Cross-Layer Optimization in Decentralized Cognitive Radio Networks

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24 April, 2019

Outline

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- Related Work – What has been done already?
- Challenges tackled in our work - What is new?
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Motivation - Why Cross-Layer Optimization?

- Objective: Maximize the throughput of a set of assigned end-to-end multi-hop flows in a Secondary User (SU) network by intelligently exploiting the spectrum holes left unused by the licensed user
- Pure divide-and-conquer protocol design strategies do not work because the performance across all layers are dependent on the resource allocation constraints and the incumbent interference constraints.
- A cross-layer optimization framework is the way-to-go because it brings in requirements from all five layers of the stack with one global objective of maximizing the throughput while enforcing strict PU non-interference compliance.
- Devise a distributed, layered solution for the optimal performance of a cognitive radio node.

Related Work – What has been done already?

- Y. Teng and M. Song, "Cross-Layer Optimization and Protocol Analysis for Cognitive Ad Hoc Communications"
  - Power Allocation, Channel Allocation, Routing, and Flow Rate Control solutions with MRR in the APP - GUOP formulations
  - Convex optimization using vertical decomposition techniques
  - Complexity analysis and heuristics to overcome the computational overhead/intractability
- A. Cammarano, F. L. Presti, G. Maselli, L. Pescosolido and C. Petrioli, "Throughput-Optimal Cross-Layer Design for Cognitive Radio Ad Hoc Networks"
  - MAC, Rate Control, and Flow Scheduling - NUM problem formulation
  - Common control channel for the dissemination of known channel occupancy behavior and queue lengths at links for different flows
  - A static multi-graph topology for the SU network and a conflict graph to capture scheduling constraints among sub-links

Challenges tackled in our work - What is new?

- MCS adaptation in the PHY – Frame it as an optimization problem and incorporate it into the cross-layer framework
- An intelligent, process-interactive agent model to learn the channel occupancy behavior of the incumbents
- The incumbent channel occupancy behavior is not independent spatially and temporally – there exists a correlation model
- Different flows have different QoS constraints and hence, some flows need to be prioritized over others – weighted flow scheduling

System Model (just the important bits)

- Network Model:
  - A Secondary User network with M licensed users, N SU nodes, and K channels of equal capacity C
  - $\mathcal{L} = \{(n, m; c) : n, m \in \mathcal{N}, c \in \mathcal{C}\}$ denotes the set of all sub-links and $\mathcal{F}$ denotes the set of end-to-end flows assigned to the SU network with flow $f \in \mathcal{F}$ having weight/priority w_f
- Link Adaptation Model
  - $PER = \phi(MCS_{choice}, \sigma_V^2, H, L)$
  - $\mathbb{P}(PER_{MCS_{choice}} > \gamma_{PER}) \leq \mu, \; 0 < \mu < 1$
  - PER Estimation and Approximation for each MCS
- Flow Routing Model:
  - Non-negative and maximum flow rate constraints for $x_f \in [0, x_M]$
  - Node balance equations for the flows,

$$\begin{cases} x_f + \sum_{l \in \mathcal{L}_i(n)} s_{fl} = \sum_{l \in \mathcal{L}_o(n)} s_{fl}, & \text{if } n = s_f,\; f \in \mathcal{F} \\ \sum_{l \in \mathcal{L}_i(n)} s_{fl} = \sum_{l \in \mathcal{L}_o(n)} s_{fl}, & \text{if } n \neq s_f,\; d_f, f \in \mathcal{F} \end{cases}$$

System Model...

- Interference Model: Two or more SUs cannot employ the same channel at the same time and none of the SUs can employ a channel that is being used by an incumbent in that time slot - captured by the conflict graph interpretation
- Incumbent(s) Channel Occupancy Model:
  Temporal Markov Chain

$$\mathbb{P}(\vec{X}(i+1)|\vec{X}(j),\ \forall j \leq i) \ = \ \mathbb{P}(\vec{X}(i+1)|\vec{X}(i))$$

  Spatio-Temporal Markov Chain

$$\mathbb{P}(\vec{X}(i+1)|\vec{X}(i)) \ = \ \prod_{k=1}^{K} \mathbb{P}(X_{k+1}(i+1)|X_{k+1}(i), X_k(i+1))$$

- Spectrum Access Model: Formulate the spectrum access problem as a POMDP denoted by $(\mathcal{X},\ \mathcal{A},\ \mathcal{Y},\ \mathcal{B},\ A,\ B)$

Solution Approach - Problem Formulation

- Separate Correlation Model Problems:
  - Learn the model: $A^*, B^* = argmax_{A,B}\mathbb{P}(\vec{y}|A,B)$ [MLE]
  - Estimate the occupancy states:
    $\vec{x}^*(i) = argmax_{\vec{x}}\mathbb{P}(\vec{X}(i) = \vec{x}(i)|\vec{Y}(i) = \vec{y}(i))$ [MAP]
- Main Cross-Layer Numerical Utility Maximization Problem
  - Objective function: $max_{f\in\mathcal{F}} \sum_{f\in\mathcal{F}} \frac{x_f^{(1-\eta)}}{(1-\eta)}$, $\eta > 0$
  - Power constraints: $\forall n \in \mathcal{N}$, $P_{n,l}^{(f)} \geq 0$,
    $\sum_{f\in\mathcal{F}}\sum_{l\in\mathcal{L}_o(n)} P_{n,l}^{(f)} \leq P_n^{max}$
  - Packet Error Rate constraint for MCS adaptation:
    $\mathbb{P}(PER_{MCS_{choice}} > \gamma_{PER}) \leq 0.05$
  - Constraints from the conflict graph interpretation:
    $\sum_{I\in\mathcal{I}} p_I\theta_{Il} \leq \alpha_l,\ \forall l \in \mathcal{L}$,
    $\sum_{I\in\mathcal{I}} p_I = 1,\ p_I \geq 0,\ \forall I \in \mathcal{I}$
  - Flow routing constraints: $x_f \in [0, x_M]$ and

$$\begin{cases} x_f + \sum_{l\in\mathcal{L}_i(n)} s_{fl} = \sum_{l\in\mathcal{L}_o(n)} s_{fl}, & \text{if } n = s_f,\ f\in\mathcal{F} \\ \sum_{l\in\mathcal{L}_i(n)} s_{fl} = \sum_{l\in\mathcal{L}_o(n)} s_{fl}, & \text{if } n \neq s_f,\ d_f, f\in\mathcal{F} \end{cases}$$

Solution Approach - Important Decomposition Details

- Solving for P^*, x^*, s^*, and p^*
- Formulate the Lagrangian and the various decomposed sub-problems are:
  - MCS adaptation: $max_{MCS}\ r_{MCS}(1 - PER_{MCS})$
    PER computation and approximation - [Tan et. al, 2008]
  - Flow Scheduling Dual Function:
    $max_s\ \sum_{l \in \mathcal{L}}\ \sum_{f \in \mathcal{F}}\ s_{fl}[w_f(q_{h(l)f} - q_{t(l)f})]$
  - Rate control dual function:
    $max_x\ (U_f(x_f) - q_{s(f)f}x_f)$
  - A POMDP agent (essentially on a quorum-designated gateway node) will disseminate the "utility" of channels in the discretized spectrum of interest to all the SU nodes and this "utility" will be encapsulated in the α_l variable in the cross-layer optimization problem.
  - MAC dual function:

$$max_p \Big[-\frac{1}{\beta} \sum_{l \in \mathcal{I}}\ p_l log p_l + \sum_{l \in \mathcal{I}}\ p_l \sum_{l} (z_{nm} - w_l) a_{ll} + \sum_{l}\ w_l(\alpha_l - \epsilon) \Big]$$

Results and Discussions - The Algorithms

- MCS selection algorithm:
  - Upon receiving a packet, the SU node computes the SNR of the sub-link using MMSE estimation and knowing the modulation scheme and code rate used at the transmitter, the SU node calculates the PER.
  - An exhaustive search (or a more optimal search, if possible) is performed over the set of MCS choices to determine their PER estimates. Then, choose an MCS such that, $MCS_{choice} = argmax_{MCS}\ r_{MCS}(1 - PER_{MCS})$
- Power allocation:
  $P_{n,l}^{f*} = \left[\frac{\mathbb{I}(PU\ \ idle)\ \mathbb{J}(SUs\ \ m{\neq}n\ \ idle)BW_c}{\lambda_n ln2} - \frac{\Gamma\sigma_V^2}{g_l}\right]^+$
- Prioritized Flow Scheduling: Maximum weighted queue differential back-pressure with priority queues...
  $s^* = argmax_s\ \sum_l\ \sum_f\ \ s_{fl}[w_f(q_{h(l)f} - q_{t(l)f})]$
- Rate Control: $x_f^* = U_f^{-1}(q_{s(f)f})$
- MAC Protocol: CSMA with back-off rate determined by,
  $R_l = \frac{e^{\beta(z_{nm} - w_l)}}{\alpha_l}$ where $l = (n, m; c),\ \ n, m \in \mathcal{N},\ \ c \in \mathcal{C}$

Fin