POWER CONTROL AND BANDWIDTH MANAGEMENT
IN WIRELESS NETWORKING / COMPUTING

Key Concepts and Reference Models

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* Joint results with:
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
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

$P_i = \text{transmitter power}$

$G_{ii} = \text{power loss}$

$G_{ij} = \text{interference}$

$G_i = \text{power loss}$

$P_j = \text{receiver power}$

$\text{thermal noise} = n_i$

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

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

Wireless Network \ldots collection of interfering communication links

Problem: find power vector satisfying QoS constraints \ldots may not exist!
Bandwidth Contention / Two-Link Example … Intuition

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

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

MULTILINK NETWORK

feasible region = multi-dim. cone

q increases:

feasible region shrinks, P* increases

#links increases:

feasible region shrinks, P* increases
Bandwidth Contention / Finding $P^*$ ...

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

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: \[ P_e(k+1) = \frac{\delta \times \text{Target SIR}}{\text{Observed SIR}} \times P_e(k) \]

New link(s): \[ P_n(k+1) = \delta \times P_n(k) \quad ... \quad P_n(0) \sim \text{small} \]
PC-Probe & Admission Control

**PC-Probe: SIR Evolution of Powering-Up Links**

\[
\text{SIR}_n(k) \approx \frac{1}{\frac{X_n}{\delta^k} + Y_n} \quad \text{... when } \delta \approx 1
\]

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

1) autonomously
2) quickly \( \ldots \) 2 steps min
3) non-invasively \( \ldots \) at low power

to estimate \( X & Y \)

\( \ldots \) and predict its SIR evolution \( \ldots \) and its ultimate level \( \ldots \) \( \text{SIR} \approx \frac{1}{Y} \)
Choose the channel where admissible at lowest power

\[ \frac{\text{SIR}}{Y} \geq \frac{1}{q} \]

... link inadmissible ... back off

\[ \text{at power } P = P(0) \times \delta^{k^*} \]

... link admissible after \( k^* \) steps

\[ \frac{\text{SIR}}{Y} \geq \frac{1}{q} \]

Channel Selection

PC-Probe & Channel Selection

\[ \frac{\Lambda + \frac{\delta^{k^*}}{X}}{Y} \geq 1 \]
PC-Probe Benefits

Admission Delay vs. Load (2 channels)

- 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
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?
transmitted power

channel stress / interference

X(b) = backlog pressure

aggressive  soft backoff  hard backoff
Mode-Power Control / M-PCMA

Mode selection: What mode to use now, given the backlog stress and channel stress, to minimize the average cost?

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 $m = \text{transmit } l(m) \text{ packets in one slot}$

$s(k;m,p,c) = \text{prob.}$

- $k$ packets received correctly &
- $l(m) - k$ will be retransmitted,

given that mode $m$ is used at power $p$ and the
channel stress is $c$
Cost-Based Formulation / Dynamic Programming / Optimal Control Policy

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

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

Optimal Power: $p^*(b,c)$
Mode-Power Control / M-PCMA

transmitted power

X(b) = backlog pressure

channel stress / interference

aggressive  soft backoff  mode switching
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

**Cost Structure:**
1) Per item access delay cost,
2) Power + BW cost
3) Item eviction risk

**Decision/Control:**
1) attempt $B \rightarrow B'$
2) at power $p$

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

\[ s(p,i) = \frac{p}{p+i} \]
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!
References 1


References 2


References 3


