Energy Efficient Spectrum Sensing and Access In Cognitive Radio Networks

NODES Pizza Seminars

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Outline

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- Why: Radio spectrum is inefficiently used. Smarter schemes: *Dynamic spectrum access* (DSA)

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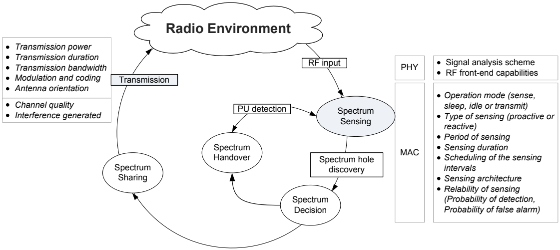

CR: a wireless device that can switch from one frequency to another.

Cognitive Radio: Challenges

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

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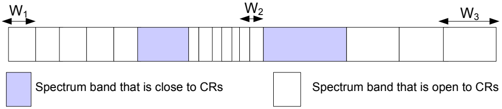
5. Spectrum fragmentation: $f_1 = 100KHz$, $f_2 = 20GHz$



Outline

Motivations

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

Energy efficiency (bits per Joule)

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

Our Contributions

Our objective is

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

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Our solution approaches

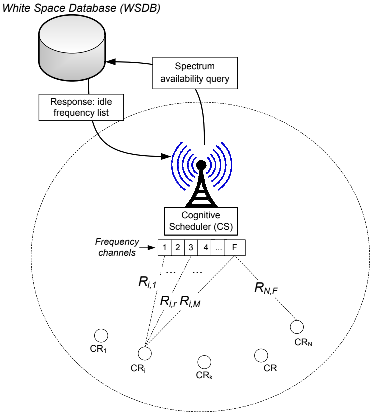
Optimization methods, design of heuristics, network flow, graph algorithms, analytic modeling and simulations

Outline

Centralized CRN Model Under Consideration

Research question

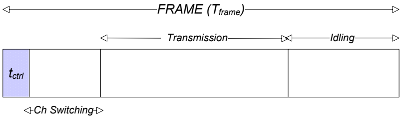
How to allocate idle frequencies out of F frequencies to N CRs such that energy efficiency is maximized? *(frequency, CR id)*



Our solutions

- NLP problem formulation and its optimal solution
- Energy-efficiency maximizing heuristic (Polynomial)
- Throughput max. but with energy consumption restriction
- Energy consumption min. but with minimum throughput guarantees
- 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)

CRN Throughput and Energy Consumption Modeling

Throughput (R)

- Shannon capacity of a link
- Number of bits in CR's buffer

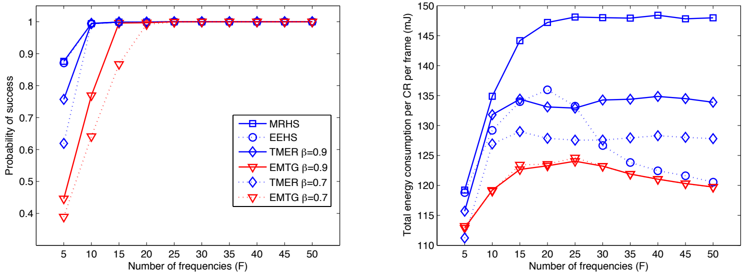
Energy Consumption (E)

- CRs in transmission state
- CRs in idling state

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

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

Contiguous Spectrum

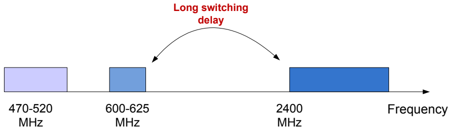


(a) Probability of success.

(b) Energy consumtion.

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

CR Clustering in Fragmented Spectrum



Effect of Fragmentation in Frequency Domain

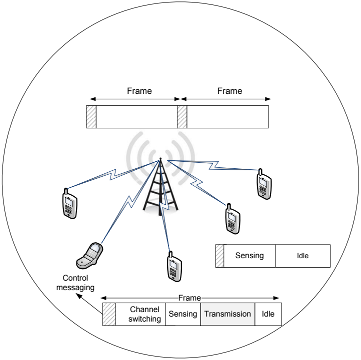
- Schedulers assign frequencies to each CR in the same/neighbor fragment
- Decreased opportunity for a CR, decreased competition for a CR.
- If tackled, fragmentation on the average *does not significantly affect* the CRN performance.

Outline

Energy-Efficient Scheduling in CRNs Considering PU Interference

Research question

How should CBS assign frequencies such that all PUs are protected and energy efficiency is maximized?



- CRs apply listen-before-talk
- Sensing time is a function of $(P_d, P_{fa}, \gamma_f, f_s)$ (Liang *et al.* [1])
- Control messaging in uplink and downlink
- PU interference ratios below max. tolerable limits

Our Solutions

- Formulate utility (energy or throughput efficiency) maximization framework
- Expected interference calculation
- Frame length optimization (short frames due to control overhead are inefficient, long frames are prone to PU collision)

Utility maximization framework

$$\max \sum_{i=1}^{N} \sum_{f=1}^{F} P_{idle}^{f} X_{i,f} U_{i,f} \tag{2}$$

$$\text{s.t. } I_{i,f} X_{i,f} \leqslant \Gamma_{thresh}^{f}$$

$$I_{i,f} = \frac{\text{Expected interference time of CR}i \text{ at } f}{\text{Mean PU activity duration at } f}$$

Utility of CR i at frequency f

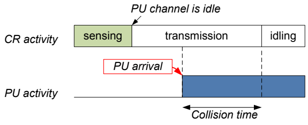
- Sensing is subject to errors: false alarm and misdetection
- $R_{i,f}$: Expected throughput, $E_{i,f}$: Expected energy consumption

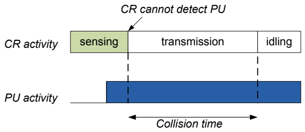
$$U_{i,f} = \begin{cases} \dfrac{R_{i,f}}{E_{i,f}} & \text{, for } EE_{max} \\ \dfrac{(1-\omega_i)R_{i,f}}{E_{i,f}} & \text{, for } EE_{max} - fair \\ R_{i,f} & \text{, for } Thr_{max} \\ (1-\omega_i)R_{i,f} & \text{, for } Thr_{max} - fair \end{cases}$$

Utility Calculation

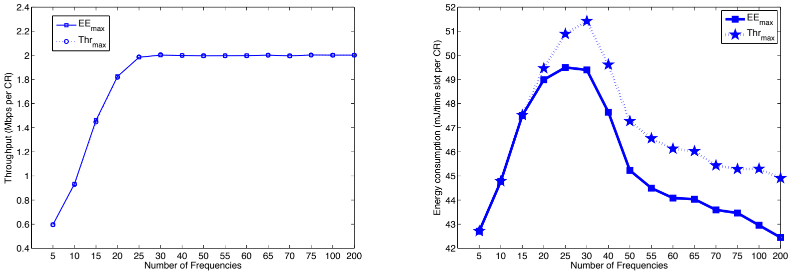
1. Channel switching (E_{sw})
2. Spectrum sensing (E_s) $\Rightarrow$ Four outcomes
3. Transmission and idling

Case	Probability	Throughput	Energy Cons.	Interference Time
1) OPP	$P^f_{idle}(1-P_{fa})$	$(1-q)t_{tx}C_{i,f}$	$P_{tx}t_{tx} + P_{id}(t_r - t_{tx})$	$t_{tx} - \beta_f(1-\exp(\frac{-t_{tx}}{\beta_f}))$
2) FA	$P^f_{idle}P_{fa}$	0	$P_{id}t_r$	0
3) PUD	$(1-P^f_{idle})P_d$	0	$P_{id}t_r$	0
4) PUM	$(1-P^f_{idle})(1-P_d)$	0	$P_{id}t_{tx} + P_{id}(t_r - t_{tx})$	t_{tx}





Comparison of EE_{max} with Thr_{max} with increasing F



(c) Throughput (d) Energy consumption

$N = 50$, $\lambda_{CR} = 2Mbps$ and $\Gamma_{thresh} = 0.05$.

Our scheduler achieves the same throughput but consumes lower energy.

Outline

EE Cooperative Sensing Scheduling

- M frequencies, N CRs,
- CRs sense a subset of channels one after another,
- CBS collects reports (e.g. $< CR_1$, f$_5$, 0$>$,$< CR_2$, f$_8$, 1$>$,) and gives the final decision (e.g., $f_1 : 0$, $f_2 : 1$...)

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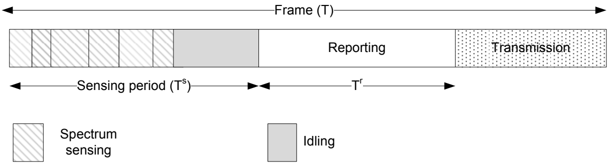
Research question

- Given that sensing must be completed in sensing period and each channel's detection reliability must be above a threshold, how should CBS choose a set of CRs to sense a particular frequency?



Problem Formulation

Merit of our work:

- Heterogeneity among CRs (channel SNR)
- The lower the SNR the longer the required sensing time.

- Mixed Integer Nonlinear Problem $\rightarrow$
- Outer Linearization Method

$$\textbf{P1:}\ \min\ w = \sum_{m=1}^{M}\sum_{n=1}^{N} P^s \tau_{m,n} + \sum_{n=1}^{N} E_n^{rep} y_n \qquad (3)$$

$$\tau_{m,n} \geq \tau_{m,n}^{min} x_{m,n} \qquad \forall m \in M, \forall n \in N \qquad (4)$$

$$\sum_{m=1}^{M} \tau_{m,n} \leq T^s y_n \qquad \forall n \in N \qquad (5)$$

$$\sum_{n=1}^{N} x_{m,n} \geq \delta^{min} \qquad \forall m \in M \qquad (6)$$

$$\sum_{n=1}^{N} x_{m,n} \leq \delta^{max} \qquad \forall m \in M \qquad (7)$$

$$\sum_{m=1}^{M} x_{m,n} \leq M y_n \qquad \forall n \in N \qquad (8)$$

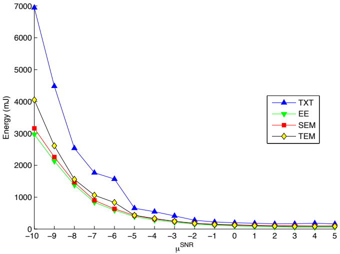
$${}_{th}Q^d - Q_m^d \leq 0 \qquad \forall m \in M \qquad (9)$$

$$x_{m,n}, y_n \in (0,1) \qquad \forall m \in M, \forall n \in N \qquad (10)$$

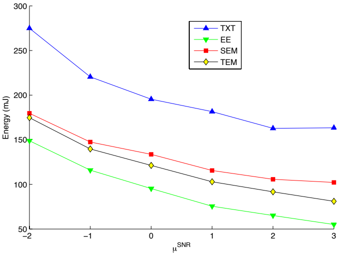
$$\tau_{m,n} \geq 0 \qquad \forall m \in M, \forall n \in N, \qquad (11)$$

Performance Analysis

- Optimal energy-efficient solution (EE)
- Transmission time maximization (TXT)
- Sensing energy minimization (SEM)
- Transmission energy minimization (TEM)

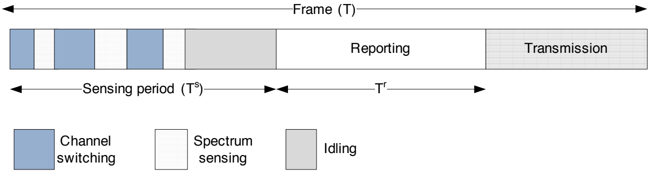


(e) μ^{SNR} between -10 dB and 5 dB.



(f) μ^{SNR} between -2 dB and 3 dB.

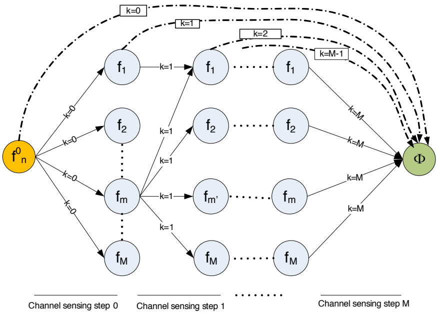
EE Cooperative Sensing Scheduling with Channel Switching



Research Challenges

- How to decide on the most EE channel sensing sequence
- For a particular CR, which frequencies should be sensed and in which order?

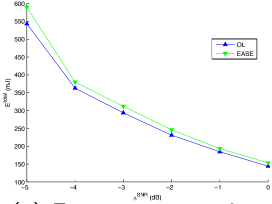
Problem Formulation using Network Flows



$$
\begin{aligned}
\textbf{P1:}\ \min\ w = & \sum_{m=1}^{M}\sum_{n=1}^{N} P^{s}\tau_{m,n} + \sum_{n=1}^{N} E_n^{tx} y_n \\
& + P^{cs} t^{cs} \sum_{n=1}^{N} \Big(\sum_{m=1}^{M} |f_n^0 - f_m| x^0_{f_n^0,m,n} \\
& + \sum_{m=1}^{M} \sum_{\substack{m'=1 \\ m' \neq m}}^{M} \sum_{k=1}^{M-1} |f_m - f_{m'}| x^k_{m,m',n} \Big)
\end{aligned}
$$

Subject to

1. Sensing quality related constraints
2. Flow related constraints
3. Sensing time related constraints



(g) Energy consumption

Outline

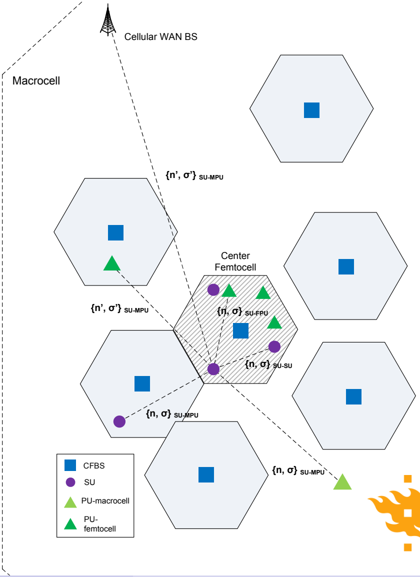
Summary

- Current CR solutions lack an energy efficiency perspective
- Resource allocation with both throughput and energy efficiency
- Channel-switching-aware, fragmentation-aware, PU-interference-aware design
- Low complexity solutions for EE spectrum sensing and access

- Suzan Bayhan and F.Alagöz, "Scheduling in Centralized Cognitive Radio Networks For Energy Efficiency", *accepted, IEEE Transactions on Vehicular Technology*, Oct. 2012.
- Salim Eryigit, Suzan Bayhan and Tuna Tugcu, "Energy-Efficient Multi-Channel Cooperative Sensing Scheduling with Heterogeneous Channel Conditions for Cognitive Radio Networks", *submitted to IEEE Transactions on Vehicular Technology*, 2012..
- Salim Eryigit, Suzan Bayhan and Tuna Tugcu, "Channel Switching Cost Aware and Energy-Efficient Cooperative Sensing Scheduling for Cognitive Radio Networks", *submitted to IEEE ICC* 2013.
- (in preparation) Suzan Bayhan and F.Alagöz, "Energy Efficiency in Spectrum Sensing and Access in CRNs: A Survey".

Ongoing/Future Research

- Energy efficient distributed channel access via reinforcement learning
- Energy efficiency analysis of wireless networks with cognitive femtocells
- A framework for energy efficient sensing and transmission
- Network wide energy efficiency analysis → Not a single cell



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H. Kim and K. G. Shin, "Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 5, pp. 533–545, May 2008.

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Questions? Comments?

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