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 underutilization and DSA

- 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.

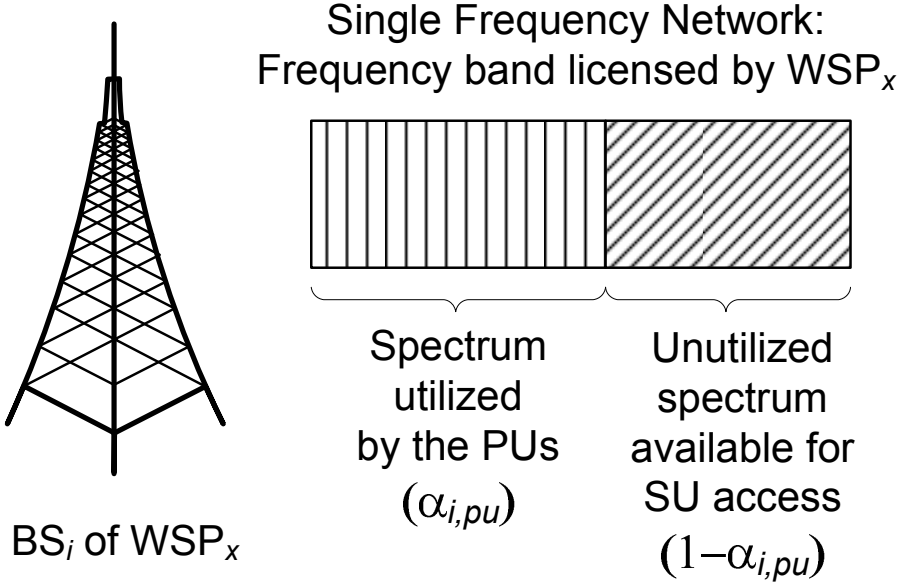
Previous Works

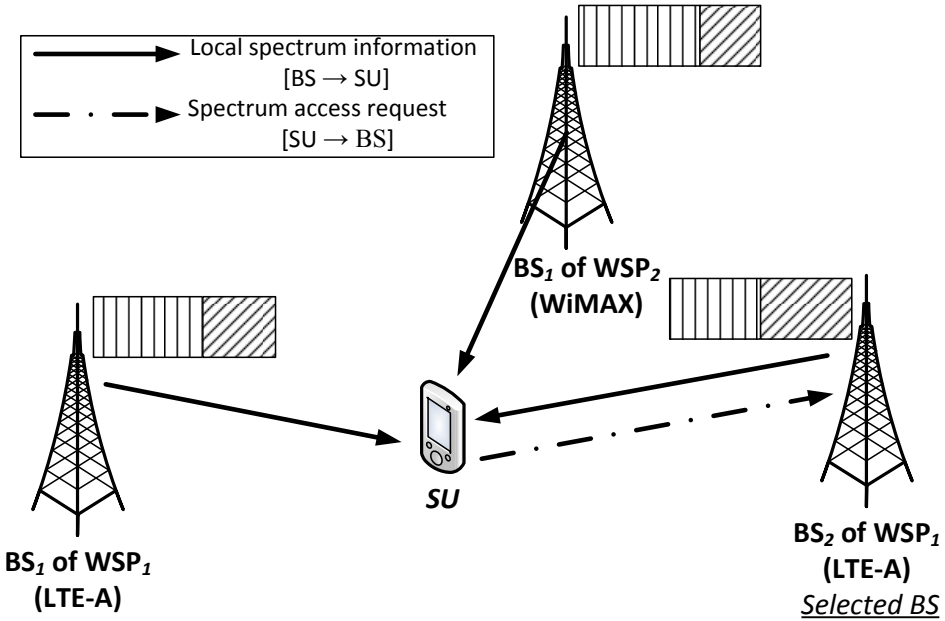
- Focus on centralized system framework with a Centralized Mediating Entity (CME) acting as a spectrum manager/broker/negotiator to pool the spectrum and manage the exchange of spectrum among WSPs and to SUs [Spectrum pooling: T. Weiss and F. Jondral '04].
  - Dimsumnet architecture: Co-ordinated access 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.

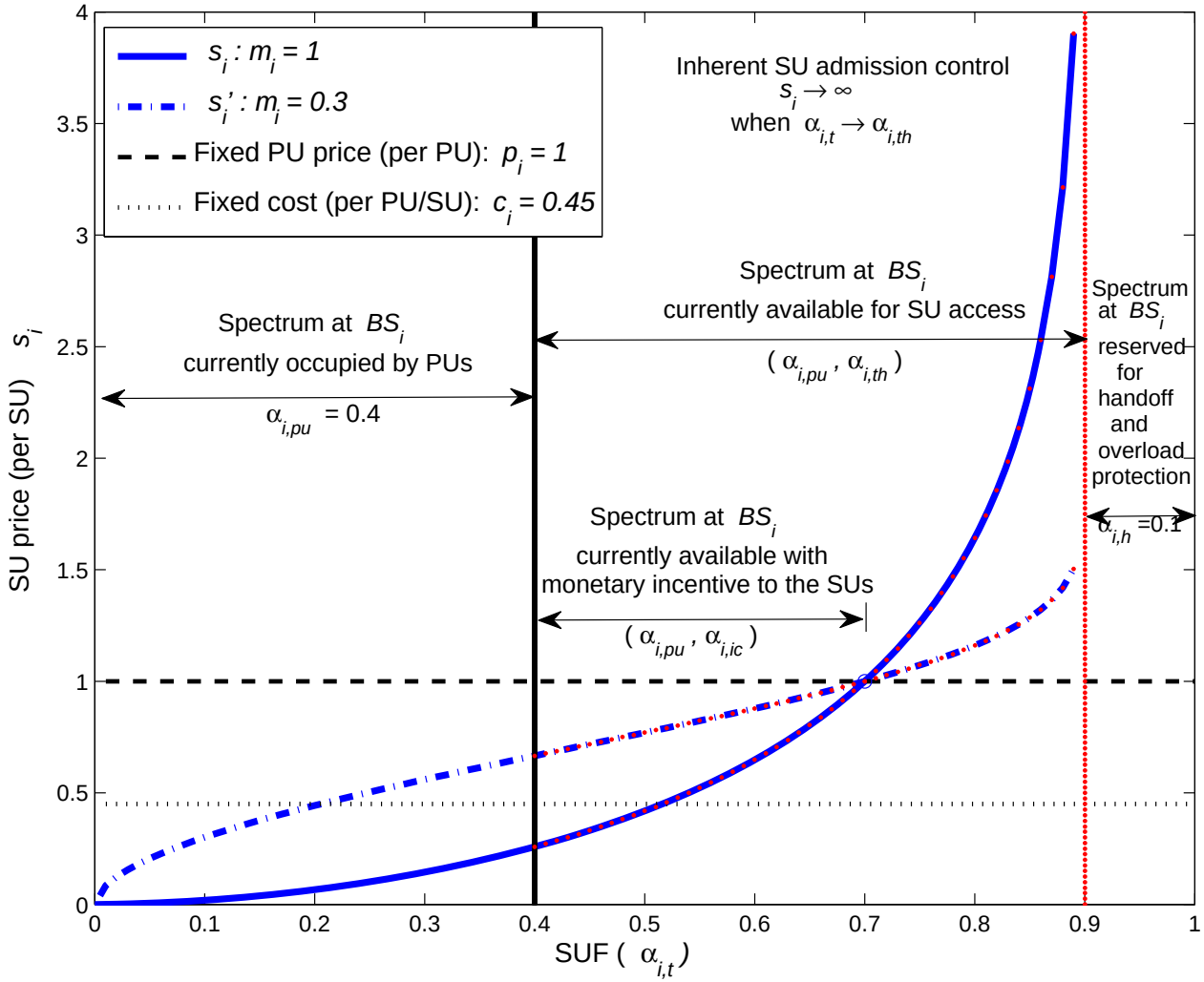
Distributed Framework and Network Scenario





- Snapshot of current spectrum utilization at a particular BS.
- Network scenario with a SU requesting temporary wireless access from the BSs in the area.

Dynamic Nature of SU Pricing: Terminology



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

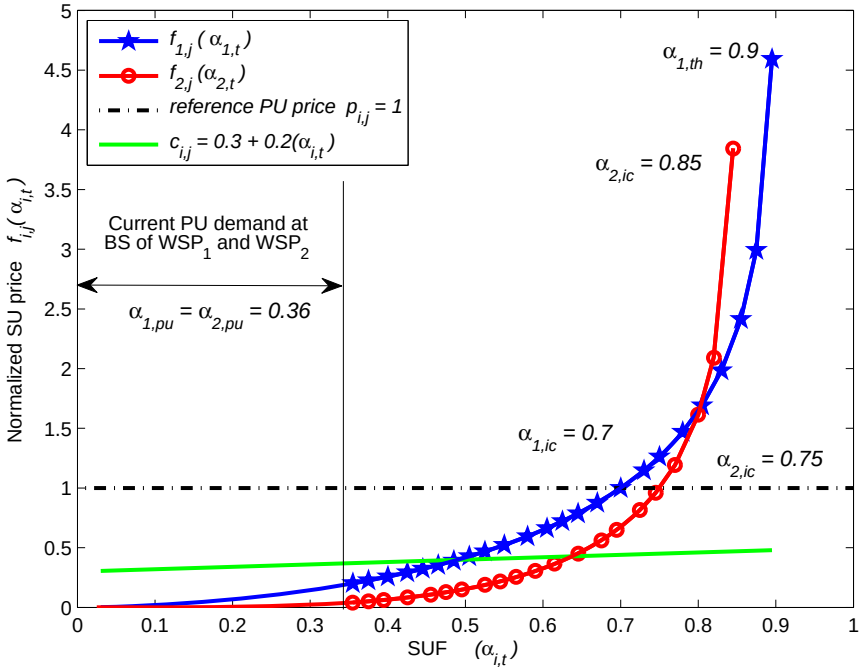
$$\bar{s_i} = (f_i(\alpha_{i,t}))^{m_i} \times p_i, \tag{1}$$

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

$$f_i(\alpha_{i,t}) = \begin{cases} -\ln\left(1 - \left(\frac{\alpha_{i,t}}{\alpha_{i,th}}\right)^{n_i}\right), & \text{if } 0 \leq \alpha_{i,t} < \alpha_{i,th}, \\ \infty, & \text{if } \alpha_{i,th} \leq \alpha_{i,t} \leq 1. \end{cases} \tag{2}$$

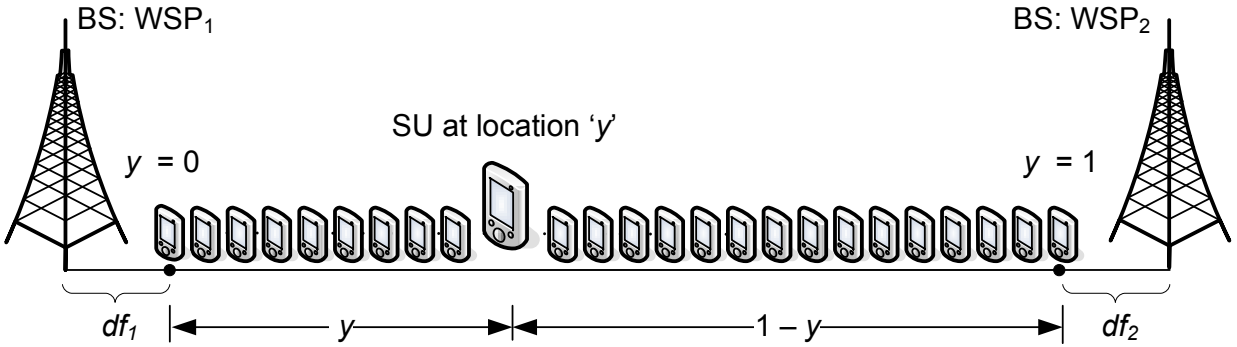
Competitive Pricing among Multiple WSPs



- 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 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 (ζ) based on the variance of the wireless channel (σ_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: $U_i(y) = S_i + (\zeta \times y)$ (\$).

Transformation for Achieving Competitive Pricing

Nash Equilibrium (NE) SU price S_i^*

$$S_i^* = C_i + \zeta, \tag{3}$$

where C_i is the fixed cost considering static SU pricing.

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

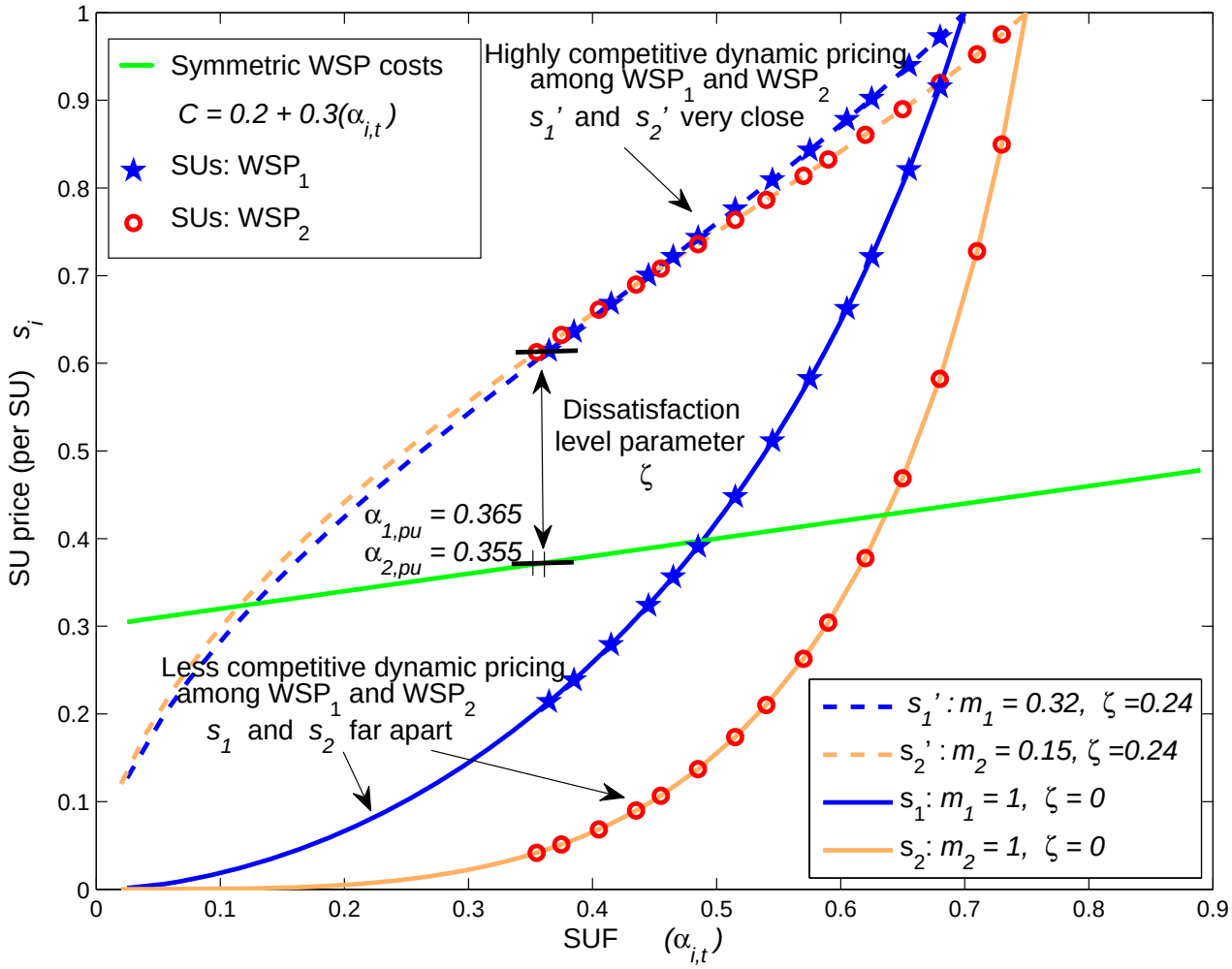
$$s_i' = (f_i(\alpha_{i,t}))^{m_i} \times p_i. \tag{4}$$

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

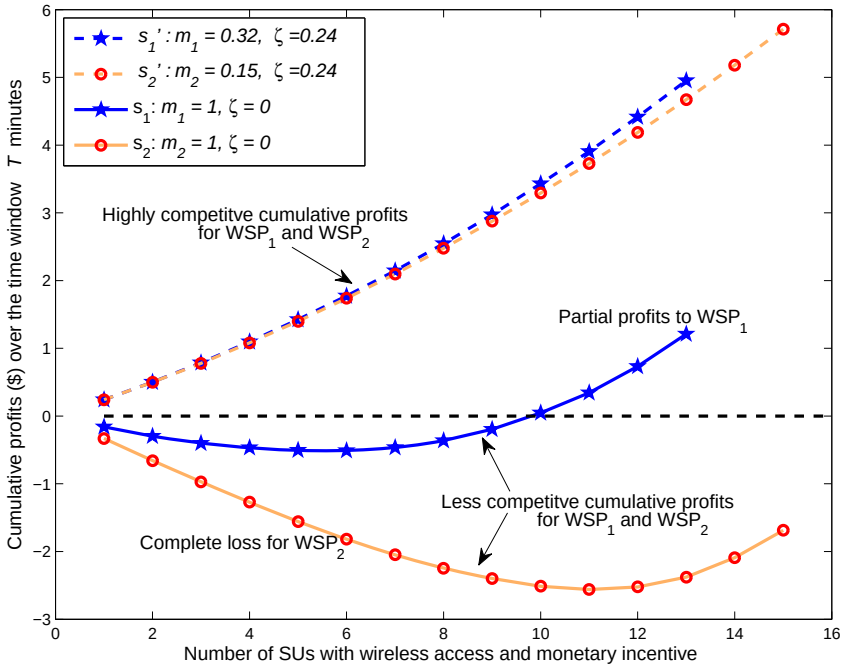
Value of m_i

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

Competitive Dynamic SU Pricing



Competitive WSP Profits



- To quantify the competitive nature: Competitiveness Metric (ψ_{s_1,s_2}).

- Competitiveness Metric: $\psi_{s_1,s_2} = \text{VAR}(\Lambda)$, where $\Lambda = |\hat{s}_1(L_1) - \hat{s}_2(L_2)|$
- $\hat{s}_1(L1) = \{s_1(1), s_1(2), ...s_1(L1)\}$. 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 !

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.