On the Diversity, Stability and Symmetry of End-to-End Internet Routes

Yaron Schwartz, Yuval Shavitt, Udi Weinsberg
Tel-Aviv University

Problem Setting

- The Internet is an extremely complex communication network
  - Evolving structure
  - Failures
  - Load balancing
- Directly affects on e2e data flow
  - Diversity – multiple routes between end points
  - Stability – consistency of routes
  - Symmetry – routes in opposite directions

Work Goal

- A measurement study aiming to quantify various aspects of e2e routes
  - Diversity, Stability and Symmetry of e2e routes
  - What has changed since Paxson's work (1995)?
  - Understand the bias in existing work due to VP distribution

Take Home Message

- Internet e2e routes are diverse but stable
- VP types highly affect the results
- Routes are mostly asymmetric but are either both stable or unstable in opposite directions
- Longitudinal analysis shows that diversity and stability are consistent, indicating trade-offs between the Internet growth and changing trends in its connectivity

Related Work

- [Paxson] was the first to study the stability of e2e flows
  - Conducted active probes from 37 VPs, mostly academic, back in 1994 and 1995
  - Found a relatively stable Internet.
- [He *et al.*] and studied asymmetry
  - Low levels of routing asymmetry in AS level
  - Few end-points are “to blame”
- [Rexford *et al.*] studied stability of popular prefixes
  - Popular prefixes have outstanding stability

Key Differences

- Leverage a broad and diverse set of VPs
  - Over 100 VPs in various AS types
- Attempt to discover all possible paths
  - Inducing per-packet and per-flow load-balancing
  - Use both ICMP and UDP probing
- Use fix time intervals in two experiments

Key Concept

- Repeat active measurements between source and destination hosts
- Resolving IP-level paths to higher levels of granularity (prefix, AS, City and Country)
- Quantify the diversity, stability and symmetry of routes as observed from measured paths

How do we measure?

- Use DIMES for conducting two experiments
  - 2006 and 2009
  - Over 100 agents measures to each other
  - Broad set of ASes and geo locations
  - Active traceroute (ICMP and UDP)
  - Each agent probes each IP address twice every two hours
  - 4 days of probing
  - Collect the route hops and e2e delay

Vantage Point Statistics (1)

- 2006
  - 113 VPs
  - Million traceroutes
  - 7040 e2e pairs
  - VPs in North America (79), Western Europe (16), Australia (10), Russia (6), Israel (2)
- 2009
  - 107 VPs
  - Million traceroutes
  - 10408 e2e pairs
  - VPs in Western Europe (49), North America (35), Israel (9), Russia (5), Australia (3), South America (3), Asia (3)

Vantage Point Statistics (2)

- 2006
  - 16% tier-1
  - 80% tier-2
  - 1% educational
  - 3% small companies
- 2009
  - 7% tier-1
  - 69% tier-2
  - 21% educational
  - 3% small companies

Only 15 agents participated both

Filtering and Processing

- Removed traceroutes
  - Only non-routable IP addresses
  - Traceroutes with repeating IP addresses
  - Traceroutes with loops (IP and AS level)
  - 400k traceroutes in 2006 and 800k in 2009 remain
- Resolution to higher level
  - Prefix and AS-level using RouteViews and WhoIS
  - Geographic resolution using MaxMind

Some Accounting

- The e2e pair $P_i=(S,D)$ contains all the routes that were measured between *S* and *D*
- For pair P_i, each route *j* was seen in $|E^i_j|$ different paths
- For pair P_i, the dominant route E^i_r is the route that was seen the most times
  - There can be several dominant routes with equal prevalence
  - For brevity we assume there is one at index *r*

What do we measure?

- Stability of e2e routes
  - Prevalence is the overall appearance ratio of a route *j* of pair P_i

$$Prevalence_j^i = |E_j^i| \Big/ \sum_{j=1}^{k_i} |E_j^i|$$

  - As a stability measure, we use the prevalence of the dominant route *r*

What do we measure?

- Stability of e2e routes
  - Use Edit Distance (ED) as a measure for difference between two routes
    - Counting insert, delete and substitute operations
  - Normalize ED by the maximal route length
    - Can compare between ED of routes with different length
    - $\widehat{ED}^{i}_{jr}$ marks normalized ED for pair *i* between routes *j* and *r*

What do we measure?

- Stability of e2e routes
  - The stability is the weighted average of ED of all non-dominant routes to the dominant route of nearest length:

$$RouteISM_i = \sum_{j \neq r} \left(|E_j^i| \cdot \widehat{ED}_{jr}^{\,i} \right) / \sum_{j \neq r} |E_j^i|$$

What do we measure?

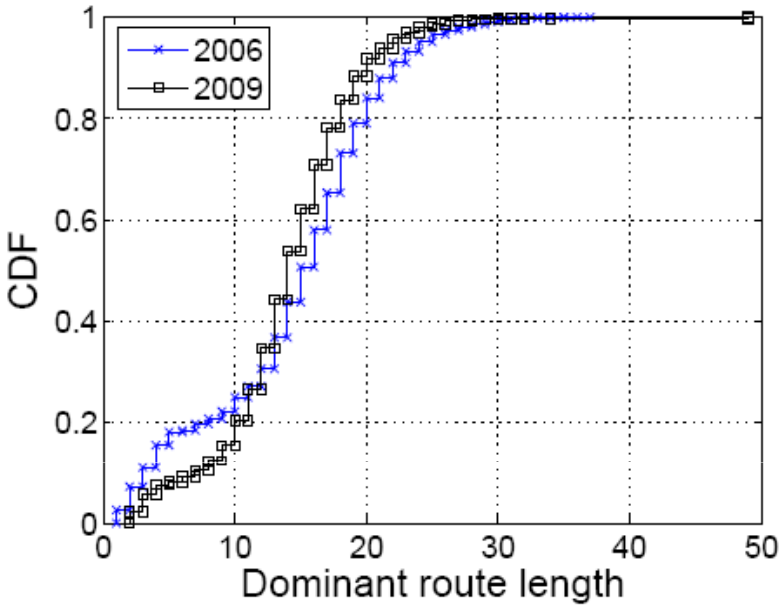
- Symmetry
  - Differential RouteISM is the difference between the RouteISM in opposite directions
  - SymRouteISM is the normalized ED between the dominant route of one direction and the inverted dominant route of the opposite direction

$$SymRouteISM_i = \widehat{ED}(R(E_r^i), \overleftarrow{R}(E_r^j))$$

Things to Note

- Using UDP and ICMP
  - Capture all possible routes, not flows
  - Upper bound for instability

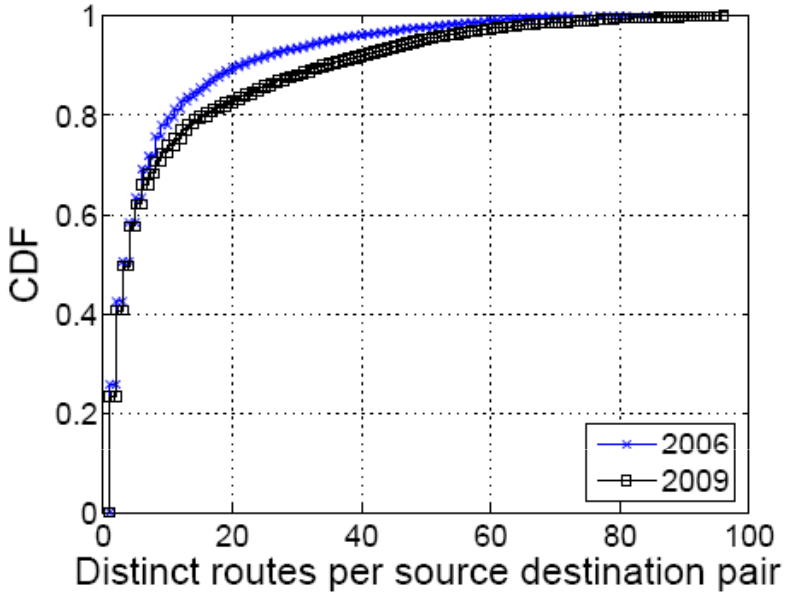
Results – Route Statistics



(a) Dominant route length

- 2006 and 2009 have roughly the same route length, similar to those found by Paxson's
- Probably a tradeoff between the increase in topology size with richer connectivity and layer-2 tunnels

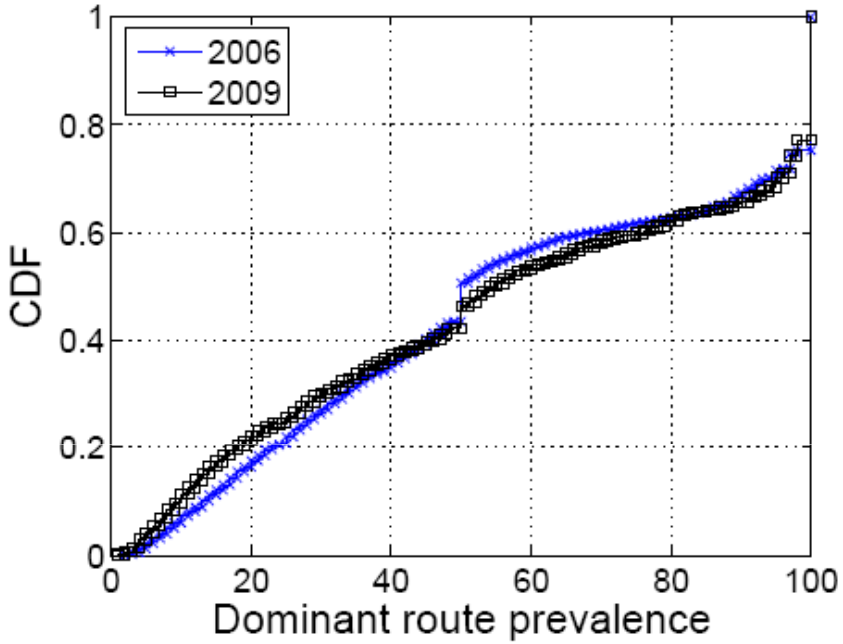
Results – Route Diversity



(b) Distinct routes per pair

- Roughly 25% of the pairs in both years have exactly one route
- Roughly 30% of the pairs witnessed more than 10 different routes
- A higher level of stability than reported by [Pucha *et at.*] (using a 20 days study, only 6% had one dominant route)
  - The longer study reduces the chances to see the exact same route

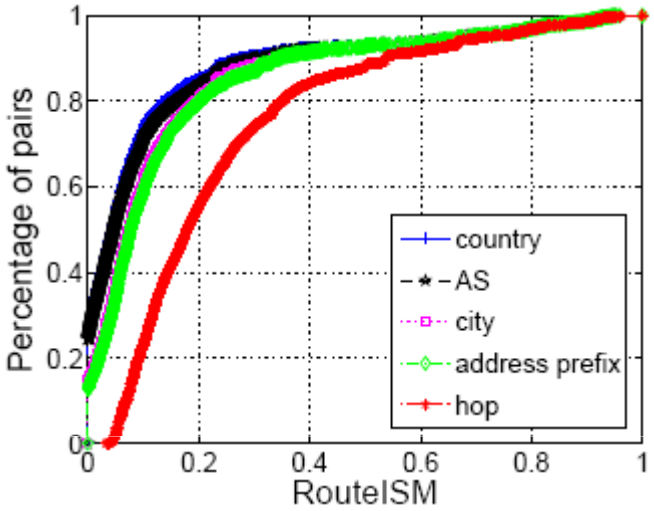
Results – Route Stability



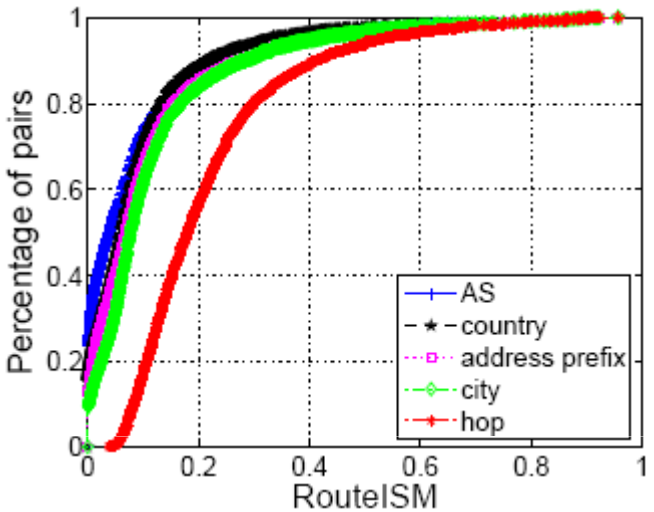
(c) Dominant route prevalence

- 100% prevalence is attributed to single route
- 8% increase in the 50% prevalence is attributed to load-balancing or prolonged flaps

Results – Route Stability



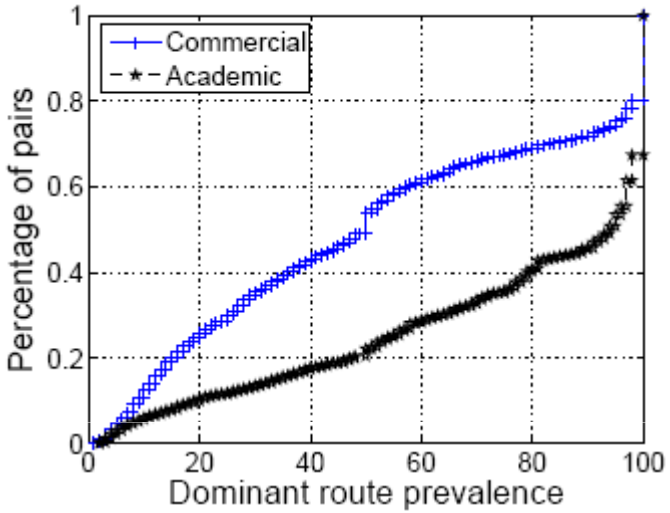
(a) 2006



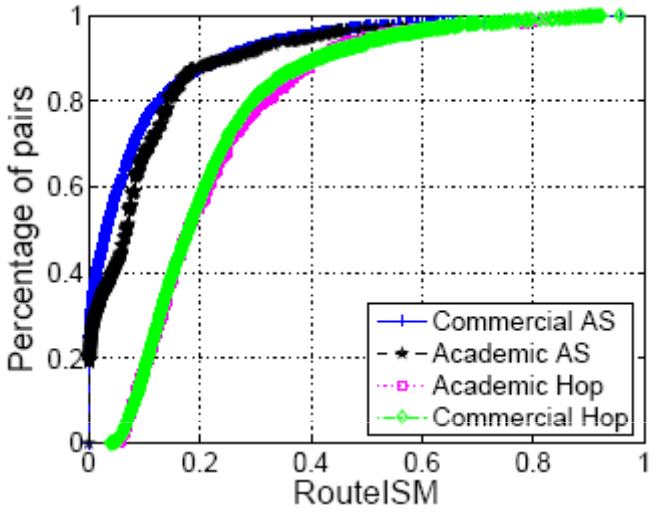
(b) 2009

- IP-level is least stable
- 2009 is more stable for all levels
- Although the Internet is increasing in topology size, the overall stability slightly improves over time
  - Improving knowledge of operators?
  - Easier management of devices?

Results – VP Bias



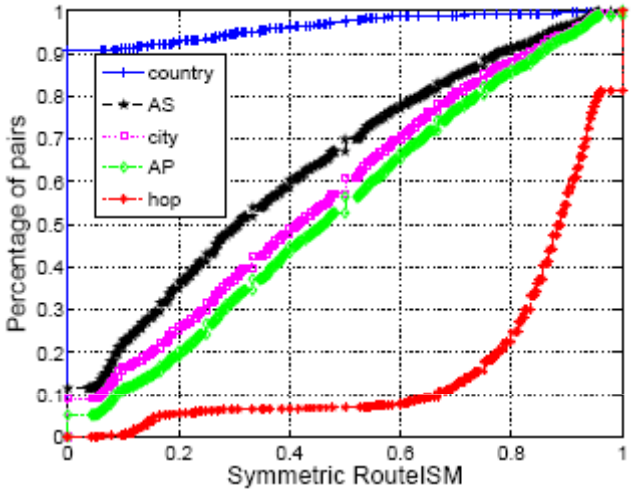
(a) Prevalence



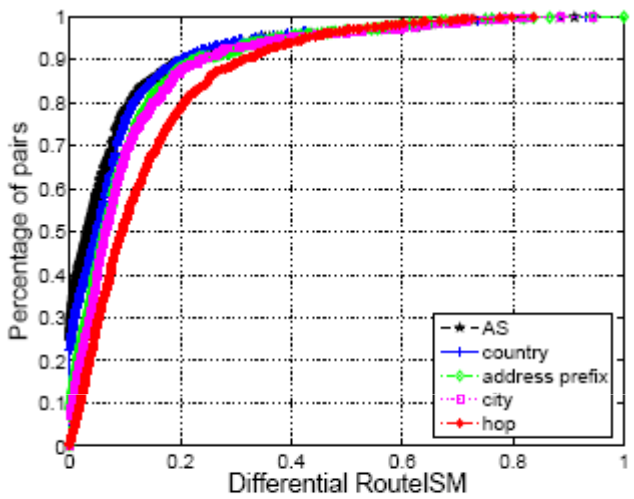
(b) Stability

- Routing in academic networks is much more stable
  - 20% in commercial and 30% in academic have single route
  - Slightly observed using RouteISM of the AS-level
- No usage of load-balancers in academic pairs
- Cross-continent pairs are slightly more stable
  - Since there are not many alternative routes
- Important to have diverse set of VPs

Results – Symmetry



(a) RouteISM symmetry



(b) Differential RouteISM

- IP level is obviously not symmetric
- AS-level routes are more symmetric than city-level routes
  - Indicates the existence of points-of-presence (PoPs) that belong to the same AS but reside in different cities
- Differential stability
  - Approximately 90% of the pairs have differential stability of less than 0.3
  - When instability exists in one direction, it is likely to appear in the opposite direction as well

Conclusions

- A measurement study of e2e routes
- The Internet today is less stable than 1995
  - Still exhibits different behavior depending on network type
- Longitudinal analysis shows that e2e route properties did not significantly change in recent years
- We attribute this to a trade-off
  - Increasing topology size of the Internet and usage of load balancers
  - The adoption of tunneling technologies that result in more stable IP-level routes

Thank You!