Research questions

● What economic incentives affect decisions by network operators to deploy IPv6?
● What factors can best explain the observed levels of IPv6 adoption?
● How do translation/tunneling technologies alter the economic incentives to remain with IPv4 or deploy IPv6?
The economics of network migration

Network externalities and the migration
- Convergence, lock in and inertia
- No one can “secede” from IPv4
- Mutual compatibility is double-edged

The dual stack model
- Does not reduce demand for IPv4 numbers
- Imposes costs of transition on IPv6 deployers

Last mover advantage?
The economics of network migration

Network growth

- IPv4 constrains growth, and rising IPv4 prices make it increasingly expensive
- IPv6 facilitates less constrained growth, but backwards compatibility requires IPv4

Cost of Growth (GC) in IPv6 vs IPv4

- For IPv6 deployers, $GC_6 = \text{Initial Costs (IC)} + \text{Cost of Compatibility (CC)} + \text{Cost of Acquiring IPv6 (v6$)}$
- For non-deployers, $GC_4 = \text{Cost of Extending (CE)} + \text{Cost of Acquiring IPv4 (v4$)}$
Worldwide aggregate IPv6 adoption
Economy-level growth trends

- No appreciable: 169
- Increasing: 26
- Plateauing: 18
- Intermittent: 2
AS-level graphs by country: increasing

United States and New Zealand
AS-level graphs by country: plateauing

Australia and Belgium
AS-level graphs by country: plateau or decrease?

Czech Republic and Ecuador
IPv6 adoption and macrosocial variables

● IPv6 deployment is expensive!
  ○ Variations in per capita GDP explains half (49.9%) of variation in IPv6 capability
  ○ Correlation is statistically strong $p = <.01$

● IPv6 does better in less concentrated markets!
  ○ Higher country-level IPv6 capability rates were correlated with lower levels of concentration in wireless (27%) and broadband (35%) markets
  ○ Negative correlation is statistically strong $p = <.01$
Market for IPv4 numbers: prices

Figure 8: Hilco Streambank IPv4 address block transfers
Market for IPv4 numbers: number of transactions

Figure 9: Number of IPv4 address block transfers, by recipient RIR
Market for IPv4 numbers: number of IP’s transferred

Figure 10: Total IPv4 address numbers transferred, by recipient RIR
## Market for IPv4 numbers: CSPs as buyers

### Table 4.1: Top 10 Recipient Organizations in ARIN region of Transferred Addresses

<table>
<thead>
<tr>
<th>Recipient Org</th>
<th>Number of Transfers</th>
<th>Number of Addresses</th>
<th>% of Total Addresses Transferred</th>
<th>Operator Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon Technologies Inc.</td>
<td>30</td>
<td>61,275,974</td>
<td>35.91%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Microsoft Corporation</td>
<td>6</td>
<td>30,998,482</td>
<td>18.16%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Charter Communications</td>
<td>33</td>
<td>8,386,444</td>
<td>4.91%</td>
<td>ISP</td>
</tr>
<tr>
<td>Amazon.com, Inc.</td>
<td>21</td>
<td>6,753,160</td>
<td>3.96%</td>
<td>eCommerce</td>
</tr>
<tr>
<td>Google LLC</td>
<td>3</td>
<td>5,243,389</td>
<td>3.07%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Alibaba.com Singapore E-Commerce Private Limited</td>
<td>1</td>
<td>5,242,878</td>
<td>3.07%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Frontier Communications Corporation</td>
<td>1</td>
<td>4,718,581</td>
<td>2.77%</td>
<td>ISP</td>
</tr>
<tr>
<td>Google Inc.</td>
<td>3</td>
<td>4,194,299</td>
<td>2.46%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Alibaba.com LLC</td>
<td>7</td>
<td>3,014,634</td>
<td>1.77%</td>
<td>Cloud</td>
</tr>
<tr>
<td>Reliance Jio Infocomm Pte Ltd</td>
<td>5</td>
<td>2,162,672</td>
<td>1.27%</td>
<td>ISP</td>
</tr>
<tr>
<td>Google Fiber Inc.</td>
<td>1</td>
<td>2,097,151</td>
<td>1.23%</td>
<td>ISP</td>
</tr>
<tr>
<td>Oracle Public Cloud</td>
<td>5</td>
<td>1,441,771</td>
<td>0.84%</td>
<td>Cloud</td>
</tr>
<tr>
<td>VODAFONE AMERICAS INC.</td>
<td>2</td>
<td>1,118,202</td>
<td>0.66%</td>
<td>ISP</td>
</tr>
<tr>
<td>Windstream Communications LLC</td>
<td>1</td>
<td>1,048,575</td>
<td>0.61%</td>
<td>ISP</td>
</tr>
</tbody>
</table>
Modeling IPv4 requirements under dual stack and conversion

Assumptions
● 15 yr timeframe
● Dual stack (separate IPv6, IPv6 networks) vs. conversion (464XLAT approach, 90% IPv6 devices)
● NAT scaling properties (80% active Subscribers during peak traffic, deterministic port sharing w/ 1024 reserved ports, compression ratio = 8)

Variables
● Subscribers
● IPv6 Traffic matrix ratio
● Growth patterns: flat, linear, plateauing, accelerating, S-curve
● Operator types: mobile ISP, enterprise, cloud service provider
Modeling dual stack vs. conversion...

Figure 11: Scenario 1 (mobile ISP, high subscriber growth, low traffic ratio growth)
Modeling dual stack vs. conversion...

Figure 12: Scenario 2 (mobile ISP, different growth patterns)
Modeling dual stack vs. conversion...

Figure 13: Scenario 3 (small, low growth enterprise network)
Modeling dual stack vs. conversion...

Figure 14: Scenario 4 (cloud service provider)
Conclusion: Get Ready for a Mixed World

IPv6 won’t become an orphan
  ● But many network operators don’t need it

Shift in traffic ratio crucial to future demand for IPv4 numbers

Limited network effects, slow growth networks, additional IPv4 resources

Hard to posit scenarios that lead to global convergence on IPv6 within 20 years
  ● What are architectural, economic and political implications of a mixed world?