Linking Interdomain Business Models to the Current Internet Topology

Vítor Jesus, **Rui L. Aguiar**

Instituto de Telecomunicações
Aveiro, Portugal

Peter Steenkiste

Carnegie Mellon University
Pittsburgh, PA, USA

http://www.vitorjesus.com
vjesus@av.it.pt

BoD 2010
Osaka, 23 April 2010

The Internet is built on a model in which Autonomous Systems (AS) peer bilaterally based on pair-wise Service Level Agreements (SLA). This results in a cascaded connectivity model in which routing decisions beyond the next hop are delegated, so an AS has limited control over paths beyond the next hop. While this is a key feature of the Internet, the impact of this cascading model on the structure of the Internet has, to the best of our knowledge, never been analyzed in detail.

Using game theory with realistic rules, we provide an analysis of the cascading model. Although our model does not intend to capture the full economic and technical complexity of the real Internet, we show that it exposes the two main business models of peering used currently: volume-based peering and transit carriers (large hubs with equivalent capacity).

- the Internet is currently 30 000 nodes (at the AS level) – CAIDA
  - stitched together using BGP
  - following a set of offline bilateral agreements
    - domains usually don't care about the 2nd-next hop
      - delegated routing operations

- this cascaded model of connectivity has been key to the Internet since the very beginning
  - easy interdomain routing
  - easy management of commercial agreements
    - only with direct neighbours
  - it is even easy on interdomain routers
    - ignore source address
    - huge simplification of routing policies

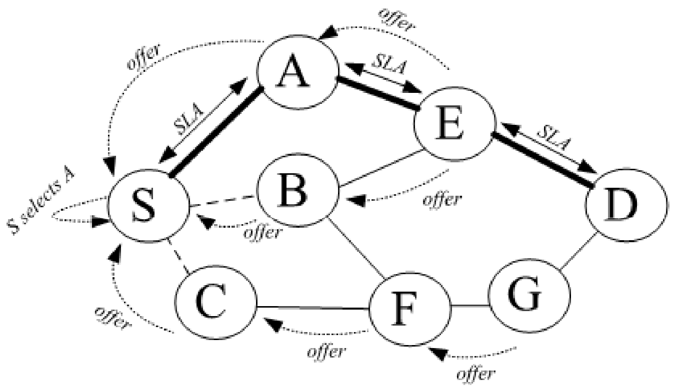


Figure 1: SLA Cascades with reverse price offers. Assume S has three candidate domains (A, B, C) to peer with and will choose the domain that offers the minimum aggregate price for the same QoS and the path $S \rightarrow D$. If we assume that S selects A and A selects E, the final composed SLA for $S \rightarrow D$ will be the cascade of bilateral SLAs between $S \rightarrow A$, $A \rightarrow E$ and $E \rightarrow D$.

- another key property of topology: Valley-free Routing
  - ASes are organized in tiers
    - stubs, regional, tier-1/2/3, …
  - Valley-free Routing puts order on the topology
    - no administrative "valleys" in e2e routing
  - the financial settlements between domains is controlled by
    - the difference in the amount of traffic they exchange
      - a big, inter-continental carrier charges a local ISP for connectivity
    - their relative market strength
      - e.g.: don't ask Google for money…

Current Internet & Problem Statement (2)

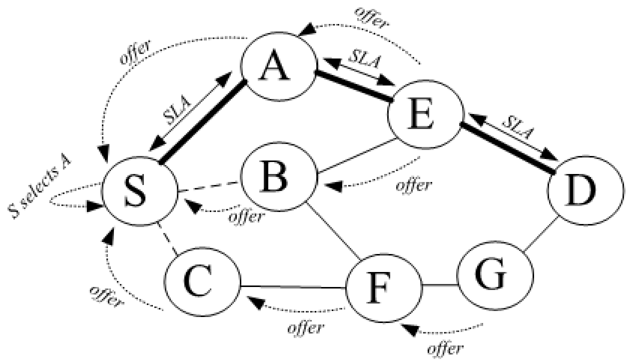
- a key questions has never been directly answered (we argue that it has even never been raised at all)
    - what is the impact of cascading SLAs?

- our work sheds some light over this topics. Using game-theory, we show that there is a link between SLA cascading and
    - Valley-free Routing
    - taxonomy of internet carriers (tiers)
    - the business models of carriers

- Under a realistic network and business model, we show that
    - there are clear ISP types (and three is a very reasonable solution of the interdomain game)
        - end-user ISPs
        - domains aggregated traffic within a (small) geographical area
        - large, wide-coverage hubs

    - two main business models that can be associated with IXPs
        - Volume-based Peering (VbP), no payments involved between same-tier domains
        - Hub-based Peering (HbP), paying a higher-tier a fee for broad connectivity

    - packets *must* follow an e2e path such that a property that we called AVfR is held
        - AVfR: Absolute Valley Free Routing
        - AVfR is a stricter form of VfR: path does not only follow customer/provider relations
            - it *MUST* also follow a particular chain of absolute domain positions, in terms of market power and posicioning
            - **this is our most important result**



- Taking the example of the figure. The Interdomain Game is:
  - S must ask for connectivity to D from A, B or C
    - A, B, C compete
  - A, B and C do the same
    - E and F compete for B
  - and so on until the cascade reaches D

- A, B, C play a game with the following generic characteristics
  - it is, presumably, *non-cooperative*, since domains are competing against each other;
  - players have *incomplete information*, since domains keep their business information such as internal provisioning costs and peering partners secret, although we will assume that some estimative is available (e.g., the Internet topology is, to high degree, easily known);
  - it is a *multi-player game*; and
  - we assume it is *non-repetitive* since S will choose the best peer once and will, for some time (that we deem long), not change its peering decision.

  - this means that we model the interdomain connectivity as a cascade of auctions

- Specific assumptions

A1 (Selection Rule) Each domain selects as the next hop the domain that, from those that provide a similar service, offers the lowest price:

$$p_{i,j+1} = \min_k p_{i,j,k}$$

A2 (Secrecy) All domains keep absolute secrecy on their neighbors, internal costs, who they select as the next hop, prices offered to other domains, etc. However, we will also assume that there are means to estimate internal costs of each competing domain and also to know, to some degree, the neighbors and the topology position of competitors.

A3 (Internal Provisioning Costs) All domains use the uniform distribution for estimating the internal costs of service provisioning of competitors. This means that the internal costs, $c_{i,j,k}$, is a random variable following a uniform distribution: $\tilde{c}_{i,j,k} \sim \text{Uniform}(\mu'_{i,j}, \sigma_{i,j})$, so that $\mu'_{i,j} - \sigma_{i,j} < c_{i,j,k} < \mu'_{i,j} + \sigma_{i,j}$ (Figure 3). Note that we only assume common statistics for the same hop. They can be different between hops.

A4 (Economical Rationale) Domains are supposed to be managed rationally, selfishly and always aiming at maximizing its monetary profit. At a given hop (i, j) all competing domains always make an offer and it must always be higher than its internal provisioning costs:

$$p_{i,j} \geq c_{i,j} + p_{i,j+1}. \quad (1)$$

A5 (Price Composition Rule) We assume that all domains use the following rule to determine its price:

$$p_{i,j} = \alpha_{i,j} + \beta_{i,j} c_{i,j} + \gamma_{i,j} p_{i,j+1}, \qquad \alpha_{i,j}, \beta_{i,j}, \gamma_{i,j} \in \Re \quad (2)$$

subject to

$$\frac{\partial \alpha_{i,j}}{\partial c_{i,j}} = \frac{\partial \beta_{i,j}}{\partial c_{i,j}} = \frac{\partial \gamma_{i,j}}{\partial c_{i,j}} = 0 \qquad (3)$$
$$\frac{\partial \alpha_{i,j}}{\partial p_{i,j+1}} = \frac{\partial \beta_{i,j}}{\partial p_{i,j+1}} = \frac{\partial \gamma_{i,j}}{\partial p_{i,j+1}} = 0.$$

A6 (Forward Prices) In a cascaded methodology,

$$\frac{\partial p_{i,j}}{\partial p_{i,j-1}} = 0. \quad (4)$$

A7 (Cooperation) Domains do not cooperate in setting prices. Each price is known only to the requesting domain. However, we assume that the destination domain charges a well known and fixed amount for interconnection which will be denoted by ϕ, $\phi \geq 0$.

A8 (Traffic Indivisibility) We assume that, for a single pair (S, D) and a single direction, traffic is not divisible. This means that there is one and only one forward traffic path active at any moment.

- Optimization Problem

Using equation (2) and defining by extension $A_{i,j,k}$ = "Domain (i, j, k) is on the selected path by S", the payoff function of domain $(i, j, k) \in \mathcal{V}$ is

$$u_{i,j,k} = \begin{cases} p_{i,j,k} - c_{i,j,k} - p_{i,j,k+1} & \text{if } A_{i,j,k} \\ 0 & \text{if } \neg A_{i,j,k} \end{cases} \qquad (5)$$

Condition $A_{i,j,k}$ is true only when domain (i, j, k) is selected as the cheapest by $(i, j-1)$, $(i, j-1)$ is selected as the cheapest by $(i, j-2)$, and so on recursively, until the cascade in the backwards direction reaches S:

$$A_{i,j,k} = \text{"Domain } (i,j,k) \text{ is on the selected path by } S\text{"} = \bigwedge_{q=0}^{j} \bigwedge_{\substack{s=1 \\ s \neq k}}^{N_{i,q}} p_{i,q,k} \leq p_{i,q,s}$$

- then

The optimization problem for this case is

$$p^*_{i,j,k} : \max_{p_{i,j,k}} \{g(i,j,k)\pi(A_{i,j,k})\}$$

where $g(p_{i,j,k}) = p_{i,j,k} - c_{i,j,k} - p_{i,j,k+1}$.

- the optimal price for any domain in the graph competing to provide service is

$$p^*_{i,j} = \frac{1}{N_{i,j}}\mu_{i,j} + \frac{N_{i,j} - 1}{N_{i,j}} c_{i,j} + p_{i,j+1}.$$

  - subject to

$$\gamma_k p_{k+1} = \gamma_s p_{s+1} \qquad \forall k, s \in \mathcal{N}_{i,j}.$$

    that we call the Equilibrium Clause

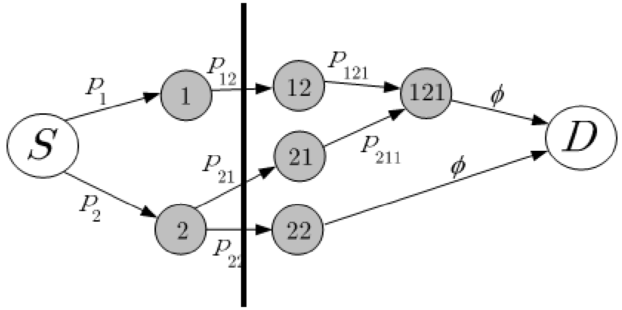
- the solution for the prices is not of particular interest.

- However, *the Equilibrium Clause dramatically shapes the final e2e topology*.

  - it is this condition that brings up a Nash Equilibrium

- the Equilibrium Clause in a nutshell:
  - after the 1st hop, the aggregated price of the remaining paths until the destination must be equal to all competing domains in the first hop.

- example of an unfeasible graph
  - domains 1 and 2 *MUST* "see" the same price ahead
    - for all possible paths ahead

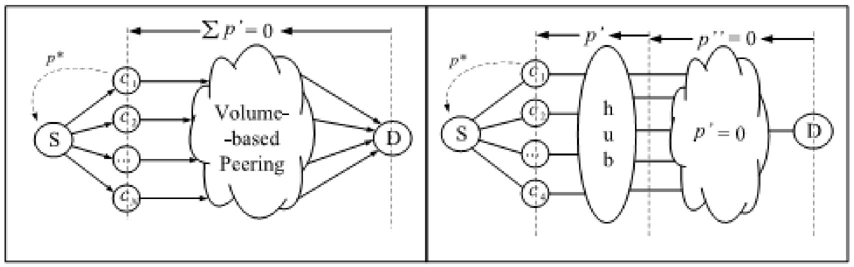


  - this means that it must be
    - p12 + p121 = p21 + p211 + phi
    - p12 + p121 = p22 + phi
    - p22 + phi = p21 + p211 + phi

    →this means that it must be

    p211 = p121 = 0 → which, rationally and economically, doesn't make any sense

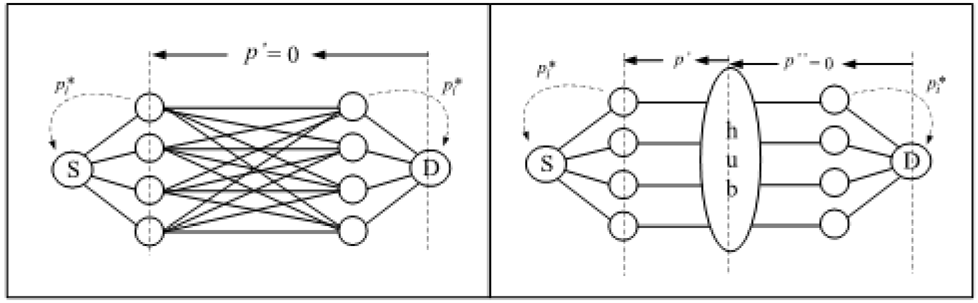
→ not all topologies are feasible



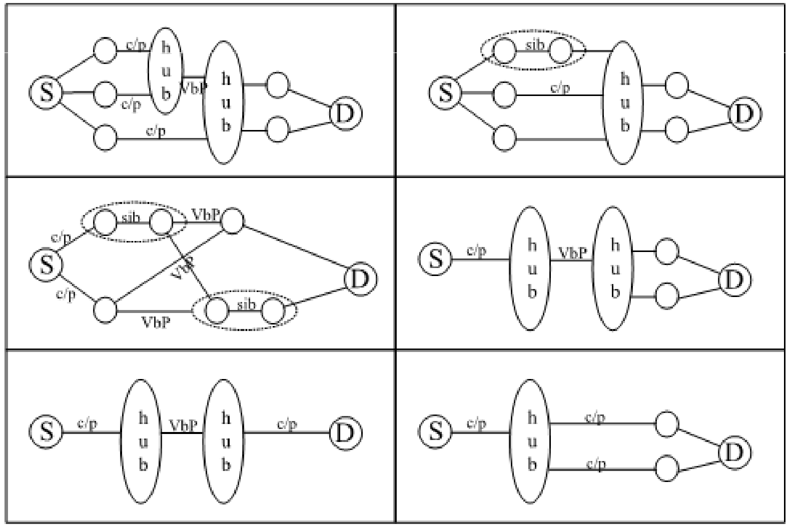
- then, which ones are?
  - we call the topology
    - on the left *Volume-based Peering* (VbP)
    - and on the right *Hub-based Peering* (HbP)

  - both topology families abide by the Equilibrium Clause

- but we have, so farm only considered unidirectional and single S/D pair topologies
  - for the general conditions, the allowed topology families are (*strictly speaking*) the following

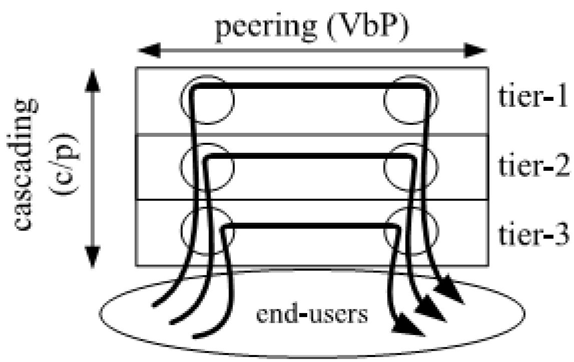


  - if we relax a little bit, we get topology families such as:



which clearly resemble the Internet as we know it

- some further consequences of our solution to the Interdomain Game
  - routes *MUST* follow what we call Absolute Valley-free Routing (AVfR)
  - AVfR is, obviously, very similar to the well-known VfR
    - however, to our very surprise, it's *stricter*
      - besides not having c/p valleys,
      - a route must not have ***rank*** valleys
    - it clearly differentiate between *peering* and *cascading*
    - the *rank* of a domain depends, in essence, on its market power
  - peers will *not* pay each other for traffic; only customers
    - two domains are *peers* if they belong to the same *absolute* rank
    - note the difference between AVfR and VfR.
      - VfR is always relative: a customer of a domain can be the provider of another



Conclusions

- We have made the theoretical exercise of analyzing, from a game-theoretical perspective, the cascading model on which the current Internet is built upon
    - we show that several common-sense results arise
        - which provide a clear link between business models and the Internet topology
    - yet, some not obvious results also arise, although intuitively they make sense
        - AVfR rule is quite remarkable

- Our next steps are two-fold
    - first, experimentally verify that AVfR is actually central in the Internet organization
    - second, discuss and propose new models for the design of e2e SLAs
        - for example, the flat model that we have proposed before (*A Stateless Architectural Approach to Inter-domain QoS*, IEEE ISCC 2008)
            - all domains negotiate directly with all (or a subset of) remote domains
            - how would the Internet look like in this case?
                - which advantages and which disadvantages?
                - how feasible would it be in practice?