A Distributed Framework with a Novel Pricing Model for Dynamic Spectrum Access to Secondary Users in Infrastructure based Wireless Networks

MASc Thesis Defence

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January 8, 2010

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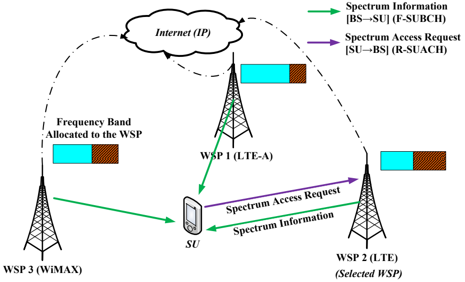
Introduction

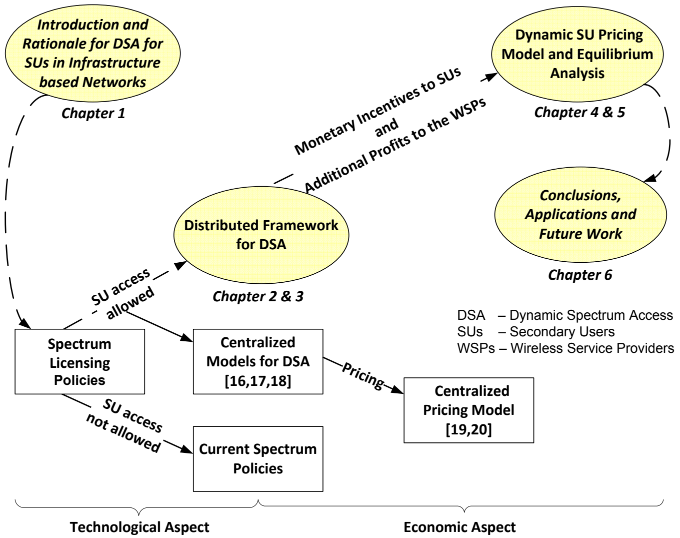
- Underutilization of the radio spectrum with respect to time and location: field measurements [1, 2].
- Dynamic Spectrum Access (DSA) techniques: intelligent and efficient use of the radio spectrum by allowing opportunistic unsubscribed Secondary User (SU) access [2-7].
- Cognitive Radios (CRs) and Software Defined Radios (SDRs): enablers for DSA with the ability for cognition and reconfigurability [3-7].
- Infrastructure based networks, the Wireless Service Providers (WSPs) by implementing DSA techniques, can potentially gain additional profits by providing access to SUs [9-11, 14-22].

Network Scenario for a SU and Thesis Goal



- Providing unsubscribed SU access
- Distributed framework (without inter-WSP co-operation) with Base Stations (BSs) broadcasting local spectrum information to the SUs
- Minimum modifications to existing infrastructure
- No deterioration to the subscribed Primary User (PU) service
- Additional profits to the WSPs in the area from SU access

Presentation Outline



Thesis Contributions (1/2)

- Distributed system framework: orthogonal coexistence of PUs and SUs at the same BS
- Chapter 2: Contributions for proposed modifications at BS
  - Signaling framework for SU access
  - SU identification at the BS based on the Differentiated Service Code Point (DSCP) byte present in the IP header
  - Structure for resource management at the BS
- Chapter 3: Contributions at the SU terminal
  - Autonomous network (BS) selection criterion
  - Price-based handoff scheme

Thesis Contributions (2/2)

- Chapter 4: Dynamic incentive based SU pricing model
  - Opportunistic SU pricing
  - SU price based on PU demand at the BS, PU price and the Spectrum Utilization Factor (SUF) at the BS
  - Inherent SU admission control
- Chapter 5: Competitive Inter-WSP pricing
  - Equilibrium analysis and differentiation of SU wireless service
  - Demonstrate the profitability potential to WSPs from SU access

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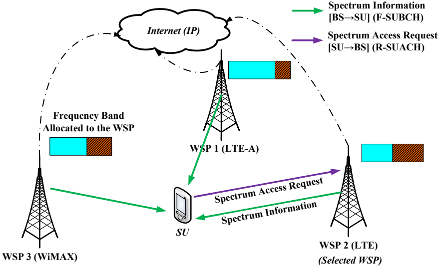
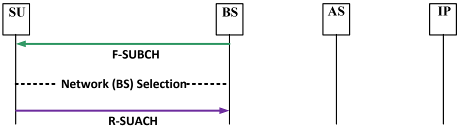
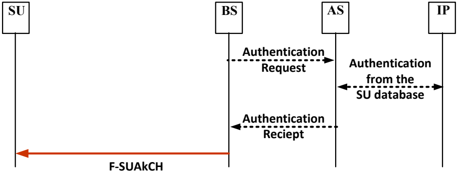
Signaling Framework for Unsubscribed SU access





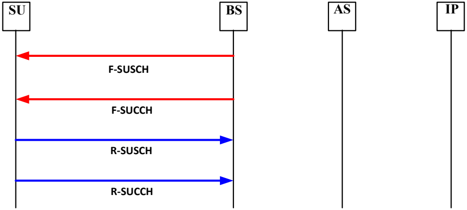
- Forward link SU Broadcast Channel (F-SUBCH): Sending spectrum information at the BS to the SUs in the coverage area.
- Selection of the most appropriate Base Station (BS) autonomously at the SU terminal based on the SU price and signal strength (Chapter 3).
- Reverse link SU Access Channel (R-SUACH): Spectrum Access Request (SAReq) to be sent by the SUs over this channel along with the channel state information.

Signaling Framework: Authentication



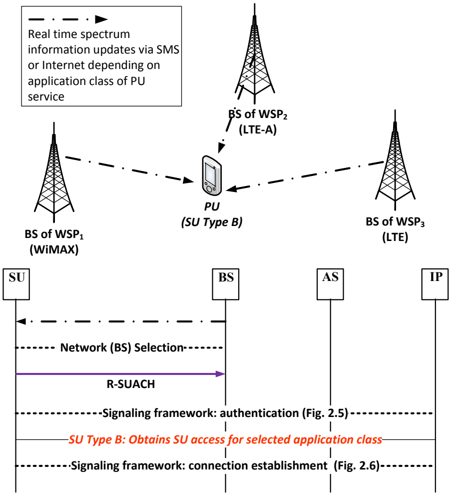
- SUs are required to be preregistered to a SU online database.
- Online database accessible to Authentication Server (AS) at the WSP.
- Forward link SU Acknowledgment Channel (F-SUAkCH): Channel useful for the BSs to send acknowledgment information and temporary wireless service contract to the authenticated SUs.

Signaling Framework: Connection Establishment



- Forward link SU Shared Channel (F-SUSCH): Downlink data transmission from BS to SU.
- Forward link SU Control Channel (F-SUCCH): Downlink control information from BS to SU
- Similar Channels for uplink (R-SUSCH and R-SUCCH).
- These channels post connection establishment will be in accordance with LTE [12] or WiMAX [13].

SU Type B: PUs temporarily converted to SUs

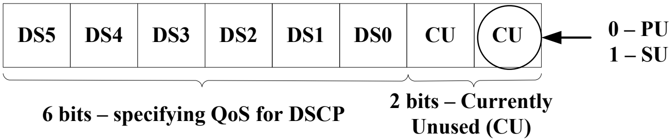


- PUs may obtain temporary service from any WSP in the area to any other application classes they are not primarily subscribed to, by temporarily converting into SUs.
- Real time spectrum updates obtained via SMS or internet (e.g. using Twitter [23]) will help save power at the SU terminal required for scanning the frequency bands in the region to obtain spectrum information from the BSs of various WSPs.

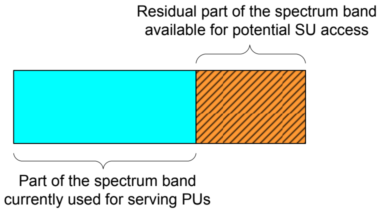
SU Identification based on DSCP Byte

- Mechanism helpful for authentication, billing and resource management at the BS
- Differentiated Service Code Point (DSCP) byte present in the IP header: Quality of Service (QoS) for a user in Diffserv architecture [24].
- Two rightmost bits of the DSCP byte are currently unused, and are default set to 0.
- SU packet identification proposed by setting the rightmost byte to 1.

DSCP byte with the proposed modification



Resource Management at the BS



- No deterioration to PU service
- Resources available to SUs: based on residual spectrum at the BS after all the PUs have been served
- First: allocate resources to provide satisfactory QoS to the PUs
- Residual Spectrum: resources allocated to SUs
- No guarantee for QoS to SUs in all circumstances, but whenever PU demand at BS is low

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- Chapter 2: Proposed Modifications at the BS
- Chapter 3: SU Terminal Initiated Network Selection and Price-based Handoff
- Chapter 4: Dynamic Incentive based SU Pricing Model
- Chapter 5: Competitive Inter-WSP Pricing
- Chapter 6: Conclusions and Future Work

Autonomous Network (BS) Selection

- SUs select BSs instead of WSPs, since BSs transmit their local spectrum information to the SUs in the coverage area
- SU Centric Approach: SU terminals autonomously select the most suitable BS based on:
  - SU price ($s_{i,j}$) quoted by BS_i for application class j
  - Signal strength, i.e., average achievable link spectral efficiency (η_i)
  - SU application class requirements
  - RATs supported by the SU terminal

Notations

- $A_{o,i} = \{j | j \in \mathbb{N}, j \leq m\}$: Application classes offered by the WSP to the SUs.
- $A_r = \{j | j \in \mathbb{N}, j \leq n\}$: Application classes requested by the SU for temporary wireless access.
- $B_{sl} = \left\{ BS_i : s_{i,j} = \min \left(\sum_{j \in A_r, j=1}^{n} s_{1,j}, \sum_{j \in A_r, j=1}^{n} s_{2,j}, \ldots, \sum_{j \in A_r, j=1}^{n} s_{w,j} \right) \right\}$ denotes the short list of BSs, which provide the temporary wireless access for application classes requested by the SU (A_r) at the same minimum SU price.
- $\mathcal{R}_{\mathcal{B}}$: Set of Radio Access Technologies (RATs) x supported by the BS_i, where x is the index of the RAT.
- $\mathcal{R}_{\mathcal{S}}$: Set of RATs supported at the SU terminal.
- Also $s_{i,j} = M$ (very large) if $j \in A_r$, but $j \notin A_r \bigcap A_{o,i}$.

Network (BS) Selection Criterion

General BS Selection Criterion

$$i^* = \begin{cases} B_{i,x} \times \left(\prod_{j \in A_r, j=1}^{n} I_{i,j} \right) \times \left(\arg \min_{i=1,2,\ldots,w} \left(\sum_{j \in A_r, j=1}^{n} s_{i,j} \right) \right), & \text{if } \exists! \; i^*, \\ B_{i,x} \times \left(\prod_{j \in A_r, j=1}^{n} I_{i,j} \right) \times \left(\arg \max_{i \in B_{sl}} (\eta_i) \right), & \text{otherwise}, \end{cases}$$

where

$$I_{i,j} = \begin{cases} 1, & \text{if } j \in A_r \bigcap A_{o,i}, \\ 0, & \text{otherwise}, \end{cases}$$

$$B_{i,x} = \begin{cases} 1, & \text{if } x \in \mathcal{R}_{\mathcal{B}} \bigcap \mathcal{R}_{\mathcal{S}}, \\ 0, & \text{otherwise}. \end{cases} \quad (1)$$

Price-based Handoff Scheme

- SU price changes dynamically w.r.t. spectrum utilization at the BS (Chapter 4).
- The SU price thus may changes from one time window (T_1) (preset by WSP, e.g., 10 minutes) to the next time window (T_2).

Handoff Criterion

$$\frac{s_{i,j}(T_2) - s_{i,j}(T_1)}{s_{i,j}(T_1)} \geq C_{th}, \qquad (2)$$

where C_{th} is a non-negative real number.

- C_{th} (SU defined parameter): Handoff triggered whenever (2) is satisfied.
- Allows the SU to select the most suitable and least expensive network in every time window.
- Regular handoff is assumed to be not required.
- C_{bd} (SU defined parameter): Allows the SU to disconnect, if prices for all BSs for T_2 are beyond the affordable price of the SU.

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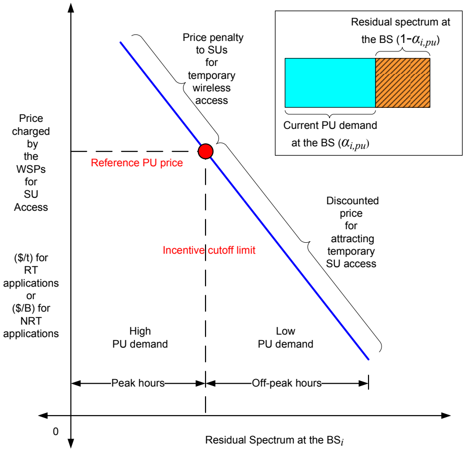
Rationale for SU Pricing



- Dynamic pricing for SUs: SU price based on PU demand ($\alpha_{i,pu}$), SUF ($\alpha_{i,t}$) at the BS and PU price ($p_{i,j}$)
- Inherent SU admission control: log barrier function
- Opportunistic: Price for each new SU entering the BS is thus different
- Incentive: $s_{i,j} < p_{i,j}$
- Attract SUs when PU demand is low

Incentive based 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 $\alpha_{i,pu} < \alpha_{i,th}$.
- $\alpha_{i,t}$: 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 Pricing w.r.t. PU price ($p_{i,j}$) and SUF ($\alpha_{i,t}$) at the BS

$$\bar{s_{i,j}} = (f_{i,j}(\alpha_{i,t}))^{m_{i,j}} \times p_{i,j}, \tag{3}$$

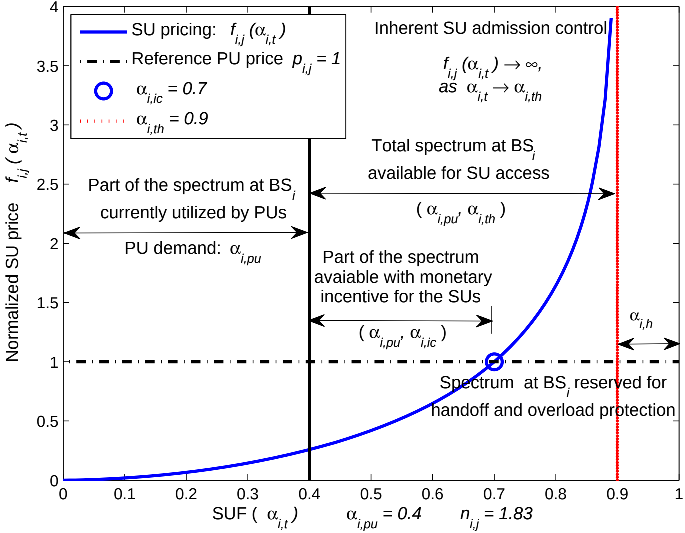
where $m_{i,j}$ is the exponent of $f_{i,j}(\alpha_{i,t})$ and is a non negative real number.

Normalized SU price [31]

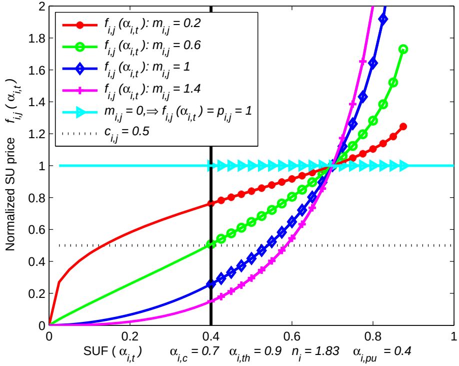
$$f_{i,j}(\alpha_{i,t}) = \begin{cases} -\ln\left(1 - \left(\frac{\alpha_{i,t}}{\alpha_{i,th}}\right)^{n_{i,j}}\right), & \text{if } 0 \leq \alpha_{i,t} < \alpha_{i,th}, \\ \infty, & \text{if } \alpha_{i,th} \leq \alpha_{i,t} \leq 1, \end{cases} \tag{4}$$

where $n_{i,j}$ is a positive real number representing the exponent in $f_{i,j}(\alpha_{i,t})$ referred to as the Incentive Cutoff Factor (ICF).

Variable Nature of the SU Pricing Model



Price Leveling Factor (PLF)



- WSP configuration parameters: $\alpha_{i,th}$ and $\alpha_{i,ic}$.

- Provides additional flexibility to the WSPs for adjusting their dynamic prices.
- SU prices may need to be adjusted for
  - ensuring profits
  - competing with the other regional WSPs
- $m_{i,j} = 0$ gives static pricing with $s_{i,j} = p_{i,j}$
- $c_{i,j} = 0.5$ is fixed cost here, and $m_{i,j} = 0.6, 0.2$ can ensure no loss to WSP for each SU served.

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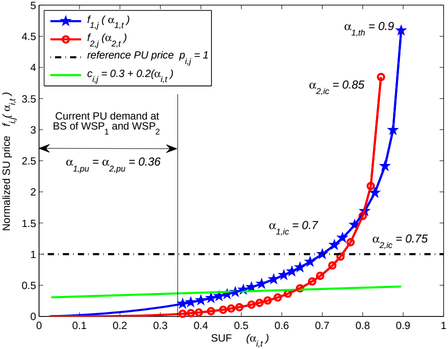
Competitive Pricing among Multiple WSPs

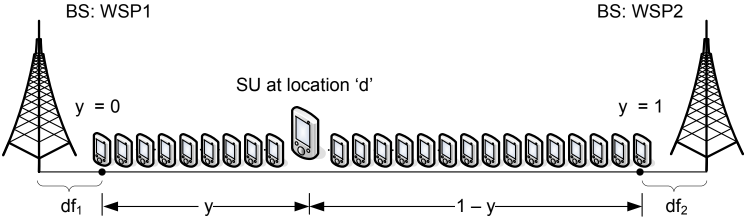


- Competitive SU pricing among regional WSPs essential for individual WSP profits
- Achieving competitive pricing very difficult with dynamically changing SU price
- Equilibrium analysis with static prices and SU service differentiation based on the wireless channel: intermediate step to achieve competitive dynamic pricing

Strategy for Competitive Inter-WSP Pricing

- SU service differentiation based on the wireless channel (Thesis: Section 5.3 and Section 5.4.1)
- Equilibrium analysis with static pricing based on SU service differentiation (Thesis: Section 5.4.2)
- Implementation of static NE SU price obtained from the above equilibrium analysis onto the proposed dynamic pricing model using the PLF (Thesis: Section 5.4.3)

Equilibrium Analysis and the Differentiation of SU service



- Identical product or service → high competition, low or zero profits
- Differentiation of product or service → low competition, higher profits
- Differentiation of the SU wireless service represented by the Dissatisfaction Price (ζ) based on the variance of the wireless channel; $\zeta = K_1 K_2$ (\$), where $K_1 = 1$ (\$); $K_2 = \left(\frac{\sigma_1+\sigma_2}{2}\right)$ [32-34].
- Perceived price to each SU: $U_{i,j}(y) = S_{i,j} + (\zeta \times y)$ (\$)

Transformation for Achieving Competitive Pricing

- Nash Equilibrium (NE) SU price ($S^*_{i,j} = C_{i,j} + \zeta$) mapped onto dynamic incentive based pricing model using PLF $m_{i,j}$.

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

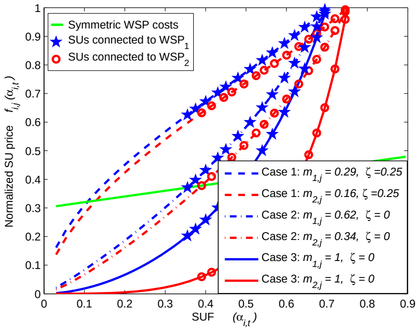
$$\bar{s_{i,j}} = (f_{i,j}(\alpha_{i,t}))^{m_{i,j}} \times p_{i,j}. \qquad (5)$$

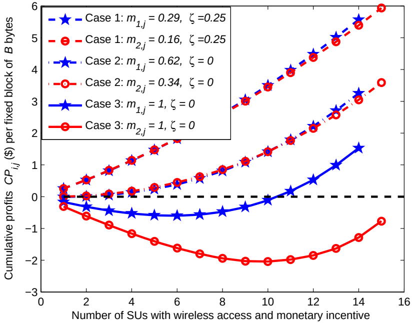
- $S^*_{i,j} = \bar{s_{i,j}}$ mapped to price for the first SU entering the BS at $\alpha_{i,t} = \alpha_{i,pu}$ by rearranging (5) as follows:

Value of $m_{i,j}$

$$m_{i,j} = \frac{\ln\left(\frac{S^*_{i,j}}{p_{i,j}}\right)}{\ln(f_{i,j}(\alpha_{i,pu}))}. \qquad (6)$$

Scenario: Similar PU Demand and Symmetric Costs

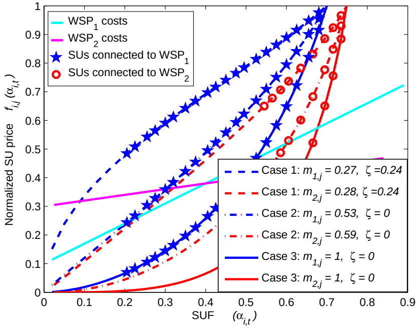


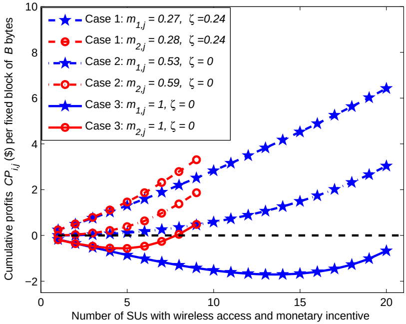


- $\alpha_{1,pu} = 0.36,\ \alpha_{2,pu} = 0.39$
- $c_{i,j} = 0.3 + 0.2(\alpha_{i,t})$

- Competitive SU prices and competitive WSP profits

Scenario: Dissimilar PU Demand and Asymmetric Costs





- $\alpha_{1,pu} = 0.22$, $\alpha_{2,pu} = 0.52$
- $c_{1,j} = 0.3 + 0.2(\alpha_{i,t})$,
  $c_{2,j} = 0.1 + 0.7(\alpha_{i,t})$

- Prices and WSP profits still highly competitive in this extreme scenario

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Conclusions

- Distributed system framework for enabling unsubscribed SU access in infrastructure based networks with minimum modifications to existing infrastructure.
- Mutual benefit of temporary wireless access to the SUs and additional profits to WSPs, without deterioration to the subscribed PU service.
- Dynamic incentive based pricing model and Competitive inter-WSP pricing demonstrating the profitability potential to the WSPs from SU access.
- Opportunity for individual WSPs to provide SU access without need for inter-WSP cooperation.

"Intermediate step between current infrastructure based networks and cognitive networks of the future"

Future Work

- Advancements in the signaling framework from the standardization perspective
- PU-SU resource management: throughput and fairness analysis
- End-to-end simulations for network selection and handoff
- Pricing model extended to handle multiple application classes at the BS
- Equilibrium analysis to access multiple (more than two) WSP scenario
- Extension of the dynamic pricing model to provide SU access in multi-hop networks

References (1/9)

1. M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, "Chicago spectrum occupancy measurements & analysis and a long-term studies proposal," in *TAPAS '06: Proceedings of the first international workshop on Technology and policy for accessing spectrum*. New York, NY, USA: ACM, 2006, p. 1.
2. Spectrum Policy Task Force, "Spectrum policy task force report," Federal Communications Commission, Tech. Rep. ET Docket No. 02-135, November 2002. [Online]. Available: `http://www.fcc.gov/sptf/reports.html`
3. Q. Zhao and B. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.

References (2/9)

4. I. Akyildiz, W.-Y. Lee, M. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, April 2008.
5. M. Buddhikot, "Understanding dynamic spectrum access: Models,taxonomy and challenges," in *Proc. of IEEE DySPAN*, April 2007, pp. 649–663.
6. J. Mitola, III and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, August 1999.
7. S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, February 2005.

References (3/9)

8. [Online]. Available: http://www.gsmarena.com/, website accessed: October 2009 - January 2010.
9. J. M. Peha and S. Panichpapiboon, "Real-time secondary markets for spectrum," *Telecommunications Policy*, vol. 28, no. 7-8, pp. 603–618, August 2004.
10. A. Attar, O. Holland, M. Nakhai, and A. Aghvami, "Interference-limited resource allocation for cognitive radio in orthogonal frequency-division multiplexing networks," *IET Communications*, vol. 2, no. 6, pp. 806–814, July 2008.
11. D. Niyato and E. Hossain, "Market-equilibrium, competitive, and cooperative pricing for spectrum sharing in cognitive radio networks: Analysis and comparison," *IEEE Transactions on Wireless Communications*, vol. 7, no. 11, pp. 4273–4283, November 2008.

References (4/9)

12. P. Lescuyer and T. Lucidarme, *Evolved Packet System (EPS): The LTE and SAE Evolution of 3G UMTS*. Wiley, 2008.
13. J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking*. Prentice Hall, 2007.
14. J. Chapin and W. Lehr, "Cognitive radios for dynamic spectrum access - the path to market success for dynamic spectrum access technology," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 96–103, May 2007.
15. M. Marcus, "Real time spectrum markets and interruptible spectrum: new concepts of spectrum use enabled by cognitive radio," in *Proc. of IEEE DySPAN*, November 2005, pp. 512–517.

References (5/9)

16. T. Weiss and F. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE Communications Magazine*, vol. 42, no. 3, pp. S8–14, March 2004.
17. M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum," in *Proc. of WoWMoM*, June 2005, pp. 78–85.
18. J. Perez-Romero, O. Salient, R. Agusti, and L. Giupponi, "A novel on-demand cognitive pilot channel enabling dynamic spectrum allocation," in *Proc. of IEEE DySPAN*, April 2007, pp. 46–54.
19. O. Ileri, D. Samardzija, and N. Mandayam, "Demand responsive pricing and competitive spectrum allocation via a spectrum server," in *Proc. of IEEE DySPAN*, November 2005, pp. 194–202.

References (6/9)

20. J. Acharya and R. Yates, "Resource and power costs in dynamic spectrum allocation," in *Proc. of CISS*, March 2008, pp. 938–943.
21. P. Cordier, P. Houze, S. B. Jemaa, O. Simon, D. Bourse, D. Grandblaise, K. Moessner, J. Luo, C. Kloeck, K. Tsagkaris, R. Agusti, N. Olaziregi, Z. Boufidis, E. Buracchini, P. Goria, and A. Trogolo, "E2R cognitive pilot channel concept," in *15th IST Mobile and Wireless Communications Summit*, June 2006.
22. Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in Ad Hoc networks: A POMDP framework," *IEEE Selected Areas in Communications*, vol. 25, no. 3, pp. 589–600, April 2007.
23. J. Comm and K. Burge, *Twitter Power: How to Dominate Your Market One Tweet at a Time*. John Wiley & Sons, 2009.

References (7/9)

24. S. Vegesna, *IP Quality of Service*. Cisco Press, 2001.
25. H. Al-Zubaidy, I. Lambadaris, and I. Viniotis, “Optimal resource scheduling in wireless multiservice systems with random channel connectivity,” in *Proc. of IEEE Globecomm*, December 2009.
26. X. Liu, E. K. P. Chong, and N. B. Shroff, “A framework for opportunistic scheduling in wireless networks,” *Computer Networks*, vol. 41, no. 4, pp. 451 – 474, 2003.
27. J. Perez-Romero, O. Sallent, and R. Agusti, “A novel metric for context-aware RAT selection in wireless multi-access systems,” in *Proc. of IEEE ICC*, June 2007, pp. 5622–5627.
28. O. Sallent, J. Perez-Romero, R. Ljung, P. Karlsson, and A. Barbaresi, “Operator’s RAT selection policies based on the fittingness factor concept,” in *16th IST Mobile and Wireless Communications Summit*, July 2007, pp. 1–5.

References (8/9)

29. F. Bari and V. C. Leung, "Automated network selection in a heterogeneous wireless network environment," *IEEE Network Magazine*, vol. 21, no. 1, pp. 34–40, Jan.-Feb. 2007.
30. A. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, Oct 1997.
31. S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K: Cambridge University Press, 2004.
32. R. Barnes, *Ecomonic Analysis, An Introduction*. London, U.K: Butterworth & Co. Ltd., 1971.
33. B. Polak, *Game Theory Lecture Notes*. Yale University open courses, 2007. [Online]. Available: `http://oyc.yale.edu/economics/game-theory`

References (9/9)

34. P. K. Dutta, *Strategies and Games: Theory and Practice*. The MIT Press, 1999.
35. R. S. Khemani and D. M. Shapiro, *Glossary of Industrial Organization Economics and Competition Law*. Directorate for Financial, Fiscal and Enterprise Affairs, Organization for Economic Co-operation and Development (OECD), 1993.
36. D. Niyato and E. Hossain, "Microeconomic models for dynamic spectrum management in cognitive radio networks," in *Cognitive Wireless Communication Networks*, E. Hossain and V. Bhargava, Eds. Springer US, 2007, pp. 391–423.
37. 3GPP TR 36.942 v1.2.0, "E-UTRA Radio Frequency (RF) system scenarios (Release 8)," June 2007.