Next-GWIN 2016
4th International Workshop on
Next Generation Green
Wireless Networks

TUTORIAL
Energy Efficiency in Cognitive Radio Networks:
Key Trade-offs

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Wireless Networks

This is a joint work with

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**Energy Efficiency is a Subtle Concept: Fundamental Trade-offs for Cognitive Radio Networks*

IEEE Communications, SI on EE Cognitive Radio Networks, vol:52, issue: 7, July, 2014.
Salim Eryigit, Gürkan Gür, Suzan Bayhan, Tuna Tugcu

Outline

- General outlook
- Why CRs?
- Key trade-offs for EE in CRNs
  - How they emerge
  - EE vs. Quality-of-service (QoS)
  - EE vs. Fairness
  - EE vs. PU interference
  - EE vs. Network architecture
  - EE vs. Security
- Conclusions

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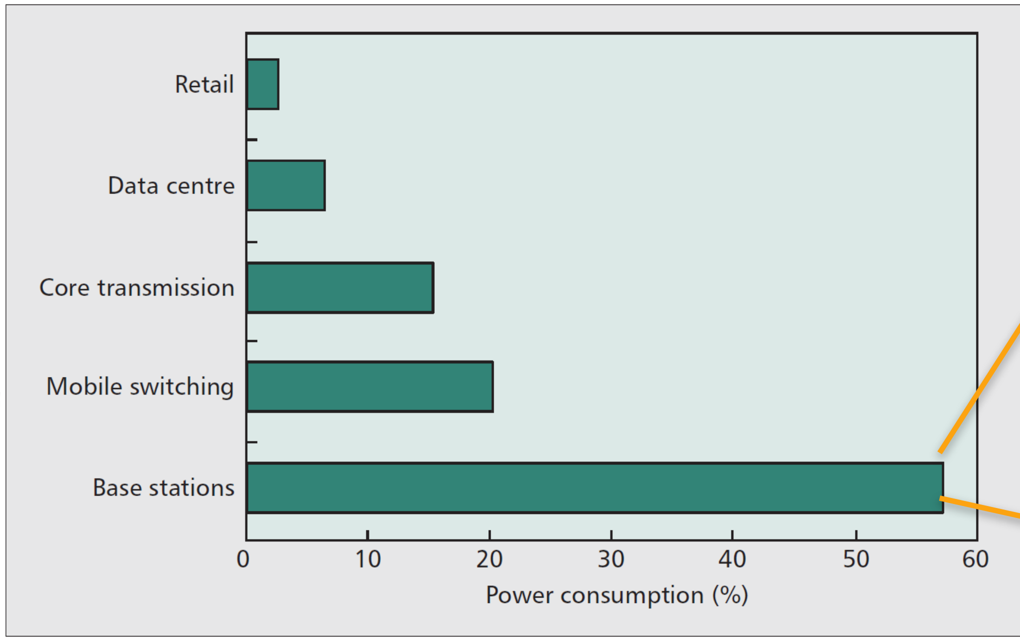
Energy breakdown of a mobile operator



50-80 % Power amplifier,
10-25 % cooling,
5-15 % signal processing,
5-10 % power supply

- Radio access and core network are the primary targets for EE.
- How about the mobile user?

Gur et al. "Green wireless communications via cognitive dimension: an overview." IEEE Network (2011): 50-56.

What can be done on different segments?

- Endpoint devices and access network
  - BS architectural enhancements (separation of duties for centralization, idle mode, ...)
  - Protocol and middleware support for EE
  - Hardware advances in RF components (e.g. Better PAs)
  - Application support (cross-layer optimizations)
- Core network
  - EE computing on core network (e.g. aggregation and caching)
  - Flat all-IP mobile network
  - Network level sleep-mode (e.g. idling of nodes based on network traffic awareness)
  - Optical switching and routing (inherently more efficient)
- Network-wide enhancements

Cognitive Radio and Cognitive Networks

Intelligence at the device and the network to **optimally use the limited resources, e.g., spectrum, energy**

- Optimality especially required to meet the gap between network capacity growth and the faster increase in wireless traffic demand

Cognitive radio (CR)

- Adapt transmission parameters, e.g., frequency, power level, modulation

Cognitive network

- Anticipate future network states and act (anticipatory networks*)

Bui, Nicola, et al. "Anticipatory Networking in Future Generation Mobile Networks: a Survey." arXiv preprint arXiv:1606.00191 (2016).

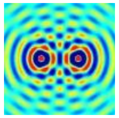
Additional benefits of CR

- Intelligence support for EE
- Network layer capabilities
- Cross-layer optimizations
- Physical layer capabilities
- Bandwidth-energy trade-offs
- Smaller impact on human health

Main trade-offs for EE in CRNs

EE vs. Quality-of-service (QoS)

EE vs. Fairness

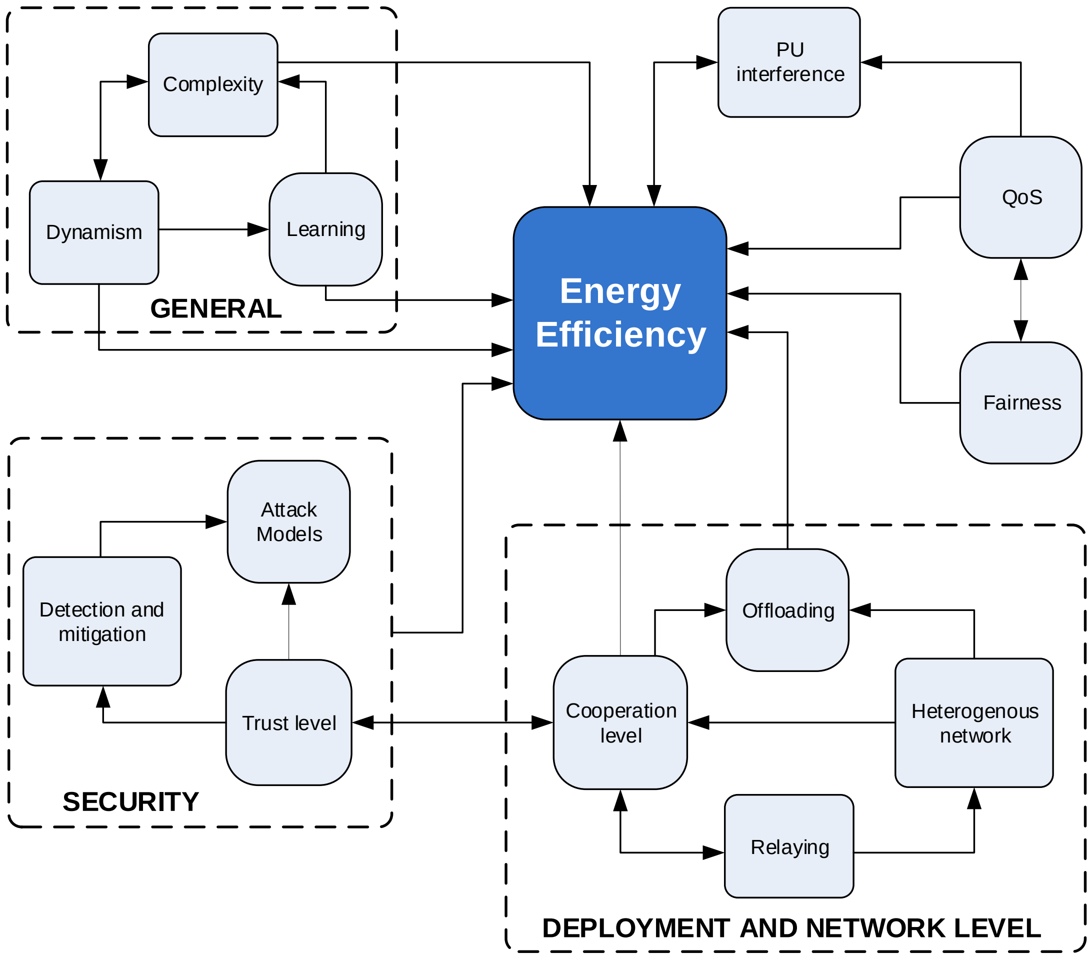


EE vs. PU Interference

EE vs. Network Architecture

EE vs. Security

Each trade-off affects the others!!!

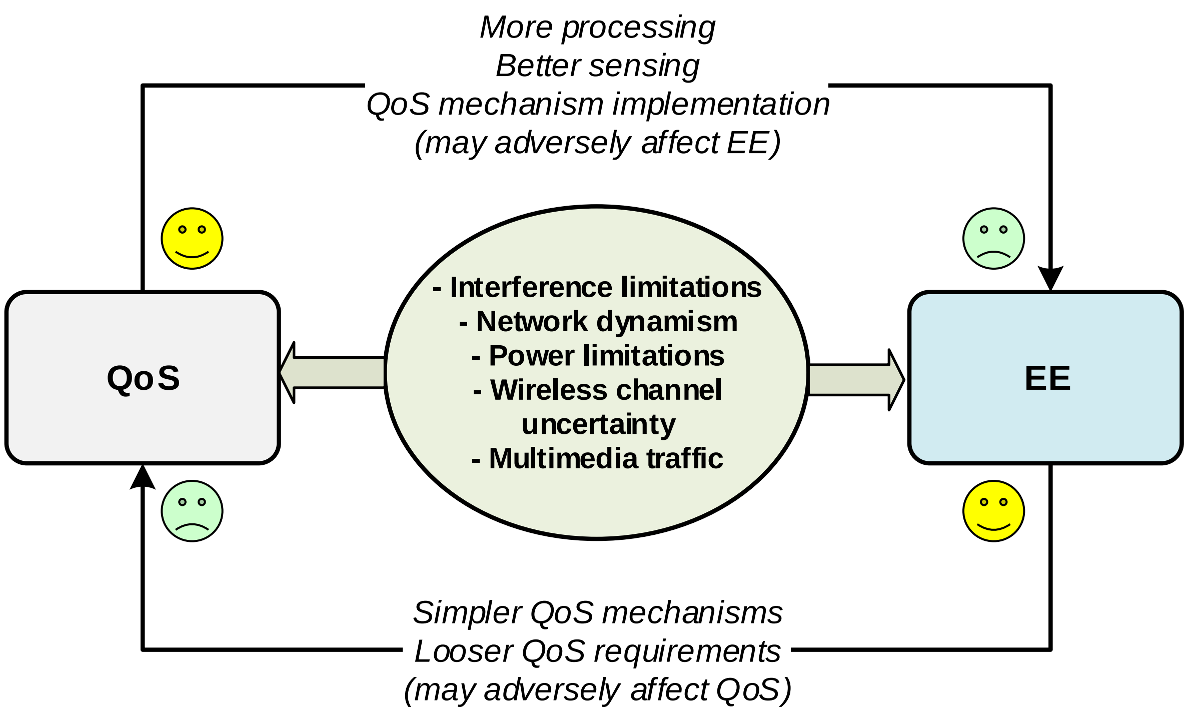


*S. Eryigit, G. Gür, S. Bayhan, T. Tugcu, “Energy Efficiency is a Subtle Concept: Fundamental Trade-offs for Cognitive Radio Networks,” IEEE Communications, SI on EE CRNs, vol:52, issue: 7, July, 2014.

EE vs. QoS

- QoS becomes harder to satisfy with EE requirements.
  - To add more salt: Interference limitations, power budget, imperfect sensing, etc.
- Three approaches:
  - *PU centric approach*: Maximum protection for PUs.
    - Minimum misdetection probability, highly conservative.
  - *SU centric approach*: Maximum opportunity for SUs.
    - Minimum false alarm probability, highly opportunistic.
  - *Hybrid approach*: Combination of both.
    - Evaluate QoS requirements in a flexible manner.

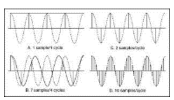
EE vs. QoS


More processing
Better sensing
QoS mechanism implementation
(may adversely affect EE)
QoS
- Interference limitations
- Network dynamism
- Power limitations
- Wireless channel uncertainty
- Multimedia traffic
EE
Simpler QoS mechanisms
Looser QoS requirements
(may adversely affect QoS)

EE vs. QoS

- False alarm probability vs. misdetection probability
  - In general, decreasing one of them increases the other.
  - To decrease both, we should increase:

SNR: Cannot be controlled.



Sampling frequency: Device dependent, hard to control.

Sensing time: Can be increased but leads to more energy consumption due to periodic nature of sensing.

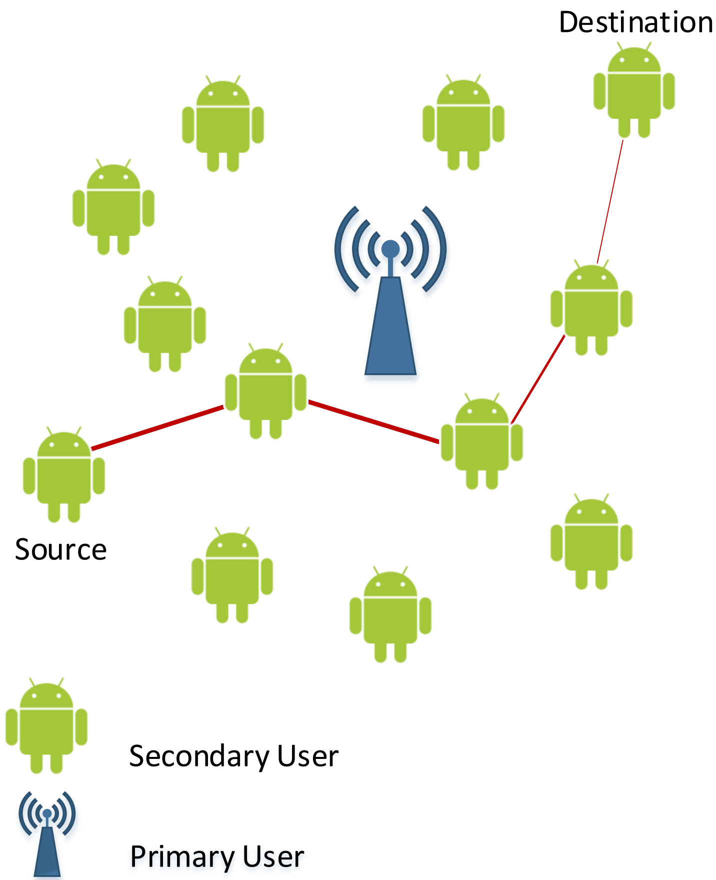
If QoS of SUs cannot be met, prioritization schemes can be used to increase user satisfaction.

EE vs. QoS

- CRN can exploit diversity techniques to enhance EE.
  - *Link diversity*
  - *Channel diversity*
  - *CR diversity*
  - *Spatial diversity*
  - *Multi-radio diversity*
- Time-varying channel conditions: Switch to a better channel.
  - How about the time and energy cost of switching?
  - 1.5 msec for USRP, 7-21msec for RTL-SDR per 1MHz.
  - Non-contiguous spectrum?

Nika et al. "Towards commoditized real-time spectrum monitoring", *ACM Hot Topics in Wireless*, 2014, pp.25-30

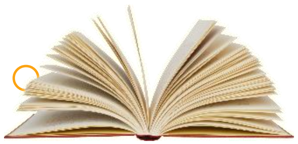
EE vs. QoS



Multi-hop CRNs, e.g. CR ad hoc networks -> D2D dimension

- Establish QoS paths on a per flow basis.
- Channel occupancy may change in a non-mobile network.
  - How to repair/reconfigure broken or non-satisfactory paths with changing channels.
  - What if the nodes are also mobile?

Example work on QoS



S. Wang et al., Energy-Efficient Resource Allocation for OFDM-Based Cognitive Radio Networks, *IEEE Transactions on Communications*, vol. 61, no. 8, 2013, pp. 3181–91.

- An OFDM-based underlay network with multiple subchannels and multiple SUs is considered.
- The goal is to decide subchannel/SU assignment (binary variables) together with SUs’ transmission powers (continous variables).

Example work on QoS

Objective

Maximize EE

- Total throughput/(Total tx power+Total circuit power)

Constraints

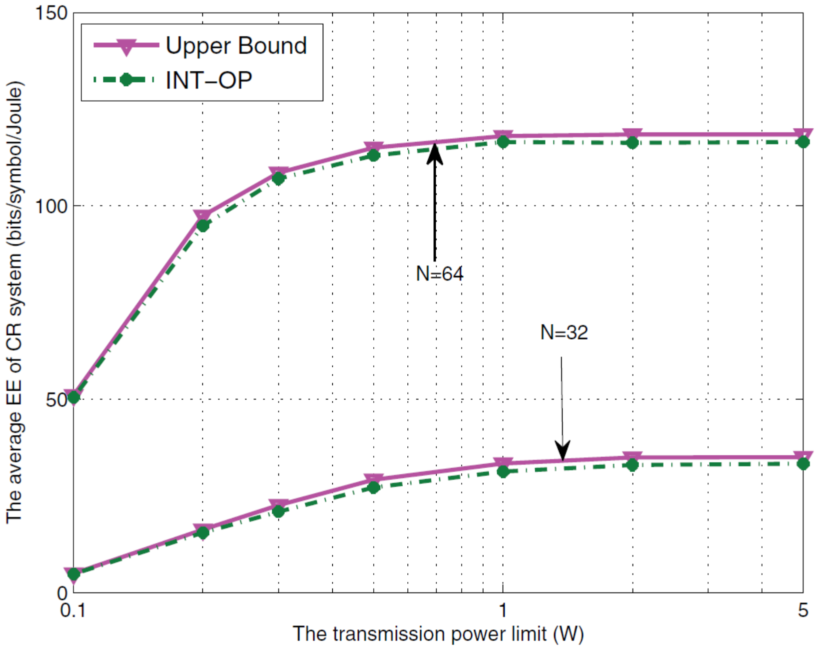
- SUs' minimum throughput requirements,
- Total power budget,
- Total interference on each subchannel,
- Use each subchannel once.

Resource allocation algorithm

- Subchannel/SU assignments,
- Transmission power levels for each assignment.

Example work on QoS

- The problem is a MINLP that is difficult to solve.
- The authors relax the integer variables, and transform the problem into convex form.
- The resulting convex problem is solved using barrier method.
- However, the binary assignment variables are [0, 1] because of relaxation.
- They are transformed by allocating the subchannel to the SU with the maximum value of the assignment variable on that channel. (Suboptimal solution)



N: number of subchannels

EE vs. fairness

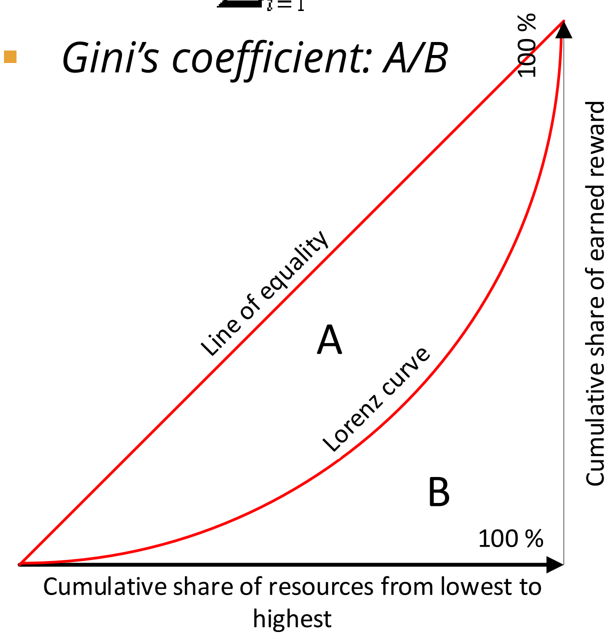
- Provide fairness for opportunistic spectrum access in a highly dynamic environment.
  - Also be energy-efficient.
  - Usually a secondary or a tertiary objective at best.
- In general energy efficiency favors unfairness.
  - e.g. Let the CR with minimum required transmission energy for a given throughput, always transmit.
- Fairness on downlink
  - EE is desired for simple hardware and less opex.
- Fairness on uplink
  - EE is required due to limited battery and mobility
- How about infrastructure sharing among different operators?
  - Fairness among different networks.

EE vs. fairness

- How to measure fairness?
  - *Jain's fairness index*

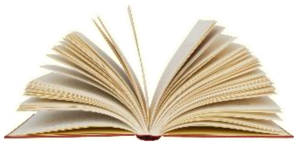
$$\frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\sum_{i=1}^{n} x_i^2}$$

  - *Gini's coefficient: A/B*



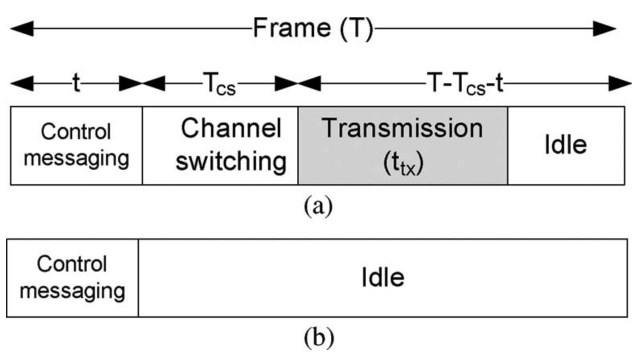
- Max-min fairness
- Fairly shared spectrum efficiency
  - portion of the system spectral efficiency that is shared equally among all active users

Example work on fairness



S. Bayhan and F. Alagöz, “Scheduling in Centralized CRNs for Energy Efficiency”, IEEE Transactions on Vehicular Technology, vol. 62, no. 2, Feb. 2013, pp. 582–95.

- A multi-channel multi-user centralized network with perfect sensing is considered.
- Buffer states of SUs and channel switching delay is taken into account.
- The goal is to perform channel-SU assignments (binary decision variables).



Example work on fairness

System state

- SNR values
- Current channel info
- Buffer states
- Power levels for tx, circuitry, switching and idling

Constraints

- Classic assignment constraints

Objective

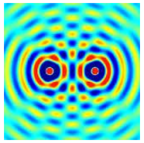
Maximize EE

- Total throughput/Total energy

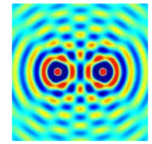
Scheduling algorithm

- Channel/SU assignments

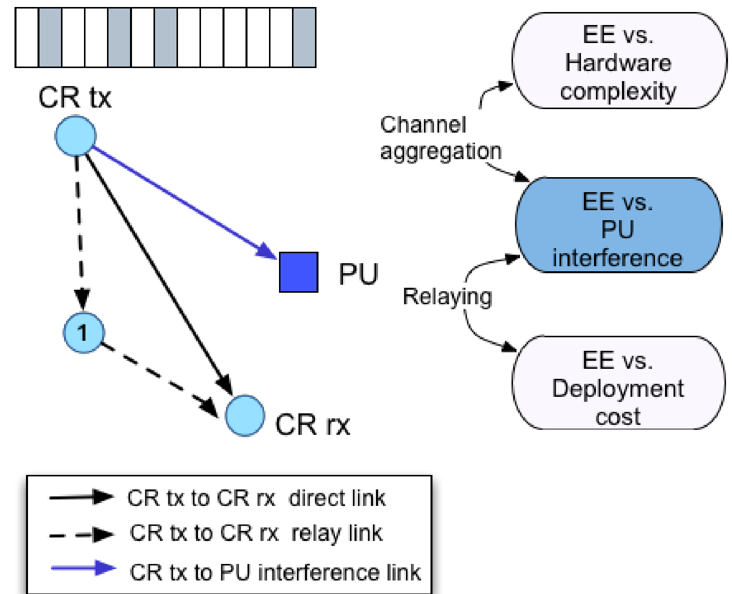
- This problem is solved by a heuristic (EEHS) that greedily makes assignments based on ***individual*** EE values.

EE vs. PU interference 

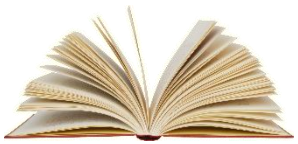
- *Underlay* vs. *overlay* operation
- Causes of interference:
  - *PU misdetection*:
    - Increase detection probability by increasing sensing time, sampling rate, CSS (and energy expenditure).
  - *PU reappearance*: PU starting to use the channel somewhere between two sensing periods.
    - Caused by periodic sensing.
    - Sense frequently: High overhead, less transmission time (throughput)

EE vs. PU interference 

- To decrease interference, CR behaves conservatively at:
  - *Sensing step*: Period adaptation and increase sensing accuracy.
  - *Transmission step*: Reduce transmission power. QoS?
- Other solutions:
  - *Relaying*
  - *Channel aggregation*: Transmit via multiple channels.
    - Compensate low transmission power by increasing bandwidth.
    - Requires complex hardware.



Example work on PU interference



M. Ge and S. Wang, “Energy-Efficient Power Allocation for Cooperative Relaying CRNs”, IEEE WCNC, Apr. 2013, pp. 691–96.

- One source node, one relay node and one destination node in an overlay network.
- There are multiple subchannels to use.
- Amplify and forward type of relaying is used, throughput is halved.
- Decision variables: Transmission and amplification power for each subchannel.

BOĞAZİÇİ ÜNİVERSİTESİ 1863

Example work on PU interference

System state
- Noise,
- Channel and power gains,

Constraints
- Throughput
- Power budgets of tx and relaying
- Interference levels of tx and relaying

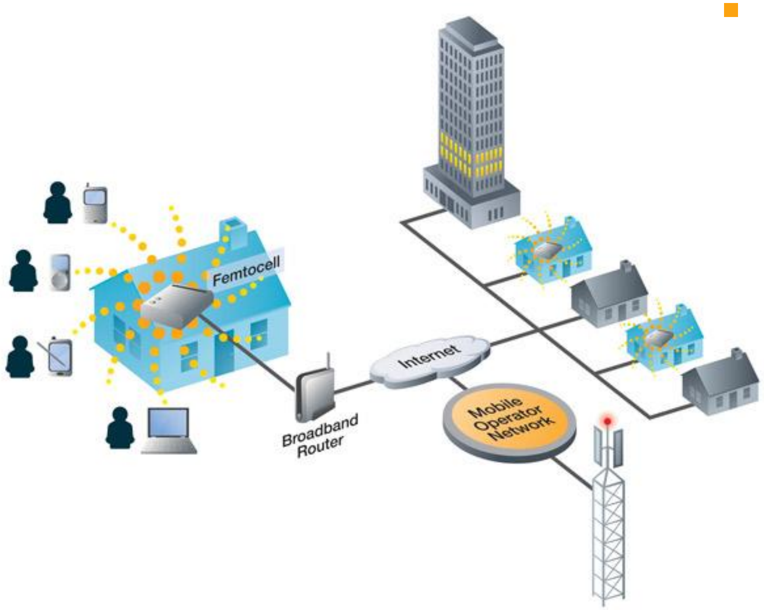
Objective
Maximize EE
- Total throughput/Total energy

Power allocation algorithm

- Transmission power levels of source and relay

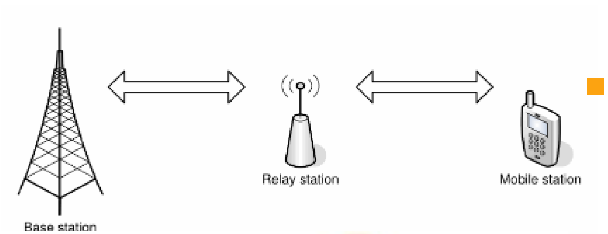
EE vs. network architecture

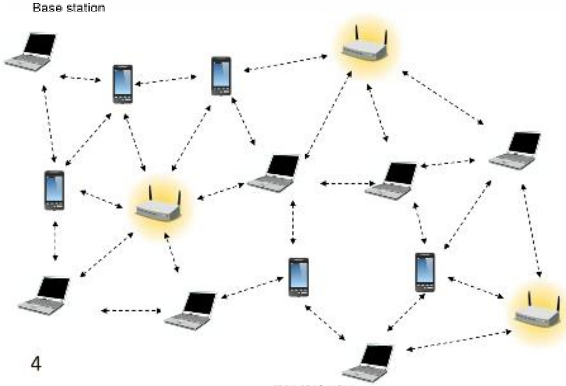
- General approach: Introduce additional hops to reduce transmission energy
  - How about QoS?

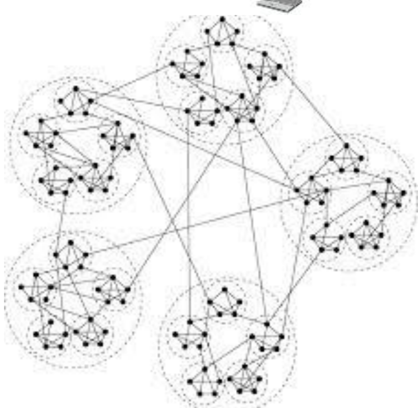


- Small cells (femto/pico/micro, etc.)
  - Majority of the traffic originates from indoors.
  - Offload user traffic to provide high capacity with better frequency reuse.
  - They should be self configurable with no centralized control.
    - Additional sensing energy required for each small cell.
  - Mobility: Complex and large number of handoffs.

EE vs. network architecture

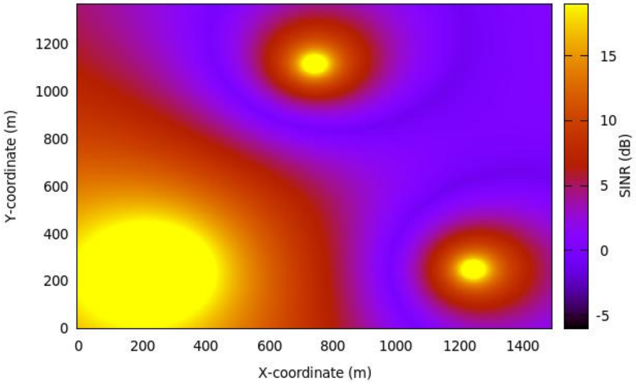






- *Relaying*
  - Amplify-and-forward vs decode-and-forward
  - Peer CRs vs dedicated relays
    - Peer CRs: Extra energy for relaying CRs, favorable CRs become bottlenecks.
  - Relaying may not be energy-efficient if traffic load is low, channel conditions are good, transmitter is close to the receiver.
    - Best strategy is to decide to use relaying on a case by case basis. How?
- *Clustering and ad hoc networks*
  - How to find a reliable common control channel?
  - Decentralized operation: Low performance and high interference.

EE vs. network architecture

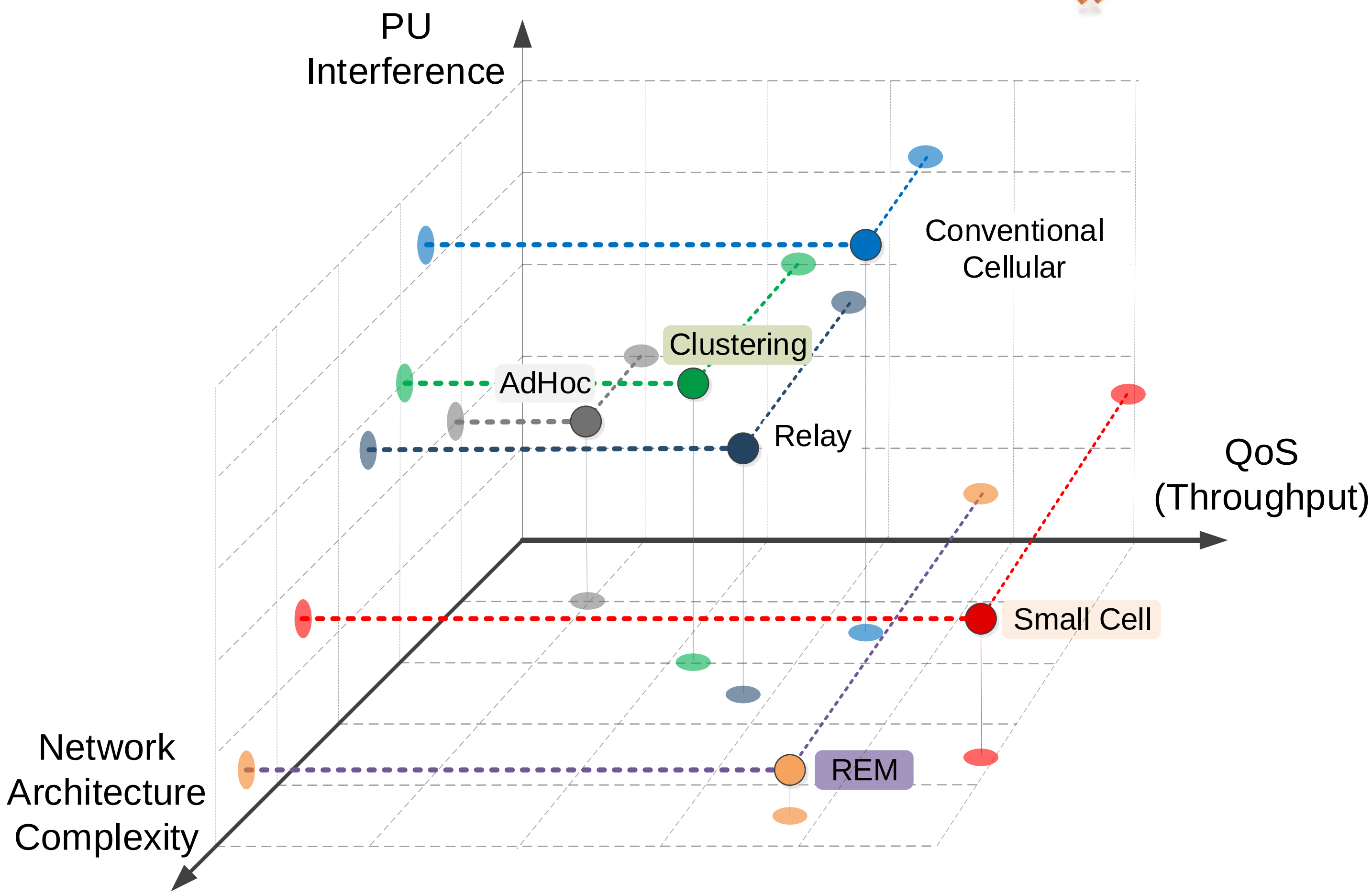


H.B.Yilmaz, S. Bayhan, T. Tugcu, F. Alagöz, "Radio Environment Map As Enabler for Practical Cognitive Radio Networks, "IEEE Communications, vol.51, no.12, Dec. 2013.

Pawełczak et al. "Will Dynamic Spectrum Access Drain My Battery?" Technical Report, TU Delft., 2014

- Additional hop
  - Additional hardware: monetary and energy OPEX
  - Idling also consumes energy.
    - Sleep scheduling: Overhead and reduced QoS.
  - Where to place these hardware?
- Sensing: Internal vs. external
- External:
  - *Radio environment maps*
    - High performance and more reliable sensing.
    - Improves the environmental awareness of CRs.
    - Do they contradict with the cognitive spirit?
    - Energy cost of operating REMs (cooling, processing, synchronization, etc.)
  - *(TV) Whitespace Spectrum DB (WSDB)*
    - Current trend - > crowd-sensing
    - Not as energy efficient as it seems.
    - More accuracy -> more crowd-sensing by the mobile devices, but more power consumption

EE vs. network architecture



EE vs. security

- Security attacks:
  - Main target is the sensing step of the cognitive cycle when CSS is employed.
    - *Insider attacks:* Spectrum sensing data falsification.
    - *External attacks*: PU emulations.
  - Solution methods:
    - *Authorization/authentication.*
    - *Trust based approach with reward/punishment.*
- More security = more energy
    - Power and time consumption for overhead of security (i.e. additional authentication, integrity packets or packet fields)

EE vs. security 

- In a trustable domain: Security protocols hinder EE.
- In a non-trustable domain: Security protocols can identify and avoid malicious/misbehaving users.
  - e.g. Consider a malicious CR that always reports “channel is occupied” in a cooperative sensing scenario.
  - May improve EE.
- Social-aware protocols?

Conclusions

- Devising energy-efficient solutions is not self-evident.
- The flexibility of CR promises inherently comes with energy costs.
- Conflicting goals in CR design (e.g., providing security may require tasks that increase energy consumption).
- Joint optimization for CRs-> dependent on parameter space and use-cases
  - Future Internet : content-centric operation
  - Video-driven networks
  - Intermittent and massive number of connectivities : IoE
  - …
- Complexity?

Thank you!

Reading List

Energy Efficiency of Cognitive/Cellular Networks

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2) Masonta et al., Energy efficiency in future wireless networks: Cognitive radio standardization requirements, IEEE CAMAD, 2012, pp. 31–35.
3) Davaslioglu et al., Quantifying Potential Energy Efficiency Gain in Green Cellular Wireless Networks, IEEE Communications Surveys and Tutorials, vol. 16, no. 4, 2014, pp. 2065–91.

QoS

1) S. Wang et al., Energy-Efficient Resource Allocation for OFDM-Based Cognitive Radio Networks, IEEE Transactions on Communications, vol. 61, no. 8, 2013, pp. 3181–91.
2) Eryigit et al., Energy-Efficient Multichannel Cooperative Sensing Scheduling With Heterogeneous Channel Conditions for Cognitive Radio Networks, IEEE TVT, vol. 62, no. 6, 2013, pp. 2690–99.
3) Wang et al., Optimal Energy-Efficient Power Allocation for OFDM-Based Cognitive Radio Networks, IEEE Communications Letters, vol. 16, no. 9, 2012, pp. 1420–23.
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5) Akin et al., On the Throughput and Energy Efficiency of Cognitive MIMO Transmissions, IEEE TVT, vol. 62, no. 7, 2013, pp. 3245–3260.

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Fairness

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2) Ren et al., CAD-MAC: A Channel-Aggregation Diversity Based MAC Protocol for Spectrum and Energy Efficient Cognitive Ad Hoc Networks, IEEE JSAC, vol. 32, no. 2, 2013, pp. 237-250.
3) Quadri et al., A fair and energy-efficient spectrum management mechanism for cognitive radio networks, IWCMC, 2012, pp. 338-343.
4) Mesodiakaki et al., Fairness evaluation of a secondary network coexistence scheme, CAMAD, 2013, pp. 180-184.

PU Interference

1) M. Ge et al., Energy-Efficient Power Allocation for Cooperative Relaying Cognitive Radio Networks, IEEE WCNC, 2013, pp. 691-696.
2) Ramamonjison et al., Energy Efficiency Maximization Framework in Cognitive Downlink Two-Tier Networks , IEEE TWC, vol. 14, no. 3, 2014, pp. 1468-79.
3) Shi et al., Energy-Efficient Joint Design of Sensing and Transmission Durations for Protection of Primary User in Cognitive Radio Systems, IEEE Communications Letters, vol. 17, no. 3, 2013, pp. 565-568.
4) Li et al., Energy-Efficient Transmission for Protection of Incumbent Users, IEEE ToB, vol. 57, no. 3, 2011, pp. 718-720.
5) Chang et al., Spectrum Sensing Optimisation for Dynamic Primary User Signal, IEEE ToC, vol. 60, no. 12, 2012, pp. 3632-40.

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Network Architecture

1) S. M. Kamruzzaman, et al., An Energy Efficient QoS Routing Protocol for Cognitive Radio Ad Hoc Networks, ICACT 2011, pp. 344–49.
2) Xie, et al., Energy-Efficient Resource Allocation for Heterogeneous Cognitive Radio Networks with Femtocells, IEEE ToWC, vol.11, no. 11, 2013, pp. 3910-20.
3) Wildemeersch et al., Cognitive Small Cell Networks: Energy Efficiency and Trade-Offs, IEEE ToC, vol. 61, no. 9, 2013, pp. 4016-29.
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Security

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3) Zhang et al., Energy-efficient and trust-aware cooperation in cognitive radio networks , ICC, 2012, pp. 1763-67.