POWER CONTROL AND BANDWIDTH MANAGEMENT IN WIRELESS NETWORKING / COMPUTING

Key Concepts and Reference Models

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* Joint results with:

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Why Power Control …?

Conserve energy … prolong battery life

Mitigate interference … increase network capacity

Adapt to channel variations … support QoS

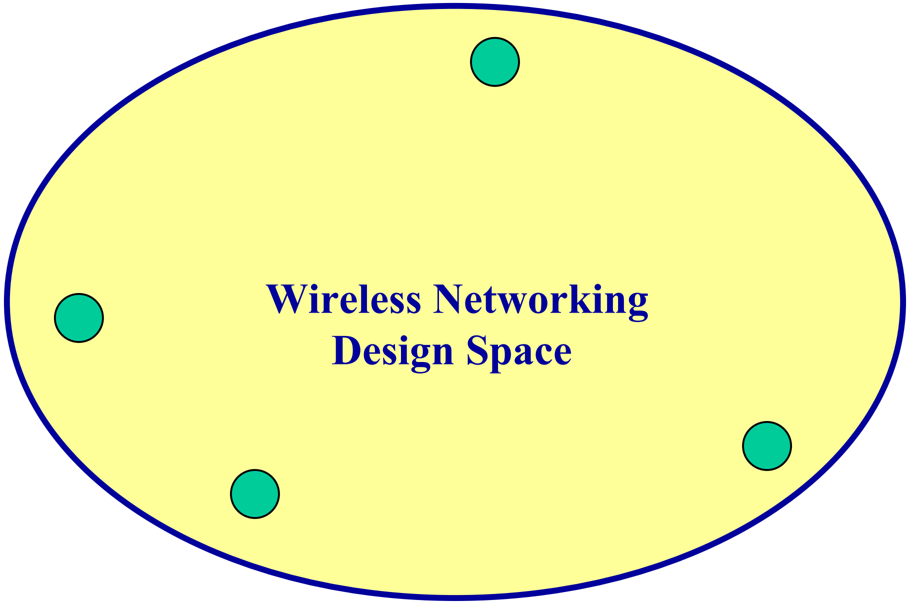
Reduce RF radiation exposure

…

Support network control functions ++

Fall-back position: isolate transmissions … suppress power issues

Approach / Strategy



Huge/complex design space of wireless networking … little explored!

Formulate "canonical" models and establish design reference points

"Triangulate" between reference points

Perspective

Network control perspective / instead of digital comm. one

Power control … part of network control

Control dilemmas, decision making, trade-offs

Resource management in varying environments

Design drivers … efficiency, scalability, robustness … etc.

Separation of concerns…

Separation of time scales…

…transmission …< …control… < …mobility…

Method / Tactical Plan

Development of an modeling framework to capture tradeoffs

Development of design methodology

Coping with design complexity:

Fundamental understanding of “key effects” and performance limits

Justified Heuristics / as opposed to ad hoc

Verify by simulation

Establish performance gains

Fine-tune parameters in particular application scenario

Operational Scenarios…

Cellular / Single Hop…

Ad Hoc…

Networked wireless terminals…

Networked embedded devices…

Densely/deeply networked spaces

Operational abstraction …interfering communication links

Talk Agenda

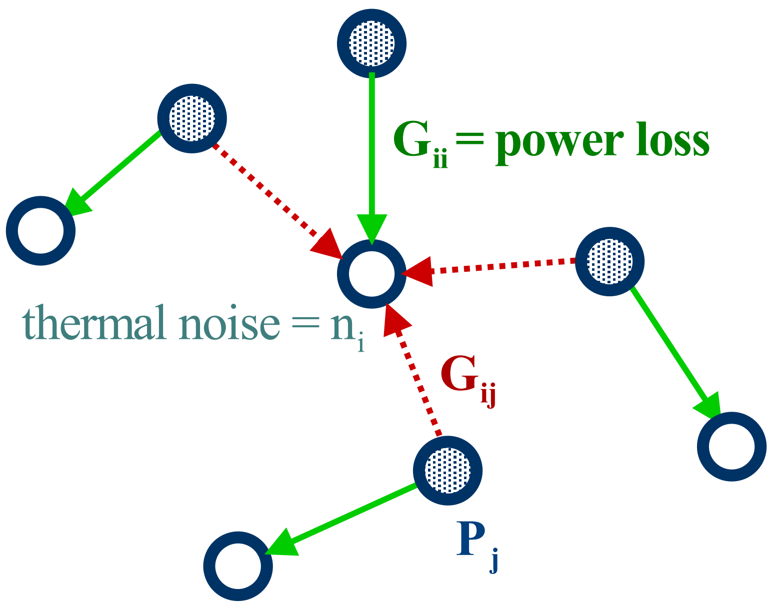
1) Power Control and Bandwidth Contention
2) Noninvasive Probing vs. Interference Sensing
3) Power/Mode Controlled Multiple Access … M-PCMA
4) Buffer Control, Pre-fetching, Caching (MAC to APP)

Stripped-down versions of the design problems…

…as simple as possible, but not simplistic

Spotlight the tradeoffs… and control dilemmas…

Power Control / Bandwidth Contention



$$R_i(\vec{P}) = \frac{G_{ii}P_i}{\sum_{i \neq j} G_{ij}P_j + n_i} \quad \text{... SIR}$$

$$R_i(\vec{P}) \geq q_i \quad \text{... QoS} \geq q$$

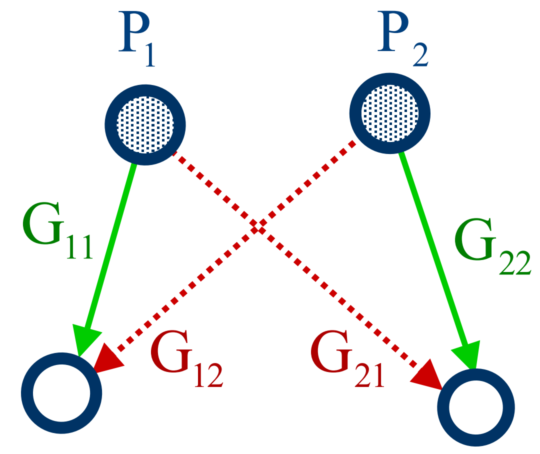
Wireless Network … collection of interfering communication links

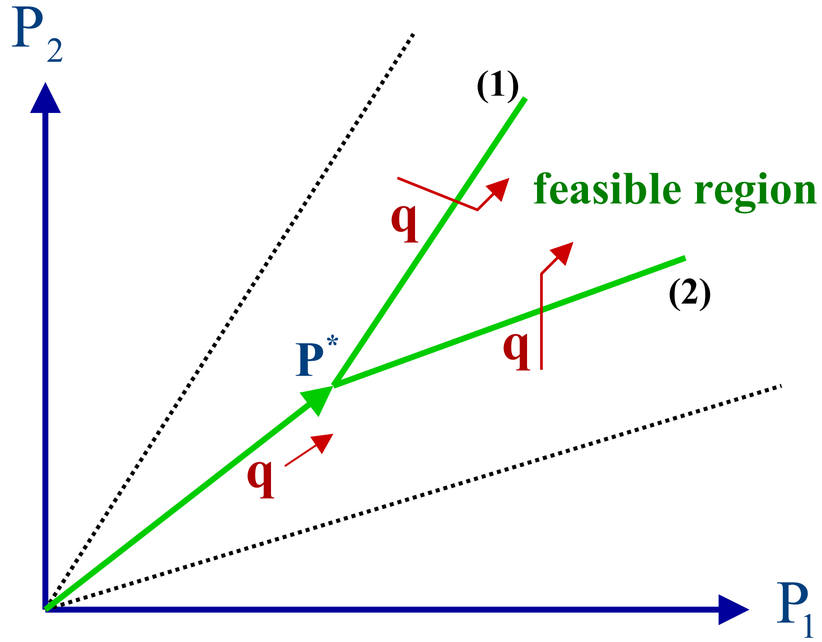
Problem: find power vector satisfying QoS constraints … may not exist!

Bandwidth Contention / Two-Link Example … Intuition

$$R_1(P_1, P_2) \geq q \;\Rightarrow\; G_{11}P_1 - qG_{12}P_2 \geq qn_1 \quad \ldots (1)$$

$$R_2(P_1, P_2) \geq q \;\Rightarrow\; G_{22}P_2 - qG_{21}P_1 \geq qn_2 \quad \ldots (2)$$





MULTILINK NETWORK

feasible region = multi-dim. cone

q increases:

- feasible region shrinks, P* increases

#links increases:

- feasible region shrinks, P* increases

Bandwidth Contention / Finding P* …

$$P_i(k+1) = \frac{q_i}{R_i(k)} P_i(k) = \frac{\text{Target SIR}}{\text{Observed SIR}} P_i(k) = \frac{\text{Target QoS}}{\text{Observed QoS}} P_i(k)$$

PC Algorithm:

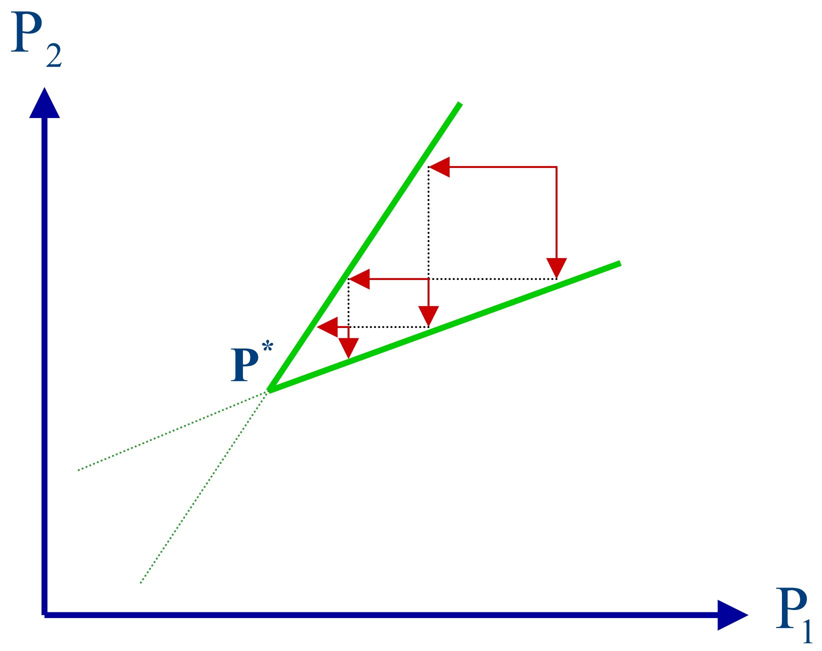
simple, scalable
autonomous

Converges geom. fast to P*

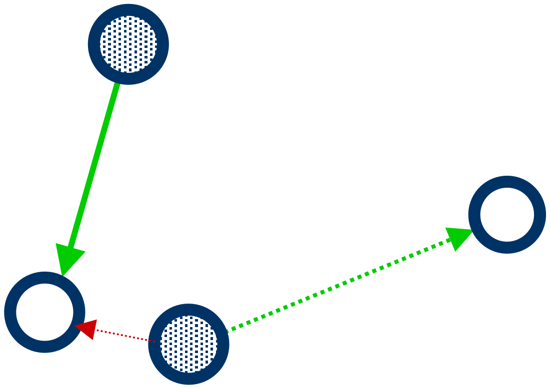
iff

q's are feasible/ compatible…

Foschini & Miljanic …1990, ++



Channel Probing vs. Sensing



Two Channels…

Which one should be chosen?

The one with least

primary + induced interference

or least resistance

PC-Probe

Established links: $$P_e(k+1) = \frac{\delta \times \text{Target SIR}}{\text{Observed SIR}} P_e(k)$$

New link(s): $P_n(k+1) = \delta \times P_n(k)$ ... $P_n(0) \sim$ small

PC-Probe & Admission Control

PC-Probe: SIR Evolution of Powering-Up Links

$$SIR_n(k) \approx \frac{1}{\frac{X_n}{\delta^k} + Y_n} \qquad \text{... when } \delta \approx 1$$

Each new link powering-up can pc-probe a channel:

1) autonomously
2) quickly ... 2 steps min
3) non-invasively ... at low power

to estimate X & Y

... and predict its SIR evolution ... and its ultimate level ... $SIR \approx \frac{1}{Y}$

PC-Probe & Channel Selection

Channel Selection:

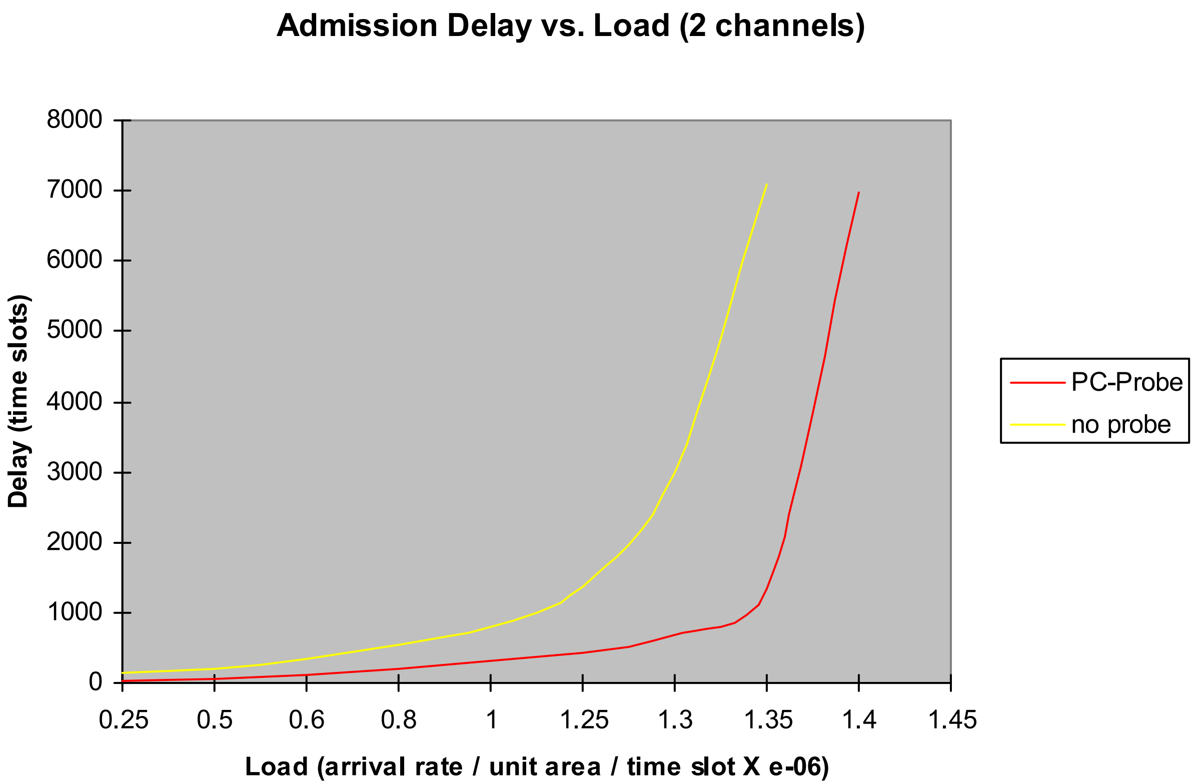
$SIR \approx \frac{1}{Y} > q$ ... link admissible after k* steps

at power $P = P(0) \times \delta^{k^*}$ .... ($q \approx \frac{1}{\frac{X}{\delta^{k^*}} + Y}$)

$SIR \approx \frac{1}{Y} > q$ ... link inadmissible ... back off

Choose the channel where admissible at lowest power

PC-Probe Benefits



Avg. Delay Decreases

Throughput Increases

Avg. Power Decreases

What about DELAY ???

Overarching theme:

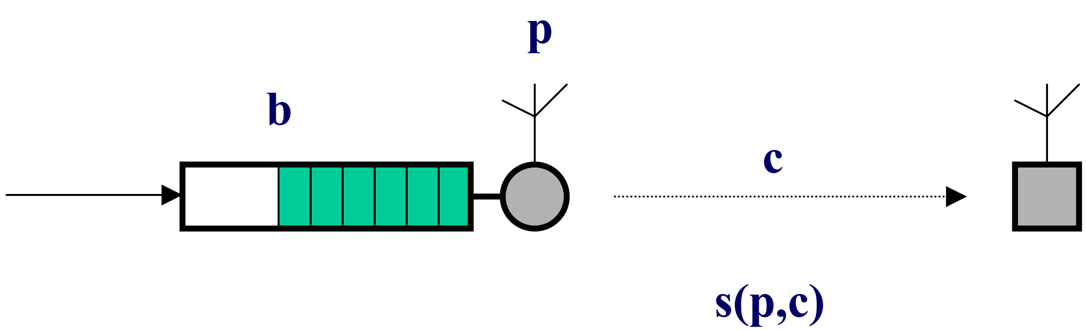
Individual link perspective : adapt to changing environment and utilize windows of opportunity

Interaction perspective: cooperate to make the environment "nice"

Key tradeoff:

delay cost vs. power cost

Power Controlled Multiple Access / PCMA



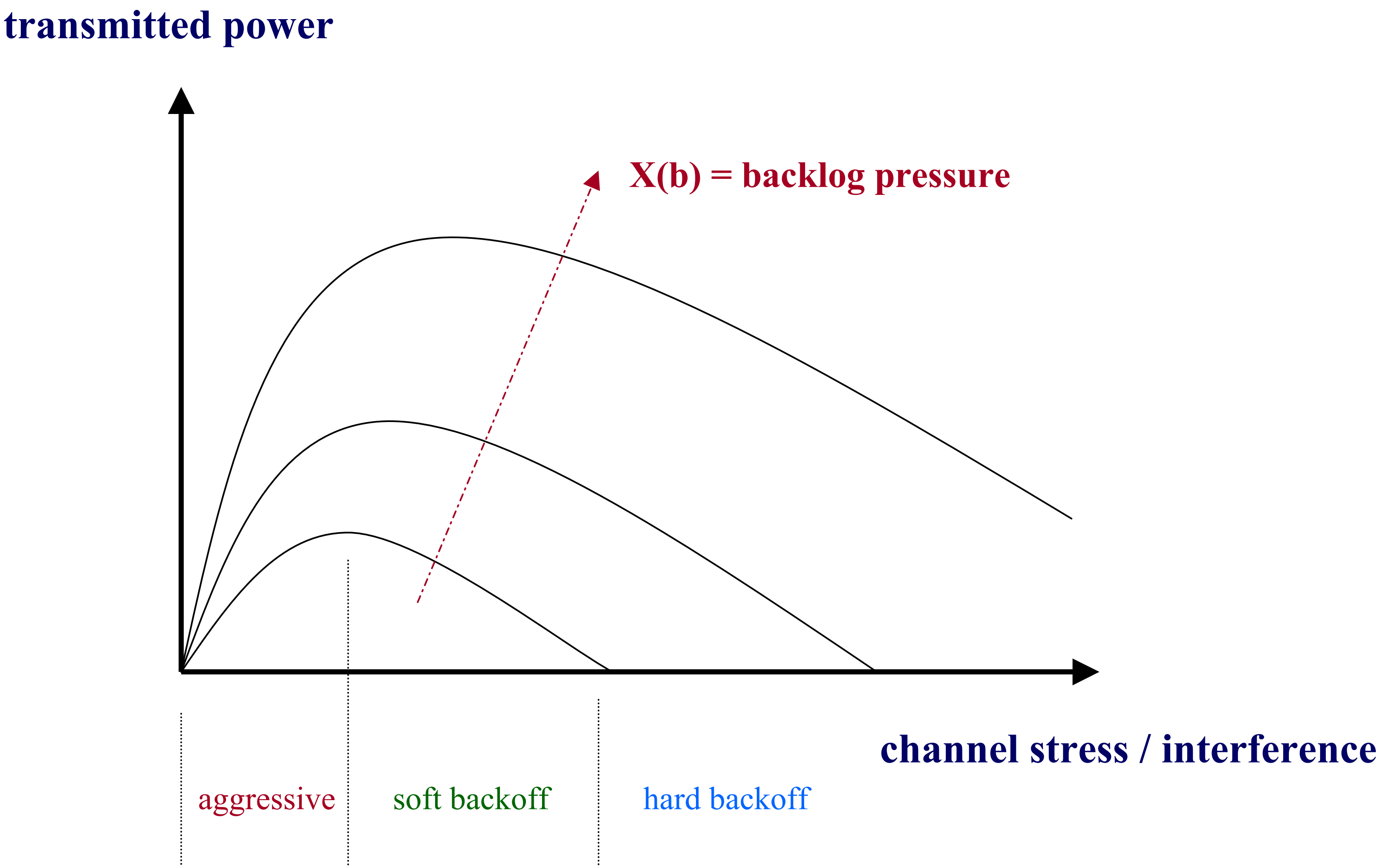
- **Slotted time / Markovian model / c = channel stress (interf.) fluctuates**
- **B(b) = backlog cost/stress, p = power cost … delay vs. power tradeoff**
- **s(p,c) = prob. of success / p-increasing, c-decreasing**
- **Dilemma/Decision … dynamic programming formulation:**

What power to transmit at now,

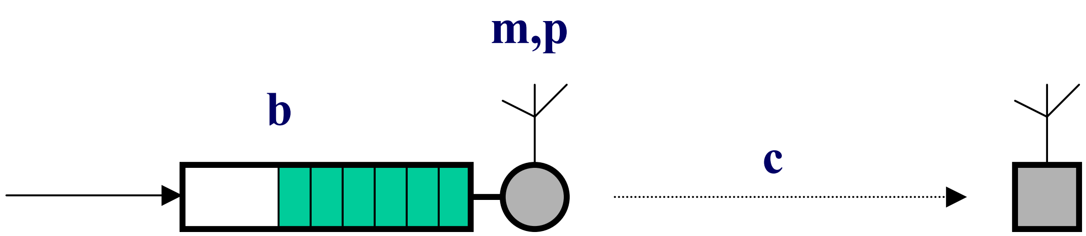
given the backlog stress and channel stress,

to minimize the average power?

Power Control / PCMA



Mode-Power Control / M-PCMA



Mode m ? … overhead cost O(m)

- Modulation scheme
- Coding scheme
- Channel selection
- Access point
- Diversity scheme
- …
- Power!

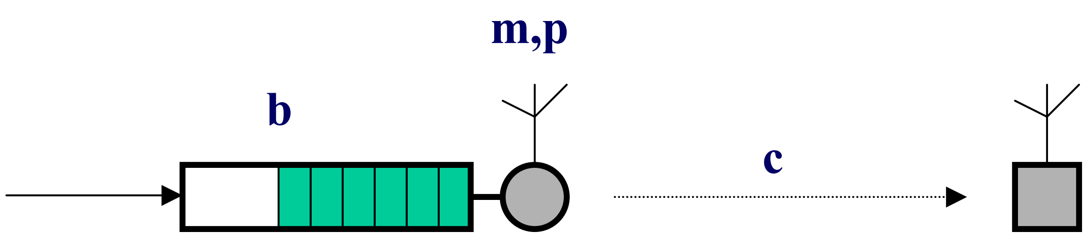
Dilemma/Decision:

What mode to use **now**,

given the backlog stress and channel stress,

to minimize the **average** cost?

Mode-Power Control / An Example



Mode m = transmit l(m) packets in one slot

s(k;m,p,c) = prob.

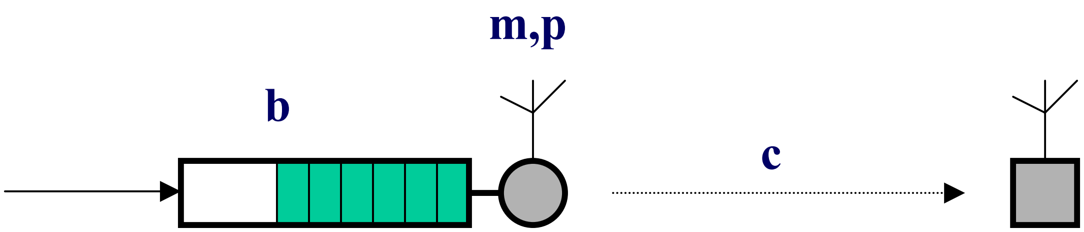
k packets received correctly &

l(m) – k will be retransmitted,

given that mode m is used at power p and the

channel stress is c

Mode-Power Control / M-PCMA



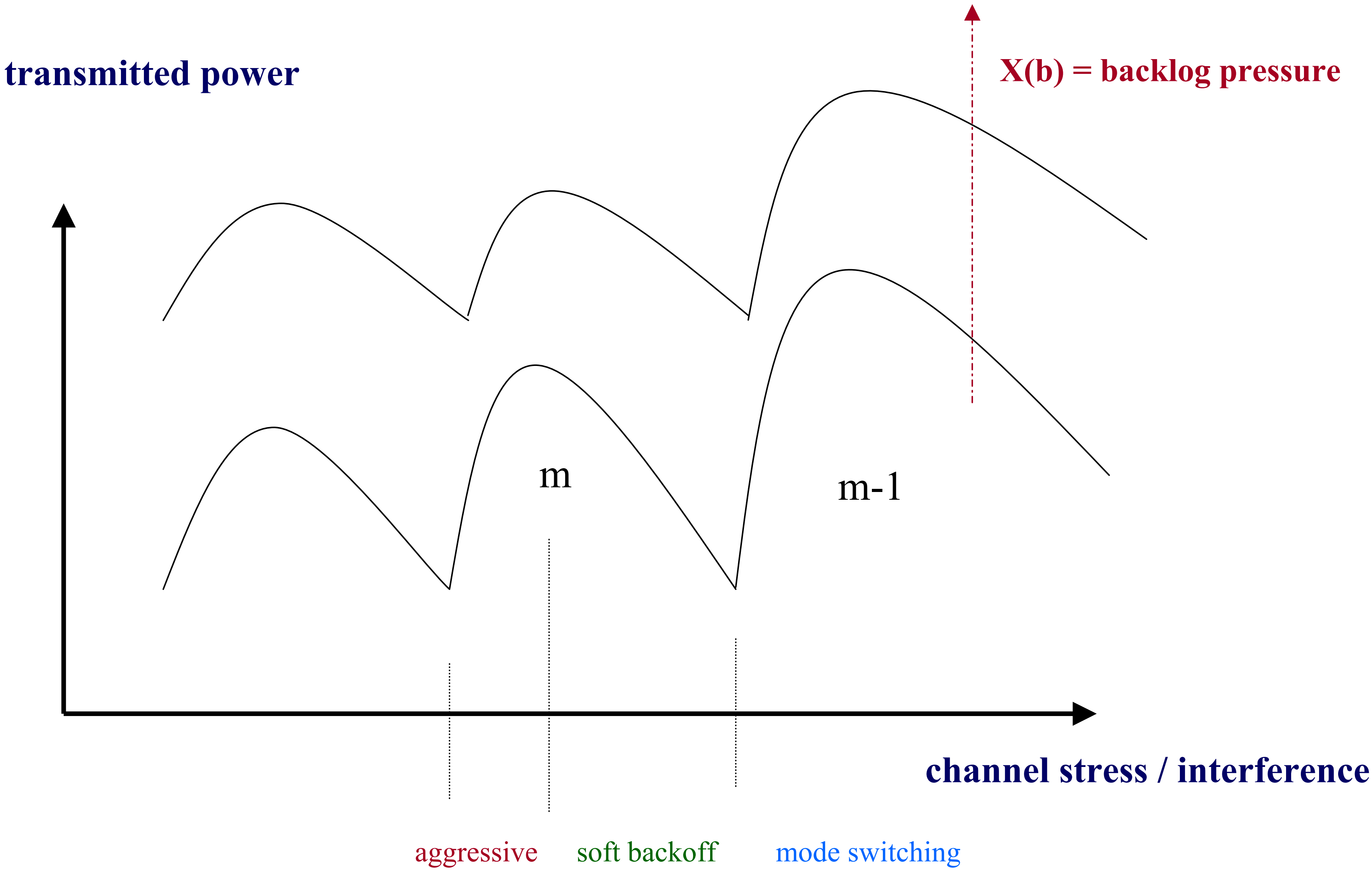
Cost-Based Formulation / Dynamic Programming / Optimal Control Policy

$$V(b,c) = \min_{m,\,p} \{ O(m) + p + B(b) + \sum_{k,c'} s(k;m,p,c)\, r_{cc'}\, V(b-k,c') \}$$

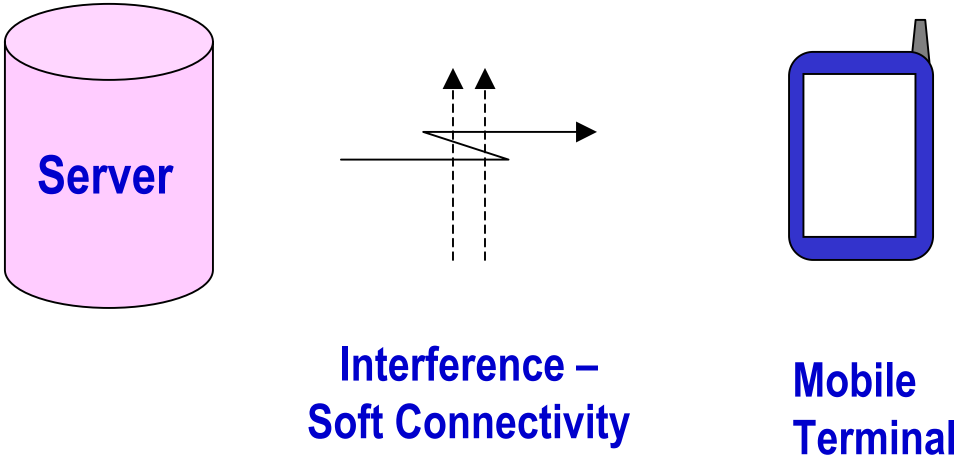
Optimal Mode: $m^*(b,c)$

Optimal Power: $p^*(b,c)$

Mode-Power Control / M-PCMA



Power Controlled Prefetching / Caching



Good channel period = window of opportunity to fetch lots of data at low power cost

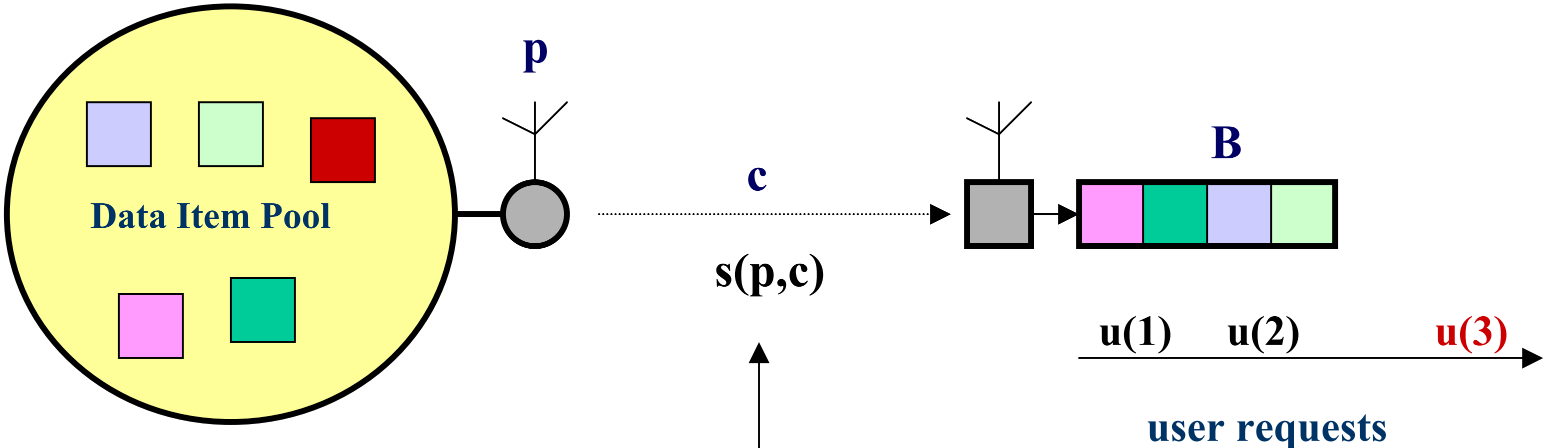
Bad channel period = pay very high power & delay premium to fetch data

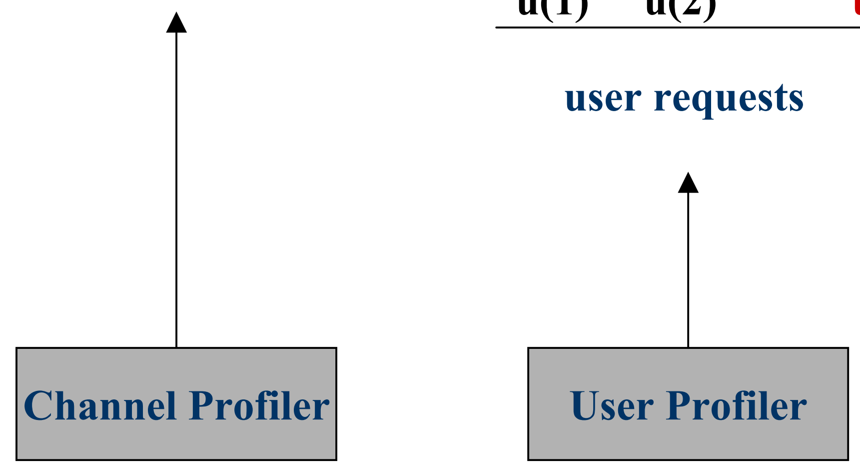
Instinct = fetch and cache lots of data when you can…

Risk = may have to evict/drop data for nothing, if targets missed…

DECISIONS: 1) what/when to (pre)fetch, 2) at what power, 3) what to evict…

Power Controlled Prefetching / Caching





<u>Cost Structure</u>:

1) Per item access delay cost,

2) Power + BW cost

3) Item eviction risk

<u>Decision/Control</u>:

1) attempt B → B'

2) at power p

Time slotted / Markovian modelling
State: (u,B,c)

Power Controlled Prefetching / Caching

Dynamic Programming Formulation

High complexity due to buffer combinatorial states

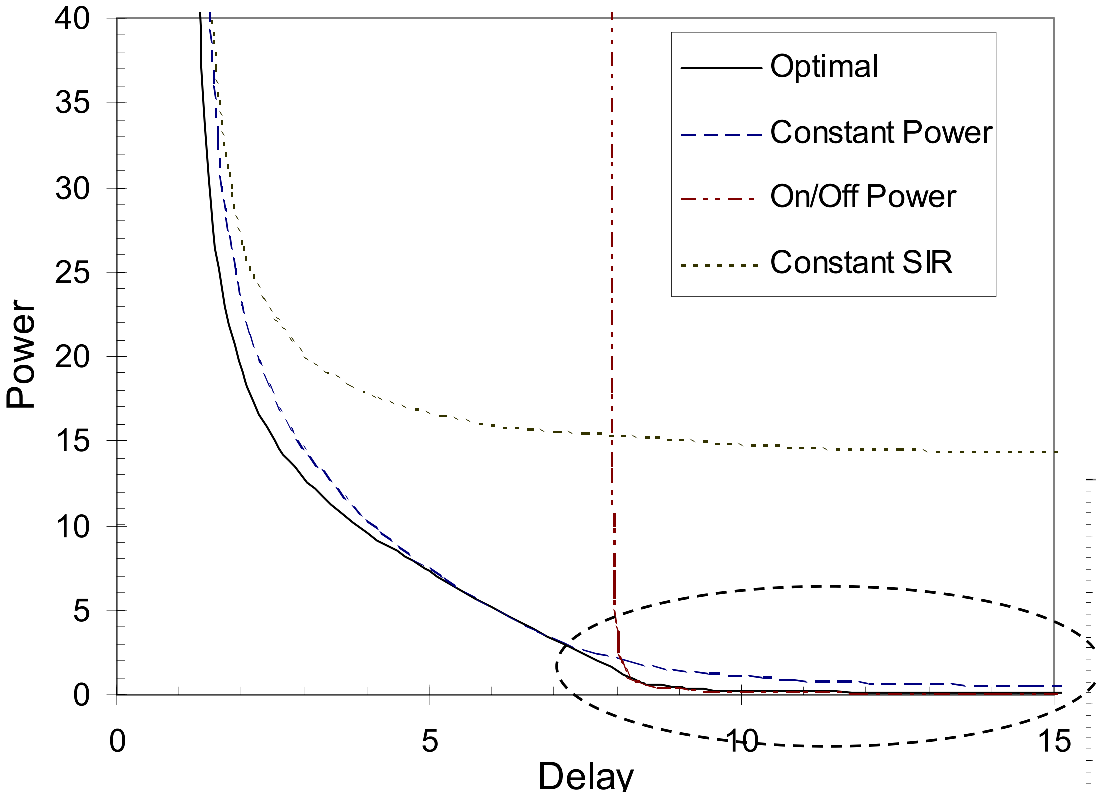
Explore ways to cope with complexity

High performance power/buffer control policies

Look-ahead strategies

MAC ←→ APP entanglement!

No Pre-fetching (easy)

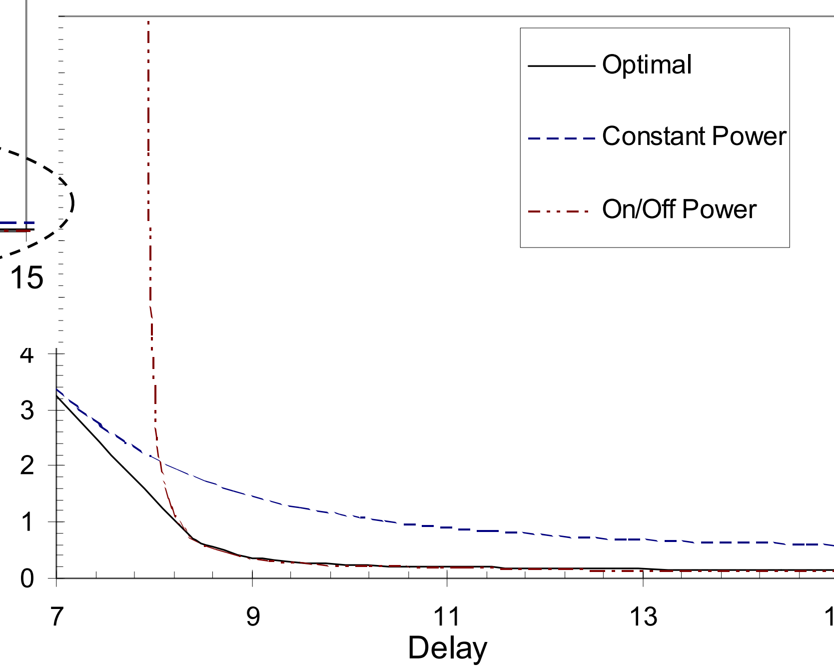


Two interference levels:

0.1(low) and 20(high)

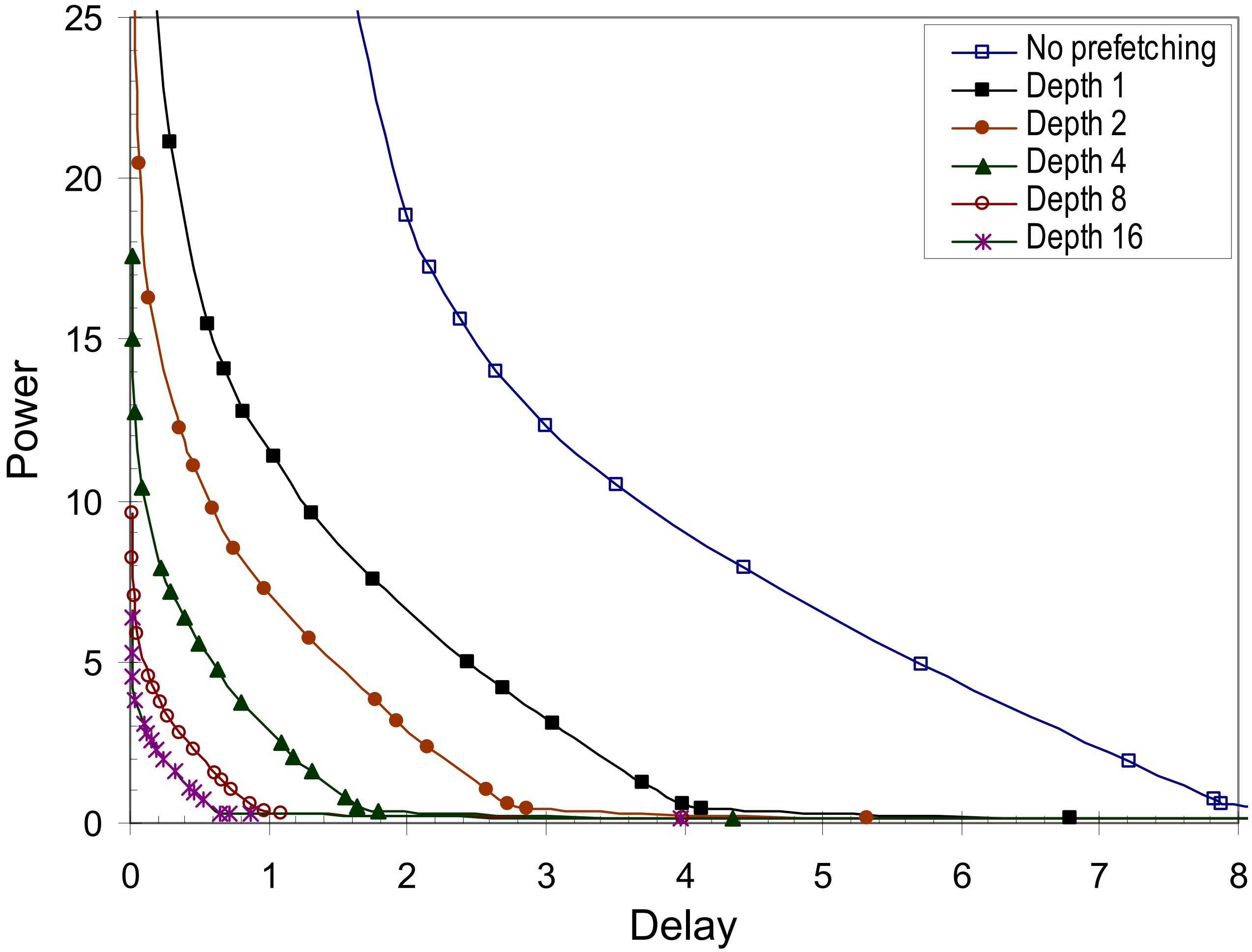
Interference stays on average

– 14 time slots on low and
– 7 time slots on high before switching

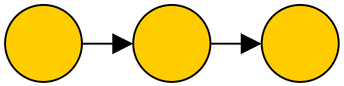


$$s(p,i)=\frac{p}{p+i}$$

Linear Request Chain



User state is a linear chain

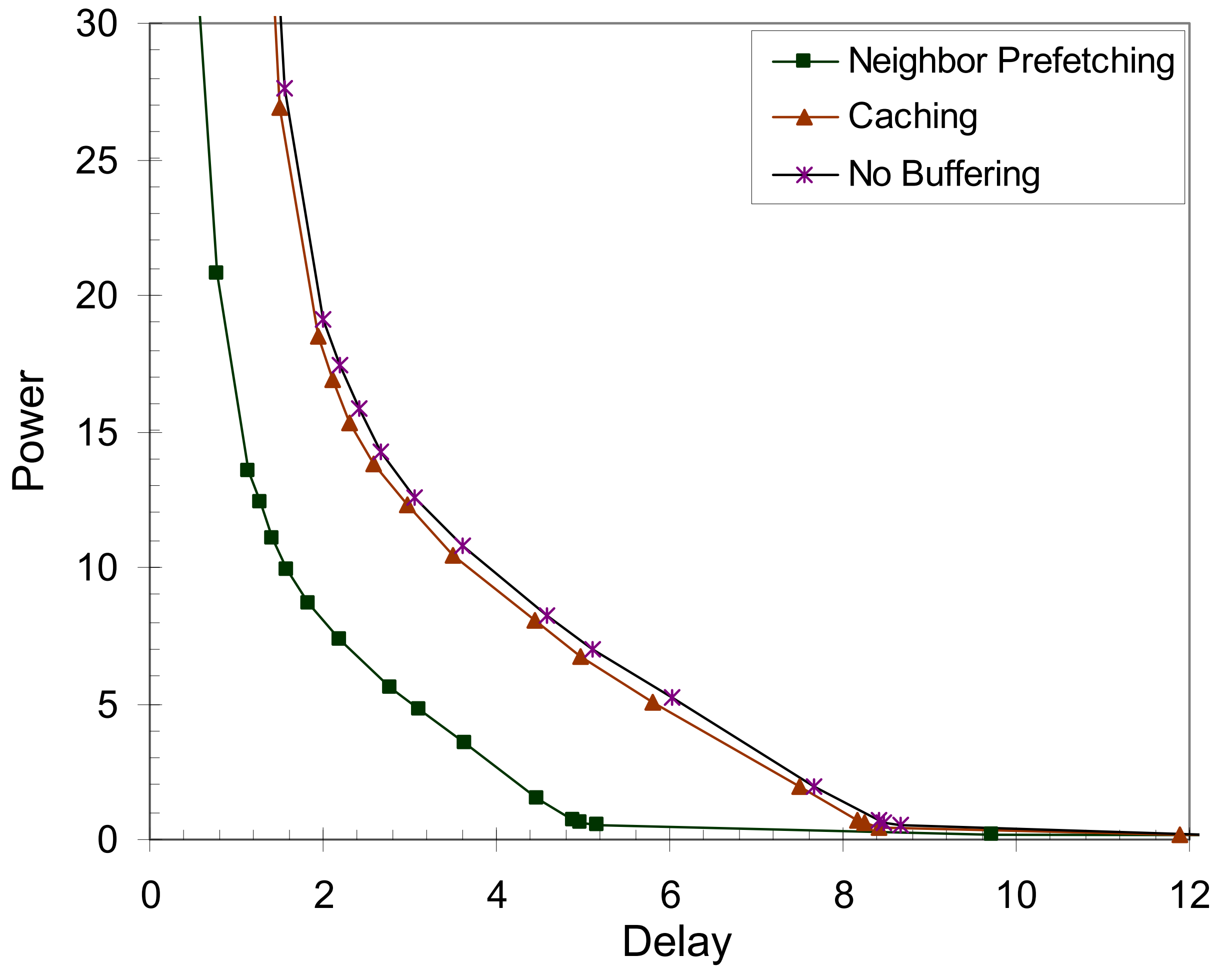


Walk recursively *h* steps in the chain and

Prefetch up to *h* items (depth)

Deep prefetching improves the performance dramatically!

Look-Ahead Trees



- Same method generalizes to a tree user-state space
- Extract a look-ahead tree, sub-tree of the user state
- Apply the Bellman's equations to calculate a cost for each data-item of the look-ahead tree (recursive walk from leaves to root)
- User State Space: 100 states and 85 distinct data items, 2 to 5 neighbors for each state
- Buffer capacity *b*=10

Conclusions

Power control is a core element of various aspects of network control

Simple, scalable, robust controls are gradually being developed

Much more to be done … both in research …and in CMOS!

Did not discuss…

> **Min-power routing**
>
> **Computation over wireless**
>
> **…**
>
> **Power control ARCHITECTURES!**

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