Exploiting Mobility in Proportional Fair Cellular Scheduling: Measurements and Algorithms

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Mobile Scheduling in Cellular Networks

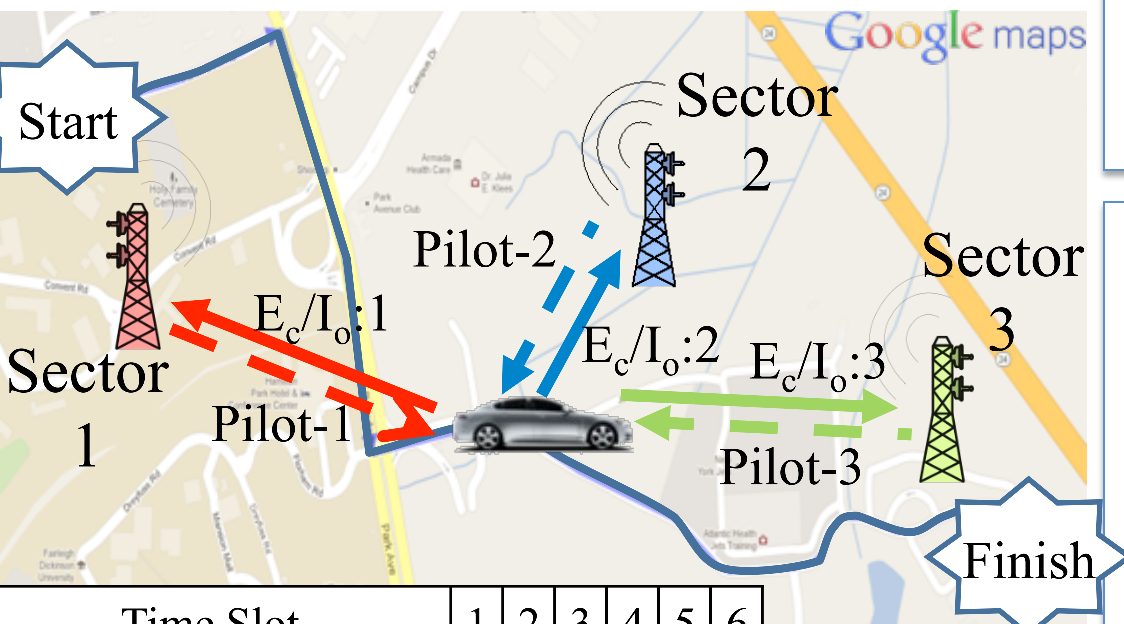
- Cellular users are constantly on the move, many times with predictable mobility (i.e., buses, trains, commuting, etc)

- Existing scheduling algorithms do not take predictable mobility into account

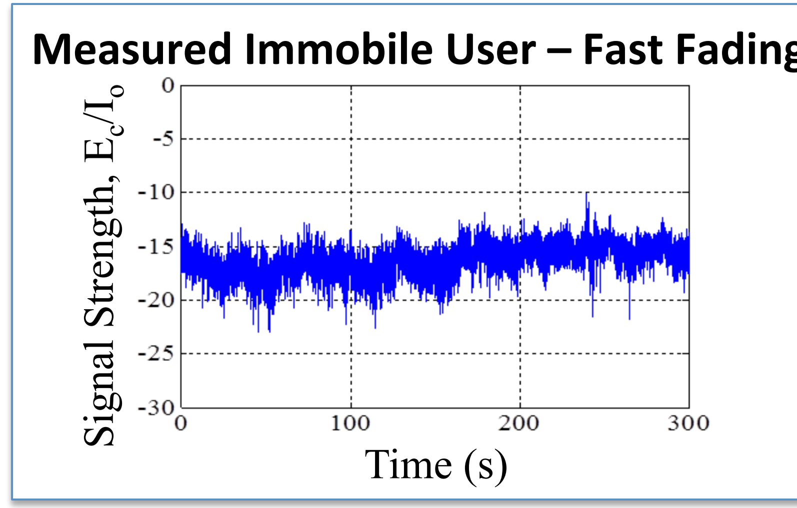
We develop a cellular scheduling framework to leverage cases with **predictable mobility**

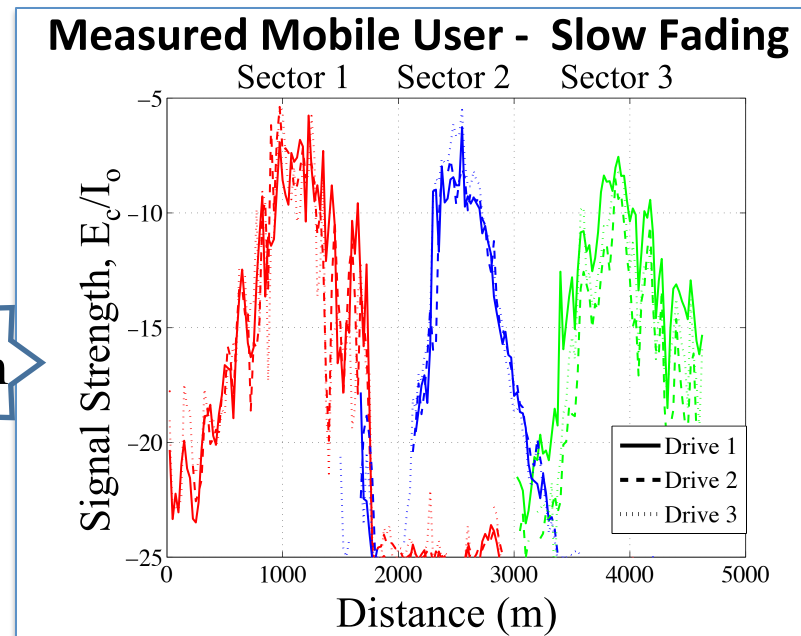
Cellular Scheduling Background

- 3G UMTS Cellular Network – WCDMA
- Pilot signals used to estimate the channel quality (E_c/I_o) for each basestation



Time Slot	1	2	3	4	5	6
Allocation for User	0	1	1	1	0	0





Finite Proportional Fair (FPF) Scheduling

$$\max_\alpha \quad C = \sum_{i=1}^{K} \log\left(\sum_{j=1}^{T} \alpha_{ij} r_{ij}\right)$$

$$\text{subject to} \quad \sum_{i=1}^{K} \alpha_{ij} = 1 \quad \forall j = 1 \ldots T$$

$$\alpha_{ij} \in \{0, 1\}.$$

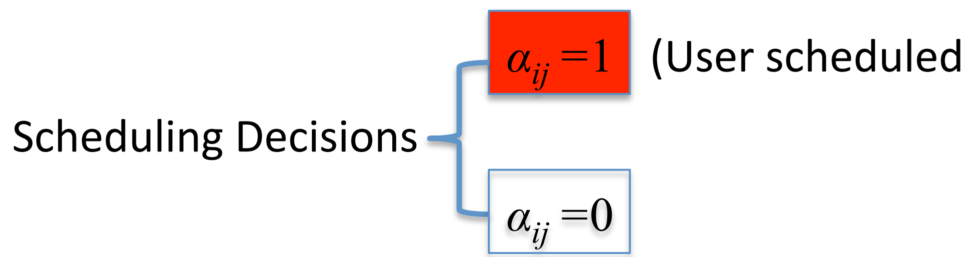
- Follows [1,2] but has a *finite time horizon*
- Users always have data to send
- T slot time horizon
- K users
- r_{ij} is the feasible data rate for user i in slot j
- $\alpha_{ij} = 1$ for the scheduled user i in slot j

Time Slot j

User i

	1	2	3	4	5	..... T
1	5	6	4	8	6	
2	2	3	4	1	2	
3	1	4	3	4	5	
⋮ K						

Data Rate, r_{ij} (Mbps)



[1] M. Andrews, L. Qian, and A. Stolyar. Optimal utility based multi-user throughput allocation subject to throughput constraints. In *Proc. IEEE INFOCOM'05*, Mar. 2005.

[2] A. Stolyar. On the asymptotic optimality of the gradient scheduling algorithm for multiuser throughput allocation. *Operations Research*, 53:12–25, 2005.

Deployed Proportional Fair Scheduler

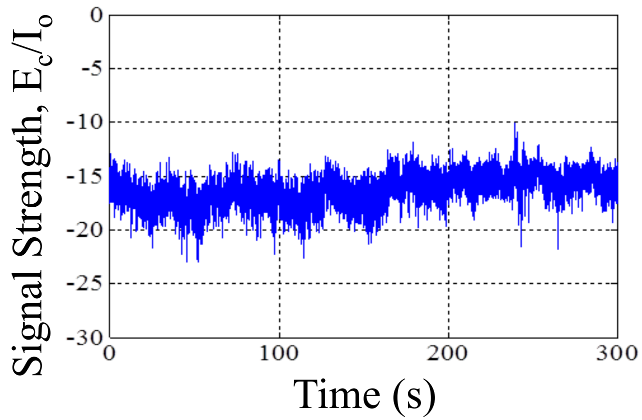
Exponential Proportional Fairness Algorithm (PF-EXP)

$$\max_{i \in K} \frac{r_{ij}}{R_i[j]}$$

$$R_i[j] = (1-\epsilon)R_i[j-1] + \epsilon \alpha_{ij} r_{ij}$$

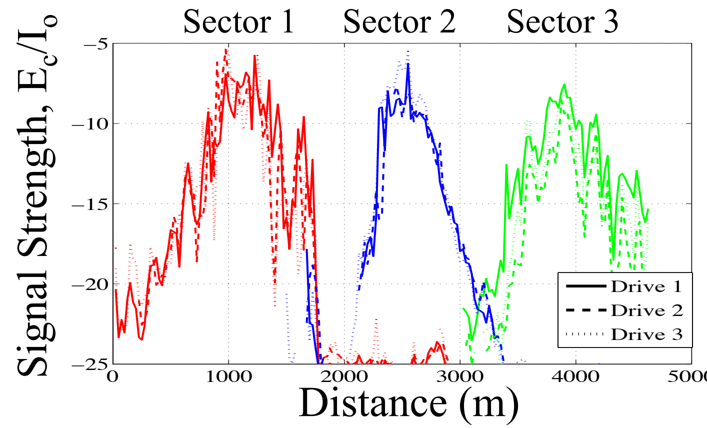
- Exploits fast fading and multi-user diversity
- $R_i[j]$ is the exponential average of user i's throughput at slot j

Measured Immobile User – Fast Fading



Optimal for long association times with stationary channel conditions

Measured Mobile User - Slow Fading



Not optimal for mobile scenarios [3]

[3] M. Andrews. Maximizing profit in overloaded networks. In *Proc. IEEE INFOCOM'05*, Mar. 2005.

Predictive FPF Solution Framework

- Consider the gradient of the cost function:

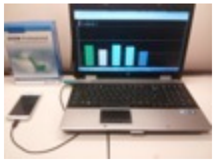
$$\frac{r_{ij}}{\sum_{t=1}^{j-1}\alpha_{it}r_{it} + \alpha_{ij}r_{ij} + \sum_{t=j+1}^{T}\alpha_{it}r_{it}}$$

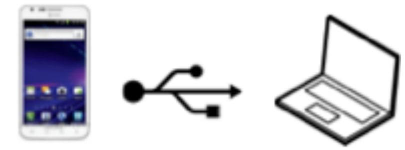
- Requires past, present, and **future** knowledge of *channel rate* and *scheduled allocations*
- Online Scheduling Framework

Estimate Future Channel Rates $\{\hat{r}_{ij}\}_{K\times T}$ → Estimate Future Channel Allocations $\{\hat{\alpha}_{ij}\}_{K\times T}$ → Online Scheduler for time slots 1 to T: schedule the user with the highest gradient

Outline

Experimental Measurement Campaign





Estimate Future Channel Rates

$$\{\hat{r}_{ij}\}_{K\times T}$$

Estimate Future Channel Allocations

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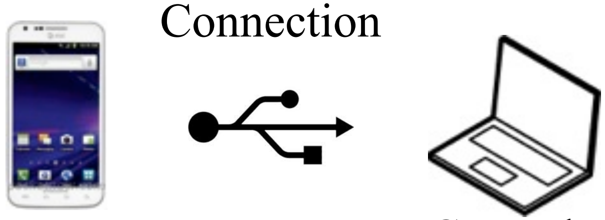
Framework Evaluation

Online Scheduler for time slots 1 to T: schedule the user with the highest gradient

$$\frac{r_{ij}}{\sum_{t=1}^{j-1}\alpha_{it}r_{it}+\hat{\alpha}_{ij}r_{ij}+\sum_{t=j+1}^{T}\hat{\alpha}_{it}\hat{r}_{it}}$$

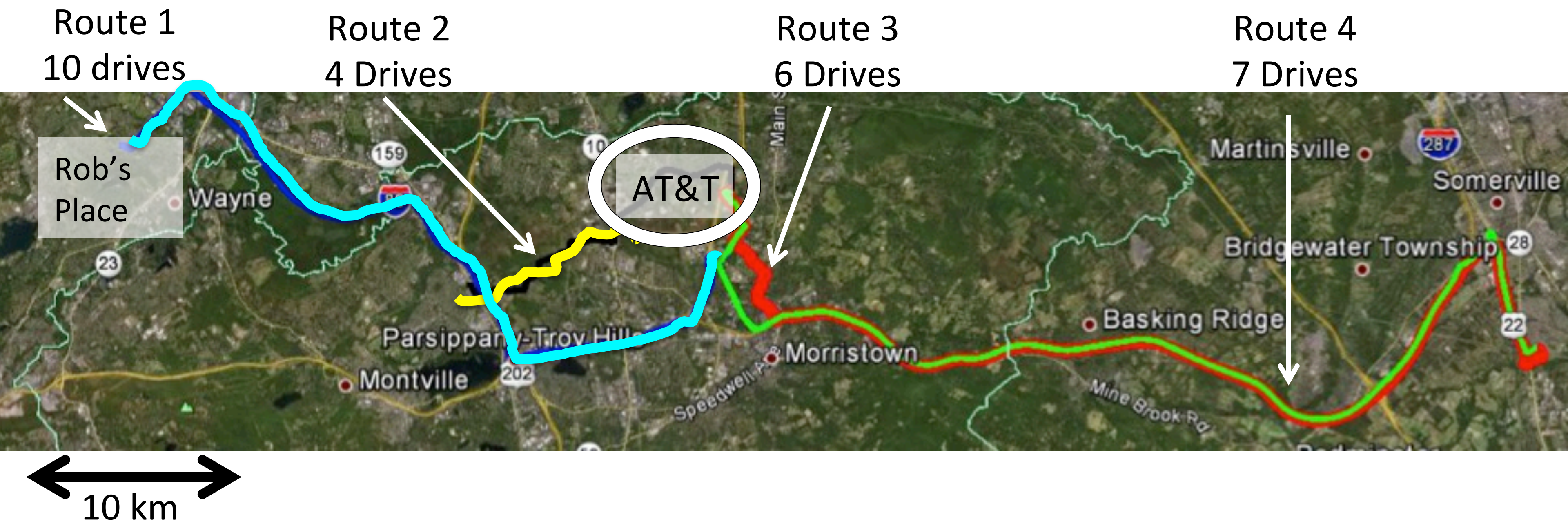
Measurement Campaign



Courtesy of Google Maps

- Qualcomm Toolkit (QXDM)
- Measuring parameters from physical layer of smartphone
- Fine granularity (milliseconds)
- 3G data network

Summary of Measurements

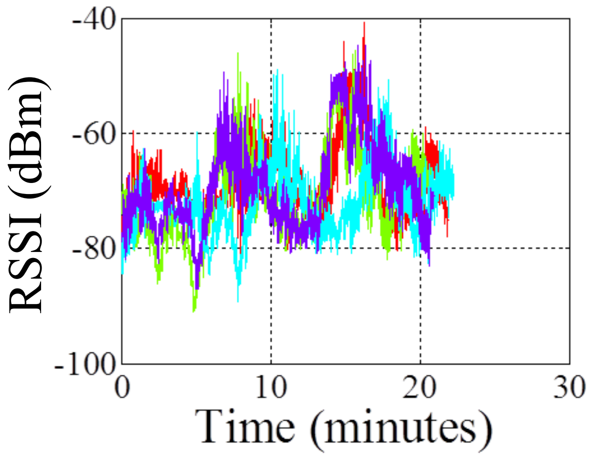


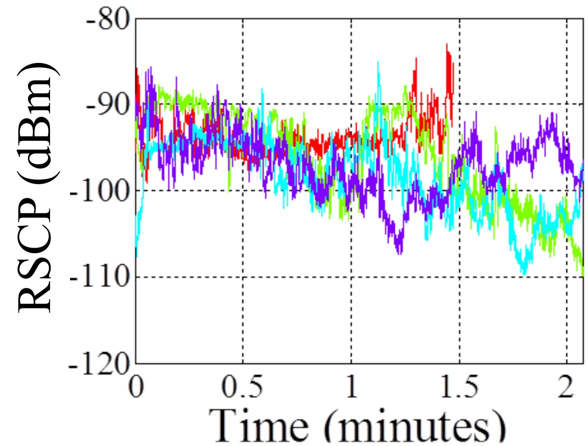
- 4 separate drive routes
- 1 set of non-mobile tests

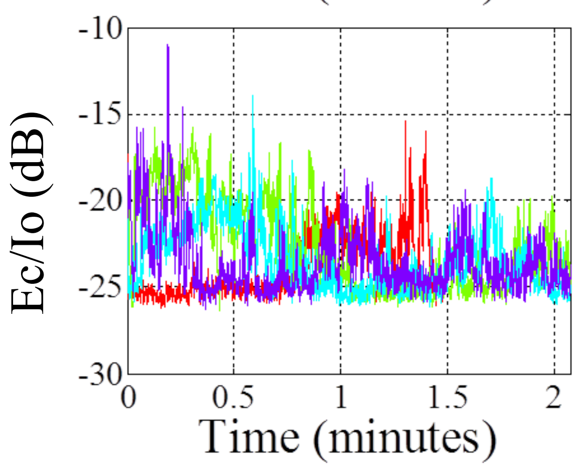
- Significant data set logged
  - ~1400 minutes
  - 810km distance traveled
  - ~522 serving sectors
  - 3+GB of data

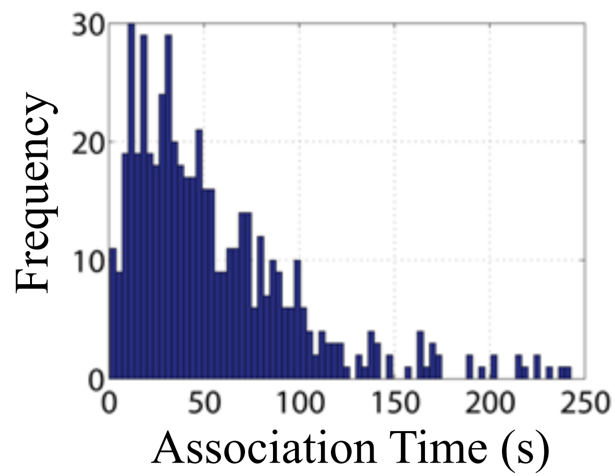
Measurements

- Received Signal Strength Indicator (RSSI): Total in-band power
- Received Signal Code Power (RSCP): Total power in each pilot channel
- E_c/I_o: Effective signal to noise ratio for pilot channel
  - $E_c/I_o(\mathrm{dB}) = \mathrm{RSSI}(\mathrm{dBm}) - \mathrm{RSCP}\ (\mathrm{dBm})$







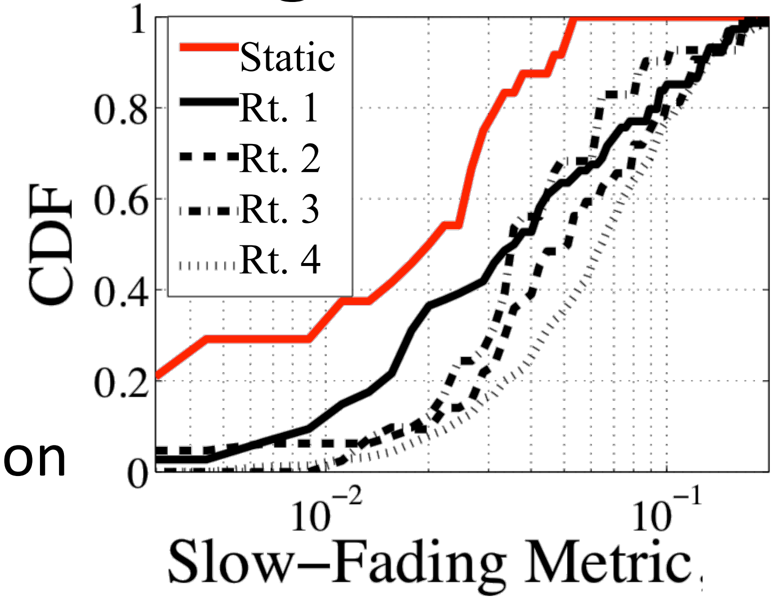


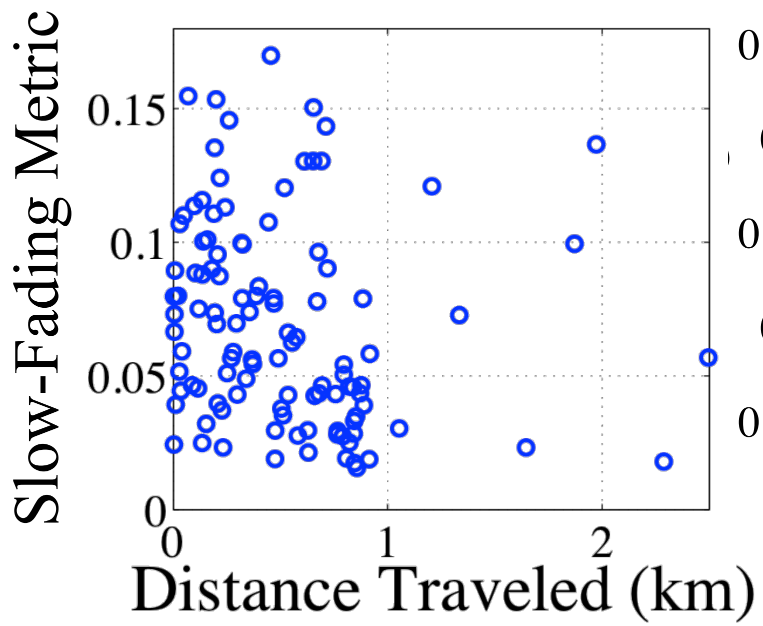
Modeling Slow Fading

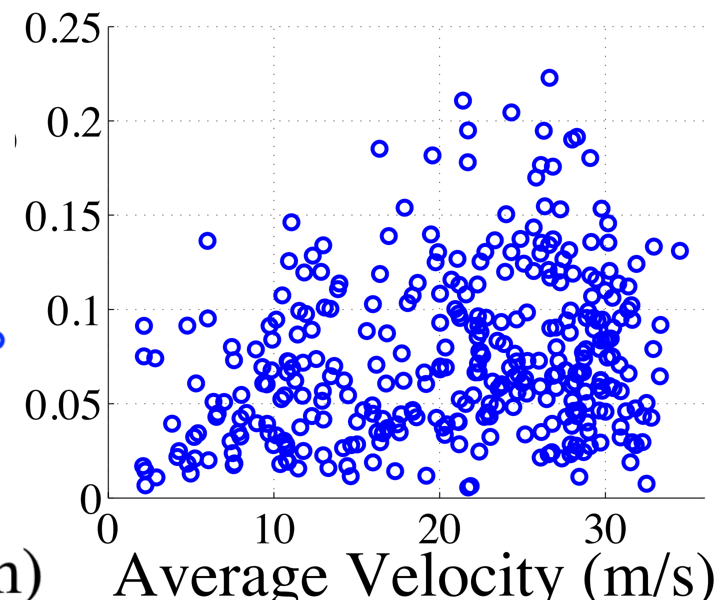
- Developed a slow-fading metric

$$\sum_{j=1}^{T} \widetilde{E_c/I_o}[j]^2/T$$

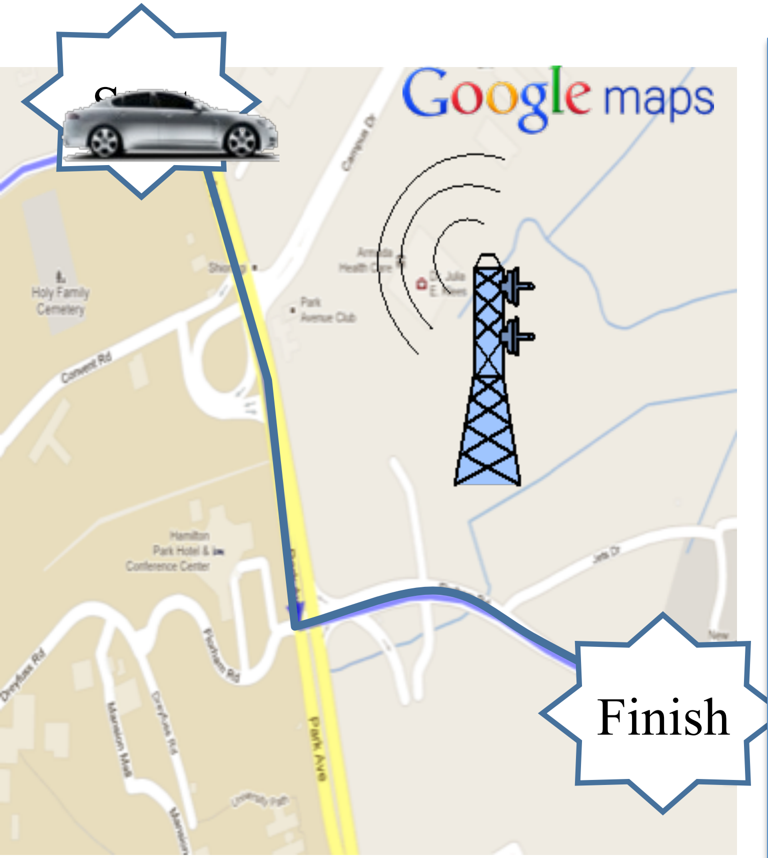
- Slow-fading showed little correlation to line-of-sight parameters

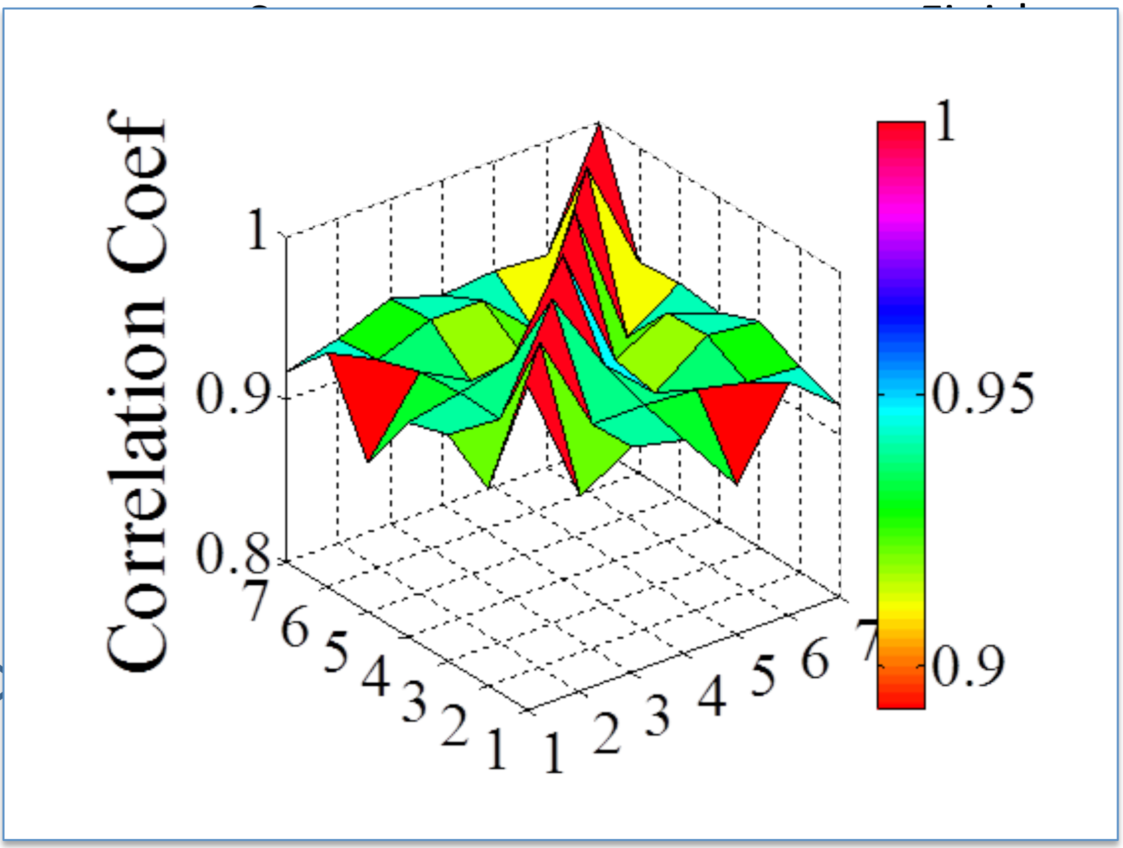






Reproducibility of Slow Fading





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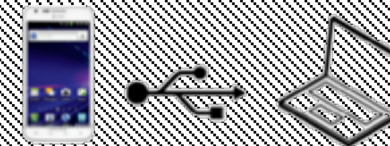

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$$\{\hat{r}_{ij}\}_{K\times T}$$

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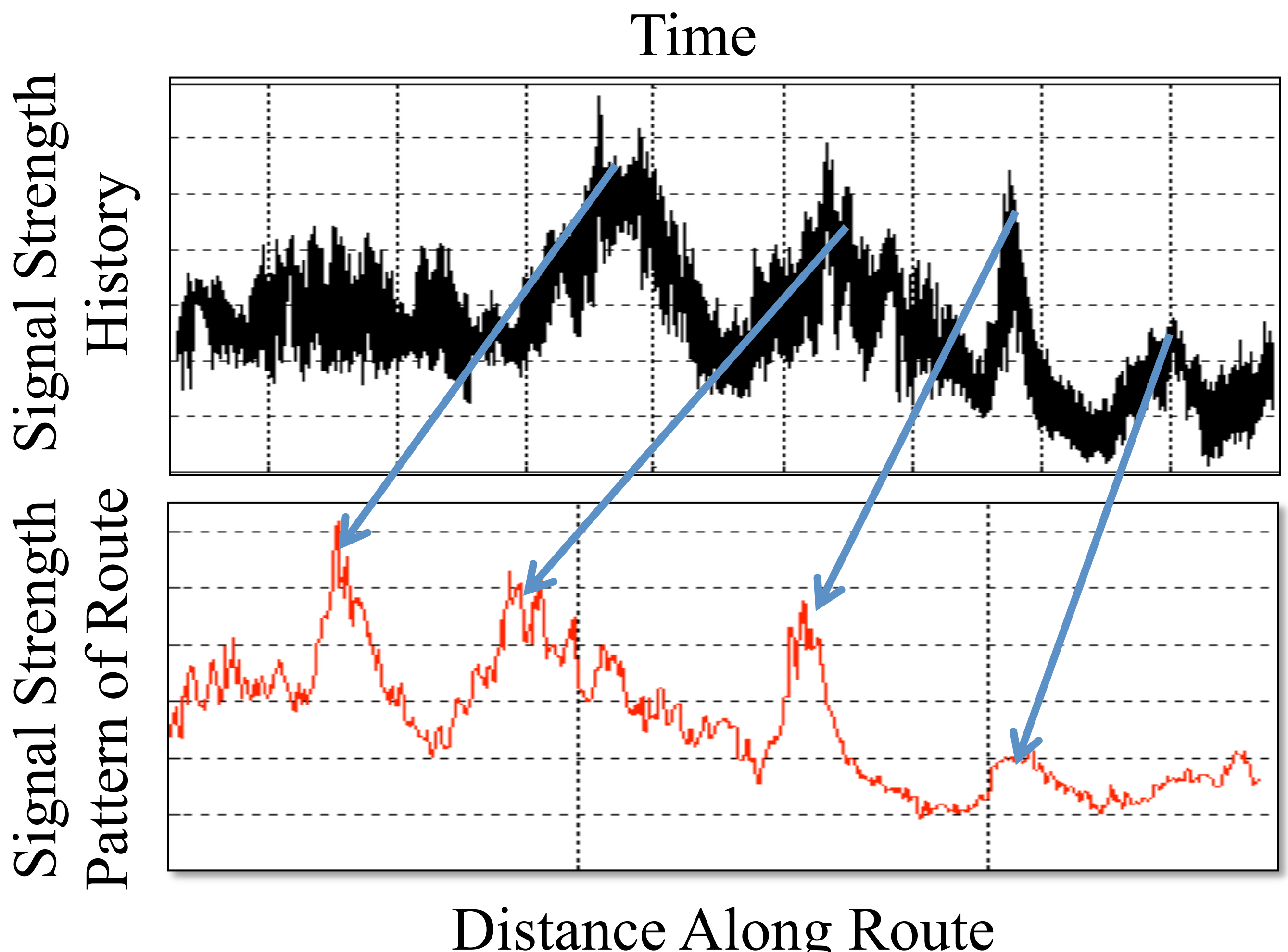
Localization using Dynamic Time Warping

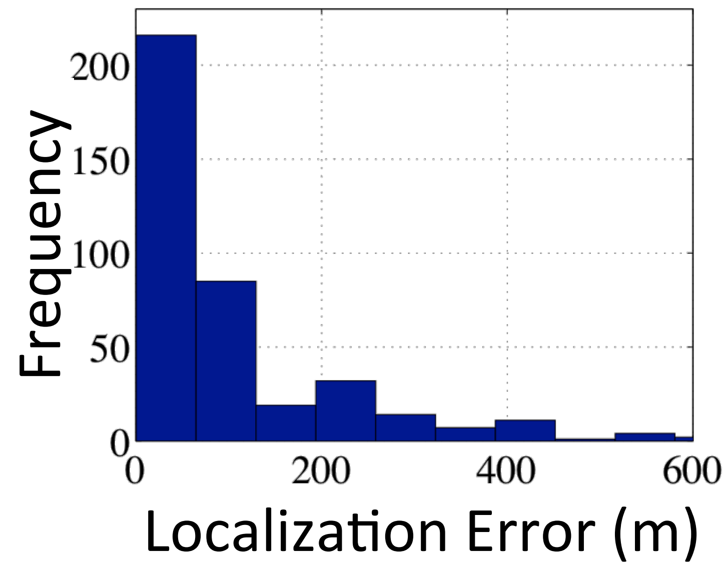


Localization using Dynamic Time Warping

$$\mathrm{c}(b,j) = (\mathrm{RSSI}[j] - \overline{\mathrm{RSSI}}\langle b\rangle)^2 + \sum_{u\in U_b} (E_c/I_{o_u}[j] - \overline{E_c/I_{o_u}}\langle b\rangle)^2 + (\mathrm{RSCP}_u[j] - \overline{\mathrm{RSCP}}_u\langle b\rangle)^2$$

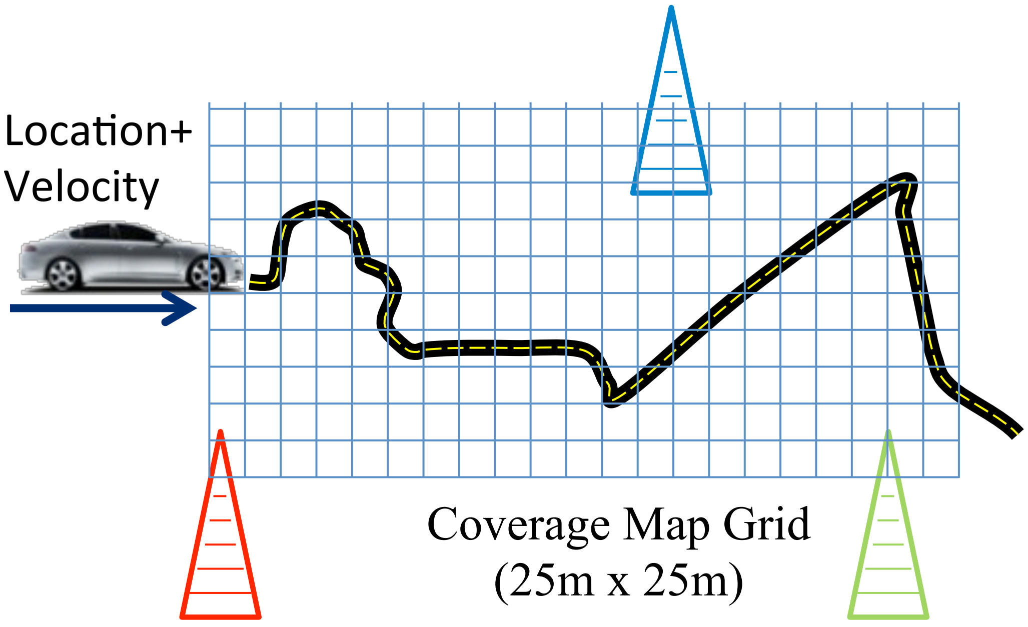
Dynamic programming solution

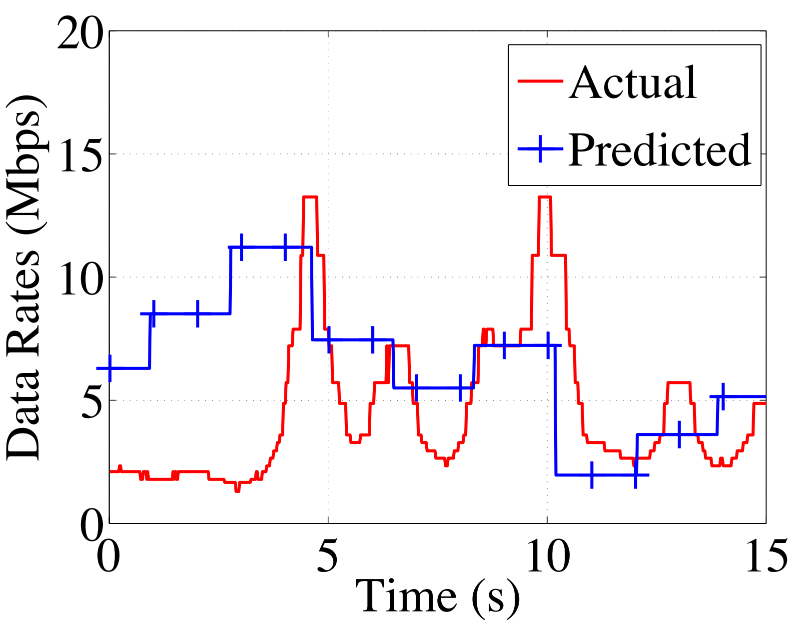
- Leverages *predictable* mobility
- RSSI – Received Signal Strength
- RSCP – Received Signal Code Power
- E_c/I_o – Effective signal to noise ratio for pilot channel



Coverage Map Prediction Mechanism

- Leverages predictable route trajectory
- Uses location and velocity from localization scheme
- Extrapolates current velocity for T time slots
- Determine future grid locations
- Coverage map used to map location into feasible data rate.





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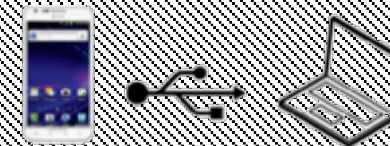

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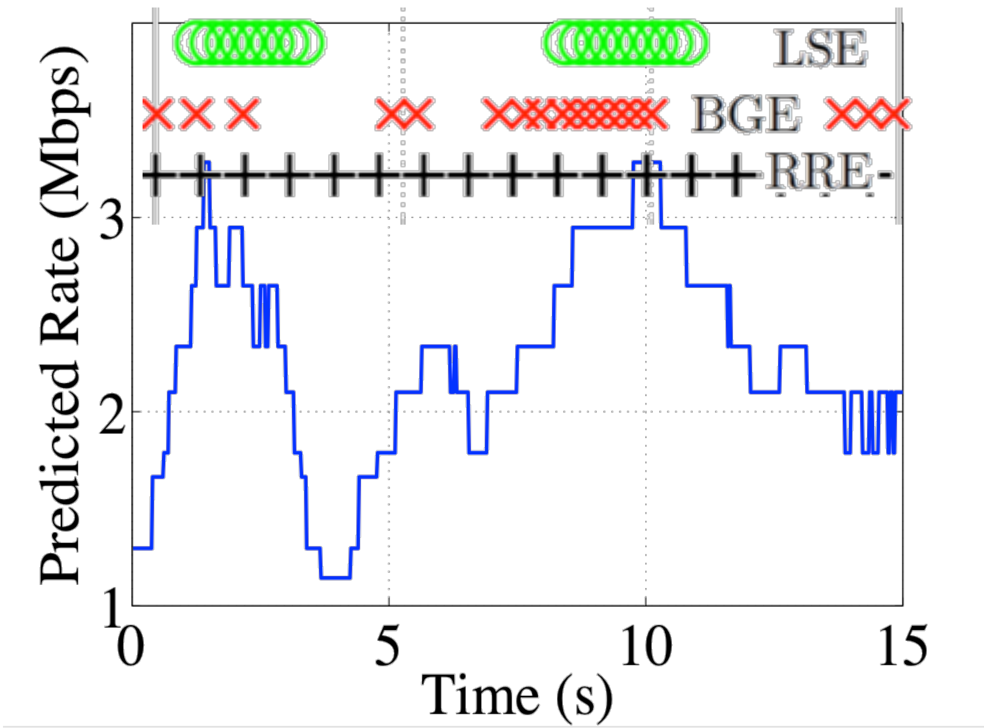
Channel Allocation (α) Estimation Heuristics

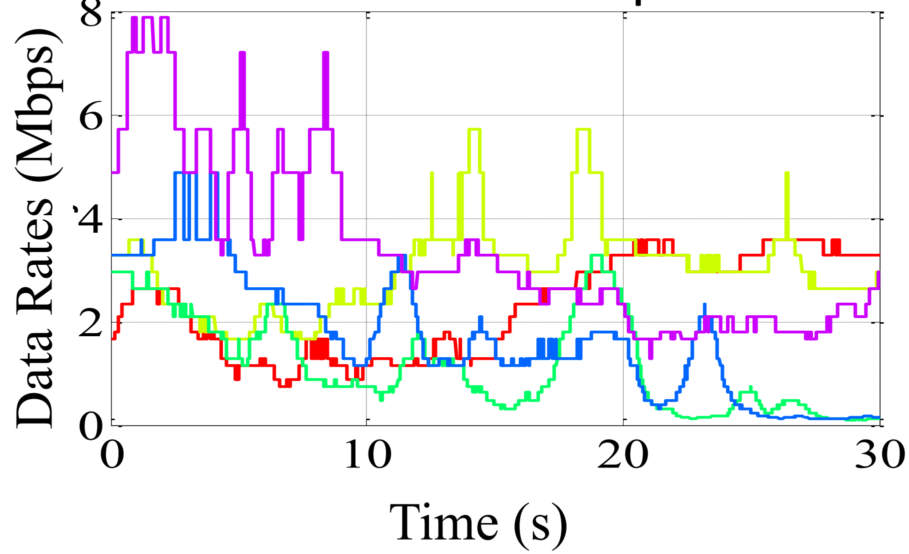
- Round Robin Estimation (RRE): Each user receives and equal fraction of each time slot
- Blind Gradient Estimation (BGE): In each slot j, select a user using the gradient with no future component
- Local Search Estimation (LSE): Begin with a random allocation and continue swapping to improve the cost function



Framework Performance Evaluation

- Test cases generated from random segments of measured traces

Test Case Example

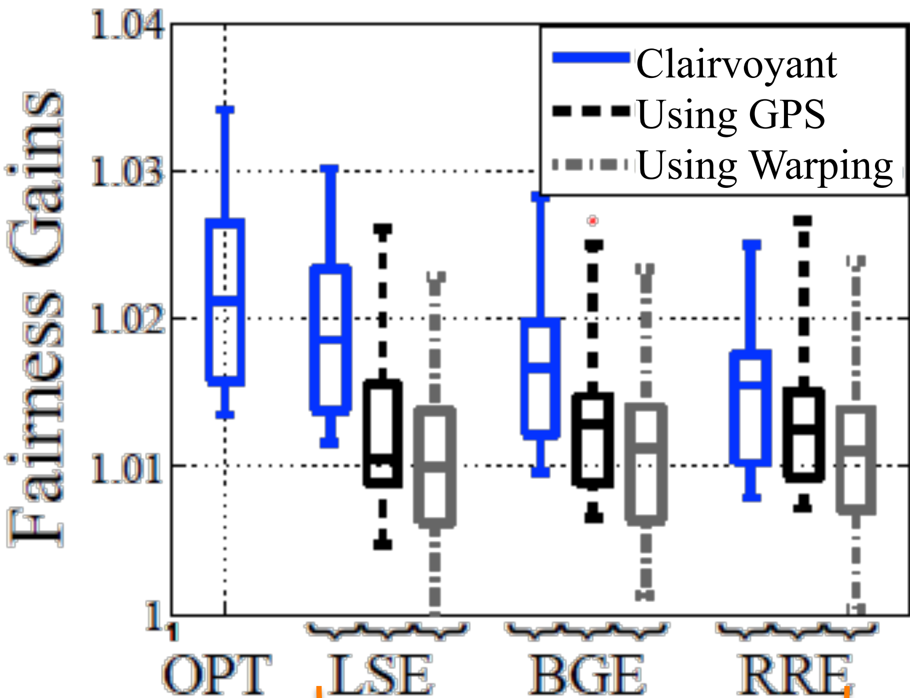


- Benchmarks
  - ❖ Numerical Solver (CVX) – solves convex relaxation without integer constraints on α.
  - ❖ Deployed Scheduler (PF-EXP)

$$\max_{i \in K} \frac{r_{ij}}{R_i[j]}$$

$$R_i[j] = (1-\epsilon)R_i[j-1] + \epsilon\alpha_{ij}r_{ij}$$

Fairness and Throughput Results

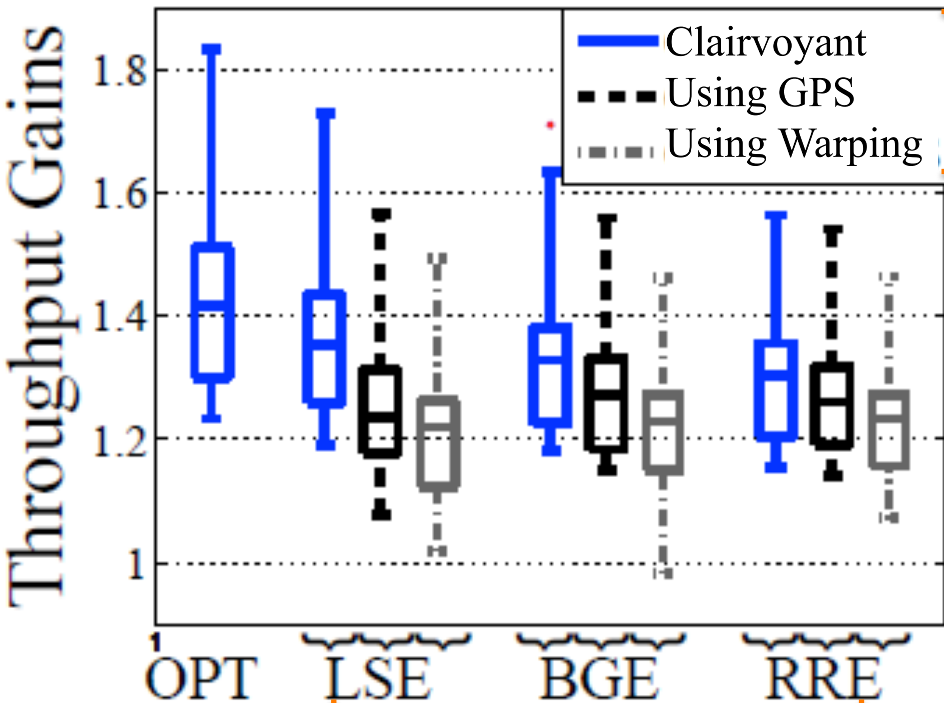


Rate prediction mechanisms

Channel allocation heuristics

Fairness gains confirm we are improving overall network fairness in addition to throughput

Fairness and Throughput Results

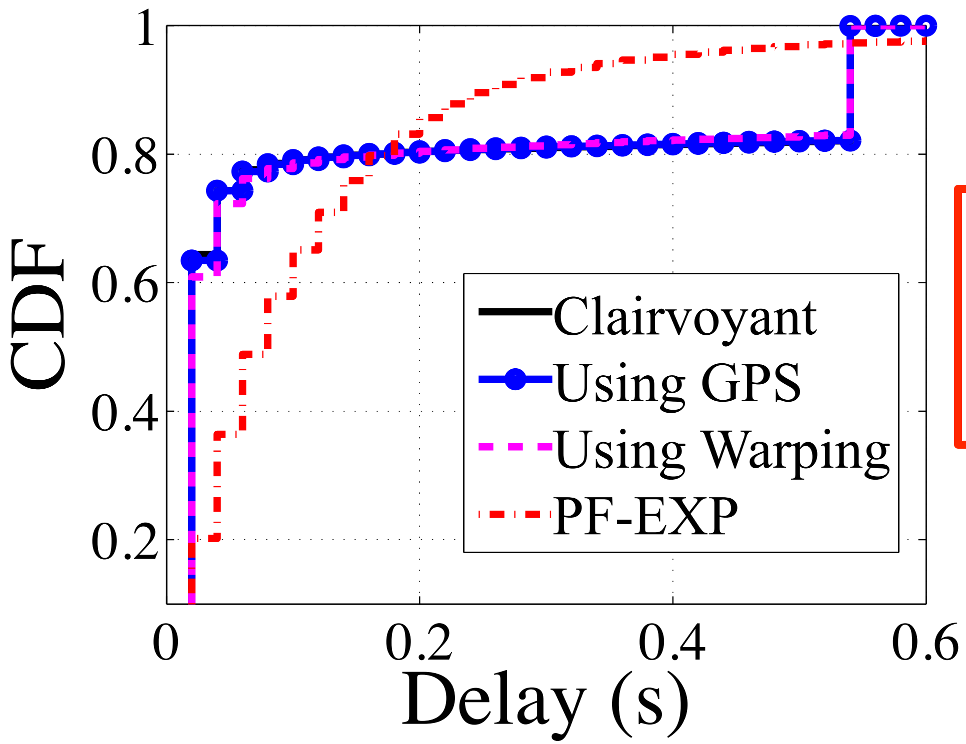


Rate prediction mechanisms

Network throughput improvements of 15 to 55% over existing scheduling algorithm

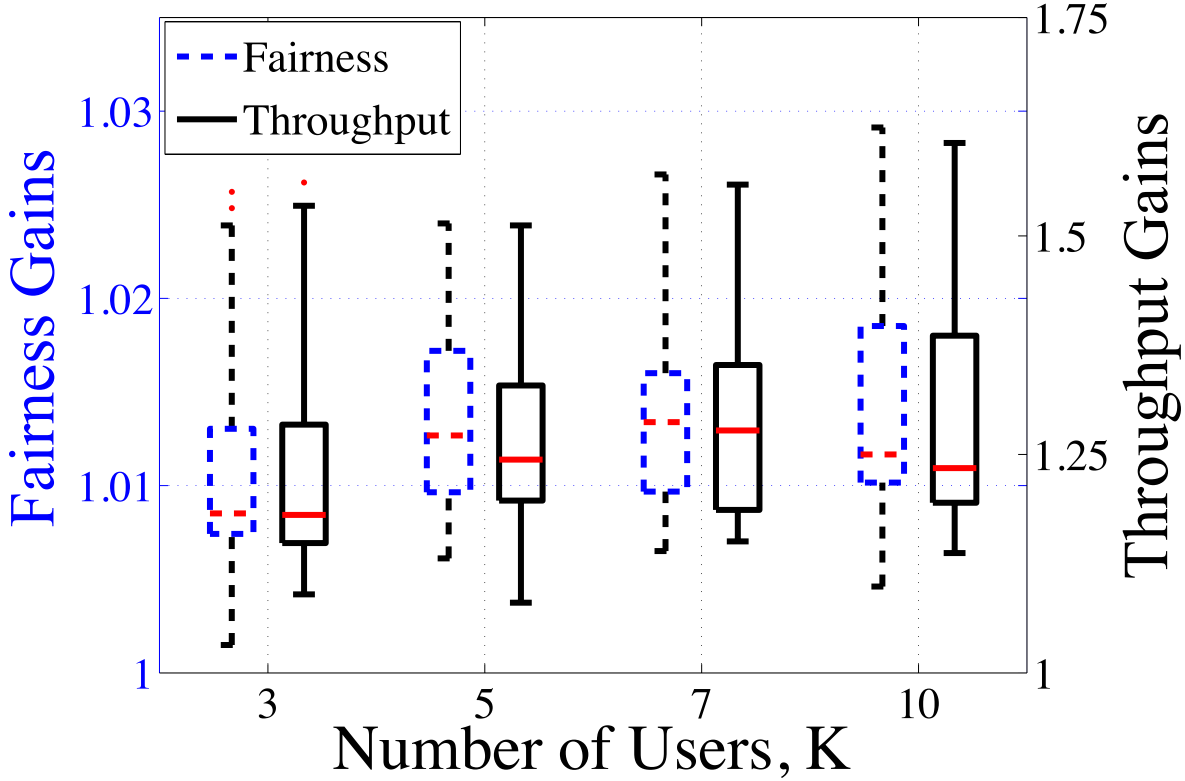
Channel allocation heuristics

Fairness and Throughput Results



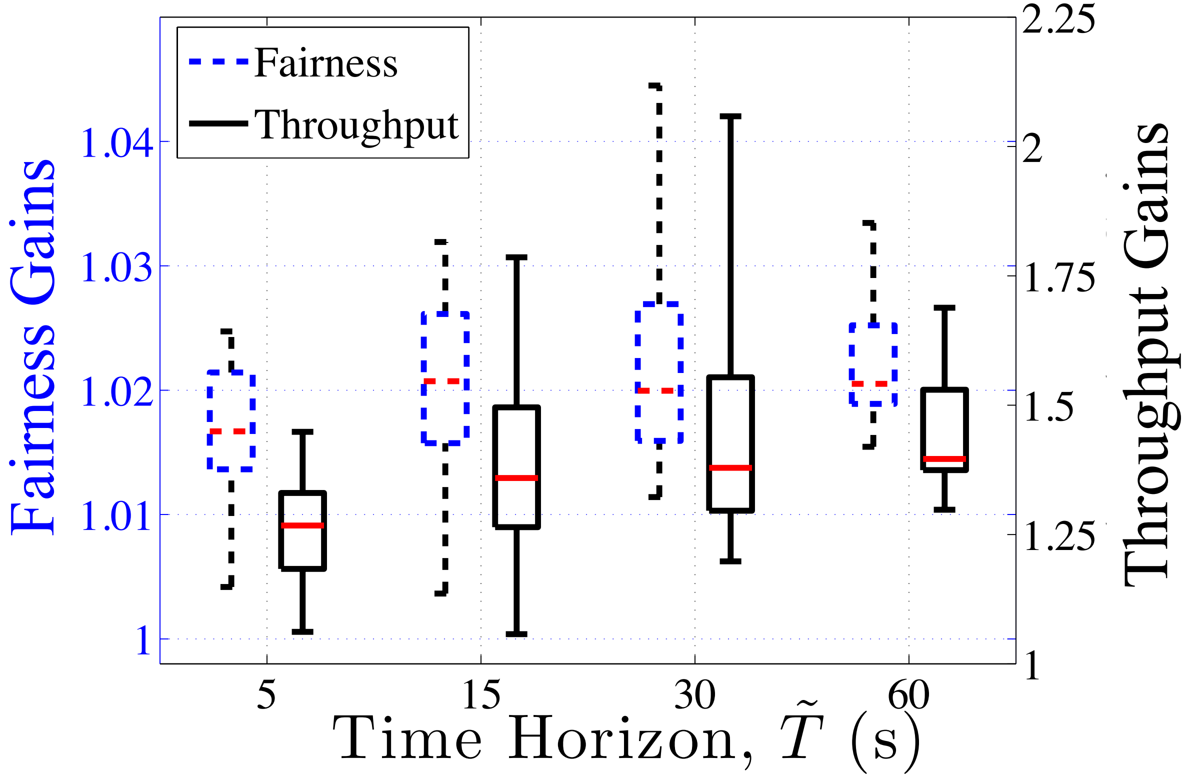
Network throughput improvements of 15 to 55% over existing scheduling algorithm

Sensitivity Results



Performance improves with number of users, K

Sensitivity Results



Performance improves with time horizon, T

Conclusions

- Proposed a predictive scheduling framework
- Characterized the repeatability of mobility through an extensive channel measurement campaign
- Developed a localization scheme utilizing user channel quality history
- Evaluated the framework's performance using traces collected from an operational 3G network and **demonstrated throughput improvements of 15-55%**
- Extendable for 4G scheduling models

- Contact Info

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  - ❖ robm@ee.columbia.edu