Opportunistic Communication:
Smart Scheduling and Dumb Antennas

David Tse
Department of EECS, U.C. Berkeley

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Intel

Communication over Wireless Channels

- Fundamental characteristic of wireless channels: fading.
- A modern view of communication over fading channels is emerging.
- This view has ramifications to the design of not only the physical layer but to the design of the entire wireless network.

Opportunistic Communication

Smart Scheduling

Downlink scheduling for Qualcomm's HDR (High Data Rate) system.

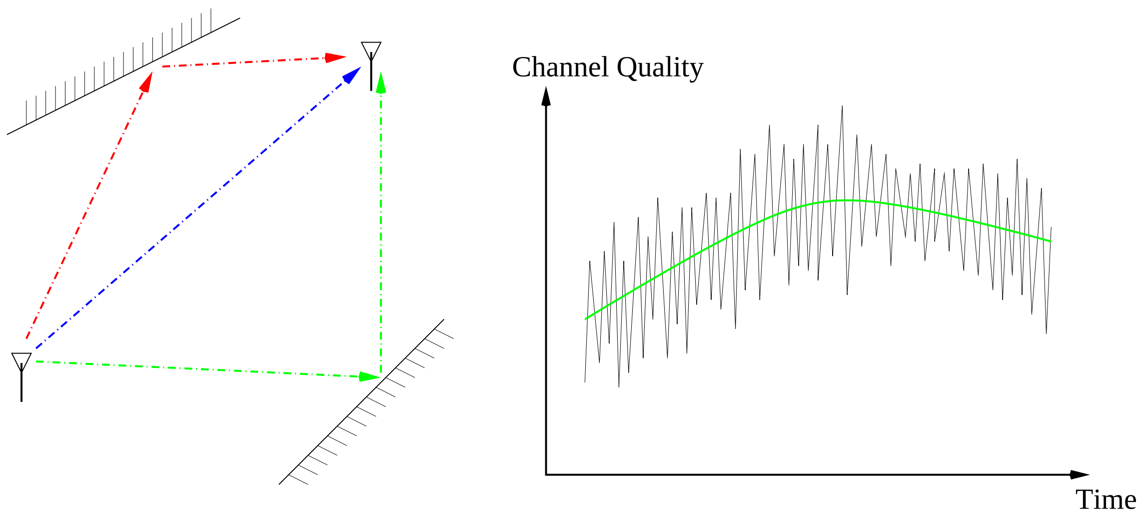
(Tse 99)

Dumb Antennas

Opportunistic beamforming using multiple transmit antennas

(Viswanath, Tse and Laroia 2001)

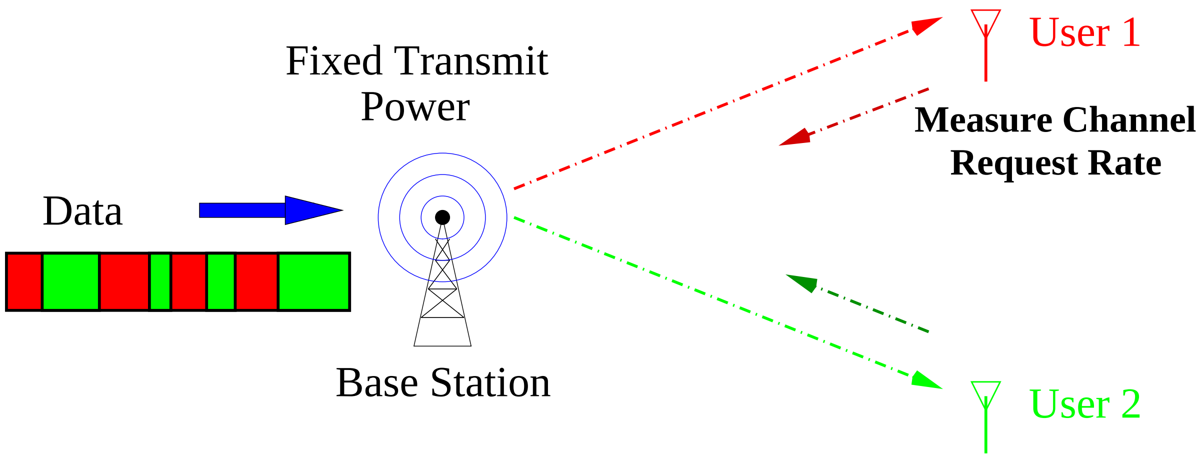
Wireless Fading Channels



- fading due to constructive and destructive interference between multiple signal paths;
- Rayleigh fading: superposition of many small paths
- Rician fading: many small paths plus one dominant path

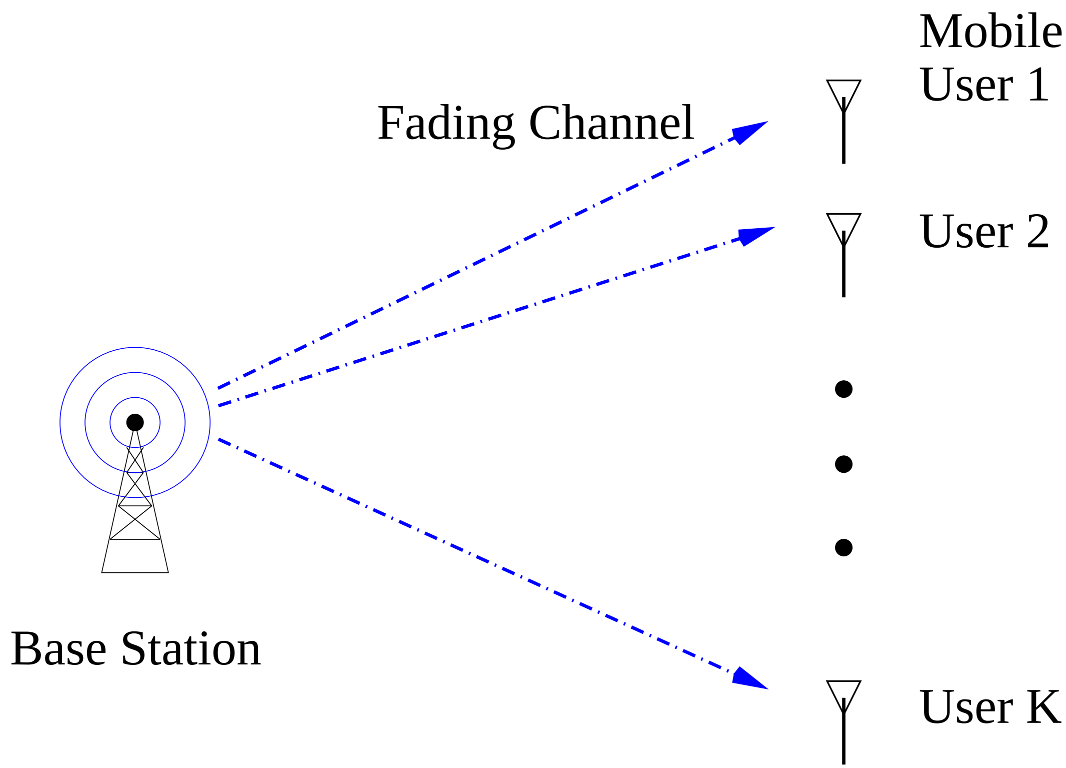
Qualcomm HDR's DownLink

HDR (1xEV-DO): a wireless data system operating on IS-95 band (1.25 MHz)



- HDR downlink operates on a time-division basis.
- Scheduler decides which user to serve in each time-slot.

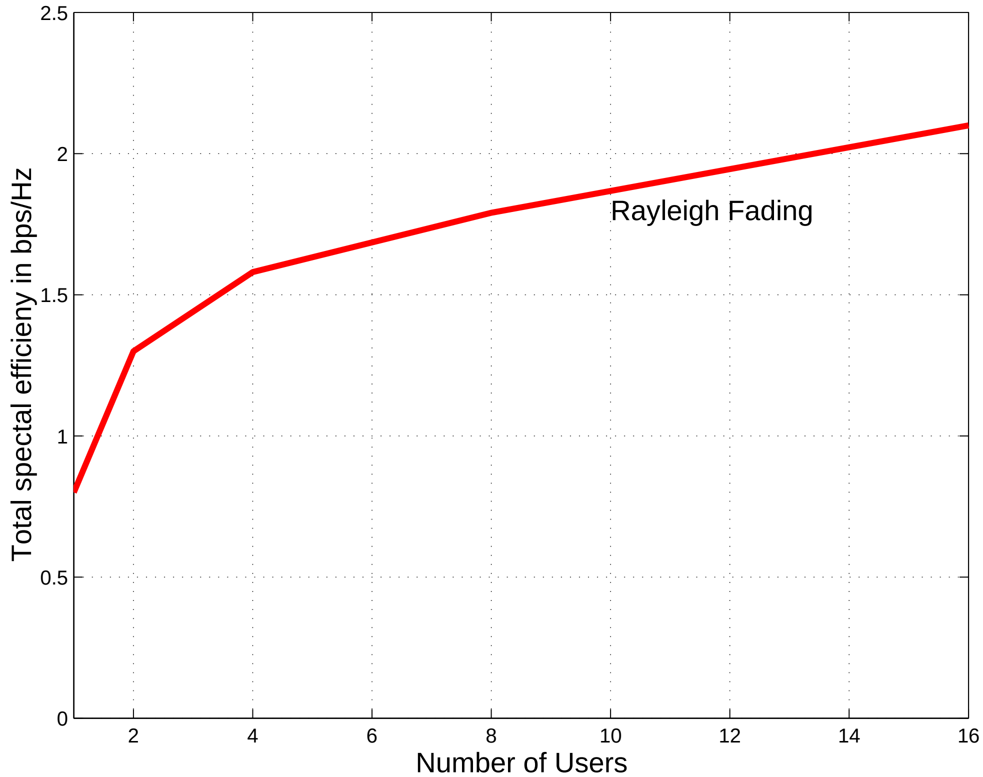
Downlink Multiuser Fading Channel



What is the sum capacity with channel state feedback?

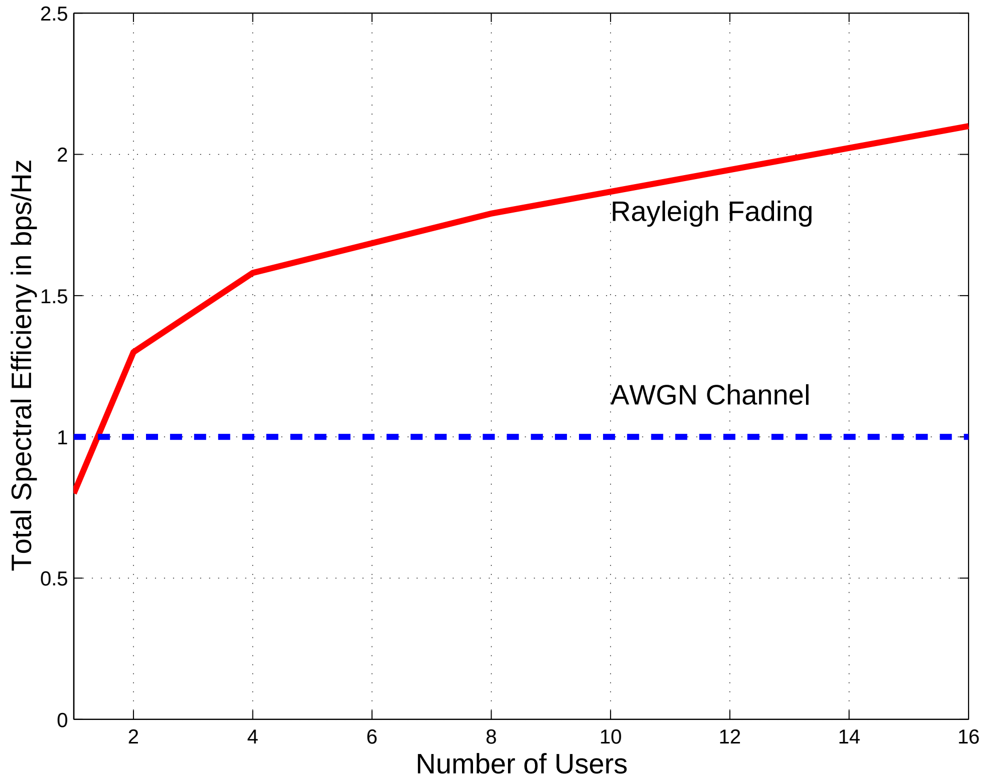
Information Theoretic Capacity of Downlink

(Tse 97)



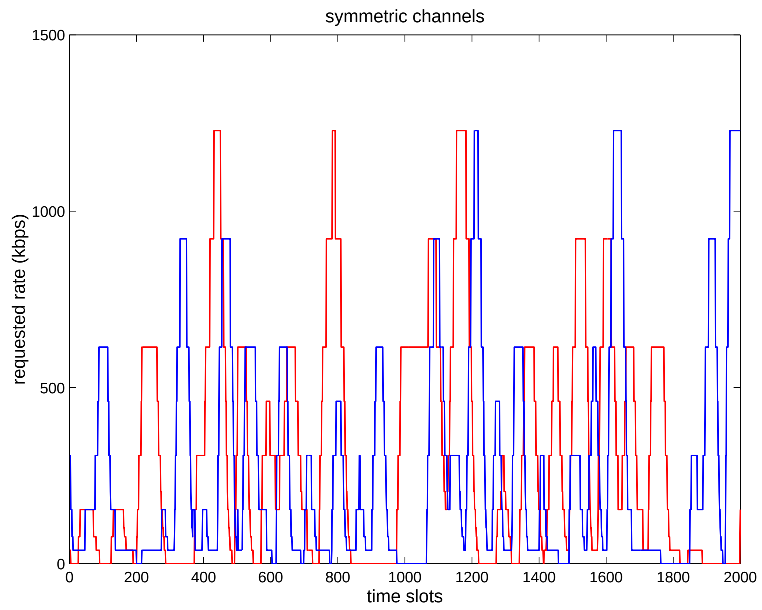
Each user undergoes independent Rayleigh fading with average received signal-to-noise ratio SNR $= 0$dB.

To Fade or Not to Fade?



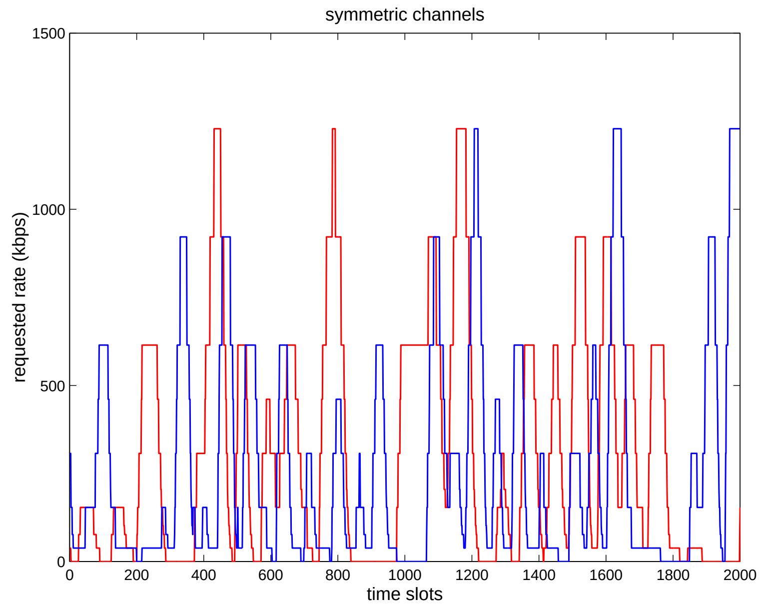
Sum Capacity of fading channel much larger than non-faded channel!

Multiuser Diversity



- In a large system with users fading independently, there is likely to be a user with a very good channel at any time.
- Long term total throughput can be maximized by always serving the user with the strongest channel.

Multiuser Diversity



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$$\text{effective SNR at time } t = \max_{1 \le k \le K} |h_k(t)|^2.$$

Multiuser Diversity

- Diversity in wireless systems arises from independent signal paths.
- Traditional forms of diversity includes time, frequency and antennas.
- Multiuser diversity arises from independent fading channels across different users.

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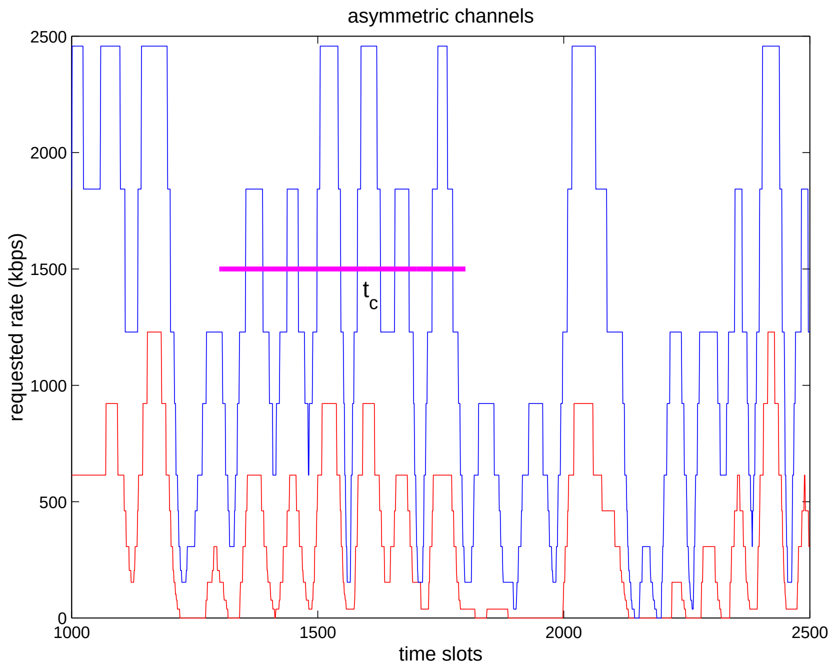
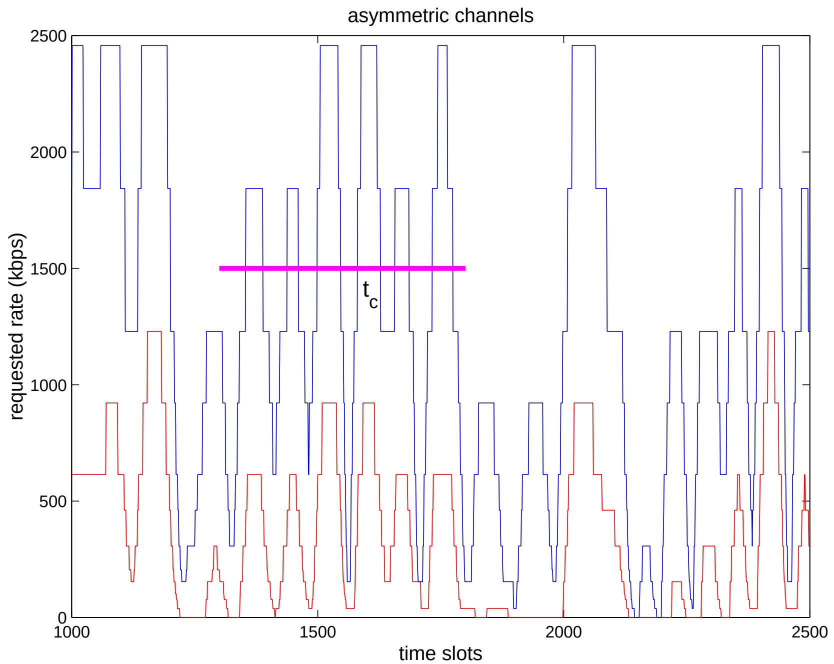
- Diversity in wireless systems arises from independent signal paths.
- Traditional forms of diversity includes time, frequency and antennas.
- Multiuser diversity arises from independent fading channels across different users.
- Fundamental difference: Traditional diversity modes pertain to point-to-point links, while multiuser diversity provides network-wide benefit.

Fairness and Delay



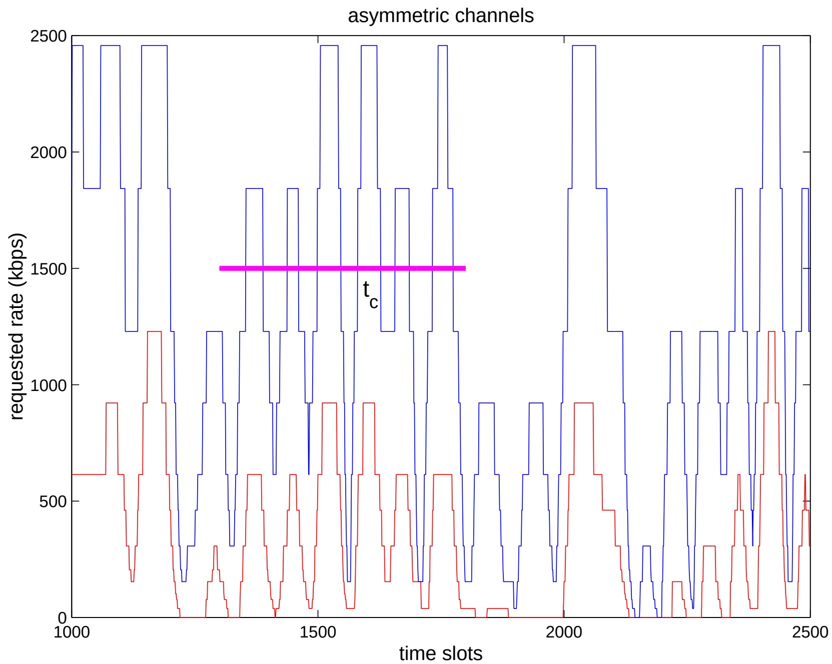
Challenge is to exploit multiuser diversity while sharing the benefits fairly and timely to users with asymmetric channel statistics.

Hitting the Peaks



- Want to serve each user when it is near its peak within a latency time-scale t_c.

Hitting the Peaks



- Want to serve each user when it is near its peak within a latency time-scale t_c.
- In a large system, at any time there is likely to be a user whose channel is near its peak.

Proportional Fair Scheduler

At time slot t, given

1) users' average throughputs $T_1(t), T_2(t), \ldots, T_K(t)$ in a past window.

2) current requested rates $R_1(t), R_2(t), \ldots, R_K(t)$

transmit to the user k^* with the largest

$$\frac{R_k(t)}{T_k(t)}.$$

Average throughputs $T_k(t)$ can be updated by an exponential filter with time constant t_c.

Comments

- If users have symmetric channel statistics, this reduces to the greedy policy of transmitting to the mobile with the highest requested rate.
- If channels have different statistics, competition for resource is made fair by normalization
- feedback is built into the metric $R_k(t)/T_k(t)$ to provide a fair bandwidth allocation over the time-scale t_c.

Comparison with Round-Robin Policy

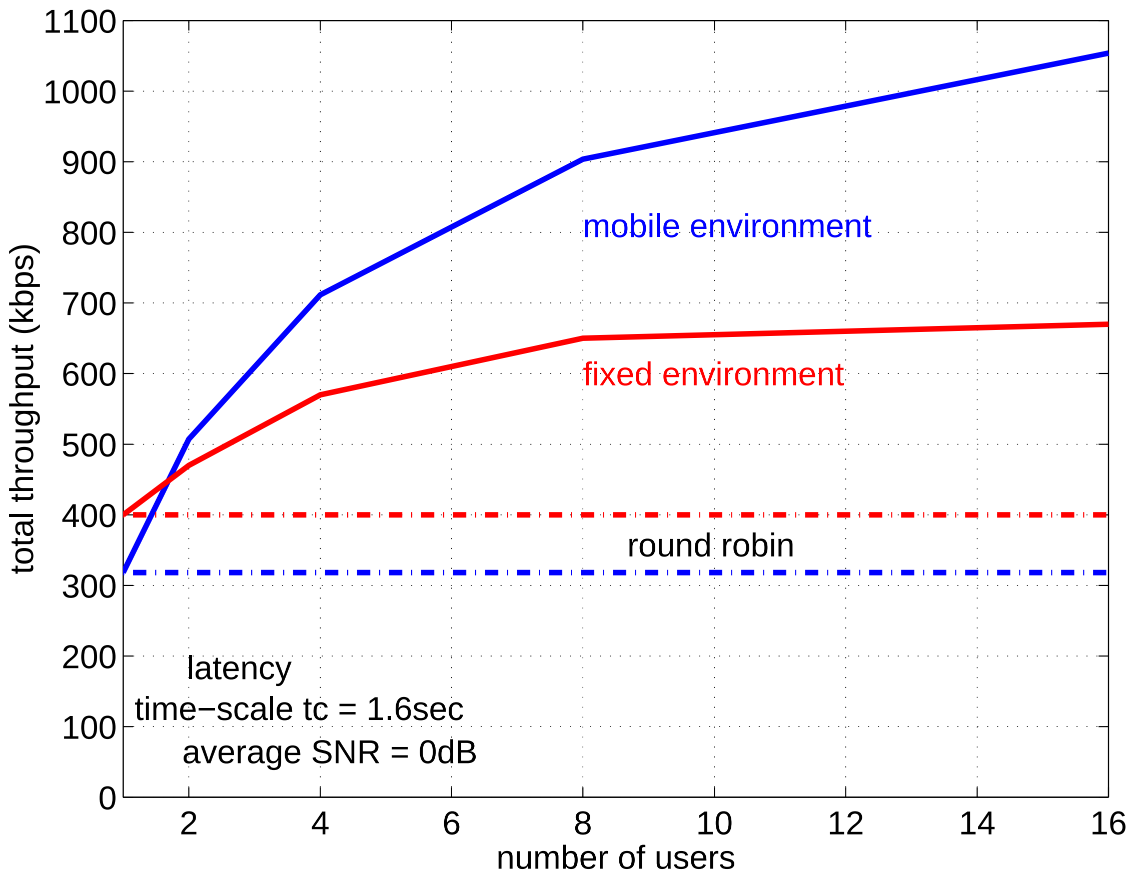
Round-Robin Policy

- Give same number of time slots to all the users in a round-robin fashion, regardless of their channel conditions.

Proportional fair policy:

- Give roughly the same number of time slots to all users, but try to transmit to a user when its channel condition is near its peak.
- Resource fair, but not necessarily performance fair.

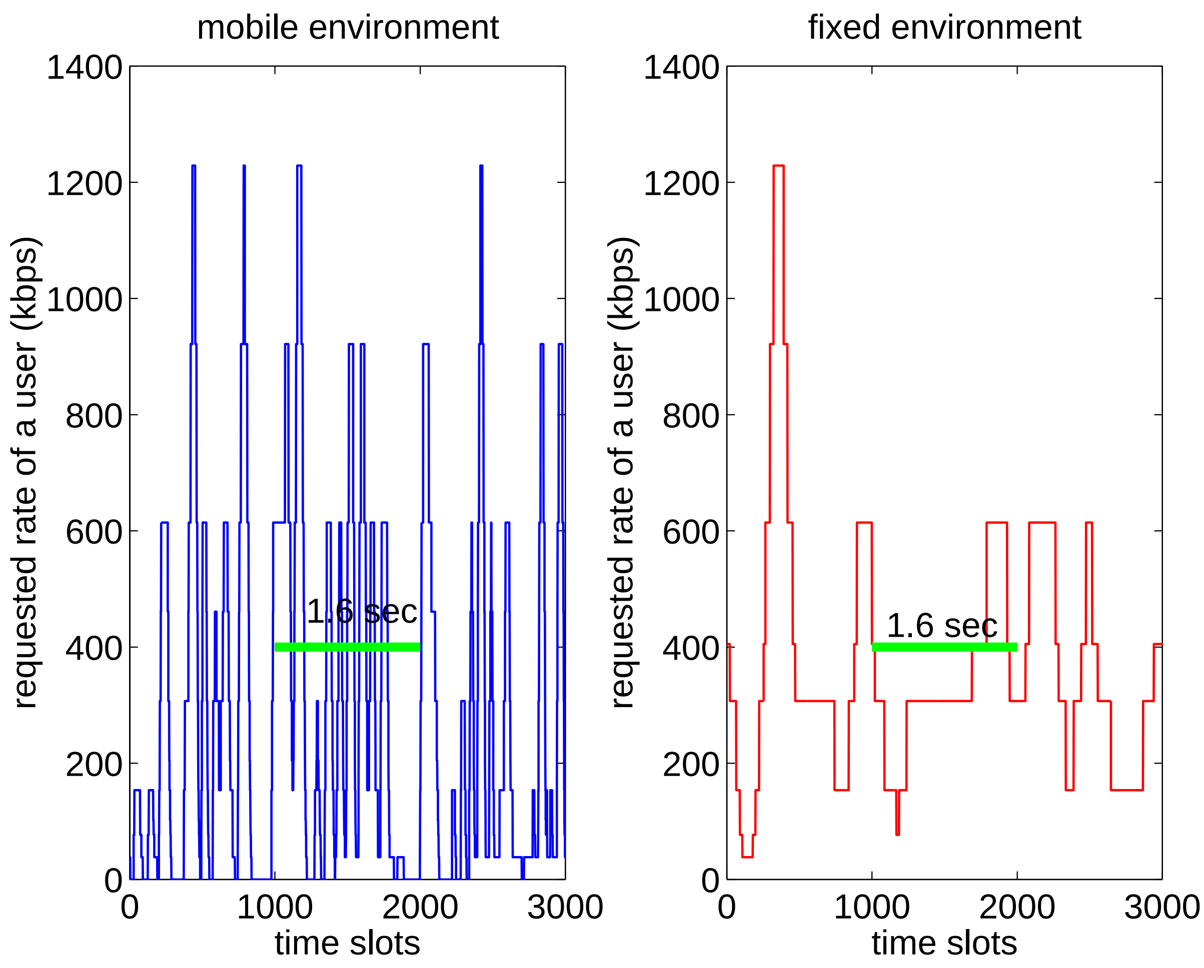
Throughput of HDR Scheduler: Symmetric Users



Mobile environment: 3 km/hr, Rayleigh fading

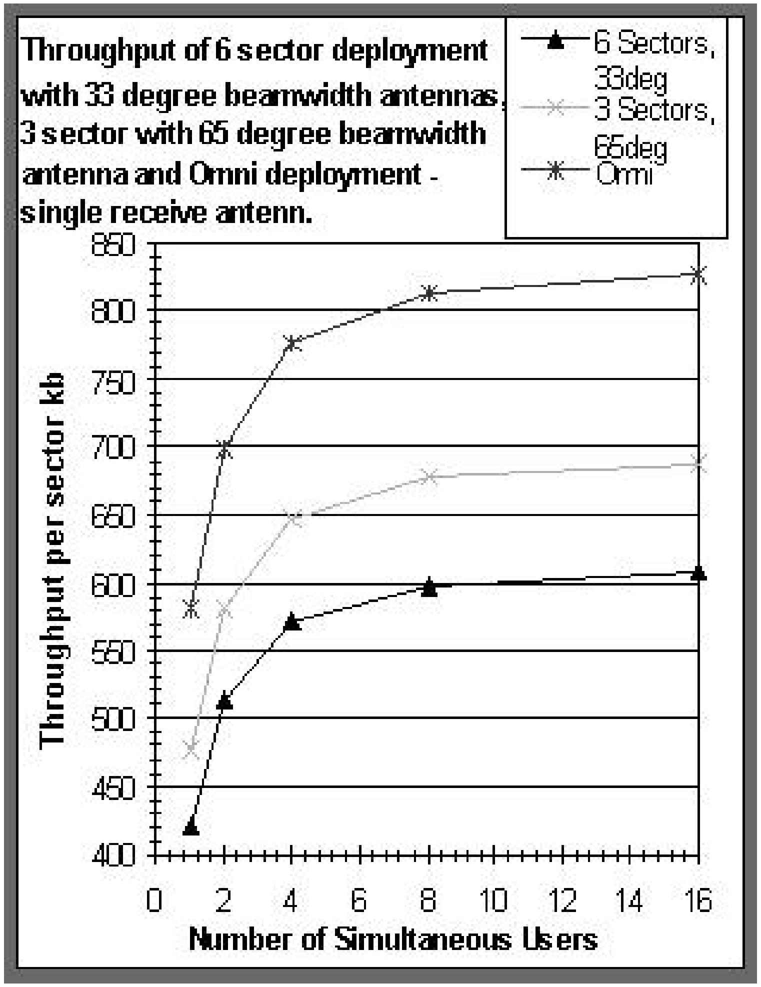
Fixed environment: 2Hz Rician fading with $E_{\text{fixed}}/E_{\text{scattered}} = 5$.

Channel Dynamics



Channel varies faster and has more dynamic range in mobile environments.

Throughput of Scheduler: Asymmetric Users

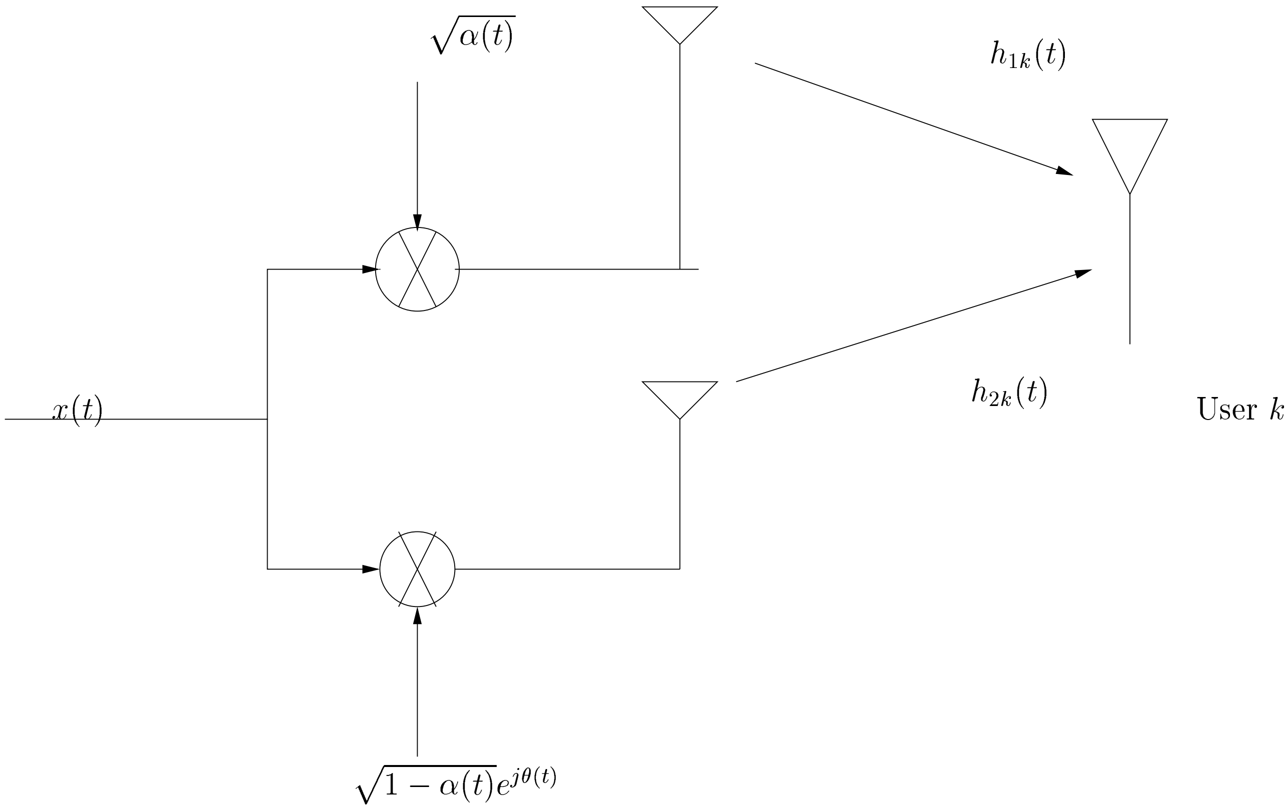


(Jalali, Padovani and Pankaj 2000)

Inducing Randomness

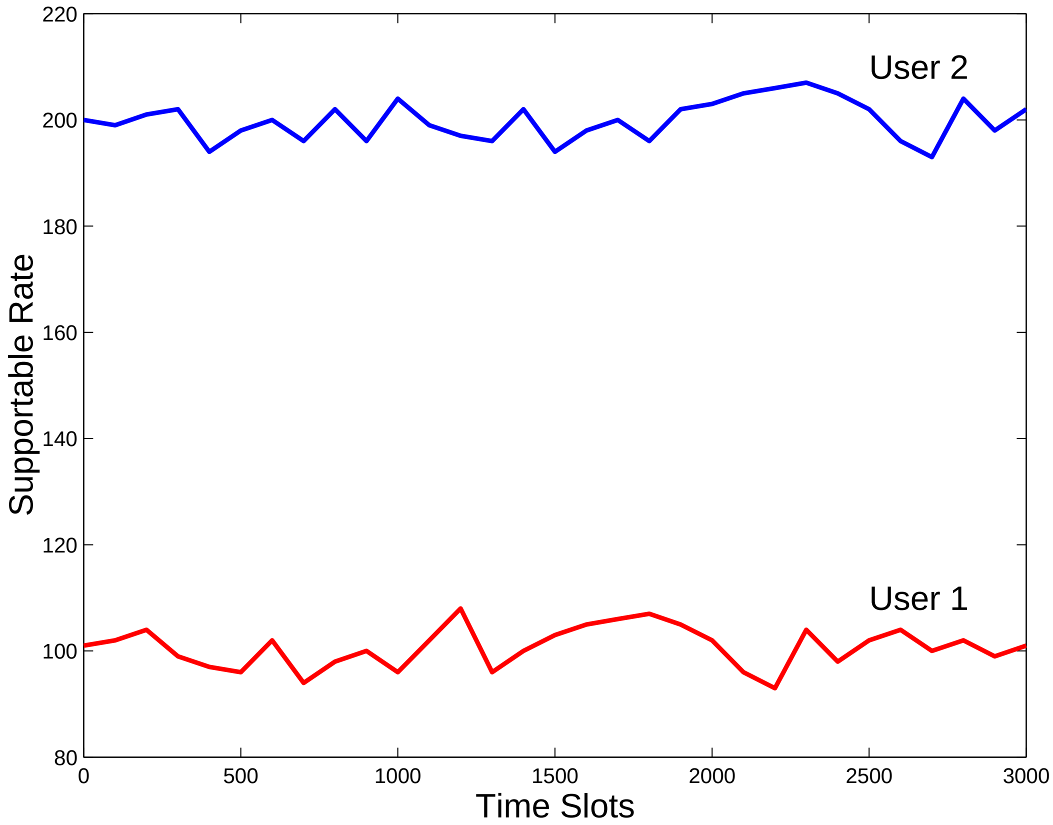
- Scheduling algorithm exploits the nature-given channel fluctuations by hitting the peaks.
- If there are not enough fluctuations, why not purposely induce them?

Dumb Antennas

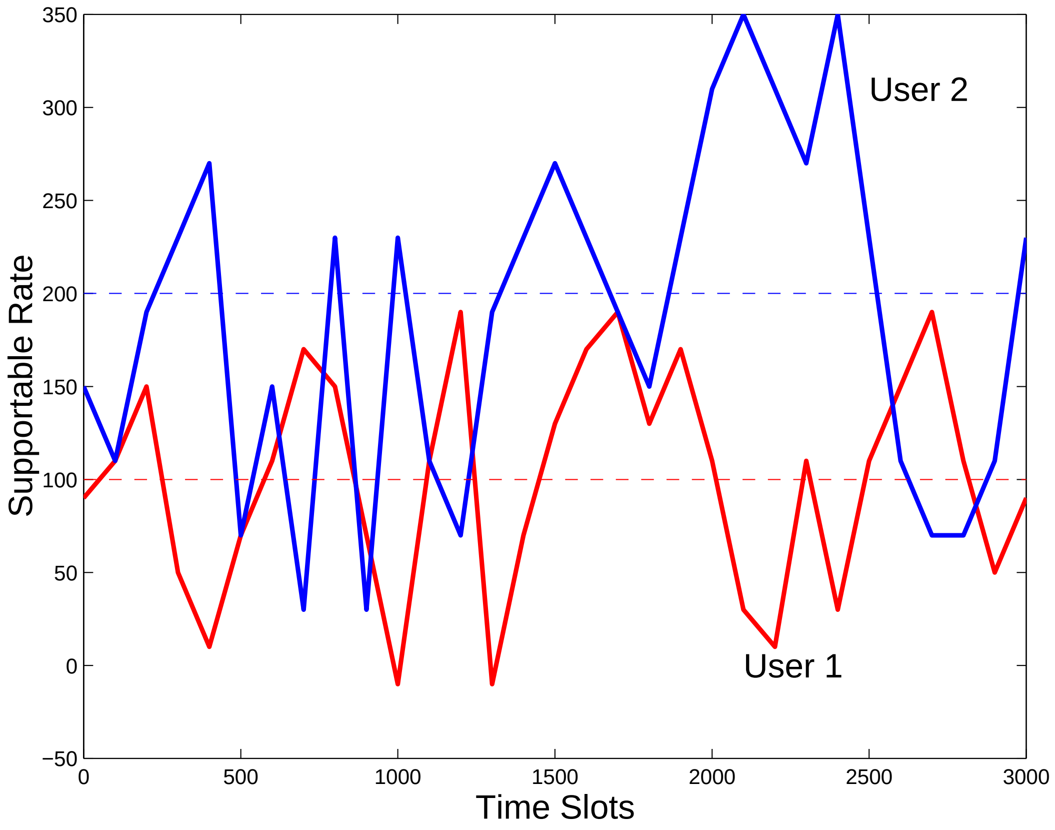


Received signal at user k: $\left[\sqrt{\alpha(t)}h_{1k}(t) + \sqrt{1-\alpha(t)}\exp(j\theta(t))h_{2k}(t)\right]x(t).$

Slow Fading Environment: Before

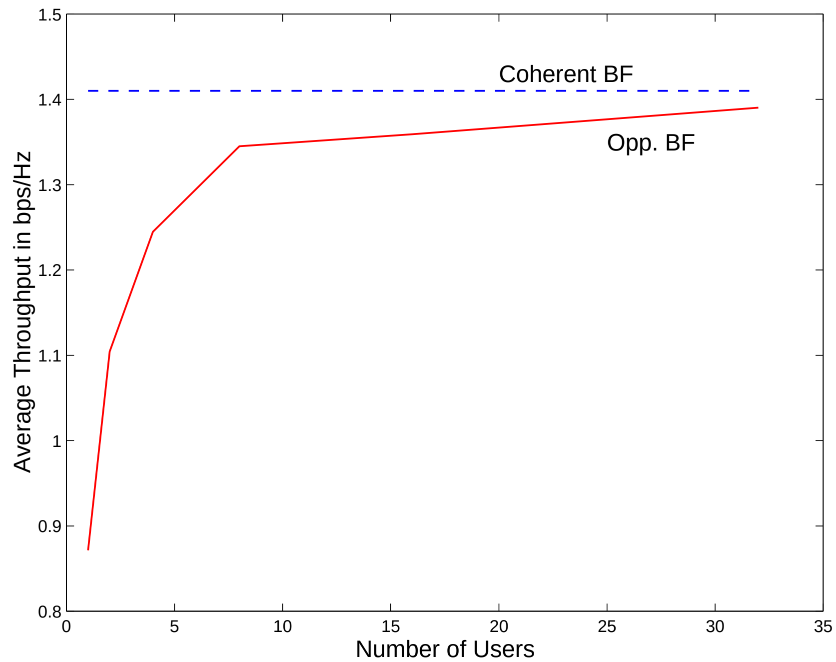


After



350
300
250
200
150
100
50
0
−50
0
500
1000
1500
2000
2500
3000
Supportable Rate
Time Slots
User 2
User 1

Opportunistic Beamforming: Slow Fading



- Consider first a slow fading environment when channels of the users are fixed (but random).
- Dumb antennas can approach the performance of true beamforming when there are many users in the systems.

Opportunistic versus True Beamforming

- If the gains h_{1k} and h_{2k} are known at the transmitter, then true beamforming can be performed:

$$
\begin{aligned}
\alpha &= \frac{|\, h_{1k} \,|^2}{|\, h_{1k} \,|^2 + |\, h_{2k} \,|^2} \\
\theta &= \angle h_{1k} - \angle h_{2k}
\end{aligned}
$$

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$$\alpha = \frac{| h_{1k} |^2}{| h_{1k} |^2 + | h_{2k} |^2}$$
$$\theta = \angle h_{1k} - \angle h_{2k}$$

- Dumb antennas randomly sweep out a beam and opportunistically sends data to the user closest to the beam.
- Opportunistic beamforming can approach the performance of true beamforming when there are many users in the systems, but with much less feedback and channel measurements.

Asymptotic Result

Assume that the slow fading states of each user are i.i.d. randomly generated (but fixed for all time).

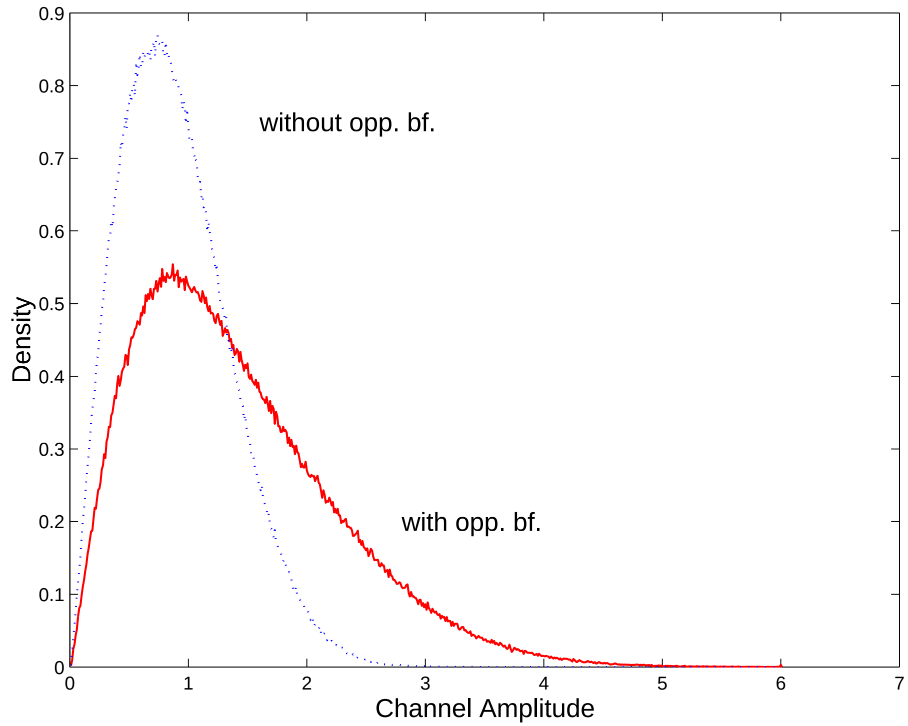
In a large system of K users, with high probability, the users achieve throughputs

$$T_k \to \frac{1}{K} R_k^{\mathrm{bf}}, \qquad k = 1, \ldots K$$

.

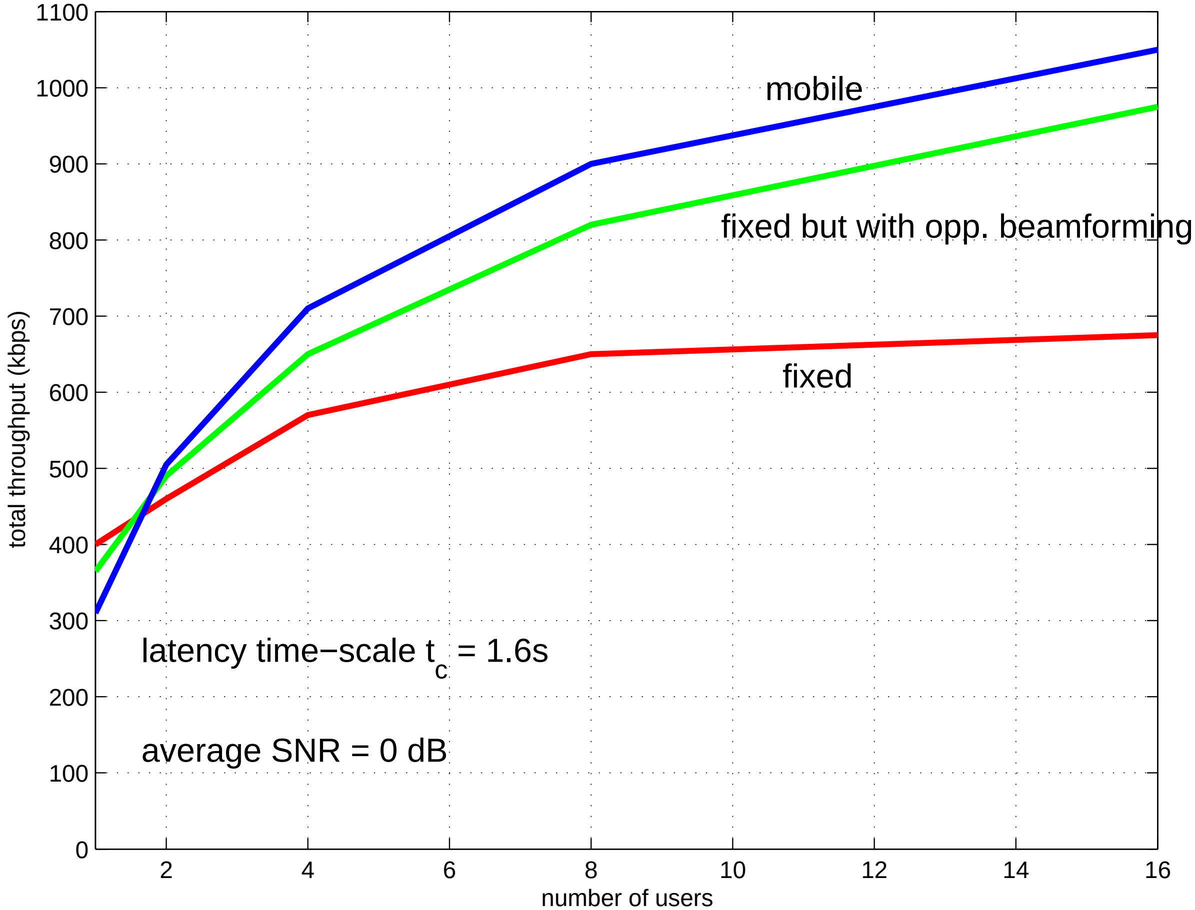
where R_k^{bf} is the rate user k gets when it is perfectly beamformed to.

Opportunistic Beamforming: Fast Fading



Improves performance in fast fading Rician environments by spreading the fading distribution.

Overall Performance Improvement



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Space Time Codes

- Space time codes: intelligent use of transmit diversity to improve reliability of point-to-point links.
- For 2 transmit antennas, Alamouti scheme is the best space-time code.
- Let us compare smart and dumb antennas in terms of both performance and complexity.

Comparison: Performance

Slow Fading:

- Alamouti: diversity gain
- dumb antennas: diversity gain plus 3 dB power gain

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Slow Fading:

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Fast Fading:

- Alamouti: reduces channel fluctuations and thereby reduces the multiuser diversity gain.
- dumb antennas: keeps the fluctuations the same in Rayleigh fading and increases the fluctuations in Rician fading.

Comparison: Complexity

Alamouti:

- requires two separate pilots to estimate the multi-antenna channel.
- special encoder/decoder.

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Dumb Antennas:

- only requires a single pilot to estimate the overall channel SNR.
- no special encoder/decoder.
- In fact the mobiles are completely oblivious to the existence of multiple transmit antennas.

Cellular System: Opportunistic Nulling

- In a cellular systems, users are scheduled when their channel is strong and the interference from adjacent base-stations is weak.

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- Multiuser diversity allows interference avoidance.
- Dumb antennas provides opportunistic nulling for users in other cells.
- Particularly important in interference-limited systems with no soft handoff.

Traditional CDMA Downlink Design

- orthogonalize users (via spreading codes)

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- Important for voice with very tight latency requirements.

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- Shifts from the point-to-point view to a multiuser network view.

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- Wants large and fast fluctuations of both channel and interference so that we can ride the peaks.
- Role of transmit antennas is to amplify the fluctuations.
- Exploits more relaxed latency requirements of data as well as MAC layer packet scheduling mechanisms.

A Broader Perspective

- Efforts on increasing wireless capacity has been on boosting spectral efficiency of point-to-point links.
- Rely on sophisticated physical layer signal processing techniques: smart antennas, interference suppression, etc.....
- Future progress will come from taking a broader network perspective.