A Game Theoretic Approach to Load Balancing in Cellular Radio Networks

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Outline

MOTIVATION

- The amount of load that the overloaded/underloaded cell should offload/accept might be vendor-specific
- The algorithm calculating the values of these load runs in the eNodeB
- The aim is to study the effect on the overall network performance if each cell seeks to maximize its own benefit in a non-cooperative manner

General Definitions

- Each user u in the mobile network has a load defined by

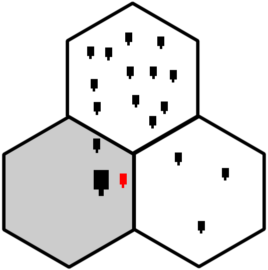
$$\kappa_u = \frac{D_u}{R(\text{SINR}_u) N_{\text{total}}}$$

  where D_u is the data rate requirement of the user, $R(\text{SINR}_u)$ is its corresponding throughput per Physical Resource Block (PRB) and N_{total} is the total number of PRBs
- The load of a cell i is denoted by

$$\rho_i = \sum_{u | X(u) = i} \kappa_u \geq 0$$

  where $X(.)$ is the connection function assigning a user u to a cell
  - If $\rho_i \leq 1$, the cell is underloaded
  - If $\rho_i > 1$, the cell is overloaded

Load Balancing Algorithm



The overloaded cell having $\rho > 1$ (Gray) generates the list of candidates to be handed over

- Users having small link imbalances
- Users having small data rate
- Spare capacities in the neighbor underloaded cells

Game and Players Definitions

- Players:
  The overloaded and the neighbor underloaded cells
- Game:
  - The underloaded cells signal to the overloaded cell the amount of load that they are willing to accept
  - The overloaded cell should offload to each underloaded neighbor cell a certain amount of users having a total load less or equal to the signaled one
- Strategies:
  Each player decides on the amount of load to accept(underloaded cells) or to offload (overloaded cell)

UTILITY FUNCTION

- If each player is considered rational, he will decide on a strategy that maximizes his payoff
- In our game, the utility function can be expressed by the number of satisfied users in the cell
  - More capacity usage
  - More income resulting from data rate charging

Utility Function

- For the underloaded cell i having a load $\rho_i < 1$ and U_i users

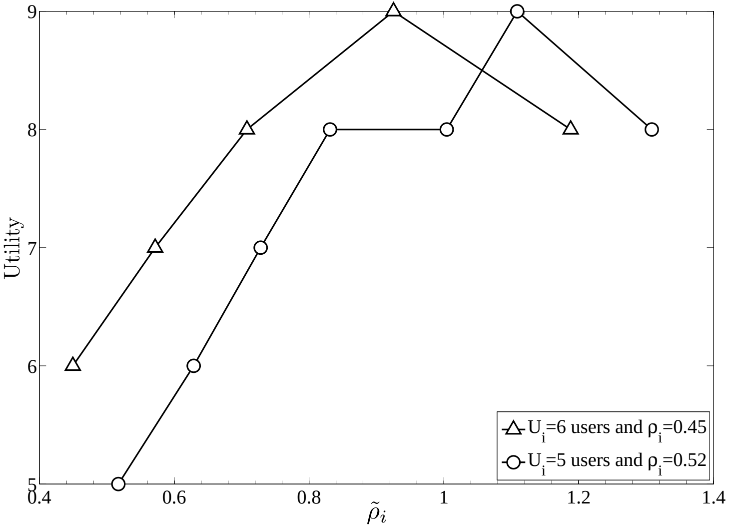
$$\text{utility}_i = \begin{cases} U_i + x_i, & \text{if } 0 \leq \tilde{\rho}_i \leq 1 \\ \left\lfloor \dfrac{(U_i + x_i)}{\rho_i + \sum_{j=1}^{x_i} \tilde{\kappa}_j} \right\rfloor, & \text{Otherwise} \end{cases}$$

  where x_i is the number of handed over users from the overloaded cell to the underloaded cell i and $\tilde{\rho}_i = \rho_i + \sum_{j=1}^{x_i} \tilde{\kappa}_j$ is the load of the cell after load balancing
- $\tilde{\kappa}_j$ is the estimated load of the j^{th} handed over user in the target cell i

UTILITY FUNCTION

$$\text{utility}_i = \begin{cases} U_i + x_i, & \text{if } 0 \leq \tilde{\rho}_i \leq 1 \\ \left\lfloor \dfrac{U_i + x_i}{\rho_i + \sum_{j=1}^{x_i} \tilde{\kappa}_j} \right\rfloor, & \text{Otherwise} \end{cases}$$

- The underloaded cell should decide and signal y_i to the overloaded cell
- The overloaded cell offload $\sum_{j=1}^{x_i} \tilde{\kappa_j} \leq y_i$
- Maximization of the utility function depends on x_i and $\tilde{\kappa_j}$ which are not known to the underloaded cell i
- Utility increases by x_i if $y_i <= 1 - \rho_i$



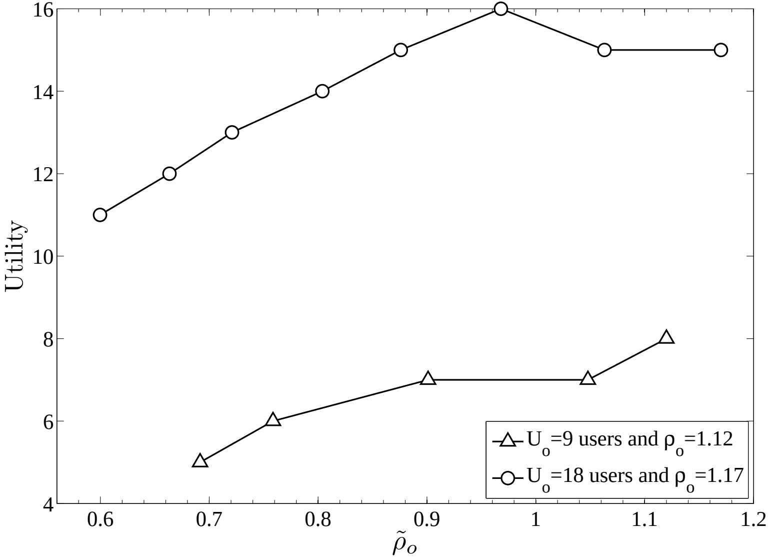
Utility
9
8
7
6
5
0.4
0.6
0.8
1
1.2
1.4
$\tilde{\rho}_i$
U_i=6 users and ρ_i=0.45
U_i=5 users and ρ_i=0.52

UTILITY FUNCTION

- For the overloaded cell having a load $\rho_o > 1$ and U_o users

$$\text{utility}_o = \begin{cases} U_o - x_o, & \text{if } 0 \leq \tilde{\rho}_o \leq 1 \\ \left\lfloor \dfrac{(U_o - x_o)}{\rho_o - \sum_{j=1}^{x_o} \kappa_j} \right\rfloor, & \text{Otherwise} \end{cases}$$

  where x_o is the total number of handed over users from the overloaded cell to the underloaded cells, κ_j is the load of the j^{th} handed over user and $\tilde{\rho}_o = \rho_o - \sum_{j=1}^{x_o} \kappa_j$ is the load of the cell after load balancing
- The overloaded cell knows the load of each user κ_j and should decide on $\mathcal{X} = \sum_{j=1}^{x_o} \kappa_j$



Utility
16
14
12
10
8
6
4
0.6
0.7
0.8
0.9
1
1.1
1.2
$\tilde{\rho}_o$
U_o=9 users and ρ_o=1.12
U_o=18 users and ρ_o=1.17

Strategy Played By The Underloaded Cell

- The cell signals a load value such that its utility will never decrease and is maximized as much as possible
- At first, the underloaded cell will accept a load y^* s.t its utility will not decrease even if 1 user is handed over

$$
\begin{aligned}
\left\lfloor \frac{U_i + 1}{\rho_i + y^*} \right\rfloor &\geq U_i \\
\frac{U_i + 1}{\rho_i + y^*} - U_i &\geq 0 \\
\rho_i + y^* &\leq \frac{U_i + 1}{U_i} \\
y^* &\leq \frac{U_i + 1}{U_i} - \rho_i = y^*_{\text{max}}
\end{aligned}
$$

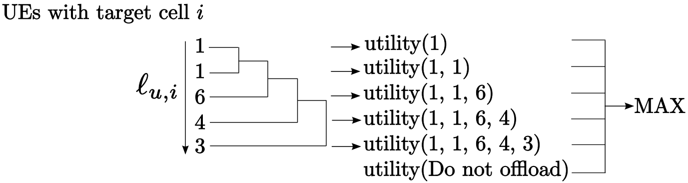
Strategy Played By The Underloaded Cell

- y^*_{max} might be large if the cell is not too much loaded and the underloaded cell might get a small utility gain
- Hence, the underloaded cell signals y^*_{max} only if it is enough loaded, i.e., $\rho_i \geq \rho_t = 0.9$

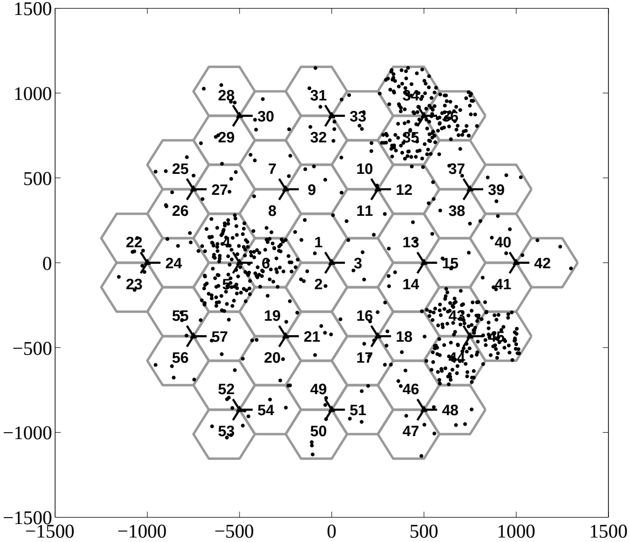
$$y_i = \begin{cases} 1 - \rho_i & \text{If } \rho_i < \rho_t \\ \\ \dfrac{U_i + 1}{U_i} - \rho_i, & \text{Otherwise} \end{cases}$$

STRATEGY PLAYED BY THE OVERLOADED CELL

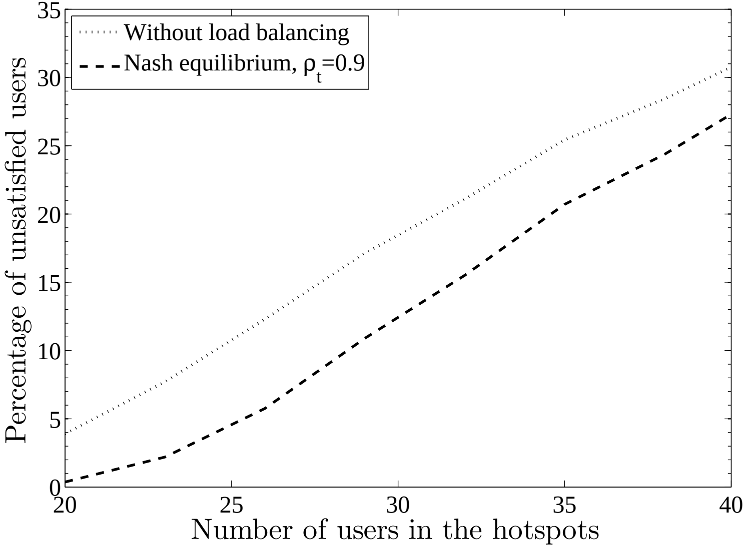
- It will choose $\mathcal{X}_{opt}$ that maximizes its utility in a straight forward manner without exceeding the signaled load of each cell



NETWORK LAYOUT



Snapshot Evaluation



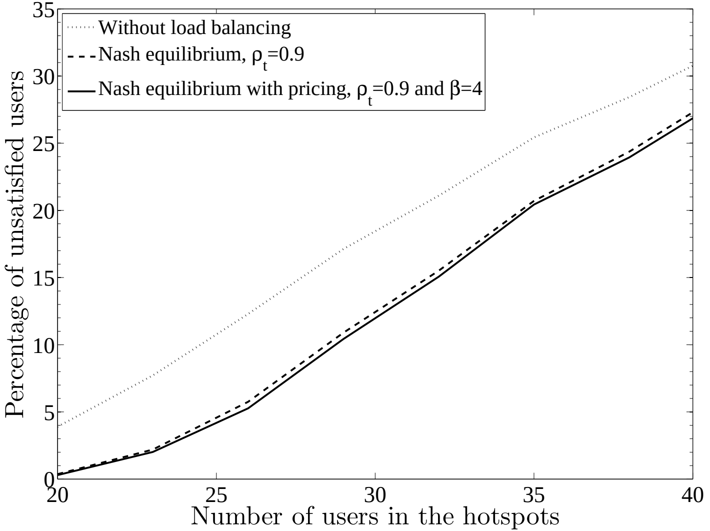
Linear Pricing

- The behavior of the players can be altered by introducing a certain cost
- The players can maximize a modified utility function defined as

$$\text{utility}^c = \text{utility} - \beta \max\{N_{\text{tot}}(\rho - 1), 0\}$$

where β is a positive scalar that should be tuned to increase the overall performance in the network

LINEAR PRICING



Conclusion

- Non-cooperative approach in load balancing can still achieve a remarkable gain when compared to the case with no load balancing
- The overall network performance can be slightly improved using linear pricing