Competing Network Technologies
The Role of Gateways

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Acknowledgments

- This is joint work with
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  - Kartik Hosanagar (Penn, Wharton)

- and in collaboration with
  - Andrew Odlyzko (U. Minn)
  - Zhi-Li Zhang (U. Minn)

Outline

- Why this work?
  – Problem formulation and motivations
- Model scope and characteristics
- A brief glance at the machinery
- The insight and surprises
  – Key findings and representative examples
- Conclusion and extensions
  – What next?

Background and Motivations

- Deploying new (network) technologies (and architectures) is rife with uncertainty and challenges
  - Presence of an often formidable incumbent (e.g., today's Internet)
  - Dependencies on what others do (externalities)
  - Migration and upgrade issues (infrastructure wide)
- Can we develop models that provide insight into
  - When, why, and how new technologies succeed?
  - What parameters affect the outcome, and how do they interact?
    - Intrinsic technology quality, price, individual user decisions, etc.
  - To what extent do gateways/converters between old an new technologies influence deployment dynamics and eventual equilibria?

P.S.: The models have applicability beyond networks

Problem Formulation

- Two competing and incompatible technologies
  - Different qualities and price
  - Value of technology also depends on number of adopters (externalities)
    - Tech. 1 is the incumbent
    - Tech. 2 enters the market with zero initial penetration
- Users individually (dis)adopt either technology or none ($0 \leq x_1 + x_2 \leq 1$)
  - Decision based on technology ***utility***
- Gateways/converters offer possible inter-operability
  - Allows users of one technology to communicate with users of the other
    - Independently developed by each technology
  - Gateways/converters characteristics/performance
    - Duplex vs. simplex (independent in each direction or coupled)
    - Asymmetric vs. symmetric (performance/functionality wise)
    - Constrained vs. unconstrained (performance/functionality wise)

Utility Function

Technology 1: $U_1(\theta, x_1, x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

Technology 2: $U_2(\theta, x_1, x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- A closer look at the parameters
  - Cost (recurrent) of each technology (p_i)
  - Externalities: linear in the number of adopters – Metcalfe's law
    - Normalized to 1 for tech. 1
    - Scaled by β for tech. 2 (possibly different from tech. 1)
    - α_i, $0 \leq \alpha_i \leq 1$, $i = 1,2$, captures gateways' performance
  - Intrinsic technology quality (q_i)
    - Tech. 2 better than tech. 1 ($q_2 > q_1$) but no constraint on magnitude, i.e., stronger or weaker than externalities (can have $q_2 > q_1 \approx 0$)
  - User sensitivity to technology quality (θ)
    - Private information for each user, but known distribution

User Decisions

- Decision thresholds associated with *indifference points* for each technology choice: $\theta_1^0(\underline{x}),\ \theta_2^0(\underline{x}),\ \theta_2^1(\underline{x})$
  - $U_1(\theta, \underline{x}) > 0$ if $\theta \geq \theta_1^0(\underline{x})$ - Tech. 1 becomes attractive
  - $U_2(\theta, \underline{x}) > 0$ if $\theta \geq \theta_2^0(\underline{x})$ - Tech. 2 becomes attractive
  - $U_2(\theta, \underline{x}) > U_1(\theta, \underline{x})$ if $\theta \geq \theta_2^1(x)$ - Tech. 2 over Tech. 1
- Which technology would a rational user choose?
  - None if $U_1 < 0,\ U_2 < 0$
  - Technology 1 if $U_1 > 0,\ U_1 > U_2$
  - Technology 2 if $U_2 > 0,\ U_1 < U_2$
- Decisions can/will change as $\underline{x}$ evolves

Anchoring the Model

1. IPv4 $\leftrightarrow$ IPv6
   – Duplex, asymmetric, constrained gateways

2. Low def. video conf. $\leftrightarrow$ High def. video conf.
   – Simplex, asymmetric, unconstrained converters

IPv4 (Tech. 1) $\leftrightarrow$ IPv6 (Tech. 2)

IPv4: $U_1(\theta,x_1,x_2) = \theta q_1 + (x_1 + \alpha_1 \beta x_2) - p_1$

IPv6: $U_2(\theta,x_1,x_2) = \theta q_2 + (\beta x_2 + \alpha_2 x_1) - p_2$

- Setting
  - We are (eventually) running out of IPv4 addresses
    - Providers will need to start assigning IPv6 only addresses to new subscribers ($p_{\mathrm{IPv4}}=p_1>p_2=p_{\mathrm{IPv6}}$)
  - IPv4 and IPv6 similar as “technologies” ($q_1 \approx q_2$ and $\beta=1$)
- Mandatory IPv6<->IPv4 gateways for transition to happen
  - Most content is ***not*** yet available on IPv6
    - Little in way of incentives for content providers to do it
  - Duplex, asymmetric, constrained converters
- Users technology choice
  - Function of price and accessible content

Low-def. video $\leftrightarrow$ High-def. video

Low-def: $U_1(\theta,x_1,x_2\ ) = \theta\, q_1+(x_1+\alpha_1\beta\, x_2) - p_1$

High-def: $U_2(\theta,x_1,x_2) = \theta\, q_2+(\beta x_2+\alpha_2 x_1) - p_2$

- Setting
  - Two video-conf service offerings: Low-def & High-def
    - Low-def has lower price ($p_1<p_2$), but lower quality ($q_1<q_2$)
  - Video as an asymmetric technology
    - Encoding is hard, decoding is easy
      - Low-def subscribers could ***display*** high-def signals but not generate them
    - Externality benefits of High-def are higher than those of Low-def ($\beta>1$)
- Converters characteristics
  - High/Low-def user can decode Low/High-def video signal
  - Simplex, asymmetric, unconstrained
- Users technology choice
  - Best price/quality offering
  - Low-def has lower price but can enjoy High-def quality (if others use it…)

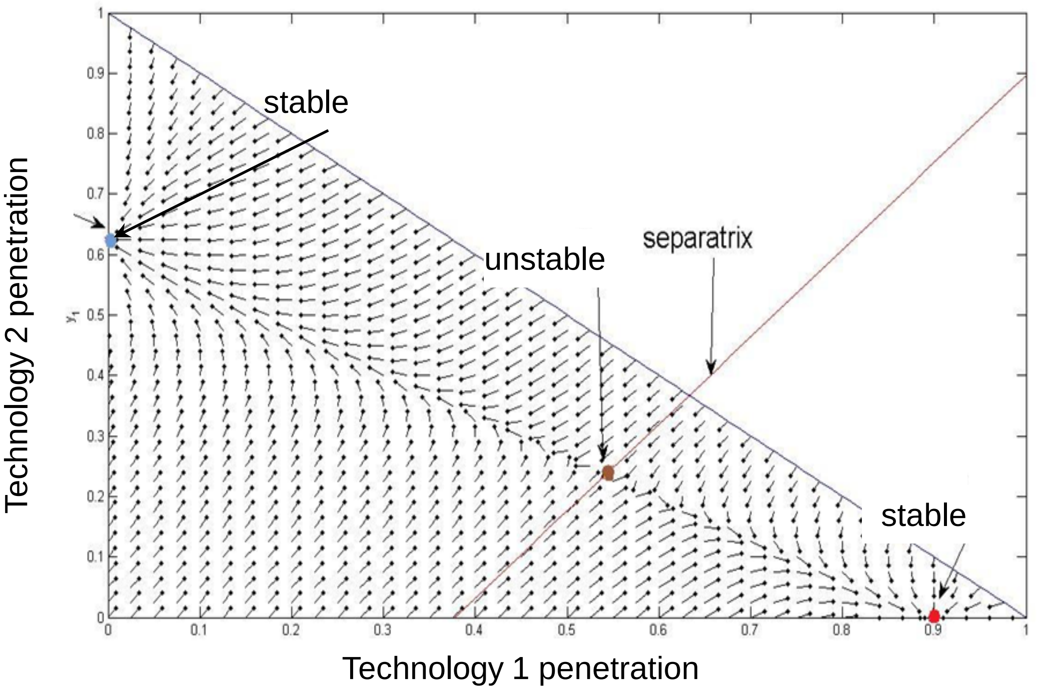
Key Findings – (1)

1. The system can have at most two stable equilibria (among Tech. 1 wins, Tech.2 wins, Tech. 1 and Tech. 2 coexist)
   – Initial penetration determines the outcome
2. Gateways can help either technology
   – Technology 2 can only benefit from better gateways, while they can harm technology 1
3. Better gateways can harm overall penetration

A "Typical" Outcome

- Separatrix passes through unstable equilibrium and demarcates basins of attraction of each stable equilibrium

- Final outcome is hard to predict simply from the evolution of adoption decisions



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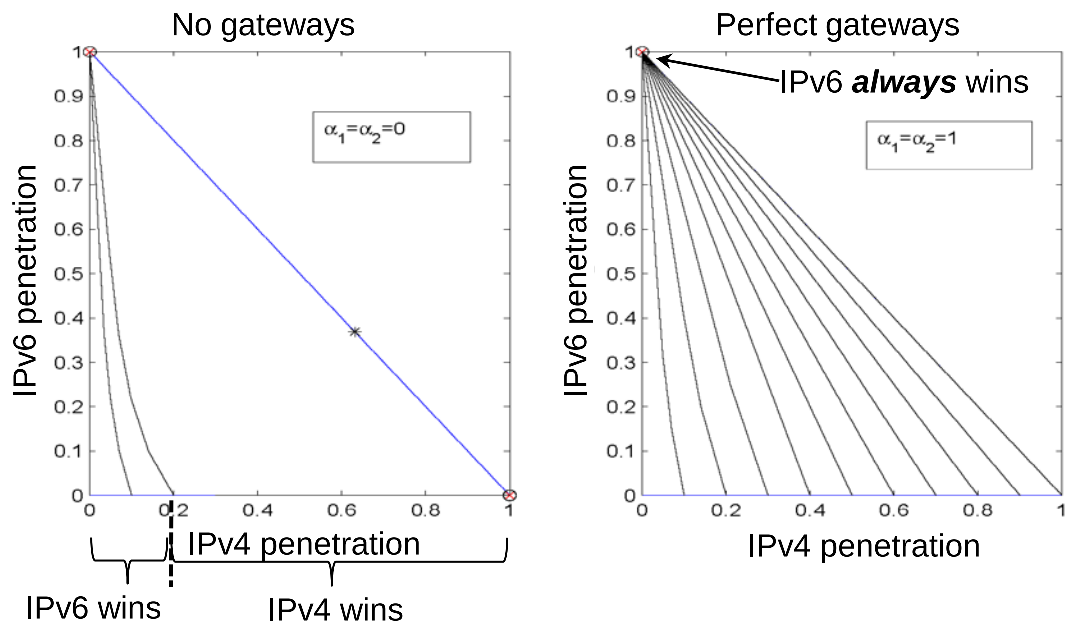
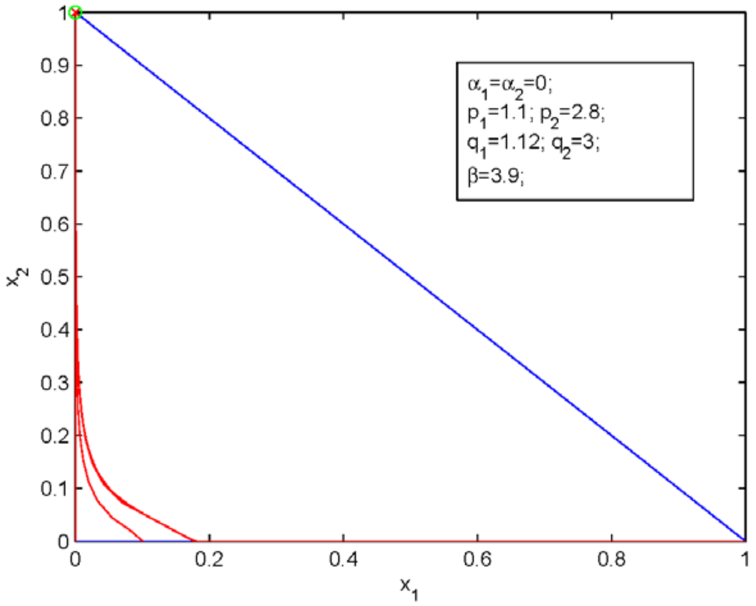
Gateways Help the IPv6 Entrant

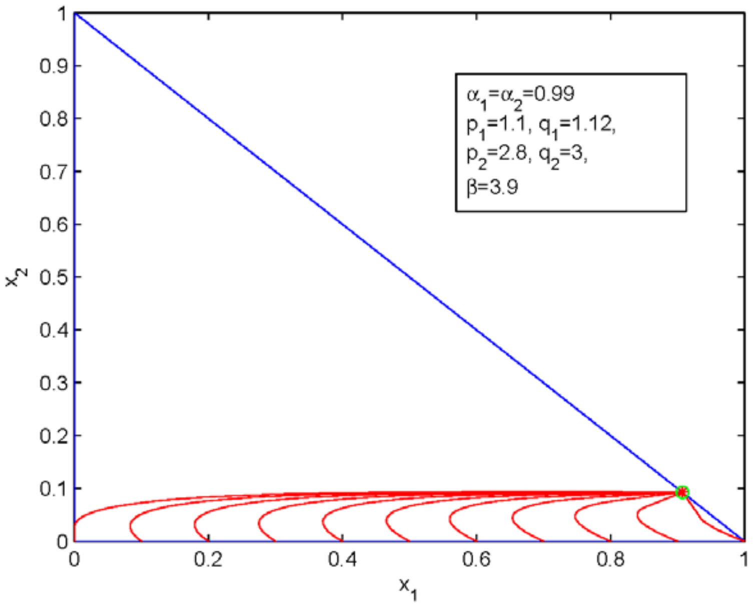
- Assumes IPv6 slightly “better” than IPv4 (same result if the other way around)
- In the absence of gateways, IPv6 never takes off unless IPv4 initial penetration is very low…
- After introducing gateways, IPv6 eventually takes over, irrespective of IPv4 initial penetration
  - There is a “threshold” value (**70%**) for gateway efficiency below which this does not happen!



Gateways Can Also Help the Incumbent

- No gateways: Tech. 2 wipes out Tech. 1
- Perfect gateways: Tech. 1 nearly wipes out Tech. 2 (cannot eliminate it entirely though)





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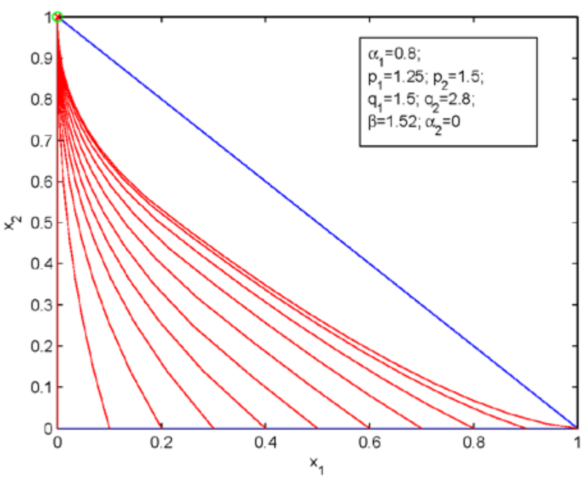
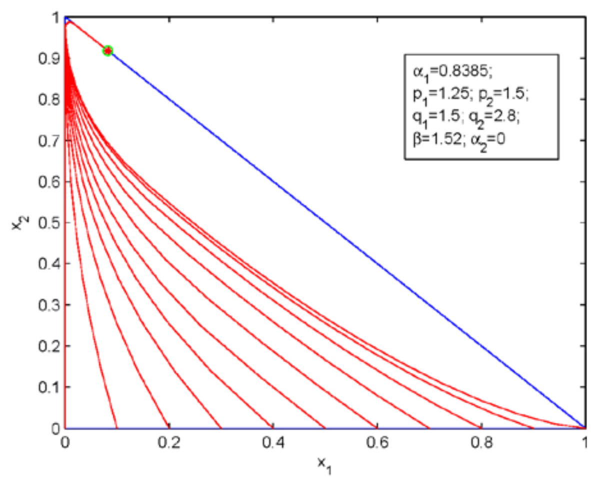
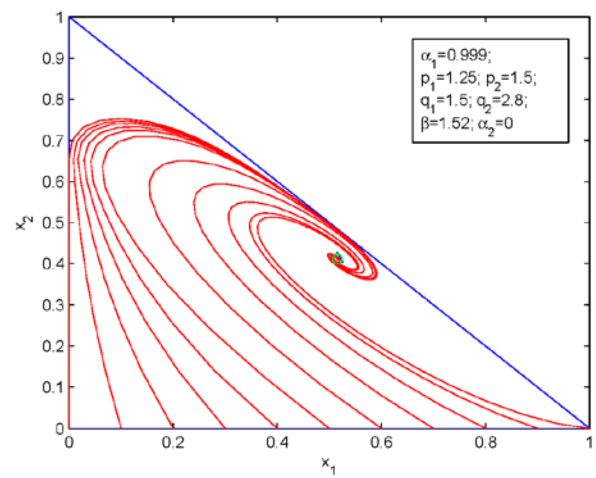
Hurting Overall Market

(Asymmetric Gateways – Tech. 1)

- In the absence of gateways, Tech. 2 takes over the entire market
- Tech. 1 introduces gateways of increasing efficiency
  - Tech. 1 reemerges, but ultimately reduces overall market penetration

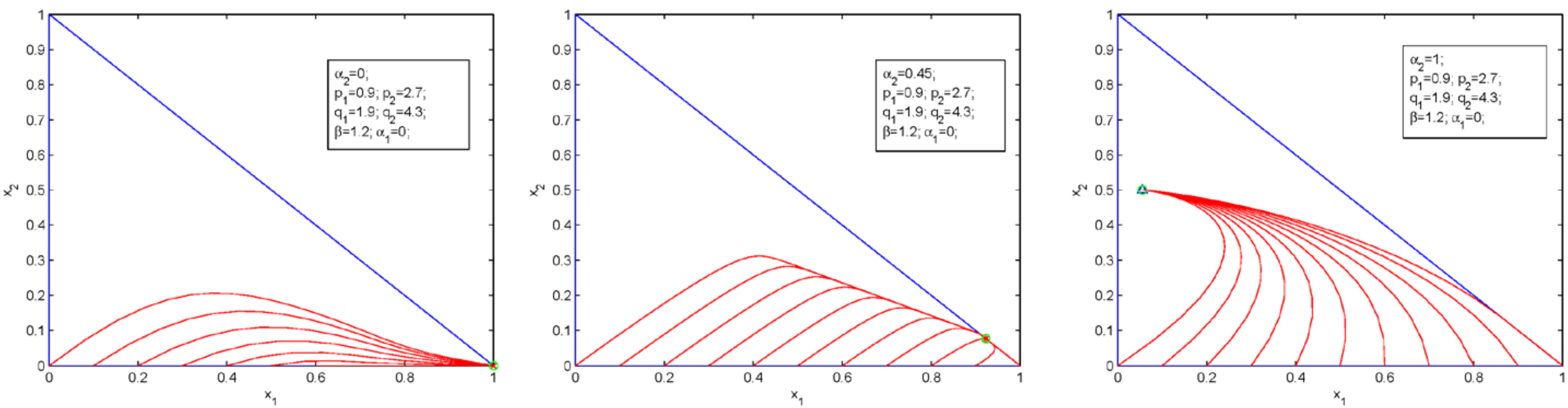






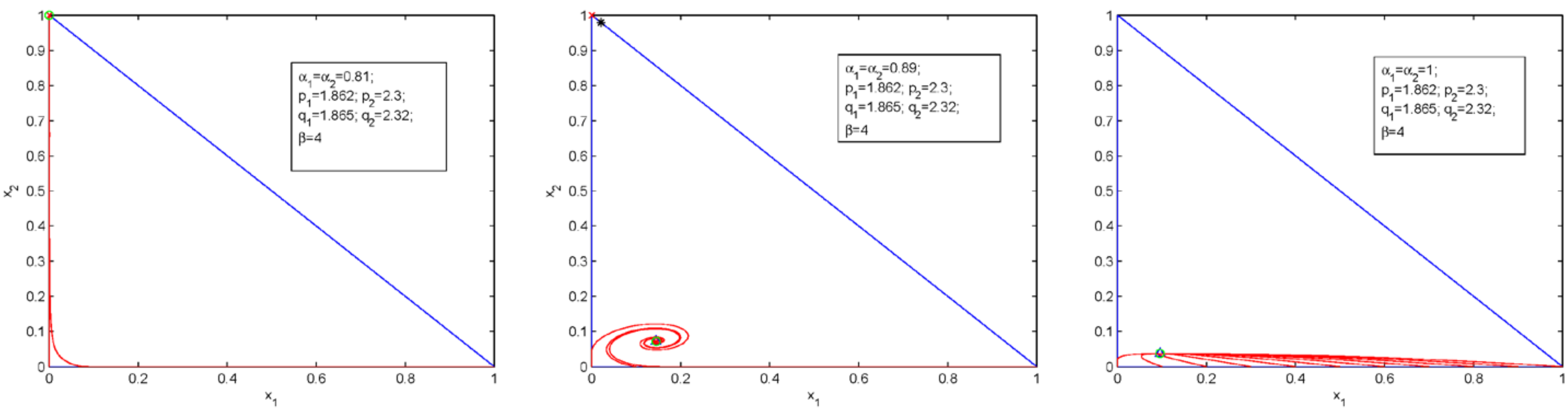
Hurting Overall Market
(Asymmetric Gateways – Tech. 2)

- Tech. 2 fails to gain market share without gateways
- Tech. 2 introduces gateways of increasing efficiency
  - Tech. 2 gains market share, but at the cost of a lower overall market penetration



Hurting Overall Market
(Symmetric Gateways)

- Better gateways take Tech. 2
  - From 100% market penetration
  - To a combined market penetration below 20%!



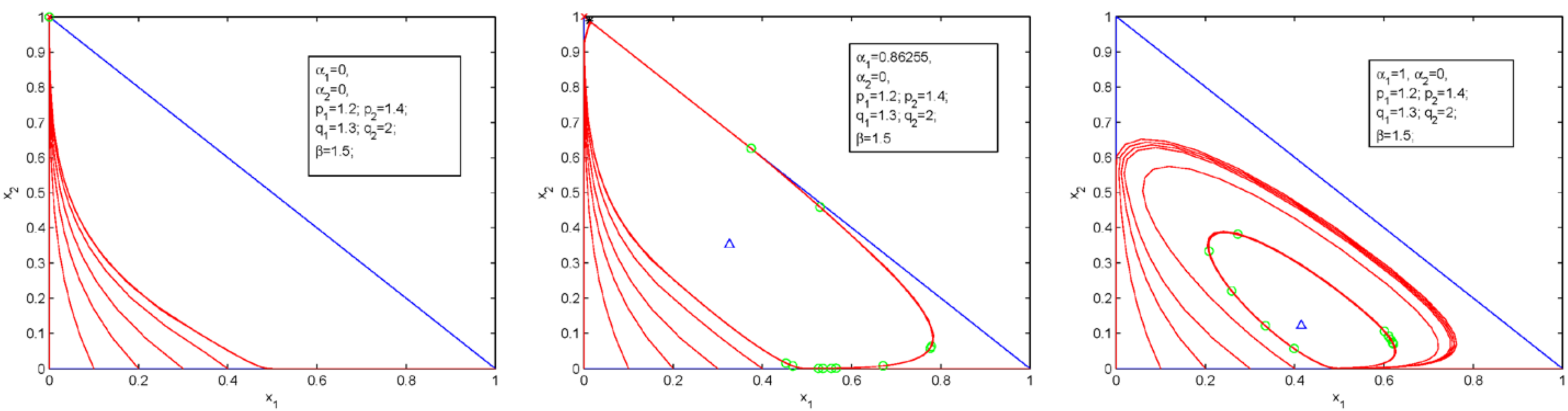
Key Findings – (2)

4. Gateways can prevent convergence of technology adoption (cyclical trajectories)
   - Does ***not*** arise when gateways are absent
   - Occurs in the presence of heterogeneous technologies with $\alpha_1\beta > 1$, *i.e.,* Tech. 1 users can access Tech. 2 externality benefits (the video-conf example)

Asymmetric Gateways

(From Stable to Unstable)

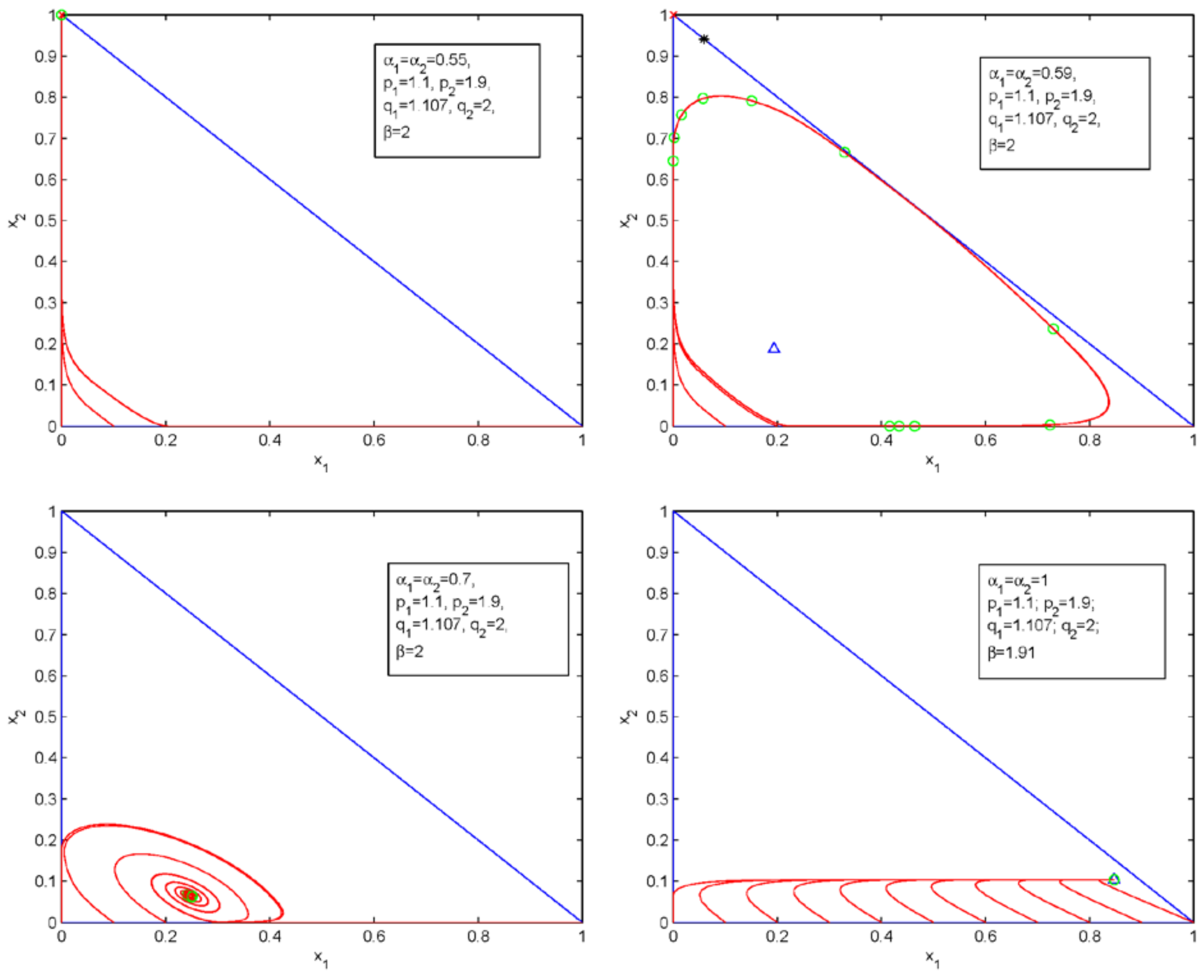
- As the efficiency of Tech. 1 gateway increases, system goes from dominance of Tech. 2 to a system with no stable state
  - No stable equilibrium for α_1=1 and α_2=0



Symmetric Gateways

(From Stable to Unstable to Stable)

- No gateways: Tech. 2 captures full market
- Low efficiency gateways: No stable outcome
- Medium efficiency gateways: Neither tech. makes much inroad
- High efficiency gateways: Tech. 1 dominates at close to full market penetration



Results Robustness

- Most/all results hold for a wide range of model variations
  - No closed-form solutions, but numerical investigations are possible
- Model variations
  - Heterogeneity in user decisions (θ)
    - Non-uniform distributions
      - Positively and negatively skewed Beta-distributions
    - Extended to externality benefits
  - Other externality models
    - Non-linear externalities
      - Sub-linear: x^{α}, $0<\alpha<1$
      - Super-linear: x^{α}, $\alpha>1$
      - Logarithmic: $\log(x+1)$
    - Pure externalities (no intrinsic technology value)

Summary

- Gateways are “good”
  - Facilitate technology coexistence and ease adoption of new technologies
  - Allow improved overall market penetration

- Gateways are “bad”
  - Hurt an individual technology (Tech. 1 only)
  - Lower overall market penetration
  - Introduce instabilities ($\alpha_1\beta>1$)

The good news: Harmful effects are largely absent in most “standard” technology transition scenarios, e.g., IPv4-IPv6 migration

- Natural extensions
  - Switching costs (non-trivial model changes, but results appear to hold)
  - Time-varying parameters (price and quality of technology)
  - Strategic policies (dynamic pricing)