Energy-Efficient Scheduling in Cellular Cognitive Radio Networks

HIIT Otaniemi Seminar Series

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October 2012

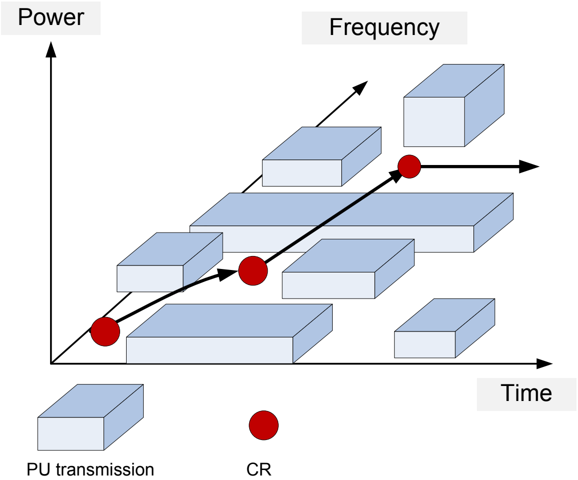
Outline

1. Cognitive Radio in Brief
2. Motivations for Energy Efficient Design in CRNs
3. Energy Efficient Scheduling in CRNs Enabled via White Space Databases
4. Performance Evaluation
5. Conclusions

Cognitive Radio: Why, What and How

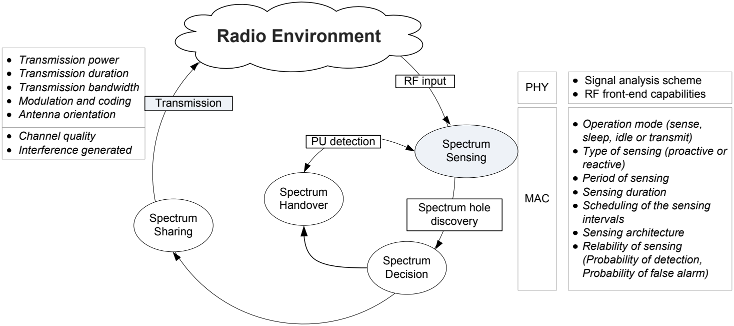
- Why: Radio spectrum is inefficiently used.
- Change in ownership; a resource is owned by the one who uses it. Sharing for sustainability.
- Static spectrum management since 1900s.
- Imagine a world with no-lane-changing.
- Smarter schemes: *Dynamic spectrum access* (DSA)

Basic Definitions



- Primary User (PU), Licensed User, Incumbent User
- Spectrum opportunity, white space, hole, gap
- Secondary User (SU), Cognitive Radio (CR)
- What: A Cognitive Radio (CR): smart radio, DSA capability, environment-aware, self-aware, adaptive

Cognitive Cycle



CR: a wireless device that can switch from one frequency to another.

Cognitive Radio: Challenges

1. Dynamicity of available frequencies: $f_1, f_2, \ldots, f_F$ owned by PUs

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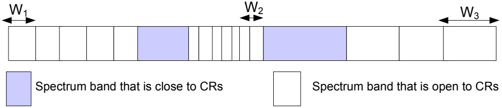
4. Cost of switching from f_i to f_j: channel switching overhead. Reduced time available for data transmission, energy consumption.
5. Spectrum fragmentation: $f_1 = 100KHz$, $f_2 = 20GHz$



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Outline

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Motivations

1. CR crucial for xG wireless communications
2. Battery-dependent devices
3. Energy may be the limiting factor

Energy efficiency (bits per Joule)

$$\text{Energy efficiency} = \frac{\text{Number of data bits transmitted (bits)}}{\text{Energy consumed (Joule)}}$$

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Our Objective

Our objective is

to design *low complexity* schemes for frequency assignment in infrastructure based cellular CRNs from an *energy efficiency* viewpoint *without sacrificing the network performance*.

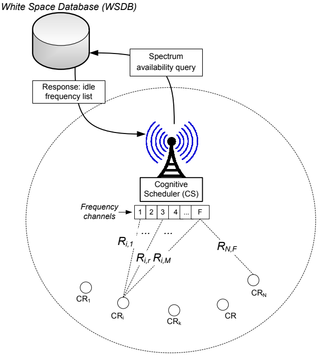
- Energy-Efficient Scheduling in Cellular CRNs with White Spectrum DataBases[1]

Outline

Centralized CRN Model

Research question

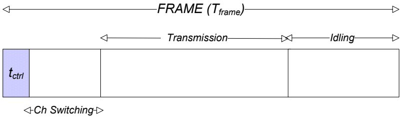
How to allocate idle frequencies out of F frequencies to N CRs such that energy efficiency is maximized? *(frequency, CR id)*



Our solutions

- NLP problem formulation and its optimal solution
- Energy-efficiency maximizing heuristic (Polynomial)
- Throughput max. but with <u>energy consumption</u> restriction
- Energy cons. min. but with <u>min. throughput guarantees</u>
- Fairness criteria

Frame organization



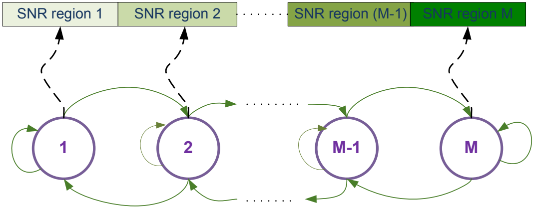
- Control messaging *(ignored)*
- Channel switching (linear function of frequency separation)
- Transmission and Idling

Our proposal

- Queue-aware (Q_i: # bits in CR i's buffer)
- Channel-aware ($L_{i,f}$: # bits in CR i can send in channel f)
- Channel-switching-aware ($\delta_{f',f} = |f - f'|$)

System dynamics

- CR-CBS channels: FSMC model, mean $\gamma_{i,f}$ in each state
- CR queues: Q_i,
- CR traffic: Batch Bernoulli process $\lambda_{CR} = \sum_{i=0}^{5} ip_i$



Utilities and Assignment

Utilities:

- $L_{i,f}$: Throughput of CR_i if assigned to f.
- $E_{i,f}$: Energy consumption of CR_i if assigned to f.

$$U_{N,F} = \begin{pmatrix} L_{1,1}, E_{1,1} & 0, 0 & \cdots & L_{1,F}, E_{1,F} \\ L_{2,1}, E_{2,1} & L_{2,1}, E_{2,1} & \cdots & L_{2,F}, E_{2,F} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 \\ L_{N,1}, E_{N,1} & L_{N,2}, E_{N,2} & \cdots & L_{N,F}, E_{N,F} \end{pmatrix}$$

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Assignments: $[F \quad 1 \quad -2 \quad -2 \quad 3 \quad 4 \quad .... \quad -2]$

$$X_{N,F} = \begin{pmatrix} L_{1,1}, E_{1,1} & 0, 0 & \cdots & L_{1,F}, E_{1,F} \\ L_{2,1}, E_{2,1} & L_{2,1}, E_{2,1} & \cdots & L_{2,F}, E_{2,F} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 \\ L_{N,1}, E_{N,1} & L_{N,2}, E_{N,2} & \cdots & L_{N,F}, E_{N,F} \end{pmatrix}$$

CRN Throughput Modeling

- Shannon Capacity of a link for a frame

$$R_{i,f} = W \log_2(1 + \gamma_{i,f})(T_{frame} - T_{sw}^{i,f}) \ bits/frame \tag{1}$$

CRN Throughput Modeling

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- Effective rate of the channel

$$L_{i,f} = \min(Q_i, R_{i,f}) \quad (2)$$

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- Total CRN throughput

$$R = \sum_{f=1}^{F} \sum_{i=1}^{N} X_{i,f} L_{i,f} \text{ bits/frame} \tag{3}$$

Energy Consumption Modeling

$$\begin{aligned}\text{Total Energy Consumption} =& \text{Energy consum. of transmitting CRs}\\ &+\text{Energy consum. of idling CRs}\\ &+\text{Energy consum. in channel switching}\end{aligned}$$

Circuitry power: P_c, Idling power: P_{id}

$$\begin{aligned}E =& \sum_{i\in\mathcal{N}_{tx}} ((P_{tx}+P_c)t_{tx} + P_{id}(T_{frame} - T_{sw} - t_{tx}))\\ &+ \sum_{i\notin\mathcal{N}_{tx}} P_{id}T_{frame}\\ &+ \sum_{i\in\mathcal{N}_{tx}} \sum_{f'=1}^{F} P_{sw}t_{sw}|f-f'|X_{i,f'}\end{aligned} \tag{4}$$

Energy-Efficient Scheduling Problem Formulation

$$\textbf{P1}: \max_{\vec{x}} \; \eta = \frac{R}{E}$$

s.t. (1) Single antenna and (2) Single transmission at a channel

Algorithmic Complexity

Non-linear Integer Programming problem

- Solution by Charnes-Cooper Transformation
- Relax binary constraints and linearize the problem via Charnes-Cooper Transformation.

Energy-Efficient Heuristic Scheduler (EEHS)

$$U_{N,F} = \begin{pmatrix} \frac{L_{1,1}}{E_{1,1}} & 0,0 & \cdots & \frac{L_{1,F}}{E_{1,F}} \\ \frac{L_{2,1}}{E_{2,1}} & \frac{L_{2,1}}{E_{2,1}} & \cdots & \frac{L_{2,F}}{E_{2,F}} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 \\ \frac{L_{N,1}}{E_{N,1}} & \frac{L_{N,2}}{E_{N,2}} & \cdots & \frac{L_{N,F}}{E_{N,F}} \end{pmatrix}$$

$$\begin{aligned} i &= \arg\max_i \left(\frac{L_{i,f}}{E_{i,f}}\right) && \text{if} \quad F_{idle} > N_{tx} \\ f &= \arg\max_f \left(\frac{L_{i,f}}{E_{i,f}}\right) && \text{ow.} \end{aligned}$$

- EEHS: For each idle frequency, select the CR attaining highest energy efficiency

Algorithmic Complexity

Polynomial time algorithm: $O(FN)$

Throughput Maximizing Scheduler with Maximum Energy Consumption Restriction (TMER)

P2: Maximize total CRN throughput
s.t. (1) Total energy consumption is less than E_{max}
(2) Single antenna (3) Single trans. at a channel

TMER objective function

$$\textbf{P2:} \quad \max_{\vec{x}} \sum_{i=1}^{N} \sum_{f=1}^{F} (1 - \omega_i) X_{i,f} L_{i,f}$$

- E_{max} : $\beta \times$ Average energy consumption in a frame
- $\beta \in (0, 1]$: Throughput-energy consumption tradeoff parameter.
- $\omega_i \in [0, 1]$: Satisfaction ratio of CR i

Energy Consumption Minimizing Scheduler with Minimum Throughput Guarantees (EMTG)

P3: Minimize CRN energy consumption

s.t.

(1) Minimum CRN throughput is greater than R_{min}

(2) All idle frequencies/CRs are assigned

(3) Single antenna

(4) Only one CR transmits at a frequency.

R_{min}: Average CRN throughput, determined by the CBS depending on the reports

$\beta \in (0, 1]$: Throughput-energy consumption tradeoff parameter.

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R_{min} and E_{max} calculation

- Based on average queue size, channel rate, idling time, transmission time, switching time.

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$$\begin{aligned} E_{max} =& \beta(K[(P_{tx} + P_c)(T - \alpha t_{cs} - T_d) + P_d T_d + P_{cs}\alpha t_{cs}] \\ &+ (N - K)P_d T) \end{aligned} \tag{5}$$

$$R_{min} = \beta K T_{avg} R_{avg} \tag{6}$$

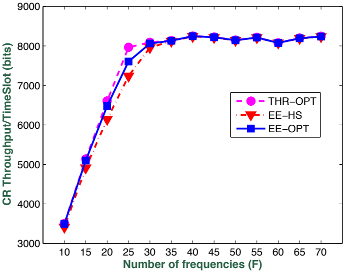
$$K = \min(N_{tx}, |\mathcal{C}_{idle}|) \qquad T_d = T - \alpha t_{cs} - T_{avg} \tag{7}$$

$$T_{avg} = \min(\frac{Q_{avg}}{R_{avg}}, T - \alpha t_{cs}) \quad Q_{avg} = \frac{\sum_i Q_i}{N_{tx}} \quad i, CR_i \in \mathcal{N}_{tx} \tag{8}$$

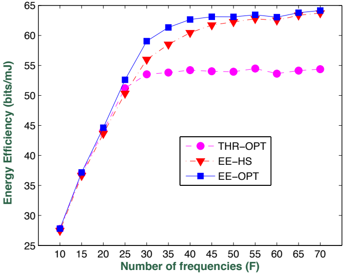
$$R_{avg} = \frac{\sum_i \sum_f B_{i,f}}{|\mathcal{C}_{idle}| N_{tx}} \quad f \in \mathcal{C}_{idle}. \tag{9}$$

Outline

Contiguous Spectrum



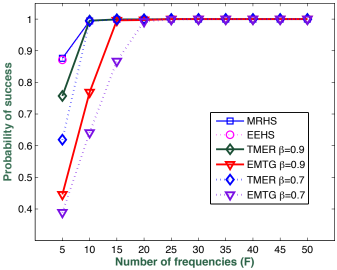
(a) Probability of success.



(b) Energy efficiency.

Heuristic solution is close to optimal.

Contiguous Spectrum



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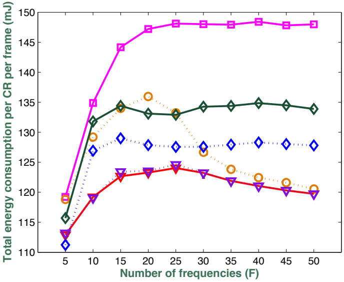

(b) Energy consumption.

[Probability of success.] [Energy consumption.]

Our energy consumption aware schedulers have the same throughput performance but consume less energy. Max.improvement 23%.

Contiguous Spectrum

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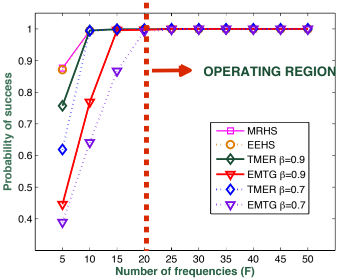

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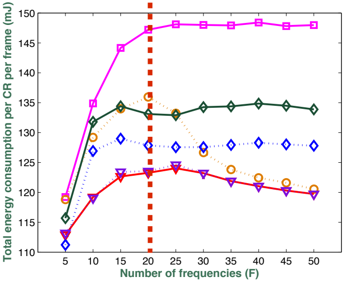

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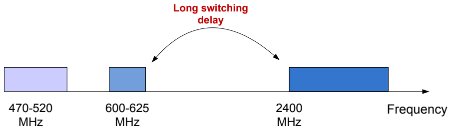
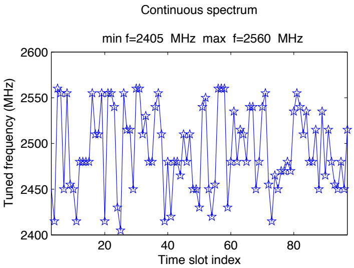
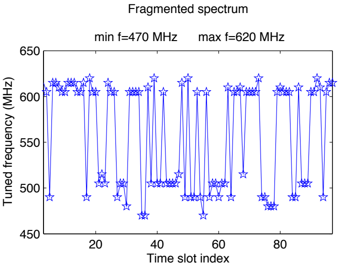
CR Clustering in Fragmented Spectrum





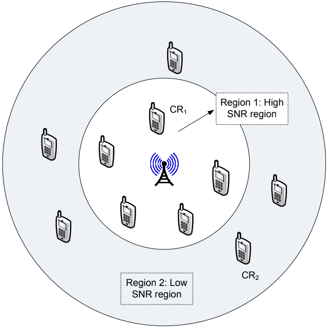


Effect of Fragmentation in Frequency Domain

Fragmentation-aware-schedulers

- Schedulers assign frequencies to each CR in the same/neighbor fragment
- Decreased opportunity for a CR, decreased competition for a CR.
- If tackled, fragmentation on the average *does not significantly affect* the CRN performance.

Fairness in Scheduling



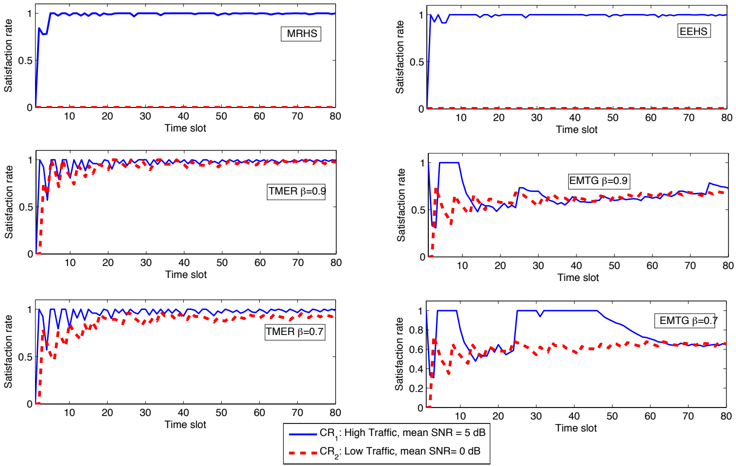
Gini index measures the fairness of the system.

$$F_{Gini} = \frac{1}{2N^2\bar{\omega}} \sum_{i=1}^{N} \sum_{k=1}^{N} |\omega_i - \omega_k|$$

$$\bar{\omega} = \frac{1}{N} \sum_{i=1}^{N} \omega_i$$

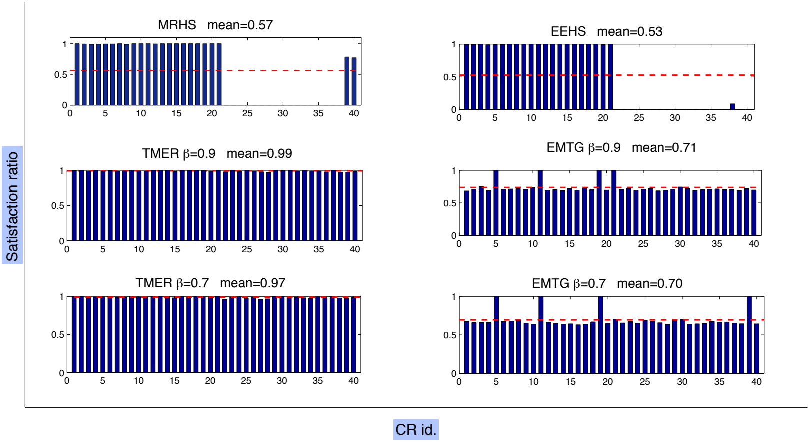
- CR_1 Higher SNR, Higher traffic
- CR_2 Lower SNR, Lower traffic

Satisfaction with Time



- CR_2 suffers in EEHS and MRHS.

Satisfaction of CRs



- EEHS and MRHS opportunistic schedulers, no fairness
- TMER and EMTG have fairness notion

Outline

Conclusions

- Formulation of energy-efficiency frequency assignment for CRNs
- Low complexity solutions without sacrificing throughput performance
- Fairness can be incorporated easily.
- For more details: Suzan Bayhan and Fatih Alagz, "Scheduling in Centralized Cognitive Radio Networks for Energy Efficiency", IEEE Transactions on Vehicular Technology, accepted, October 2012.

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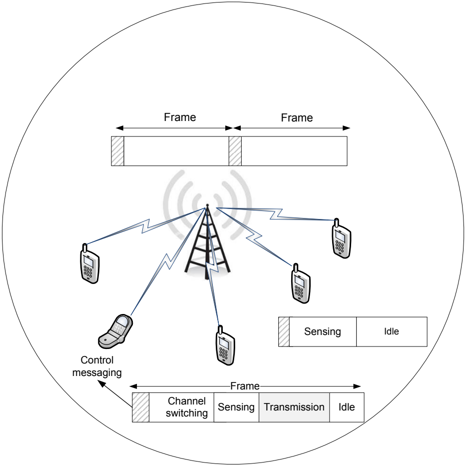
Future Directions

- A CRN without database access, i.e., internal sensing
- Power adaptation



Thank you.

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