Communications Network Economics

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March 2017
The Role of Economics in Networking

1. Explain operator behaviors
2. Predict network equilibrium
3. Envision network services
4. Provide policy recommendations
Explain Operator Behaviors

- Operators of similar sizes upgrade technologies at different times
- A tradeoff between market share and upgrading cost
- Network effect provides additional benefit to late upgrade

On-demand data offloading from cellular networks to Wi-Fi networks
When, where, and how much to offload?
Market clearing through an iterative double auction mechanism

Monetization of the public Wi-Fi networks
Free ad-sponsored Wi-Fi access vs. premium paid Wi-Fi access
Optimal pricing mechanisms based on user valuation, visiting frequency, and advertisement concentration

Provide Policy Recommendations

- TV white space as golden **unlicensed spectrum resources**
- White space **database operator** manages the interferences
- Information market provides **differentiated** service to users

Media Coverage

- Coverage by CUHK and in 20+ Hong Kong and Mainland Chinese news agencies (e.g., Mingpo, Sina, Sohu, and ChinaDaily)
Economics of User-Provided Networks

Joint work with Ming Tang & Lin Gao (CUHK)
Haitian Pang & Shou Wang & Lifeng Sun (Tsinghua University)
A user obtains network connectivity from a network provider.
No network connectivity outside the network coverage.
Clear distinction between “providers” and “users”.
Users serve as micro-providers, offering connectivity to other users

- Exploit the diversity of user devices
- Extend coverage and service of network operators
- Better match demand and supply in heterogeneous networks
### Commercial UPNs

<table>
<thead>
<tr>
<th></th>
<th>Fixed Hosts</th>
<th>Mobile Hosts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network-Assisted</strong></td>
<td>Fon</td>
<td>Karma</td>
</tr>
<tr>
<td><strong>Autonomous</strong></td>
<td>BeWiFi</td>
<td>Open Garden</td>
</tr>
</tbody>
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Costs and Incentives

- Resource sharing **induces costs**:
  - Reduced internet access bandwidth
  - Increased data usage cost
  - Reduced battery energy (for *mobile* users)

- Proper incentive mechanisms are **critical** for the success of UPNs
Costs and Incentives

Resource sharing induces costs:

- Reduced internet access bandwidth
- Increased data usage cost
- Reduced battery energy (for mobile users)

Proper incentive mechanisms are critical for the success of UPNs

We will focus on the incentive mechanism design for UPN-based mobile video streaming.
Single-User Video Streaming

My downloading speed is 0.5Mbps, want to watch video.

I can watch 240p in YouTube Live, with the downloading speed of 0.5Mbps.

My downloading speed is 1Mbps, do not watch video.

My resource is idle.
Multi-User Cooperative Video Streaming

My downloading speed is 0.5Mbps, want to watch video.

My downloading speed is 1Mbps, do not watch video.

Cooperate

I can watch 720p in YouTube Live, with the downloading speed of 1.5Mbps.

Resource is utilized, any reward for me?
Crowdsourced Mobile Video Streaming

Crowdsourcing network resources from multiple near-by mobile users from potentially different service providers.

Each mobile user watches a different video.
Adaptive BitRate Streaming

To achieve flexible Quality of Experience in wireless video streaming

- Single user case: choose the bitrate of each video segment based on real-time network conditions and user QoE preferences.
Multi-User Collaborative Video Streaming

- **Three** decisions when downloading a video segment

  - **Receiver Selection:** Whose segment?
  - **Bitrate Adaptation:** What bitrate?
  - **Cost Compensation:** How much to pay?
Multi-User Collaborative Video Streaming

- Three decisions when downloading a video segment
  - Receiver Selection: Whose segment?
  - Bitrate Adaptation: What bitrate?
  - Cost Compensation: How much to pay?

- Need decentralized and asynchronous algorithm without complete network information
Social Welfare, Utility, and Cost

- User $n$ downloads a segment of bitrate $r$ for user $m$ at time $t_0$
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Social welfare

$$W_{nm}(r) \triangleq U_m(r) - C_n(r)$$
Social Welfare, Utility, and Cost

- **User** $n$ downloads a segment of bitrate $r$ for **user** $m$ at time $t_0$

- **Social welfare**
  \[
  W_{nm}(r) \triangleq U_m(r) - C_n(r)
  \]

- **Utility of receiver user** $m$
  \[
  U_m(r) \triangleq \log(1 + \theta_m r) - \phi^{QD} [R_m^{PRE} - r]^+ - \phi^{REB} [T_n(r, t_0) - B_m^{CUR}]^+
  \]
  - (Private) valuation information $\theta_m$
  - (Private) state information $\mu = (R_m^{PRE}, B_m^{CUR})$
Social Welfare, Utility, and Cost

- **User** \( n \) downloads a segment of bitrate \( r \) for **user** \( m \) at time \( t_0 \)

- **Social welfare**
  
  \[
  W_{nm}(r) \equiv U_m(r) - C_n(r)
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- **Utility of receiver user** \( m \)

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  U_m(r) \equiv \log(1 + \theta_m r) - \phi^{QD} \left[ R_m^{\text{PRE}} - r \right]^+ - \phi^{\text{REB}} \left[ T_n(r, t_0) - B_m^{\text{CUR}} \right]^+
  \]

  - (Private) valuation information \( \theta_m \)
  - (Private) state information \( \mu = (R_m^{\text{PRE}}, B_m^{\text{CUR}}) \)

- **Cost of downloader user** \( n \)

  \[
  C_n(r) \equiv G_n^{\text{CELL}}(r) + E_n^{\text{CELL}}(r) + E_{nm}^{\text{WIFI}}(r)
  \]

  - Cellular data payment
  - Cellular energy
  - WiFi energy
Design Objectives

- **Truthfulness**: users truthfully reveal their utility functions despite of private information
- **Efficiency**: design a resource allocation mechanism to maximize the social welfare
- **Optimality**: design a resource allocation mechanism to maximize the downloader’s benefit
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- **Efficiency**: design a resource allocation mechanism to maximize the social welfare

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- **Efficiency and optimality** are conflicting objectives.
Design Objectives

- **Truthfulness**: users truthfully reveal their utility functions despite of private information
- **Efficiency**: design a resource allocation mechanism to maximize the social welfare
- **Optimality**: design a resource allocation mechanism to maximize the downloader’s benefit
- Efficiency and optimality are conflicting objectives.
- We will focus on achieving truthfulness and efficiency through a multi-dimensional auction mechanism
Auction-Based Incentive Mechanism

User 1
(Ready to download)
Initiate an auction

User 1, 2, 3
Submit bid with
(bitrate, price)
-Bitrate Adaptation

User 1
Winner & Payment
-Receiver Selection
-Cost Compensation

Initiate an Auction

User 1's Segment
User 2's Segment
User 3's Segment
Auction-Based Incentive Mechanism

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User 2
Winner & Payment
Challenge: Multi-Dimensional Bids

- Each bid is multi-dimensional: \((\text{bitrate}, \text{price})\)
  - \((0.2\text{Mbps}, 20\text{¥})\) vs. \((0.4\text{Mbps}, 35\text{¥})\) vs. \((1.3\text{Mbps}, 70\text{¥})\)

- How to rank vectors to decide the winner and the payment?

- Solution: Second Score Auction
Score Function

- Score function: transforms a multi-dimensional bid to a scalar
  - Determined by the auctioneer (mechanism design)
  - Each user $m$ can have a unique score function $S_m(r, p)$
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- Winner: bidder with the highest score
- Payment: determined by the second highest score
- How to choose the score function?
Additive Score Function

\[ S_m(r, p) = p - C_n(r) \]

- Difference between the bidder m’s price and the downloader n’s cost
- All bidders have the same score function (related to downloader n)
**Winner Selection and Payment Determination**

- **Winner** = the bidder with the highest score

\[ m^* = \arg \max_{m \in \mathcal{N}_n} (p_m - C_n(r_m)) \]
Winner Selection and Payment Determination

**Winner** = the bidder with the highest score

\[ m^* = \arg \max_{m \in \mathcal{N}_n} (p_m - C_n(r_m)) \]

**Winner’s bitrate** = the winner’s bid bitrate \( r_{m^*} \)
**Winner Selection and Payment Determination**

**Winning Rule & Payment Rule**

1. **Winner** = the bidder with the highest score
   
   \[ m^* = \arg \max_{m \in \mathbb{N}_n} (p_m - C_n(r_m)) \]

2. **Winner’s bitrate** = the winner’s bid bitrate \( r_{m^*} \)
3. **Winner’s payment** ≠ the winner’s bid price \( p_{m^*} \)
   - Payment \( \hat{p}_{m^*} \) represents the score damage to other users
   
   \[ \hat{p}_{m^*} - C_n(r_{m^*}) = \max_{m \in \mathbb{N}_n/m^*} S_m(r_m, p_m) \]

\[ \hat{p}_{m^*} \] represents the winner’s revised score
\[ S_m(r_m, p_m) \] represents the second highest bidding score
An Example

- A total of 3 bidders, and the score function is

\[
S(r, p) = p - C_n(r) = p - 50 \cdot r
\]

Bids (\(r_m, p_m\)):
- A: (0.2Mbps, 20)
- B: (0.4Mbps, 35)
- C: (1.3Mbps, 70)

Scores:
- \(S(r_A, p_A) = 20 - 50 \cdot 0.2 = 10\)
- \(S(r_B, p_B) = 35 - 50 \cdot 0.4 = 15\)
- \(S(r_C, p_C) = 70 - 50 \cdot 1.3 = 5\)

Hence B is the winner, and the bitrate is 0.4Mbps.

The payment of B is \(\hat{p}_B\):

\[
\hat{p}_B - C_n(r_B) = \hat{p}_B - 50 \cdot 0.4 = \max_{m \in \mathbb{N} / B} S(r_m, p_m) = 10 \Rightarrow \hat{p}_B = 30
\]
An Example

- A total of 3 bidders, and the score function is
  \[ S(r, p) = p - C_n(r) = p - 50 \cdot r \]

- Bids \((r_m, p_m)\):
  A: (0.2Mbps, 20¥),  B: (0.4Mbps, 35¥),  C: (1.3Mbps, 70¥)
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- Bids \((r_m, p_m)\):
  - A: (0.2Mbps, 20€),  B: (0.4Mbps, 35€),  C: (1.3Mbps, 70€)

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\[
S(r_A, p_A) = 20 - 50 \cdot 0.2 = 10 \\
S(r_B, p_B) = 35 - 50 \cdot 0.4 = 15 \\
S(r_C, p_C) = 70 - 50 \cdot 1.3 = 5
\]

Hence B is the winner, and the bitrate is 0.4Mbps.

The payment of B is \(p_B\):

\[ \hat{p}_B - C_n(r_B) = \hat{p}_B - 50 \cdot 0.4 = \max_{m \in \mathbb{N}/B} S(r_m, p_m) = 10 \Rightarrow \hat{p}_B = 30€. \]
An Example

- A total of 3 bidders, and the score function is
  \[ S(r, p) = p - C_n(r) = p - 50 \cdot r \]

- Bids \((r_m, p_m)\):
  A: (0.2Mbps, 20\$),  B: (0.4Mbps, 35\$),  C: (1.3Mbps, 70\$)

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- Hence **B** is the winner, and the bitrate is 0.4Mbps.
An Example

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  \[ S(r, p) = p - C_n(r) = p - 50 \cdot r \]

- Bids \((r_m, p_m)\):
  A: (0.2Mbps, 20¢),  B: (0.4Mbps, 35¢),  C: (1.3Mbps, 70¢)

- Scores:
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  S(r_A, p_A) = 20 - 50 \cdot 0.2 = 10 \\
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  \]

- Hence B is the winner, and the bitrate is 0.4Mbps.
- The payment of B is \(\hat{p}_B\):
  \[
  \hat{p}_B - C_n(r_B) = \hat{p}_B - 50 \cdot 0.4 = \max_{m \in \mathcal{N}_n / B} S(r_m, p_m) = 10 \\
  \Rightarrow \hat{p}_B = 30¢.
  \]
Equilibrium User Bidding Behavior

Theorem (Truthful Price Choice)
Given any bitrate $r$, a bidder $m$'s equilibrium bidding price $p_m(r)$ is his true utility under $r$:
$$p_m(r) = U_m(r).$$

Theorem (Bitrate Selection)
A bidder $m$'s equilibrium bitrate $r_m$ maximizes its score function, which corresponds to the social welfare if downloading for bidder $m$:
$$r_m = \arg \max_r (U_m(r) - C_n(r)) = \arg \max_r W_{nm}(r).$$
Equilibrium User Bidding Behavior

**Theorem (Truthful Price Choice)**

Given any bitrate $r$, a bidder $m$’s *equilibrium bidding price* $p_m$ is his *true utility* under $r$:

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Equilibrium User Bidding Behavior

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$$r_m = \arg \max_r (U_m(r) - C_n(r)) = \arg \max_r W_{nm}(r).$$
Efficiency

**Theorem (Efficient Auction)**

*Under the following score function*

\[ S_m(r, p) = p - C_n(r), \]

*the auction is efficient as it maximizes the social welfare.*
Multi-Object Multi-Dimensional (MOMD) Auction

- One auction per segment may induce high signaling overhead
- How about allocating multiple objects (segments) per auction?
- Same design objectives: truthfulness and efficiency.
- A challenging problem in multi-dimensional auction.
MOMD Auction: Bidding

- Assume that the auctioneer allocates $K$ segments in each auction
MOMD Auction: Bidding

- Assume that the auctioneer allocates $K$ segments in each auction
- A bidder $m$ submits bid in the form of (bitrate matrix, price vector)
MOMD Auction: Bidding

- Assume that the auctioneer allocates $K$ segments in each auction
- A bidder $m$ submits bid in the form of (bitrate matrix, price vector)
  - bitrate matrix
    
    $$R^m = \begin{bmatrix}
    r_1^m \\
    r_2^m \\
    \vdots \\
    r_K^m
    \end{bmatrix} = \begin{bmatrix}
    r_{11}^m & 0 & \cdots & 0 \\
    r_{21}^m & r_{22}^m & \cdots & 0 \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{K1}^m & r_{K2}^m & \cdots & r_{KK}^m
    \end{bmatrix}$$

  - $r_{li}^m$: the bitrate for the $i^{th}$ segment if bidder $m$ is allocated $l$ segments.
MOMD Auction: Bidding

- Assume that the auctioneer allocates $K$ segments in each auction
- A bidder $m$ submits bid in the form of \((\text{bitrate matrix}, \text{price vector})\)
  - bitrate matrix
    \[
    R^m = \begin{bmatrix}
    r^m_1 \\
    r^m_2 \\
    \vdots \\
    r^m_K \\
    \end{bmatrix}
    = \begin{bmatrix}
    r^m_{11} & 0 & \cdots & 0 \\
    r^m_{21} & r^m_{22} & \cdots & 0 \\
    \vdots & \vdots & \ddots & \vdots \\
    r^m_{K1} & r^m_{K2} & \cdots & r^m_{KK} \\
    \end{bmatrix}
    \]
  - $r^m_{li}$: the bitrate for the $i^{th}$ segment if bidder $m$ is allocated $l$ segments.
  - price vector
    \[
p^m = (p^m_1, p^m_2, \ldots, p^m_K)
    \]
  - $p^m_l$: the total price if bidder $m$ is allocated $l$ segments.
An Example

- An auction allocates $K = 4$ segments.
- User $m$’s bid: $(\bm{R}^m, \bm{p}^m)$
  - bitrate matrix
    \[
    \bm{R}^m = \begin{bmatrix}
    r_1^m \\
    r_2^m \\
    r_3^m \\
    r_4^m \\
    \end{bmatrix} = \begin{bmatrix}
    1.3 \text{Mbps} & 0 & 0 & 0 \\
    0.4 \text{Mbps} & 1.3 \text{Mbps} & 0 & 0 \\
    0.4 \text{Mbps} & 0.4 \text{Mbps} & 0.4 \text{Mbps} & 0 \\
    0.2 \text{Mbps} & 0.2 \text{Mbps} & 0.2 \text{Mbps} & 0.4 \text{Mbps} \\
    \end{bmatrix}
    \]
  - Different segments can have different bitrates (e.g., 2nd row)
  - As the number of segment allocation changes, the bitrates of the same segment can change (e.g., 3rd column)
- price vector
  \[
  \bm{p}^m = (70\text{¢}, 105\text{¢}, 120\text{¢}, 135\text{¢})
  \]
MOMD Auction: Score Function

- **Score function** if bidder $m$ is allocated $l$ segments:

$$\phi(r^m_l, p^m_l) = p^m_l - C_n(r^m_l), \forall l \in \{1, \ldots, K\}$$

  - $r^m_l$ is $l$th row of bidder $m$'s bidding matrix.
Score function if bidder $m$ is allocated $l$ segments:

$$\phi(r_l^m, p_l^m) = p_l^m - C_n(r_l^m), \forall l \in \{1, \ldots, K\}$$

- $r_l^m$ is $l$th row of bidder $m$’s bidding matrix.

Compute the marginal scores:

$$S^m = \{S_1^m, S_2^m, \ldots S_K^m\},$$

where

$$S_k^m = \left\{ \begin{array}{ll}
\phi(r_1^m, p_1^m), & l = 1 \\
\phi(r_l^m, p_l^m) - \phi(r_{l-1}^m, p_{l-1}^m), & l \geq 2
\end{array} \right.$$
MOMD Auction: Winner & Payment

- Winners: the bidders that submit the highest marginal scores
  - Can have multiple different winners

- Payment: the marginal score damage that caused by the winner
An Example

- A total of 3 bidders, and an auction allocates $K = 4$ segments.
- The marginal score $S^m$ for three bidders:

\[ S^1 : \{8, 7, 5, 2\}; \]
\[ S^2 : \{9, 6, 3, 2\}; \]
\[ S^3 : \{4, 4, 3, 1\}. \]
An Example

- A total of 3 bidders, and an auction allocates $K = 4$ segments.
- The marginal score $S^m$ for three bidders:

  \[ S^1 = \{8, 7, 5, 2\}; \]

  \[ S^2 = \{9, 6, 3, 2\}; \]

  \[ S^3 = \{4, 4, 3, 1\}. \]

- **Winners** based on the highest 4 marginal scores $S^\dagger = \{9, 8, 7, 6\}$
  - User 1 wins two segments, and user 2 wins two segments
An Example

- A total of 3 bidders, and an auction allocates $K = 4$ segments.
- The marginal score $S^m$ for three bidders:

  $$S^1: \{8, 7, 5, 2\};$$
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  $$S^3: \{4, 4, 3, 1\}.$$

- Winners based on the highest 4 marginal scores $S^\dagger = \{9, 8, 7, 6\}$
  - User 1 wins two segments, and user 2 wins two segments
- Payment of user 1 based on marginal score damage
  - Without user 1, the highest 4 marginal scores are $\hat{S}^{-1} = \{9, 6, 4, 4\}$
  - Due to user 1, user 3 loses two segments with marginal scores $\{4, 4\}$
  - User 1’s payment $\tilde{p}_1$ needs to compensate his marginal core damage

$$\tilde{p}_1 - C_n(r^1_2) = 4 + 4$$

(score function score damage)
Theorem (Truthfulness and Efficiency)

Under a mild technical condition, we can prove the truthfulness of the users' bidding at the equilibrium, and show that the auction is efficient.
Simulation

- 50 video users
- Link capacities derived from real traces
- 3 schemes for single-object multi-dimensional auction
  - Non: Non-cooperative benchmark
  - Partial: Partially cooperative benchmark (in pairs)
  - Full-E: Fully cooperative with efficient score function
Social welfare decreases with the disconnected use percentage.

When 80% of users do not have Internet connection, full cooperation is 5 times better than non-cooperation.
Downloader’s payoff increases with disconnected user percentage

When 80% of users are disconnected, full cooperation is 5 times better than partial cooperation.
Mobile devices: Raspberry Pis, with monitors, LTE USB modems, and Wi-Fi adapters.

Devices can dynamically join and leave the cooperative group in a decentralized fashion.
Future Work

- Mobility management
- Impact of social relationship
- Trust and security
The Big Picture

- New paradigm of network sharing
  - Blurring the boundaries among networks
  - New perspectives on network competition and cooperation
  - New pricing plans and economic mechanisms

- The rise of collaborative economy in communication networks
  - Business-to-Business (B2B) collaborations
  - Business-to-Consumer (B2C) collaborations
  - Peer-to-Peer (P2P) collaborations

- The need of data-driven network economics
  - Data analytics lead to new opportunities for technology improvement and economic mechanism design
Thank you