A Competitive and Dynamic Pricing Model for Secondary Users in Infrastructure based Networks

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Outline

- Spectrum underutilization and Dynamic Spectrum Access (DSA)
- Distributed framework for Secondary User (SU) access
- Dynamic pricing model for SUs
- Multiple Wireless Service Providers (WSPs) and competitive SU pricing
- Achieving competitive yet dynamic SU pricing: Non-cooperative game theoretic analysis
- Dual benefits for SUs and WSPs
Spectrum occupancy field measurements: Underutilization of the radio spectrum in the spatial and temporal domains [Spectrum measurements, M. A. McHenry et al., '06].

Dynamic Spectrum Access (DSA): Intelligent and efficient use of the radio spectrum by allowing opportunistic SU(unsubscribed) access.

Software Defined Radios (SDRs) or Cognitive Radios (CRs): envisioned to be enablers for DSA with the ability for cognition and reconfigurability.

For infrastructure based networks: Potential for WSPs to gain additional profits by providing access to SUs.
Focus on **centralized system framework** with a **Centralized Mediating Entity (CME)** acting as a spectrum manager/broker/negotiator to pool the spectrum and manage the exchange of spectrum among WSPs and to SUs [Spectrum pooling: T. Weiss and F. Jondral ’04].

- **Dimsumnet architecture**: Co-ordinated access band (spectrum pool) with 'spectrum broker' for spectrum management [M. Buddhikot et al. ’05].
- **Spectrum Policy Server (SPS)**: negotiate spectrum on behalf of WSPs to SUs [O. Ileri et al. ’05].
- **Cognitive Pilot Channel (CPC)**: CPC manager for information exchange [J. Perez-Romero et al. ’07].

**Competitive SU pricing and microeconomic models**: [D. Niyato, E. Hussein, ’07].
Distributed System Framework

- Distributed Framework: Base Station (BSs) and not Wireless Service Providers (WSPs) individually advertise and sell their local unutilized spectrum to Secondary Users (SUs) [S. Dixit, S. Periyalwar, H. Yanikomeroglu, ’09].
  - Harmonious operation of Primary Users (PUs) and SUs at the same BS at equivalent power levels on different frequencies.
  - Prioritized PU-SU scheduling: SU service subject to instantaneous spectrum availability after PUs have been served.
  - SUs provided the freedom to select their preferred BS based on variety of parameters (i.e., price/service class, signal strength).
  - Dynamic pricing model: SU price depends on spectrum resources utilized at the BS by its subscribers, i.e., PUs.
Distributed Framework and Network Scenario

- **Snapshot of current spectrum utilization at a particular BS.**

  - BS$_i$ of WSP$_x$
  - Single Frequency Network: Frequency band licensed by WSP$_x$
  - Spectrum utilized by the PUs ($\alpha_{i,pu}$)
  - Unutilized spectrum available for SU access ($1 - \alpha_{i,pu}$)

- **Network scenario with a SU requesting temporary wireless access from the BSs in the area.**

  - BS$_1$ of WSP$_1$ (LTE-A)
  - BS$_2$ of WSP$_2$ (WiMAX)
  - BS$_1$ of WSP$_2$ (LTE-A)
  - SU
  - Local spectrum information [BS $\rightarrow$ SU]
  - Spectrum access request [SU $\rightarrow$ BS]
  - Selected BS
Introduction

Inter-WSP Competition with Dynamic SU Pricing

Overview

System Concept

SU Pricing

Dynamic Nature of SU Pricing: Terminology

\[ s_i : m_i = 1 \]

\[ s'_i : m_i = 0.3 \]

Fixed PU price (per PU):

\[ p_i = 1 \]

Fixed cost (per PU/SU):

\[ c_i = 0.45 \]

Spectrum at \( B_S_i \) currently available for SU access

\( \alpha_{i,pu} = 0.4 \)

Spectrum at \( B_S_i \) currently occupied by PUs

Spectrum at \( B_S_i \) currently occupied with monetary incentive to the SUs

Inherent SU admission control

\[ s_i \rightarrow \infty \]

when \( \alpha_{i,t} \rightarrow \alpha_{i,th} \)

Spectrum at \( B_S_i \) reserved for handoff and overload protection

\[ \alpha_{i,h} = 0.1 \]

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Dynamic Incentive based SU Pricing Model

- $\alpha_{i,h}$: Spectrum reserved for handoff; $\alpha_{i,th} = 1 - \alpha_{i,h}$.
- $\alpha_{i,su}$: Spectrum at BS$_i$ occupied by SUs; $\alpha_{i,su}$ iff $\alpha_{i,pu} < \alpha_{i,th}$.
- $\alpha_{i,t}$: Spectrum Utilization Factor (SUF); $\alpha_{i,t} = \alpha_{i,pu} + \alpha_{i,su}$.
- $\alpha_{i,ic}$: Incentive cutoff limit beyond which $s_{i,j} > p_{i,j}$.

SU Price ($s_i$) w.r.t. PU price ($p_i$) and SUF ($\alpha_{i,t}$) at the BS

$$\bar{s}_i = (f_i(\alpha_{i,t}))^{m_i} \times p_i,$$  \hspace{1cm} (1)

where $s_i$, $p_i$, $(f_i(\alpha_{i,t})$, $m_i$ are non negative real numbers.

$m_i$: Price Leveling Factor (PLF) - additional pricing flexibility.

Normalized SU price

$$f_i(\alpha_{i,t}) = \begin{cases} -\ln \left(1 - \left(\frac{\alpha_{i,t}}{\alpha_{i,th}}\right)^{n_i}\right), & \text{if } 0 \leq \alpha_{i,t} < \alpha_{i,th}, \\ \infty, & \text{if } \alpha_{i,th} \leq \alpha_{i,t} \leq 1. \end{cases}$$  \hspace{1cm} (2)
Multiple WSPs: Aim to maximize individual WSP profits from SUs, while competing on prices.

- Achieving competitive pricing with dynamic SU prices: prohibitively complex.
- For competitive dynamic pricing:
  1) Use static SU prices ($S_i$).
  2) Find equilibrium static SU prices.
  3) Implement on dynamic model using $\text{PLF}(m_i)$.
- Tools (in step 2):
  Non-cooperative game theoretic analysis with SU service based differentiation.
Two WSPs and the Differentiation of SU service

- Identical service: high competition, low or zero profits.
- Differentiation of service: low competition, higher profits.
- Differentiation of the SU wireless service: using Dissatisfaction Price ($\zeta$) based on the variance of the wireless channel ($\sigma_i$); $\zeta = K_1 K_2$ ($\$\$), where $K_1 = 1$ ($\$\$); $K_2 = \left(\frac{\sigma_1 + \sigma_2}{2}\right)$.
- Perceived price to each SU: $U_i(y) = S_i + (\zeta \times y)$ ($\$\$).
Nash Equilibrium (NE) SU price $S_i^*$

$$S_i^* = C_i + \zeta,$$

where $C_i$ is the fixed cost considering static SU pricing.

SU Pricing w.r.t. PU price and SUF at the BS

$$s_i' = (f_i(\alpha_i,t))^{m_i} \times p_i.$$  (4)

Mapping: $s_i' = S_i^*$, i.e., Static SU price mapped to first SU entering the BS at $\alpha_{i,t} = \alpha_{i,pu}$.

Value of $m_i$

$$m_i = \frac{\ln \left( \frac{S_i^*}{p_i} \right)}{\ln(f_i(\alpha_{i,pu}))}.$$  (5)
Competitive Dynamic SU Pricing

- Symmetric WSP costs: $C = 0.2 + 0.3(\alpha_{i,t})$
- SUs: WSP1
- SUs: WSP2

- Dissatisfaction level parameter: $\zeta_1 = 0.365$, $\zeta_2 = 0.355$
- SU price (per SU): $s_1$, $s_2$
  - $s_1$: $m_1 = 1$, $\zeta = 0$
  - $s_2$: $m_2 = 1$, $\zeta = 0$

- Competitive Dynamic Pricing:
  - Less competitive: $s_1$ and $s_2$ far apart
  - Highly competitive: $s_1'$ and $s_2'$ very close

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Competitive WSP Profits

- Competitiveness Metric: 
  \[ \psi_{s_1, s_2} = \text{VAR}(\Lambda), \]
  where \( \Lambda = |\hat{s}_1(L_1) - \hat{s}_2(L_2)| \)
  
  \( \hat{s}_1(L_1) = \{s_1(1), s_1(2), \ldots s_1(L_1)\} \)
  
  \( L_i \): Total number of SUs with WSP\(_i\).

- \( psi_{s_1, s_2} = 5.24 \times 10^{-2} \),
  \( psi_{s'_1, s'_2} = 3.44 \times 10^{-4} \).

- Competitiveness improvement: factor of 100!

To quantify the competitive nature: Competitiveness Metric \( (\psi_{s_1, s_2}) \).
Conclusions and Future Work

- BS-centric distributed framework demonstrating the profitability potential for the WSPs and opportunistic temporary wireless access for SUs is presented.
- Methodology to achieving competitive yet dynamic SU pricing without co-operation among WSPs was elaborated.
- Non-cooperative game theoretic analysis with the SU wireless service differentiated based on the wireless channel was used to achieve competitive yet dynamic SU pricing.
- The competitive dynamic SU price set by the BS for direct temporary SU access was observed to depend upon:
  - Wireless environment,
  - Spectrum utilization (PUs + SUs) at the BS,
  - Incentives provided by WSPs through their BSs,
  - Current PU demand and the PU price.

Future Work: Resource Allocation, and Relay Networks perspective.