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

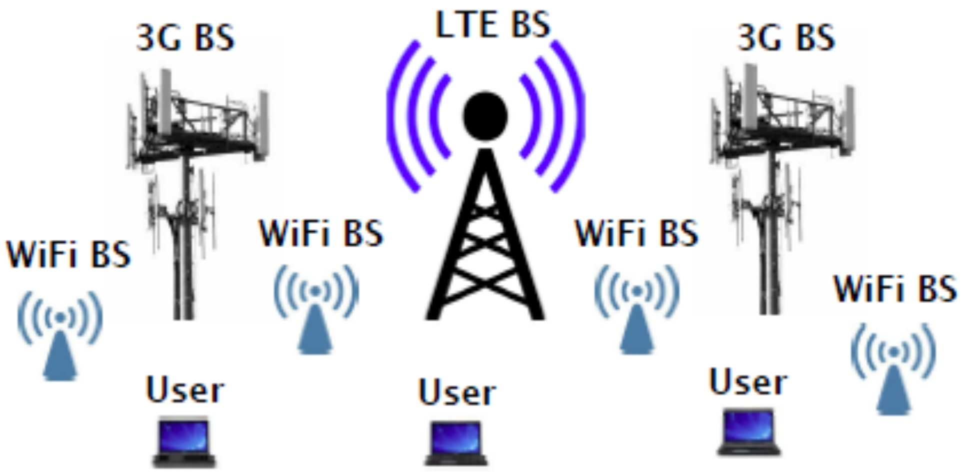


Fig. 1. An example heterogeneous network.

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

$$\omega_{i,k} = \frac{L}{\sum_{j \in N_k} \frac{L}{R_{j,k}}} \quad \forall i \in N_k$$

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

$$\omega_{i,k} = \frac{R_{i,k}}{n_k} \quad \forall i \in N_k$$

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 $\sigma = (\sigma_1, \sigma_2, \ldots, _N)$

Nash Equilibrium

Strategy profile σ is at "Nash Equilibrium" if each chosen strategy σ_i is the best for each player given the other σ_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** $\boldsymbol{\eta}$
  - Exceed for at least **switching frequency** $\boldsymbol{T}$ timesteps
- **Randomization** $\boldsymbol{p}$
  - 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 Calss-2

BS	a	b	c	d
User RAT Selection and Trajectory	1	2	ϕ	ϕ
	ϕ	1, 2	ϕ	ϕ
	ϕ	1	ϕ	2
	ϕ	ϕ	1	2
	ϕ	ϕ	1, 2	ϕ
	1	ϕ	2	ϕ
	1	2	ϕ	ϕ

Transition Inequality

$$R_{1,a} < \left(\frac{1}{R_{1,b}} + \frac{1}{R_{2,b}}\right)^{(-1)}$$

$$\left(\frac{1}{R_{1,b}} + \frac{1}{R_{2,b}}\right)^{(-1)} < R_{2,d}$$

$$R_{1,b} < R_{1,c}$$

$$R_{2,d} < \frac{R_{2,c}}{2}$$

$$\frac{R_{1,c}}{2} < R_{1,a}$$

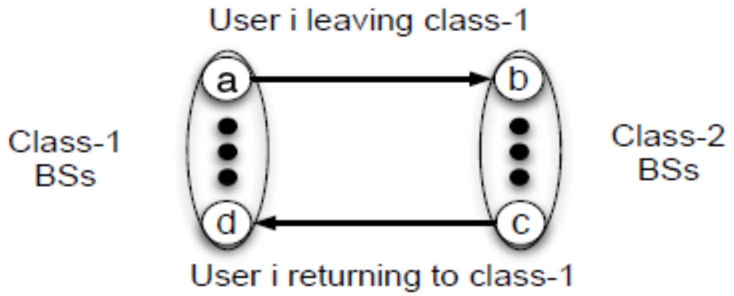
$$R_{2,c} < R_{2,b}$$

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 σ' ***Pareto-dominates*** *strategy profile* σ if it holds that

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

- **Average Pareto-Efficiency Gain**

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

$$\frac{\sum_{i=1}^{N} \frac{\omega_{i,\sigma'_i}}{\omega_{i,\sigma_i}}}{N}$$

Pareto-Efficiency for Class-1

Theorem 4:

Let *G* be a Class-1 RAT selection game with N users.

σ^P: Pareto-Optimal strategy profile

σ^n: Nash Profile

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

Then:

1) G has Pareto-optimal Nash Equilibrium,
2) The average Pareto-efficiency gain of σ^P to σ^n can become unbounded as $\Upsilon \rightarrow \infty$

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 σ_p *to* σ_n is bounded by

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

For Proof, see Page 7

Pareto-Efficiency for Class-2

(Proportional-Fair)

Theorem 7:

For a proportional-fair RAT selection game with **N** users and **M** BSs, the average Pareto-efficiency gain of σ_p *to* σ_n is bounded by

$$\begin{cases} 2 \times (1 + \ln(N)) & \text{if } N \le M \\ \frac{N+M}{N} \times (1 + \ln(N)) & \text{if } N > M \end{cases}$$

For Proof, see Page 7

Measurement-Driven Simulations

Cellular Statistics

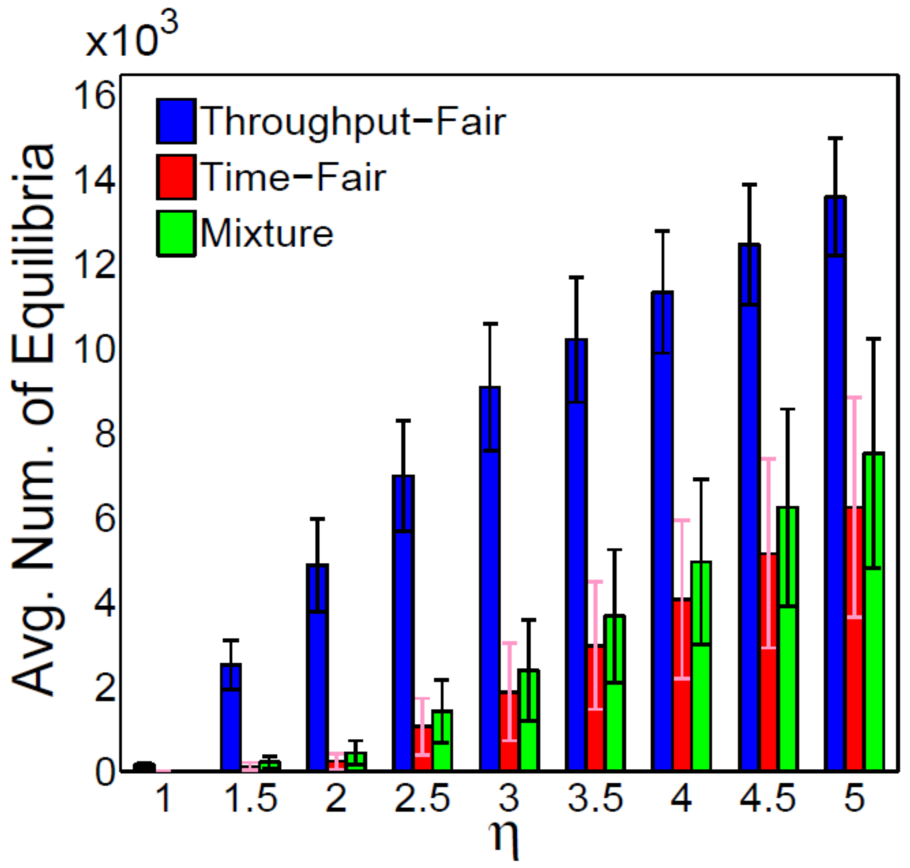
- Measured number of accessible wireless towers, frequencies and type of technology, and received SNR
- 100 randomly-selected locations across three floors of a large university building
- AT&T's Cellular Network

Wi-Fi Statistics

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

Average Number of Equilibria

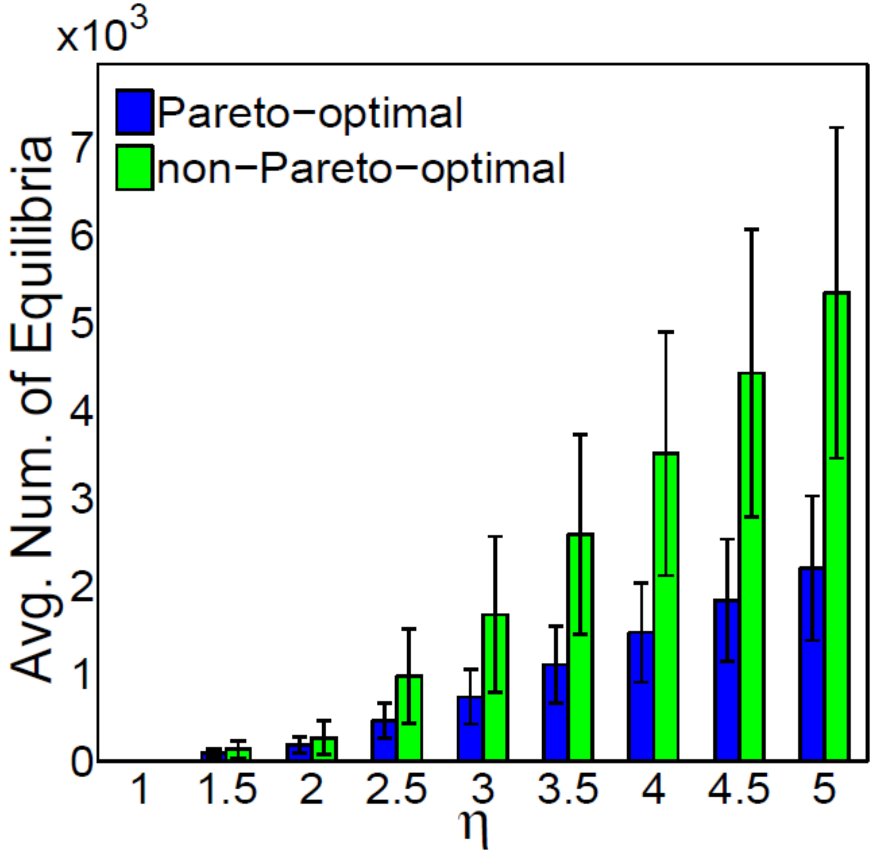
- 9-User system with 3 RATs (2x WiFi and 1x 3G). Number of system states: 3^9
- Users randomly selected from measurement database
- Equilibria averaged over 20 realizations



Pareto-Optimality of Equilibria

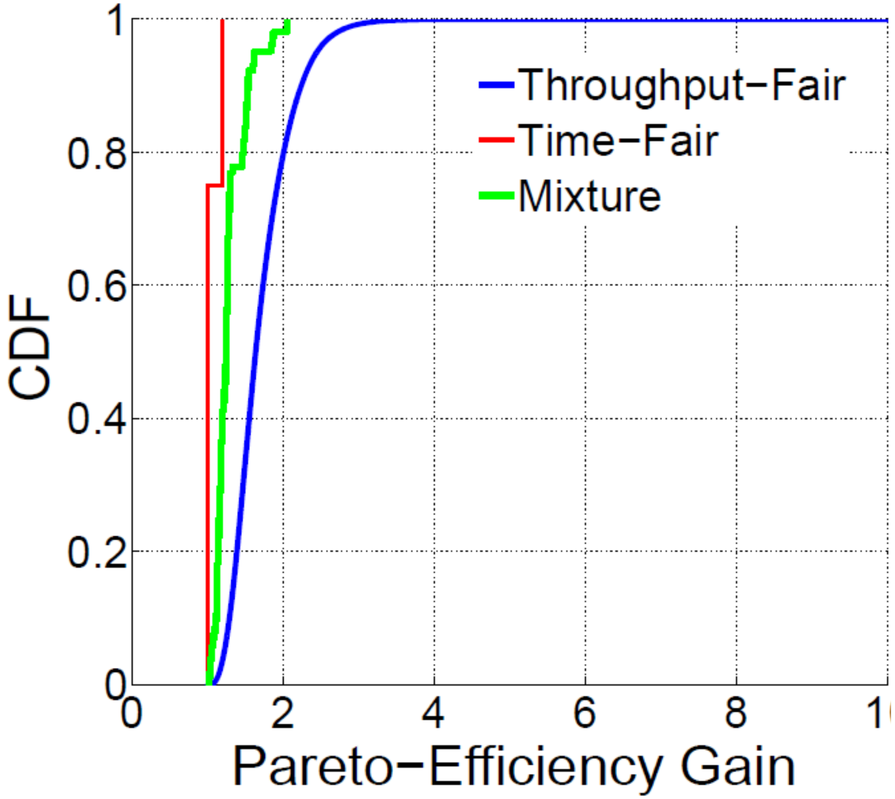
- $Num.\ Pareto / Num.\ non\!-\!Pareto$ similar for different values of η

- Increasing η can significantly increase number of equilibria

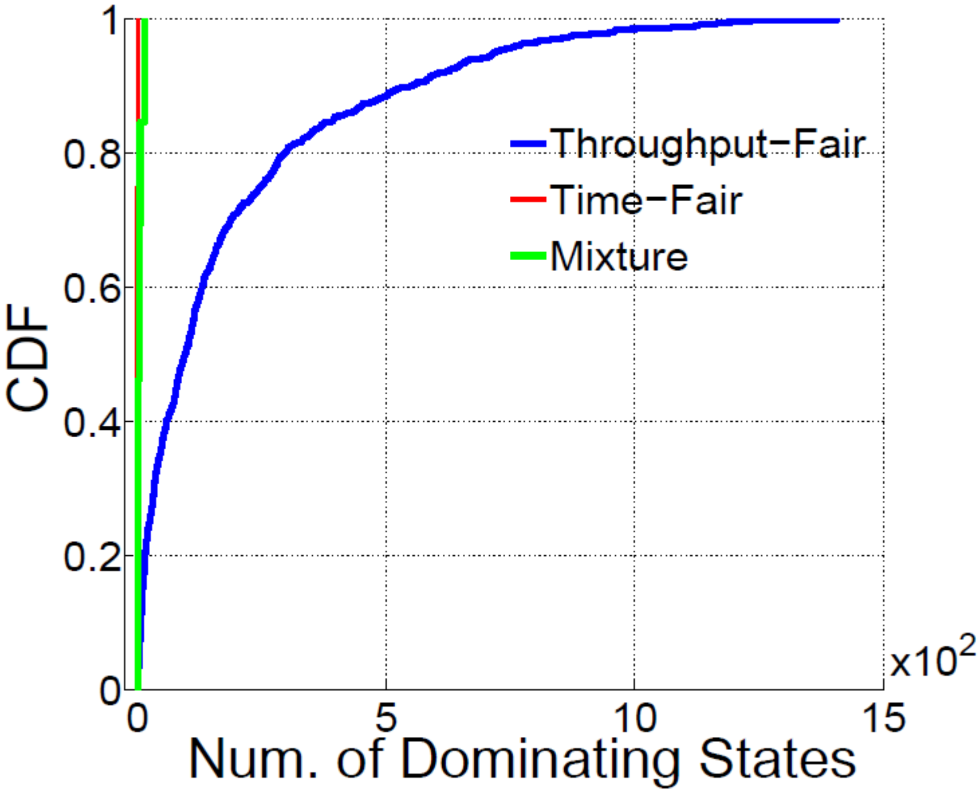


Comparing Throughput Types

Pareto-Efficiency Gain



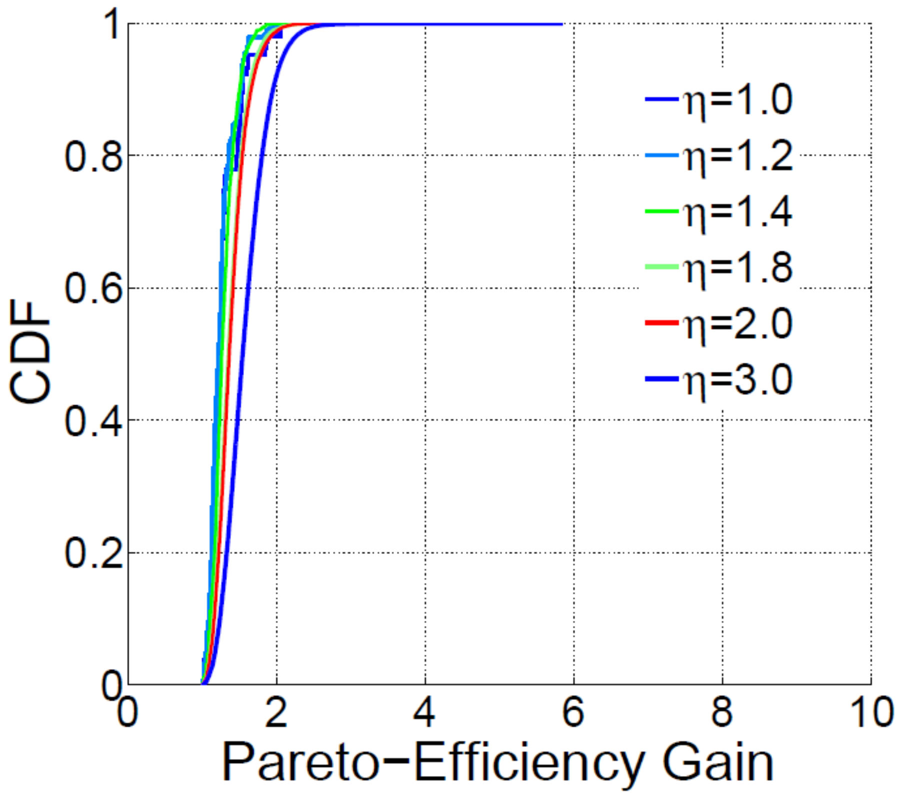
Pareto-Dominating States



Effect of Threshold η

- Know that as η increases, the number of equilibria increases rapidly

- Limiting η 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* η

Thank you!

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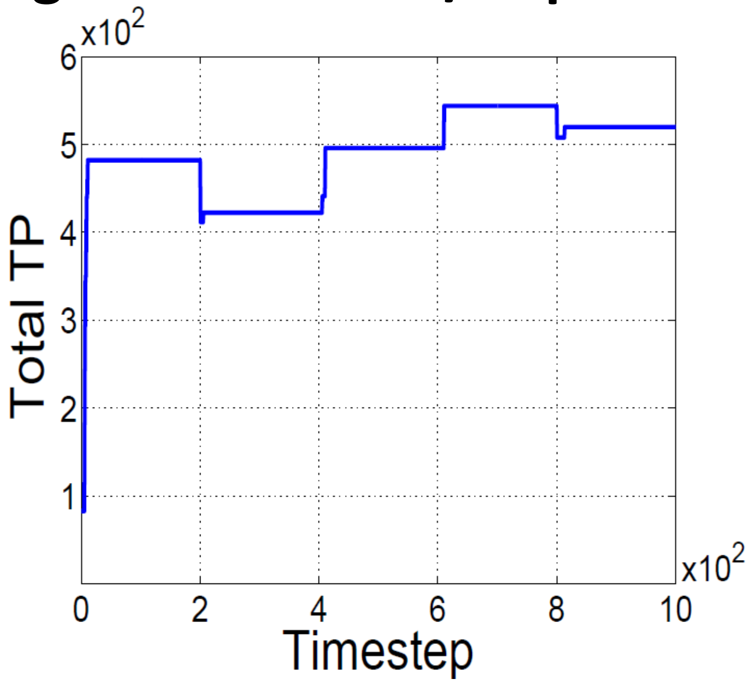
Back Up Slides

Effect of User Arrival/Departure on Throughput

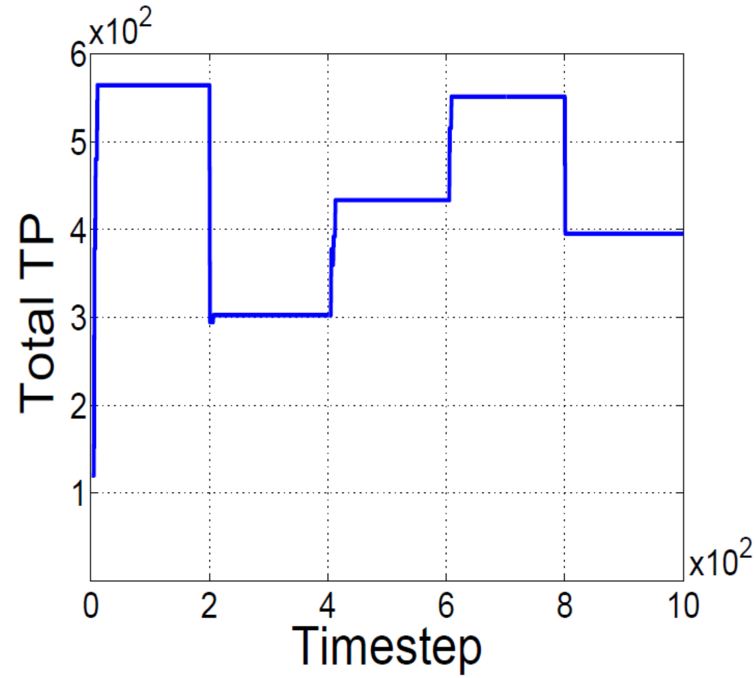
Single-User Arrival/Departure



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

10 initial users; rates and users randomly chosen from 802.11a and 3G HSDPA

Multi-User Arrival Departure



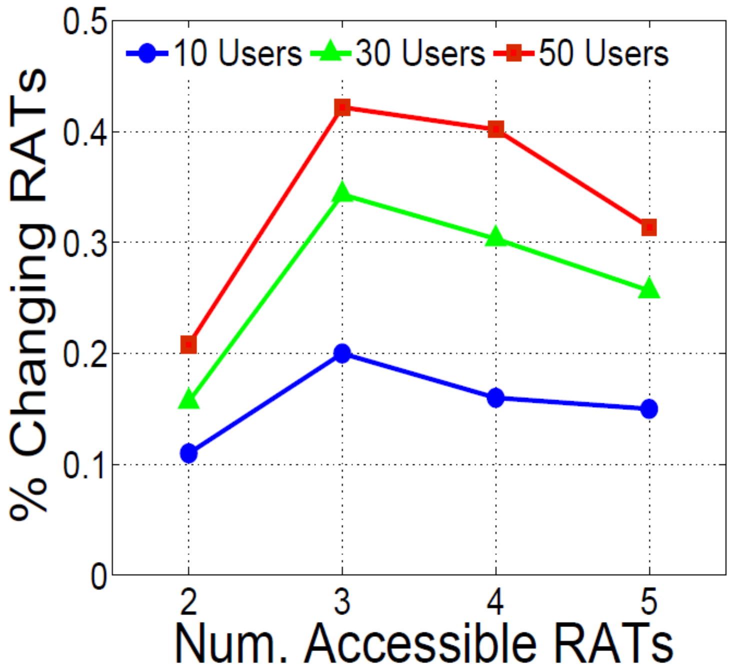
T=200: 5 users depart
T=400: 5 users arrive
T=600: 2 users arrive
T=800: 3 users depart

10 initial users; rates and users chosen from 802.11a and 3G HSDPA

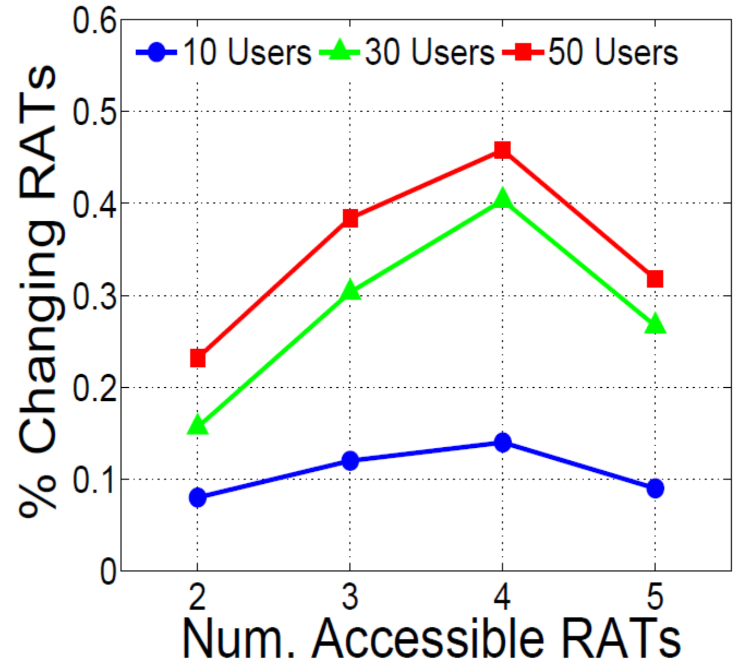
Fraction of Users Switching RATs

(due to single-user arrival/departure)

Single-User Arrival



Single-User Departure



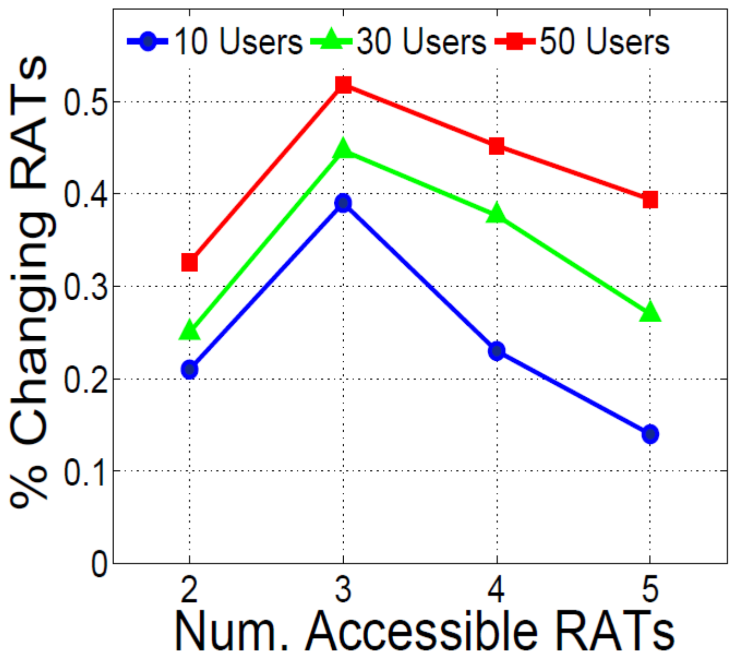
Departing user chosen randomly

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

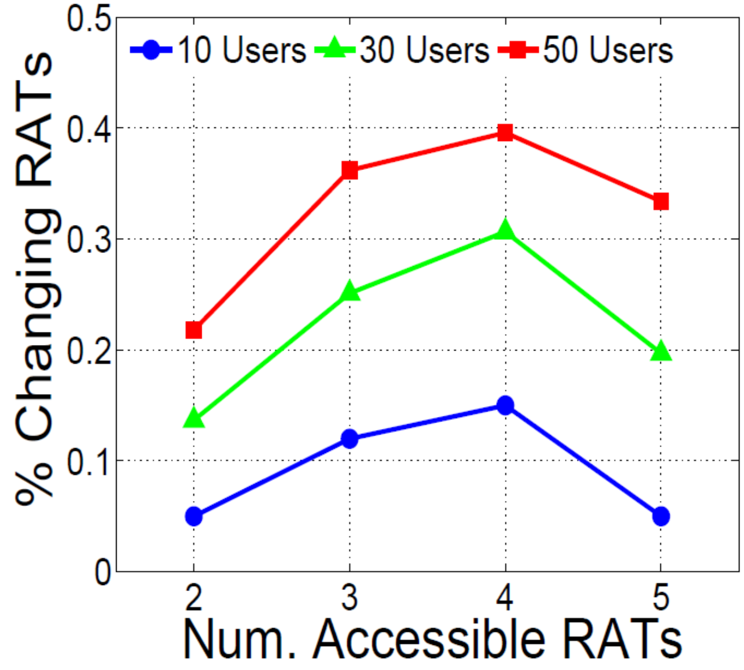
Fraction of Users Switching RATs

(due to multi-user arrival/departure)

Multi-User Arrival



Multi-User Departure



Departing user chosen randomly

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

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User throughput depends on the rates of all users on that network.

$$\omega_{i,k} = f_k(R_{1,k}, R_{2,k}, \ldots, R_{n_k,k}) \quad \forall i \in N_k$$

e.g. 802.11 DCF

$$\omega_{i,k} = L \Big/ \sum_{j \in N_k} L / R_{j,k} \quad , \forall i \in N_k$$

Class-2

User throughput depends only on the number of users on that network.

$$\omega_{i,k} = R_{i,k} \times f_k(n_k) \quad \forall i \in N_k$$

e.g. Time-Fair TDMA MAC

$$\omega_{i,k} = R_{i,k} / n_k \quad , \forall i \in N_k$$