

A Distributed Framework with a Novel Pricing Model for Enabling Dynamic Spectrum Access for Secondary Users

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Outline

- Distributed framework: Base Station(BSs) of a Wireless Service Provider(WSP) individually advertize and sell their current unutilized spectrum to Secondary Users (SUs)
 - Harmonious operation of Primary Users (PUs) and SUs at the same BS at equivalent power levels on different frequencies
 - Criterion for autonomous network (WSP) selection
 - Signaling framework for SU-BS interaction
 - DSCP based mechanism for PU-SU differentiation at the BS
- Novel pricing model
 - Monetary incentive for SUs w.r.t. to PU price during low spectrum utilization at the BS, while monetary penalty when spectrum utilization at the BS is high
 - SU price depends upon: PU demand, PU price and the total spectrum utilization at the BS (PUs + SUs)
 - Price based handoff scheme

Introduction

- **Underutilization of the radio spectrum** in the spatial and temporal domains has been evident through field measurements [Spectrum measurements, M. A. McHenry et al., '06].
- **Dynamic Spectrum Access (DSA) techniques** aim at intelligent and efficient use of the radio spectrum by allowing opportunistic SU(*unsubscribed*) access.
- **Software Defined Radios (SDRs) or Cognitive Radios (CRs)** are envisioned to be enablers for DSA with the ability for **cognition and reconfigurability** [Q. Zhao and B. Sadler, '07].
- In infrastructure based networks, the Wireless Service Providers (WSPs) by implementing DSA techniques, can potentially **gain additional profits** by providing **access to SUs**.

Centralized spectrum pooling framework

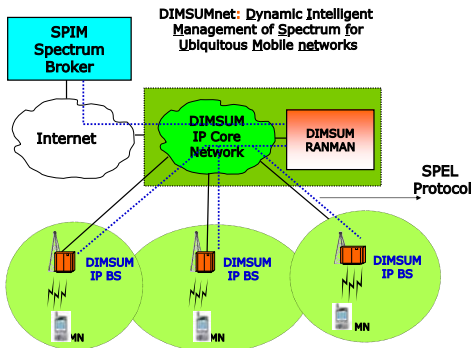
Spectrum or spectrum information pooling

- Includes a **Centralized Mediating Entity (CME)** for **regulation, brokerage, co-ordination or arbitration** between WSPs
- Requires **mesh based architecture with regional CMEs**, due to dynamic nature of spectrum usage

Disadvantages

- WSPs invest heavily in **infrastructure and spectrum lease**
- **Huge extra costs** to WSPs due to:
 - **New protocols for co-ordination** between WSPs, CME and SUs
 - Increase in **complexity** and **additional signaling overhead**
 - Possible **delays in co-ordination** and operation due to presence of CMEs
 - **Operation and maintenance** of the new hardware and software

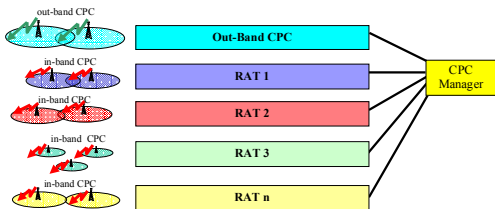
[DIMSUMnet, M. Buddhikot et al., '05]



- **CME: Spectrum Broker** for spectrum pooling, information co-ordination and regulation

- Regional Access Network MANagers(RANMAN) for handling regional dynamics of spectrum usage
- SPEctrum Lease (SPEL) protocol and SPectrum Information Channel (SPIC) protocols
- Concerns: Co-operation and co-ordination among WSPs for supporting spectrum broker and RANMANs. Overhead in system implementation and protocols

[Cognitive Pilot Channel (CPC), J. Perez-Romero et al., '07]



- Universally harmonized frequency for global user terminal operation
- Spectrum information from all the WSPs in the area sent over CPC to the SUs

- Multiband spectrum scanning not required at SU terminal
- Mesh based architecture with regional CPC managers for localized spectrum information of regional WSPs in the area
- Concerns: Co-operation and co-ordination among WSPs for supporting regional CPC manager. Overhead in system implementation and protocols

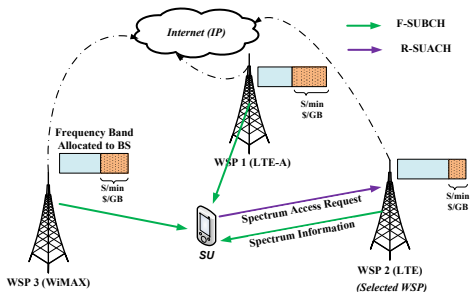
Pricing for SUs

- **SU pricing** critical aspect for implementation of DSA techniques in infrastructure based networks
- **Spectrum policy server** as arbitrator for SU-WSP connection [Demand responsive pricing, Ileri et al., '05]

[Resource and power based pricing, J. Acharya and R. Yates, '08]

- WSP obtains the spectrum requested based on the SU demand from a **central clearinghouse**
- WSP also incurs a cost proportional to the power transmitted to each of the SUs, which is paid by the SU along with a fixed subscription fee
- Concern:
 - 1) Tractability due to power based pricing
 - 2) Co-ordination with the centralized spectrum clearinghouse

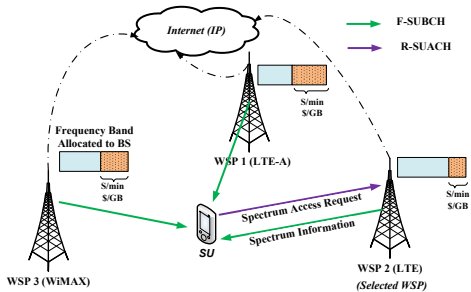
Proposed approach - key features



- Approach based on **all-IP 4G** framework

- The **BS of every WSP i** advertise their spectrum individually to the **SUs** in the area, with **minimum changes to current infrastructure**
- Harmonious operation of **PU**s and **SU**s at the same BS at equivalent power levels
- SU access granted** if and only if, there remains spectrum available at the BS **after all the PUs have been served**

System framework



- Allows a **standalone WSP** to **provide SU access**, without CMEs and co-operation or co-ordination with other WSPs

- Spectrum **currently utilized** at the BS of WSP i - Light blue
- Spectrum **currently available for SU access** at the BS of WSP i - Dotted orange
- BSs of WSPs **advertize their spectrum availability and SU price** over the Forward link SU Broadcast Channel (F-SUBCH)
- The SUs respond to the **selected BS** over the Reverse link SU Access Channel (R-SUACH)

Criterion for autonomous network selection at SU terminal

- SU terminal: **Multimode-SDR**
- SU input: (1) **Application class required**
(2) **Cost threshold** C_{th} (for price based handoff)
- It is assumed that application class requested by the SU is offered by the BS of WSP i
- Aim: Selection of the network (BS of a WSP) with the **least SU price** s_i and the **best signal strength** η_i at the SU location

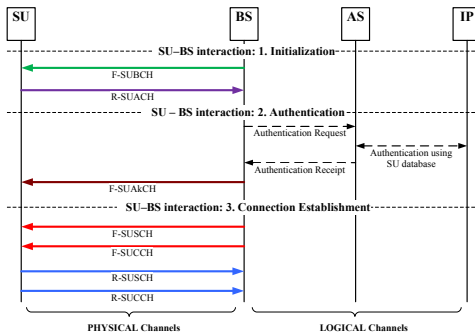
Autonomous network selection metric calculated at SU terminal

$$\text{Minimize } U_{SU,i} = \left(\frac{s_i}{\eta_i} \right), \quad (1)$$

where η_i represents the **average achievable link spectral efficiency** based on γ_i . γ_i is the average Signal to Noise Ratio (SNR) at the SU terminal after detection of F-SUBCH from the BS of WSP i

Signaling structure for SU-BS interaction

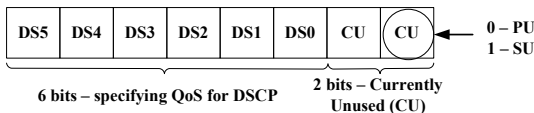
- **Initialization** - Advertisement of spectrum by the BSs and selection of the most suitable BS (WSP) by the SU
- **Authentication** - Verification over the SU database (registration required for potential SUs)
- **Connection Establishment** - in accordance to signaling in 4G



Novel DSCP based mechanism for PU-SU differentiation

Differentiated Service Code Point (DSCP)

- Byte in the IP header specifying the QoS requested by the user - defined by the IETF for Diffserv architecture
- Proposed use of a single bit (last bit) currently unused

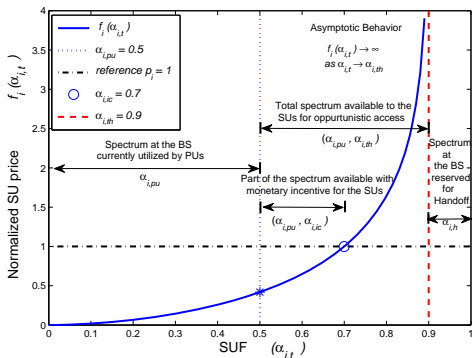


Advantages

- **Fast separation between PU and SUs** at the BS in comparison to identifying PU/SU based on IP or MAC address for the purpose of **pricing, authentication and billing**

Terminology

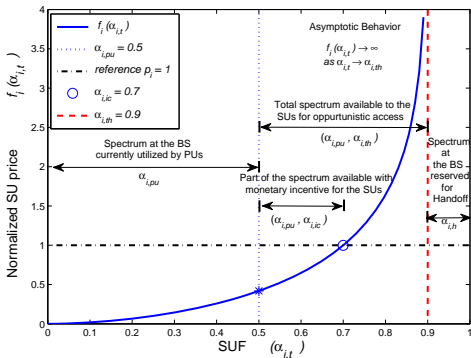
- **PU utilization** at the BS - $\alpha_{i,pu}$
- **SU utilization** at the BS - $\alpha_{i,su}$



- The SU price s_i related to **Spectrum Utilization Factor (SUF)** given as $\alpha_{i,t} = \alpha_{i,pu} + \alpha_{i,su}$ at the BS of WSP i , where $\alpha_{i,t}, \alpha_{i,pu}, \alpha_{i,su} \in [0, 1]$
- Amount of spectrum at the BS **reserved for handoff** - $\alpha_{i,h}$
- The amount of **usable spectrum** is limited to $\alpha_{i,th} = 1 - \alpha_{i,h}$
- **Incentive cutoff limit** - $\alpha_{i,ic}$

Pricing Model - Terminology (cont'd)

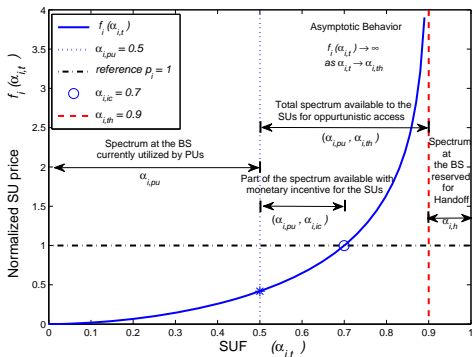
- **SU price** s_i , **PU price** p_i : e.g. price of 'Pay as you go' service
- Normalized SU price = s_i/p_i



- Prices per user per application class, i.e., ($\$/seconds$): **delay sensitive apps** and ($\$/bytes$): **delay insensitive apps**
- **BS configuration parameters** set by WSP i : $\alpha_{i,ic}, \alpha_{i,th}$
- Spectrum **currently occupied by PUs**: $[0, \alpha_{i,pu}]$
- Spectrum available for SUs with **monetary incentive**: $(\alpha_{i,pu}, \alpha_{i,ic})$
- Spectrum available for SUs with **monetary penalty**: $[\alpha_{i,ic}, \alpha_{i,th})$

Idea of incentive based SU pricing

- Inherent resource management at the BS such that $\lim_{\alpha_{i,t} \rightarrow \alpha_{i,th}} s_i = \infty$



- SU price s_i depends upon:
 - PU price p_i
 - SUF $\alpha_{i,t}$
 - PU demand $\alpha_{i,pu}$
 - BS configuration parameters $\alpha_{i,ic}$ and $\alpha_{i,th}$ set by WSP i
- Monetary incentive to SUs w.r.t. PU price when SUF is low, i.e., $s_i < p_i$ when $\alpha_{i,t} \in (\alpha_{i,pu}, \alpha_{i,ic})$, while monetary penalty when SUF is high, i.e., $s_i \geq p_i$ when $\alpha_{i,t} \in [\alpha_{i,ic}, \alpha_{i,th})$

SU price and log barrier function

SU price

$$s_i = f_i(\alpha_{i,t}) \times p_i, \quad (2)$$

where $s_i, f_i(\alpha_{i,t}), p_i$ are nonnegative real numbers

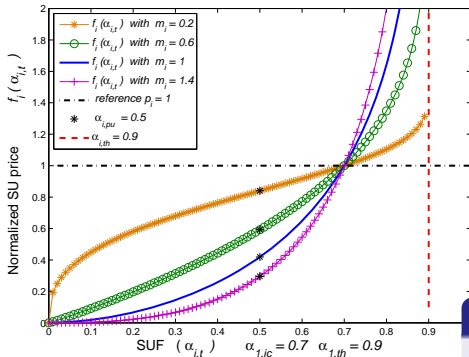
Normalized SU price - based on log barrier function [Convex Optimization, S. Boyd and L. Vandenberghe, '04]

$$f_i(\alpha_{i,t}) = -\ln \left(1 - \left(\frac{\alpha_{i,t}}{\alpha_{i,th}} \right)^{n_i} \right) \text{ if } \alpha_{i,t} < \alpha_{i,th} \quad (3)$$

$$f_i(\alpha_{i,t}) = \infty \quad \text{if } \alpha_{i,t} \geq \alpha_{i,th} \quad (4)$$

where n_i is a nonnegative real number, i.e., **Incentive Cutoff Factor (ICF)** found by rearranging (3) with $\alpha_{i,t} = \alpha_{i,ic}$ and $f_i(\alpha_{i,t}) = 1$.

Price Levelling Factor (PLF): m_i



- PLF provides **additional flexibility** to WSPs for **adjusting** the SU price

- With the **configuration parameters** $\alpha_{i,ic}$ and $\alpha_{i,th}$ fixed, WSPs can adjust the SU price to **achieve profit maximization** by tackling the following concerns:

- Costs** incurred by the WSPs
- Price competition** in a multiple WSP environment

Adjusted SU price \bar{s}_i

$$\bar{s}_i = f_i(\alpha_{i,t})^{m_i} \times p_i, \quad (5)$$

Price based handoff for SUs

- SU price may increase beyond the capability of SU due to:
 - Increase in PU demand
 - Change in location of SU
- Price based handoff provides the flexibility to the SU terminal to **handoff** to a **lower priced WSP** without compromising on the quality of service
- It is **assumed** that a **SNR based handoff is not required**
- Price based handoff can take place when the SU price for the next time interval t_2 increases over a cost threshold C_{th} ,

Price based handoff criterion

$$s_i(t_2) \geq (1 + C_{th}) \times s_i(t_1), \quad (6)$$

where C_{th} is a positive real number.

Conclusions and future work

- **Distributed framework** for DSA demonstrating the revenue potential for the WSPs and opportunity for SUs is presented.
- Potential for **harmonious operation of PUs and SUs** at the same BS with equivalent power levels is demonstrated.
- **Novel incentive based pricing model with inherent radio resource management** at the BS is developed.
- Distributed framework allows **standalone WSP** to provide SU access **without coordination with other WSPs through CMEs**.
- Proposed system can be considered as the **intermediate step** between **current infrastructure based networks** and the **cognitive networks of the future**.
- **Future work** involves equilibrium analysis for WSP profit maximization using the pricing model in a multiple WSP environment.