An Iterative Double Auction for Mobile Data Offloading

George Iosifidis, **Lin Gao**, Jianwei Huang, Leandros Tassiulas

The Centre for Research and Technology Hellas (CERTH)
University of Thessaly (UTH), Volos, Greece

Network Communications and Economics Lab (NCEL)
The Chinese University of Hong Kong (CUHK), Shatin, Hong Kong

Background

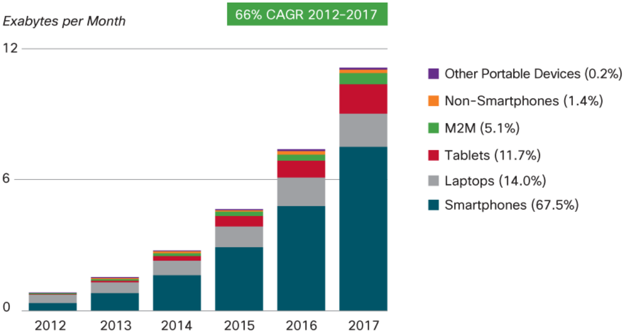


Fig. Global Mobile Data Traffic, 2012 to 2017 (from *Cisco VNI*)

- Mobile data traffic explosive growth: 66% annual grow rate
  - Reaching 11.2 exabytes per month by 2017, a 13-fold increase over 2012 or a 46-fold increase over 2010.

Background

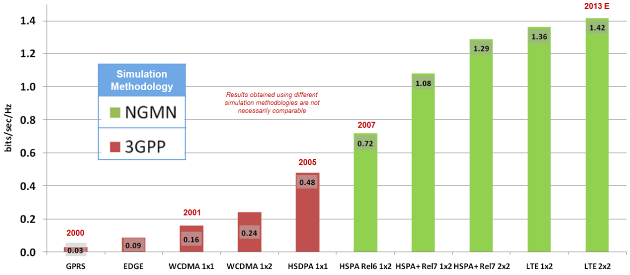


Fig. Historical Increases in Spectral Efficiency (from *Femtoforum*)

- 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

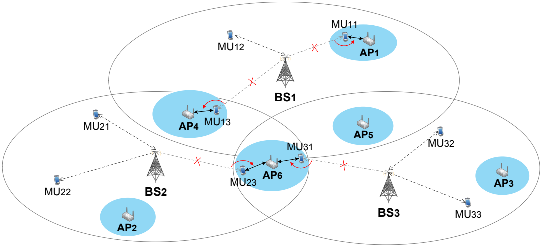
29% vs 66%

Fig. Slow network capacity growth and Fast data traffic growth

- Traditional network expansion methods
  - Upgrading access technology (e.g., WCDMA → LTE → 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: $MU_{11} \rightarrow AP_1$, $MU_{13} \rightarrow AP_4$, $MU_{23} \rightarrow AP_6$, $MU_{31} \rightarrow AP_6$.

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 dense 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**
  - MNOs offload the traffic of their MUs to the employed APs;
  - APs ask for certain monetary compensation from MNOs.

The Key Problems

- From the MNO's Perspective: How much traffic should each BS offload to each AP, and how much to pay?
- From the AP owner's Perspective: How much traffic should each AP admit for each BS, and how much to charge?

Outline

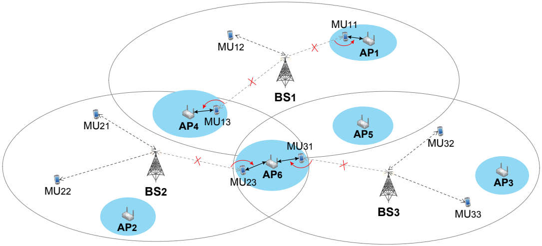
1. Background
2. System Model
3. Iterative Double Auction
4. Conclusion

Outline

1. Background
2. System Model
3. Iterative Double Auction
4. Conclusion

System Model

- A general model of multiple BSs and multiple APs
  - $\mathcal{M} \triangleq \{1, ..., M\}$: the set of BSs;
  - $\mathcal{I} \triangleq \{1, ..., I\}$: the set of involved APs.
  - Every BS or AP has private information (*information asymmetry*).



Example: $\mathcal{M} = \{1, 2, 3\}$ and $\mathcal{I} = \{1, 2, 3, 4, 5, 6\}$.

System Model

- For each BS $m \in \mathcal{M}$,
  - x_{mi}: *request*, the bytes of data that BS m want to offload to AP i;
  - $\mathbf{x}_m \triangleq \{x_{m1}, ..., x_{mI}\}$: *offload request vector* of BS m (to all APs);
  - $J_m(\mathbf{x}_m)$: the utility (cost reduction) function of BS m,
    - Positive, increasing, and strictly concave.
- For each AP $i \in \mathcal{I}$,
  - C_i: *capacity constraint* of AP i;
  - y_{im}: *admission*, the bytes of data that AP i want to admit from BS m;
  - $\mathbf{y}_i \triangleq \{y_{i1}, ..., y_{iM}\}$: *offload admission vector* of AP i (for all BSs);
  - $V_i(\mathbf{y}_i)$: the cost function of AP i,
    - Positive, increasing, and strictly convex.
- **A market outcome is feasible only if the BSs and APs finally agree on the outcome:**

$$x_{mi} = y_{im}, \quad \forall m \in \mathcal{M}, i \in \mathcal{I}.$$

System Model

- Information Asymmetry
  - The utility function $J_m(\mathbf{x}_m)$ is the private information of BS m:
    - ★ $J_m(\mathbf{x}_m)$ is only known by BS m, and not known by other BSs, APs, and possible market controllers.
  - The cost function $V_i(\mathbf{y}_i)$ is the private information of AP i:
    - ★ $V_i(\mathbf{y}_i)$ is only known by AP i, and not known by other APs, BSs, and possible market controllers.

A Benchmark Solution

Social Welfare Maximization (Efficiency)

$$\underset{\mathbf{x}_m, \mathbf{y}_i, \forall m, \forall i}{\textbf{maximize}} \quad \sum_{m \in \mathcal{M}} J_m(\mathbf{x}_m) - \sum_{i \in \mathcal{I}} V_i(\mathbf{y}_i) \qquad \text{......}\textit{Social Welfare}$$

$$\textbf{subject to} \quad \text{(i)} \quad \textstyle\sum_{m \in \mathcal{M}} y_{im} \leq C_i, \ \forall i \in \mathcal{I}, \qquad \text{......}\textit{Capacity constraint}$$

$$\text{(ii)} \quad x_{mi} = y_{im}, \ \forall m \in \mathcal{M}, i \in \mathcal{I}. \qquad \text{......}\textit{Feasibility}$$

KKT Conditions

$$\text{(A1)}: \ \frac{\partial J_m(\mathbf{x}_m)}{\partial x_{mi}} - \mu_{mi} = 0, \quad \text{(A2)}: \ \frac{\partial V_i(\mathbf{y}_i)}{\partial y_{im}} - \mu_{mi} + \lambda_i = 0,$$

$$\text{(A3)}: \ \lambda_i \cdot \left(\sum_{m \in \mathcal{M}} y_{im} - C_i \right) = 0, \quad \text{(A4)}: \ \mu_{mi} \cdot (y_{im} - x_{mi}) = 0,$$

$$\text{(A5)}: \ x_{mi} = y_{im}.$$

{socially optimal KKT}

Challenge

- However, it is difficult to achieve the efficiency (social welfare maximization solution).
  - Conflict of interests: BSs want to offload more traffic with less payment, while APs want to admit less traffic with more payment.
  - Asymmetry of information: the utility function of each BS and the cost function of each AP are private information.

Traditional Approach

- A traditional approach: Two-sided Market → Double Auction
  - A market controller or broker acts as the auctioneer;
  - BSs and APs act as bidders;
  - The auctioneer decides the allocation and payment rules such that all bidders truthfully disclose their private information.
- **Double auction may be unavailable in our model !**
  - Every bidder may have infinite amount of private information due to the continuity of the utility/cost function.
  - According to [Myerson, J. Econ. Theory, 1983], there does *not* exist a double auction that possesses an (i) efficient, (ii) individually rational, (iii) incentive compatible and (iv) budget balanced outcome.

Our Approach

- Our proposed approach: Iterative Double Auction
  - Basically, it is a round-based mechanism, and each round constructs a double auction.

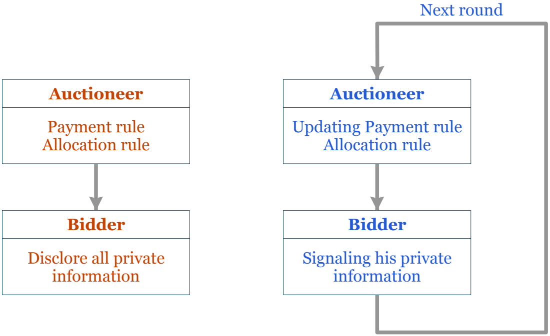


Fig. Double Auction vs Iterative Double Auction

Outline

1 Background

2 System Model

3 Iterative Double Auction

4 Conclusion

Iterative Double Auction – IDA

Basic Idea of IDA

- **Step 1**: The auctioneer broadcasts the payment rule $h_m(\cdot)$ to every BS m and the reimbursement rule $l_i(\cdot)$ to every AP i;
- **Step 2**: Every BS m determines his bids p_{mi} to every AP i. Every AP i determines his bid α_{im} to every BS m. Both aim at maximizing their respective objectives. (Signals)
- **Step 3**: The auctioneer determines the allocation rule x_{mi} or y_{im} between every BS m and AP i, aiming at maximizing a public auxiliary objective function:

$$W(\mathbf{x}, \mathbf{y}) \triangleq \sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{I}} \left(p_{mi} \log x_{mi} - \frac{\alpha_{im}}{2} y_{im}^2 \right).$$

IDA - Step 3

The Auctioneer's Allocation Problem in Step 3

$$\underset{\mathbf{x}_m, \mathbf{y}_i, \forall m, \forall i}{\textbf{maximize}} \quad \sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{I}} \left(p_{mi} \log x_{mi} - \frac{\alpha_{im}}{2} y_{im}^2 \right)$$

subject to (i) $\sum_{m \in \mathcal{M}} y_{im} \leq C_i, \ \forall i \in \mathcal{I},$

(ii) $x_{mi} = y_{im}, \ \forall m \in \mathcal{M}, i \in \mathcal{I}.$

KKT Conditions

$$\text{(B1)}: \ x_{mi} = \frac{p_{mi}}{\mu_{mi}}, \quad \text{(B2)}: \ y_{im} = \frac{\mu_{mi} - \lambda_i}{\alpha_{mi}},$$

$$\text{(B3)}: \ \lambda_i \cdot \left(\sum_{m \in \mathcal{M}} y_{im} - C_i \right) = 0, \quad \text{(B4)}: \ \mu_{mi} \cdot (y_{im} - x_{mi}) = 0,$$

$$\text{(B5)}: \ x_{mi} = y_{im}.$$

{**auctioneer optimal KKT**}

IDA - Step 3

$\{$**socially optimal KKT**$\} \Longleftrightarrow \{$**auctioneer optimal KKT**$\}$

Observation from Step 3

The auctioneer's solution in Step 3 is equivalent to the social welfare maximization solution, if bidders submit the following bids:

$$(\text{C1}): \; p_{mi} = x_{mi} \cdot \frac{\partial J_m(\mathbf{x}_m)}{\partial x_{mi}}, \quad (\text{C2}): \; \alpha_{im} = \frac{1}{y_{im}} \cdot \frac{\partial V_i(\mathbf{y}_i)}{\partial y_{im}}.$$

$\{$**socially desirable bids**$\}$

- **Then, the next question is:**

  What is the payment rule $h_m(\cdot)$ and the reimbursement rule $l_i(\cdot)$ such that BSs and APs bid according to (C1) and (C2)?

IDA - Step 2

The Bidder's Bidding Problem in Step 2

$$\underset{p_{mi},\forall i}{\textbf{maximize}} \quad J_m(\mathbf{x}_m) - h_m(\mathbf{p}_m), \quad \text{for every BS } m;$$

$$\underset{\alpha_{im},\forall m}{\textbf{maximize}} \quad -V_i(\mathbf{y}_i) + l_i(\boldsymbol{\alpha}_i), \quad \text{for every AP } i.$$

KKT Conditions

$$\text{(D1)}: \frac{\partial J_m(\mathbf{x}_m)}{\partial x_{mi}} = \mu_{mi} \frac{\partial h_m(\mathbf{p}_m)}{\partial p_{mi}}, \quad \ldots$$

$$\text{(D2)}: \frac{\partial V_i(\mathbf{y}_i)}{\partial y_{im}} = \frac{\alpha_{im}^2}{\lambda_i - \mu_{mi}} \frac{\partial l_i(\boldsymbol{\alpha}_i)}{\partial \alpha_{im}}, \quad \ldots$$

{**individually optimal bids**}

IDA - Step 1

{**socially desirable bids**} $\Longleftrightarrow$ {**individually optimal bids**}

The Optimal Payment Rule to BS m in Step 1

$$(\text{F1}): \ h_m(\mathbf{p}_m) = \sum_{i \in \mathcal{I}} p_{mi}.$$

The Optimal Reimbursement Rule for AP i in Step 1

$$(\text{F2}): \ l_i(\boldsymbol{\alpha}_i) = \sum_{m=1}^{M} \frac{(\lambda_i - \mu_{mi})^2}{\alpha_{im}}$$

IDA - A Brief Summary

Traffic Offload and Payment of BS m

- BS m's traffic offloaded to an AP i is proportional to the bid p_{mi} proposing to AP i;
- BS m pays exactly his bid, i.e., the amount he proposed;

$$\text{(B1)}: \ x_{mi} = \frac{p_{mi}}{\mu_{mi}}; \quad \text{(F1)}: \ h_m(\mathbf{p}_m) = \sum_{i \in \mathcal{I}} p_{mi}.$$

Traffic Admit and Reimbursement of AP i

- AP i's admitted traffic from a BS m is inversely proportional to the bid α_{im} to BS m;
- AP m's reimbursement from a BS m is proportional to the traffic he admits from BS m;

$$\text{(B2)}: \ y_{im} = \frac{\mu_{mi} - \lambda_i}{\alpha_{mi}}; \quad \text{(F2)}: \ l_i(\boldsymbol{\alpha}_i) = \sum_{m \in \mathcal{M}} \frac{(\lambda_i - \mu_{mi})^2}{\alpha_{im}} = \sum_{m \in \mathcal{M}} y_{im} \cdot (\mu_{mi} - \lambda_i).$$

IDA - The Algorithm

The Detailed IDA Algorithm

- Initialize the Lagrange multipliers $\mu_{mi}^{t} = \mu_{mi}^{0}$ and $\lambda_{i}^{t} = \lambda_{i}^{0}$;
- **while** not converging in round t **do**
- The auctioneer announces the payment rule and reimbursement rule;
- Every BS m computes the optimal bids $p_{mi,i=1,\dots,I}$;
- Every AP i computes the optimal bids $\alpha_{im,m=1,\dots,M}$;
- The auctioneer computes the allocation solution x_{im} and y_{im};
- The auctioneer updates the Lagrange multipliers μ_{mi}^{t} and λ_{i}^{t}.
- **end**

IDA - Convergence

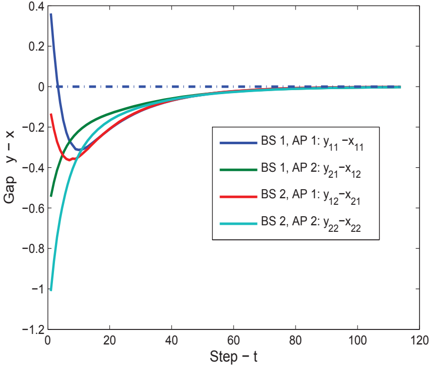


Fig. Evolution of the gap between x_{mi} and y_{im}, i.e., $y_{im} - x_{mi}$.

Lemma - Convergence of IDA

The IDA algorithm converges to a stationary state.

IDA - Property

Lemma - Property of IDA

- Efficient
  - The IDA mechanism achieves the social welfare maximization;
- Weakly Budget Balanced
  - The auctioneer does not lose money by organizing an IDA;
  - If there is no capacity constraint, the auctioneer neither lose money nor gain money by organizing an IDA (strongly budget balanced);
- Incentive Compatible
  - All bidders (price-taking) act in a truthful manner;
- Individually Rational
  - All bidders achieve non-negative utilities.

Outline

1 Background

2 System Model

3 Iterative Double Auction

4 Conclusion

Main Contribution

- We study a general mobile data offloading market with multiple BSs and multiple APs under information asymmetry.
- We propose an iterative double auction mechanism, which achieves an efficient, weakly budget balanced, individually rational, and incentive compatible outcome.

Future Work

- Upcoming Plan: What is the impacts of price-participation and collusion of bidders (BSs and APs) on the algorithm and the market outcome?
- Milestone Plan: How to involve the behavior of MUs into the data offloading market?

Our Related Recent Results

- In [Lin&George&Jianwei Huang, Infocom SDP 2013], we studied the mobile data offloading market under symmetric and complete information.

  → **Multi-leader multi-follower Stackelberg game.**

- In [Michael&Jianwei Huang, WiOpt 2013], we studied the Wi-Fi offloading problem with delay tolerant applications.

  → **Finite-horizon sequential decision problem.**

Contact

Dr. Lin Gao

gaolin021@gmail.com

ncel.ie.cuhk.edu.hk

Thank You !