RAT Selection Games in HetNets

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Motivation

- Key feature of current- and next-gen wireless networks is **heterogeneity**, or coexistence, of network architectures.

- Many mobile devices now are equipped with **multiple** Radio Access Technologies (RATs) (e.g. 3G/4G, 802.11).

- Devices can choose to connect to **specific access technologies**.
Central Question

With all of these different choices of RATs, one needs to ask the question:

*How should a user select the best access network at any given time?*
Prior Work

• Heterogeneous Network Selection with Network Assistance
  – S. Deb, et al., (’11), and Coucheney, et al., (’09)
• Heterogeneous Network Selection with a centralized controller
  – Ibrahim, et al., (’09), and Ye, et al., (’12)
• Congestion Games and Network Selection (e.g., single type of throughput sharing)
  – Rosenthal (’72), and Even-Dar, et al., (’07)

We present an algorithm that addresses the access network selection problem from a fully-distributed approach
Network Model

- Heterogeneous wireless environment
- User-specific set of RATs
- Multiple BSs modeled as multiple RATs
- Each user uses 1 RAT at a time

Fig. 1. An example heterogeneous network.
Throughput Models

Class-1
User throughput depends on the rates of all users on that network (User $i$, BS $k$).

\[ \omega_{i,k} = f_k(R_{1,k}, R_{2,k}, \ldots, R_{n_k,k}) \]

\[ \forall i \in N_k \]

E.g., 802.11 DCF

\[ \omega_{i,k} = \frac{L}{\sum_{j \in N_k} \frac{L}{R_{j,k}}} \]

\[ \forall i \in N_k \]

Class-2
User throughput depends only on the number of users on that network (User $i$, BS $k$).

\[ \omega_{i,k} = R_{i,k} \times f_k(n_k) \]

\[ \forall i \in N_k \]

E.g., Time-Fair TDMA MAC

\[ \omega_{i,k} = \frac{R_{i,k}}{n_k} \]

\[ \forall i \in N_k \]
RAT Selection Game + Nash Equilibrium

Non-Cooperative Game

User goal: Maximize Individual Throughput

Player Set: Set of \( N \) users

Strategy Profile: Set of RATs chosen by the users \( \sigma = (\sigma_1, \sigma_2, \ldots, \sigma_N) \)

Nash Equilibrium

Strategy profile \( \sigma \) is at “Nash Equilibrium” if each chosen strategy \( \sigma_i \) is the best for each player given the other \( \sigma_j \)
Improvement Path

- A *Path* is the sequence of strategy profiles in which each subsequent profile differs in only one coordinate.

- An *Improvement Path* is a path in which the unique deviator in each step strictly increases its throughput.
Distributed RAT Selection Algorithm

To switch from RAT $k$ to $k'$:

- Expected gain must exceed threshold $\eta$
  - Exceed for at least switching frequency $T$ timesteps

- Randomization $p$
  - similar to binary exponential backoff

- Hysteresis $h$
  - prevent inter-Class oscillations
Randomization $P$ - Single-User Arrival/Departure

- Different users can occasionally join and/or leave a single BS concurrently

- Randomization parameter $p$ forces such events to occur infrequently and diminish rapidly with network congestion
Single-Class RAT Selection Games

Theorem 1:

Class-1 RAT selection games converge to a Nash Equilibrium.

Proof: See pg. 4.

Theorem 2:

Class-2 RAT selection games converge to a Nash Equilibrium.

Proof: See pg. 4.
Mixed-Class RAT Selection Games

- Infinite Improvement Paths may exist for a Mixed-Class RAT Selection Game

Example:
\[ R_{1} = (7.2, 9, 10.1, 0) \]
\[ R_{2} = (0, 48, 23.4, 9) \]

RATs \{b,d\} are Class-1
RATs \{a,c\} are Class-2

Rates chosen from 802.11a for Class-1
Rates chosen from 3G HSDPA for Class-2
Mixed-Class Convergence with Hysteresis

**Theorem 3:**

*Mixed-Class RAT selection games, with hysteresis policy, converge to an equilibrium.*

Proof: See pg. 6.

- Guarantees convergence for RAT selection games with many different types of RATs
- Hysteresis prevents the existence of an infinite improvement path
Definitions

• Pareto-Domination

Let $G$ be a game with a set of $N$ players. We say a strategy profile $\sigma'$ *Pareto-dominates* strategy profile $\sigma$ if it holds that

$$\forall i \in N : \omega_{i,\sigma'} \geq \omega_{i,\sigma}$$

• Average Pareto-Efficiency Gain

Let $G$ be a game with $N$ players. Let $\sigma'$ denote a strategy profile that Pareto-dominates strategy profile $\sigma$. The average Pareto-efficiency gain of $\sigma'$ to $\sigma$ is

$$\sum_{i=1}^{N} \frac{\omega_{i,\sigma'}}{N} \frac{\omega_{i,\sigma}}{\omega_{i,\sigma_i}}$$
Theorem 4:
Let $G$ be a Class-1 RAT selection game with $N$ users.

$\sigma^p$: Pareto-Optimal strategy profile

$\sigma^n$: Nash Profile

$\gamma = R_{\text{max}} / R_{\text{min}}$: Ratio between max and min rates across all users.

Then:
1) $G$ has Pareto-optimal Nash Equilibrium,
2) The average Pareto-efficiency gain of $\sigma^p$ to $\sigma^n$ can become unbounded as $\gamma \to \infty$

Proof: See page 6
Pareto-Efficiency for Class-2
(Time-Fair)

**Theorem 6:**
For a time-fair RAT selection game with $N$ users and $M$ BSs, the average Pareto-efficiency gain of $\sigma_p$ to $\sigma_n$ is bounded by

$$
\begin{cases}
\frac{2}{N + M} & \text{if } N \leq M \\
\frac{N}{N} & \text{if } N > M
\end{cases}
$$

For Proof, see Page 7
Theorem 7:
For a proportional-fair RAT selection game with $N$ users and $M$ BSs, the average Pareto-efficiency gain of $\sigma_p$ to $\sigma_n$ is bounded by

\[
\left\{
\begin{array}{ll}
2 \times (1 + \ln(N)) & \text{if } N \leq M \\
\frac{N + M}{N} \times (1 + \ln(N)) & \text{if } N > M
\end{array}
\right.
\]

For Proof, see Page 7
Measurement-Driven Simulations

Cellular Statistics

- Measured number of accessible wireless towers, frequencies and type of technology, and received SNR
- 100 randomly-selected locations across three floors of a large university building
- AT&T’s Cellular Network

Wi-Fi Statistics

- Measured received SNR, frequencies and technology (802.11a/b/g)
- Same locations as Cellular Statistics
Average Number of Equilibria

- 9-User system with 3 RATs (2x WiFi and 1x 3G). Number of system states: $3^9$
- Users randomly selected from measurement database
- Equilibria averaged over 20 realizations
Pareto-Optimality of Equilibria

- *Num. Pareto/Num. non-Pareto* similar for different values of $\eta$

- Increasing $\eta$ can significantly increase number of equilibria
Comparing Throughput Types

**Pareto-Efficiency Gain**

- Throughput-Fair
- Time-Fair
- Mixture

**Pareto-Dominating States**

- Throughput-Fair
- Time-Fair
- Mixture

CDF

Pareto-Efficiency Gain

Num. of Dominating States

x10^2
Effect of Threshold $\eta$

- Know that as $\eta$ increases, the number of equilibria increases rapidly.
- Limiting $\eta$ to less than 2 only slightly increases the average Pareto-efficiency gains.
Summary of Key Results

• Proved convergence to Nash Equilibrium for single-class RAT selection games; same for multiple-class RAT selection games with hysteresis.

• Described conditions under which Nash Equilibria are Pareto-Optimal, and quantified average pareto-efficiency gain when not met.

• Showed that average pareto-efficiency gain can be unbounded for Class-1, and tightly bounded by constant approximation for Class-2.

• Described the effects of switching threshold $\eta$. 
Thank you!

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Back Up Slides
Effect of User Arrival/Departure on Throughput

**Single-User Arrival/Departure**

- T=200: 1 user departs
- T=400: 1 user arrives
- T=600: 1 user arrives
- T=800: 1 user departs

**Multi-User Arrival Departure**

- T=200: 5 users depart
- T=400: 5 users arrive
- T=600: 2 users arrive
- T=800: 3 users depart

10 initial users; rates and users randomly chosen from 802.11a and 3G HSDPA
Fraction of Users Switching RATs
(due to single-user arrival/departure)

**Single-User Arrival**

Departing user chosen randomly
Arriving user’s rates randomly chosen from 802.11a and 3G HSDPA

**Single-User Departure**
Fraction of Users Switching RATs
(due to multi-user arrival/departure)

Multi-User Arrival

Departing user chosen randomly
Arriving user’s rates randomly chosen from 802.11a and 3G HSDPA
Throughput Models

**Class-1**
User throughput depends on the rates of all users on that network.

\[ \omega_{i,k} = f_{i,k}(R_{1,k}, R_{2,k}, \ldots, R_{n,k}, k) \]
\[ \forall i \in N \]

E.g. 802.11 DCF

\[ \omega_{i,k} = \frac{L}{\sum_{j \in N} k} \]
\[ R_{j,k}, k \quad \forall i \in N \]

**Class-2**
User throughput depends only on the number of users on that network.

\[ \omega_{i,k} = R_{i,k} \times f_{i,k}(n_{i,k}) \]
\[ \forall i \in N \]

E.g. Time-Fair TDMA MAC

\[ \omega_{i,k} = \frac{R_{i,k}}{n_{i,k}} \quad \forall i \in N \]