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

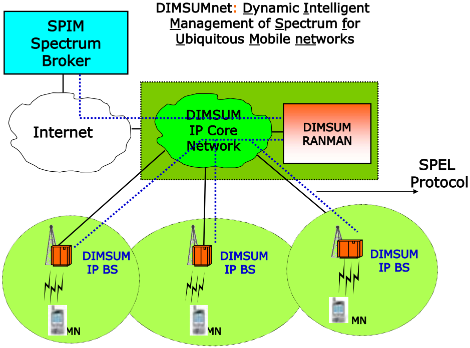
Spectrum or spectrum information pooling

- 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

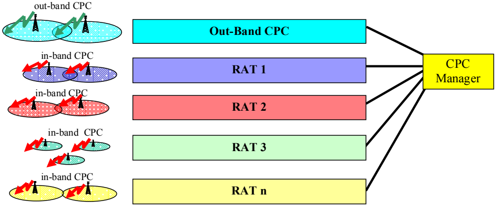
[DIMSUMnet, M. Buddhikot et al., '05]



- 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

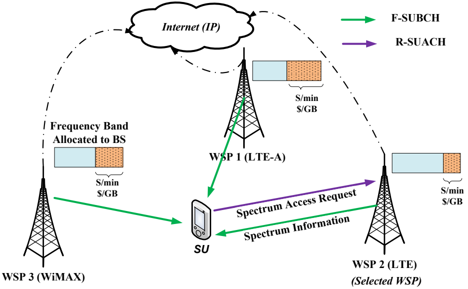
Pricing for SUs

- 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

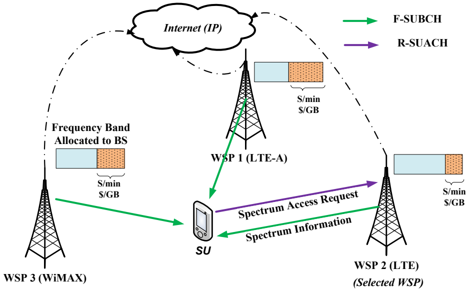
Proposed approach - key features



- Approach based on all-IP 4G framework

- The BS of every WSP *i* advertize their spectrum individually to the SUs in the area, with minimum changes to current infrastructure
- Harmonious operation of PUs and SUs 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

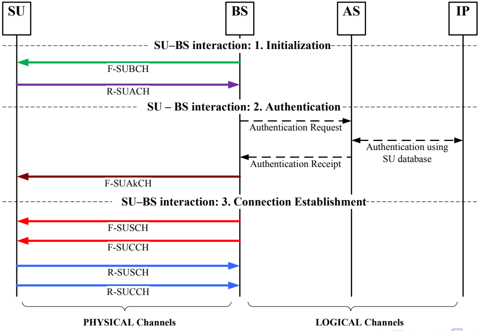
Autonomous network selection metric calculated at SU terminal

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

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

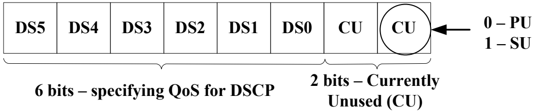
- Initialization - Advertisement of spectrum by the BSs and selection of the most suitable BS (WSP) by the SU
- Authentication - Verification over the SU database (registration required for potential SUs)
- Connection Establishment - in accordance to signaling in 4G



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

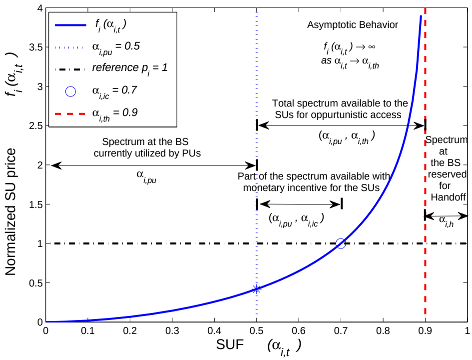


Advantages

- 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

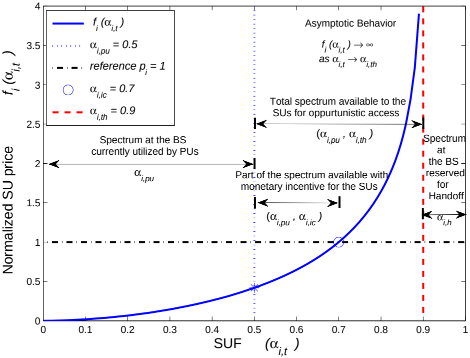
- PU utilization at the BS - $\alpha_{i,pu}$
- SU utilization at the BS - $\alpha_{i,su}$



- 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)

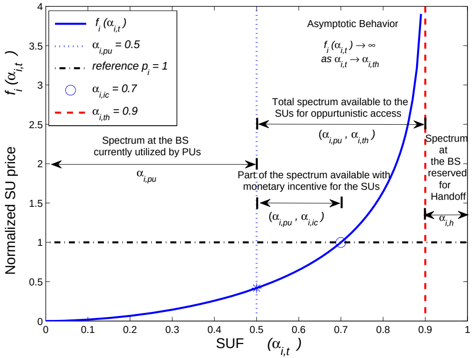
- SU price s_i, PU price p_i: e.g. price of 'Pay as you go' service
- Normaized SU price $= s_i/p_i$



- 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

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

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

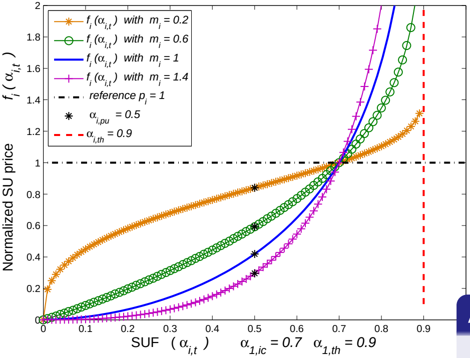
Normalized SU price - based on log barrier function [Convex Optimization, S. Boyd and L. Vandenberghe, '04]

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

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

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



- 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 $\bar{s}_i$

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

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

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.