Bargaining-based Mobile Data Offloading

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Outline

1. Background
2. Nash Bargaining Theory
3. System Model
4. Bargaining-based Offloading Solution
5. Simulation and Conclusion

Background

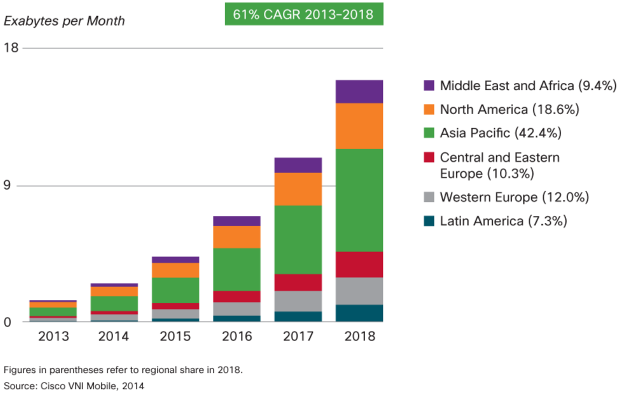


Fig. Global Mobile Data Traffic, 2013 to 2018 (from *Cisco VNI*)

- Mobile data traffic explosive growth: 61% annual grow rate
  - Reaching 15.9 exabytes per month by 2018, nearly a 11-fold increase over 2013.

Background

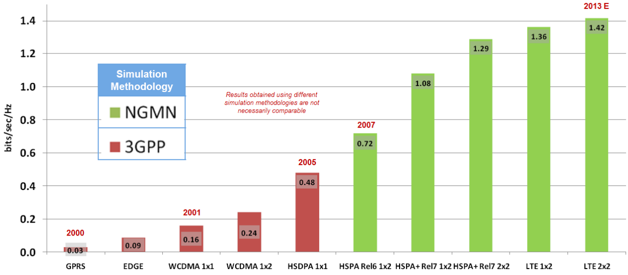


Fig. Historical Increases in Spectral Efficiency (from *Femtoforum*)

- Network capacity slow growth: less than 29% annual grow rate
  - Available spectrum band growth: 8% per year
  - Cell site increase: 7% per year
  - Spectrum efficiency growth: less than 12% per year from 2007 to 2013

$$108\% \cdot 107\% \cdot 112\% = 129\%$$

Background

- Network capacity growth vs Data traffic growth

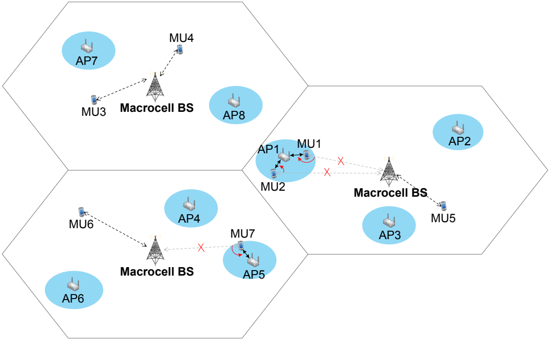
29% vs 61%

Fig. Slow network capacity growth and Fast data traffic growth

- Traditional network expansion methods
  - Upgrading access technology (e.g., WCDMA $\rightarrow$ LTE $\rightarrow$ LTE-A)
  - Acquiring new spectrum license (e.g., TV white space)
  - Developing high-frequency wireless technology (e.g., $>$ 5GHz)
  - Building more pico/micro/macro cell sites
- However, all of these methods are costly and time-consuming.

Mobile Data Offloading

- A novel approach: Mobile Data Offloading
  - **Basic idea**: Transfer the traffic of mobile cellular networks to complementary networks, such as WiFi and femtocell networks.



Example: MU1, MU2 → AP1, MU7 → AP5.

Mobile Data Offloading

- Two offloading schemes: (i) network-initiated vs (ii) user-initiated
  - Depending on which side – mobile network operators (network side) or mobile users (user side) – initiates the data offloading process.
- **In this paper, we consider the network-initiated offloading.**
  - MNOs initiates the data offloading process of every MU.
  - MUs will always follow the instructions from the network side.

Mobile Data Offloading

- To improve availability (i.e., *coverage area*) of APs, MNOs can
  - (i) deploy new APs in hotspot areas.
    - ★ Examples: AT&T and T-Mobile;
    - ★ However, the ubiquitous development of APs by MNOs themselves is expensive.
  - (ii) employ existing third-party APs in an on-demand manner.
    - ★ Examples: O2 and British Telecom;
- **In this paper, we consider the employ-based data offloading.**
  - APs are already out there, operated by personal customers, companies, stors, and even other MNOs.
  - *Just lease them whenever you need them!*

Problem

- **Mobile Data Offloading Market**
  - An MNO offloads the traffic of its MUs to the employed APs;
  - APs ask for certain monetary compensation from the MNO.

Key Problems

- **Efficiency**: How to offload traffic efficiently (e.g., maximizing the offloading benefit)?
- **Fairness**: How to share the benefit among the MNO and APOs fairly?

Our Idea

- **Nash Bargaining Theory**
  - A promising theoretic tool to achieve the efficient and fair resource allocation.

Bargaining-based Data Offloading

- **Key Idea**: The MNO negotiates with each APO for the amount of offloading traffic and the respective compensation to the APO, based on the Nash bargaining theory.

Outline

Bargaining Problem

- **Bargaining** is one of the most common activities in daily life.
  - Examples: price bargaining in an open market, wage bargaining in a labor market.
- **Bargaining problems** represent situations in which:
  - There is a common interest among players to address a mutually agreed outcome (agreement);
  - Players have specific objectives (payoff).
  - No agreement may be imposed on any player without his approval, i.e., disagreement is possible.
  - There is a conflict of interest among players about agreements.

A Simple Example

- **Scenario**: Player 1 sells a book to Player 2 at a price $p = ?$
  - Problem: Two players bargain for the price p.
  - The objective (payoff) of players: $u_1 = p,\ u_2 = 1 - p$.
    - ★ Suppose the book is worth 0 to player 1, and 1 to player 2.
  - The set of feasible agreements: $U = \{(u_1, u_2) | u_1 + u_2 = 1\}$
  - The disagreement: $D = (d_1, d_2)$, e.g., $D = (0, 0)$
  - A bargaining solution is an outcome $(v_1, v_2) \in U \cup D$

- **Key Problem**: What is a proper bargaining solution?

Bargaining Theory

- **Bargaining theory** is a theoretic tool used to identify the bargaining solution, given
  - (i) the set of all feasible agreements;
  - (ii) the disagreement.
- **Axiomatic** Approach vs **Strategic** Approach
  - Axiomatic Approach
    - ⋆ (i) Abstracting away the details of the bargaining process;
    - ⋆ (ii) Considering only the set of outcomes that satisfy certain pre-defined properties (i.e., Axioms).
    - ⋆ Typical Example: Nash Bargaining Model, 1950
  - Strategic Approach
    - ⋆ (i) Modeling the bargaining process as a game explicitly;
    - ⋆ (ii) Considering the game outcome (i.e., Nash equilibrium) that results from the players self-enforcing interactions.
    - ⋆ Typical Example: Rubinstein Bargaining Model, 1982

Nash Bargaining Theory

- **Nash bargaining theory**
  - An axiom-based bargaining theory (i.e., axiomatic approach)
  - Nash's Axioms:
    - ⋆ (i) Pareto Efficiency
    - ⋆ (ii) Symmetry
    - ⋆ (iii) Invariant to Affine Transformations
    - ⋆ (iv) Independence of Irrelevant Alternatives

- **Nash bargaining solution**
  - Nash bargaining solution is the unique solution that satisfies the Nash's 4 axioms.

Nash Bargaining Solution

Nash Bargaining Solution (NBS)

- Nash bargaining solution is the unique solution that satisfies the Nash's 4 axioms. Meanwhile, it solves the optimization problem:

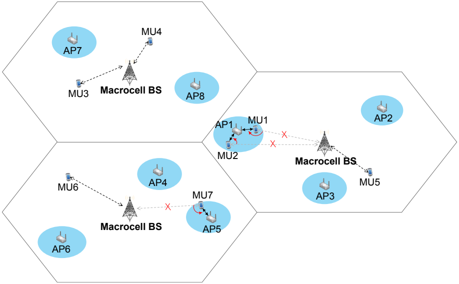
$$\max_{v_1, v_2} \quad (v_1 - d_1) \cdot (v_2 - d_2)$$
$$\textit{subject to} \quad (v_1, v_2) \in U$$
$$v_1 \geq d_1, \;\; v_2 \geq d_2$$

- Recall the previous example:
  - When $(d_1, d_2) = (0, 0)$: NBS is $(v_1, v_2) = (0.5, 0.5)$;
  - When $(d_1, d_2) = (0, 0.4)$: NBS is $(v_1, v_2) = (0.3, 0.7)$;

Outline

System Model

- One Mobile Network Operator (MNO)
  - Operating one or multiple macrocell base stations (BSs);
  - Serving many mobile users (MUs);
- N Access Point Owners (APOs)
  - Each operating one WiFi or femtocell access point (AP);
  - APs are geographically non-overlapping with each other;



Example: $N = 8$ APs. The traffic of MU 1 and MU 2 can be offloaded to AP 1, and the traffic of MU 7 can be offloaded to AP 5.

System Model

- Key Variables
  - The traffic offloaded to each AP;
  - The payment to each AP;
- **Traffic Offloading Profile**: $\mathbf{x} = (x_1, ..., x_N)$
  - x_n: the traffic offloaded to AP n;
- **Payment Profile**: $\mathbf{z} = (z_1, ..., z_N)$
  - z_n: the payment to AP n;

System Model

- **MNO's Payoff** — cost reduction

$$\mathrm{U}(\mathbf{x};\mathbf{z}) = \mathrm{R}(\mathbf{x}) - \sum_{n=1}^{N} z_n$$

  ★ $\mathrm{R}(\mathbf{x})$: the MNO's serving cost reduction;
  ★ $\sum_{n=1}^{N} z_n$: the MNO's total payment to APOs;

- **APO's Payoff** — profit improvement

$$\mathrm{V}_n(x_n;z_n) = \mathrm{Q}_n(x_n) + z_n$$

  ★ $\mathrm{Q}_n(x_n)$: the APO n's profit loss from its own traffic;
  ★ z_n: the APO n's profit from serving the MNO;

System Model

- **Social Welfare** — sum of the MNO's and all APOs' payoffs

$$\Psi(\mathbf{x}) = \mathrm{R}(\mathbf{x}) + \sum_{n=1}^{N} \mathrm{Q}_n(x_n)$$

  ⋆ The payment between the MNO and each APO is canceled out.

Key Problems

Key Problems

- How much traffic should each APO offload for the MNO?
- How much should each APO be paid for the offloading?

  Considering the efficiency and fairness issues,
  - **Efficiency**: maximizing the offloading benefit;
  - **Fairness**: sharing the benefit among the MNO and APOs fairly.

Outline

A Simple One-to-One Bargaining

- We first consider a simple network scenario with one APO n.
  $\rightarrow$ **One-to-One Bargaining**

One-to-One Bargaining Problem

$$\max_{(x_n, z_n)} \ \mathrm{U}(x_n; z_n) \cdot \mathrm{V}_n(x_n; z_n)$$
$$\text{s.t.} \ \ \mathrm{U}(x_n; z_n) \geq \mathrm{U}^0, \ \mathrm{V}_n(x_n; z_n) \geq \mathrm{V}_n^0$$

- $\mathrm{U}^0 = 0$: the disagreement of the MNO;
- $\mathrm{V}_n^0 = 0$: the disagreement of the APO;

A Simple One-to-One Bargaining

- Introduce a new variable $\pi_n = \mathrm{V}_n(x_n; z_n)$ (denoting APO's payoff)
  $\rightarrow$ **An Equivalent Bargaining**

An Equivalent Bargaining Problem

$$\max_{(x_n, \pi_n)} \; (\Psi(x_n) - \pi_n) \cdot \pi_n$$

$$\text{s.t.} \;\; \Psi(x_n) - \pi_n \geq 0, \;\; \pi_n \geq 0$$

A Simple One-to-One Bargaining

One-to-One NBS

The NBS (x_n^*, π_n^*) for the one-to-one bargaining is

$$x_n^* = x_n^o, \quad \text{and} \quad \pi_n^* = \frac{1}{2} \cdot \Psi(x_n^o)$$

- $x_n^o = \arg\max_{x_n} \Psi(x_n)$: bargaining solution maximizes social welfare;
- $\pi_n^* = \frac{1}{2} \cdot \Psi(x_n^o)$: the APO gets half of the generated social welfare;
- $\mathrm{U} = \Psi(x_n^o) - \pi_n^* = \frac{1}{2} \cdot \Psi(x_n^o)$: the MNO gets half of the generated social welfare;

A General One-to-Many Bargaining

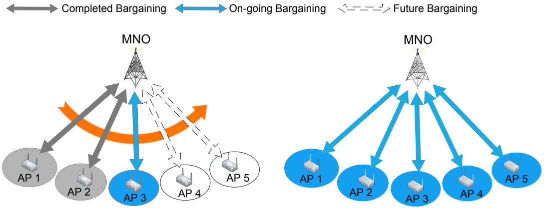
- We now consider a general network scenario with N APOs.

  → **One-to-Many Bargaining**

  - N coupled one-to-one bargainings
    - Bargaining between the MNO and APO 1 for (x_1, z_1)
    - Bargaining between the MNO and APO 2 for (x_2, z_2)
    - ...
    - Bargaining between the MNO and APO N for (x_N, z_N)
  - Bargaining Solution: $\{\mathbf{x}, \mathbf{z}\} = \{(x_n, z_n)\}_{n \in \mathcal{N}}$

A General One-to-Many Bargaining

- **Bargaining Protocol**
  - Sequential Bargaining: The MNO bargains with all APOs sequentially, in a predefined order;
  - Concurrent Bargaining: The MNO bargains with all APOs concurrently;



(a) Sequential Bargaining (b) Concurrent Bargaining

- **APO Grouping Structure**
  - APOs can either bargain individually with the MNO, or form one or multiple groups bargaining with the MNO jointly.

Sequential Bargaining

Sequential Bargaining

- **Sequential Nash Bargaining Solution (NBS)**

$$\{\mathbf{x}^*, \boldsymbol{\pi}^*\} = \{(x_n^*, \pi_n^*)\}_{n\in\mathcal{N}}$$

Sequential NBS

The NBS $\{\mathbf{x}^*, \boldsymbol{\pi}^*\}$ under the sequential bargaining is

$$x_n^* = x_n^o, \quad \pi_n^* = \frac{\bar{\Delta}_n}{2}, \quad \forall n = 1, ..., N$$

- $\mathbf{x}^o = \arg\max_{\mathbf{x}} \Psi(\mathbf{x})$: bargaining solution maximizes social welfare;
- $\bar{\Delta}_n$: the virtual marginal social welfare generated by APO n;

Sequential Bargaining

- Virtual Marginal Social Welfare generated by APO n

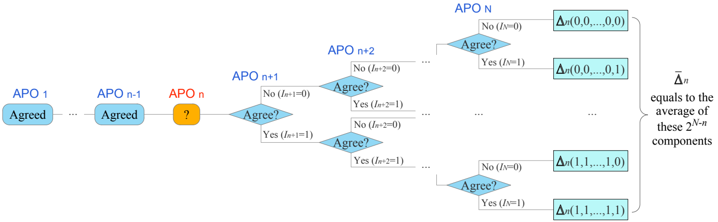
$$\bar{\Delta}_n = \sum_{I_{n+1}=0}^{1} \dots \sum_{I_N=0}^{1} \frac{\Delta_n(I_{n+1}; \dots; I_N)}{2^{N-n}}$$

  - The average marginal social welfare generated by APO n, assuming
    - ⋆ the MNO has reached agreements with all APOs $1, \dots, n-1$ (before n);
    - ⋆ the MNO will reach agreement with each APO in $\{n+1, \dots, N\}$ (after n) with a probability of 0.5.

  - $\Delta_n(I_{n+1}; \dots; I_N) = \Psi(x_1^*, \dots, x_{n-1}^*, x_n^*, I_{n+1}x_{n+1}^*, \dots, I_N x_N^*) - \Psi(x_1^*, \dots, x_{n-1}^*, 0, I_{n+1}x_{n+1}^*, \dots, I_N x_N^*)$.
    - ⋆ The marginal social welfare generated by APO n, assuming the MNO has reached agreements with all APOs $1, \dots, n-1$, and will ($I_i = 1$) or will not ($I_i = 0$) reach agreement with each APO $i \in \{n+1, \dots, N\}$.

Sequential Bargaining

- Illustration of $\bar{\Delta}_n$



- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - $\bar{\Delta}_4 = \Delta_4 = \log(\frac{5}{4})$
  - $\bar{\Delta}_3 = \frac{\Delta_3(1)+\Delta_3(0)}{2} = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$
  - $\bar{\Delta}_2 = \frac{\Delta_2(1,1)+\Delta_2(1,0)+\Delta_2(0,1)+\Delta_2(0,0)}{4} = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \ldots = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$

Property of Sequential NBS

Early-Mover Advantage

Under the sequential bargaining, an APO will obtain a higher payoff, if it bargains with the MNO earlier.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_3 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$, $\bar{\Delta}_2 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$
  - **Early-Mover Advantage**: $\bar{\Delta}_4 < \bar{\Delta}_3 < \bar{\Delta}_2 < \bar{\Delta}_1$

Property of Sequential NBS

Invariance to APO-order Changing

Under the sequential bargaining, the bargaining order of APOs does not affect the MNO's payoff.

- The MNO's payoff: $U^* = \sum_{I_1=0}^{1} \sum_{I_2=0}^{1} \cdots \sum_{I_N=0}^{1} \frac{\Psi(I_1 x_1^*, I_2 x_2^*, \ldots, I_N x_N^*)}{2^N}$

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_3 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$, $\bar{\Delta}_2 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$
  - **The MNO's payoff**:
    $U^* = \Psi(5) - \frac{\bar{\Delta}_4+\bar{\Delta}_3+\bar{\Delta}_2+\bar{\Delta}_1}{2} = \frac{\log 5+4\log 4+6\log 3+4\log 2+\log 1}{16}$

Group Effect in Sequential Bargaining

Grouping Benefit

Under the sequential bargaining, group bargaining always benefits the group APO members.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - With no group:
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_3 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$, $\bar{\Delta}_2 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$
  - With a group $\{2, 3\}$ (APOs 2 and 3 form a group):
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_{2,3} = \frac{\log(\frac{5}{3})+\log(\frac{4}{2})}{2}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})+\log(\frac{3}{2})+\log(\frac{2}{1})}{4}$
  - **Grouping Benefit**: $\bar{\Delta}_{2,3} > \bar{\Delta}_2 + \bar{\Delta}_3$

Group Effect in Sequential Bargaining

Positive Externality

Under the sequential bargaining, group bargaining improves the payoffs of all APOs bargaining before the group, while does not affect the APOs bargaining after the group.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - With no group:
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_3 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$, $\bar{\Delta}_2 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$
  - With a group $\{2, 3\}$ (APOs 2 and 3 form a group):
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_{2,3} = \frac{\log(\frac{5}{3})+\log(\frac{4}{2})}{2}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})+\log(\frac{3}{2})+\log(\frac{2}{1})}{4}$
  - **Positive Externality**: $\bar{\Delta}_1$ (group) $>$ $\bar{\Delta}_1$ (no group)
$\bar{\Delta}_4$ (group) $=$ $\bar{\Delta}_4$ (no group)

Concurrent Bargaining

Concurrent Bargaining

- **Concurrent Nash Bargaining Solution (NBS)**

$$\{\mathbf{x}^*, \boldsymbol{\pi}^*\} = \{(x_n^*, \pi_n^*)\}_{n\in\mathcal{N}}$$

Concurrent NBS

The NBS $\{\mathbf{x}^*, \boldsymbol{\pi}^*\}$ under the concurrent bargaining is

$$x_n^* = x_n^o, \quad \pi_n^* = \frac{\widetilde{\Delta}_n}{2}, \quad \forall n = 1, ..., N$$

- $\mathbf{x}^o = \arg\max_{\mathbf{x}} \Psi(\mathbf{x})$: bargaining solution maximizes social welfare;
- $\widetilde{\Delta}_n = \Psi(\mathbf{x}_{-n}^*, x_n^*) - \Psi(\mathbf{x}_{-n}^*, 0)$: the actual marginal social welfare generated by APO n;

Property of Concurrent NBS

Invariance to AP-index Changing

The APO-index has no impact on the APO's payoff under the concurrent bargaining.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_3 = \log(\frac{5}{4})$, $\widetilde{\Delta}_2 = \log(\frac{5}{4})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - **Invariance to AP-index Changing**: $\widetilde{\Delta}_4 = \widetilde{\Delta}_3 = \widetilde{\Delta}_2 = \widetilde{\Delta}_1$

Property of Concurrent NBS

Concurrently Moving Tragedy

The payoff of each APO under the concurrent bargaining equals to the worst-case payoff that it can achieve under the sequential bargaining.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - Under concurrent bargaining,
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_3 = \log(\frac{5}{4})$, $\widetilde{\Delta}_2 = \log(\frac{5}{4})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - Under sequential bargaining,
  - $\bar{\Delta}_4 = \log(\frac{5}{4})$, $\bar{\Delta}_3 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})}{2}$, $\bar{\Delta}_2 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 2+\log(\frac{3}{2})}{4}$
  - $\bar{\Delta}_1 = \frac{\log(\frac{5}{4})+\log(\frac{4}{3})\cdot 3+\log(\frac{3}{2})\cdot 3+\log(\frac{2}{1})}{8}$
  - **Concurrently Moving Tragedy**: $\widetilde{\Delta}_4 = \bar{\Delta}_4$, $\widetilde{\Delta}_3 < \bar{\Delta}_3$, $\widetilde{\Delta}_2 < \bar{\Delta}_2$, $\widetilde{\Delta}_1 < \bar{\Delta}_1$

Group Effect in Concurrent Bargaining

Grouping Benefit

Under the concurrent bargaining, grouping of APOs always benefits the group members.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - With no group:
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_3 = \log(\frac{5}{4})$, $\widetilde{\Delta}_2 = \log(\frac{5}{4})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - With a group $\{2, 3\}$ (APOs 2 and 3 form a group):
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_{2,3} = \log(\frac{5}{3})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - **Grouping Benefit**: $\widetilde{\Delta}_{2,3} > \widetilde{\Delta}_2 + \widetilde{\Delta}_3$

Group Effect in Concurrent Bargaining

Non-Externality

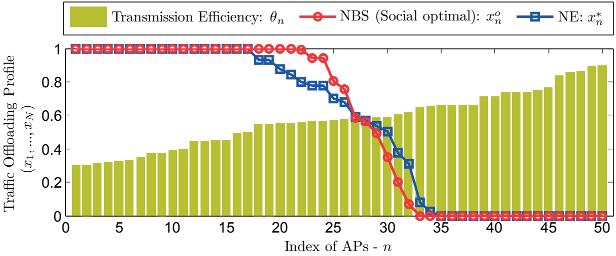
Under the concurrent bargaining, grouping of APOs does not affect the APOs not in the group.

- Example: $N = 4$ APOs, $x_n^* = 1$, $\Psi(\mathbf{x}) = \log(1 + sum(\mathbf{x}))$
  - With no group:
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_3 = \log(\frac{5}{4})$, $\widetilde{\Delta}_2 = \log(\frac{5}{4})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - With a group $\{2, 3\}$ (APOs 2 and 3 form a group):
  - $\widetilde{\Delta}_4 = \log(\frac{5}{4})$, $\widetilde{\Delta}_{2,3} = \log(\frac{5}{3})$, $\widetilde{\Delta}_1 = \log(\frac{5}{4})$
  - **Non-Externality**: $\widetilde{\Delta}_1$ (group) $= \widetilde{\Delta}_1$ (no group)
    $\widetilde{\Delta}_4$ (group) $= \widetilde{\Delta}_4$ (no group)

Outline

Simulations

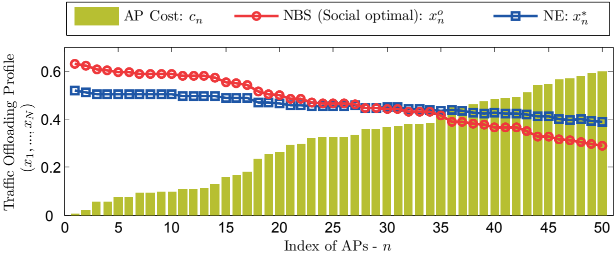
- **Offloading Solution vs Transmission Efficiency θ_n**



★ Green Bar: The transmission efficiency of MUs in each APO;
★ Red Circle Curve: The traffic offloading solution (social optimality) based on the Nash bargaining solution;
★ Blue Square Curve: The traffic offloading solution based on the non-cooperative game equilibrium;

Simulations

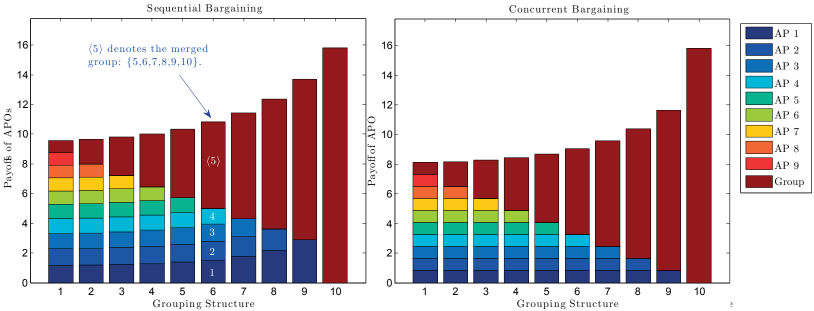
- **Offloading Solution vs AP Serving Cost c_n**



★ Green Bar: The transmission efficiency of each APO;
★ Red Circle Curve: The traffic offloading solution (social optimality) based on the Nash bargaining solution;
★ Blue Square Curve: The traffic offloading solution based on the non-cooperative game equilibrium;

Simulations

- **Payoff Division and Grouping Effect**



★ Left figure: Payoffs of APOs under sequential bargaining;
– Observation: Early-mover advantage, grouping benefit, positive externality

★ Right figure: Payoffs of APOs under concurrent bargaining;
– Observation: Concurrently moving tragedy, grouping benefit, non-externality

Conclusion

- We study a general mobile data offloading market with one MNO and multiple APOs.
- We propose a one-to-many bargaining framework for the data offloading problem, which can achieve efficient offloading solution and fair benefit division (among the MNO and APOs).
- We analyze the one-to-many bargaining systematically under different bargaining protocols and grouping structure.