A Revenue Enhancing Stackelberg Game for Owners in Opportunistic Spectrum Access

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Motivation

- Worst case scenario allocations result in under-utilization of the spectrum
- Opportunistic spectrum access (OSA) proposed for better utilization
- Opponents of OSA:
  - Impossible to utilize vacancies w/o interfering primaries
  - Owner will not allow OSA not to lose her customers
- Our viewpoint:
  - Spectrum is a valuable economical commodity
  - Underutilization = loss in revenues
- Goal: Show that spectrum owner can enhance revenues by adopting OSA

Previous Work

- [Neel et al. 2005, Nie and Comaniciu 2006, Bloem et al. 2007, Stanojev et al. 2007,…]: strategic behaviors for cognitive radio networks using game theory
  - Not in economical perspective
- [Niyato and Hossein 2007, 2008]: revenue maximization and pricing problems for spectrum owners
  - Interference from secondary users not considered
- [Mutlu et al. 2008] takes interference into account
  - The primary and secondary users use same protocol
- Our work is first one to
  - Show economical incentives for spectrum owners under OSA model
  - Secondary users follow a non-perfect listen-before-send strategy

Outline

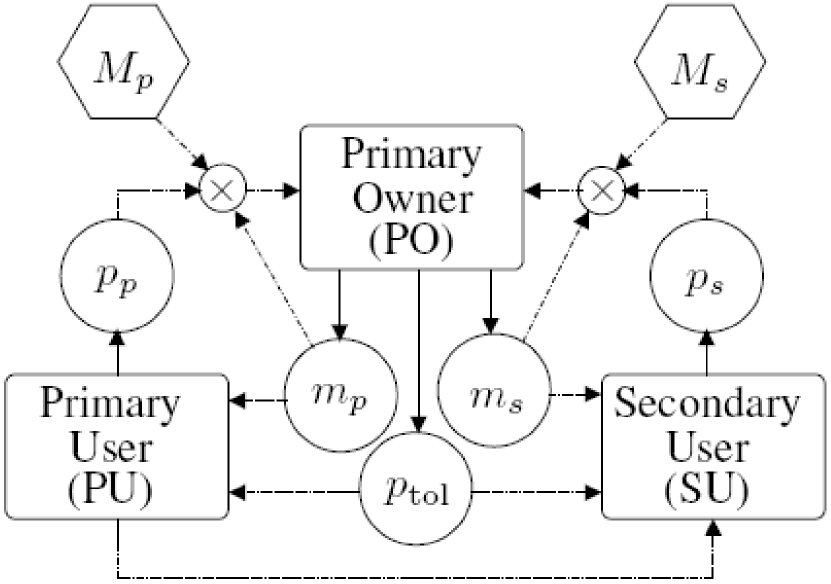
- Setup and assumptions
  - Stackelberg game model
  - Secondary user model
  - Primary user model
  - Primary (spectrum) owner model
- Simulations

Stackelberg Game Model

- Opportunistic spectrum access in time dimension
  - One channel with capacity C
- User utility measured with throughput
- Primary (secondary) user willing to pay 1$ per α ($K\alpha$) bits communicated (K>1)
- Channel utilized x% of the time → throughput achieved = xC

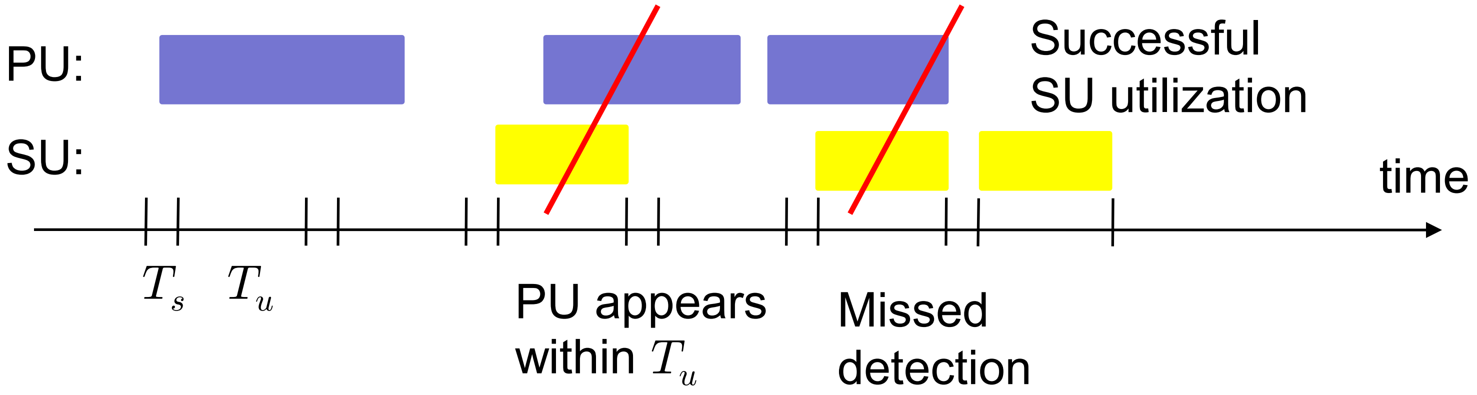
Stackelberg Game Model

- Primary (secondary) users pay subscription fee m_p (m_s)
- Maximum interference probability tolerated: p_{tol}
- Primary owner sets m_p, m_s and p_{tol}
- Primary (secondary) users buy service w.p. p_p (p_s)
- Primary owner optimizes for maximum revenues



Secondary User Model [Motamedi & Bahai, 2008]

- Secondary network is assumed to act as a single body
- Slots of deterministic length $T_s + T_u$
- Attempt sensing w.p. p_a, if attempted, sense for T_s
- If idle, utilize for T_u



Secondary User Model [Motamedi & Bahai, 2008]

- Interference probability:

$$p_{\text{int}} = p_a(1-p_{\text{D}})\text{P}(\mathcal{H}_1)+p_a(1-p_{\text{FA}})\text{P}(\mathcal{H}_0)(1-\exp(-T_u/I))$$

False alarm probability

Probability of detection of the primaries

- Utilization: $U_s = p_a\text{P}(\mathcal{H}_0)(1-p_{\text{FA}})\exp(-T_u/I)\dfrac{T_u}{T_u+T_s}$
- Secondary user optimization:

$$\begin{aligned} &\underset{T_u,p_a}{\text{maximize}} \;\; U_s \\ &\text{subject to} \;\; p_{\text{int}} \le p_{\text{tol}} \\ &\qquad\quad \text{and} \;\; 0 \le p_a \le 1. \end{aligned}$$

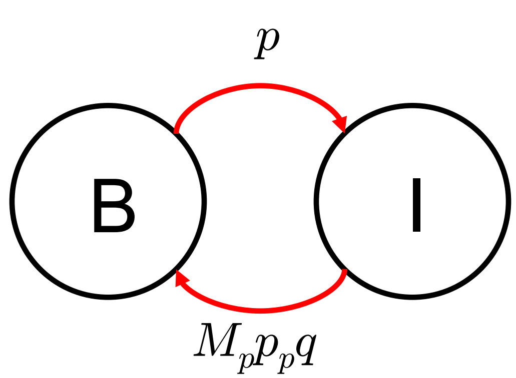
- At equilibrium: $\dfrac{CU_s}{M_s p_s} = K\alpha m_s \;\rightarrow\; p_s = \dfrac{CU_s}{M_s K \alpha m_s}$

Primary User Model

- A primary user generates (ends) calls at a rate q (p)
- Channel is busy (idle) with mean 1/p (1/$M_p p_p q$)
- Average throughput scales by (1-p_{tol})
- Equilibrium:

$$C(1 - p_{\text{tol}})\frac{q}{p + M_p p_p q} = \alpha m_p,$$

$$p_p = \frac{1}{M_p q}\left(\frac{C(1 - p_{\text{tol}})q}{\alpha m_p} - p\right)$$



Primary Owner Model

- Revenue:

$$R = M_p p_p m_p + M_s p_s m_s$$
$$= M_p p_p m_p + \frac{CU_s}{K\alpha},$$

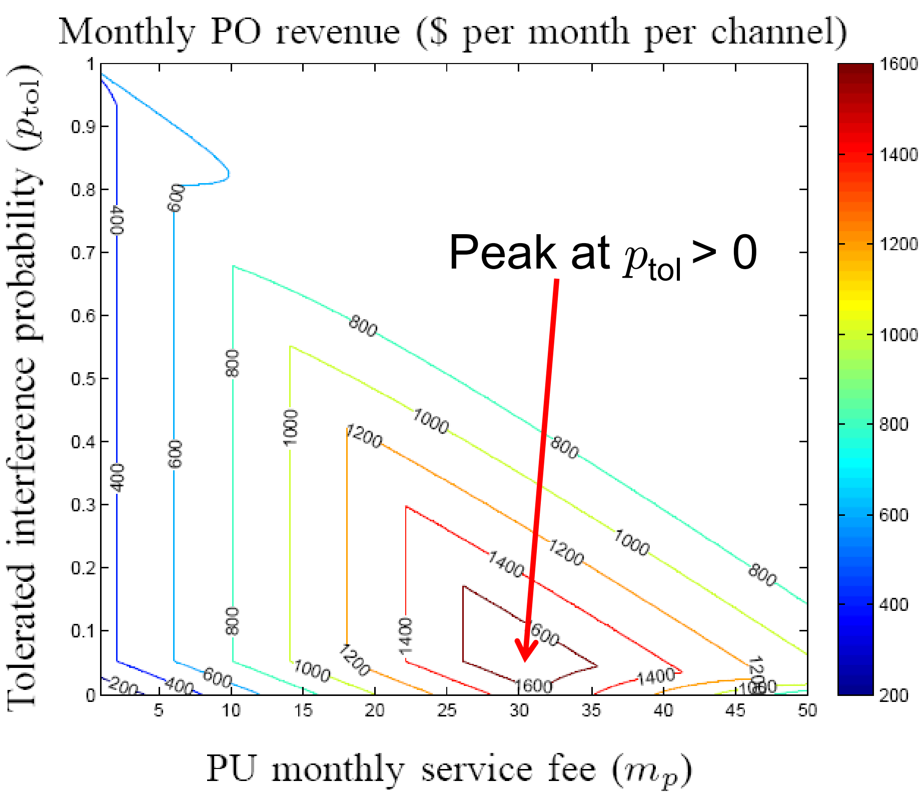
- Second line: w/o effecting revenue, set:

$$p_s = 1 \qquad m_s = \frac{CU_s}{M_s K\alpha}$$

- Optimization problem:

$$\begin{aligned} &\underset{p_{\text{tol}}, m_p}{\text{maximize}} \; R \\ &\text{subject to } \; 0 \le p_{\text{tol}} \le 1 \\ &\qquad \text{and } \; 0 \le m_p. \end{aligned}$$

Simulations



Parameter	Explanation	Value
C	Channel capacity	50 kbps
M_p	Number of potential PUs	50
M_s	Number of potential SUs	50
$B = 1/p$	Mean channel busy time	180s
q	PU call generation rate	10 per day
α	Value of $1 in bits for a typical PU	5 MB/$
K	Value of primary service relative to secondary	5
p_D	PU detection probability (by SU)	0.9
p_{FA}	False alarm probability (by SU)	0.01
T_s	Sensing time for PU detection	10 ms

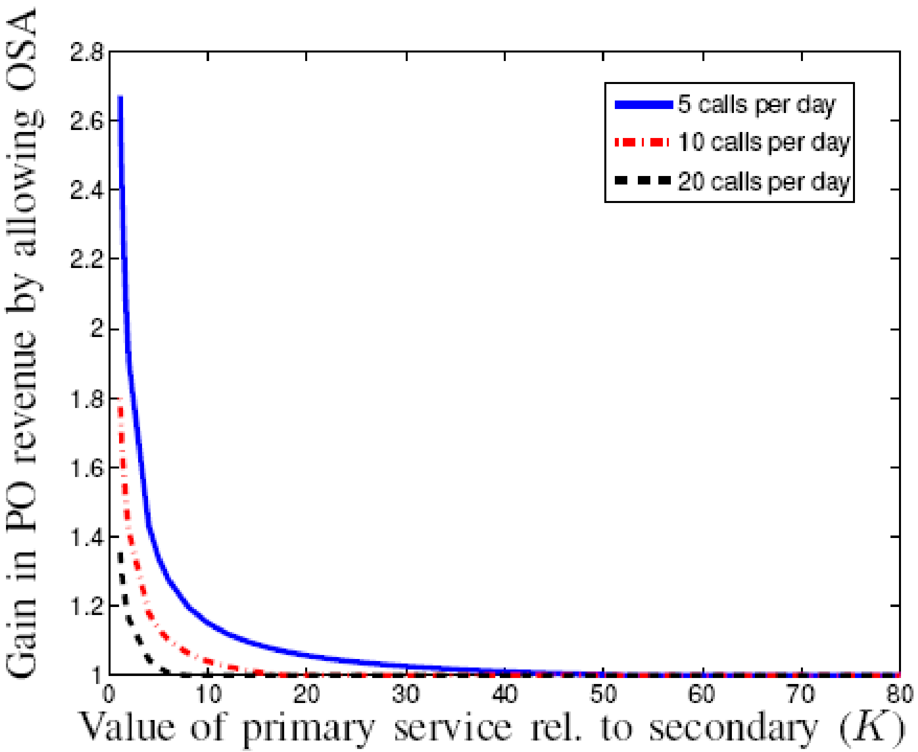
Optimal	w/OSA	w/o OSA
p_{tol}	5.31%	–
m_p (monthly)	$29.84	$31.5
m_s (monthly)	$5.89	–
PO revenue (monthly, per channel)	$1,786.4	$1,575.4
SU utilization	47.6%	–
PU acceptance prob. (p_p)	1	1

PU utilization: 51%, SU utilization: 47.6%, total: 98.6%

Primary owner revenues enhanced, by allowing OSA

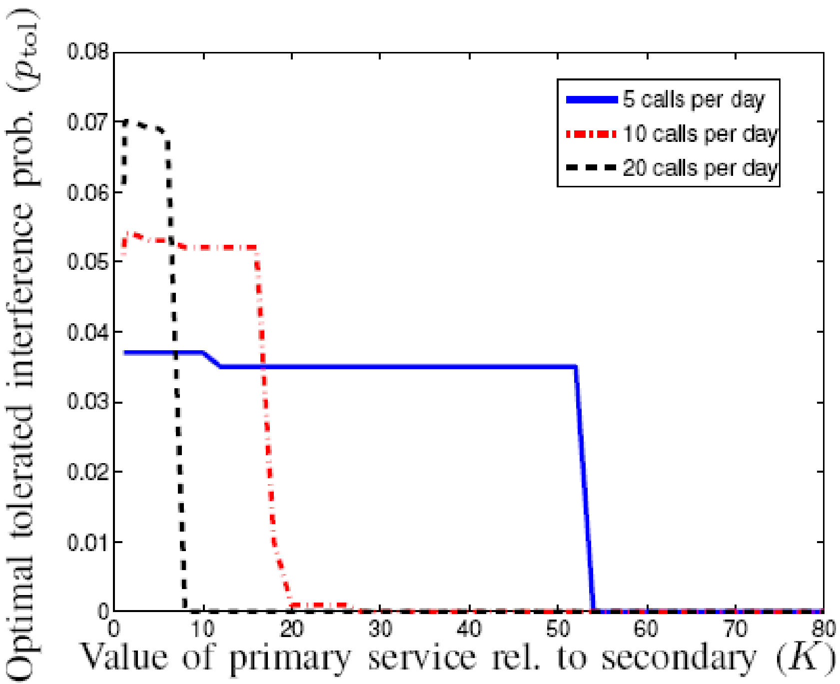
Gain in Revenue vs. K

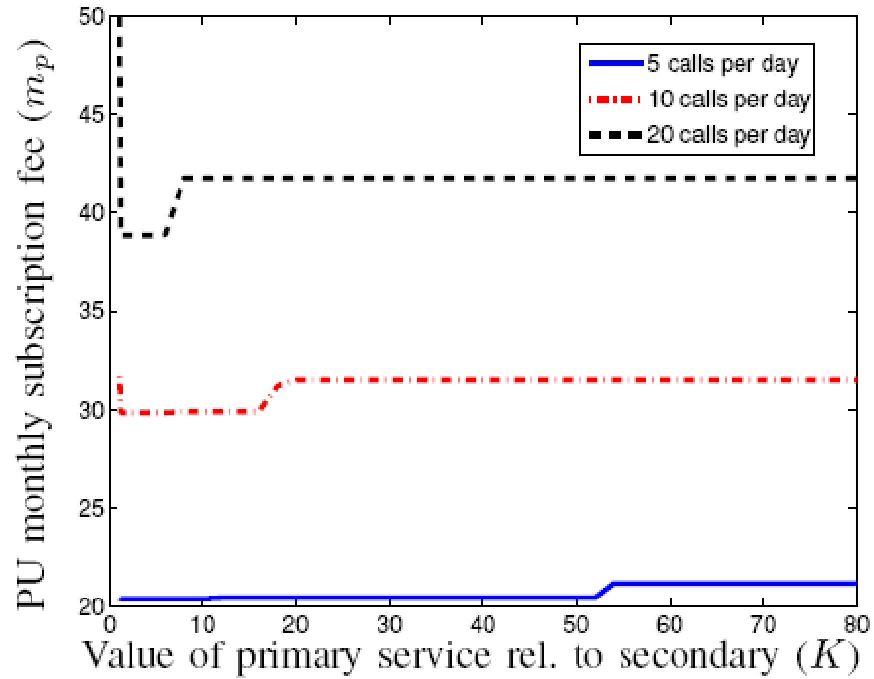
- K is the value of primary service relative to secondary
- Can be found by surveys
  - Results in a confidence interval
- Spectrum owner's questions
  - For what range of K values is OSA profitable?
  - How sensitive are my actions against K?



Primary owner revenues increase for a large range of K values

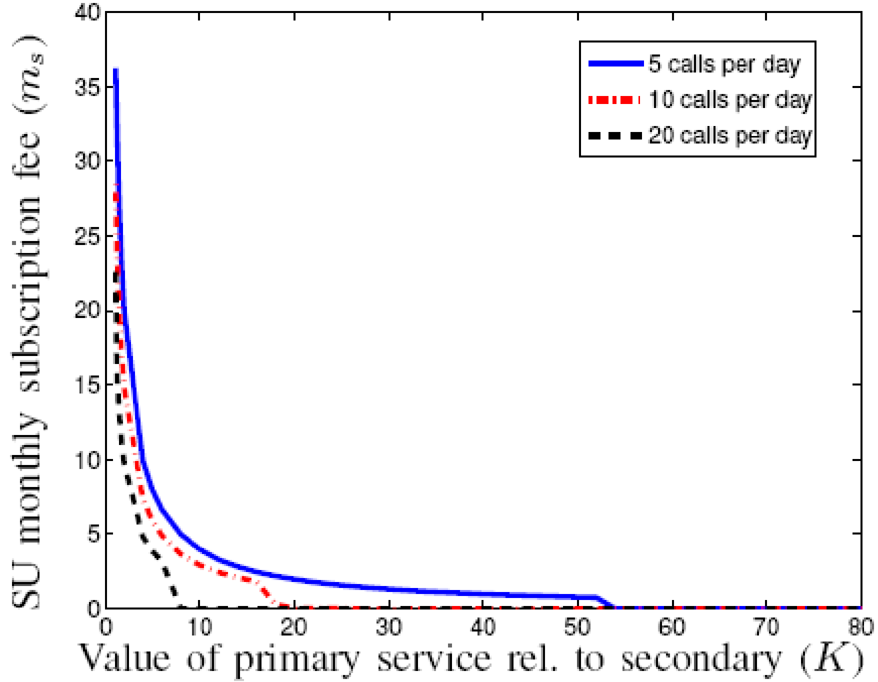
Max Tolerated Interference and Primary Service Fee vs. K





Primary owner actions p_{tol} and m_p show little sensitivity against K

Secondary Service Fee vs. K



$$p_s = 1,\ m_s = \frac{CU_s}{M_s K \alpha}$$

Robustness of primary owner action m_s against K can be achieved by over-shooting

Conclusion

- We showed:
  - Spectrum owner’s revenues increase by allowing OSA
  - Primary users buy the service provided lower service fee
  - Revenue enhancement due to service fees to secondaries and better spectrum utilization
  - Revenue enhancement available for a range of user preferences
  - Actions of the owner is robust against uncertainties in them

- Future work:
  - Multiple channels with variable capacities
  - Different utility functions
  - Analysis of cases when OSA is or isn’t more profitable
  - Effect of competition among spectrum owners

Acknowledgments

- Ali Motamedi, Ahmad Bahai, Jean Walrand and Adam Wolisz for helpful discussions
- Member companies of Berkeley Wireless Research Center (BWRC)
- National Science Foundation
- Member companies of Gigascale Systems Reseach Center (GSRC) and Focus Center Research Program (FCRP)