Power-Controlled Multiple Access Schemes for Next-Generation Wireless Packet Networks

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Outline

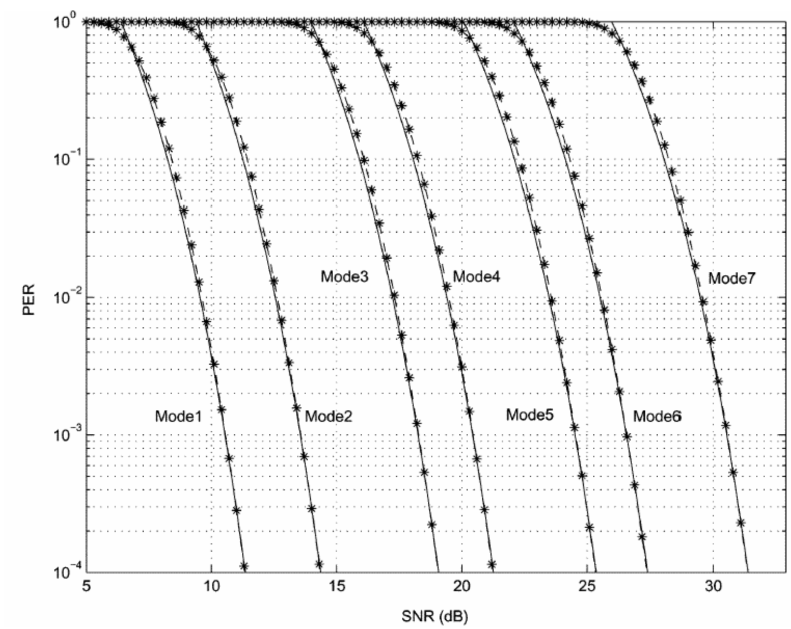
- Motivation of this paper
- Related Work
- Formulation of Optimal Power Control Problem
- Fundamental Properties
- Two Power Control Algorithms for Realistic Systems
- Contribution & Limitations

Transmitter Power Control

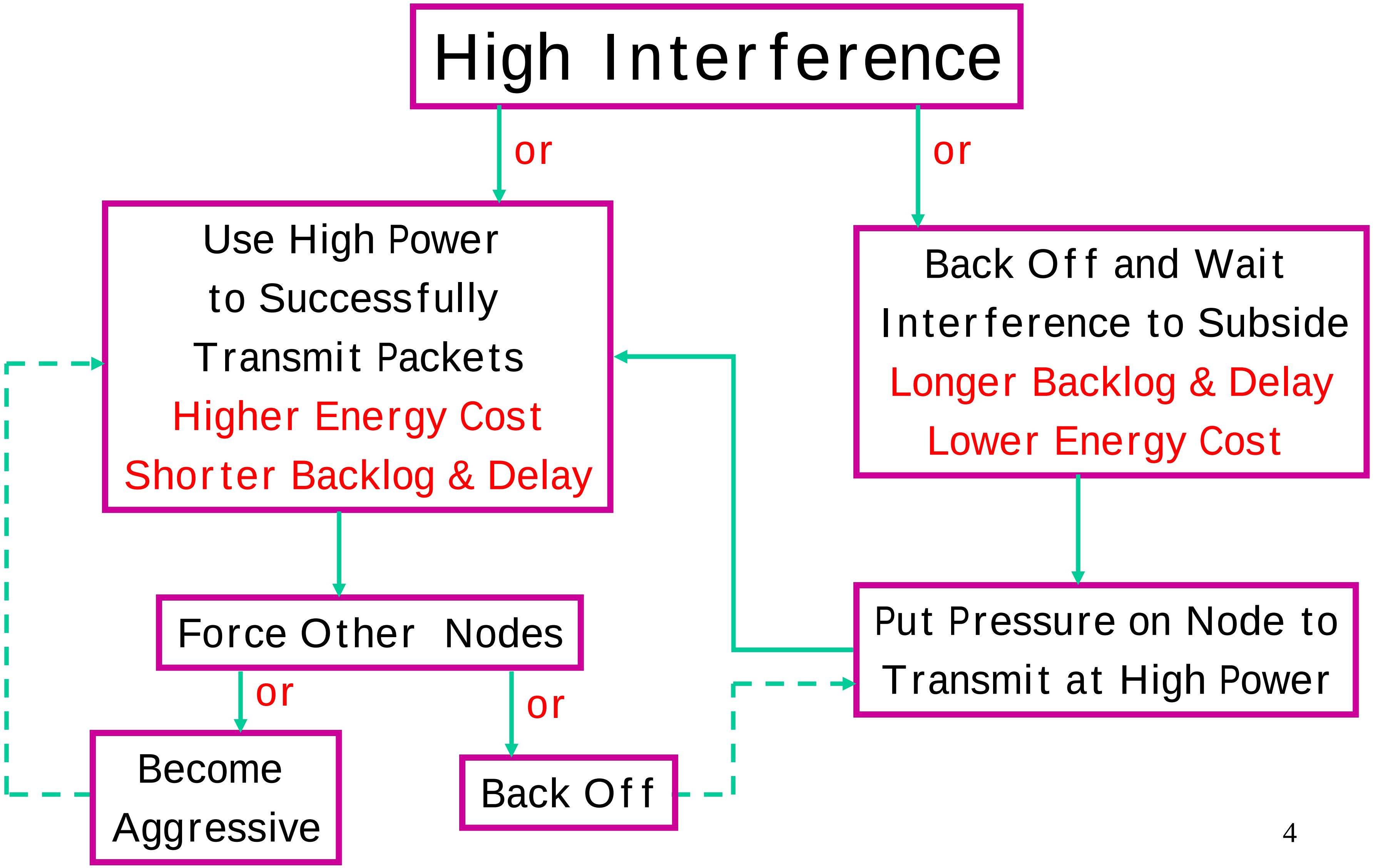
- A link represents a pair of transmitter and receiver
- Let $G_{i,j}$ be the power gain (loss) from the transmitter of the i^{th} link to the receiver of j^{th} one
- P_i denotes the i^{th} link transmitter power
- η_i denotes the i^{th} link receiver thermal noise

$$\mathrm{SINR}_i = \frac{G_{i,i}P_i}{\sum_{j \neq i} G_{i,j}P_j + h_i}$$

- Goals:
  - Achieve the required QoS levels
  - Minimize energy consumption
  - Maximize network/link capacity
- A key in the development of efficient cross-layer networking protocols



Power vs. Delay Dilemma



Motivation of This Paper

Reveal the Trade Off of Transmitter Power Cost and Backlog/Delay Cost in Power Control Schemes

Design Cross-Layer Power-Controlled Multiple Access Algorithms for QoS

Main Technique

- Formulate the problem based on simplified system
- Reveal the fundamental properties
- Design algorithms for realistic systems

Related Work

- Power control + rate adaptation è efficiently support media stream

> "Power-Controlled Wireless Links for Media Streaming Applications"
>
> Y. Li & N. Bambos, IEEE Wireless Telecommunications Symposium 2004

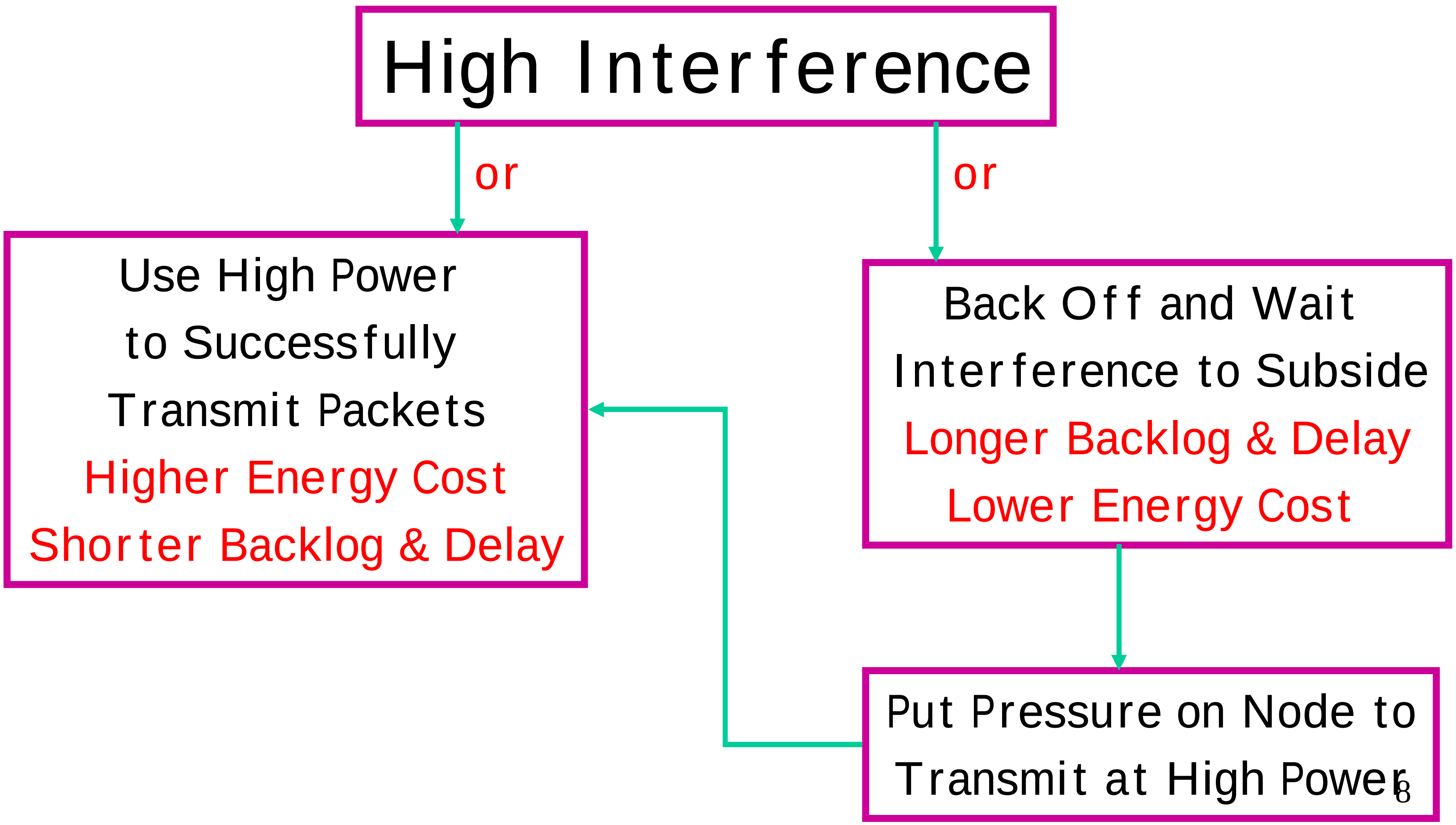
- Embedding Power Information in control packets è increase network capacity

> "A power controlled multiple access protocols for wireless packet networks"
>
> J. Monks, V. Bharghavan, and W. Hwu, INFOCOM 2001

- Power control + Scheduling è limit interference & increase throughput & prolong battery lifetime for wireless ad-hoc networks with TDAM/CDMA

> "Joint scheduling and power control for wireless Ad-Hoc networks"
>
> T. Elbatt and A. Ephremides, IEEE Transaction on Wireless Communications, 2004

Simplified Scenario (non-responsive)



System Description & Assumptions

- Time is slotted into 1,2,....... (one time slot for one packet transmission)
- Transmitter with a FIFO queue and initially holds **K** packets
- $\mathbf{i_n}$ denotes the channel interference during the n^{th} time slot; all interference states form a finite set denote as **I**
- Interference fluctuation are characterized by a homogeneous Markov chain with transition probability $\mathbf{Pr[i_{n+1}=j|i_n=i]=q_{i,j}}$ and stationary distribution p_i for any i, j belongs to I
- $\mathbf{p_n}$ denotes the power used during the n^{th} time slot

System Description & Assumptions

- **s(p, i)** denotes the probability of a packet being successfully transmitted used power p and with channel interference i
- Packet transmission events are statistically independent of each other
- Unsuccessfully transmitted packet will be re-transmitted in the next time slot until it is successfully received
- There is a reliable feedback channel from receiver to transmitter with negligible delay
- $\mathbf{b_n}$ denotes the backlog in the n^{th} time slot

Optimization Objective

- Two Cost Components
  - p_n : power cost at the n^{th} time slot
  - $B(b_n)$: backlog cost for backlog b_n

- Objective
  - Minimize the overall cost until K packets being successfully transmitted by choosing the optimal powers $\{p_1, p_2, \ldots\ldots\}$

Dynamic Programming (Bellman's Principle of Optimality)

- An optimal policy has the property that whatever the initial state and the initial decision are, the remaining decisions must constitute an optimal policy with respect to the state which results from the initial decision

Every optimal policy consists only of optimal sub-policies

Problem Formulation

- V(b,i) denotes the minimal overall system cost under optimal power control until the buffer empty for the system with initial baklog b and interference i

$$V(b,i) = \inf_{p\geq 0}\left\{ p + B(b) + s(p,i)\sum_{j\in I} q_{i,j} V(b-1, j) + \left(1 - s(p,i)\right)\sum_{j\in I} q_{i,j} V(b, j) \right\}$$

$$\text{initial condition } V(0,i) = 0 \text{ for any } i$$

- Goal: given transmission probability $q_{i,j}$ and stationary distribution π_i for all i, j in I to find optimal power values p*(b,i) for b=1,…,K, and all i in I

Per-Slot-Independent Interference: Insightful Cases

- Interference levels in various time slots are i.i.d. è $p_{i,j} = \pi_j$ for all i and j

$$V(b,i) = \inf_{p\geq 0}\left\{ p + B(b) + s(p,i)\sum_{j\in I} p_j V(b-1,j) + \left(1 - s(p,i)\right)\sum_{j\in I} p_j V(b,j)\right\}$$

- Simplify

$$V(b,i) = \inf_{p\geq 0}\left\{ p - s(p,i)X(b) + Y(b)\right\}$$

$$\textit{with}\ \ \mathrm{X(b)} = \sum_{\mathrm{j}\in\mathrm{I}} p_{\mathrm{j}}\left[V(b,j) - V(b-1,j)\right]$$

$$\mathrm{Y(b)} = \sum_{\mathrm{j}\in\mathrm{I}} p_{\mathrm{j}}\left[B(b) + V(b,j)\right]$$

Case 1

- Let $s_1(p,i) = \dfrac{p}{ap+bi}, \; a \geq 1 \text{ and } b \geq 0$

$$p_1^*(b,i) = \begin{cases} \dfrac{1}{a}\left(\sqrt{bX(b)i} - bi\right), & i \leq \dfrac{X(b)}{b} \\ 0, & \text{otherwise} \end{cases}$$

- For maximum power constraint $p \in [0, P_{\max}]$

$$p_1^*(b,i) = \begin{cases} \min\left\{\dfrac{1}{a}\left(\sqrt{bX(b)i} - bi\right), P_{\max}\right\}, & i \leq \dfrac{X(b)}{b} \\ 0, & \text{otherwise} \end{cases}$$

Case 2

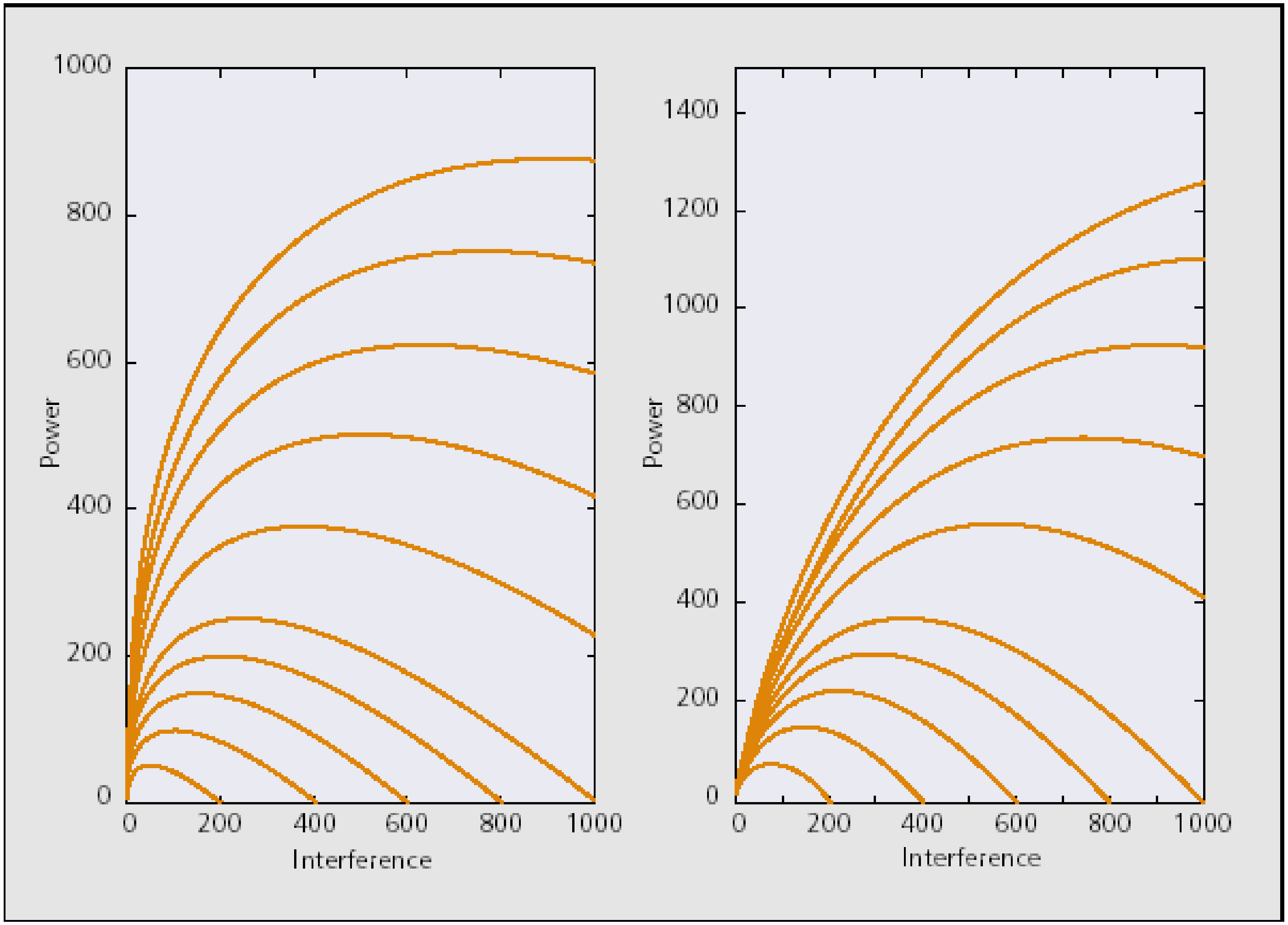
- Let $s_2(p,i) = 1 - e^{-d\frac{p}{i}}, d > 0$

$$p_2^*(b,i) = \begin{cases} -\frac{i}{d}\log\left(\frac{i}{dX(b)}\right), & i \le dX(b) \\ 0, & \text{otherwise} \end{cases}$$

- For maximum power constraint $p \in [0, P_{\max}]$

$$p_2^*(b,i) = \begin{cases} \min\left\{-\frac{i}{d}\log\left(\frac{i}{dX(b)}\right), P_{\max}\right\}, & i \le dX(b) \\ 0, & \text{otherwise} \end{cases}$$

Numerical Results



■ Figure 1. *a) Plots of the power* $p_1^*(i) = \sqrt{Xi} - i$ *of (8) as a function of interference* $i \in [0,1000]$ *(with* $\alpha = \beta = 1$*) for fixed values o fthe backlog pressure* $X = 200, 400, 600, 800, 1000, 1500, 2500, 3000, 3500$ *corresponding (the lowest curve is for* $X = 200$ *and the highest for* $X = 3500$*); b) plots of the power* $p_2^*(i) = -i\log(i/X)$ *in (10) as a function of* $i \in [0, 1000]$ *where* $\delta = 1$*), for fixed values of the backlog pressure* $X = 200, 400, 600, 800, 1000, 1500, 2000, 2500, 3000, 3500$ *correspondingly (the lowest curve is for* $X = 200$ *and the highest for* $X = 3500$*).*

Observations:

- Ubiquitous behaviors across both packet success transmission probability formulas s(b,i)
  - Three phases:
    - § Aggressive in low interference zone:
      - o Backlog/delay cost is highly overweight power cost
      - o Transmitter power increases with interference increases
    - § Soft backoff in middle interference zone:
      - o Power cost gradually becomes overweight backlog/delay cost
      - o Transmitter power gradually decreases with interference increases
    - § Hard backoff in high interference zone:
      - o power cost is highly overweight Backlog/delay cost
      - o Transmitter power is sets to zero
- Backlog/delay pressure
  - § X(b) is an increasing function of backlog
  - § Larger X(b), larger backlog/delay cost, larger aggressive zone

Realistic Scenario (responsive interference)

- Multiple interference links è responsive interference environment
- Closed loop
  - A link increases its power, the interference on all other links increases è cause other links increase their power in response è cause increased interference on the original link
- Each link only knows
  - Its packet queue length
  - Its last transmitted power level
  - The aggregated interference level at the receiver during last time slot

Distributed PCMA Algorithms for Realistic Scenario

- PCMA-1 algorithm: each link updates its power autonomously according to

$$p_{n+1} = \begin{cases} \frac{1}{a}\left(\sqrt{bX(b_n)i_n} - b i_n\right), & i_n \le \frac{X(b_n)}{b} \\ 0, & \text{otherwise} \end{cases}$$

- PCMA-2 algorithm:

$$p_{n+1} = \begin{cases} -\frac{i_n}{d}\log\left(\frac{i_n}{dX(b_n)}\right), & i_n \le dX(b_n) \\ 0, & \text{otherwise} \end{cases}$$

- Constant SIR Algorithm (Benchmark)

$$p_{n+} = \begin{cases} \frac{g^t}{g^n} p_n, & b_n > 0 \\ 0, & \text{otherwise} \end{cases}$$

Note: g^t = target SIR

SIR observed during n^{th} time slot: $g^n = \frac{Gp_n}{i_n}$

Simulation Parameters

- 4 by 4 square lattice with 16 square cells
- Each square cell has a communication link
- Ignore boundary effects
- $G_{i,j}$ denotes the power gain between the transmitter of the j^{th} link and the receiver of the i^{th} one; $G_{i,i}$ =1 and $G_{i,j}=1/r_{ij}^2$ and r_{ij} is the distance between transmitter and receiver
- Time slot is one packet transmission time
- In each time slot, a packet arrives to the buffer of each link with probability λ
- $X(b) = 4+b$
- Constant SIR algorithm
  - Target SIR = 1.5
- PCMA-1 algorithm
  - $\alpha=\beta=1$
- PCMA-2 algorithm
  - $\delta=1$

Simulation Results

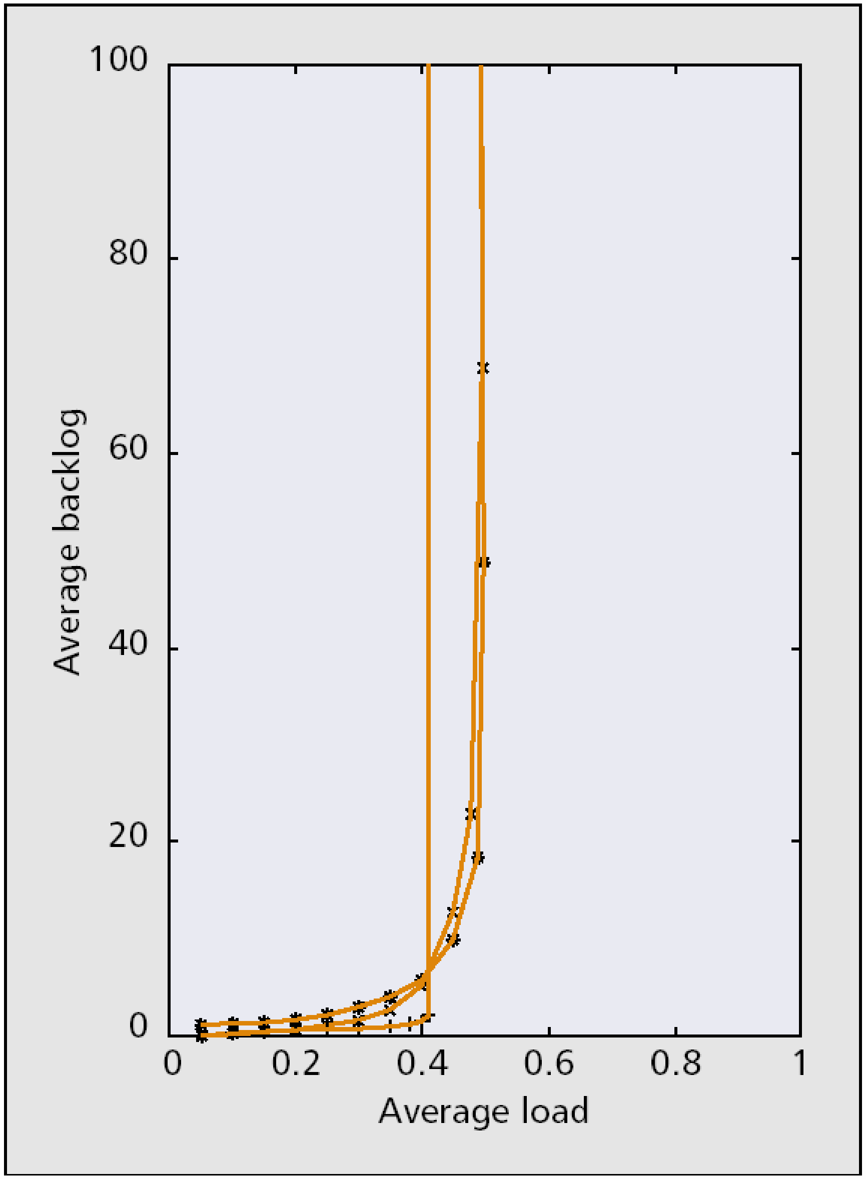


Figure 2. *Plots of the average backlog vs. average load (arrival rate λ) performance curves for a wireless network topology operating under the three power control algorithms: 1) Constant-SIP (vertical bar marks); 2) PCMA-1 (asterisk marks); and 3) PCMA-2 (cross marks). Note that the maximal throughput of Constant-SIR is about 0.4, while both PCMA-1 and PCMA-2 show a maximal throughput of about 0.5 (i.e., a 20 per-cent improvement over Constant-SIR).*

Observations:

- Constant SIR algorithm only support system load l about 0.4, but PCMA-1 and PCMA-2 algorithms can support traffic load about 0.5; more than 20 percent improvement

- Constant SIR algorithm is overly aggressive trying to keep a certain SIR

- PCMA-1 or PCMA-2 adaptively adjust the power to interference and backlog/delay and utilize the channel better **è** PCMA-1 and PCMA-2 achieve the almost same performance

Contribution of This Paper

- Obtained optimal power control strategy: (take channel conditions and delay constraint into account)
  - Low-power transmission
    - If channel is poor and tolerable delay is large
  - Middle-power transmission
    - If channel and delay are average
  - high-power transmission
    - If delay constrain is tight

Final Comments:

- Limitation of This Paper
  - The feedback channel is perfect
  - Interference levels in various time slots are i.i.d
  - The burstness of network traffic is not taken into account
- Potential Research Topics
  - The burstness of network traffic
  - Imperfect feedback channel
  - More realistic s(b,i) and X(b) functions