Fair and Optimal Mobile Assisted Offloading

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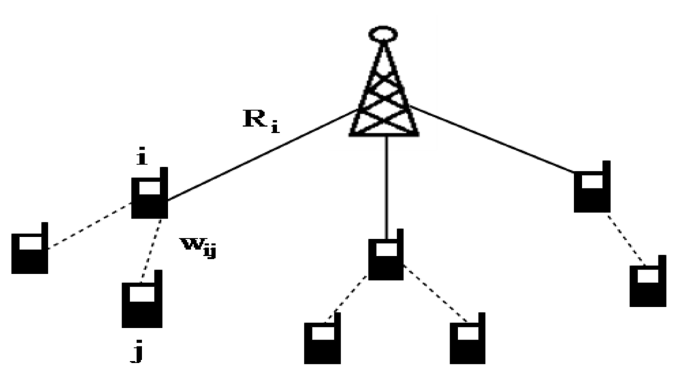
Introduction

- Unprecedented growth in mobile data traffic, but not so much in network capacity and coverage.
- Offloading through WiFi allows more efficient use of cellular resources; also extends coverage.
- Offloading mechanisms: Offloading through WiFi routers, mobile assisted offloading.
- Mobile assisted offloading: mobiles with good cellular links act as WiFi hotspots; offload cellular data of nearby mobiles with poor cellular links.
- **Objective**: BS resource allocation, hotspot selection and hotspot mobile association to achieve fair and optimal network wide throughputs.

Network Model



- One Base Station (BS), N mobiles.
- R_i: throughput of mobile i if it uses all the BS resources.
- **Assumed legacy setup**: BS resources divided equally among all the mobiles: mobile i receives a throughput R_i/N.
- Mobiles with good cellular links act as hotspots; provide the internet access to other mobiles over WiFi.
- W_{ij}: maximum possible WiFi rate between mobiles i and j.
- We consider both PCF and DCF based WiFi access.
- **Objective**: BS resource allocation, hotspot selection and hotspot mobile association to achieve fair and optimal network wide throughputs.
  - $a_{ii} \in \{0,1\}$; equals 1 iff i is a hotspot.
  - $a_{ij} \in \{0,1\}, i \neq j$; equals 1 iff i serves j.
  - α_i: fraction of BS resources allocated to hotspot i.
  - T_j: throughput received by mobile j.

Problem Formulation

- **Throughput Optimization**

$$\mathcal{P}_1 : \text{maximize} \quad \sum_j T_j \quad \text{subject to}$$

$$T_j \geq \frac{R_j}{N}, \ \forall j \quad (1) \qquad \sum_{j=1}^{N} a_{ij} T_j = \alpha_i R_i, \ \forall i \quad (4)$$

$$\sum_{i=1}^{N} a_{ij} = 1, \ \forall j \quad (2) \qquad \sum_{i=1}^{N} \alpha_i \leq 1, \ \forall i \quad (5)$$

$$a_{ij} \leq a_{ii}, \ \forall i, j \quad (3) \qquad \sum_{j=1: j \neq i}^{N} a_{ij} \frac{T_j}{W_{ij}} \leq 1, \ \forall i \quad (6)$$

- **Proportional Increment Optimization**

$$\mathcal{P}_2 : \text{maximize} \quad \xi$$
$$\text{subject to} \quad T_j = \xi \frac{R_j}{N}, \ \forall j$$
$$(2), (3), (4), (5) \text{ and } (6)$$

Equivalent Formulation

$$\mathcal{P}_3^{\theta} : \text{minimize} \quad \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij} \frac{R_j}{N R_i},$$
$$\text{subject to} \quad \sum_{j \neq i} a_{ij} \frac{R_j}{N W_{ij}} \leq \theta, \ i = 1, \ldots, N, \quad (7)$$
$$(2), (3)$$

$\gamma(\theta)$: optimal value of $\mathcal{P}_3^{\theta}$.

- $\mathcal{P}_1$ is equivalent to $\mathcal{P}_3^1$.
- $\mathcal{P}_2$ can be solved by solving sequence of $\mathcal{P}_3^{\theta}$, with different values of θ.
  - Start with θ_0, solve $\mathcal{P}_3^{\theta_0}$.
  - For $k = 0, 1, \ldots, \theta_{k+1}$ is obtained as a function of θ_k and $\gamma(\theta_k)$.
  - Solve $\mathcal{P}_3^{\theta_{k+1}}$ and so on.
  - For sufficiently large k, θ_k and $\gamma(\theta_k)$ give a solution to $\mathcal{P}_2$.

$\mathcal{P}_3^{\theta}$ as Capacitated Facility Location Problem (CFLP)

- Hotspots equivalent to facilities and mobiles to customers.
- Facility opening costs are $1/N$ for all the hotspots.
- Service cost from hotspot i to mobile j is equal to $\frac{R_j}{N R_i}$.
- Hotspot capacity constraint are as in (7).
- CFLPs focus on opening facilities and assigning them to customers so as to minimize the total cost.

Belief Propagation (BP) Algorithm

- The proposed BP algorithm is for general CFLP.
- BP algorithms have been proposed for uncapacitated facility location problem and generalized assignment problems, special cases of CFLPs. These algorithms can be deduced from our algorithm.
- Define $g_{ij} = \begin{cases} \frac{R_j}{N R_i} \text{ if } j \neq i \\ 0 \text{ if } j = i, \end{cases}$

1. *Initialization:*
$$\mu^0_{M_j \to H_i} = \mu^0_{H_i \to M_j} = 0$$
2. *Messages at kth iteration:*
$$\mu^k_{M_j \to H_i} = -g_{ij} - \max_{l \neq i} (\mu^{k-1}_{H_l \to M_j} - g_{lj})$$
$$\mu^k_{H_i \to M_j} = \max_{\substack{\psi \in \mathcal{H}_i: \\ j \in \psi}} \left[\sum_{p \in \psi: p \neq j} \mu^{k-1}_{M_p \to H_i} \right] - \max \left\{ \max_{\substack{\psi \in \mathcal{H}_i: \\ j \notin \psi, \psi \neq \emptyset}} \left[\sum_{p \in \psi} \mu^{k-1}_{M_p \to H_i} \right], 1/N \right\}$$
3. *Belief at kth iteration:*
$$\tilde{b}^k_{M_j}(l) = g_{lj} - \mu^k_{H_l \to M_j}$$
4. *Assignment at the end of kth iteration:*
$$\tilde{a}^k_{M_j} = \arg\min_l \{\tilde{b}^k_{M_j}(l)\}$$

- For k large enough $\tilde{a}^k_{M_j}$ is optimal assignment of mobile j.
- This BP algorithm need not converge.
- We use damped messages to deal with the message oscillations.
  - In damped message passing, the new messages are weighted averages of the old messages and the updates.

Incentivizing Hotspots

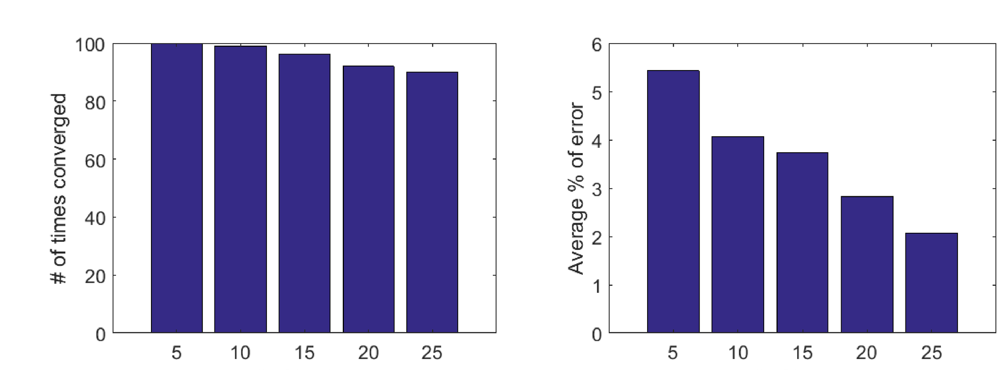
- Mobiles spend energy, memory, etc when acting as hotpsots; they may seek incentives.
- We incentivize a hotspot by providing additional throughput, proportional to the throughput the hotspot provides to other mobiles.
- η: proportionality factor.
- The throughput optimization problem with incentives, can be reduced to the following problem:

$$\mathcal{P}_4 : \text{minimize} \quad (1+\eta) \sum_i \sum_{j \neq i} a_{ij} \frac{R_j}{N R_i} + \sum_i a_{ii} \frac{1}{N}$$
$$\text{subject to} \quad (2), (3), (7) \text{ with } \theta = 1.$$

Offloading using DCF

- The problem is similar to $\mathcal{P}_1$, with the constraint (6) replaced by: for all hotspots i,
$$T_j = \frac{1}{\sum_{l=1}^{N} a_{il} \frac{1}{w_{il}}}, \forall j \neq i \text{ such that } a_{ij} = 1,$$
where $w_{il} \leq W_{il}$ are the actual WiFi rates between hotspot i and the mobiles.
- We reduce this complex problem into a linear optimization problem.
- We use local search based heuristic to the solve the optimization problem.
- Local search heuristic is as follows:
  - *Initialize*: an arbitary feasible solution a.
  - *In each iteration*: explore all the neighboring solutions of a; choose the best neighboring solution. (a' is a neighboring solution to a, if a and a' differ only at a single position).
  - *Stop*: if all the neighboring solutions are inferior.

Results



(a) # of times converged. (b) Average % error.

Figure: Performance of Message Passing Algorithm.

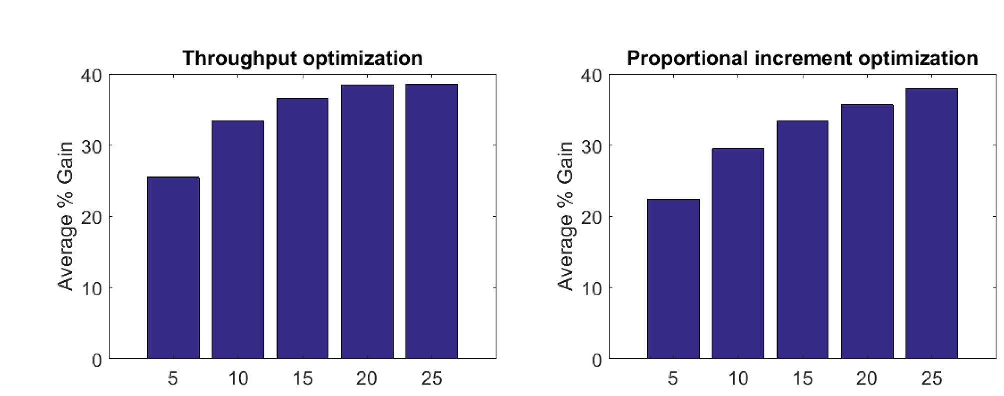
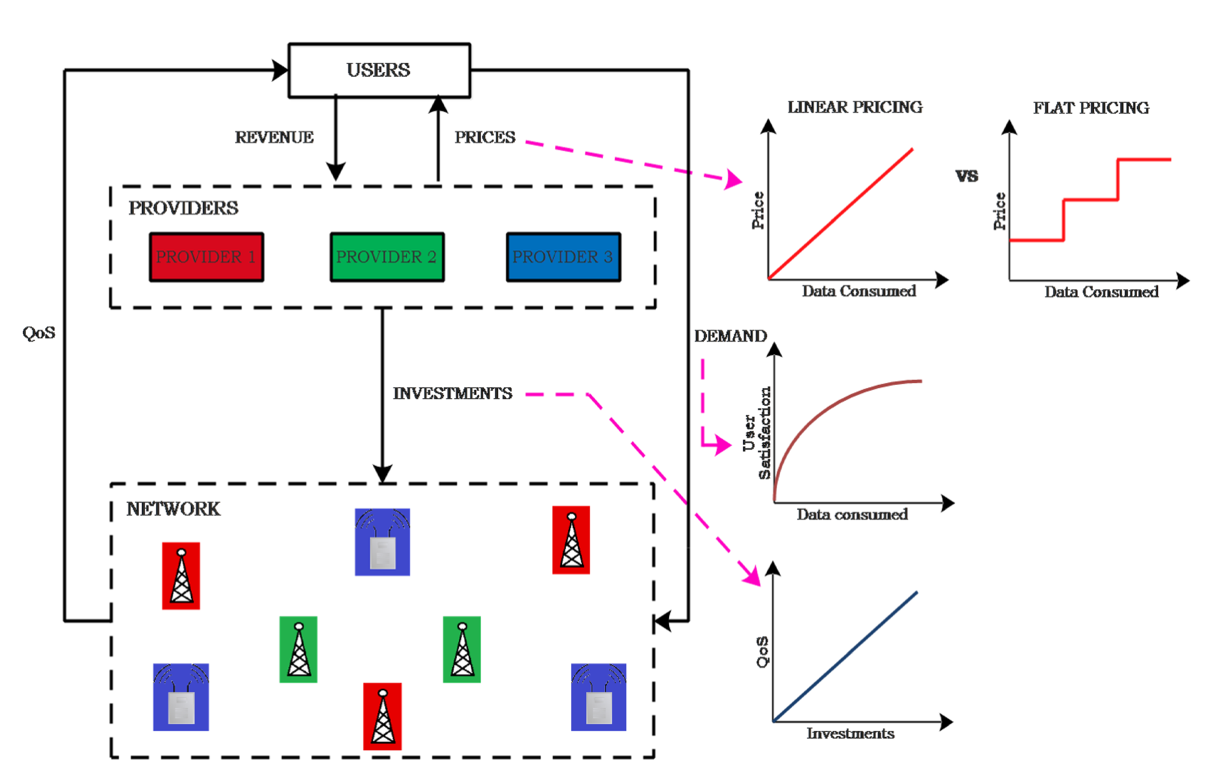


Figure: Average % gain for both throughput optimization and the proportional increment optimization problems.

Economics of Heterogeneous Networks

Introduction

- Rapid data growth leading to congestion in networks.
- Focus is mainly on technology layer involving designing of protocols and improving the underlying network infrastructure.
- These protocols are based on certain assumptions about the network utility.
- But, the network utility depends on the pricing and the QoS.
- Action of users and service providers constitutes the 'Economic layer'.
- The economic and technology layer interact in a complex manner and should be studied together.
- Users motive: Max (Utility - price paid).
- Operators motive: Max Revenue.



Model

- Each user characterized by a parameter θ.
- User joins the network with price-p and QoS-Q, if $\theta \geq p$ and $\theta \leq Q$.
- J. Walrand studied differentiation of services in network, by dividing the network with capacity c into two parts:
  - Network 1: Capacity $= \alpha c$, price $= p_1$.
  - Network 2: Capacity $= (1-\alpha)c$, price $= p_2$.
- This differentiation of service helps in increasing the revenue of operators and better customer satisfaction.

Objective

- To prove the existence of unique α and to analyse the asymptotic behavior of α as function of capacity.
- Non-linear pricing vs Linear pricing.