

$$\frac{\partial U_{ki}}{\partial p_{ki}}(\overline{p}_1, \overline{p}_2) \quad = \quad 0 \;\; \text{for } k = 1, 2,$$

  *i.e.*, a local maximum in revenue for all players.

## Without side payments (cont)

- Solving, we get that at the NEP

$$
\begin{aligned}
D^* &= \frac{n_1 n_2}{n_1 n_2 + n_1 + n_2} D_{\mathsf{max}}, \\
U_{ki}^* &= \frac{n_{3-k}^2}{(n_1 n_2 + n_1 + n_2)^2} U_{\mathsf{max}} \quad \text{for } k = 1, 2.
\end{aligned}
$$

- As expected, customers benefit from competition among the providers.

- With 2 ISPs and 2 CPs, demand is only 50% of its potential $D_{\mathsf{max}}$, while it is about 70% of $D_{\mathsf{max}}$ with 5 ISPs and 5 CPs.

- Competition in a provider's own group has much greater impact on their income than competition in another group.

## With side payments

- Usage-based fee $p_s$ referenced from the CPs to the ISPs.
- Again, when $p_s > 0$ (Internet case), CPs remunerate the ISPs, *e.g.*, to support the bandwidth costs or share in advertising revenue (*e.g.*, Ma *et al.* '08).
- On the other hand, if $p_s < 0$ (ICN case), ISPs give money to the CPs, *e.g.*, to supplement copyright-related royalties and for CPs' operating/networking costs.
- With all demand and price factors are non-negative,

$$
\begin{aligned}
U_{1i} &= \sigma_{1i} D(p_{1i}, \overline{p}_2)(p_{1i} + p_s), \quad i \in \{1, ..., n_1\}, \\
U_{2j} &= \sigma_{2j} D(\overline{p}_1, p_{2j})(p_{2j} - p_s), \quad j \in \{1, ..., n_2\},
\end{aligned}
$$

- Again, expect $p_s$ will *not* be any player's decision variable.
- Since revenues are monotonic in $p_s$, those controlling it would always be incentivized to increase or decrease it (if they are ISPs or CPs respectively), leading the other players to opt out of usage-pricing - thus, again assume $p_s$ is regulated (fixed).

## Side payments (cont)

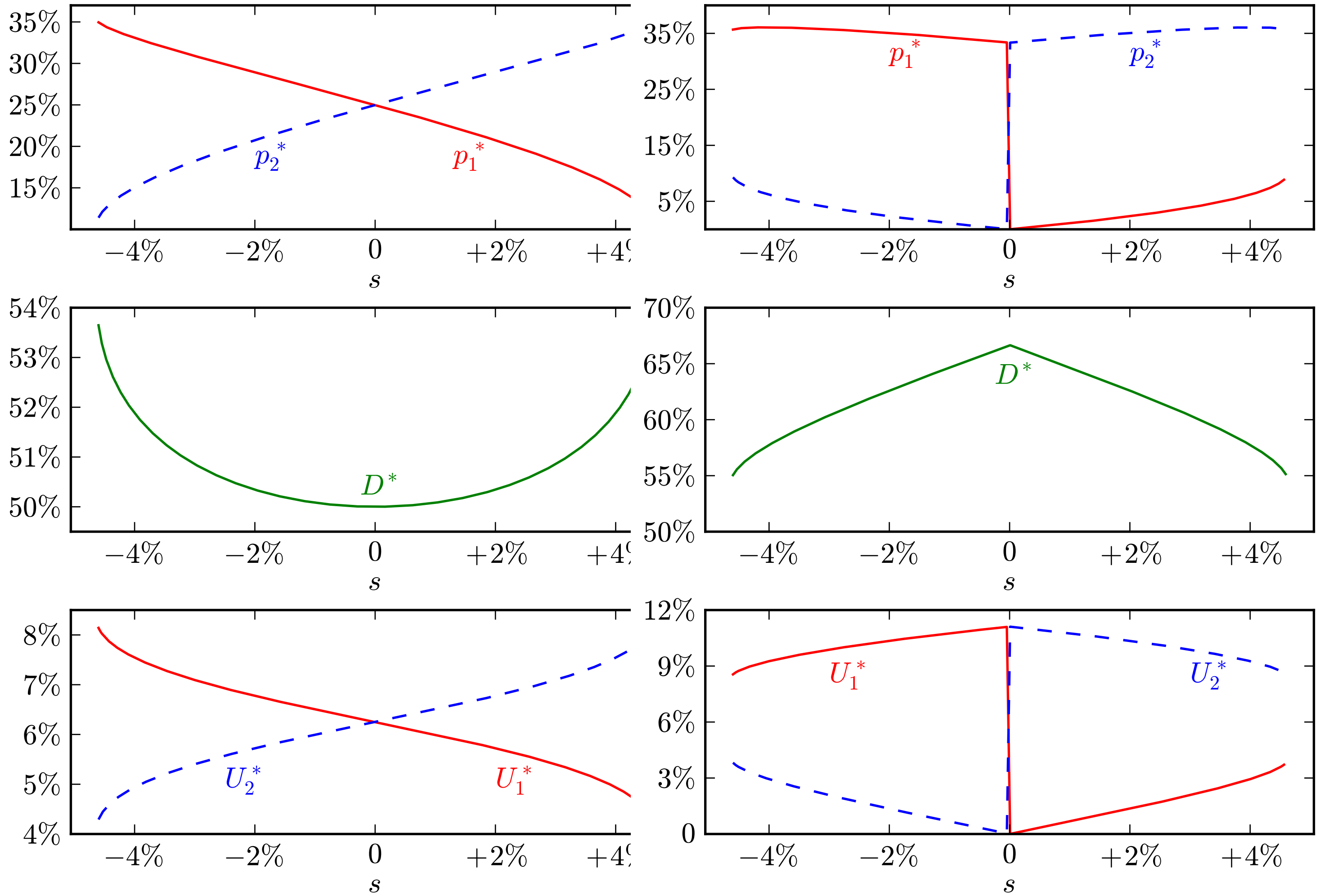
**Theorem 1** *When* $n_1 = n_2 = 2$*, there is an interior NEP if and only if*

$$\left|\frac{p_s}{p_{\max}}\right| \leq \max_{x \in [\frac{1}{4}, \frac{1}{2}]} \sqrt{\frac{(1-x)(1-2x)^2(4x-1)}{36x}} \approx 4.64\%,$$

*where* $p_{\max} := \frac{D_{\max}}{d} \geq p_{1i} + p_{2j}$.

- For proof see Caron *et al.* arxiv.org tech report (v.1 Aug. 2010).
- So, regulated side payments can only occur *to a small extent* ($|p_s| < 4.64\%$ of $p_{\max}$),
- otherwise there will be *no interior* NEP, which means one of the two groups of players will opt out of the usage-based pricing game.
- There are two solutions to the NEP necessary conditions, $\text{NEP}_1$ and $\text{NEP}_2$.
- Generally, additional NEPs may exist on the boundary of the play-action space.

# Demand and revenues at interior NEPs ($s = p_s$)




NEP$_1$ at left and NEP$_2$ at right.
x-axes: $s := p_s/p_{\mathsf{max}}$.
y-axes: % of maximal values.

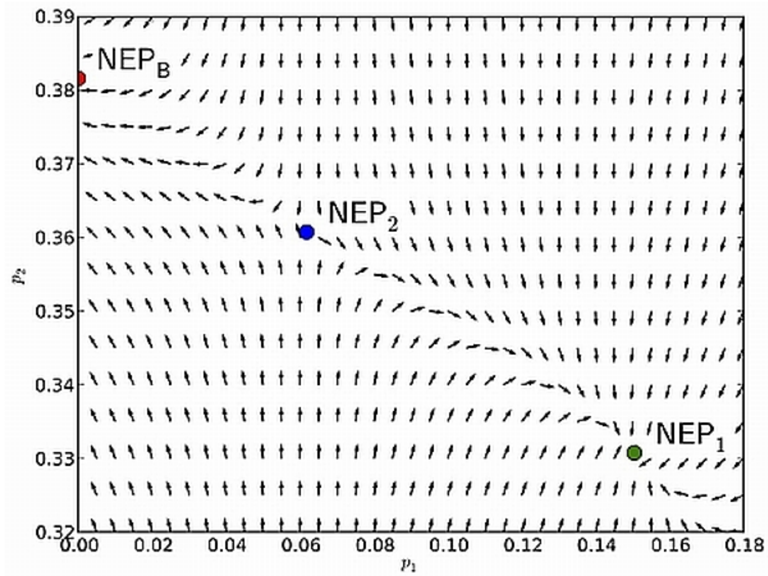
## A paradox of NEP demand and revenues

- $\text{NEP}_1$ is consistent with the results of the non-discriminating setting (when $p_s = 0$, $\overline{p}_k^* = p_{\text{max}}/4$, $D^* = D_{\text{max}}/2$ and $U_k^{i*} = U_{\text{max}}/16$ for $k = 1, 2$),
- while $\text{NEP}_2$ does not exist when $p_s = 0$ (there is a discontinuity in equilibrium prices at this point).
- Both interior NEPs share the same "paradox": providers receiving side payments eventually achieve *less* revenue than the others.
- Now assume $p_s > 0$ (Internet case), otherwise the roles of ISPs and CPs are swapped.
- Assume all providers act independently under a best-response behavior.
- Thus, the ("better response") vector field

$$(\overline{p}_1, \overline{p}_2) \mapsto \left( \frac{\partial U_{1i}}{\partial p_{1i}}(\overline{p}_1, \overline{p}_2), \frac{\partial U_{2j}}{\partial p_{2j}}(\overline{p}_1, \overline{p}_2) \right)$$

is an appropriate indicator of the aggregate "trends" of the system.

# Convergence to equilibrium




"Macroscopic" trends of the system for $n_1 = n_2 = 2$ and $p_s = 4\%$ of $p_{\mathsf{max}}$.

- If $\overline{p}_1 > \overline{p}_1^*(\mathsf{NEP}_2)$, the system $\to$ NEP$_1$;

- otherwise, unless $\overline{p}_1$ is precisely equal to $\overline{p}_1^*(\mathsf{NEP}_2)$, the system $\to$ NEP$_\mathsf{B}$ (where usage-based revenues for ISPs come only from side payments);

- NEP$_2$ is an unstable (saddle) point.

# Convergence to equilibrium

- Solving NEP necessary conditions with $\overline{p}_1 = 0$ yields
$$\overline{p}_2^*(\mathsf{NEP_B}) = \frac{p_{\mathsf{max}}}{6}\left(1 + s + \sqrt{s^2 + 14s + 1}\right),$$
with corresponding expressions for demand and revenues following directly.

- Demand higher at boundary $\mathsf{NEP_B}$ than at interior NEPs,

- while ISP revenues turn out to be lower (and CP revenues higher) than at $\mathsf{NEP_2}$.

- Consider two crude example types of applications, each provided by different CPs indexed 2 and 3.
- Users choose an ISP, a type-2 CP and a type-3 CP; again no coalitions.
- In a neutral setting, the $i^{\text{th}}$ ISP charges a single price $p_{1i}$ for all types of traffic;
- otherwise it may set up two different prices $p_{12,i}$ and $p_{13,i}$ for type 2 and type 3 traffic respectively.
- Denote by $p_{2j}$ (resp. $p_{3j}$) the usage-based price charged by the $j^{\text{th}}$ CP2 (resp. CP3).
- When ISP $i$, CP2 $j$ and CP3 $l$ are chosen, demands for type-2 and type-3 content are, respectively,

$$\begin{aligned} D_2 &= D_{2\max} - d_2(p_{12,i} + p_{2j}), \\ D_3 &= D_{3\max} - d_3(p_{13,i} + p_{3l}), \end{aligned}$$

  with $p_{12,i} = p_{13,i} = p_{1i}$ in the neutral setting.
- As previously, define $p_{k\max} := D_{k\max}/d_k$.

## Application neutrality (cont)

- Revenues are based on these demand profiles and the consumer stickiness model described before.
- For the normalized sensitivity to usage-based pricing and the maximum prices ratio, resp. $\alpha := \frac{d_2}{d_2+d_3}$ and $\gamma := p_{2\mathsf{max}}/p_{3\mathsf{max}}$, *assume*:
  - $\alpha \geq 1/2 \Leftrightarrow d_2 > d_3$: consumers are more sensitive to usage-based pricing for type-2 content than for type-3 content.
  - $\gamma < 1 \Leftrightarrow p_{2\mathsf{max}} < p_{3\mathsf{max}}$: customers are ready to pay more for type-3 content than for type-2 content.

## Not application-neutral setting

- The NEP for the application neutral setting is straightforward from the necessary conditions.
- For non-neutral pricing, the $i^{\text{th}}$ ISPs utility is $U_{1i} = \sigma_{1i}(D_2 p_{12,i} + D_3 p_{13,i})$, where $\sigma_{1i}$ refers to the portion of users gathered by ISP $i$ given his prices $p_{12,i}$ and $p_{13,i}$.
- There are different ways to generalize the model of consumer stickiness to multiple criteria.
- We chose $\sigma_{1i} := \sigma(i, \widetilde{\mathbf{p}}_1) = 1/\widetilde{p}_{1i}/\sum_{j=1}^{n_1} 1/\widetilde{p}_{1j}$ with $\widetilde{p}_{1i} := \sqrt{\alpha\gamma}\, p_{12,i} + (1 - \sqrt{\alpha\gamma})\, p_{13,i}$ because
  - $\sigma_{1i}$ still satisfies the basic properties expected for a stickiness function given before,
  - the weight of $p_{12,i}$ in the combination is increasing in $p_{2\text{max}}$ and $d_2$,
  - similarly the weight of $p_{13,i}$ is increasing in $p_{3\text{max}}$ and $d_3$; and
  - the resulting model is solvable in closed form.
- Computations yield a single admissible NEP here.

## Numerical results for application neutrality

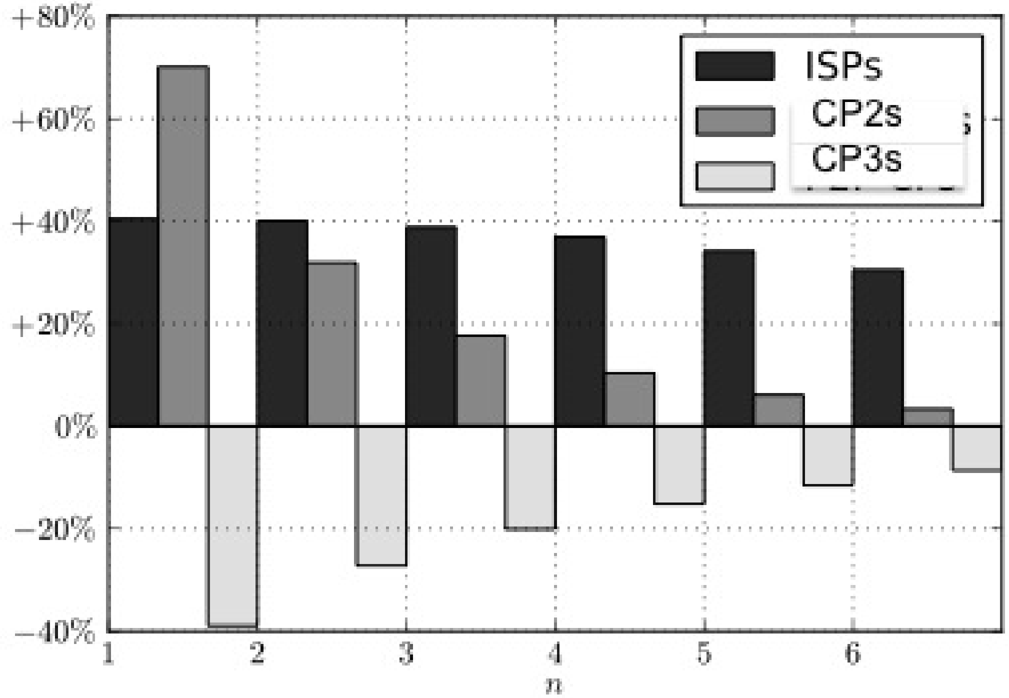
- In our numerical Sage experiments, we compared revenues at this NEP with those of the neutral scenario for $\alpha = 0.8$ and $\gamma = 0.3$.

- The main result we observed is that ISPs and type-2 CPs prefer the non-neutral setting, while type-3 CPs benefit from neutrality regulations.

- The impact of non-neutral pricing on providers' revenues varies with competition: increased competition brings less benefit for type-2 CPs and less loss for type-3 CPs.

- Yet, competition among CPs has almost no effect on ISP gains.

# Numerical results for application neutrality

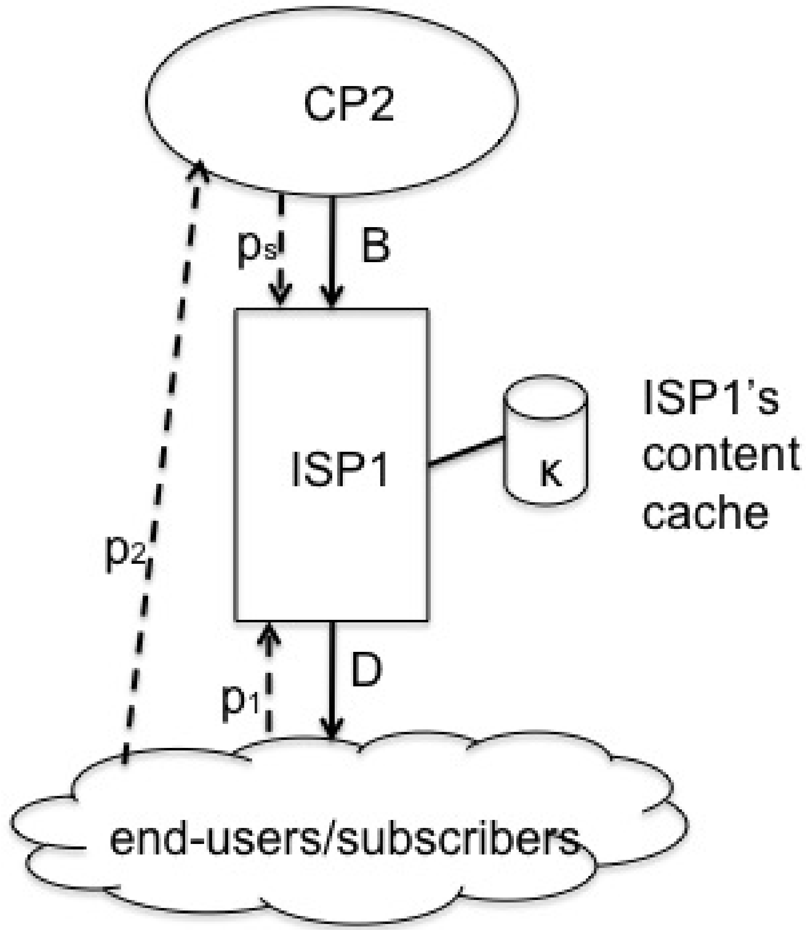



Relative variation in revenue,
*i.e.*, the ratio of revenues (non-neutral - neutral)/neutral at the NEP,
where $n$ is the number of providers of each type.

## ISP caching for ICN and convex demand-response

- In the following, we will address the issue of ISP caching in ICN.
- Note that ISP caching is simply not incented for this Internet ISP-CP model.
- We'll also reconsider our demand response model which is linear in price.
- For delay sensitive applications that are likely to pay for usage-priced premium service (instead of best-effort service covered by the flat-rate monthly access fee), we will argue that demand response is convex in price.

## Limited bandwidth $B$ between ISP and CP



## Price-convex demand-response: Delay sensitivity

- Suppose the applications associated with usage-based charges are delay sensitive.
- Suppose "implicitly" model their demand

$$D \quad = \quad [g(D)]^{+}$$

with

$$g(D) = (D_{\mathsf{max}} - dp)\left(1 - \frac{\lambda}{B - D}\right) / \left(1 - \frac{\lambda}{B}\right),$$

where

- $B$ is the bandwidth reserved *between CP and ISP* for delay-sensitive applications under usage-based total price $p$ to consumers,
- $\lambda$ is demand sensitivity to mean delay, here modeled as $1/(B - D)$ (an expression for mean delay taken from the M/M/1 queue).

## Price-convex demand-response: Delay sensitivity (cont)

- Let

$$\tilde{D} \;:=\; (D_{\max} - dp)/(1-\lambda/B) \;=\; D_{\max}(1-p/p_{\max})/(1-\lambda/B),$$

  and assume $\tilde{D} > 0$.

- The interior fixed-point $D$ of $g^+$ (*i.e.*, fixed point of $g$), gives the "explicit" demand response

$$D = \frac{1}{2}\left[(B+\tilde{D}) - \sqrt{(B-\tilde{D})^2 + 4\lambda\tilde{D}}\right].$$

- This demand-response model has the following properties
  - $D \to D_{\max}$ as $B \to \infty$ and $p \to 0$.
  - If $B > \lambda$ then $D$ is a convex function of $\tilde{D}$ and hence also a convex function of price $p$.

# Simplified price-convex demand-response, $D(\cdot)$

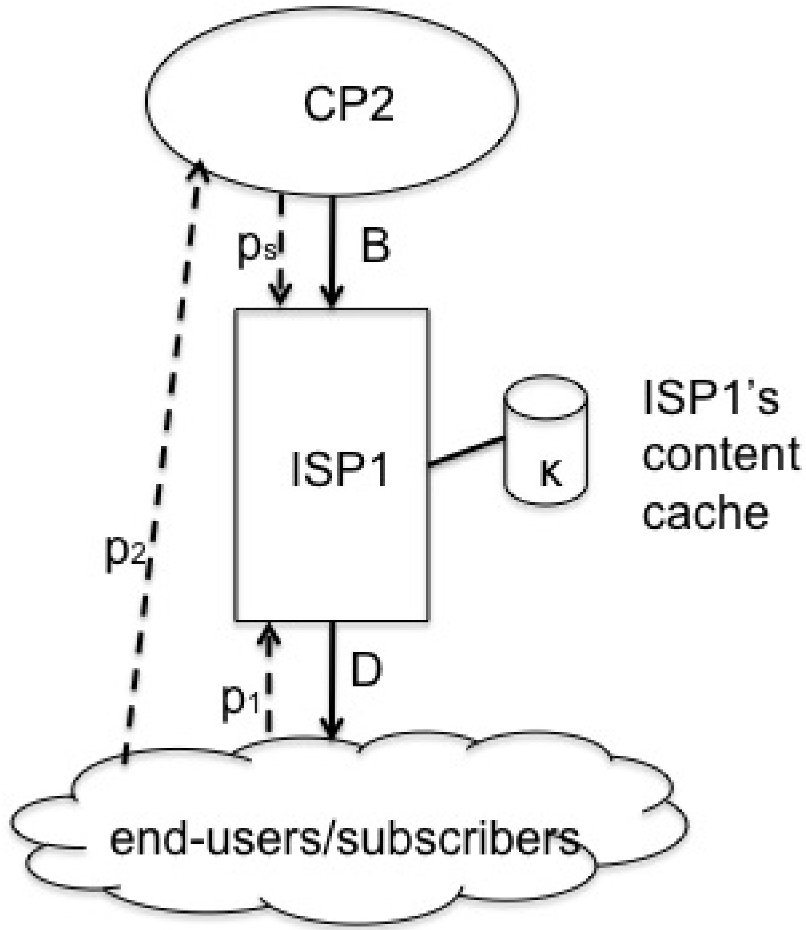
- Suppose that $U_1 = (p_1 + p_s)D(p_1 + p_2)$ and $U_2 = (p_1 - p_s)D(p_1 + p_2)$.

- By adding the first-order conditions $\partial U_i/\partial p_i = 0$, $i \in \{1, 2\}$, we get that the interior Nash equilibrium for a strictly price-convex demand response $D$ is
$$p_1^* = p^*/2 - p_s \quad \text{and} \quad p_2^* = p^*/2 + p_s,$$
when $|p_s| < p^*/2$, where $p^* = p_1^* + p_2^*$ solves
$$2D(p^*) + p^* D'(p^*) \;=\; 0.$$

- For the simple example
$$D(p) \;=\; D_{\mathsf{max}}(1 - p/p_{\mathsf{max}})^a \;\text{ with } a > 1,$$
the Nash equilibrium prices and utilities are given by
$$\begin{aligned} p^* &= \frac{2}{2+a} p_{\mathsf{max}}, \\ U_1^*, U_2^* &= \frac{p}{2} D(p) \;=\; \frac{D_{\mathsf{max}} p_{\mathsf{max}}}{2+a} \left(\frac{a}{2+a}\right)^a, \end{aligned}$$
where $D_{\mathsf{max}}$ is decreasing in $B$.

- Again, under communal demand response with only one provider of each type, neither $p^*$ nor $U_1, U_2$ depend on $p_s$ when $|p_s| < p^*/2$.

# ISP caching in ICN



# Implicit demand-response formulation with caching

- As a result of ISP caching, only a fraction $(1-\kappa)$ of the demand $D$ is transmitted through the the bandwidth $B$ between ISP and CP.

- So, $D = [g_\kappa(D)]^+$, where

$$\begin{aligned} g_\kappa(D) &= (D_{\mathsf{max}} - dp)\left(1 - \frac{\lambda}{B-(1-\kappa)D}\right) \Big/ \left(1 - \frac{\lambda}{B}\right) \\ &= (D_{\mathsf{max}} - dp)\left(1 - \frac{\lambda/(1-\kappa)}{B/(1-\kappa) - D}\right) \Big/ \left(1 - \frac{\lambda/(1-\kappa)}{B/(1-\kappa)}\right) \end{aligned}$$

- So, solving $D = g_\kappa(D)$ results in the previous demand-response with $B$ and $\lambda$ replaced by $B/(1-\kappa)$ and $\lambda/(1-\kappa)$, respectively:

$$D = \tfrac{1}{2}\left[\frac{B}{1-\kappa} + \tilde{D} - \sqrt{\left(\frac{B}{1-\kappa} - \tilde{D}\right)^2 + 4\frac{\lambda}{1-\kappa}\tilde{D}}\right].$$

# Demand-response increasing in caching factor

- Since, $g_\kappa(D) = g_0((1-\kappa)D) := g((1-\kappa)D)$, is decreasing in $(1-\kappa)D$ (hence increasing in caching factor $\kappa$), the solution

$$D_\kappa \quad = \quad g_\kappa(D_\kappa)$$

  is an increasing function of caching factor $\kappa$ (in particular) $D_\kappa \geq D_0$).

- To see this, note that

$$D_0 \;=\; g_0(D_0) \;\;<\;\; g_0((1-\kappa)D_0) \;=\; g_\kappa(D_0).$$

- So, if $D_\kappa \leq D_0$, then we would have

$$D_\kappa \leq D_0 \;\;<\;\; g_\kappa(D_0) \;\leq\; g_\kappa(D_\kappa),$$

  which contradicts the definition of $D_\kappa$ in the first display above.

- Also note that, as $\kappa \to 0$, the demand tends to the previous demand response, *i.e.*, convex in price.

- On the other hand, as $\kappa \to 1$, the demand response tends to linear in price.

## Simplified demand-response convex in price with caching

- We have motivated the following generalization of the simple demand response model,

$$\begin{aligned} D(p) &= D_{\mathsf{max}}(B)(1 - p/p_{\mathsf{max}})^{\kappa + a(1-\kappa)} \quad \text{with } a > 1 \\ &= D_{\mathsf{max}}(B)(1 - p/p_{\mathsf{max}})^{a - \kappa(a-1)} \end{aligned}$$

  where as a result of the previous discussion,
  - $D_{\mathsf{max}}(B)$ is decreasing in $B$ (effect of two types of users),
  - $p_{\mathsf{max}} := p_{\mathsf{max},b}$, *i.e.*, that of the less price-sensitive type of user.

- Note that $D$ is increasing in $\kappa$ and tends to price-linear as $\kappa \to 1$.

- So, we can employ the previous result to get that the interior NEP here is:

$$\begin{aligned} p_1^* &= p^*/2 - p_s \\ p_2^* &= p^*/2 + p_s \\ p^* &= \frac{2}{2 + \kappa + a(1-\kappa)} p_{\mathsf{max}} \end{aligned}$$

- ISP1's net revenue (utility) with cost of caching is

$$U_1 = (p_1 + p_s) D(p_1 + p_2) - c(\kappa).$$

## Caching cost convex in caching factor

- Assume that the cost of caching is proportional to the number of cached items (content), in turn proportional to the (mean) amount of memory required to store them.
- For a fixed population of $N$ end-users (a proximal group served by an ISP), let $\pi(j)$ be the proportion of the items that will soon be of interest to precisely $j$ end-users.
- Finally, suppose the ISP effectively prioritizes its cache to hold the most popular content.
- So, a caching factor $\kappa$, based on all-or-none decisions to cache content of the same popularity, would satisfy

$$\kappa \quad \propto \quad \sum_{j=N-f(\kappa)}^{N} j\pi(j).$$

  for some $f(\kappa) \in \{0, 1, 2, ..., N\}$.

- The cost of caching would be proportional to the number of cached items, *i.e.*,

$$c(\kappa) \quad \propto \quad \sum_{j=N-f(\kappa)}^{N} \pi(j).$$

- Suppose that the great majority of potentially desired content is only minimally popular, *i.e.*, $\pi(j)$ is decreasing.

## Caching cost convex in caching factor (cont)

- We now argue that the caching cost $c(\kappa)$ is convex and increasing for the simplified continuous scenario ignoring the (positive) constants of proportionality:

$$\kappa = \int_{N-f(\kappa)}^{N} z\pi(z)\mathrm{d}z \quad \text{and} \quad c(\kappa) = \int_{N-f(\kappa)}^{N} \pi(z)\mathrm{d}z,$$

with $c(0) = 0$ and $c(1) = 1$.

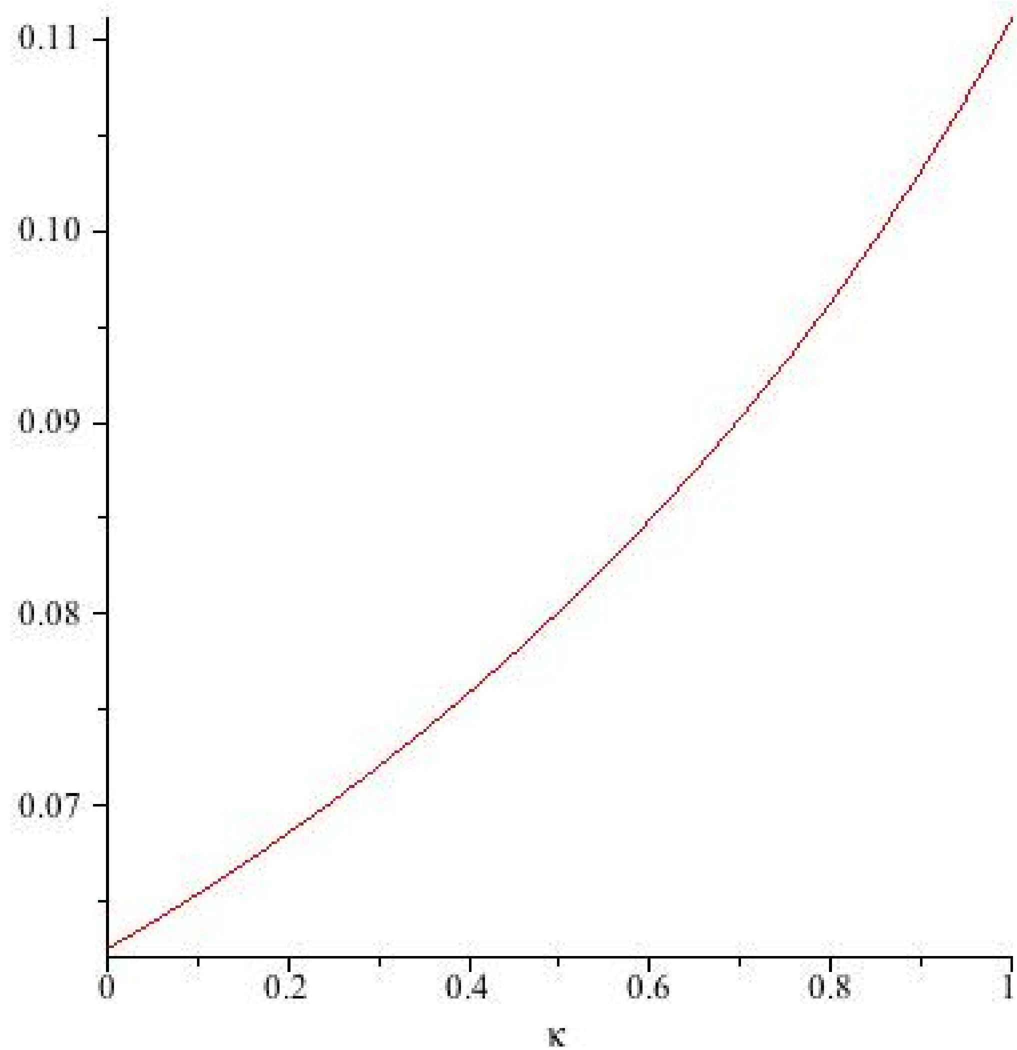
- By differentiating successively, we get

$$\begin{aligned} 1 &= (N - f(\kappa))\pi(N - f(\kappa))f'(\kappa) \\ c'(\kappa) &= \pi(N - f(\kappa))f'(\kappa) \\ \Rightarrow 1 &= (N - f(\kappa))c'(\kappa) \\ \Rightarrow c''(\kappa) &= f'(\kappa)(N - f(\kappa))^{-2} \end{aligned}$$

- Note that $f' > 0$ by first equ. above, and therefore $c'' > 0$ by last equ.

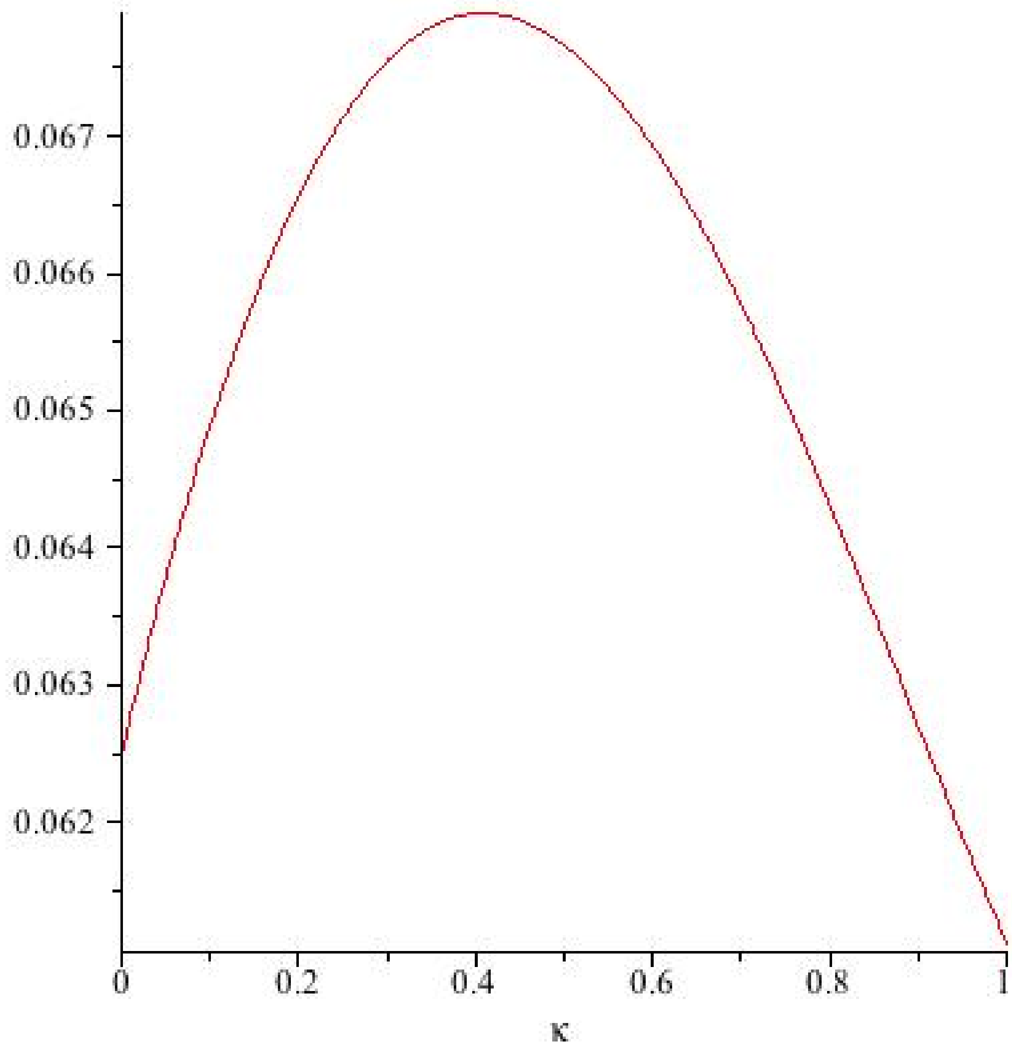
# ISP caching with price-convex demand response: Expt'l results

ISP utility $U_1^*/(D_{\mathsf{max}} p_{\mathsf{max}})$ with: $a = 2$ and no cache cost, $c = 0$. Note how $U_1^*$ increases with caching factor $\kappa$.

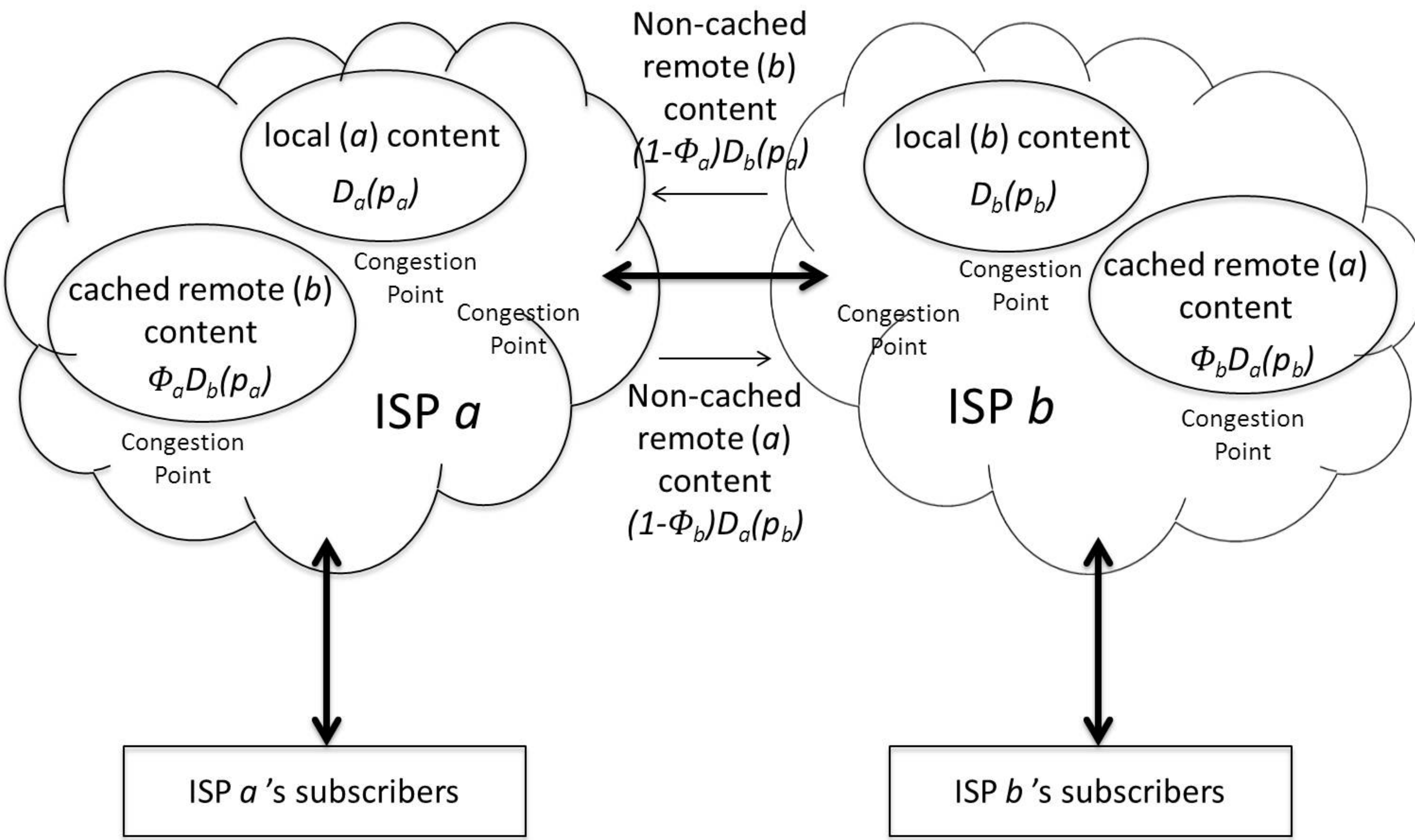


# ISP caching with price-convex demand response: Expt'l results (cont)

ISP utility $U_1^*/(D_{\text{max}} p_{\text{max}})$ with: $a = 2$, quadratic (convex) cache cost, $c(\kappa) = b D_{\text{max}} p_{\text{max}} \kappa^2$ with $b = 0.05$. Note optimal choice here is fractional $\kappa \approx 0.4$.



## Caching remote content by two eyeball ISPs



# Two Eyeball ISPs: Background

- Revenue of an eyeball-ISP: $pD$
- Recall convex, piecewise-linear demand response
  - parameters: $D_\theta < D_{\max}$ and $d_{\max} > d_\theta$
  - $D(p) = \max\{D_{\max} - d_{\max}p,\ \hat{D}_\theta - d_\theta p\}$ where

$$\begin{aligned}\hat{D}_\theta =& D_\theta + (D_{\max} - D_\theta)d_\theta/d_{\max},\\ p_\theta =& (D_{\max} - D_\theta)/d_{\max},\\ p_{\max} =& \hat{D}_\theta/d_\theta = p_\theta + D_\theta/d_\theta\end{aligned}$$

- Convex, differentiable demand model: $D(p) = D_{\max}(1 - p/p_{\max})^\alpha$

## Three different congestion points per ISP, fixed caching factors

- Utilities:

$$
\begin{aligned}
U_a(p_a, p_b) =& D_a(p_a)p_a + \Phi_a D_b(p_a)p_a \\
&+ [(1 - \Phi_a)D_b(p_a) - (1 - \Phi_b)D_a(p_b)]^+ p_t, \\
U_b(p_a, p_b) =& D_b(p_b)p_b + \Phi_b D_a(p_b)p_b \\
&+ [(1 - \Phi_b)D_a(p_b) - (1 - \Phi_a)D_b(p_a)]^+ p_t
\end{aligned}
$$

- $D_k(p) = D_{\max,k}\left(1 - \frac{p}{p_{\max}}\right)^{\alpha}$, where $p_{\max} > 0$ and $\alpha \geq 1$ (recall price-*convex* demand at congestion points)

- Assume the demand ratio $\delta := \frac{D_{\max,b}}{D_{\max,a}} \leq 1$

- Nash equilibrium $(p_a^*, p_b^*)$:

$$
\begin{aligned}
\arg\max_{p_a} U_a(p_a, p_b^*) =& p_a^* \quad \text{and} \\
\arg\max_{p_b} U_b(p_a^*, p_b) =& p_b^*.
\end{aligned}
$$

## Three different congestion points per ISP, fixed caching factors - Nash equilibrium for a special case

- Case condition:

$$(1-\Phi_a)D_b(p_a^*) > (1-\Phi_b)D_a(p_b^*) \quad \text{equivalently,}$$

$$1 < \frac{(1-\Phi_a)\delta}{1-\Phi_b}\left(1+\frac{(1-\Phi_a)\delta p_t}{(1+\Phi_a\delta)p_{\text{max}}}\right)^{\alpha}.$$

- Solution:

$$p_a^* = \frac{p_{\text{max}}}{1+\alpha} - \frac{p_t(1-\Phi_a)\delta\alpha}{(1+\alpha)(1+\Phi_a\delta)},$$
$$p_b^* = \frac{p_{\text{max}}}{1+\alpha}$$

with the condition

$$\frac{p_{\text{max}}}{p_t} > 1+\frac{\alpha(\delta+1)}{1+\delta\Phi_b}$$

on $p_t$ implied by $p_t < p_a^* < p_b^* < p_{\text{max}}$.

- Note that $p_a^*$ is increasing in $\Phi_a$ and how the case condition depends on $\Phi_b$.

## Discussion: ISP caching

- The other cases for the model involving three points of congestion are similarly, easily derived.
- In Kocak *et al.* '13, we also considered:
  - a single-point of congestion model, and
  - competition among ISPs for the same group of end-users.
- One can conclude from the form of the NEPs and numerical experiments how eyeball ISPs with more popular content and less competition (larger $D_{\text{max}}$) can charge higher prices and garner more revenue, *i.e.*, demand is less price sensitive at NEP (obviously, an intuitive result for this case).
- Hopefully, such simple revenue models can be used to assess and compare more complex data caching (or name resolver) spatial deployment strategies trading off bandwidth *and* caching costs.

## Discussion: Advertising revenue

- Some authors have also considered advertising revenue for the content provider, *e.g.*, here simply by adding a term $p_a D$ to the utility $U_2$ of the CP.

- In ICNs will advertising revenue be shared, or even be ISP-centric?

# Discussion: Usage-priced service - security issues

- Again, envision a flat rate monthly fee for best effort service, fee depends on max asymmetric download/upload bandwidth.

- End-users need to securely authorize, *e.g.*, by CAPTCHA, if usage-priced premium CoS on an app-by-app basis.

- Such authorization could be chained in the network to allow status as (authenticated) premium-access applications to be known by CPs.

- Respond to a DDoS attack on a public-domain server by upstream blocking only all best-effort (not thus authorized) packets.

## Discussion: Digital Rights Management (DRM) of CPs

- Copyright holders of content need to be able to securely collect royalties.
- Under the current neutral Internet, ISPs are arguably not liable for copyright violations.
- How will DRM be different in an ICN?

## Concluding remarks

- We considered game theoretic models for simple, generic networking scenarios.
- The performance results in terms of usage-based revenues at Nash equilibrium can be used to compare the economic consequences of the network actors in ICN versus IP.