Spectrum Sharing with Distributed Interference Compensation

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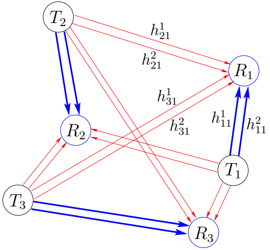
DySPAN'05

Motivation

- Several bands available for spectrum sharing.
  - Commercial bands offered in the secondary markets.
  - Government owned bands available to other service providers.
- Several users want to share the bands.
  - Can be end-users or service providers.
  - Each user can use only one band.
  - Concurrent transmissions in the same band cause mutual interferences.
- We consider the problem of joint channel selection and power control.

Multi-channel Wireless Network Model



- Each user is represented by a transmitter-receiver node pair.
- Single-hop and half-duplex transmissions.
- Several channels available with fixed gains (slow fading).
- No centralized controller.
- How to select channel and control power in a distributed way with limited (scalable) information exchange?

Related Work

- Channel selection in cellular networks has been studied extensively (e.g., Katzela and Naghshineh'96, Aardal et. al.'03)
- Recently extended to IEEE 802.11 WLANs (e.g., Kyasanur and Vaidya'05)

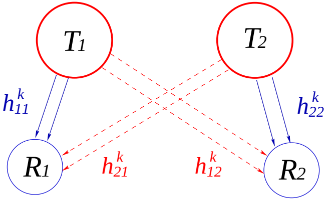
Related Work

- Channel selection in cellular networks has been studied extensively (e.g., Katzela and Naghshineh'96, Aardal et. al.'03)
- Recently extended to IEEE 802.11 WLANs (e.g., Kyasanur and Vaidya'05)
- We consider joint channel selection and power control in an ad hoc setting:
  - Allow different users to use the same channel.
  - Mitigate interference by exchanging limited information.
  - Fast convergence and substantial performance improvements compared with other heuristics.

Talk Outline

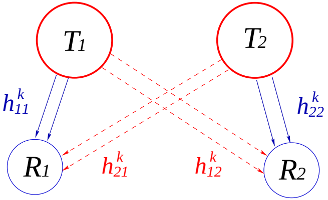
- Network model and performance metric.
- Price-based channel selection and power control algorithm.
- Convergence analysis.
- Numerical performance study.

Network Model



- I transmitter-receiver pairs (users).
- K parallel channels for all users.

Network Model



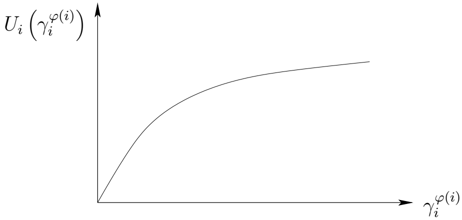
- I transmitter-receiver pairs (users).
- K parallel channels for all users.
- User i chooses to transmit in one channel, $\varphi(i)$, with power $p_i^{\varphi(i)}$:
  - Transmission power constraint

$$P_i^{\min} \leq p_i^{\varphi(i)} \leq P_i^{\max}$$

  - Received SINR in channel $\varphi(i)$

$$\gamma_i^{\varphi(i)} = \frac{p_i^{\varphi(i)} h_{ii}^{\varphi(i)}}{n_0^{\varphi(i)} + \sum_{j \neq i} p_j^{\varphi(i)} h_{ji}^{\varphi(i)}}$$

Utility Functions



- User i's QoS preference is given by utility $U_i\left(\gamma_i^{\varphi(i)}\right)$.
  - U_i is increasing and strictly concave in $\gamma_i^{\varphi(i)}$.
  - Rate-adaptive applications with elastic demands.
  - Private information, only known to the user.
- Network performance = total network utility

Total Utility Maximization Problem

- **Goal**: select channel and allocate power in a distributed way to maximize total utility.
- **Challenges**:
  - Channel selection is a discrete (combinatorial) optimization problem.
  - Power assignments across users are coupled due to mutual interference.
  - Objective function may not be concave in power.
- **Our approach**: distributed cooperation by exchange of interference prices.

Single-Channel Asynchronous Distributed Pricing (SC-ADP) Algorithm

- **Price Announcement**: user i announces an interference price $\pi_i^{\varphi(i)}$ in the currently selected channel $\varphi(i)$

$$\pi_i^{\varphi(i)} = \left| \frac{\partial U_i(\gamma_i^{\varphi(i)})}{\partial \left(\sum_{j \neq i} p_j^{\varphi(i)} h_{ji}^{\varphi(i)} \right)} \right|.$$

- **Channel Selection and Power Update**: user i chooses channel $\varphi(i)$ and power $p_i^{\varphi(i)}$ to maximize surplus

$$s_i = U_i \left(\gamma_i^{\varphi(i)} \left(p^{\varphi(i)} \right) \right) - p_i^{\varphi(i)} \sum_{j \neq i} \pi_j^{\varphi(i)} h_{ij}^{\varphi(i)}$$

- Repeat two steps asynchronously across users.
- Only need to announce a single price and measure local channel gains (h_{ij}^k for all j and k).

Convergence of SC-ADP

- Depends on the concavity of utility functions.
  - Define the coefficient of relative risk aversion of a utility U_i to be

$$Q_i(\gamma_i) = -\frac{\gamma_i U_i''(\gamma_i)}{U_i'(\gamma_i)}.$$

  - larger $Q_i(\gamma_i) \Rightarrow$ "more concave" U_i.

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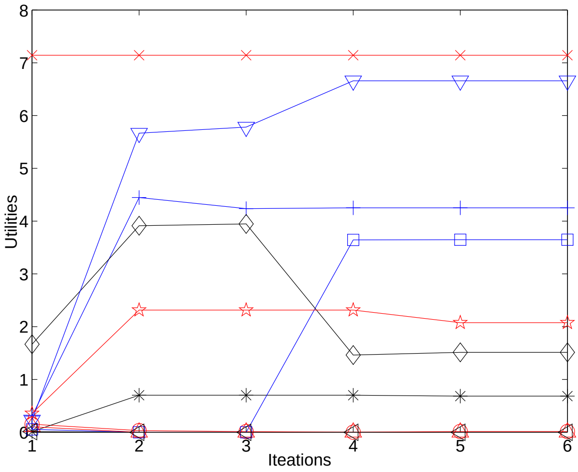
- **Prop**: For a two-user K-channel network, the SC-ADP algorithm with sequential updates converges if
  (1) Both users have $Q_i(\gamma_i) \in (0, 1]$, or
  (2) Both users have $Q_i(\gamma_i) \in (0, 2]$, and $0 < P_i^{\min} = P_i^{\max}$.

- Examples:
  - $U_i(\gamma_i) = \log(1 + \gamma_i) \Rightarrow Q_i(\gamma_i) \in (0, 1]$.
  - $U_i(\gamma_i) = \theta_i \gamma_i^{\alpha}/\alpha$ (with $\alpha \in [-1, 1]$) $\Rightarrow Q_i(\gamma_i) \in (0, 2]$.

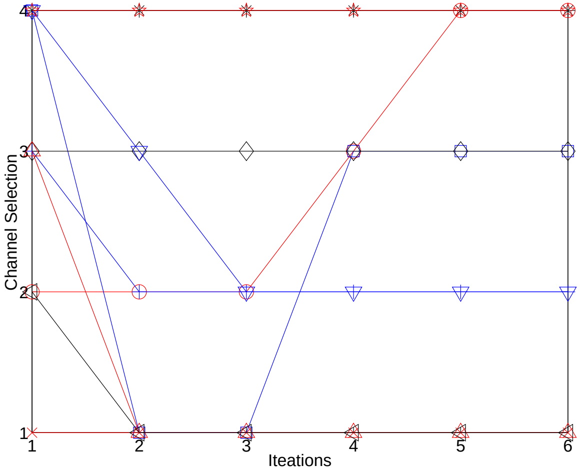
- Proof: show users will not oscillate in channel selection.

Convergence of SC-ADP: Utility



utility $\log(1 + \gamma_i^{\varphi(i)})$, 4 channels, 10 users

Convergence of SC-ADP: Channel Selection



utility $\log(1 + \gamma_i^{\varphi(i)})$, 4 channels, 10 users

Performance Comparison

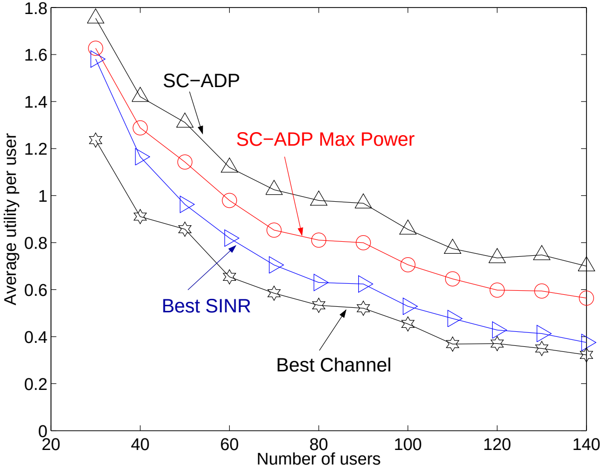
- **SC-ADP Max Power**: user i transmits with maximum power in the channel that maximizes surplus.
- **Best SINR**: user i transmits with maximum power in the channel that yields the highest SINR:

$$\varphi(i) = \arg\max_k \frac{h_{ii}^k}{n_0 + \sum_{j \neq i} p_j^k h_{ji}^k}.$$

- **Best Channel**: user i transmits with maximum power in the channel with the largest channel gain

$$\varphi(i) = \arg\max_k h_{ii}^k.$$

Performance Comparison



utility $\log(1+\gamma_i^{\varphi(i)})$, 4 channels, $10m \times 10m$ area

Performance Comparison

- **Multi-channel ADP(MC-ADP)**: user i allocates power across K channels to maximize surplus

$$\sum_{k=1}^{K} \log\left(1+\gamma_i^k\right) - \sum_{k=1}^{K} p_i^k \sum_{j\neq i} \pi_j^k h_{ij}^k,$$

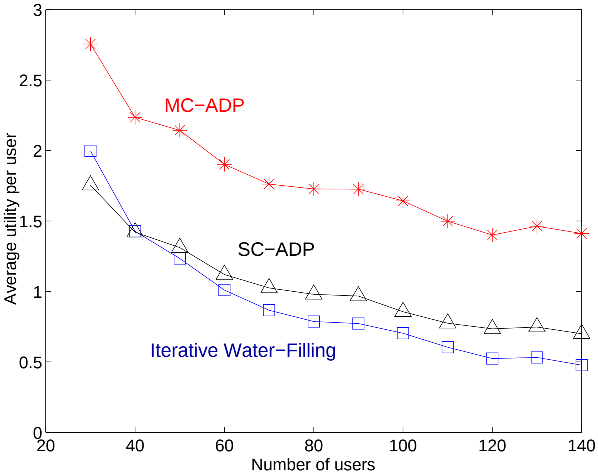
  subject to total power constraint $\sum_k p_i^k \leq P_i^{\max}$.

- **Iterative Water-filling (IWF)** [Yu, Ginis, Cioffi'02]: user i allocates power across K channels to maximize rate

$$\sum_{k=1}^{K} \log\left(1+\gamma_i^k\right),$$

  subject to total power constraint $\sum_k p_i^k \leq P_i^{\max}$.

Performance Comparison



4 channels, $10m \times 10m$ area

Conclusions

- Presented distributed channel selection and power control algorithm for multi-channel wireless networks.
- Users exchange prices, which reflect their sensitivities to interference.
- Each user chooses a channel, and adjusts power to maximize its surplus.
- Proved convergence of the SC-ADP algorithm in some special cases.
- Showed substantial performance improvement over other heuristics.

Related Paper

- J. Huang, R. Berry and M. L. Honig, "Distributed Interference Compensation for Wireless Networks," accepted by *IEEE Journal on Selected Areas in Communications*, 2005
- Other papers can be found at www.princeton.edu/∼jianweih