ETH zürich

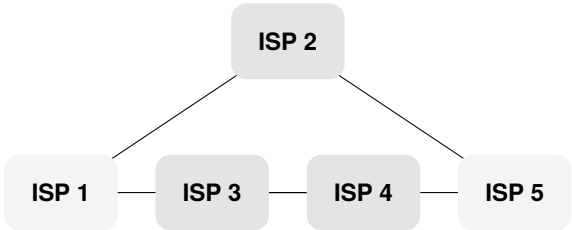
Network Security Group
Department of Computer Science

Quality Competition Among Internet Service Providers

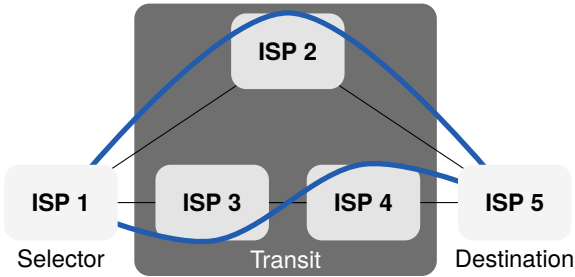
Simon Scherrer, Seyedali Tabaeiaghdaei, Adrian Perrig
Network Security Group, ETH Zürich

PERFORMANCE Conference, Evanston
14–17 November 2023

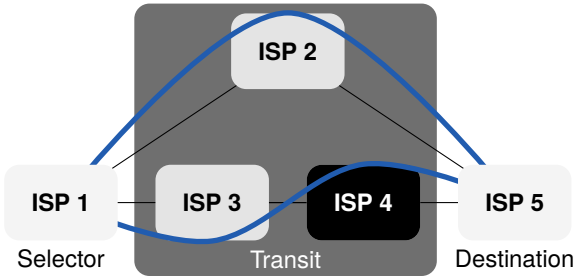
Competing ISPs face a complex optimization problem



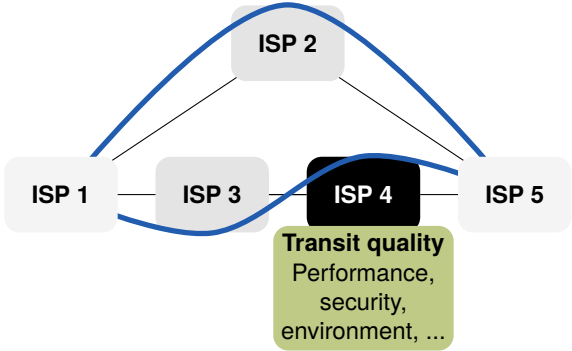
Competing ISPs face a complex optimization problem



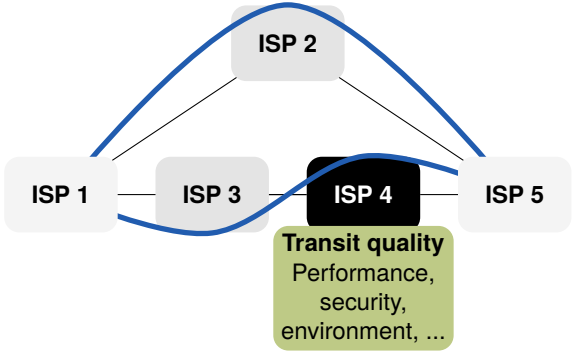
Competing ISPs face a complex optimization problem



Competing ISPs face a complex optimization problem

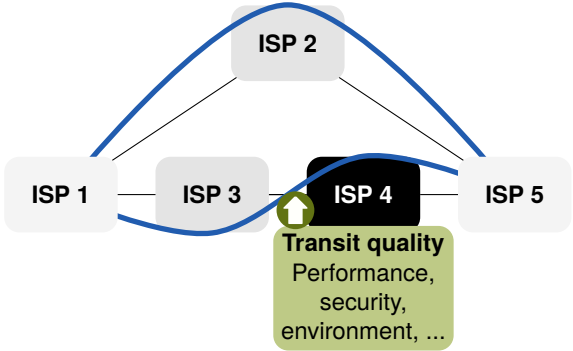


Competing ISPs face a complex optimization problem



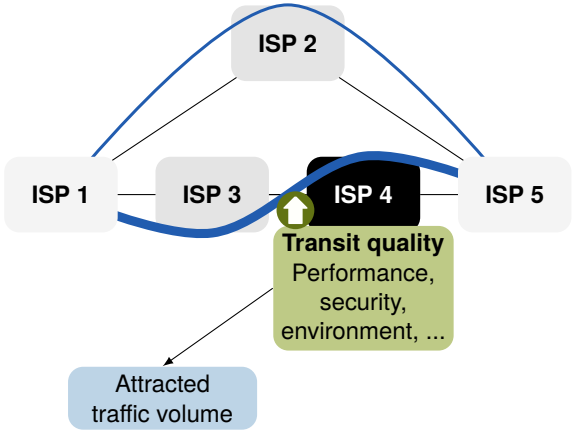
Multiple attributes
define ISP transit quality

Competing ISPs face a complex optimization problem



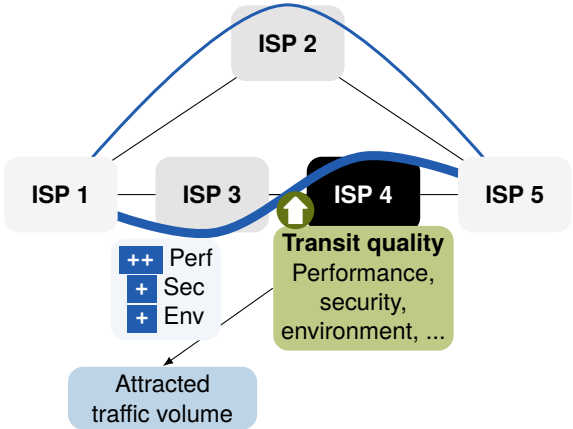
Multiple attributes define ISP transit quality

Competing ISPs face a complex optimization problem



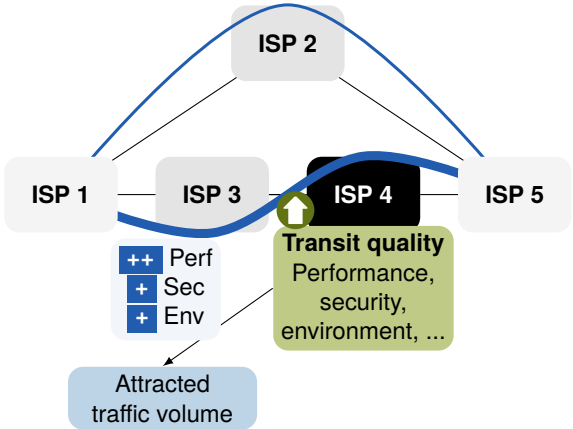
Multiple attributes define ISP transit quality

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

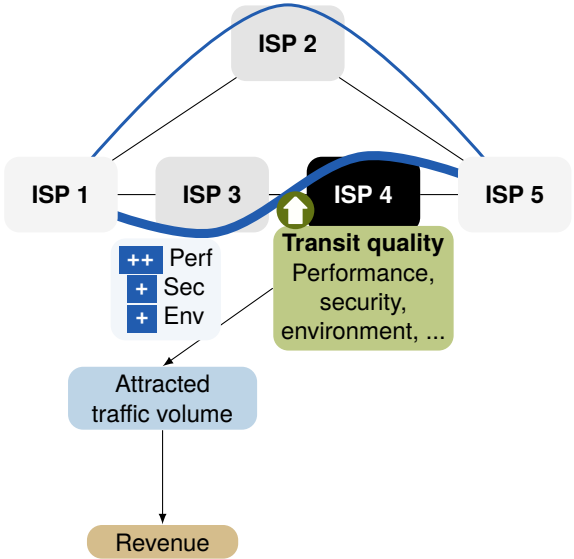
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

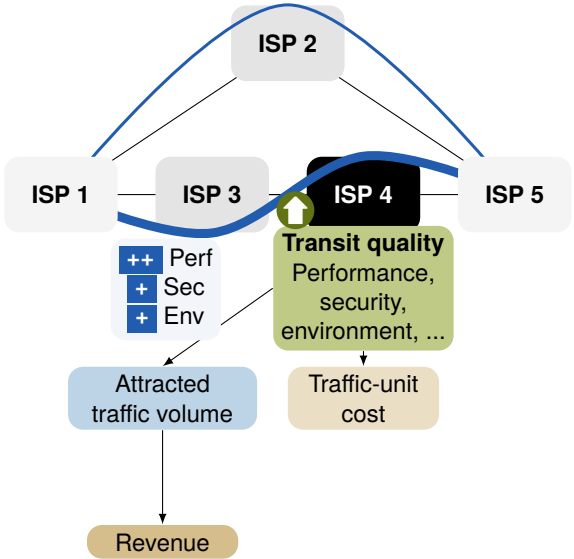
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

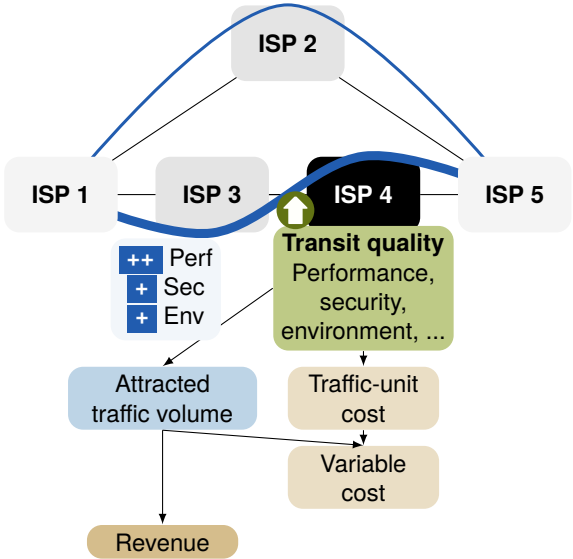
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

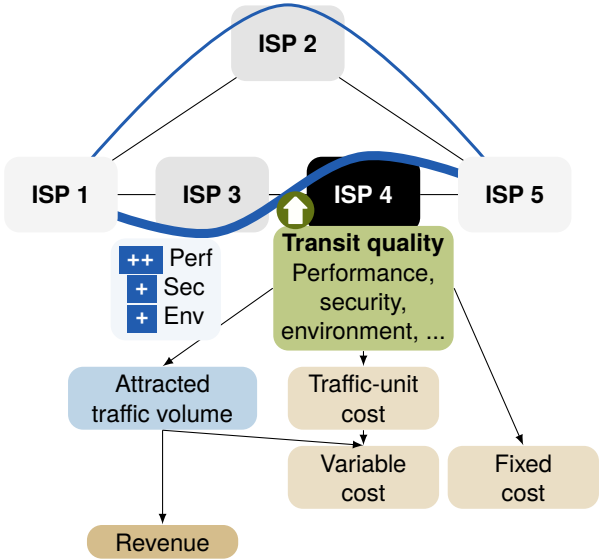
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

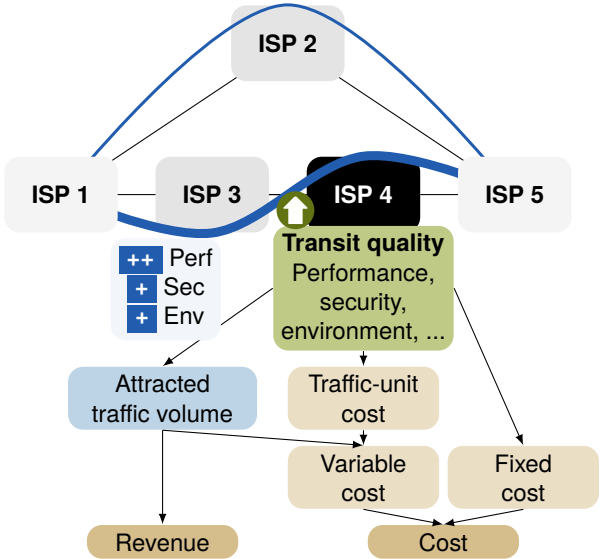
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

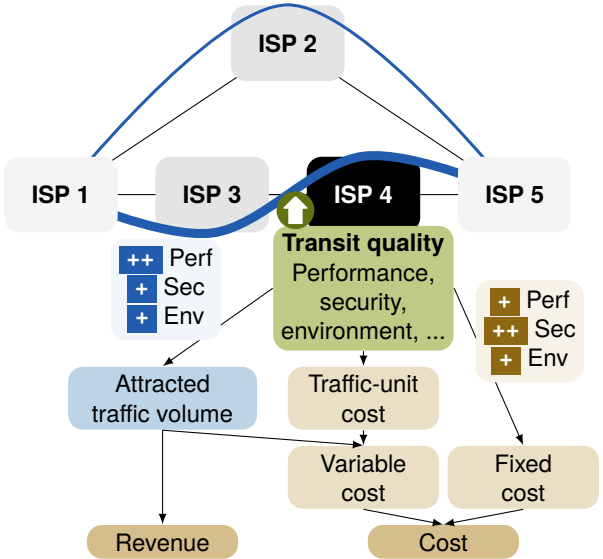
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

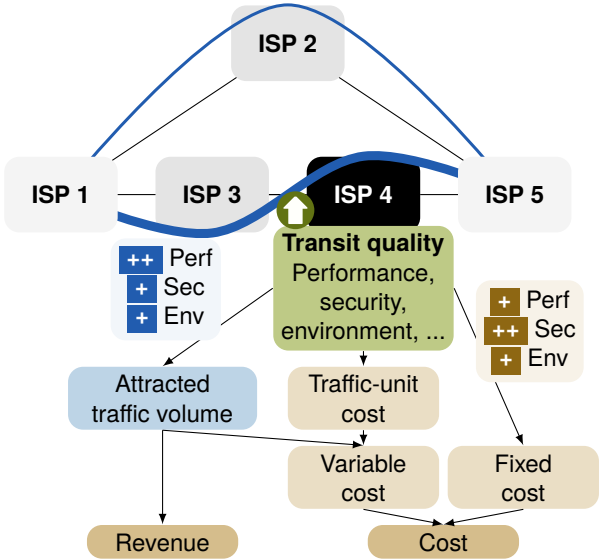
Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Competing ISPs face a complex optimization problem

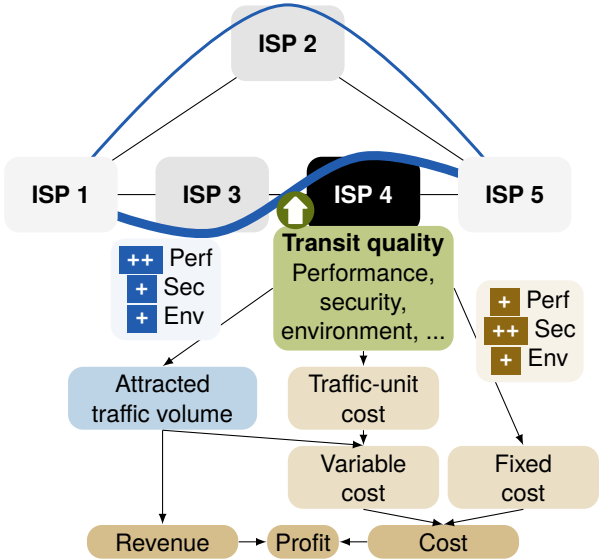


Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

Competing ISPs face a complex optimization problem

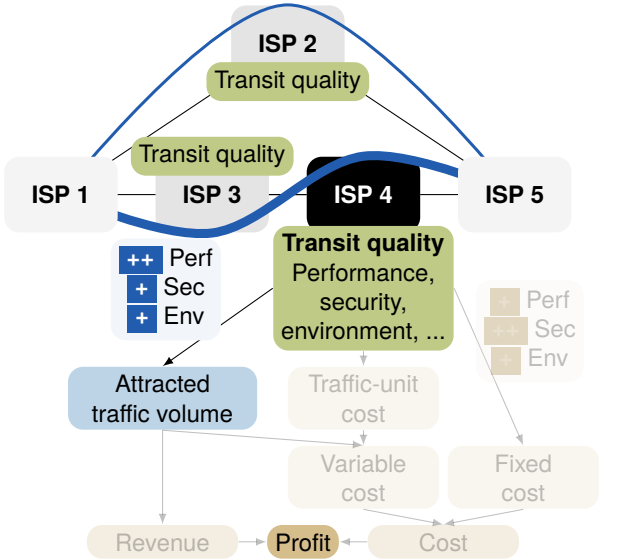


Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

Competing ISPs face a complex optimization problem

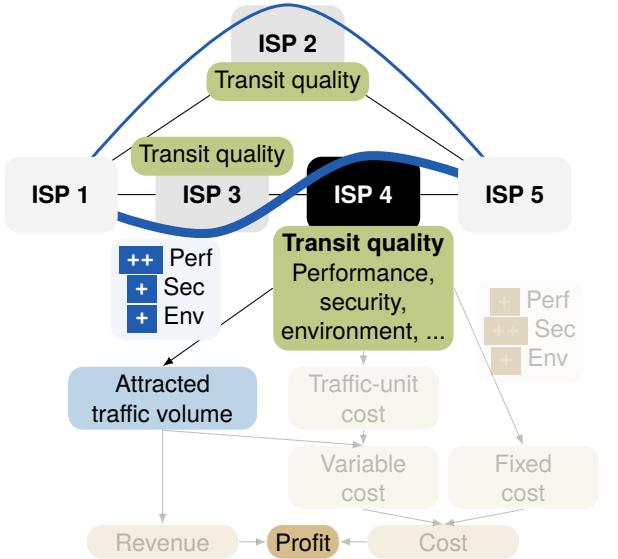


Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

Competing ISPs face a complex optimization problem



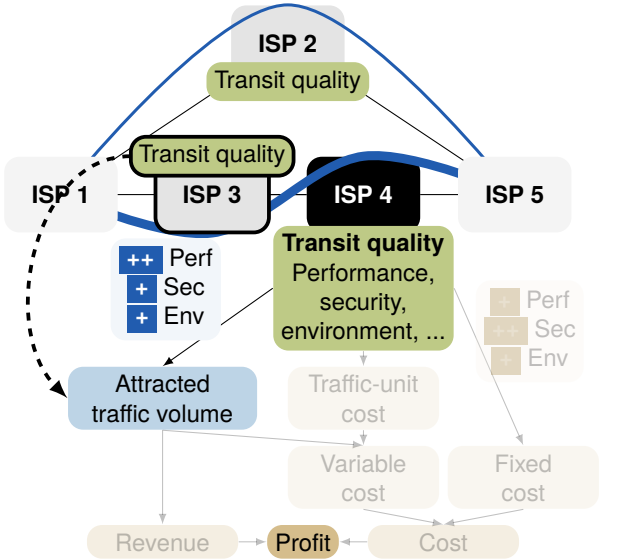
Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

Multiple other ISPs affect profit

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

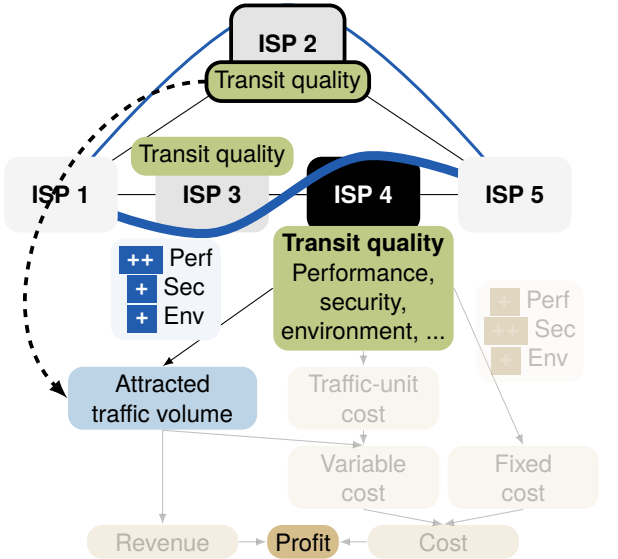
Attributes with different attractiveness

Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

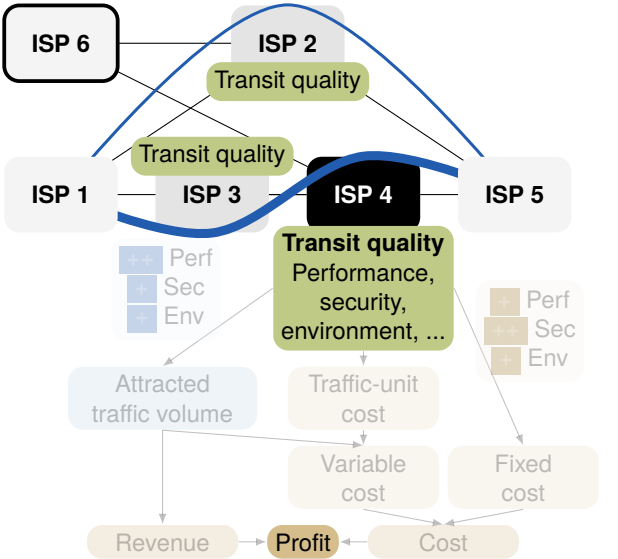
Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

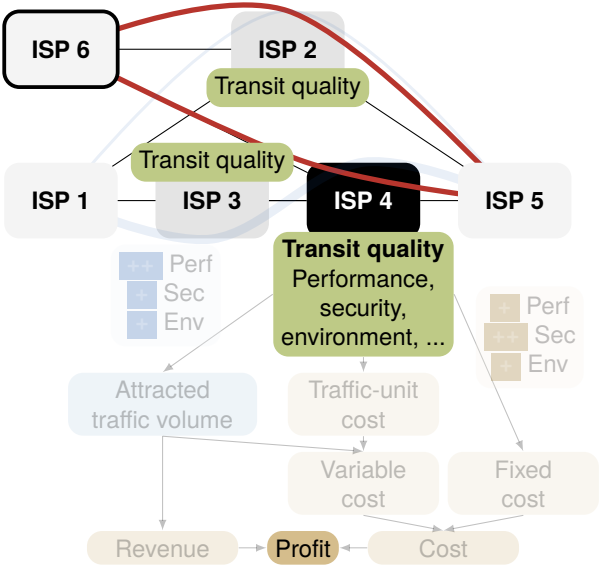
Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

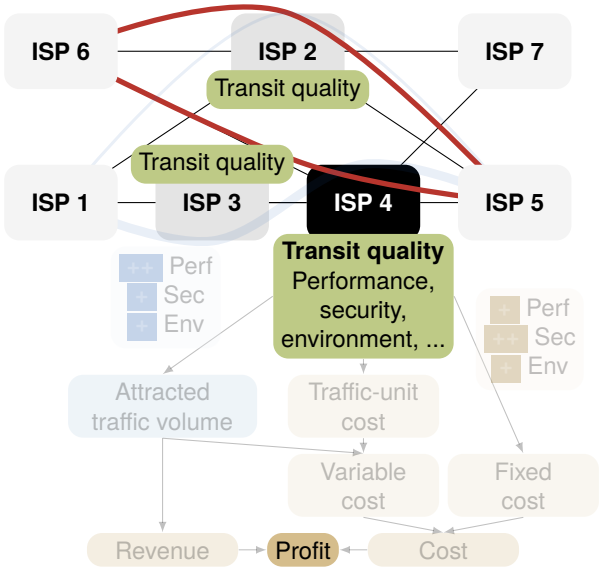
Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

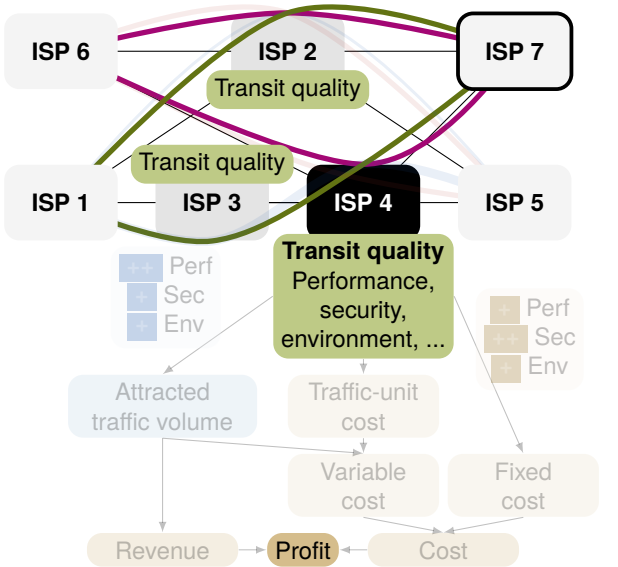
Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

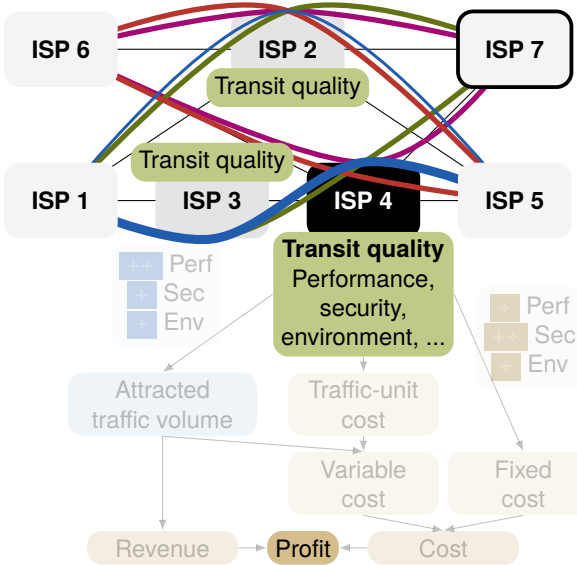
Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

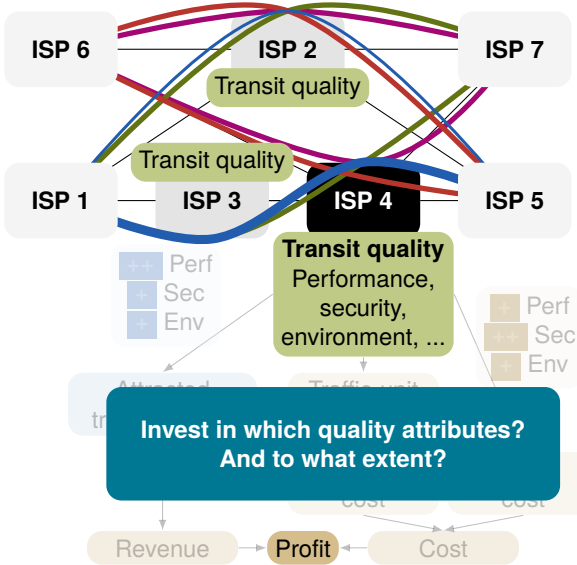
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

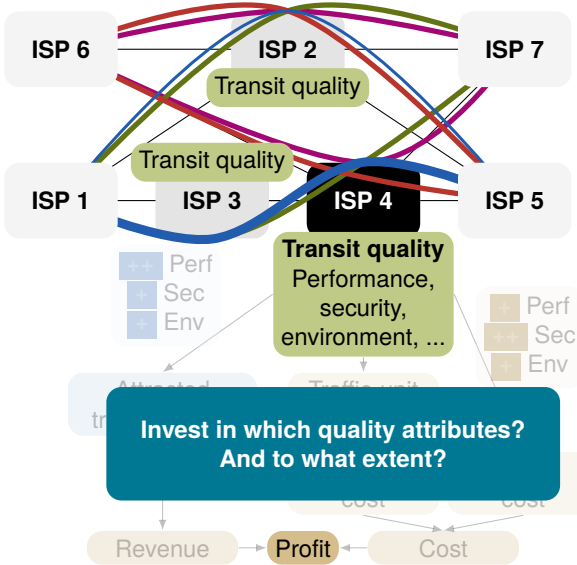
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

Competing ISPs face a complex optimization problem



Multiple attributes define ISP transit quality ?

Attributes with different attractiveness ?

Attributes with different costs ?

Multiple other ISPs affect profit

ISPs on shared paths ?

ISPs on competing paths

Multiple markets shape ISP interaction ?

Our contribution: A model-based analysis of ISP quality competition

Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation

Our contribution: A model-based analysis of ISP quality competition

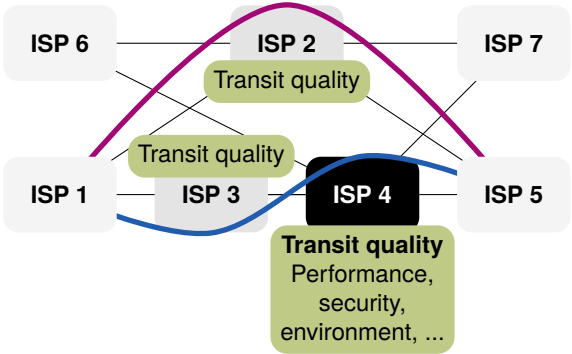
Model of multi-attribute quality competition

Game-theoretic analysis

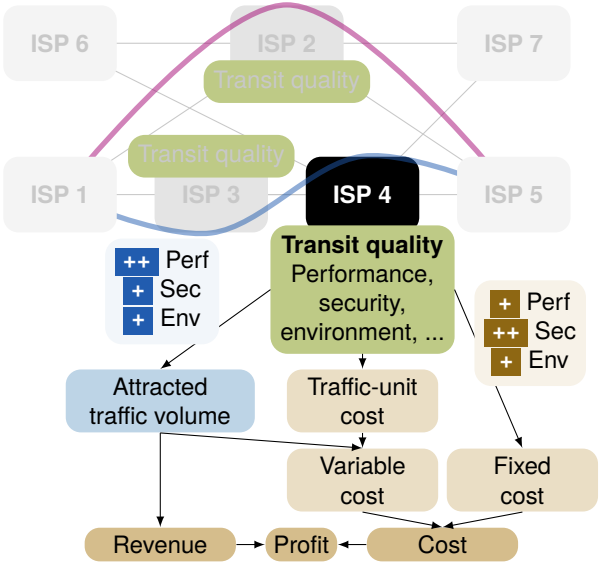
Large-scale simulation

How to mathematically describe ISP quality competition?

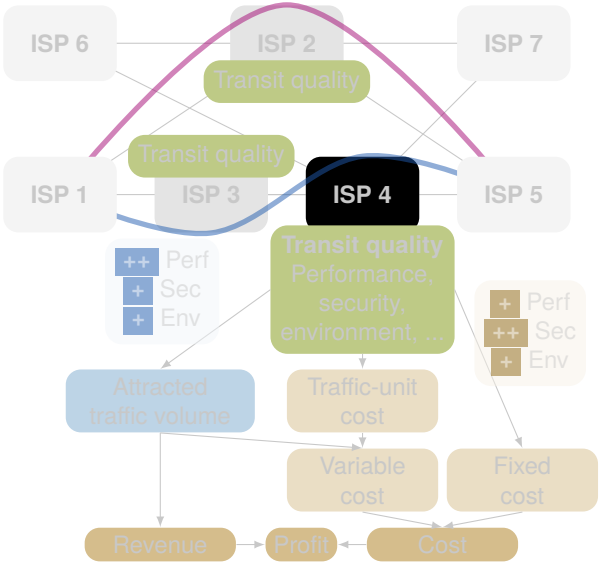
How to mathematically describe ISP quality competition?



How to mathematically describe ISP quality competition?



How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

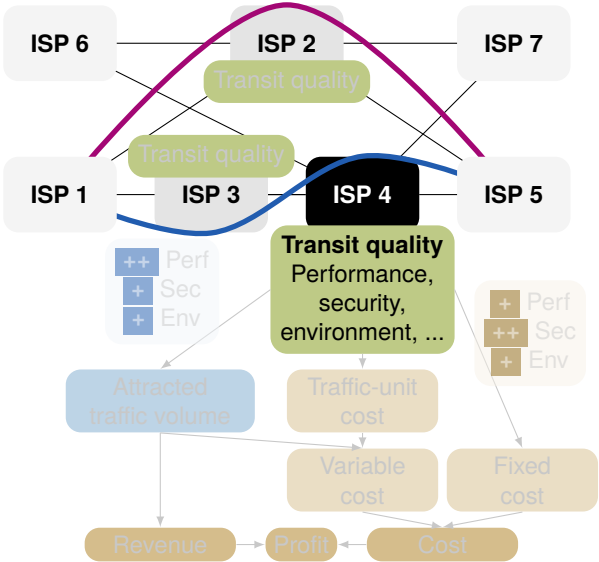
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

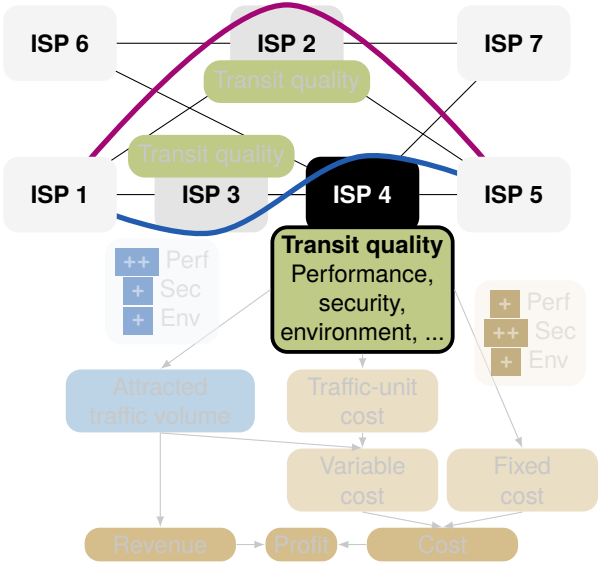
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

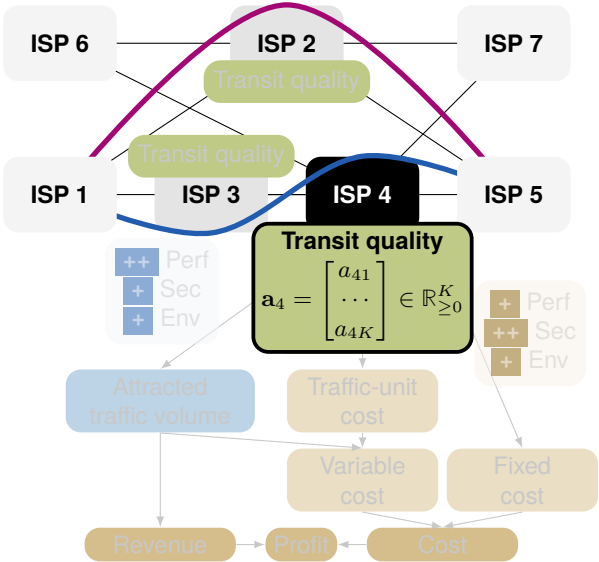
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

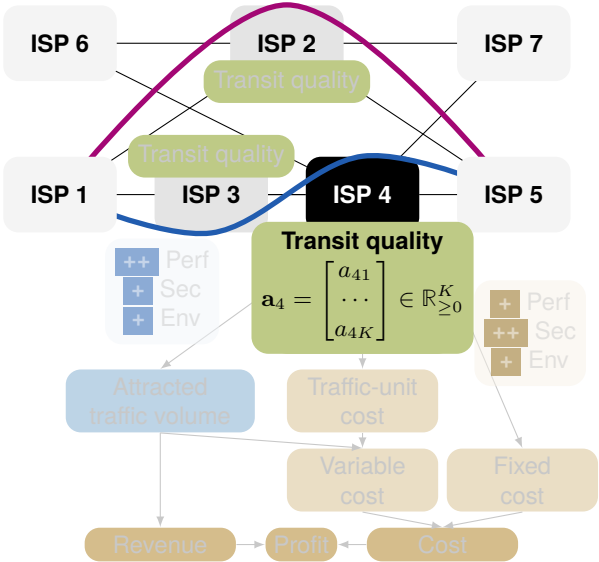
- Attributes with different attractiveness
- Attributes with different costs

Multiple other ISPs affect profit

- ISPs on shared paths
- ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

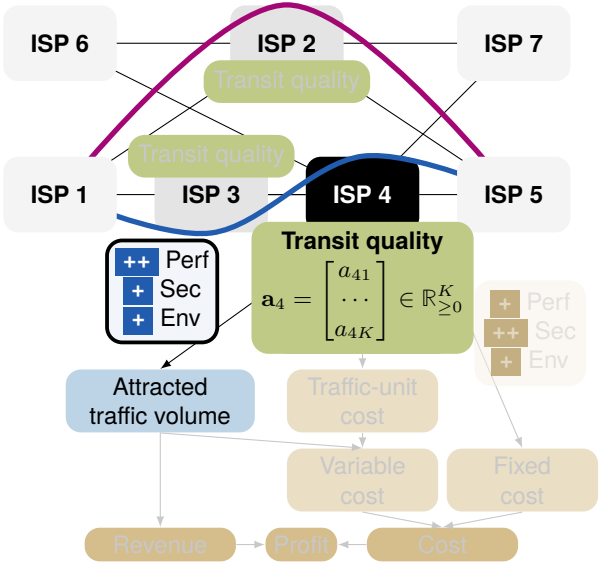
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

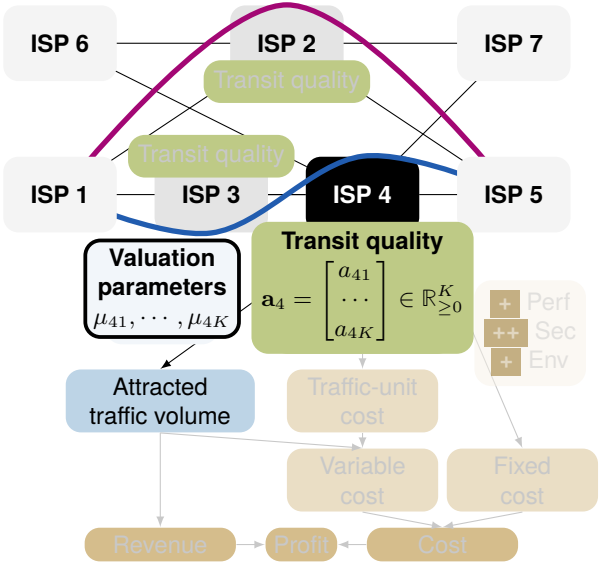
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

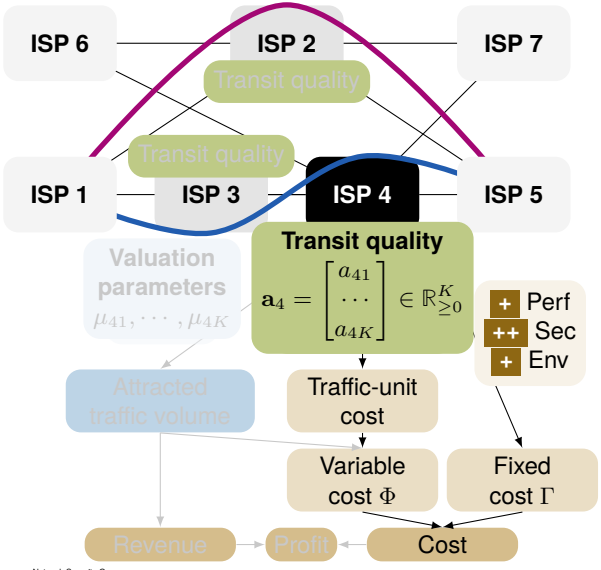
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

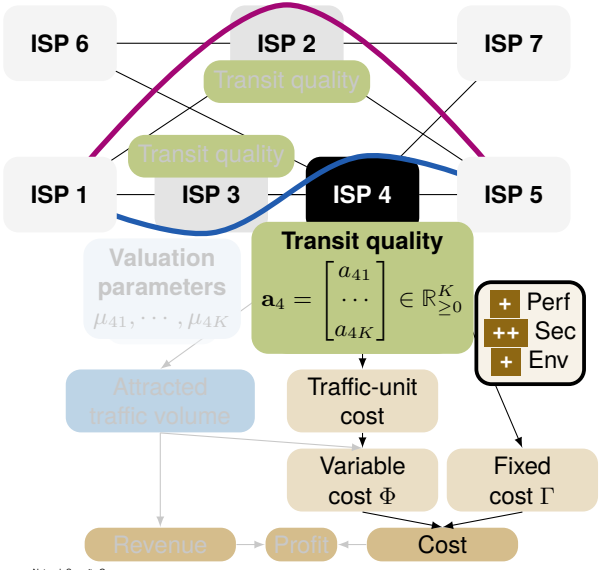
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

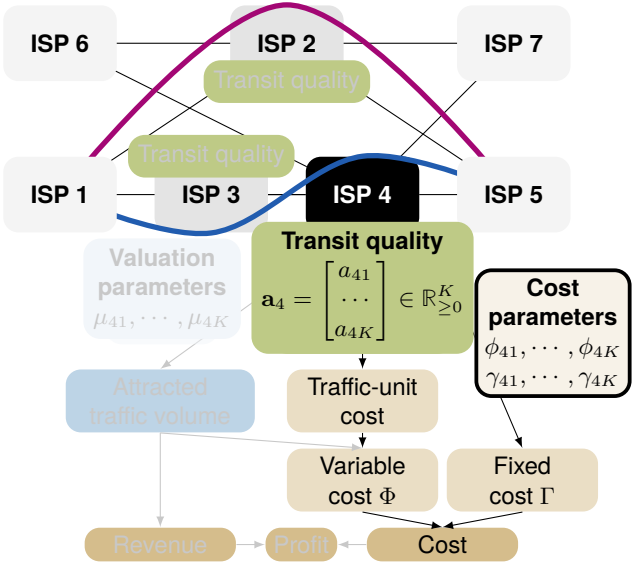
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

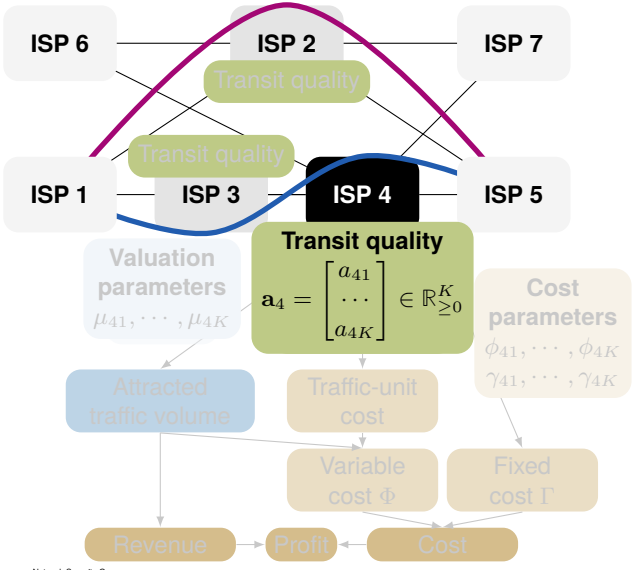
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

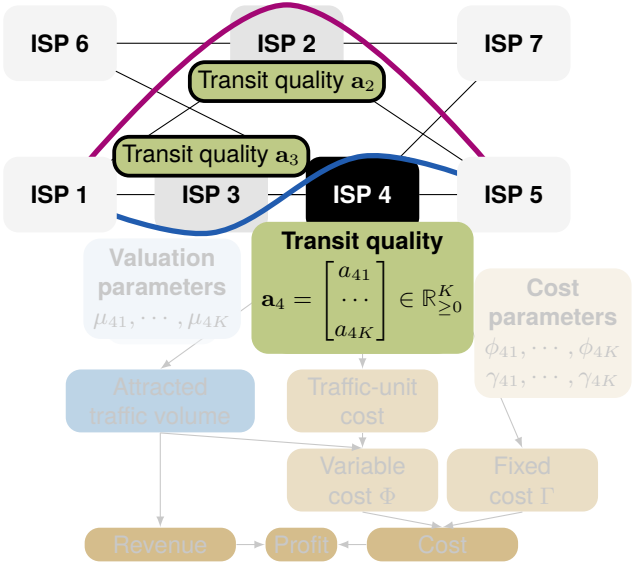
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

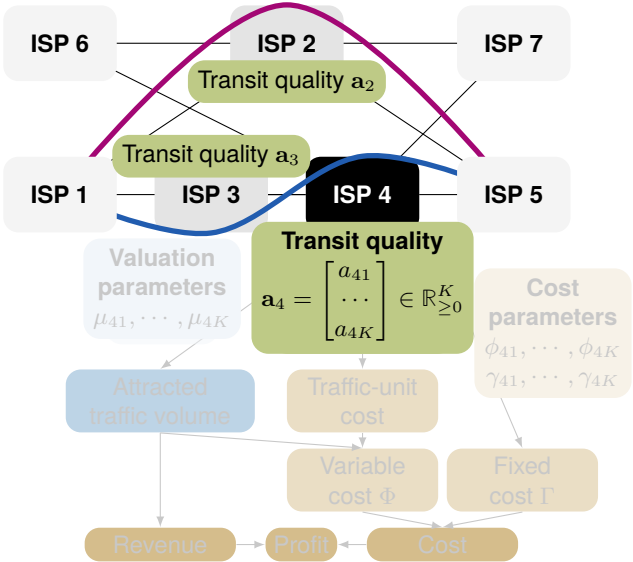
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

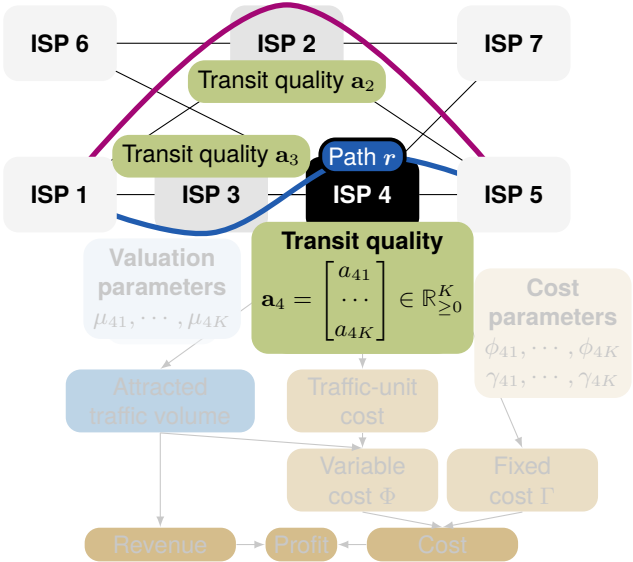
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

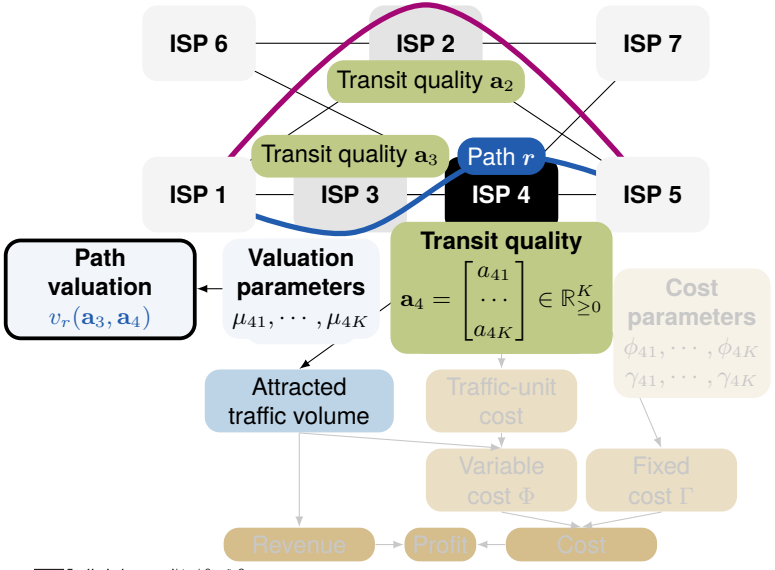
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

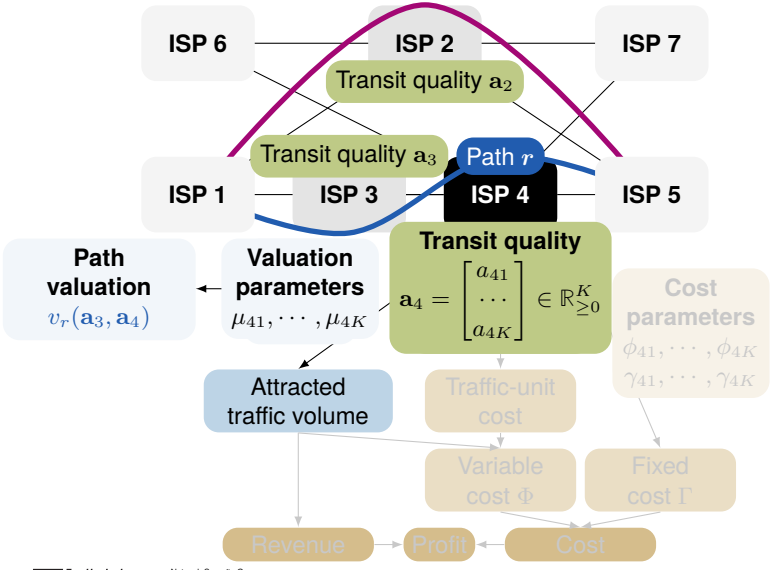
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

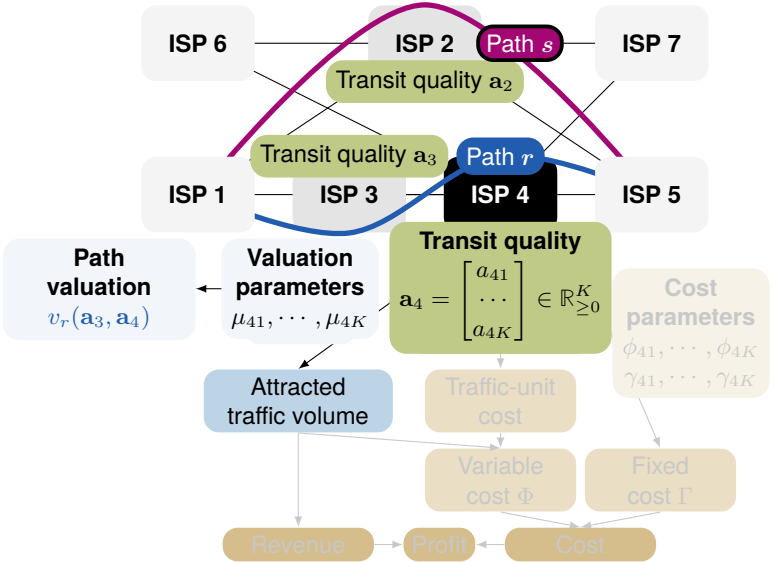
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

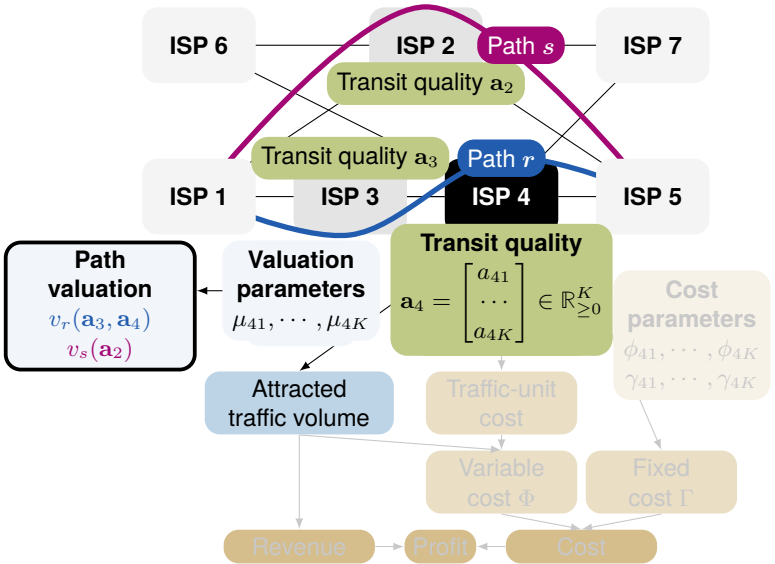
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

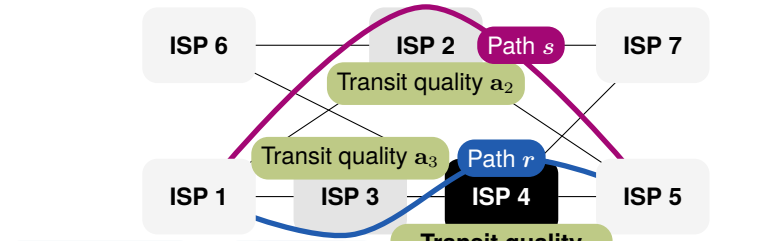
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Path valuation
$v_r(\mathbf{a}_3, \mathbf{a}_4)$
$v_s(\mathbf{a}_2)$

Valuation parameters
$\mu_{41}, \cdots, \mu_{4K}$

Transit quality
$\mathbf{a}_4 = \begin{bmatrix} a_{41} \\ \cdots \\ a_{4K} \end{bmatrix} \in \mathbb{R}^K_{\geq 0}$

Cost parameters
$\phi_{41}, \cdots, \phi_{4K}$
$\gamma_{41}, \cdots, \gamma_{4K}$

Selection probability
$$\frac{v_r}{1 + v_r + v_s}$$

Attracted traffic volume

Traffic-unit cost

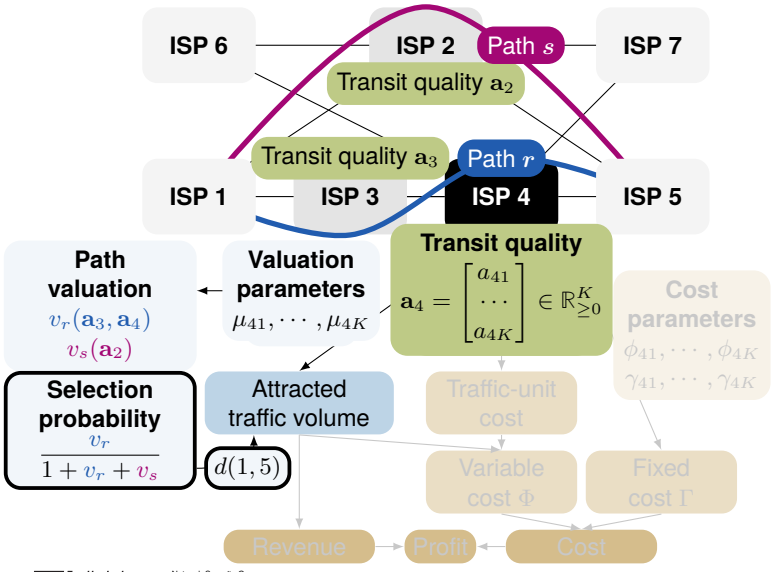
Variable cost Φ

Fixed cost Γ

Revenue → Profit ← Cost

- Multiple attributes define ISP transit quality
- Attributes with different attractiveness
- Attributes with different costs
- Multiple other ISPs affect profit
- ISPs on shared paths
- **ISPs on competing paths**
- Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

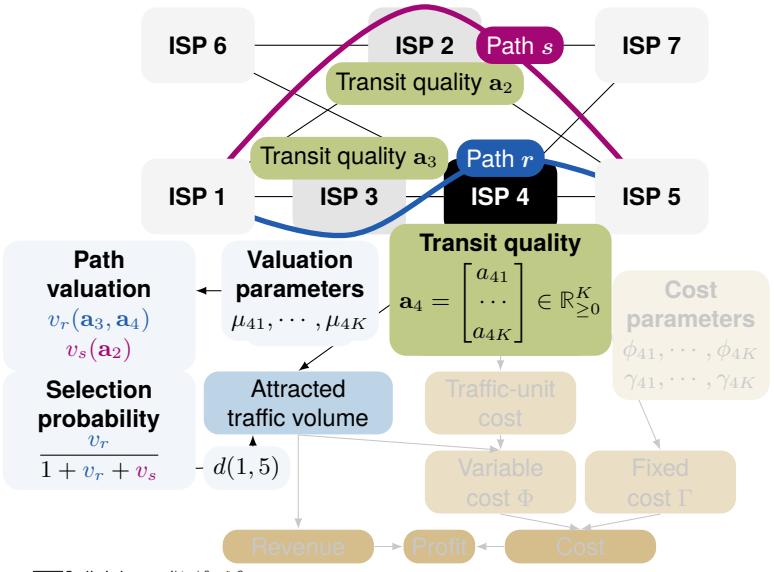
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

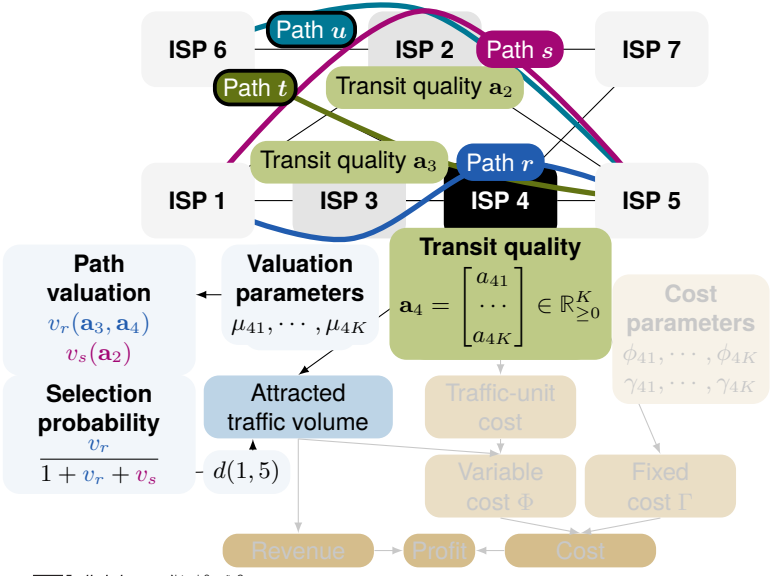
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

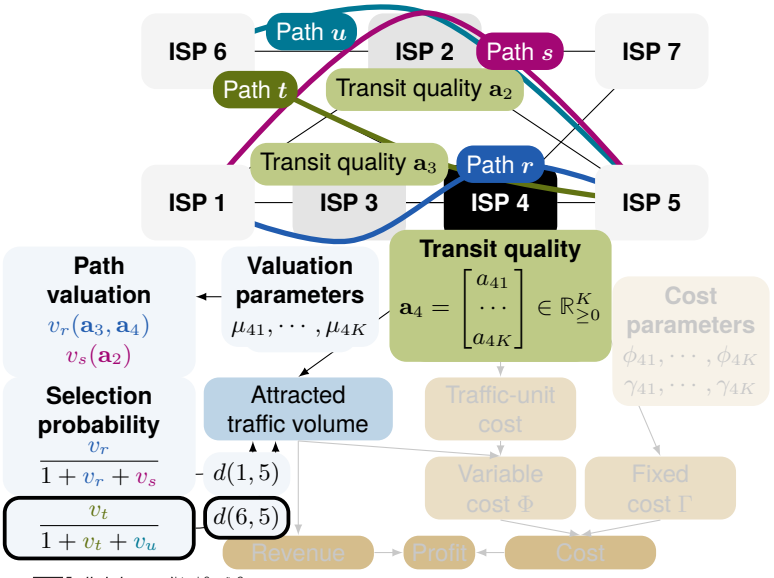
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

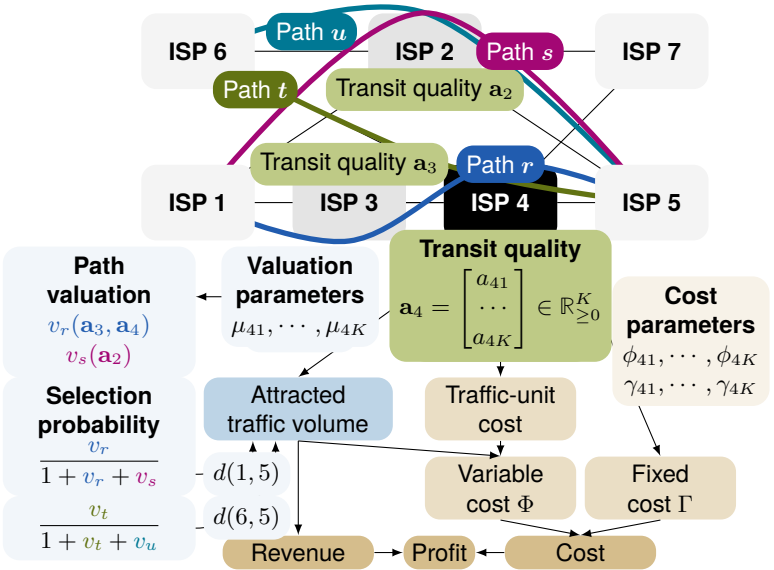
Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

Multiple markets shape ISP interaction

How to mathematically describe ISP quality competition?



Multiple attributes define ISP transit quality

Attributes with different attractiveness

Attributes with different costs

Multiple other ISPs affect profit

ISPs on shared paths

ISPs on competing paths

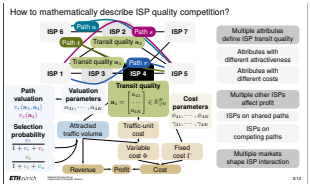
Multiple markets shape ISP interaction

Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation

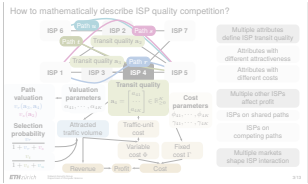


Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation



What can we learn from a theoretical analysis based on our model?

What can we learn from a theoretical analysis based on our model?

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

What can we learn from a theoretical analysis based on our model?

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$ $\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

Nash equilibrium $\mathbf{A}^{\text{eq}}$

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

Nash equilibrium $\mathbf{A}^{\text{eq}}$

$$\mathbf{A}^{\text{eq}} = \begin{bmatrix} \mathbf{a}_1^{\text{eq}} & \cdots & \mathbf{a}_N^{\text{eq}} \end{bmatrix}$$

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

Nash equilibrium $\mathbf{A}^{\text{eq}}$

$\mathbf{a}_n^{\text{eq}}$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n}^{\text{eq}})$ for each ISP n

$$\mathbf{A}^{\text{eq}} = \begin{bmatrix} \mathbf{a}_1^{\text{eq}} & \cdots & \mathbf{a}_N^{\text{eq}} \end{bmatrix}$$

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

Nash equilibrium $\mathbf{A}^{\text{eq}}$

$$\mathbf{A}^{\text{eq}} = \begin{bmatrix} \mathbf{a}_1^{\text{eq}} & \cdots & \mathbf{a}_N^{\text{eq}} \end{bmatrix}$$

$\mathbf{a}_n^{\text{eq}}$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n}^{\text{eq}})$ for each ISP n

$\Longrightarrow$ Equation system: $\mathbf{a}_n^{\text{eq}} = \mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n}^{\text{eq}})$ for each ISP n

What can we learn from a theoretical analysis based on our model?

Attribute choices of all ISPs other than n

For a single market, and affine functions for valuation and cost:

Best response $\mathbf{a}^{\text{best}}$

$\mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n})$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n})$ for each ISP n

$\Longrightarrow$ Closed form of $\mathbf{a}_n^{\text{best}}$

Nash equilibrium $\mathbf{A}^{\text{eq}}$

$$\mathbf{A}^{\text{eq}} = \begin{bmatrix} \mathbf{a}_1^{\text{eq}} & \cdots & \mathbf{a}_N^{\text{eq}} \end{bmatrix}$$

$\mathbf{a}_n^{\text{eq}}$ optimizes $\textsc{Profit}_n(\mathbf{a}_n \mid \mathbf{A}_{-n}^{\text{eq}})$ for each ISP n

$\Longrightarrow$ Equation system: $\mathbf{a}_n^{\text{eq}} = \mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n}^{\text{eq}})$ for each ISP n

Intractable in the general case!

The general case is intractable, so what can we do instead?

The general case is intractable, so what can we do instead?

We analyze two types of networked markets

The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)

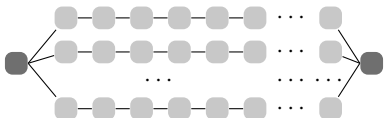
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



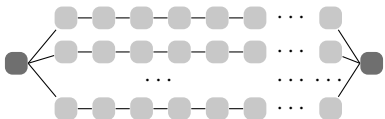
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

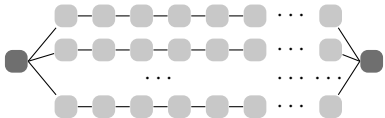
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk} VarCost ϕ_{nk} FixCost γ_{nk}

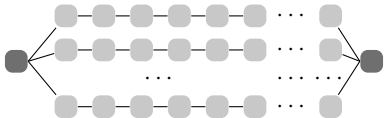
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

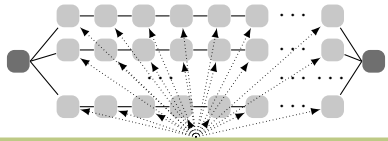
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk} VarCost ϕ_{nk} FixCost γ_{nk}

μ ϕ γ

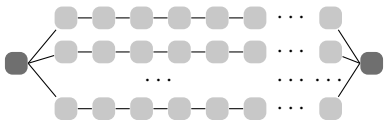
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Heterogeneous markets
(2 paths, attributes $\not\rightarrow$ unit cost)

Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

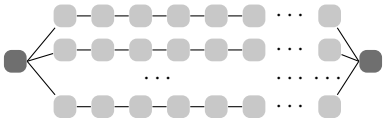
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

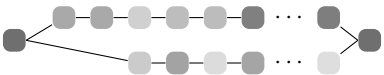
... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

Homogeneous markets
(Arbitrary size)



Heterogeneous markets
(2 paths, attributes $\not\rightarrow$ unit cost)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

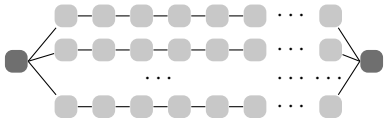
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

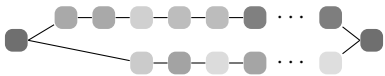
Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

Heterogeneous markets
(2 paths, attributes $\not\to$ unit cost)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ_{nk}	$\mathbf{0}$	γ_{nk}

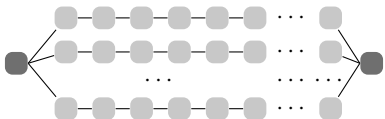
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

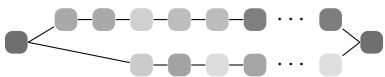
Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

Heterogeneous markets
(2 paths, attributes $\not\rightarrow$ unit cost)



Parameters (for attribute a_{nk}):

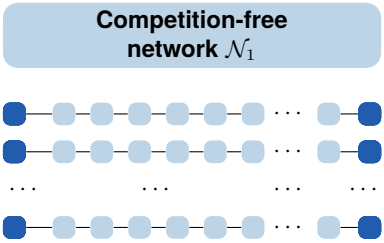
Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ_{nk}	$\mathbf{0}$	γ_{nk}

What can we learn from homogeneous markets about **competition**?

What can we learn from homogeneous markets about **competition**?

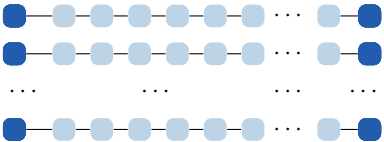
Competition-free network $\mathcal{N}_1$

What can we learn from homogeneous markets about **competition**?



What can we learn from homogeneous markets about **competition**?

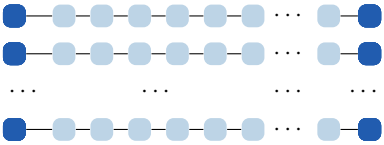
Competition-free network $\mathcal{N}_1$



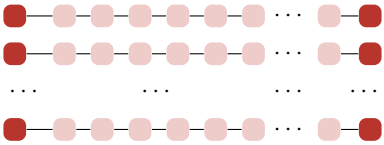
Competitive network $\mathcal{N}_2$

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$

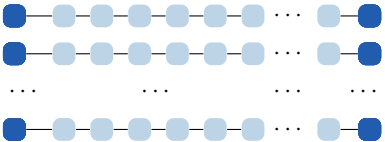


Competitive network $\mathcal{N}_2$

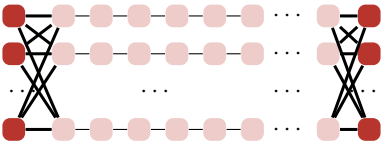


What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$

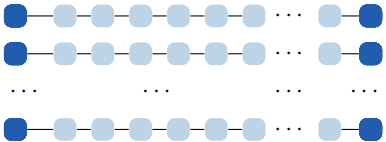


Competitive network $\mathcal{N}_2$



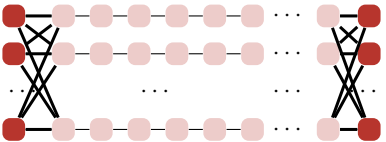
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

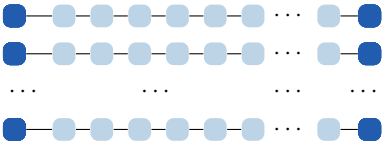
Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_2^{\text{eq}}$

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$

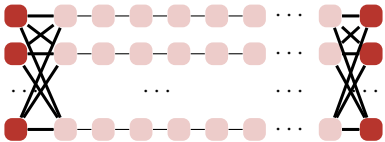


Equilibrium $\mathbf{A}_1^{\text{eq}}$

asymptotically stable w.r.t.

$$\dot{\mathbf{a}}_n = \mathbf{a}_n^{\text{best}}(\mathbf{A}_{-n}) - \mathbf{a}_n$$

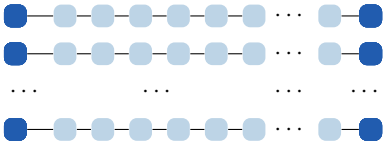
Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_2^{\text{eq}}$

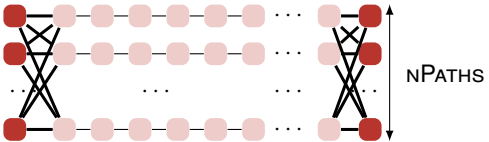
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

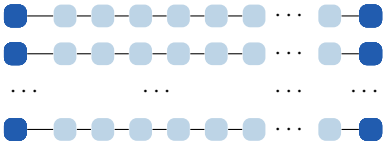
Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$

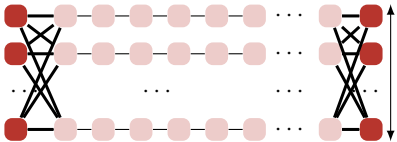
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

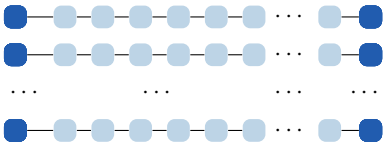
Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

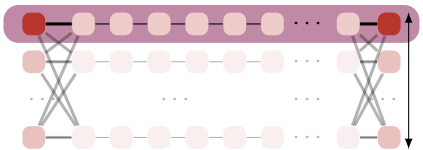
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

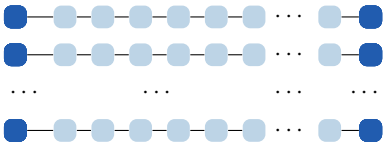
Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

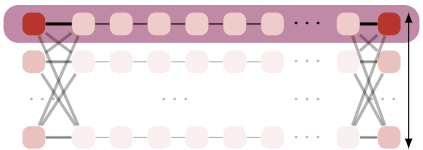
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

Competitive network $\mathcal{N}_2$

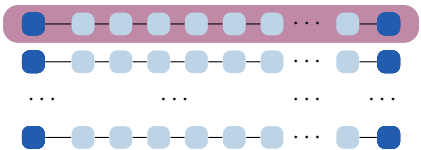


Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

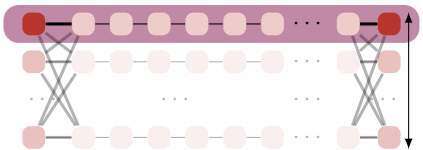
What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

Competitive network $\mathcal{N}_2$

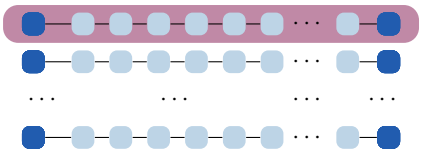


Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

What can we learn from homogeneous markets about **competition**?

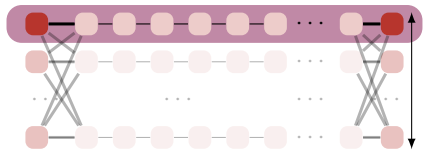
Competition-free network $\mathcal{N}_1$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{\text{nPaths duplications}}$

Competitive network $\mathcal{N}_2$

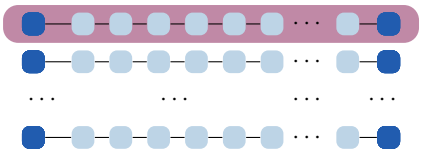


Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

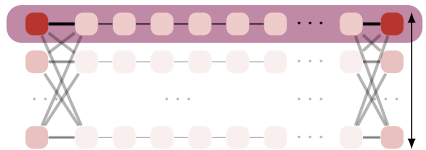
Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{n\text{Paths duplications}}$

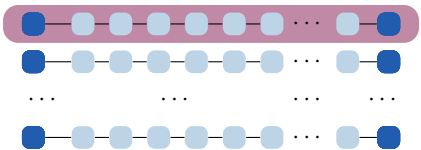
Easier comparison allows proofs

Equilibrium $\mathbf{A}_2^{\text{eq}}(n\text{Paths})$ ← Closed form

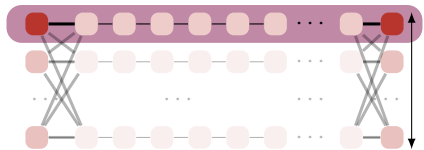
Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{n\text{PATHS duplications}}$

Easier comparison allows proofs

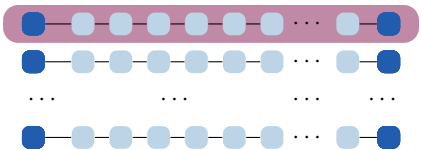
Equilibrium $\mathbf{A}_2^{\text{eq}}(n\text{PATHS})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

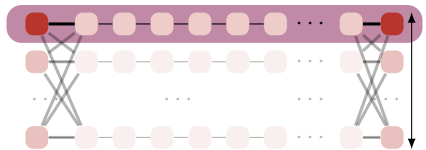
Competition raises path value **q.e.d.**

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{\text{nPaths duplications}}$

Easier comparison allows proofs

Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

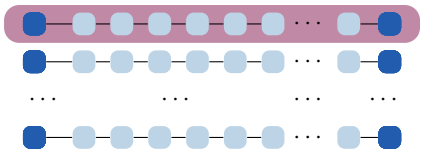
Competition raises path value **q.e.d.**

For all nPaths ≥ 1.

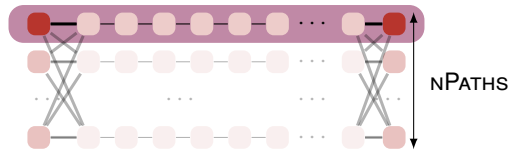
$\text{Value}(\mathbf{A}_1^{\text{eq}}) \leq \text{Value}(\mathbf{A}_2^{\text{eq}}(\text{nPaths}))$

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{\text{nPaths duplications}}$

Easier comparison allows proofs

Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

Competition raises path value q.e.d.

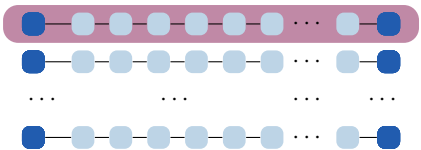
For all nPaths ≥ 1.

Value($\mathbf{A}_1^{\text{eq}}$) $\leq$ Value($\mathbf{A}_2^{\text{eq}}(\text{nPaths})$)

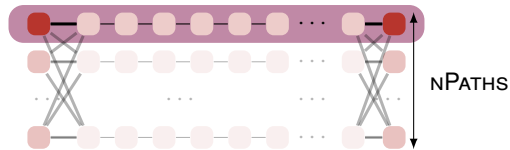
Competition raises profits (sometimes) q.e.d.

What can we learn from homogeneous markets about **competition**?

Competition-free network $\mathcal{N}_1$



Competitive network $\mathcal{N}_2$



Equilibrium $\mathbf{A}_1^{\text{eq}}$

$= \underbrace{\left[\mathbf{A}_2^{\text{eq}}(1) \quad \cdots \quad \mathbf{A}_2^{\text{eq}}(1)\right]}_{\text{nPaths duplications}}$

Easier comparison allows proofs

Equilibrium $\mathbf{A}_2^{\text{eq}}(\text{nPaths})$ ← Closed form

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

Competition raises path value — q.e.d.

For all $\text{nPaths} \geq 1$.

$\text{Value}(\mathbf{A}_1^{\text{eq}}) \leq \text{Value}(\mathbf{A}_2^{\text{eq}}(\text{nPaths}))$

Competition raises profits (sometimes) — q.e.d.

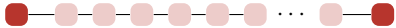
It is possible that

$\text{GlobalProfit}(\mathbf{A}_1^{\text{eq}}) < \text{GlobalProfit}(\mathbf{A}_2^{\text{eq}}(\text{nPaths}))$

What can we learn from homogeneous markets about **cooperation**?

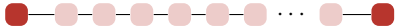
What can we learn from homogeneous markets about **cooperation**?

Single path



What can we learn from homogeneous markets about **cooperation**?

Single path



Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1)$

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1, n\text{ISPs})$

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1, n\text{ISPs})$ → Closed form

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1, n\text{ISPs})$ → Closed form

Single-path optimum $\mathbf{A}_2^{\text{opt}}(1, n\text{ISPs})$

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1, n\text{ISPs})$ → Closed form

Single-path optimum $\mathbf{A}_2^{\text{opt}}(1, n\text{ISPs})$ → Nash Bargaining Solution: $\max \prod_n \text{PROFIT}_n$

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium $\mathbf{A}_2^{\text{eq}}(1, \text{nISPs})$ → Closed form

Single-path optimum $\mathbf{A}_2^{\text{opt}}(1, \text{nISPs})$ → Nash Bargaining Solution: $\max \prod_n \text{PROFIT}_n$

Closed form

What can we learn from homogeneous markets about **cooperation**?

Single path

Single-path equilibrium

$\mathbf{A}_2^{\text{eq}}(1, n\text{ISPs})$ → Closed form

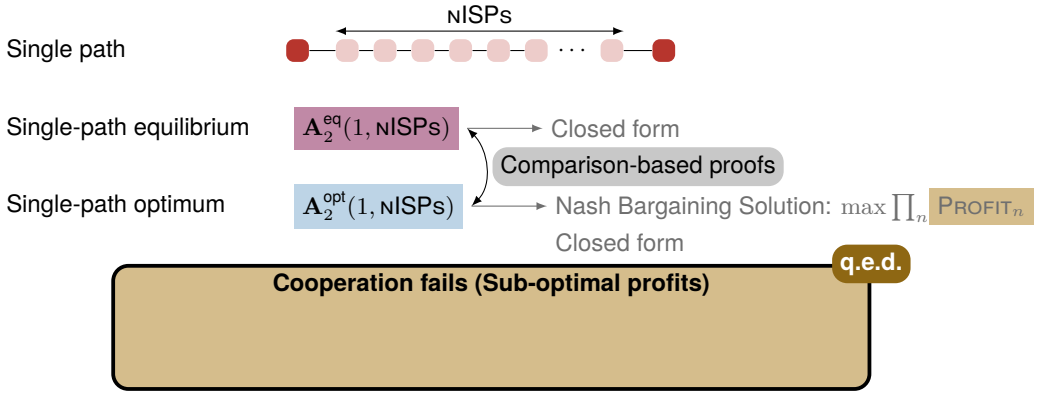
Comparison-based proofs

Single-path optimum

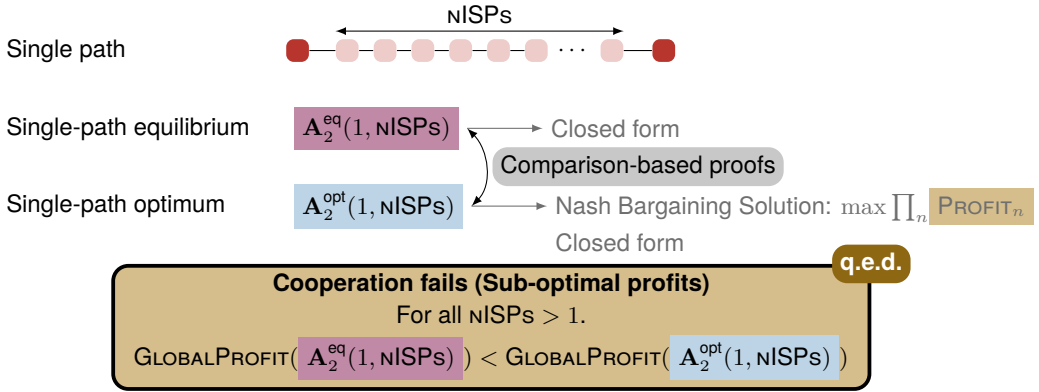
$\mathbf{A}_2^{\text{opt}}(1, n\text{ISPs})$ → Nash Bargaining Solution: $\max \prod_n \text{PROFIT}_n$

Closed form

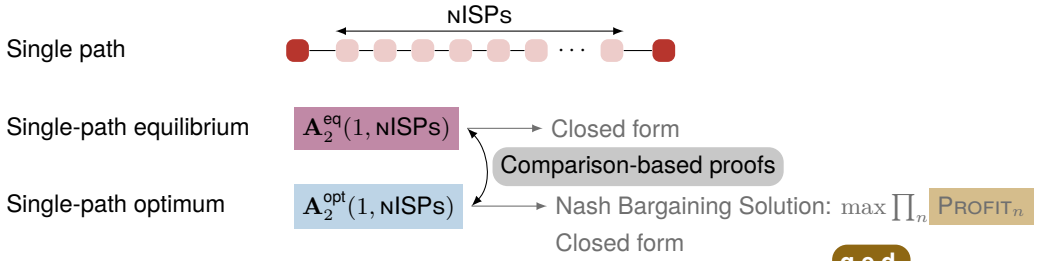
What can we learn from homogeneous markets about **cooperation**?



What can we learn from homogeneous markets about **cooperation**?



What can we learn from homogeneous markets about **cooperation**?



What can we learn from homogeneous markets about **cooperation**?

Cooperation fails (Sub-optimal profits) q.e.d.

For all nISPs > 1.

$\text{GlobalProfit}(\ \mathbf{A}_2^{\text{eq}}(1, \text{nISPs})\ ) < \text{GlobalProfit}(\ \mathbf{A}_2^{\text{opt}}(1, \text{nISPs})\ )$

Cooperation fails (Path value) q.e.d.

For all nISPs > 1.

$\text{Value}(\ \mathbf{A}_2^{\text{eq}}(1, \text{nISPs})\ ) < \text{Value}(\ \mathbf{A}_2^{\text{opt}}(1, \text{nISPs})\ )$

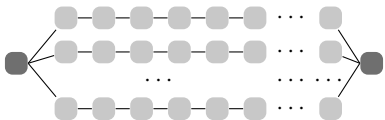
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

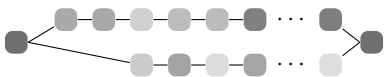
Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

Heterogeneous markets
(2 paths, attributes $\not\rightarrow$ unit cost)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ_{nk}	$\mathbf{0}$	γ_{nk}

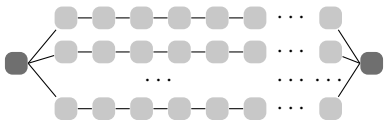
The general case is intractable, so what can we do instead?

We analyze two types of networked markets

... with a structure allowing equilibrium derivation

... still reflecting fundamental aspects of competition

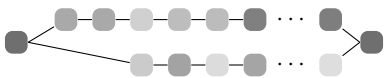
Homogeneous markets
(Arbitrary size)



Parameters (for attribute a_{nk}):

Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ	ϕ	γ

Heterogeneous markets
(2 paths, attributes $\not\rightarrow$ unit cost)



Parameters (for attribute a_{nk}):

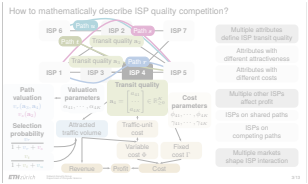
Valuation μ_{nk}	VarCost ϕ_{nk}	FixCost γ_{nk}
μ_{nk}	$\mathbf{0}$	γ_{nk}

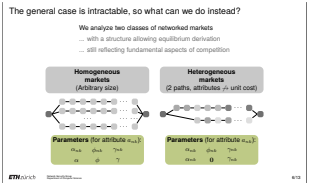
Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation



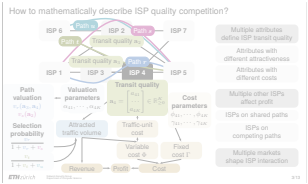


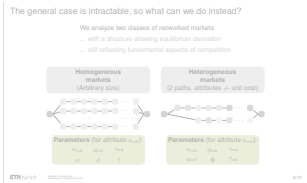
Our contribution: A model-based analysis of ISP quality competition

Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation





How could we confirm our analytical findings by means of simulation?

How could we confirm our analytical findings by means of simulation?

Topology

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)

BGP-compliant paths

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)

BGP-compliant paths

Attributes

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)

BGP-compliant paths

Attributes

$k = 1$: Internal bandwidth of transit ISP

$k = 2$: Clean-energy share of transit ISP

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)
BGP-compliant paths

Attributes

$k = 1$: Internal bandwidth of transit ISP
$k = 2$: Clean-energy share of transit ISP

Parameters

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)
BGP-compliant paths

Attributes

$k = 1$: Internal bandwidth of transit ISP
$k = 2$: Clean-energy share of transit ISP

Parameters

Valuation parameters μ_{nk}
Cost parameters ϕ_{nk}, γ_{nk}
Traffic matrix

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)
BGP-compliant paths

Attributes

$k = 1$: Internal bandwidth of transit ISP
$k = 2$: Clean-energy share of transit ISP

Parameters

Valuation parameters μ_{nk}
Cost parameters ϕ_{nk}, γ_{nk}
Traffic matrix

} Estimation from real-world data

How could we confirm our analytical findings by means of simulation?

Topology

CAIDA AS-Relationships-Geo topology (Top 2000 ASes)
BGP-compliant paths

Attributes

$k = 1$: Internal bandwidth of transit ISP
$k = 2$: Clean-energy share of transit ISP

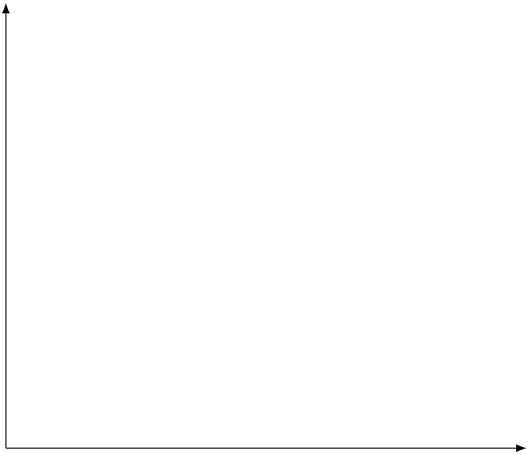
Parameters

Valuation parameters μ_{nk}
Cost parameters ϕ_{nk}, γ_{nk}
Traffic matrix

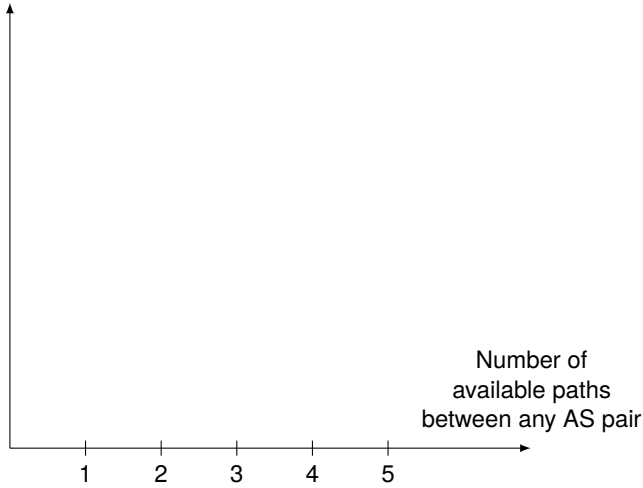
Estimation from real-world data

Random variation for robustness

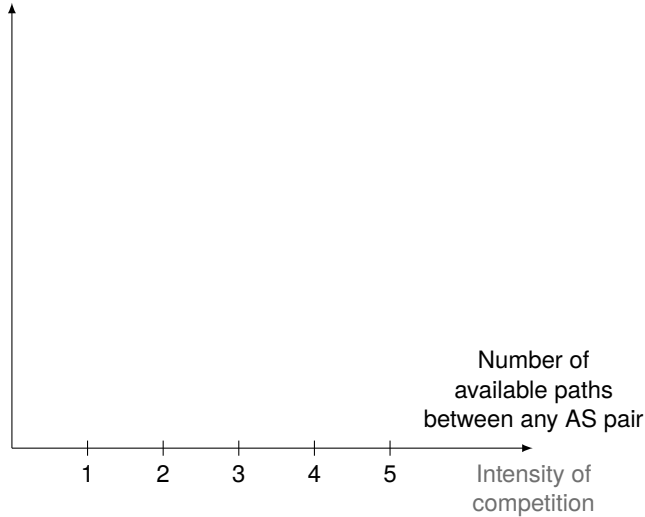
What does our simulation show?



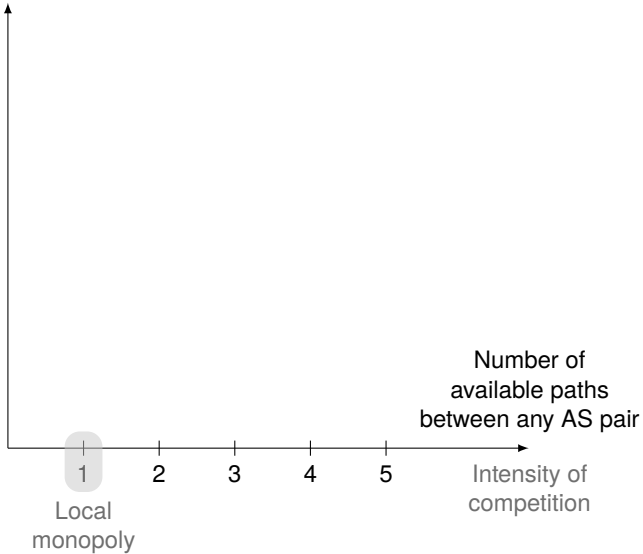
What does our simulation show?



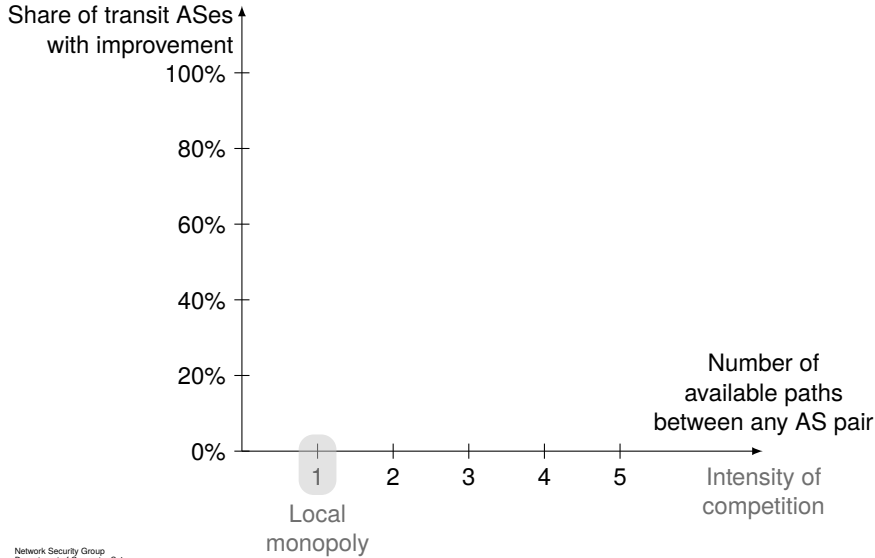
What does our simulation show?



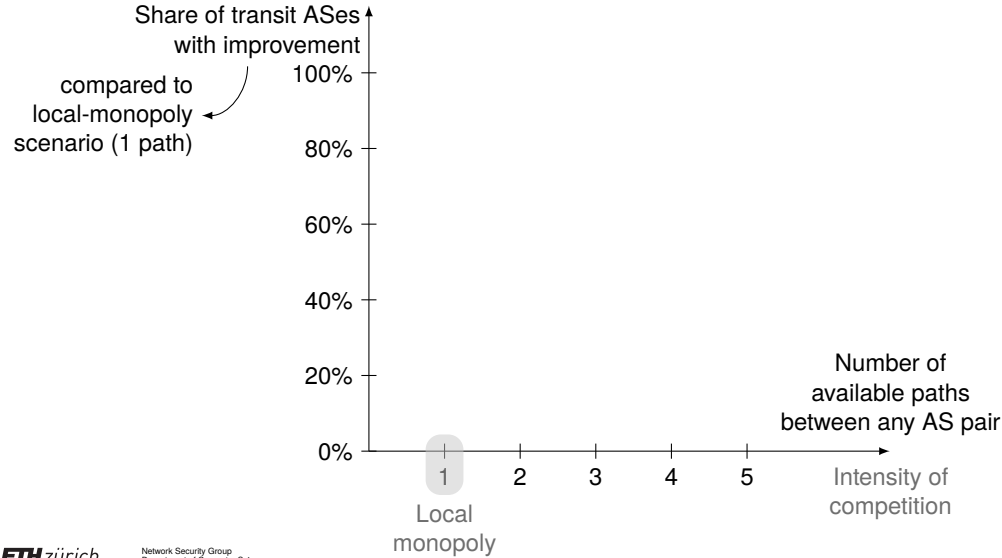
What does our simulation show?



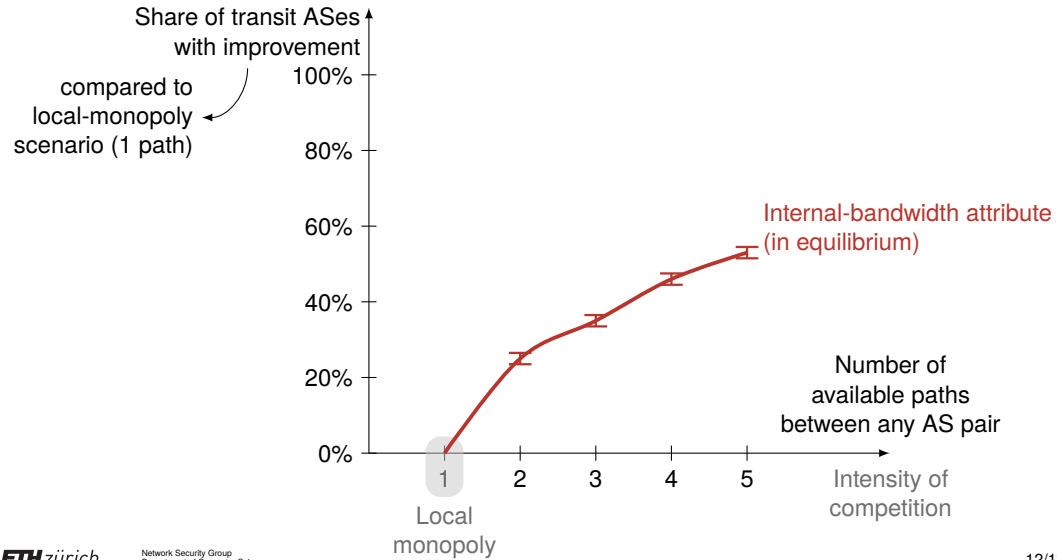
What does our simulation show?



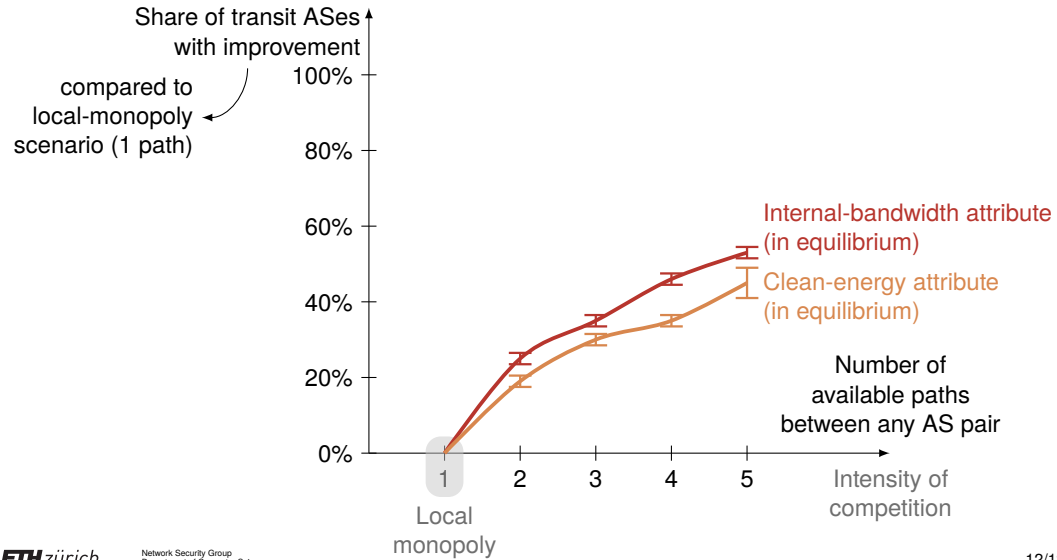
What does our simulation show?



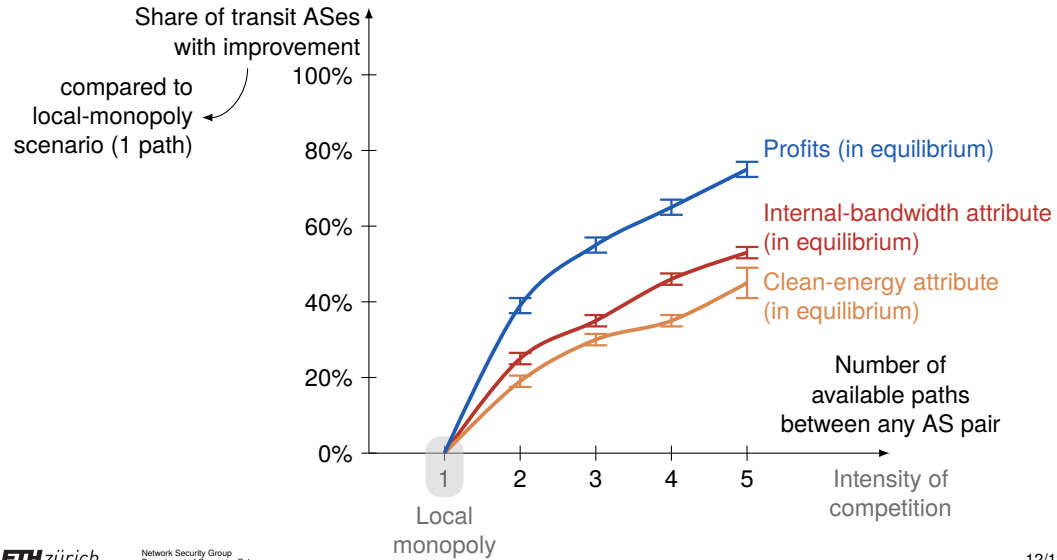
What does our simulation show?



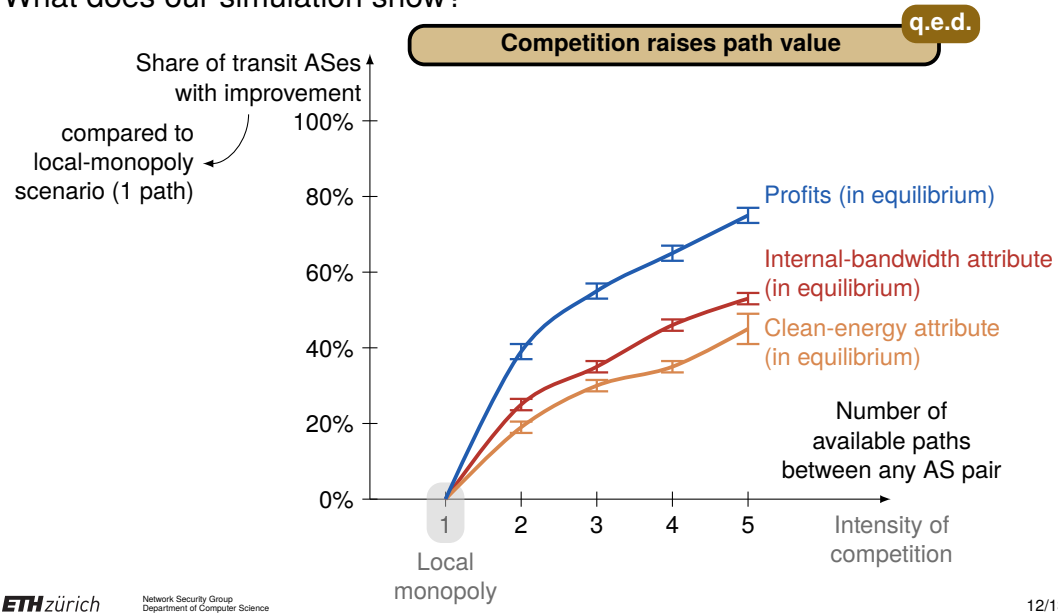
What does our simulation show?



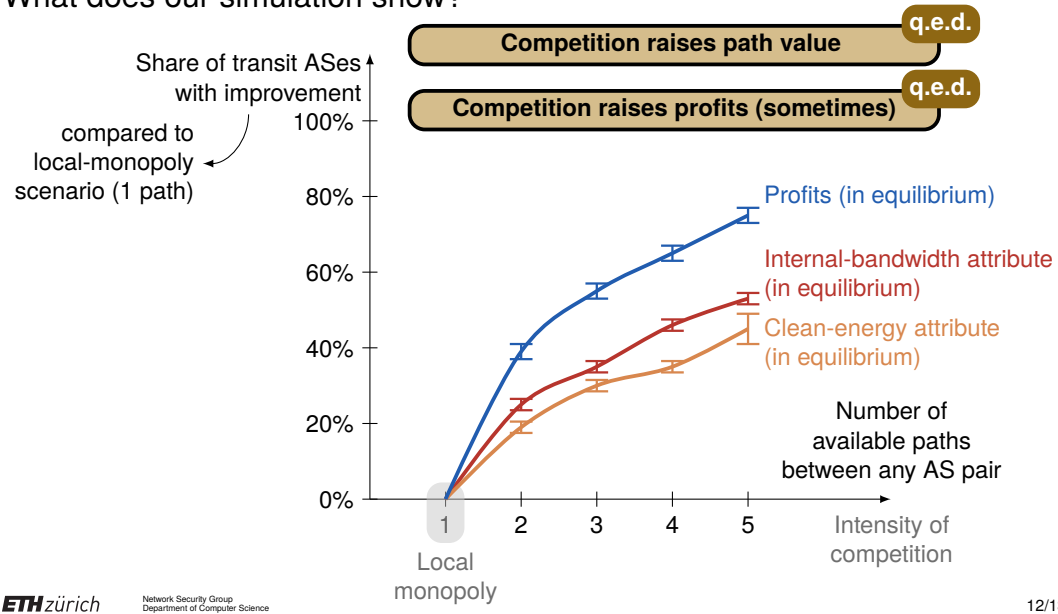
What does our simulation show?



What does our simulation show?

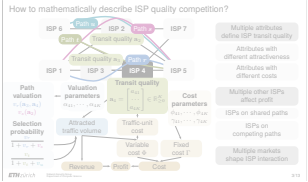


What does our simulation show?

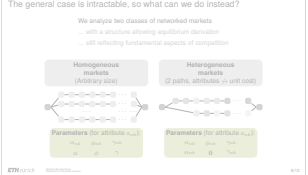


Our contribution: A model-based analysis of ISP quality competition

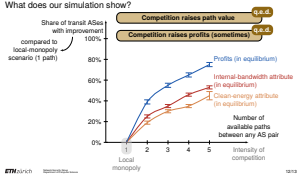
Model of multi-attribute quality competition



Game-theoretic analysis



Large-scale simulation

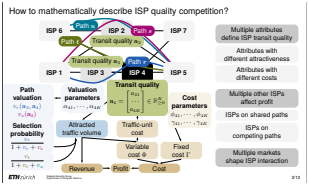


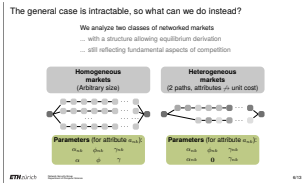
Our contribution: A model-based analysis of ISP quality competition

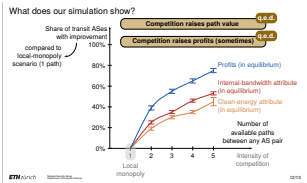
Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation

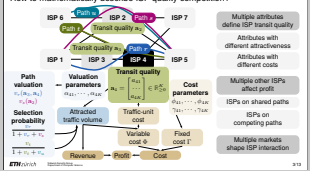




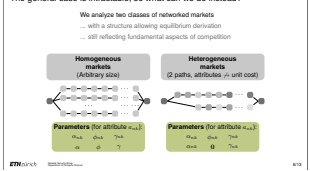


Our contribution: A model-based analysis of ISP quality competition

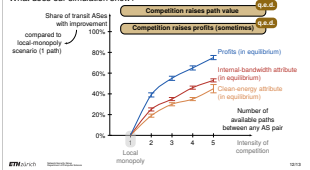
Model of multi-attribute quality competition



Game-theoretic analysis

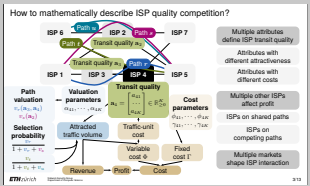


Large-scale simulation

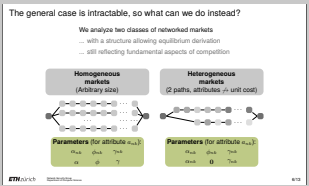


Our contribution: A model-based analysis of ISP quality competition

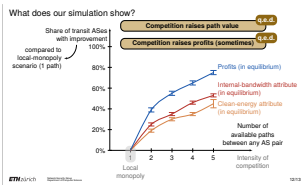
Model of multi-attribute quality competition



Game-theoretic analysis

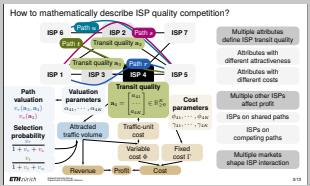


Large-scale simulation

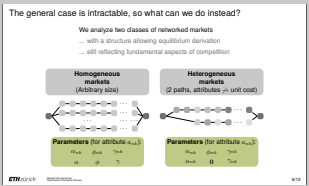


Our contribution: A model-based analysis of ISP quality competition

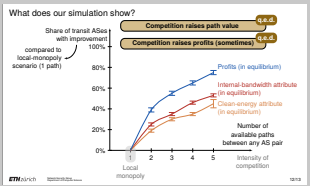
Model of multi-attribute quality competition



Game-theoretic analysis



Large-scale simulation

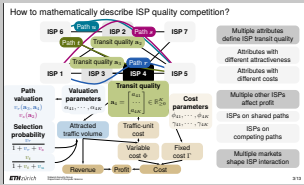


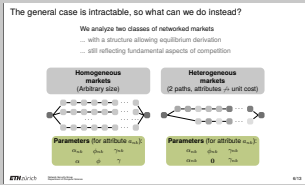
Our contribution: A model-based analysis of ISP quality competition

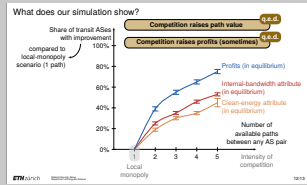
Model of multi-attribute quality competition

Game-theoretic analysis

Large-scale simulation







Questions?

simon.scherrer@inf.ethz.ch