TUTORIAL

Energy Efficiency in Cognitive Radio Networks: Challenges, Trade-offs, and Solutions

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Why are we concerned about EE?

- **ICT as consumer:** 1.5 billion computers in the world consume about 90 000 MW of electric power, which is about 10% of global consumption
  - Similar case for wireless comm.
- **ICT as enabler to improve energy efficiency and reduce costs:**
  - The production and use of electricity (the operation of power plants to electricity transport)
  - Model, simulate and optimize these processes

+

- **Environmental concerns**
- **Cost**
- **Feasibility**
- **Availability**
- **Scalability**
- **Robustness**

⇨ **Energy Efficiency**

Outline

- Part I: Preliminaries on energy efficiency (EE) in wireless networks
  - Motivation
  - EE metrics
  - Initiatives and standardization
  - Research efforts

- Part II: 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

- Part III: Opportunities for (higher EE) CRNs
  - Short-range communications
  - Social-networks

Part I

Preliminaries on energy efficiency in wireless networks

Gürkan Gür

Motivation for Energy Efficiency (EE) research

- New and more pervasive mobile technologies (such as LTE) being deployed

- ICT Sector : ***Responsible for 2% to 10 % of the world energy consumption.***
- Drastic traffic surge in mobile networks
- Increasing detrimental effects of energy generation & consumption + increasing energy costs

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Energy consumption in wireless systems

Energy consumption is critical in wireless systems, in terms of

- Cost
- Availability
- Feasibility
- Quality of Service
- Usability
- Robustness

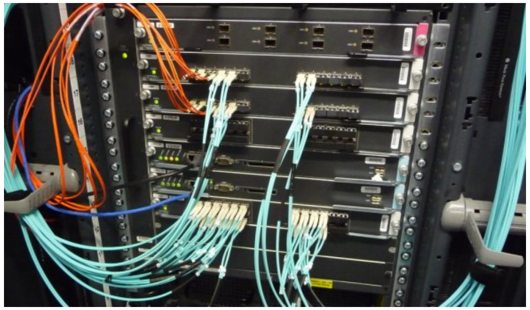
- Multiobjective setting
- Usually contradicting

Energy efficient wireless networks

Two approaches towards Energy Efficient Wireless Networks

To find apropriate solutions to the energy efficiency challenges for already existing networks

1



To design future networks from energy (and cost) efficient perspective (Greenfield perspective)

2

Cisco VNI: Global mobile data traffic forecast 2014–2019

- Global mobile data traffic grew 69 percent to 2.5 exabytes per month in 2014.
- Last year's mobile data traffic was nearly 30 times the size of the entire global Internet in 2000.
- Mobile video traffic exceeded 50 percent of total mobile data traffic for the first time in 2012.
- Almost half a billion (497 million) mobile devices and connections were added in 2014.

Source: Cisco VNI: Global Mobile Data Traffic Forecast 2014–2019

Driving factors for EE in wireless systems

- **Smaller** form-factor devices
- More **mobility** and more ad hoc settings
- The requirement of more **complex** and **diverse** capabilities
- The emergence of **green communications concept** and environmental issues related to energy consumption and sustainable development
- Operational expenditure reduction via minimization of **energy costs**
- The **widening gap** between the development of energy storage capabilities (i.e., batteries) and the advances in circuit design

Source: F. Alagöz and G. Gür. "Energy Efficiency and Satellite Networking: A Holistic Overview," *Proceedings of the IEEE* , vol.99, no.11, pp.1954-1979, Nov. 2011

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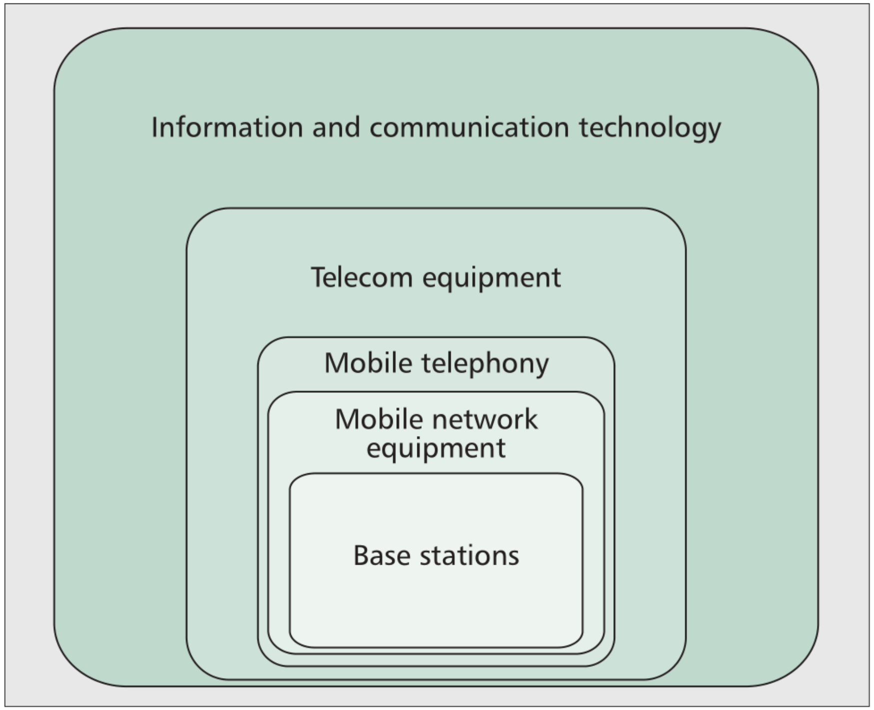
Where and how much energy consumption?



The proportions of energy consumption of different subsectors.

Detailed insight into the energy consumed to operate mobile telephony services reveals that **only around 10 percent** of the entire consumption is associated with the end-user equipment, while the **remaining 90 percent** is taken up by network components , of which around **two thirds** is used by the base stations (BSs) .

Source: Humar et al., "Rethinking energy efficiency models of cellular networks with embodied energy," *IEEE Network,* vol.25, no.2, pp.40,49, March-April 2011.

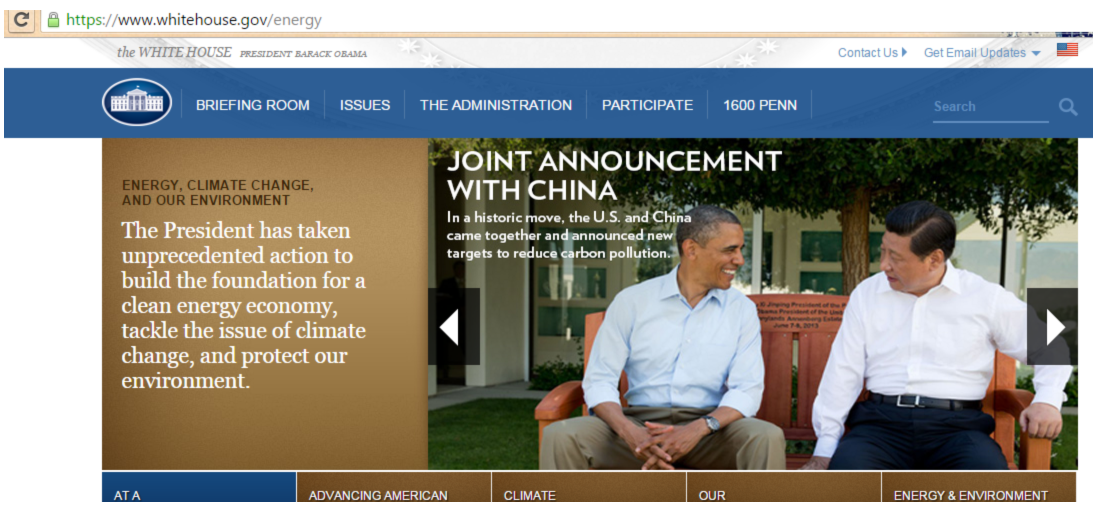
Policy makers

- The European Council has endorsed achieving **at least 27% renewable energy** in the EU's final energy consumption and a **27% or greater improvement in energy efficiency by 2030**.

23 October, 2014

European Commission

http://ec.europa.eu/energy/en/news/european-council-agrees-climate-and-energy-goals-2030



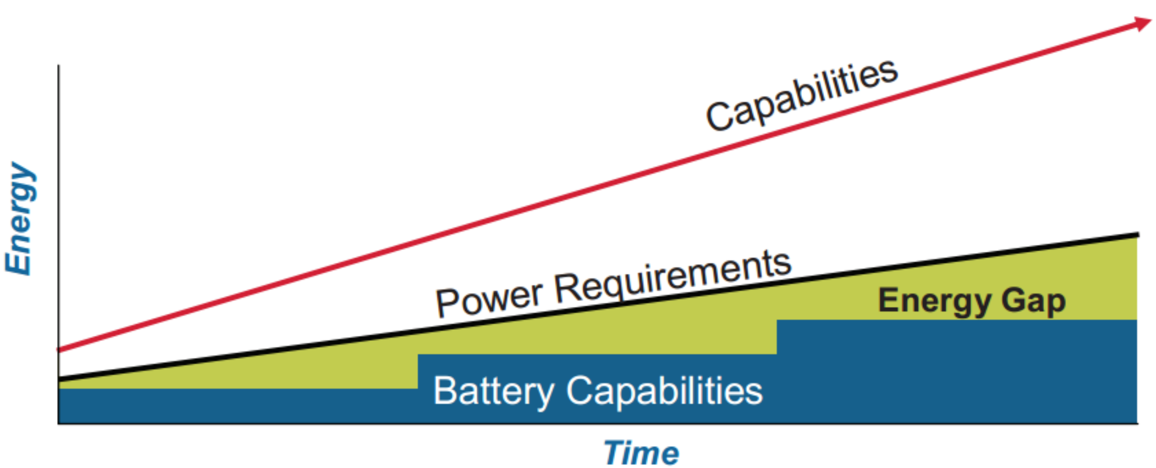
https://www.whitehouse.gov/energy

"In November 2014, in a historic joint announcement with China, President Obama laid out an ambitious but achievable target to reduce greenhouse gas emissions in the United States in **the range of 26 to 28 percent below 2005 levels by 2025."**

The chasm between battery capacity and surge in mobile data demand

The sluggish improvement in battery technology , increasing a **modest 10% every two years** → **exponentially** increasing gap between the demand for energy and the battery capacity offered.

The shrinking device sizes → ergonomic limit on the battery capacity available.



Source: Miao, G. et al, "Cross-layer optimization for energy-efficient wireless communications: A survey," *Wirel. Commun. Mob. Comput.*, 9: 529–542, 2009.

C. Chun and A. Barth. eXtreme energy conservation for mobile communications. *Freescale Technology Forum* , July 2006.

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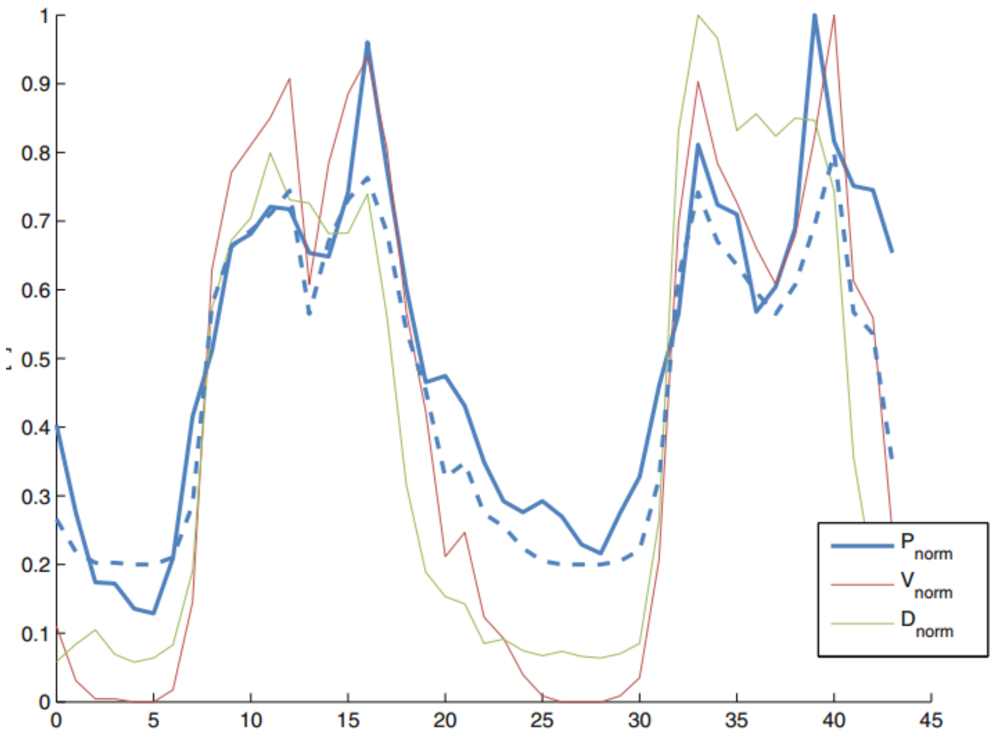
Mobile networks are extremely dynamic



Example: User behavior and traffic load

Comparison of P_{norm} (power), V_{norm} (voice calls), and D_{norm} (data calls) as a function of time during 24 h for a HSPA macrocell base station (suburban environment, Belgium)

Source: Deruyck et al. "Characterization and optimization of the power consumption in wireless access networks by taking daily traffic variations into account," *EURASIP Journal on Wireless Communications and Networking* 2012 2012:248.

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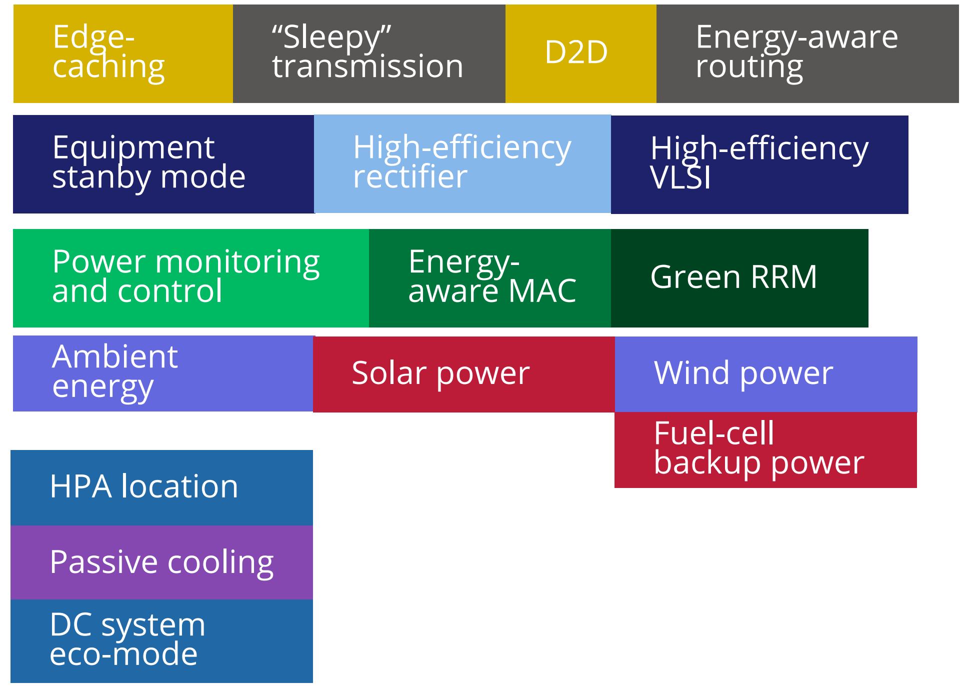
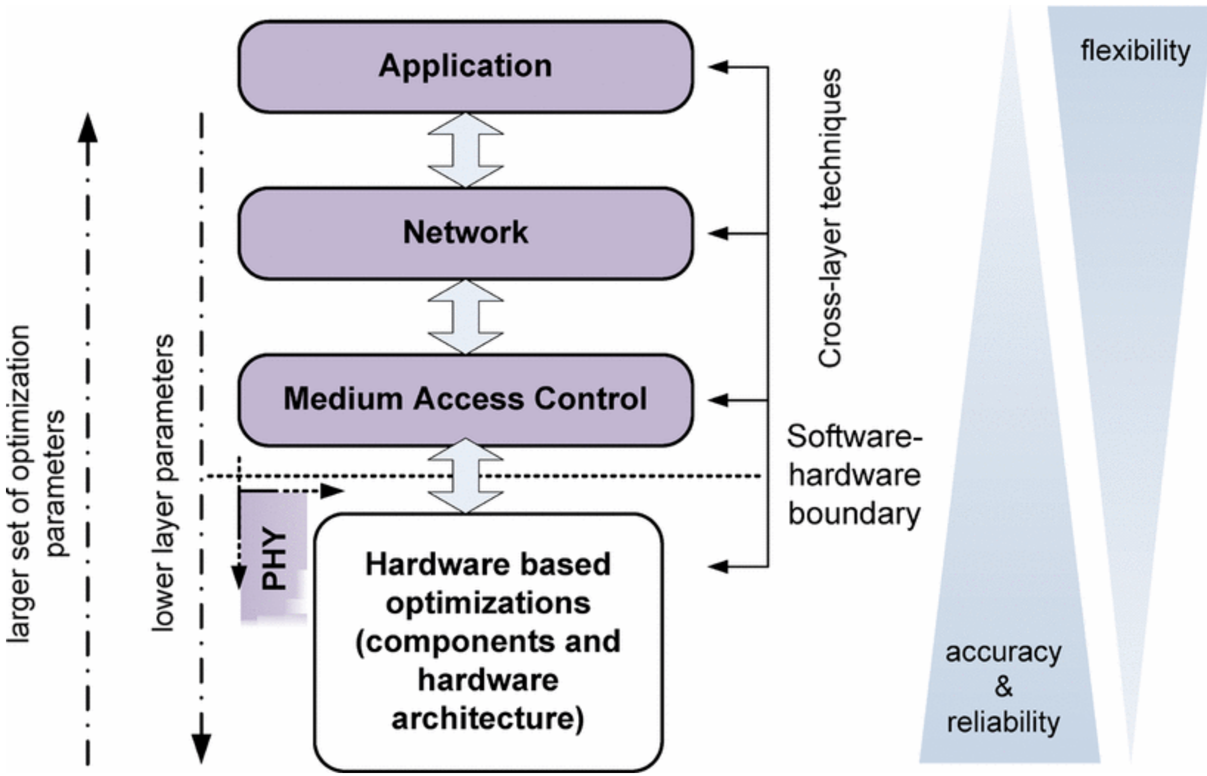
Greenfield design: Toolbox

- Energy-oriented network and application design
- New generation energy-efficient hardware
- Energy optimized algorithms
- New energy sources
- Energy-aware network node design
  - Access network
  - Mobile device
  - Core and transport network



Optimization levels for power minimization



Cross-layer problem

Source: F. Alagöz and G. Gür. "Energy Efficiency and Satellite Networking: A Holistic Overview,“ *Proceedings of the IEEE* , vol.99, no.11, pp.1954-1979, Nov. 2011

Energy efficiency metrics

Energy efficiency is formally defined as **the number of bits that can be successfully transmitted with unit energy consumption:**

- Bits-per-Joule capacity

$$B_e = \left[W \log_2\left(1 + \frac{P}{WN_0}\right)\right] / P$$

- Energy-per-bit

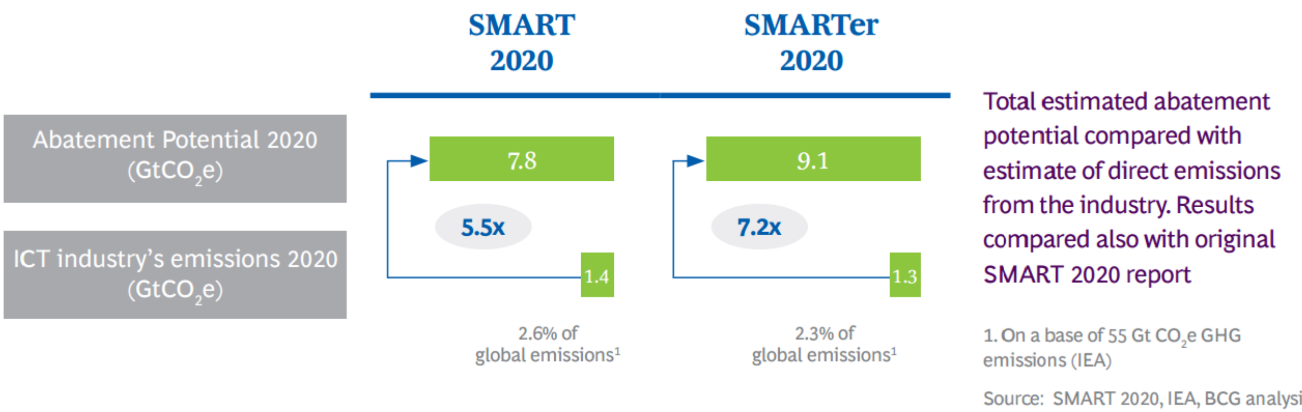
$$t_b = \frac{1}{R} = \left[W \log_2\left(1 + \frac{P}{WN_0}\right)\right]^{-1}$$

$$\Rightarrow E_b = Pt_b = (2^{\frac{1}{Wt_b}} - 1)WN_0 t_b$$

Initiatives and standardization

ETSI performs energy efficiency related work in support of European Commission Mandates. Several of ETSI's Technical Committees (TCs) are actively involved in specifying technologies to improve energy efficiency.

ITU-R Working Party 5D (WP 5D) - IMT Systems



Aim: Deliver the architecture, specifications and technologies – and demonstrate key components needed to increase network energy efficiency by a factor of 1000 compared to 2010 levels

www.greentouch.org

More than 40 partners

ITU measurement standard

ITU L.1310, “Energy efficiency metrics & measurement methods for telecommunications equipment”

$$Energy\ efficiency = \frac{functional\ unit}{energy\ needed\ to\ deliver\ that\ \ functional\ unit}$$

- Functional units. «bits»
- Variants on «joules per bit»
  - Instantaneous $$E(t) = \frac{P(t)}{C(t)}$$
  - Average instantaneous $$\langle E(t;T) \rangle = \frac{1}{T} \int_{t}^{t+T} \frac{P(t')}{C(t')} dt'$$
  - Total energy/total bits $$\bar{E}(t;T) = \int_{t}^{t+T} P(t')dt' \Big/ \int_{t}^{t+T} C(t')dt'$$

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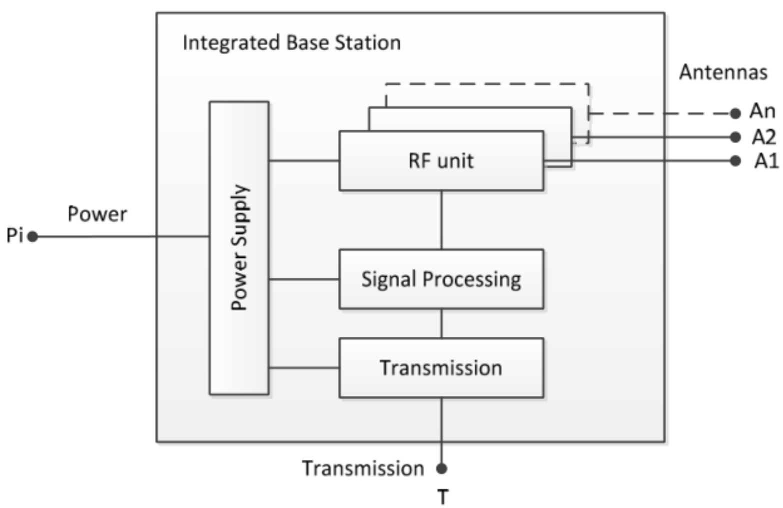
ETSI - Power consumption and EE of wireless access network equipment - I

Static Measurement procedure by ETSI:

The average power consumption [W] of integrated BS equipment in static method is defined as:



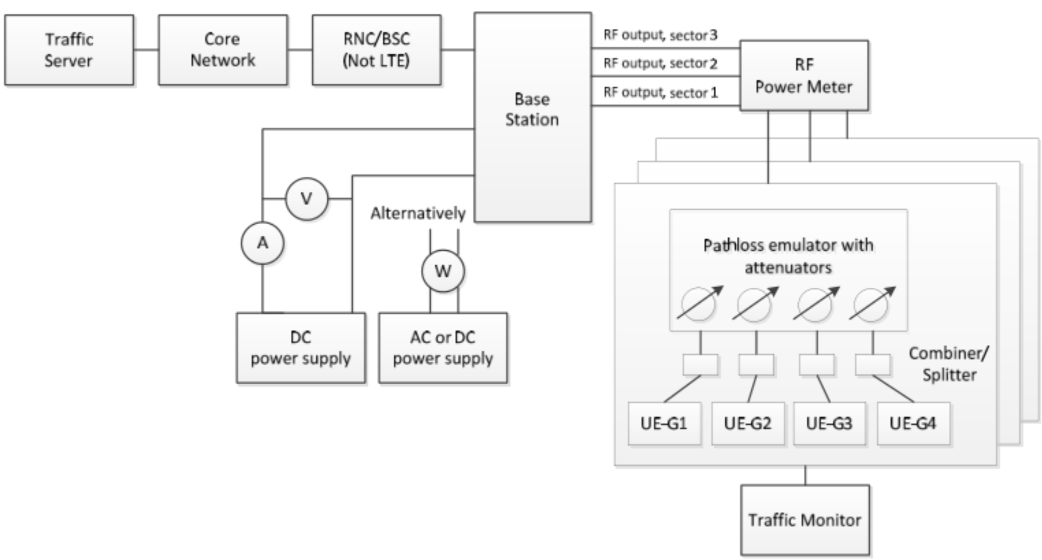
$$P_{equipment,static} = \frac{P_{BH} \cdot t_{BH} + P_{med} \cdot t_{med} + P_{low} \cdot t_{low}}{t_{BH} + t_{med} + t_{low}}$$

P_{BH} is the power consumption with busy hour load.
P_{med} is the power consumption with medium term load.
P_{low} is the power consumption with low load.

Source: ETSI ES 202 706 V1.4.1 (2014-12), *Environmental Engineering (EE); Measurement method for power consumption and energy efficiency of wireless access network equipment*

Power consumption and EE of wireless access network equipment - II

Dynamic Measurement procedure by ETSI:



Test setup with a three sectors BS

- Capacity test procedure
- Coverage efficiency test procedure
- Uncertainty

Power consumption and EE of wireless access network equipment - III

The global efficiency indicator $EE_{equipment}$

LTE

$$EE_{equipment} = \frac{\sum_{ALx=1}^{l} c_{ALx} \cdot DV^{ALx}}{\sum_{ALx=1}^{l} c_{ALx} \cdot E_{equipment}^{ALx}} \quad [\text{kbit/J}]$$

$$E_{equipment}^{ALx} = \frac{1}{n} \cdot \sum_{k=1}^{n} \left(\Delta t_m \cdot \sum_{i=1}^{T_D / \Delta t_m} P_{i,k,equipment}^{ALx} \right)$$

The average energy which is consumed by the BS during one duty cycle period and for the x^{th} activity level **[J]**

$$DV^{ALx} = \frac{1}{n} \cdot \sum_{k=1}^{n} \left(\sum_{j=1}^{m} DV_{j,k}^{ALx} \right)$$

The average net data volume during one duty cycle period and x^{th} activity level **[kbit]**

$$EE_{equipment}^{ALx} = \frac{DV^{ALx}}{E_{equipment}^{ALx}}$$

The efficiency indicator for x^{th} activity level **[kbit/J]**

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Research projects

Energy Aware Radio and Network Technologies : Effective mechanisms to drastically reduce energy wastage and improve energy efficiency of mobile broadband communication systems, without compromising users perceived "quality" of service and system capacity.
2010 -2012
15 partners

Towards Real Energy-efficient Network Design : TREND aims at integrating the activities of major European players in networking, including manufacturers, operators, research centers, to quantitatively assess the energy demand of current and future telecom infrastructures, and to design energy-efficient, scalable and sustainable future networks. http://www.fp7-trend.eu/
2011-2013
12 Partners

Cognitive Radio and Cooperative Strategies for POWER saving in multi-standard wireless devices : research, develop and demonstrate energy saving technologies for multi-standard wireless mobile devices, exploiting the combination of cognitive radio and cooperative strategies www.ict-c2power.eu
2010-2012
10 partners

Research projects

'Demonstration project for power supply to telecom stations through FC technology' : Hydrogen and fuel cell technologies as key enabling technology for radio base stations (RBSs) powered by renewable energies; 15 RBS installations live in Italy and 2 in Europe research centres
2012-2015, 6 partners
http://fcpoweredrbs.eu/

Analysis, design, and optimization of energy efficient wireless communication systems and networks.
Initial Training Network (ITN) Marie Curie project
http://www.fp7-greenet.eu/

Studying and exploiting dynamic adaptive technologies (based on standby and performance scaling capabilities) for wired network devices that allow saving energy when a device (or part of it) is not used.
2010-2013
https://www.econet-project.eu/

Research projects

Connectivity management for eneRgy Optimised Wireless Dense networks : Targets very dense heterogeneous wireless access networks and integrated wireless-wired backhaul networks
2012-2015, 7 partners
http://www.ict-crowd.eu/

Energy-aware layer of plug-in on top of the current data centres' management tools to orchestrate the allocation of ICT resources and turning off unused equipments
2010-2013, 10 partners
http://www.fit4green.eu/

Research projects

Green Terminals for Next Generation Wireless Systems - **Aim:** Overcome the energy trap of 4G mobile systems by investigating and demonstrating energy saving technologies for multi-standard wireless mobile devices
2011-2014, 9 partners
http://greent.av.it.pt/

Spectrum and energy efficiency in 4G communication systems and beyond - **Aim:** Designing and validating new techniques for spectrum and energy efficiency in 4G communication systems and beyond
2010 – 2014, 7 partners
http://spectra-celtic.eu/

Beyond the conventional

- For a more **accurate** and **holistic** energy efficiency analysis, a communication system should be analyzed from a broader perspective
  - From the **system level** to the **component level**
  - From **manufacturing process** to the **maintenance of the system**
  - **Alternative metrics**

    Not only the throughput capacity or energy consumption performance of the system, but other quality-of-service (QoS) related metrics and spatial efficiency (bits per Joule per unit area)]

General EE in wireless comm. research

Systemic Solutions

Domain-specific or driven solutions

Auxilliary Endeavors

Empirical Findings

Emerging Systems/ Technologies

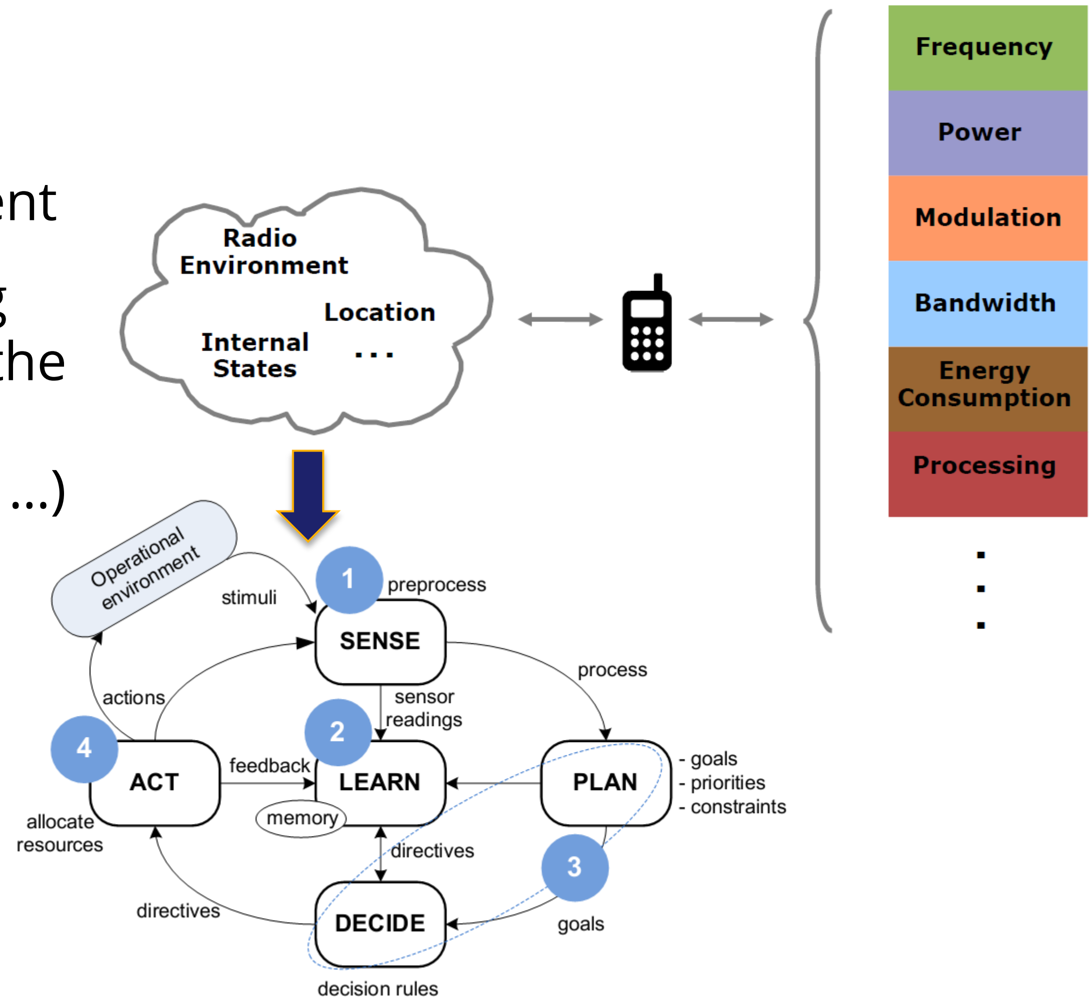
OUR TOPIC

EE and Cognitive Radios

Cognitive Radio (CR): The grand idea

A radio that is

- **Aware** of its environment
- Can **adapt** its operating parameters according to the **environment** (spectrum, application configuration, ...)
- Agile, adaptive, and **learning** → Efficient utilization of resources



Energy consumption components in CR

Energy consumption component		Note
Transmission	P_t	Usually proportional to transmission amount
Frequency Switching	P_f	Usually proportional to frequency separation
Sensing	P_s	Usually proportional to sensing duration
Processing	P_p	Usually proportional to processed data quantity
Control and signaling overhead	P_c	Depends on the network protocol and configuration
Idling	P_i	Depends on hardware attributes, proportional to idling duration
Deep sleep	P_d	Depends on hardware attributes, proportional to deep-sleep duration
….	…..	…….

Power consumption of a wireless transceiver – some representative figures *

Mode	802.11b	802.11a	802.11g
Sleep	132 mW	132 mW	132 mW
Idle	544 mW	990 mW	990 mW
Receive	726 mW	1320 mW	1320 mW
Transmit	1089 mW	1815 mW	1980 mW

$$\text{Energy consumption} = f\,(P_x)$$

Source: *Miao, G. et al, “Cross-layer optimization for energy-efficient wireless communications: A survey,” *Wirel. Commun. Mob. Comput.*, 9: 529–542, 2009.

Example work on CR EE

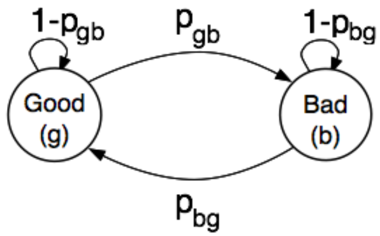
M. Emre, G. Gür, S. Bayhan , and F. Alagöz, «CooperativeQ: Energy-Efficient Channel Access Based on Cooperative Reinforcement Learning,» *IEEE ICC 2015, Workshop on Next Generation Green ICT*, London, UK, June 2015.

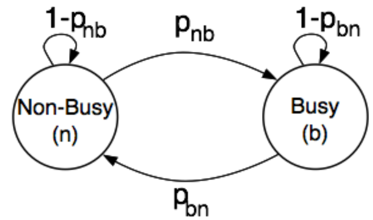
- A CRN which consists of a set of (non)cooperative CRs seeking for spectrum opportunities in *M* primary user channels.
- The objective of each CR is to transmit the packets in its buffer with maximum EE while not causing a buffer overflow.
- Each CR can adapt its power to one of *K* different transmission power levels

$$P_{tx}(k) = P_k \in \mathcal{P} = \{P_1, P_2, \cdots, P_K\}$$

System model

- Gilbert-Elliot Channels & Traffic
- Time Slot Structure: Backoff, **Switch**, Sense, Transmit
- CR Actions & Outcomes
  1. Staying idle
  2. Correct detection of spectrum opportunity
  3. All packets are lost in channel
  4. False alarm
  5. Correct detection of PU presence
  6. Misdetection of spectrum opportunity





$$E_1 = P_{id}T_{slot}.$$
$$\begin{aligned}E_2 = {} & |f-i|t_{sw}P_{sw}+t_sP_s+t_{tx}(f,k,t)P_{tx}(k)\\ & +P_{id}(T_{slot}-t_s-t_{sw}|f-i|-t_{tx}(f,k,t)).\end{aligned}$$
$$E_3 = |f-i|t_{sw}P_{sw}+t_sP_s+P_{id}(T_{slot}-t_s-t_{sw}|f-i|).$$
$$E_4 = |f-i|t_{sw}P_{sw}+t_sP_s+P_{id}(T_{slot}-t_s-t_{sw}|f-i|).$$
$$E_5 = |f-i|t_{sw}P_{sw}+t_sP_s+P_{id}(T_{slot}-t_s-t_{sw}|f-i|).$$
$$\begin{aligned}E_6 = {} & |f-i|t_{sw}P_{sw}+t_sP_s+t_{tx}(f,k,t)P_{tx}(k)\\ & +P_{id}(T_{slot}-t_s-t_{sw}|f-i|-t_{tx}(f,k,t)).\end{aligned}$$

$$r_1(s,a) = -\beta_{idle}\mathcal{R}\frac{T_{slot}}{E_1}$$
$$r_2(s,a) = \frac{b}{E_2}$$
$$r_3(s,a) = -\beta_{loss}\mathcal{R}\frac{T_{slot}}{E_3}$$
$$r_4(s,a) = -\mathcal{R}\frac{T_{slot}}{E_4}$$
$$r_5(s,a) = -\beta_{idle}\mathcal{R}\frac{T_{slot}}{E_5}$$
$$r_6(s,a) = -\beta_{md}\mathcal{R}\frac{T_{slot}}{E_6}$$

System parameters

Total simulation time t_{total}	30000 time slots = 300 s
Number of agents N_{agent}	7
Number of stationary agents	$\lfloor \frac{N_{agent}}{2} \rfloor$
Number of channels N_{ch}	5
Number of Type-I channels $N_{C_{\mathrm{I}}}$	{1, 3, 5}
Radius of simulated area r_{init}	5000 m
Buffer size M_{max}	2560 packets = 320 KiB
Packet size L	1024 bits
Package generation rate per agent	$N \sim \mathcal{U}(n;0,8)\,\frac{\text{packets}}{\text{time slot}}$
Base transmission power P_{tx}	200 mW
Transmission powers $\mathcal{P}$	$\{0.5P_{tx}, P_{tx}, 2P_{tx}, 4P_{tx}\}$
Switching power P_{sw}	$0.5P_{tx}$
Sensing power P_s	$0.5P_{tx}$
Idle power P_s	$0.2P_{tx}$
Time slot duration T_{slot}	10 ms
Sensing time t_s	$0.1T_{slot}$
Switching time between adjacent channels t_{sw}	$0.05T_{slot}$
Frequency of first channel F_0	900 MHz

Channel bandwidth W	1 MHz
Spectral noise densities N_0 of Type-I channels	$N_{0_{good}} = -158.2\frac{\text{dBmW}}{\text{Hz}}$, $N_{0_{bad}} = -157.2\frac{\text{dBmW}}{\text{Hz}}$
Spectral noise densities N_0 of Type-II channels	$N_{0_{good}} = -156.7\frac{\text{dBmW}}{\text{Hz}}$, $N_{0_{bad}} = -148.2\frac{\text{dBmW}}{\text{Hz}}$
Traffic generation probabilities $p_{traffic}$	Busy channel: 0.7, Non-busy channel: 0.3
State transition probabilities of channels	$p_{gb} = 0.05$, $p_{bg} = 0.4$
Transition probabilities of traffic states	$p_{nb} = 0.3$, $p_{bn} = 0.9$
Bitrate that agents transmit $\mathcal{R}$	3.75 Mbps
Q-Learning Parameters	
Buffer levels B	6
Exploration probability ε	0.03
Discount factor γ	0.2
β_{idle}	{0.5, 1, 8, 20}
β_{md} and β_{loss}	1 and 2
Sharing period $T_{sharing}$	$\{500, 1000, 2000\}$ time slots

May turn into complex models

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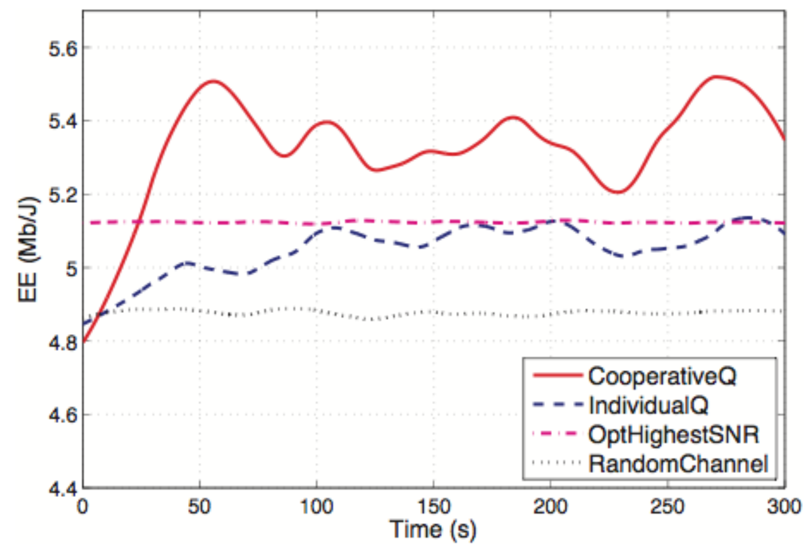
Cooperative Q-Learning

- *Q-Learning:* Converging to a reward-maximizing policy. Define rewards and penalties in terms of EE
- *Expertness-Based Cooperative Q-Learning:* Periodically update Q-values with **weighted sum of Q-values based on expertness** to combine knowledge of learners.
- Greedy behavior
- Sensitive to parameters

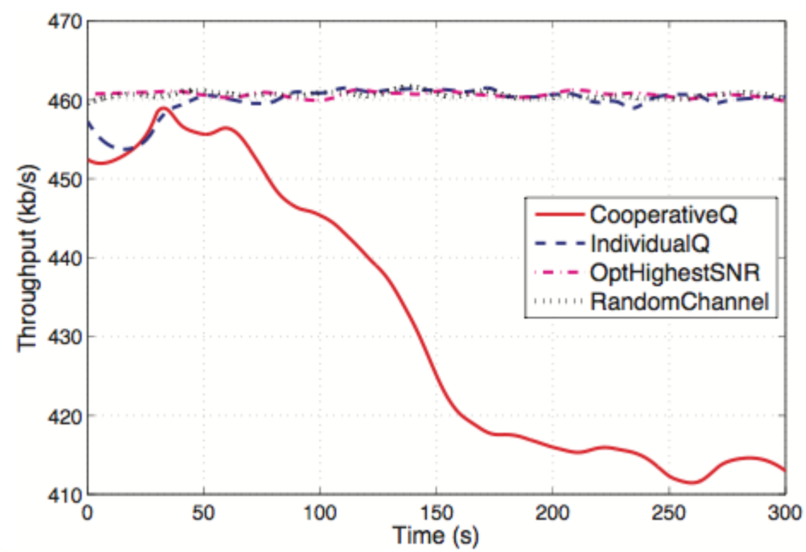
▷ Cooperative Learning
  Choose $\mathcal{E}_i$ among subsets of $\{1, 2, \ldots, N_{agent}\} \setminus \{i\}$
  $Q_i^{new} \leftarrow 0$
  for $j \leftarrow 1, \ldots, n$ **do**
    $e_j \leftarrow \sum_{t=1}^{now} r_j(t) u(r_j(t))$
  for $j \leftarrow 1, \ldots, n$ **do**
    $W_{ij} \leftarrow \text{ComputeWeights}(e_i, e_j, \mathcal{E}_i)$
    $Q_i^{new} \leftarrow Q_i^{new} + W_{ij} Q_j^{old}$

Results

- EE vs. Time and Throughput vs. Time, both smoothed using local regression.



- *CooperativeQ* maintains better EE in expense of throughput. The Q-Learning parameters (penalties) can be adjusted to get a more throughput-oriented algorithm.



Thank you

End of Part I

Preliminaries on energy efficiency in wireless networks

Reading list

1) G. Auer , I. Godor , L. Hevizi , M. Imran , J. Malmodin , P. Fazekas , G. Biczok , H. Holtkamp , D. Zeller , O. Blume and R. Tafazolli, "Enablers for energy efficient wireless networks“, *Proc. IEEE 72nd Veh. Technol. Conf. Fall*, 2010

2) F. Alagöz and G. Gür, "Energy Efficiency and Satellite Networking: A Holistic Overview," *Proceedings of the IEEE* , vol.99, no.11, pp.1954,1979, Nov. 2011

3) G. Gür and F. Alagöz "Green wireless communications via cognitive dimension: An overview", *IEEE Network*, vol. 25, no. 2, pp.50 -56 2011

4) Cisco VNI: Global Mobile Data Traffic Forecast 2014–2019, http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.pdf

5) A. Ephremides "Energy concerns in wireless networks", *IEEE Wireless Commun.*, vol. 9, no. 4, pp.48 -59 2002

6) C. Bae and W. Stark "Energy and bandwidth efficiency in wireless networks", *Proc. Int. Conf. Commun. Circuits Syst.*, vol. 2, pp.1297 -1302 2006.

7) Y. Chen , S. Zhang , S. Xu and G. Li "Fundamental trade-offs on green wireless networks", *IEEE Commun. Mag.*, vol. 49, no. 6, pp.30 -37 2011.

8) G. Miao , N. Himayat , Y. Li and A. Swami "Cross-layer optimization for energy-efficient wireless communications: A survey", *Wireless Commun. Mobile Comput.*, vol. 9, no. 4, pp.529 -542. 2009

Reading list

9) C. Han , T. Harrold , S. Armour , I. Krikidis , S. Videv , P. Grant , H. Haas , J. Thompson , I. Ku , C.-X. Wang , T. A. Le , M. Nakhai , J. Zhang and L. Hanzo "Green radio: Radio techniques to enable energy-efficient wireless networks", *IEEE Commun. Mag.,* vol. 49, no. 6, pp.46 -54 2011.

10) Deruyck et al. “Characterization and optimization of the power consumption in wireless access networks by taking daily traffic variations into account,” *EURASIP Journal on Wireless Communications and Networking* 2012 2012:248.

11) Humar, I.; Xiaohu Ge; Lin Xiang; Minho Jo; Min Chen; Jing Zhang, "Rethinking energy efficiency models of cellular networks with embodied energy," *Network, IEEE* , vol.25, no.2, pp.40,49, March-April 2011.

12) M. Emre, G. Gür, S. Bayhan , and F. Alagöz, “CooperativeQ: Energy-Efficient Channel Access Based on Cooperative Reinforcement Learning,” *IEEE ICC 2015, Workshop on Next Generation Green ICT*, London, UK, June 2015.

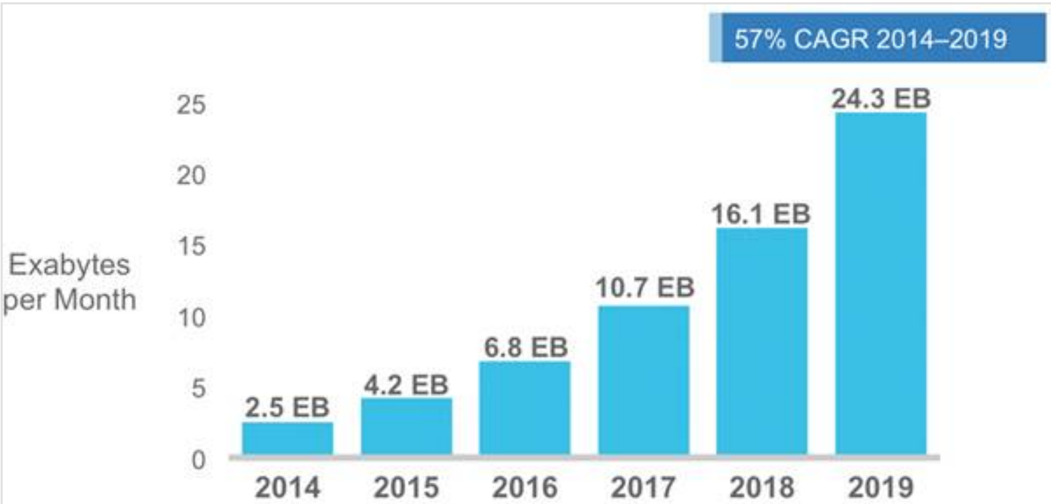
13) C. Chun and A. Barth, “eXtreme energy conservation for mobile communications”, *Freescale Technology Forum* , July 2006.

14) ETSI ES 202 706 V1.4.1 (2014-12), *Environmental Engineering (EE); Measurement method for power consumption and energy efficiency of wireless access network equipment.*

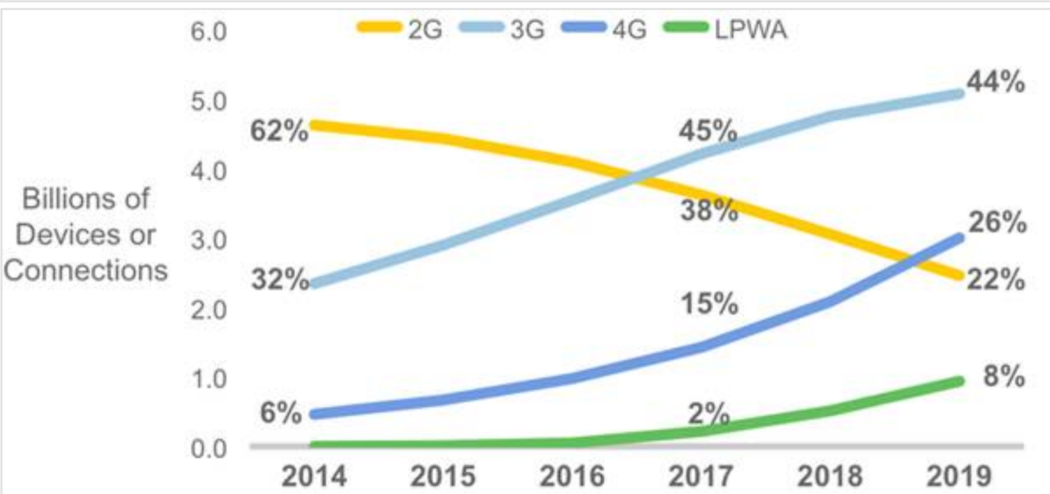
15) Eryigit, S.; Gür, G.; Bayhan, S.; Tugcu, T., "Energy efficiency is a subtle concept: fundamental trade-offs for cognitive radio networks," *Communications Magazine, IEEE* , vol.52, no.7, pp.30-36, July 2014

Additional Slides

Mobile data trends



Forecact: **24.3 Exabytes per Month of Mobile Data** Traffic by **2019**



Significant cross-over : In 2019, when 4G will also surpass 2G connection share. By 2019, 26 percent of all global devices and connections will be 4G-capable

Source: Cisco VNI: Global Mobile Data Traffic Forecast 2014–2019

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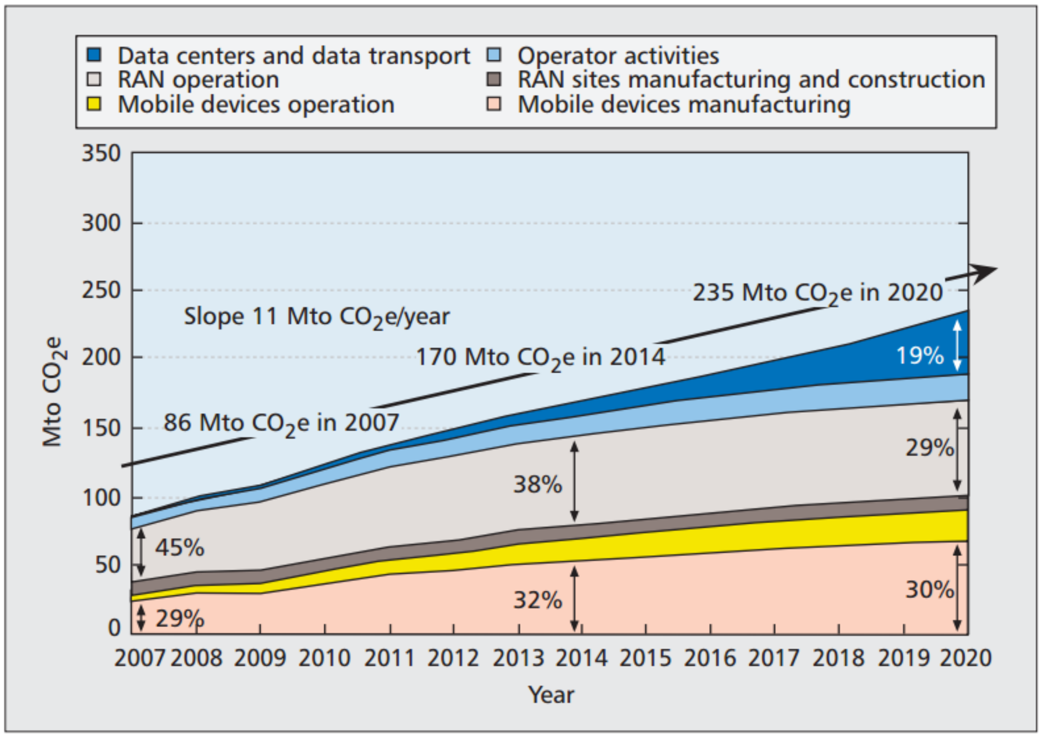
The total lifecycle of mobile comm.: Carbon footprint

- The entire lifecycle and activities surronding mobile communications

is a more inclusive view, e.g. carbon footprint:



- Manufacturing of mobile devices
- Mobile devices operation
- RAN sites manufacturing and construction
- RAN sites operation
- Operator activities
- Data centers and data transport

Source: Fehske, A.; Fettweis, G.; Malmodin, J.; Biczok, G., "The global footprint of mobile communications: The ecological and economic perspective," *IEEE Communications Magazine*, vol.49, no.8, pp.55,62, August 2011

Q-Learning

- An agent, states S_i and a set of actions A_i per state
- The goal of the agent is to maximize its total reward.
- It does this by learning which action is optimal for each state.
- The core of the algorithm is a simple **value iteration update.**

$$Q_{t+1}(s_t,a_t) = \underbrace{Q_t(s_t,a_t)}_{\text{old value}} + \underbrace{\alpha_t(s_t,a_t)}_{\text{learning rate}} \cdot \left(\overbrace{\underbrace{R_{t+1}}_{\text{reward}} + \underbrace{\gamma}_{\text{discount factor}} \underbrace{\max_a Q_t(s_{t+1},a)}_{\text{estimate of optimal future value}}}^{\text{learned value}} - \underbrace{Q_t(s_t,a_t)}_{\text{old value}} \right)$$

determines to what extent the newly acquired information will override the old information

determines the importance of future rewards

http://en.wikipedia.org/wiki/Q-learning

TUTORIAL

Energy Efficiency in Cognitive Radio Networks: Challenges, Trade-offs, and Solutions

Dr. Suzan Bayhan, University of Helsinki, Helsinki, Finland
Dr. Gürkan Gür, Provus - A MasterCard Company, Istanbul, Turkey
Dr. Salim Eryigit, Idea Technology, Istanbul, Turkey

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Outline

- Part I: Preliminaries on energy efficiency (EE) in wireless networks
  - Motivation
  - EE metrics
  - Initiatives and standardization
  - Research efforts
- Part II: 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
- Part III: Opportunities for (higher EE) CRNs
  - Short-range communications
  - Social-networks

Part II

Main trade-offs for EE in CRNs

Salim Eryigit

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

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

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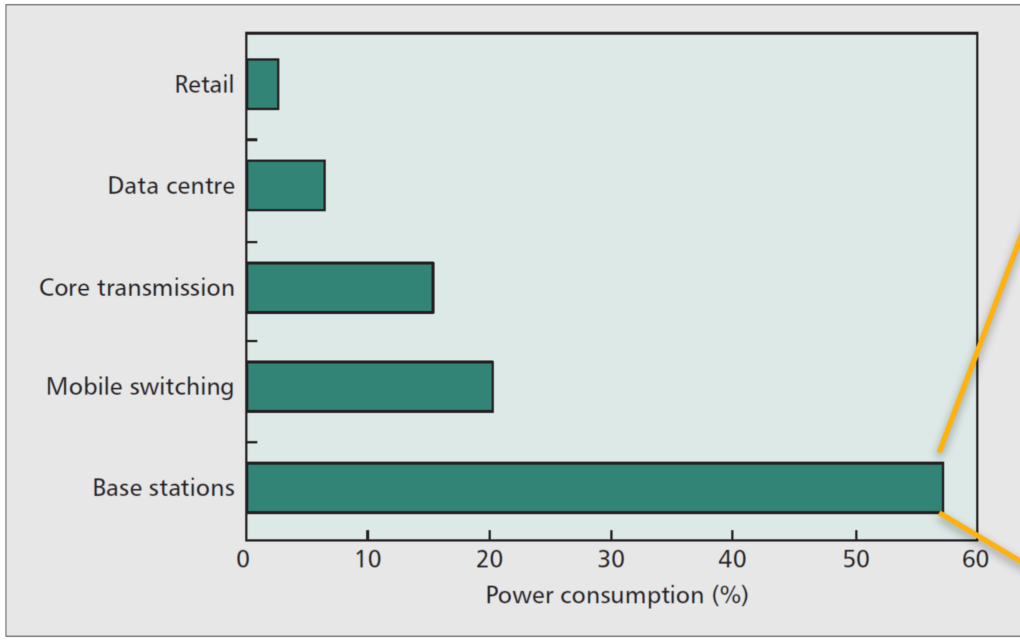
Energy breakdown of a mobile operator



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
  - Protocol and middleware support for EE
  - Hardware advances in RF components
  - Application support
- Core network
  - EE computing on core network
  - Flat all-IP mobile network
  - Network level sleep-mode
  - Optical switching and routing
- Network-wide enhancements

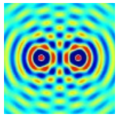
Additional benefits of CR

- Intelligent 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

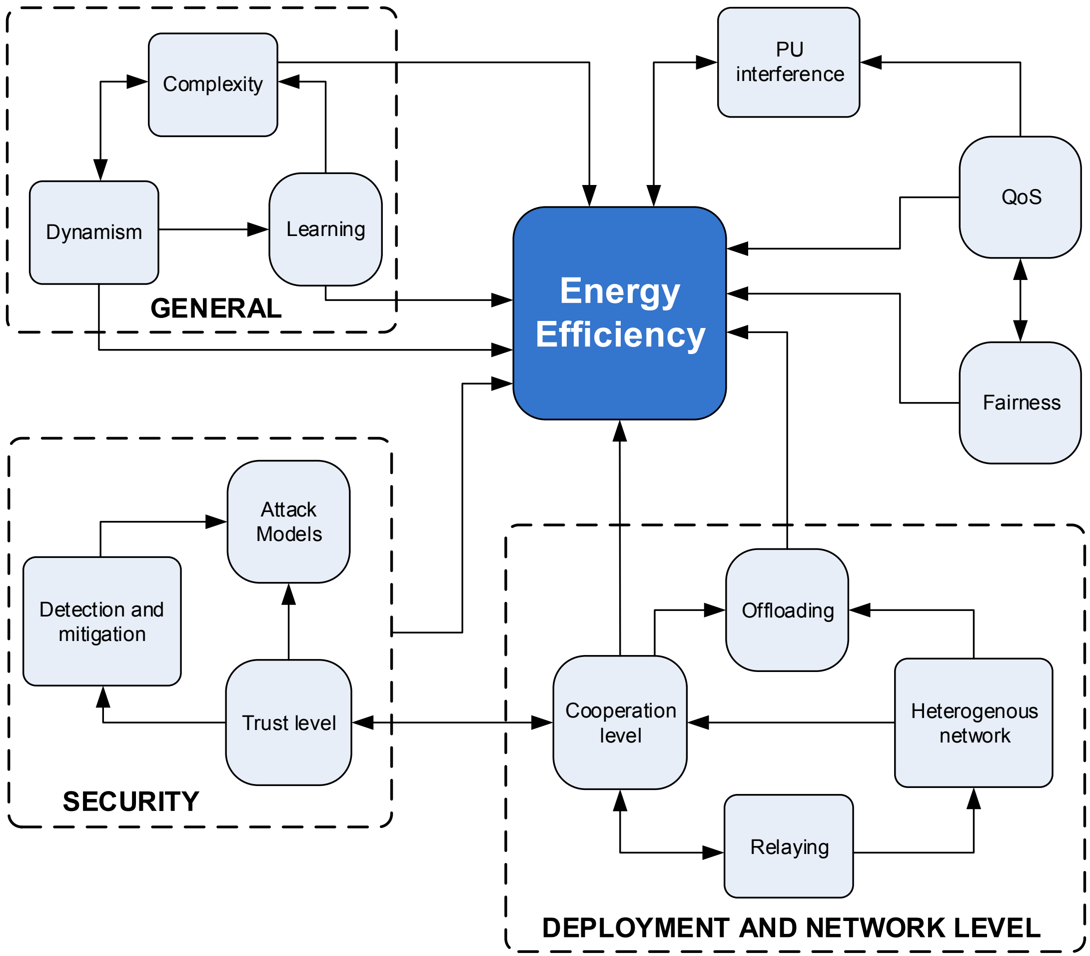


EE vs. PU Interference

EE vs. Network Architecture

EE vs. Security

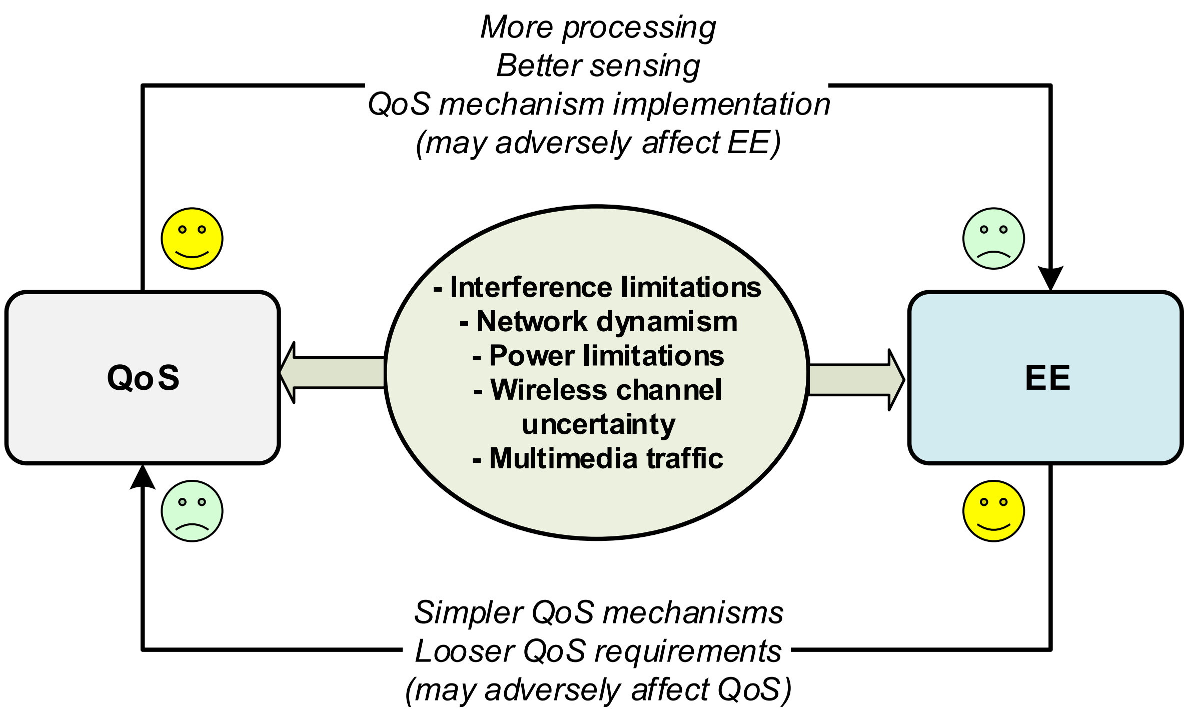
Each trade-off affects the others!!!



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.

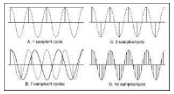
EE vs. QoS


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.

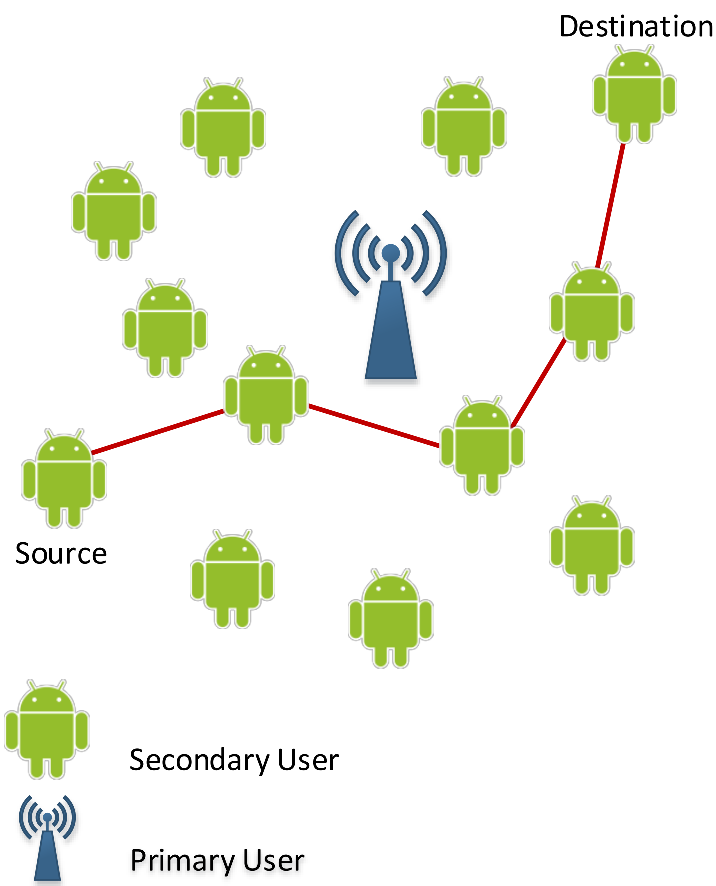
If QoS of SUs cannot be met, prioritization schemes can be used to increase user satisfaction.

EE vs. QoS

- CRN can exploit diversity techniques to enhance EE.
  - *Link diversity*: Among all candidate receivers, select the one with best link conditions.
  - *Channel diversity*: Employ the best channel for communication.
  - *CR diversity*: Utilize varying CR properties (e.g. SNR, hardware)
  - *Spatial diversity*: Better frequency reuse.
  - *Multi-radio diversity*: Use multiple channels at the same time. Requires multiple radio units. Hardware cost?
- 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, 25-30

EE vs. QoS



Multi-hop CRNs, e.g. CR adhoc networks.

- 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.

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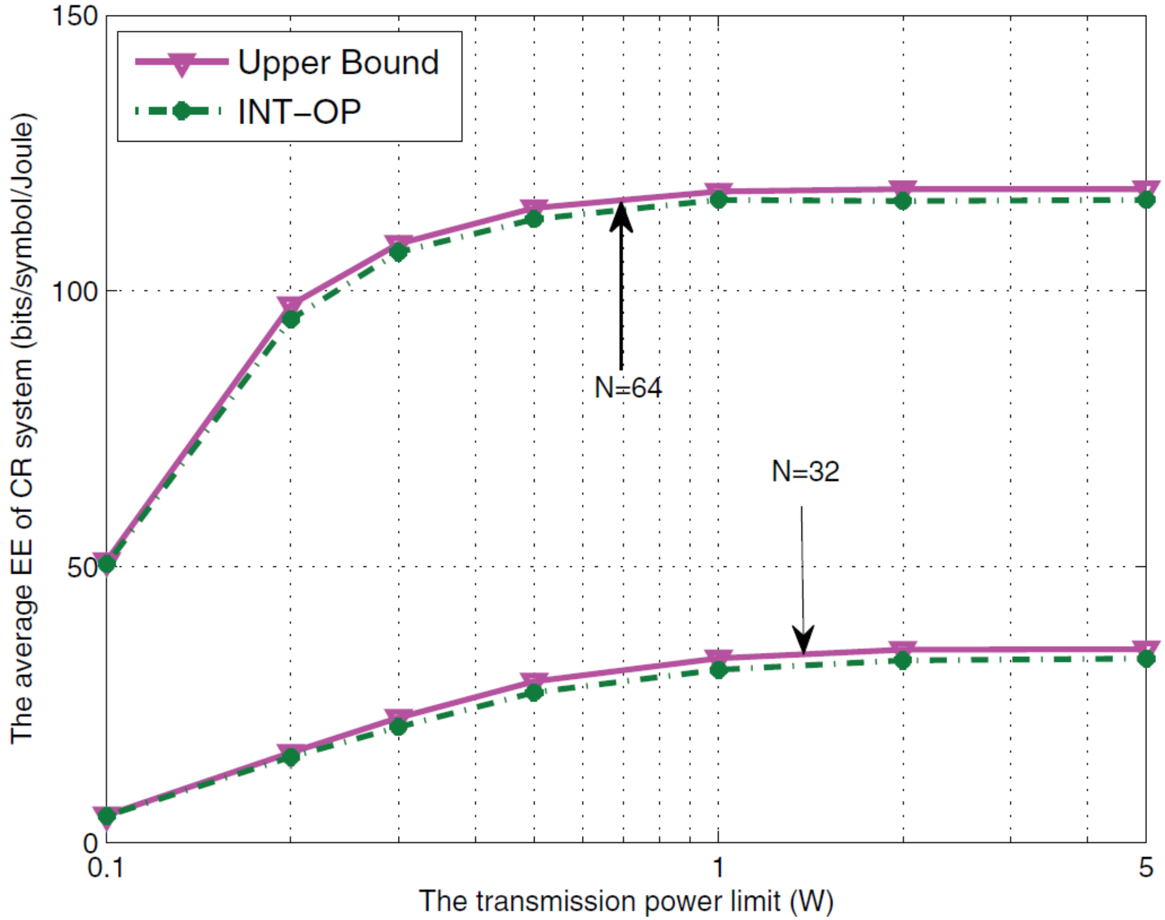
Example work on QoS

- 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)

Example work on QoS



N: number of subchannels

EE vs. fairness

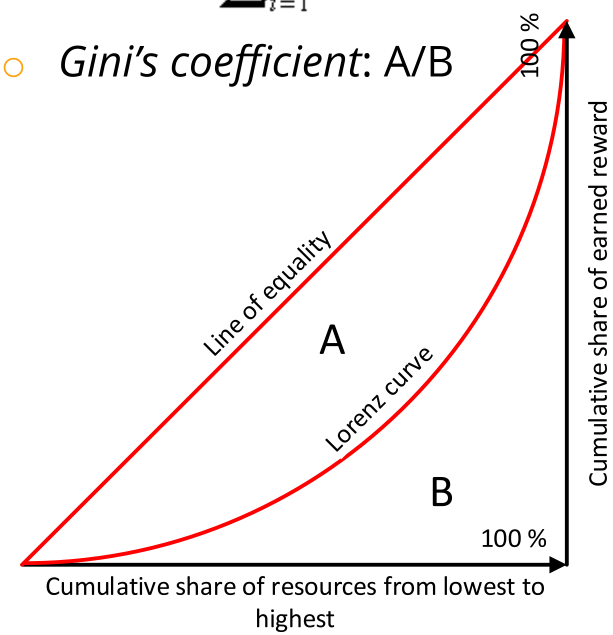
- Provide fairness for opportunistic spectrum access in a highly dynamic environment.
  - Also be energy-efficient.
  - Usually a secondary or a tertiary objective at best.
- In general energy efficiency favors unfairness.
  - e.g. Let the CR with minimum required transmission energy for a given throughput, 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

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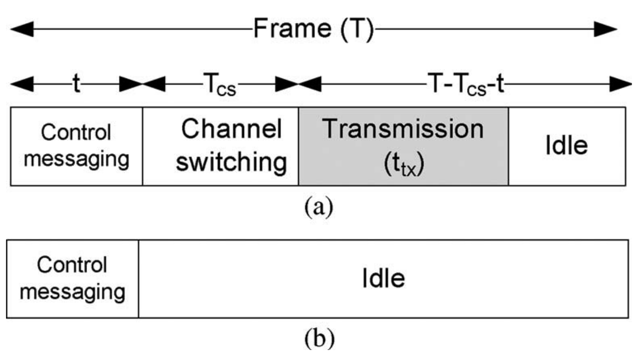
Example work on fairness

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

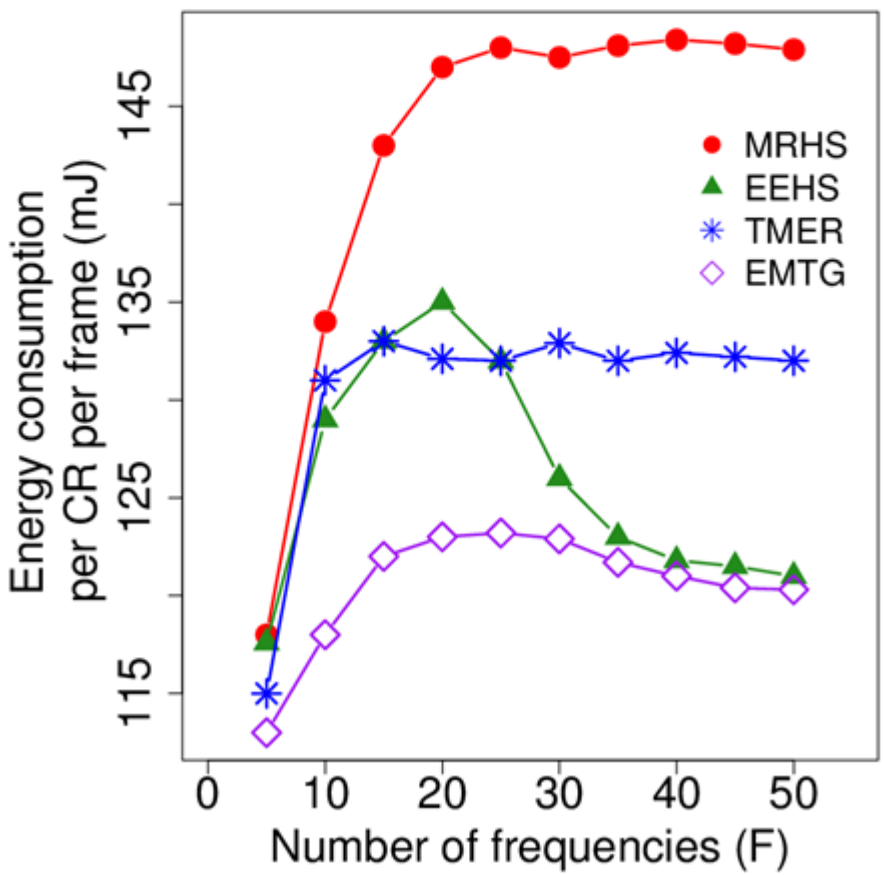
Scheduling algorithm

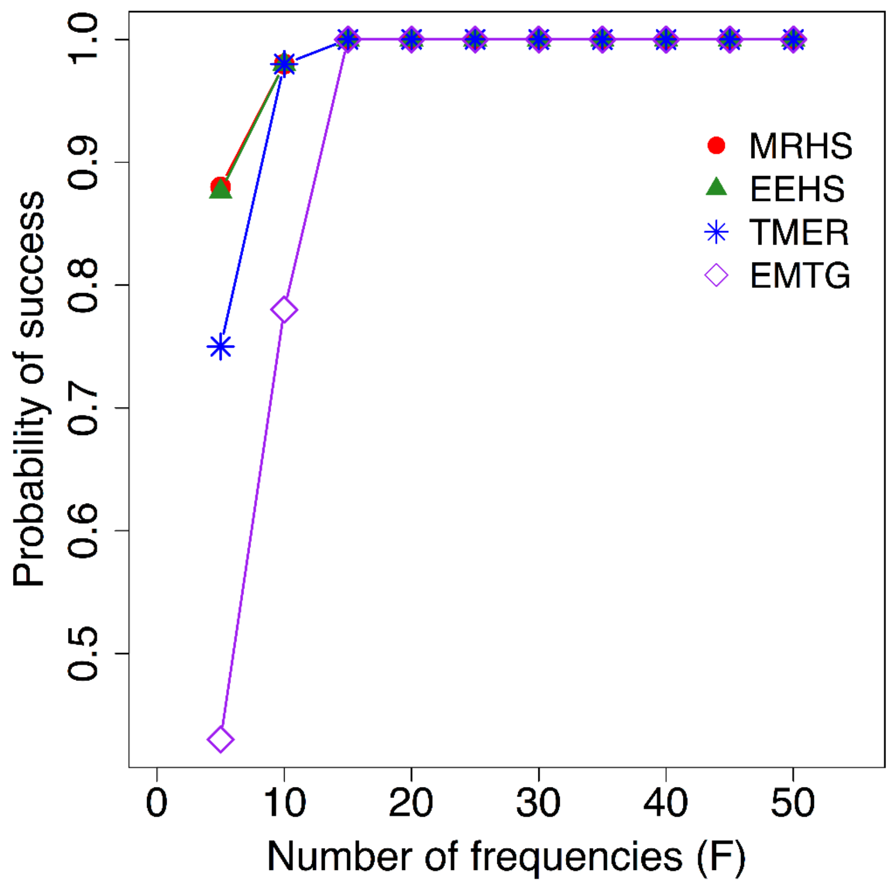
- Channel/SU assignments

Example work on fairness

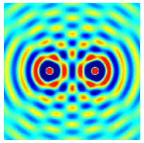
- This problem is solved by a heuristic (*EEHS*) that greedily makes assignments based on ***individual*** EE values.
- Three more alternatives are considered:
  - *TMER*: Throughput maximization with energy constraint. For calculating the throughput, a satisfaction ratio is used for prioritizing starving SUs.
  - *EMTG*: Energy minimization with throughput constraint. Satisfaction ratio is included for **fairness**.
  - *MRHS*: Pure throughput maximization.
  - All three alternatives can be solved to optimality.

Example work on fairness





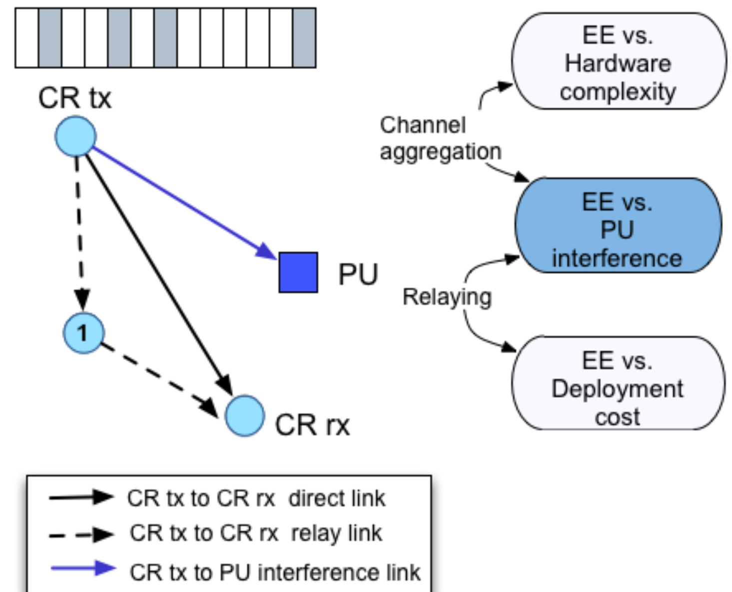
EE vs. PU interference



- *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.

Example work on PU interference

Objective

Maximize EE

- Total throughput/Total energy

System state

- Noise,
- Channel and power gains,

Constraints

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

Power allocation algorithm

- Transmission power levels of source and relay

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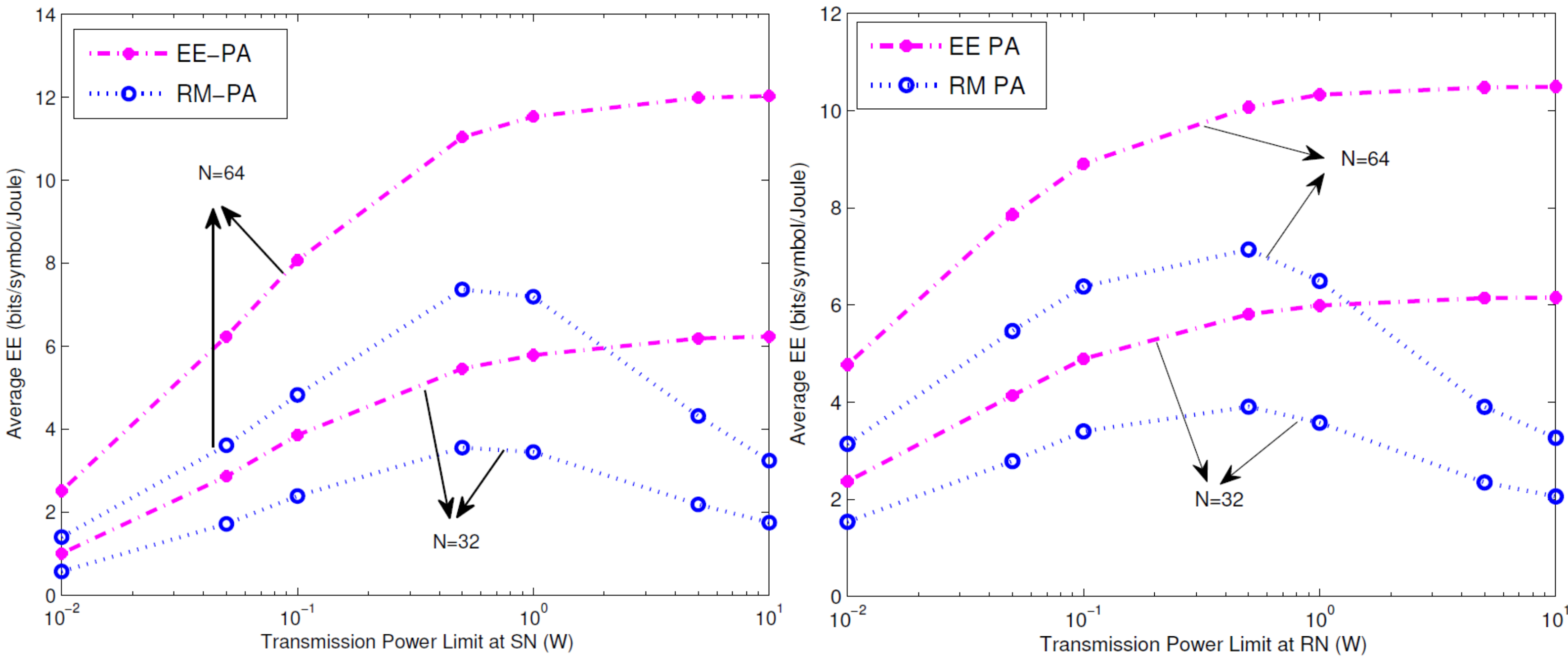
Example work on PU interference

Convex optimization methods are used for solution



N: number of subchannels.
EE-PA: Energy-efficient power allocation.
RM-PA: Rate adaptive (throughput optimal) power allocation.

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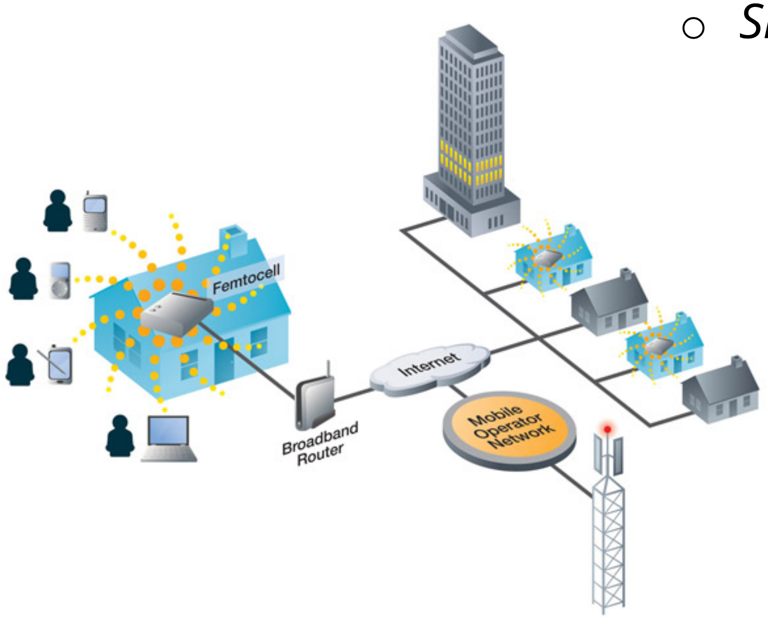
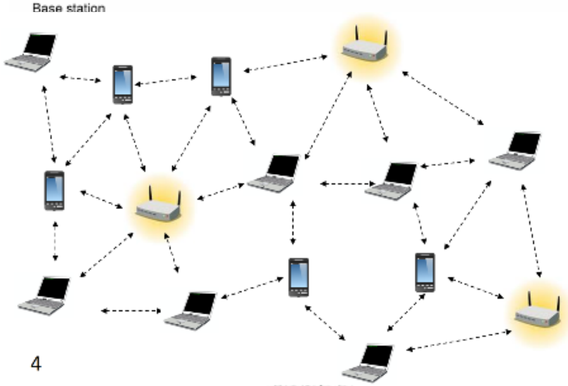
EE vs. network architecture

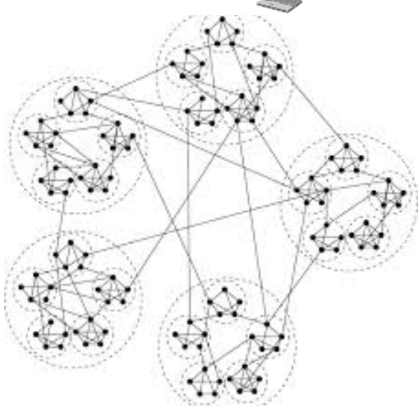
- General approach: Introduce additional hops to reduce transmission energy
  - How about QoS?



- *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

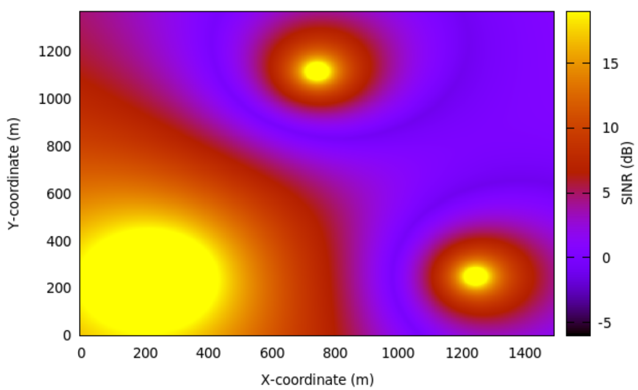




- *Relaying*
  - Amplify-and-forward vs decode-and-forward
  - Peer CRs vs dedicated relays
    - Peer CRs: Extra energy for relaying CRs, favorable CRs become bottlenecks.
  - Relaying may not be energy-efficient if traffic load is low, channel conditions are good, transmitter is close to receiver.
    - 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

- 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*
    - Not as energy efficient as it seems.



Pawełczak et al. "Will Dynamic Spectrum Access Drain My Battery?" Technical Report

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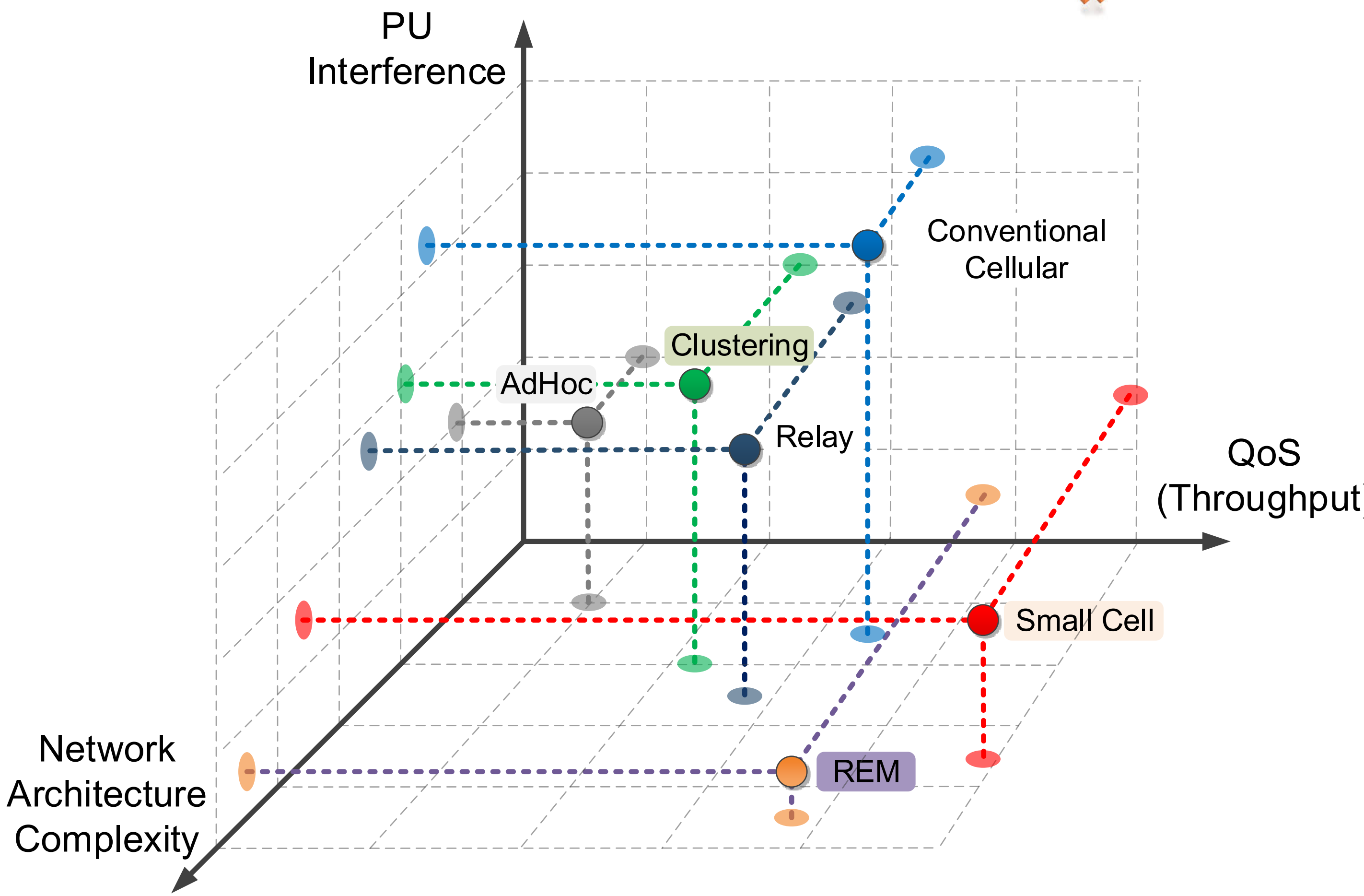
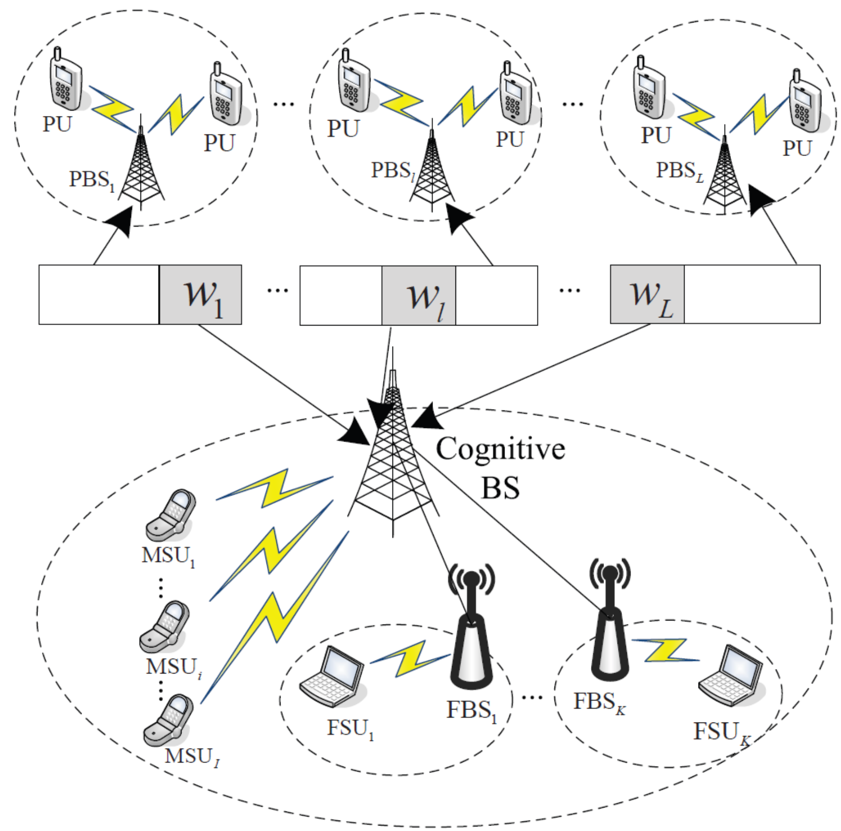
EE vs. network architecture



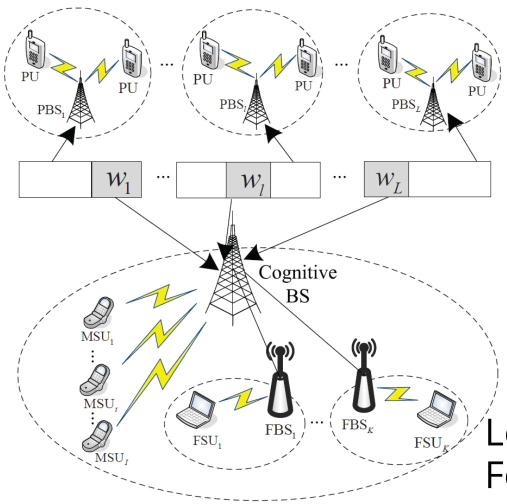
Example work on small cells

Xie, et al., "Energy-Efficient Resource Allocation for Heterogeneous Cognitive Radio Networks with Femtocells", IEEE ToWC, vol.11, no. 11, 2013, pp. 3910-20.

- A heterogeneneous CR is considered:
  - Mobile SUs (*MSUs*) directly connected to macrocell,
  - Femtocell SUs (FSUs) connected to femtocell BS (*FBS*).
- Primary networks offer to lease their spectrum resource (***w***) to CRN with a price (***c***).
- The problem is modeled as a three-stage Stackelberg game



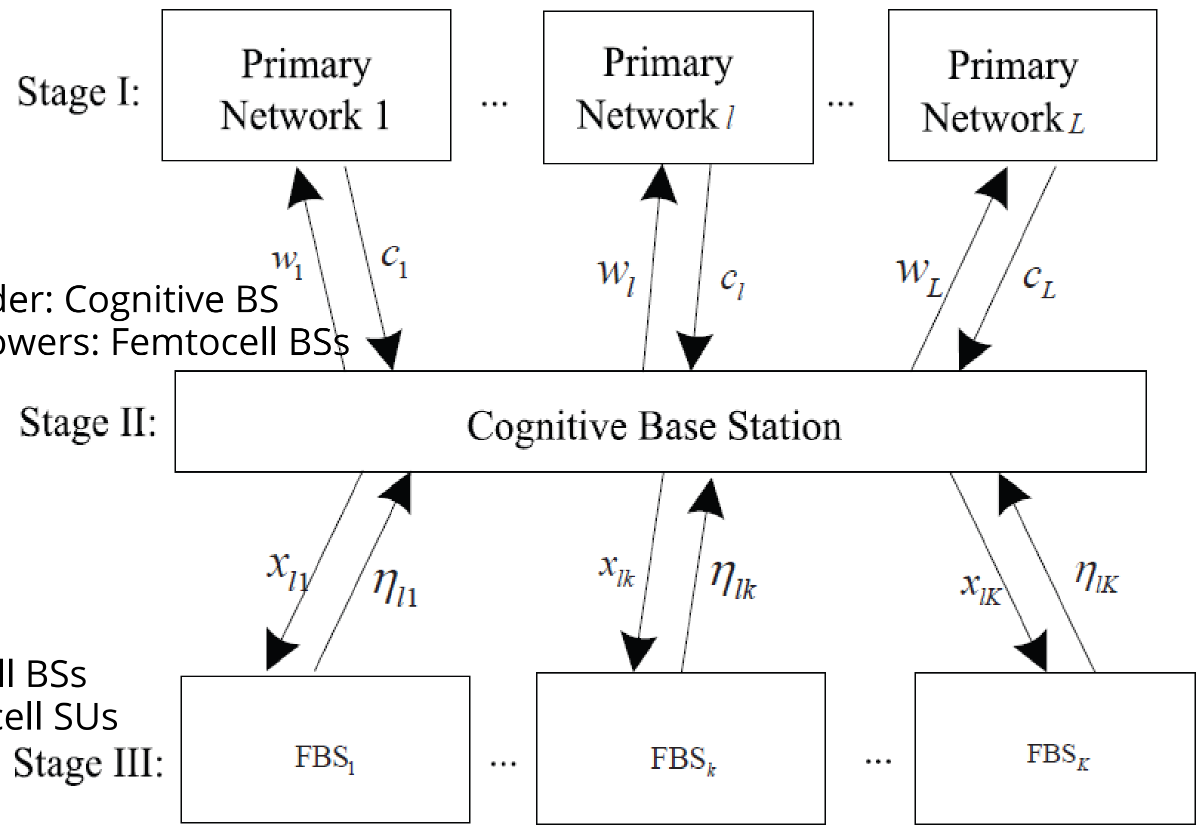
Example work on small cells



Leaders: Primary networks
Follower: Cognitive BS

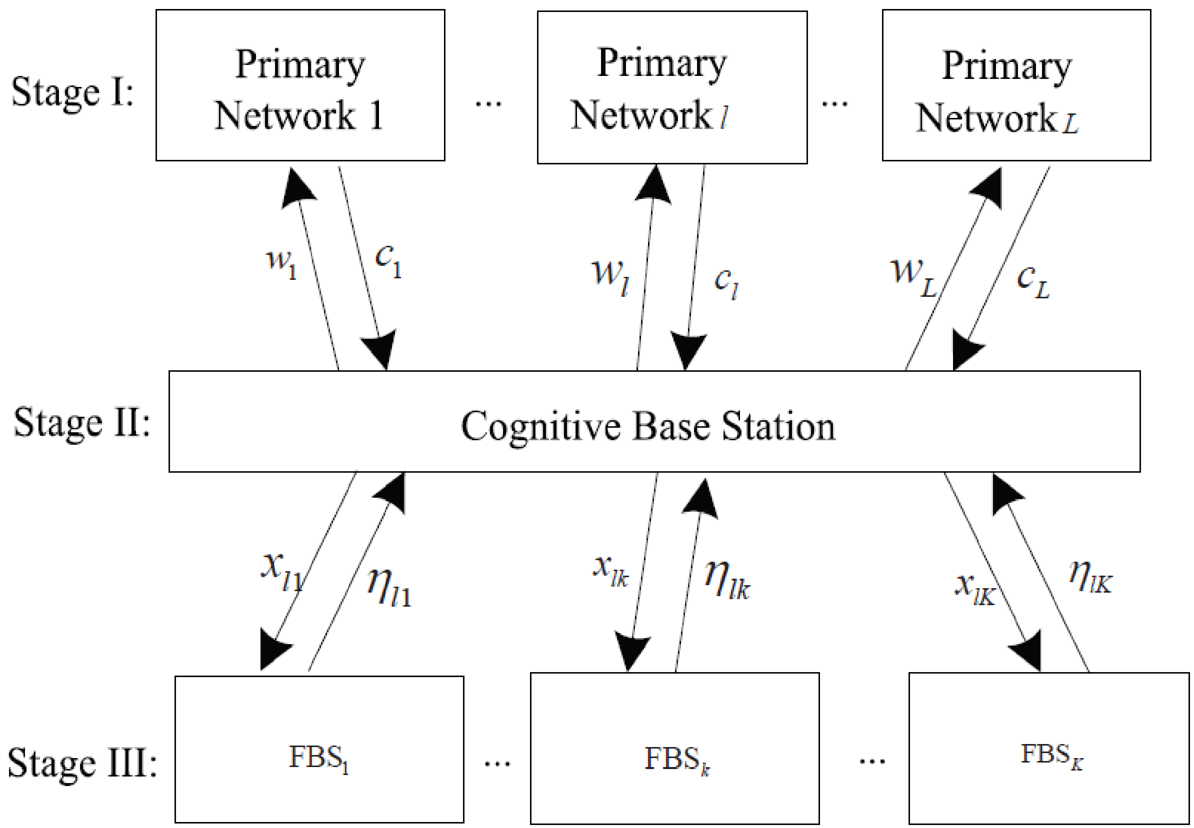
Leader: Cognitive BS
Followers: Femtocell BSs

Leaders: Femtocell BSs
Followers: Femtocell SUs



w: spectrum resource
c: selling price
x: spectrum allocation
η: EE of femtocell

Example work on small cells

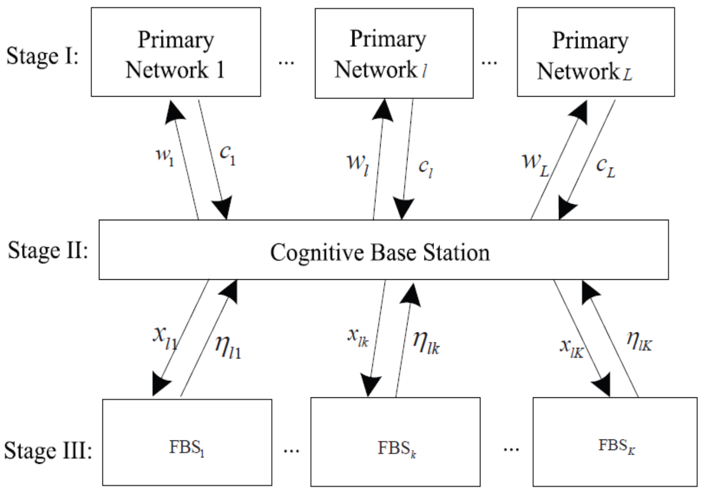


Utility:
○Revenue – importance of spectrum

Utility: A concave function of ***x*** depending on:
- ○ EE of femtocells
- ○ Cost of leasing
- ○ Generated revenue

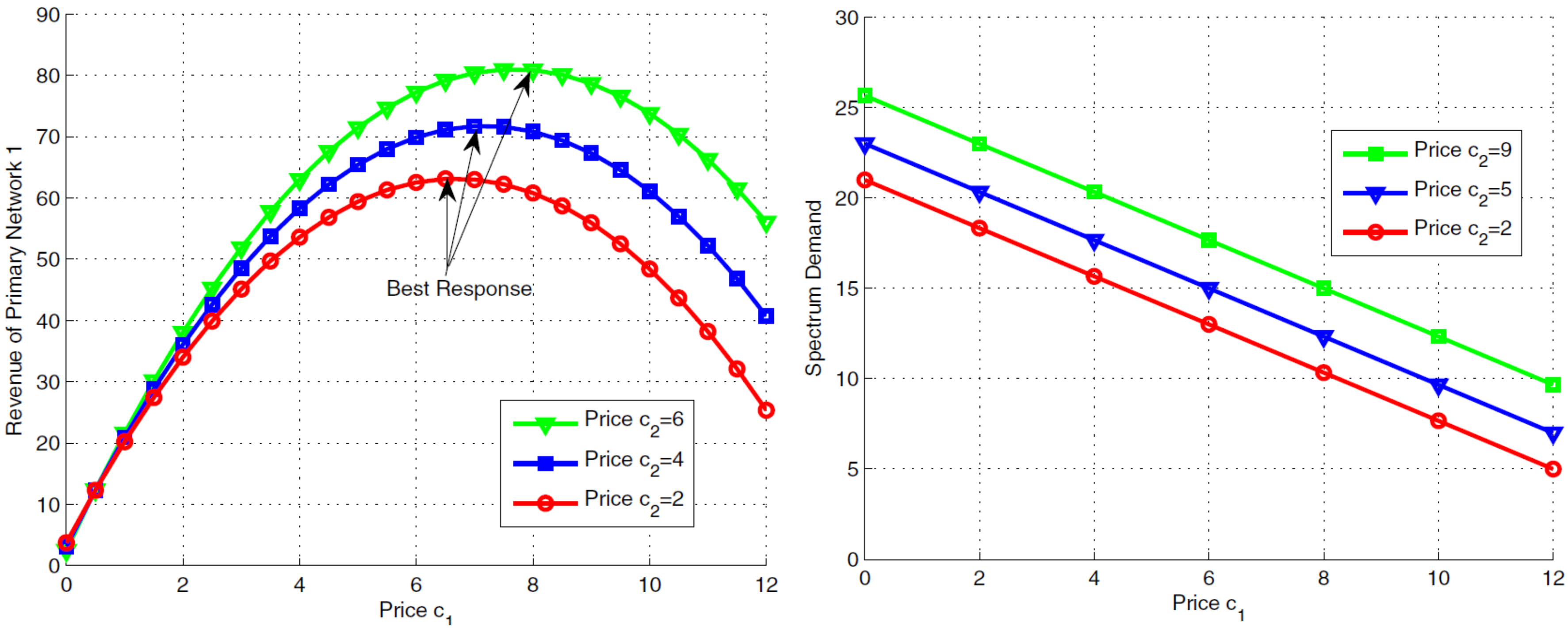
Utility:
- ○ A linear function of ***x***:
  - ○ Profit x EE x ***w***

Example work on small cells



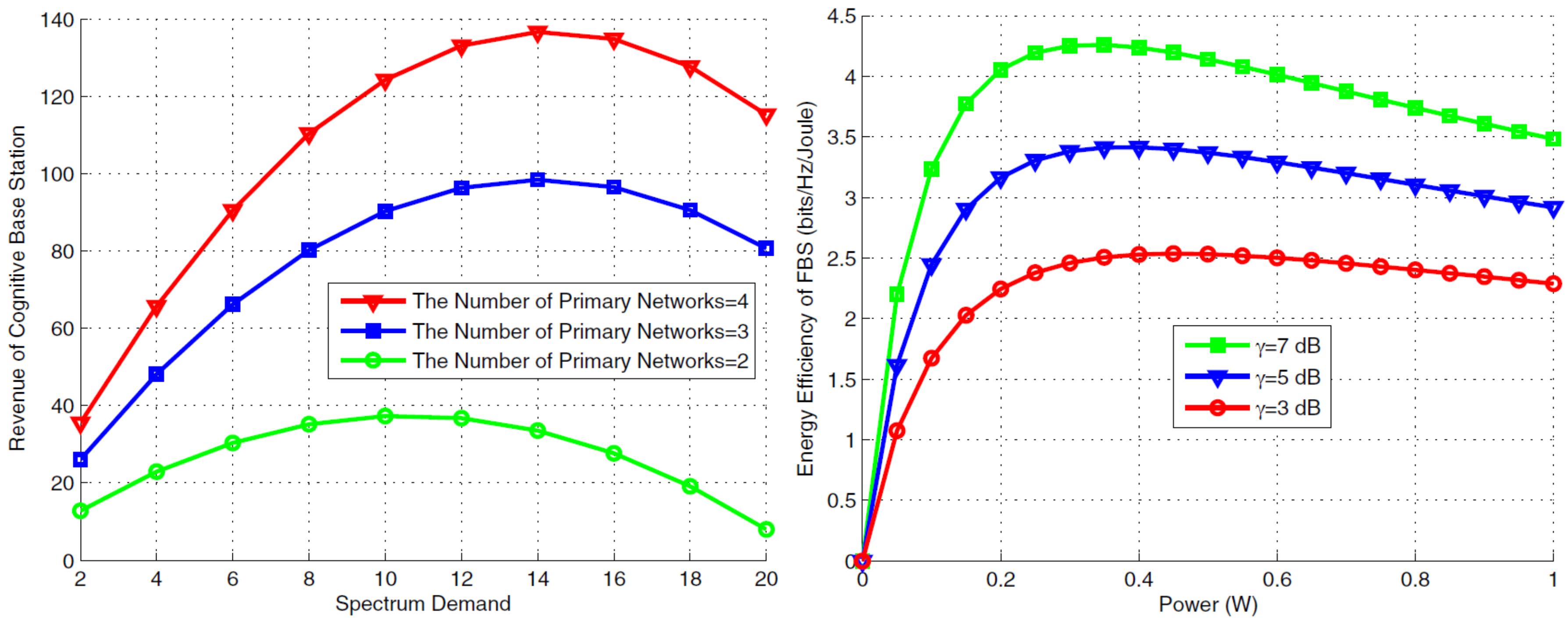
- Stage 3 (power allocation) is solved using gradient assisted binary search.
- Stage 2 (spectrum demand and allocation) is solved greedily.
- Stage 1 (lease price) is solved by solving a set of linear equations to obtain Nash equilibrium.
- These steps are iterated using a gradient iteration algorithm until convergence to obtain Stackelberg equlibrium.

Example work on small cells



With 2 primary networks

Example work on small cells



γ: Channel state

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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?

Example work on security

S. Althunibat et al., “On the Trade-Off between Security and Energy Efficiency in Cooperative Spectrum Sensing for CR”, IEEE Communications Letters, vol.17, no. 8, 2013, pp. 1564–67.

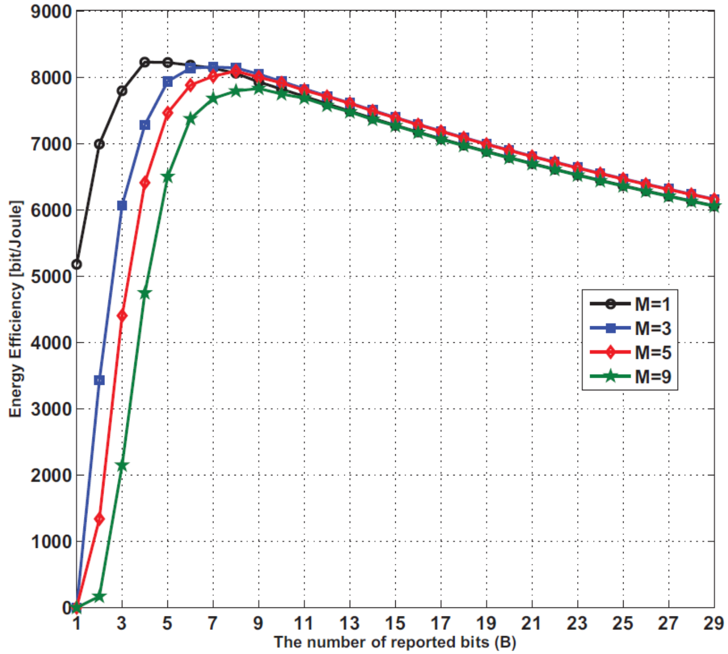
- A *CSS* system with both legitimate and malicious users.
- *CSS* uses hard decisions together with ***k of N*** fusion rule. Detection and false alarm probabilities are assumed to be same.
- Malicious users **always** report 1 in order to use the channel themselves.

Example work on security

- To prevent these attacks, the authors employ *MAC* by hashing: temporary key (generated from master key), sequence number, and the sensing decision.
- The overhead is large for just reporting **one** bit decision (128/256 bits).
- How many bits can be trimmed so that maximum EE is obtained:
  - Expected throughput: (Channel availability prob.)(1-Coop. F.A. prob)(Throughput)
  - Energy consumption: (Total sensing energy + SU transmission energy)
  - EE: Expected throughput / Energy consumption

Example work on security

- Optimal number of *MAC* bits is calculated for *OR* rule using iterative search (concave problem).
- The calculated bits are also used for other rules.



10 legitimate, ***M*** malicious users

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Thank you

End of Part II

Main trade-offs for EE in CRNs

Reading List

Energy Efficiency of Cognitive/Cellular Networks

1) Gür et al., Green wireless communications via cognitive dimension: an overview, IEEE Network, vol. 25, no. 2, 2011, pp. 50-56.
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.
4) Xionag et al., Energy-Efficient Spectrum Access in Cognitive Radios, IEEE JSAC, vol. 32, no. 3, 2014, pp. 550–562.
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

1) Bayhan et al., Scheduling in Centralized Cognitive Radio Networks for Energy Efficiency, IEEE TVT, vol. 62, no. 2, 2013, pp. 582–95.
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.
4) Yue et al., Spectrum and Energy Efficient Relay Station Placement in Cognitive Radio Networks , IEEE JSAC, vol. 31, no. 5, 2013, pp. 883-93.
5) Yilmaz et al., Radio environment map as enabler for practical cognitive radio networks, IEEE Communications Magazine, vol. 51, no. 12, 2013, pp. 162-169.
6) Bayhan et al., Low Complexity Uplink Schedulers for Energy-Efficient Cognitive Radio Networks, IEEE WCL, vol. 2, no. 3, 2013, pp. 363-366.
7) Ramamonjison et al., Joint Optimization of Clustering and Cooperative Beamforming in Green Cognitive Wireless Networks , IEEE ToWC, , vol. 13, no. 2, 2014, pp. 982-997.

Security

1) S. Althunibat et al., On the Trade-Off between Security and Energy Efficiency in Cooperative Spectrum Sensing for Cognitive Radio, IEEE Communications Letters, vol.17, no. 8, 2013, pp. 1564–67.
2) S. Althunibat et al., A Punishment Policy for Spectrum Sensing Data Falsification Attackers in Cognitive Radio Networks, IEEE VTC, 2014, pp. 1-5.
3) Zhang et al., Energy-efficient and trust-aware cooperation in cognitive radio networks , ICC, 2012, pp. 1763-67.

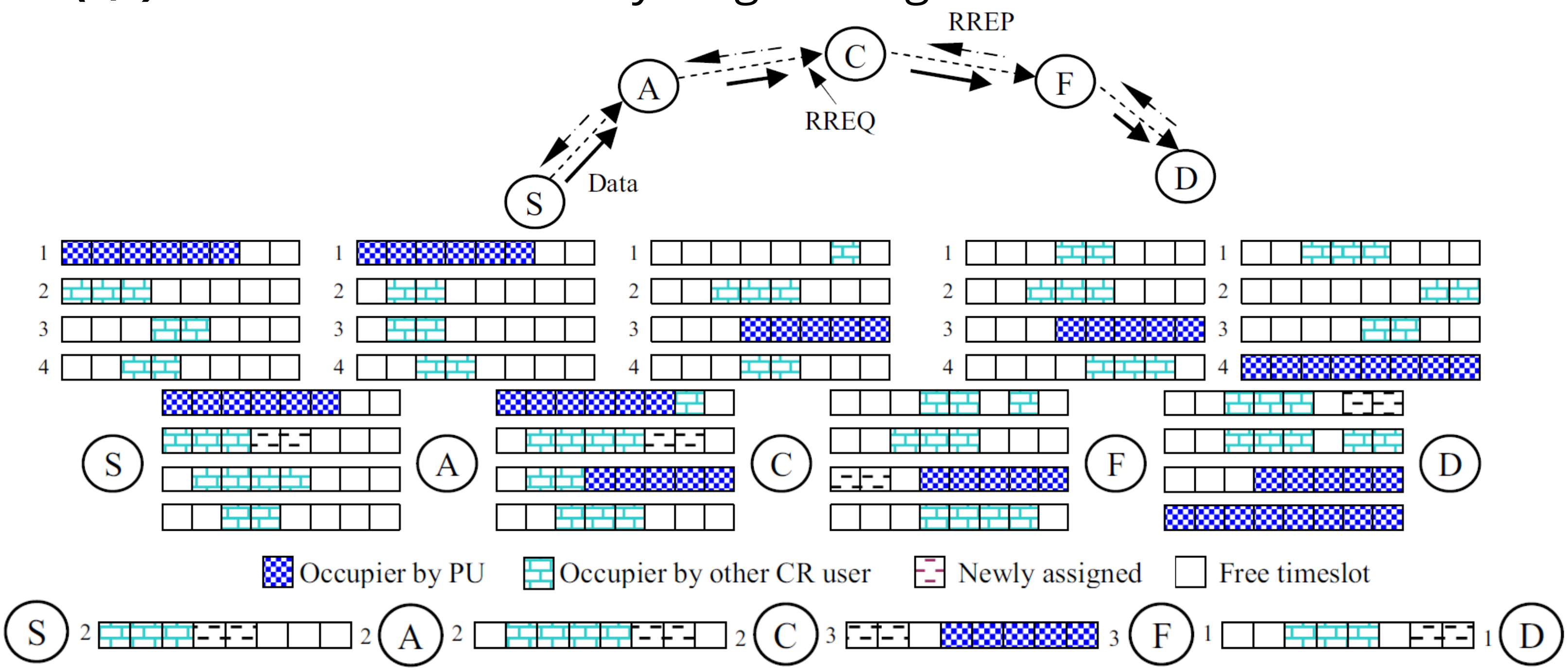
Example work on CR ad hoc networks

S. M. Kamruzzaman, et al., “An Energy Efficient QoS Routing Protocol for Cognitive Radio Ad Hoc Networks”,
ICACT 2011, pp. 344–49.

- For an ad hoc CRN with multiple channels that works on a TDMA scheme, how to find the route with maximum EE?
- EE is defined as: the minimum residual energy among the nodes on the path / hop count of the path.
- Authors propose a DSR based solution.
- The decision variables are the channel-time slot assignments for each node along the path.

Example work on CR ad hoc networks

- In order to assign a channel-time slot ***(c,t)*** to a link between nodes ***u*** and ***v***:
- ***t*** should be available for ***u*** and ***v***.
- ***(c,t)*** should not be used by neighboring nodes of ***u*** and ***v***.



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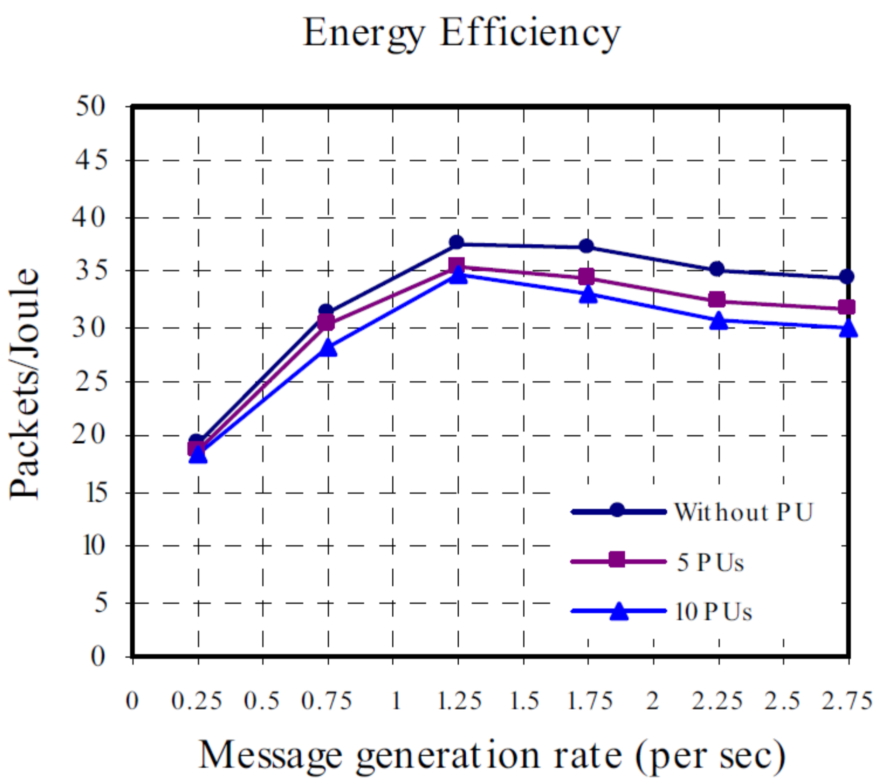
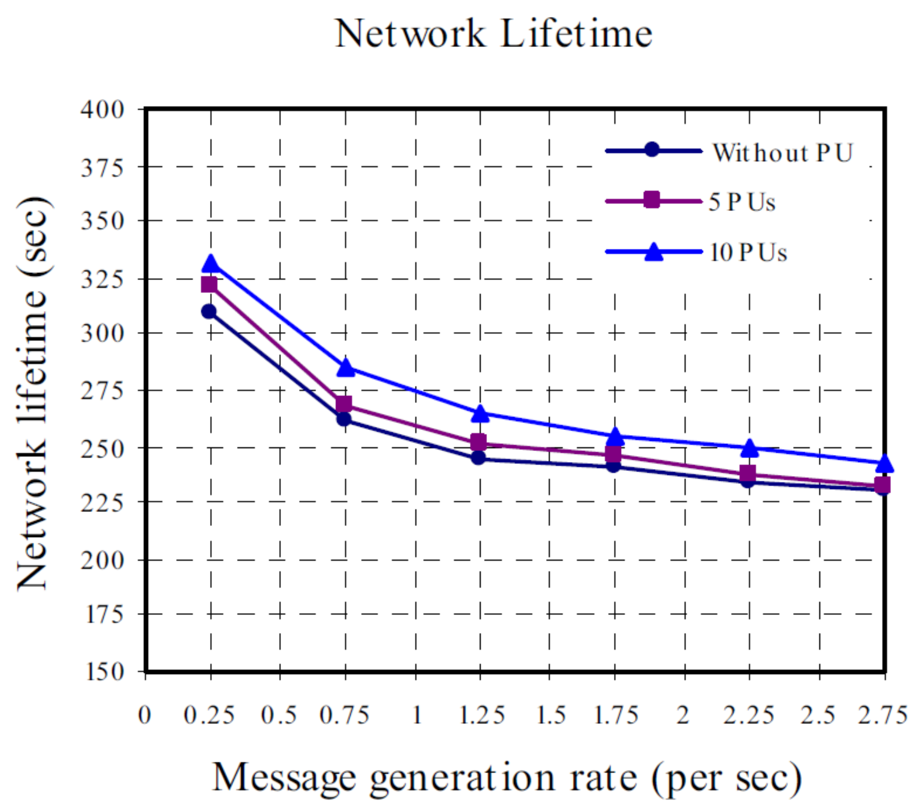
Example work on CR ad hoc networks





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TUTORIAL

Energy Efficiency in Cognitive Radio Networks: Challenges, Trade-offs, and Solutions

Dr. Suzan Bayhan, University of Helsinki, Helsinki, Finland
Dr. Gürkan Gür, Provus - A MasterCard Company, Istanbul, Turkey
Dr. Salim Eryigit, Idea Technology, Istanbul, Turkey

Outline

- Part I: Preliminaries on energy efficiency (EE) in wireless networks
  - Motivation
  - EE metrics
  - Initiatives and standardization
  - Research efforts
- Part II: 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
- Part III: Opportunities for (higher EE) CRNs
  - Short-range communications
  - Social-networks

Part III

Opportunities for (higher EE) CRNs

Suzan Bayhan
bayhan@hiit.fi

Three observations

1

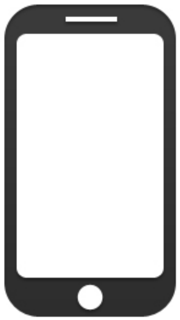
Densification of the networks (more devices)
- ☹ Limited spectrum, interference
- ☺ **Easier ad hoc connectivity**

2

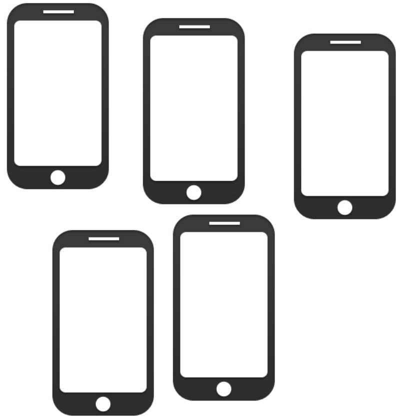
Video dominating the mobile data traffic [2/3 of the traffic, 2017]
- ☹ Limited spectrum, interference, energy consumption
- ☺ **Zipf-like content requests, content centricity**

3

Crowdsensing (environmental, infrastructure, social) apps becoming more popular
- ☹ Processing at the end device, energy consumption
- ☺ **Mobile device has valuable information, device centricity**

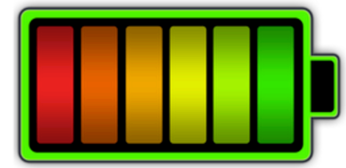


Mobile-centric

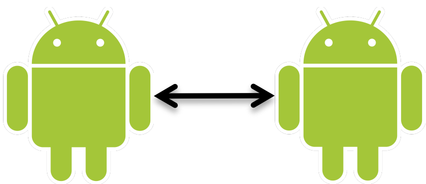


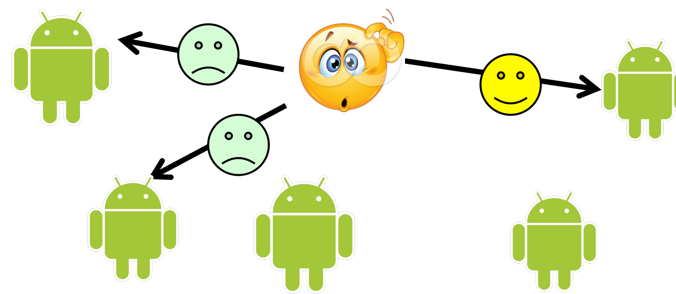
Ad hoc

Video content



Limited battery



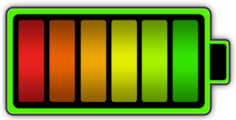


Short range communications

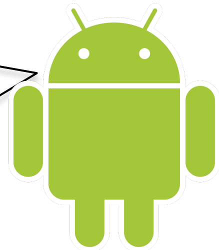
Social-aware communications

Higher EE?

EE impact assessment rubric



- QoE



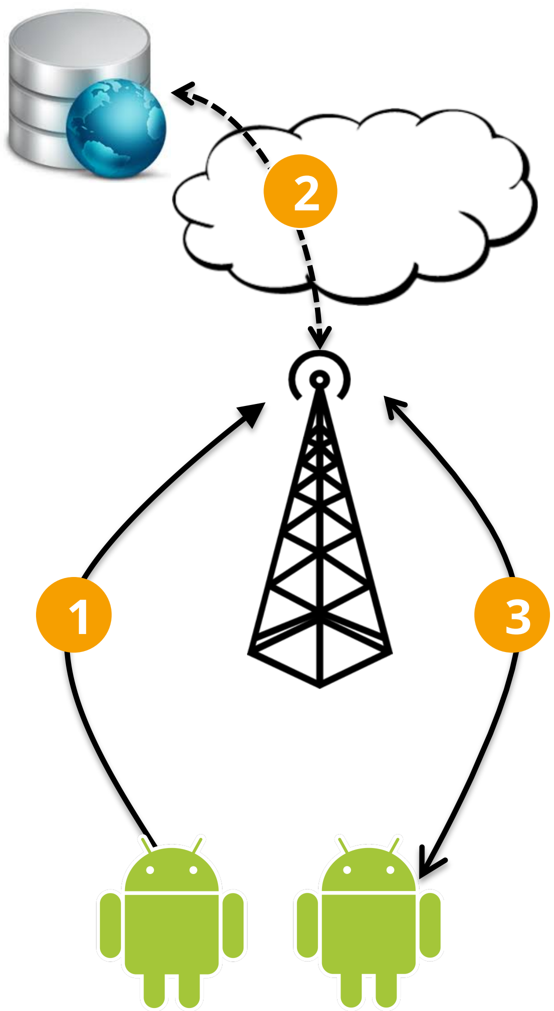
(Mobile) user

Operator

- Opex
- Capex
- Spectral eff.
- Energy cost
- User's QoE

Tx Power	Interference	Spectrum efficiency	Effective tx time	Energy consumption (Misc)

Short-range communications



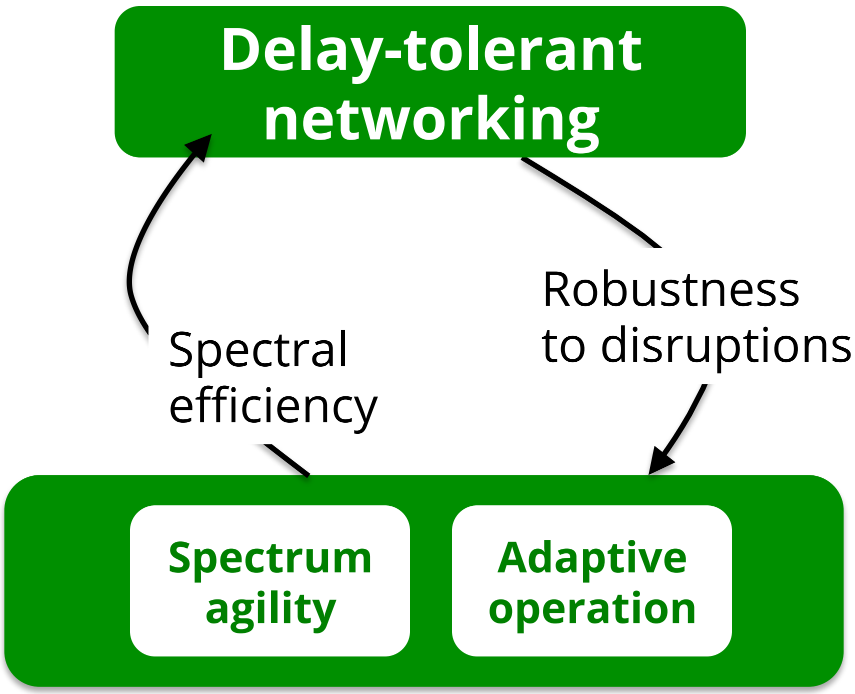
- Message through many diverse networks
- Convenient but creates dependencies
- Energy consumption and core network traffic
- Security and privacy issues

Why not bypass BS and transfer directly?

- The bottleneck (BS link) removed (proximity gain, hop gain, reuse gain)
- Uncertain, less reliable
  - Opportunistic
  - Network-assistance

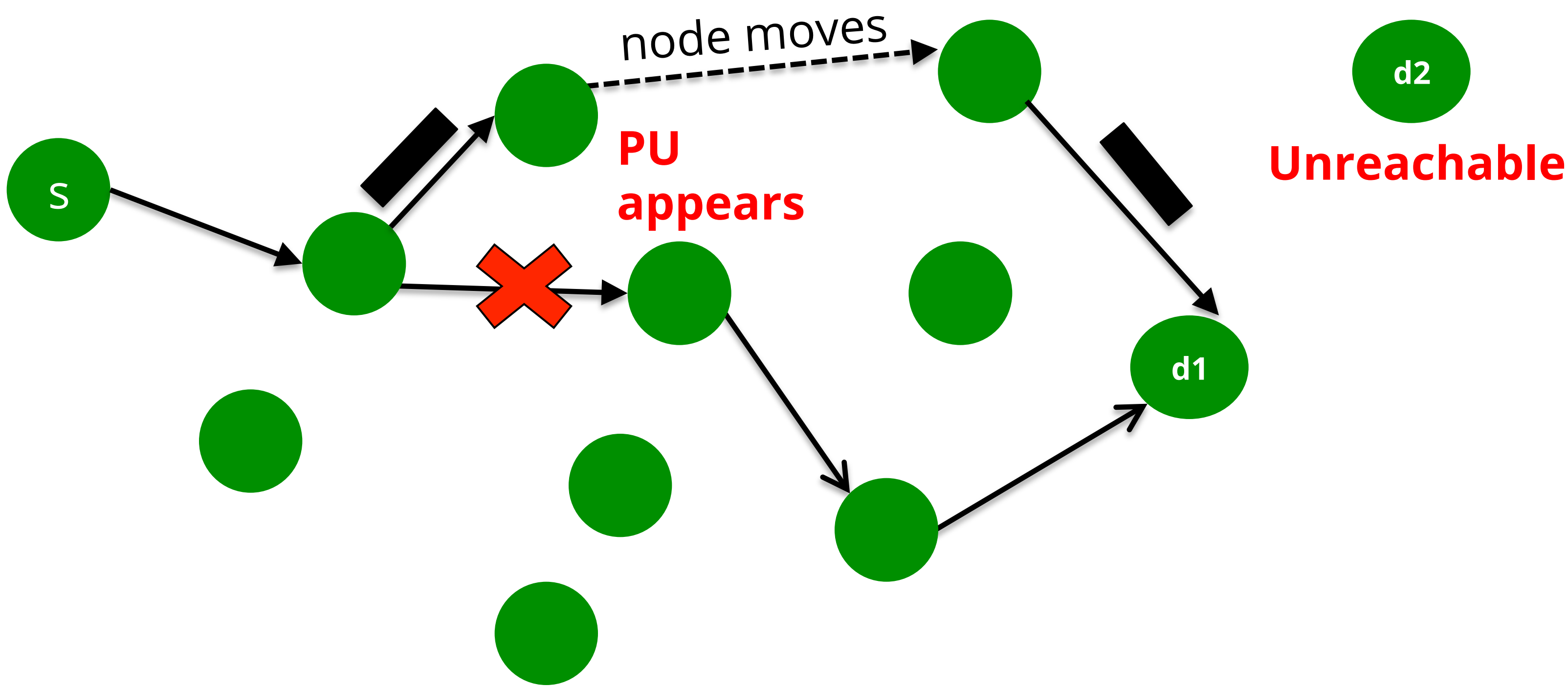
No network assistance: delay-tolerant CRN

- DTN for delay-tolerant applications
- Short-range radio, e.g. WiFi, Bluetooth
- *Store-carry-forward*
- Lack of end-to-end links or intermittent connectivity
- No “kill switch” of networks
- No monetary cost
- Delay-tolerant CRNs bring highly-occupied PU channels into use.



CR building blocks

Increase the redundancy



- In multi-hop CRNs, route stability is difficult to attain
- No end-to-end route but hop-by-hop decisions
- Multi-hop CR with **store-carry-forward** approach

DTNs and CRNs: a comparison

Opportunism

- DTN: If nodes happen to be at the transmission range of each other at a time (time and space)
- CRN: If frequency is idle (frequency, time, space)

Intermittent connections

- DTN: due to low node density, node mobility
- CRN: due to disruptions from PUs, node mobility

Robust to

- DTN: connection breakdowns, mobility as enabler
- CRN: lack of assigned spectrum
  - spectrum mobility as enabler
  - mobility as a curse

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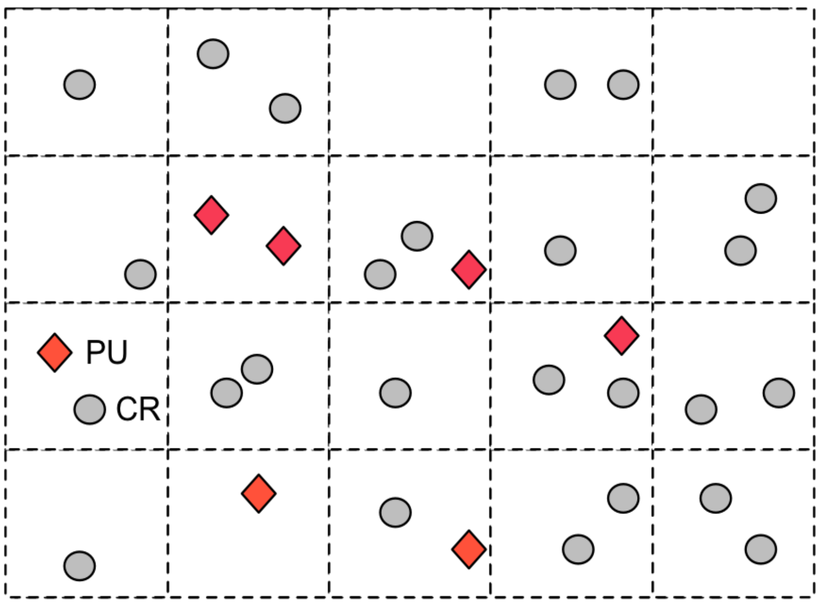
Delay-tolerant CRN: challenges

- Mobility as enabler
- Predictable **mobility** to some extent, high regularity

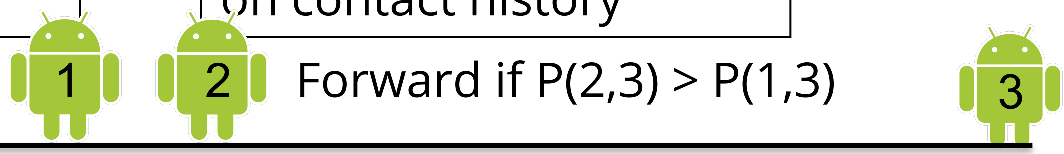


Spatial differences in spectrum availability

How to operate if CRs

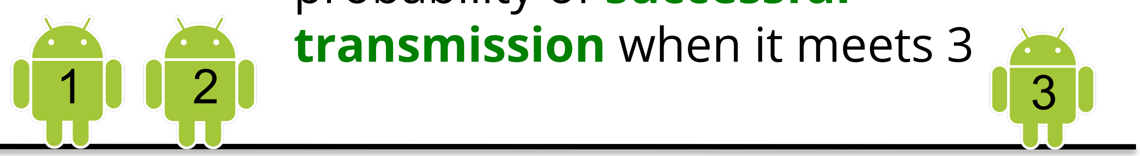
Forward packet to 2 or not?

Probability of meeting destination P(2,3) based on contact history



DTN
- Inter-contact time distribution
- Contact time dist.
- Community structure

Forward if 2 has higher probability of **successful transmission** when it meets 3



Delay-tolerant CRN
- All the above
- Spatial distribution of contacts
- Spectrum availability distribution

Selecting good relays

Jianhui Huang *et al.*, Mobility-Assisted Routing in Intermittently Connected Mobile CRNs IEEE TPDS, Nov. 2014.

Exchanged info

1. Home zones → Places that this node visits frequently or manually selected as the home zone
2. Visiting times of home zones → Exploit the regularity of visiting times
3. Spectrum availability at the time of visiting → PU traffic follows regular patterns

A relay is **a better relay** if it has a higher frequency of visiting the destination's home zone(s) AND with high spectrum availability.

Network-assisted short-range communications

- Key challenges
  - High device discovery ratio
  - Energy-efficient discovery
  - **Scanning interval** for balancing discovery ratio vs. energy consumption
- Network assistance can improve performance
  - Device discovery
  - Resource sharing
  - Reliability

Power consumption of discovery operations, Samsung Galaxy Nexus

Abbr.	*Operation*	*Power/Energy*	*STD*
P^{BT}_{disc}	Bluetooth discoverable	2.59 mW	0.56 mW
P^{AP}_{on}	Wi-Fi AP on	210.97 mW	11.72 mW
P^{D}_{disc}	Wi-Fi Direct discovery	340.89 mW	4.02 mW
E^{BT}_{disc}	Bluetooth discovery	2027.38 mJ	146.70 mJ
E^{WIFI}_{scan}	Wi-Fi scan	697.47 mJ	115.07 mJ
E^{AP}_{on}	Wi-Fi AP turn on	754.03 mJ	257.30 mJ
E^{D}_{on}	Wi-Fi Direct turn on	633.31 mJ	115.59 mJ

Sacha Trifunovic et al, Adaptive role switching for fair and efficient battery usage in device-to-device communication. SIGMOBILE Mobile Computing and Communications Review , Volume 18 Issue 1, 2014.

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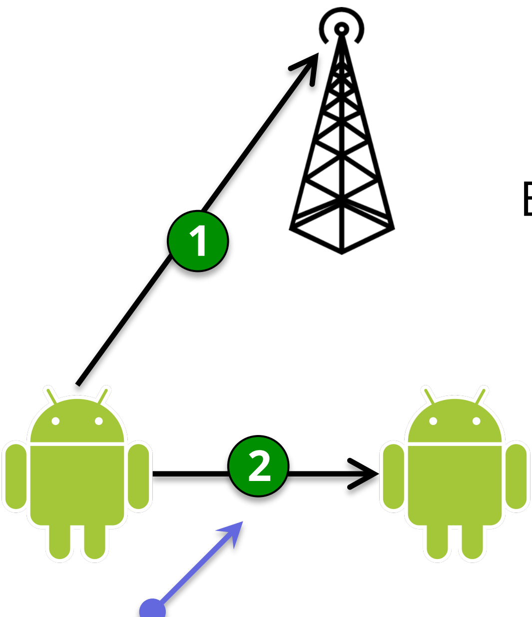
A CR with short-range operation mode



Operation mode

- BS mode 1
- D2D mode 2

Frequency allocation

- **In-band**
  - **Overlay** Different licensed frequency
  - **Underlay** Same licensed frequency
- **Out-band**
  - 1 Licensed frequency
  - 2 Unlicensed frequency

a CR with D2D mode: exploit the unused PU frequencies for 2

- Higher spectral efficiency
- Spectrum sensing overhead
- Higher EE? Possibly!
- Requires additional interface

Sensing for PU channel: Peng Cheng *et al*, Resource Allocation for Cognitive Networks with D2D Communication: An Evolutionary Approach, WCNC 2012.

Sensing for BS channel: Ahmed Hamdi Sakr *et al*. Cognitive and Energy Harvesting-Based D2D Communication in Cellular Networks: Stochastic Geometry Modeling and Analysis, arXiv:1405.2013 (2014).

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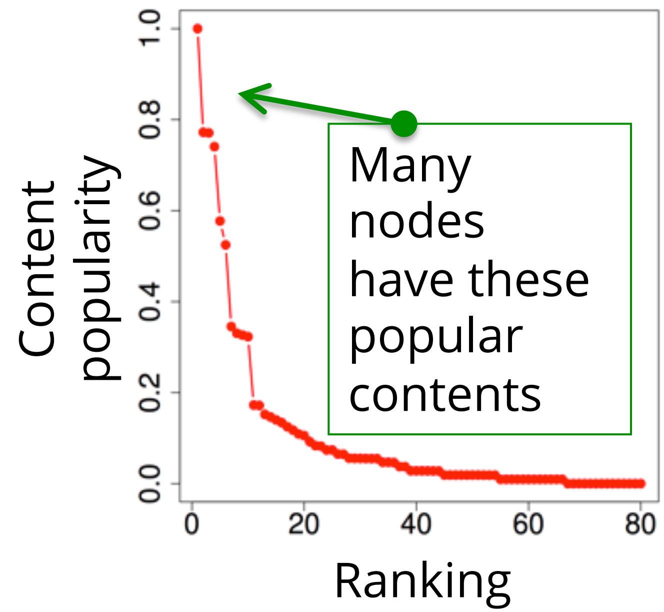
How CRs can benefit: research directions

- Can CR deliver wireless video?

Ubiquitous Video over Dynamic Spectrum, Princeton University, Aalto University, University of Helsinki, 2015-2017.

- Retrieve content from nearby CRs: advantages for both provider and user
- Caching: Content closer to the edge
- Interplay between EE, short-range, spectrum discovery, incentives for device-to-device relaying



EE implications of short-range communications

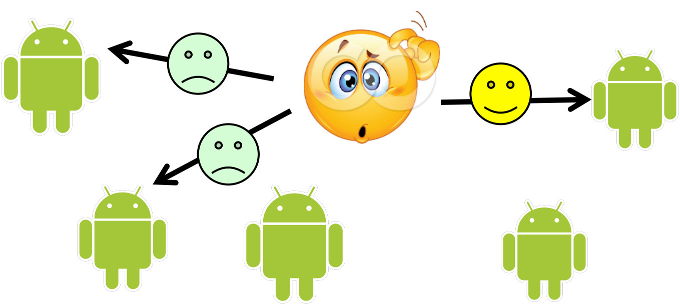
Tx Power	Interference	Spectrum efficiency	Effective tx time	Energy consumption (Misc)

- Lower transmission power
- Lower interference due to lower distance, lower tx power, Intracell interference non-negligible
- Spatial frequency efficiency
- Higher tx time compared to BS-based time sharing
- Device discovery and spectrum sensing overhead

- Power consumption migrated from operator (BS) to the user
- Lower energy consumption for network coverage
- Lower number of BS-to-user content delivery (hop gain)
- Higher spectrum efficiency
- Coordination overhead

Social-aware CRNs

"Understand the self, understand the network"



Why social?

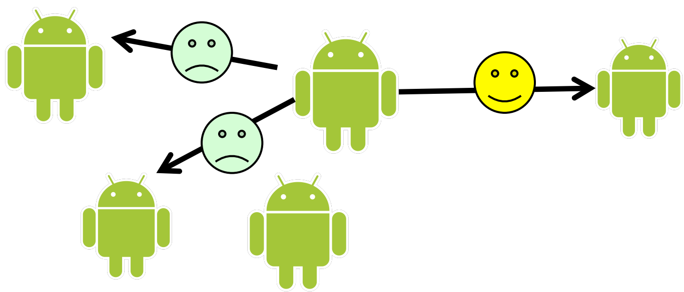
- Context
- Realistic protocol design
- Wisdom of crowds
- Be Cognitive!

Context

Being more than a decade-old concept, CR research has matured a lot. But CR research takes CRs as wireless devices with no/little ***context***.

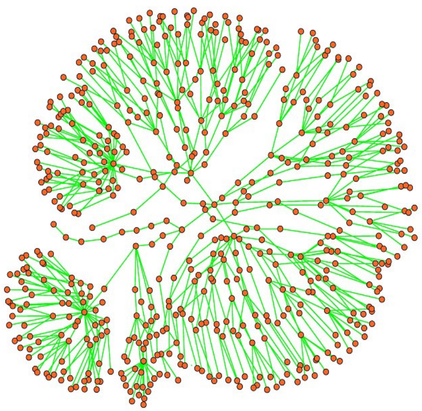
- Who are the users of CR? Operators, humans, base stations, femtocells?
- What are the relations/interactions among the network entities?
- Can we exploit these relations?

Social Network views a network as a group of nodes with their interrelations (e.g., physical distance, contact frequencies) to benefit from these **structural** and **social ties** for higher efficiency.



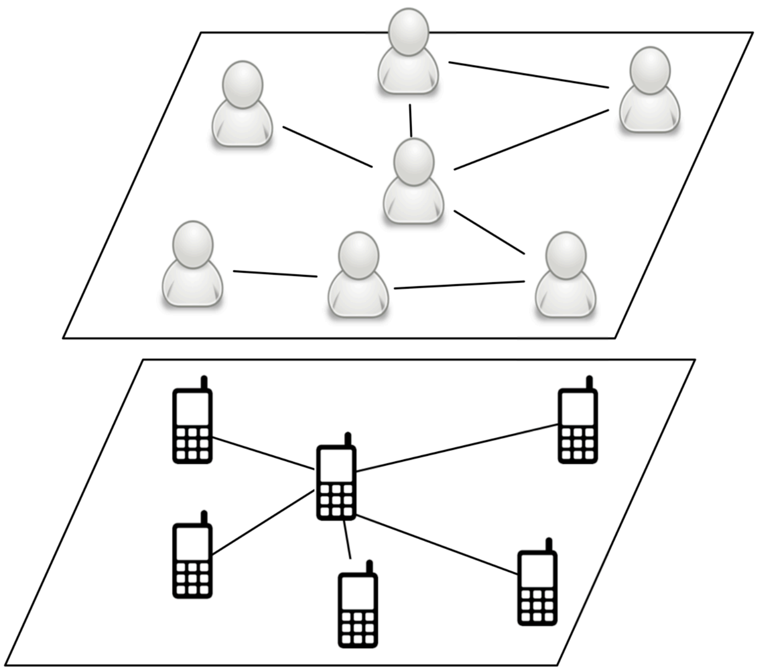
Social network as an indication of the **social agents**:

- Operation and interaction of the agents
- Users of CR (or hand-held devices) are human beings which act depending on social ties, **important for cooperative networking**



Social network as a **metaphor**: Structure of the network -- topology

Two-layered view of a network



Social Connectivity Layer (SCL)

Social graph

More intertwined
Time evolving
Key to capturing context
Social network analysis

Wireless Connectivity Layer (WCL)

Connectivity graph

Physical locations
Transmitter range
Wireless channel
Mobility models

CR research by and large considers only WCL

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Social-awareness

We call a protocol **social-aware** if it exploits its knowledge about the social connectivity layer.

- Network structural properties
  - Centrality (edge, betweenness, eigenvector)
  - Clustering coefficient
  - Assortativity, rich-clubness
  - Density
  - Connectivity metrics

- Social interactions among nodes
  - Friendship, community, cooperation willingness

Why social?

Context

Realistic protocol design

Wisdom of crowds

Be Cognitive!

Cooperative spectrum sensing

- Improves sensing reliability *Pd* owing to multi-user diversity gain
- Are CRs really **unconditionally** cooperative?
- Is this mode of operation EE?
  - Simple answer: No!

More realistic

Exploit social connectivity layer for modeling realistic cooperation schemes

Two extremes in network optimization

- **Network utility maximization (NUM):**

All CRs aim to attain the highest performance from the perspective of the network

- **Game theory**:

CRs are selfish and act to maximize self-interest

Game theory (non-cooperative games)

Social Crowd

Network utility maximization

Figure adapted from Social Group Utility Maximization paper in IEEE INFOCOM 2014

Social group utility

Xu Chen *et al.*, A Social Group Utility Maximization Framework with Applications in Database Assisted Spectrum Access, IEEE INFOCOM 2014.

Social tie between
n and m (if all zero, NUM)

Individual utility of n

Individual
utility of m

Social group utility of n

$$S_n(\boldsymbol{x}) = U_n(\boldsymbol{x}) + \sum_{m \in \mathcal{N}_n^s} w_{nm} U_m(\boldsymbol{x})$$

How to sense optimally in a social CRN?

Salim Eryigit, S. Bayhan, J. Kangasharju, T. Tugcu, Optimal Cooperator Set Selection in Social CRNs, under review, 2014

- CRs **do not have to cooperate** but prefers cooperation for higher network efficiency.
- Cooperation probability pij

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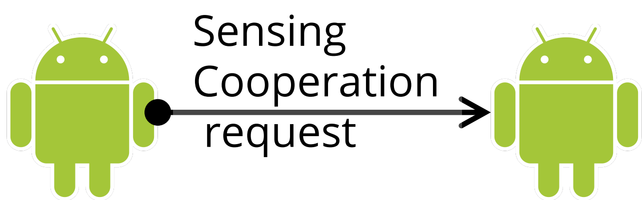
Requesting CR

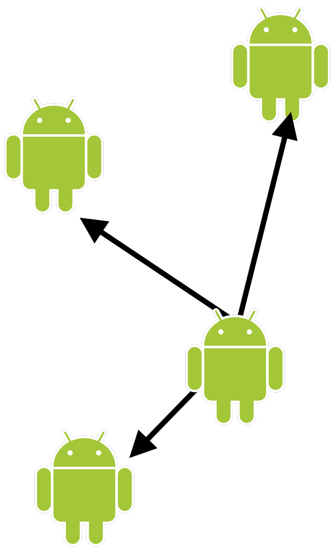
- Avoid non-cooperating CRs (waste of tx.energy)
- Avoid malicious CRs (decrease in reliability)
- Keep track of interactions (i.e., learning)



Requested CR

- Cooperate with CRs depending on **some criteria.**
- Self-state (e.g., remaining energy) or social-tie (e.g. a friend requests).
- Penalize non-cooperating CRs by not sensing for them in return.

Given PU sensing constraints, how to select cooperators such that **throughput** is maximized and CR cooperates with the nodes it **trusts**?



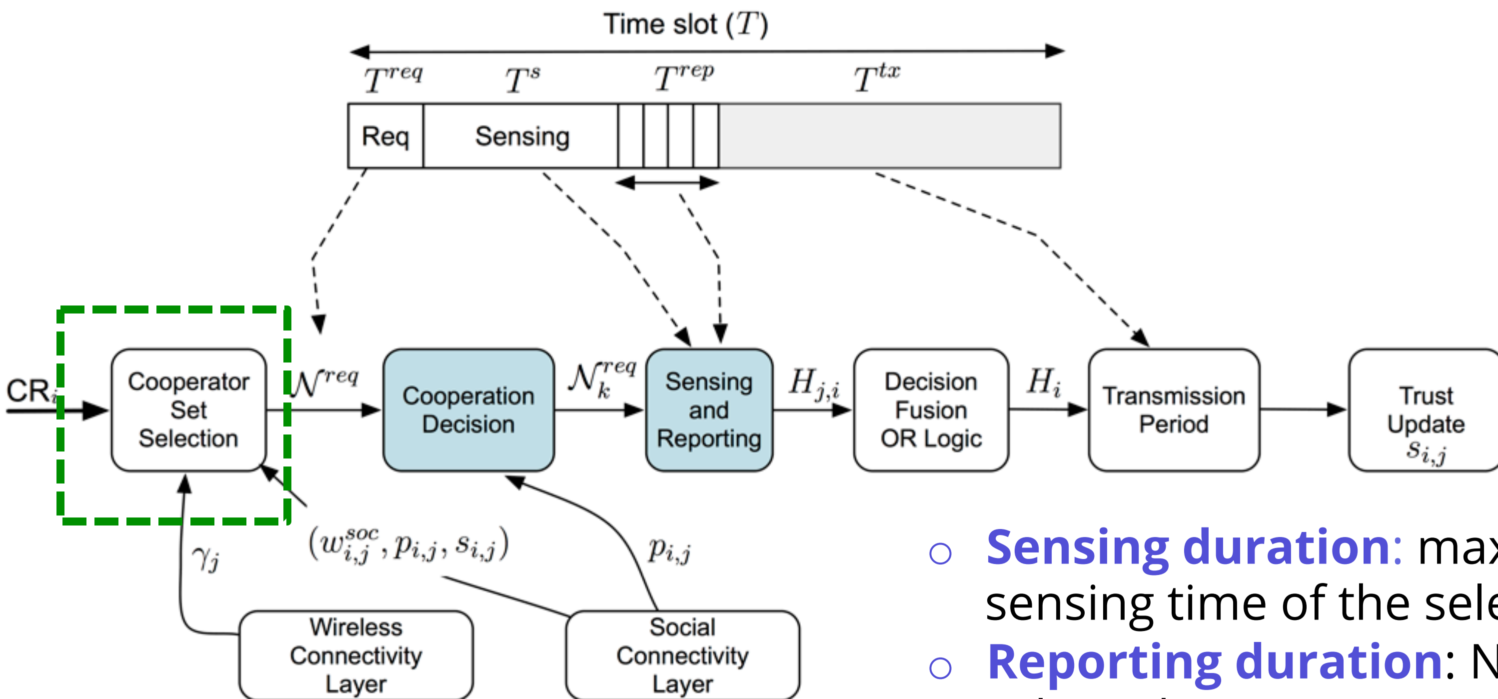
Vertex: CR node

- Distance from the PU
- Received signal strength of PU (determines sensing duration)

Edge: Relation between these CRs (directional)

- Social tie, [0,1]
- Cooperation probability, [0,1]
- Trust for sensing accuracy, [0,1]

Social-aware sensing cooperator selection



- **Sensing duration**: maximum sensing time of the selected CRs
- **Reporting duration**: Number of selected CRs (-1)
- **Sensing accuracy**: Number of sensing CRs

Selected CRs ≠ sensing CRs!

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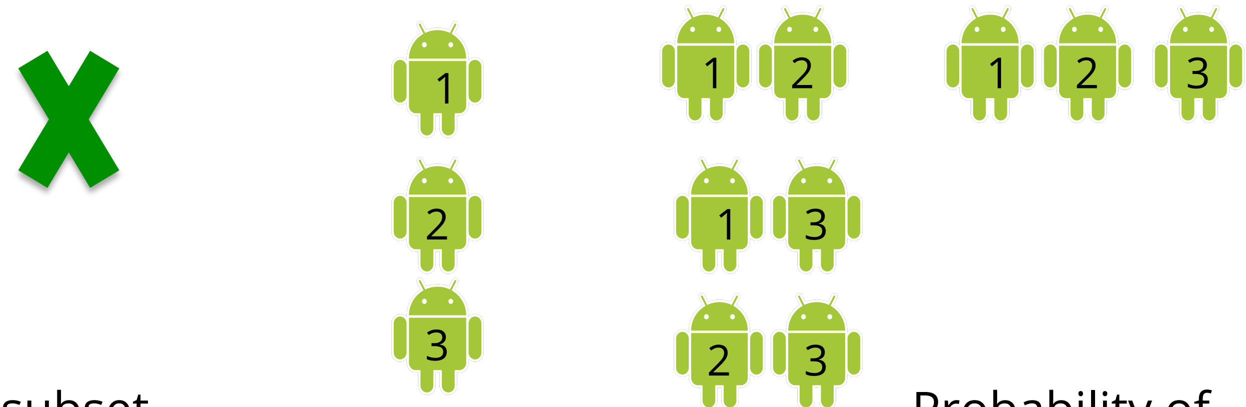
Why is it a difficult problem?

Selected set of cooperators

No one senses | Only 1 senses | 2 senses | All of them senses



Probability that this subset is realised

Probability of detection for this subset

$$P^{d,soc}_{\mathcal{N}^{req}} = E[P^d_{\mathcal{N}^{req}}] = \sum_{\mathcal{N}_k^{req} \in \mathcal{P}(\mathcal{N}^{req})} P(\mathcal{N}_k^{req}) P^d(\mathcal{N}_k^{req})$$

Difficult due to the stochastic nature of the CRs

EMOA: Evolutionary multi-objective solution

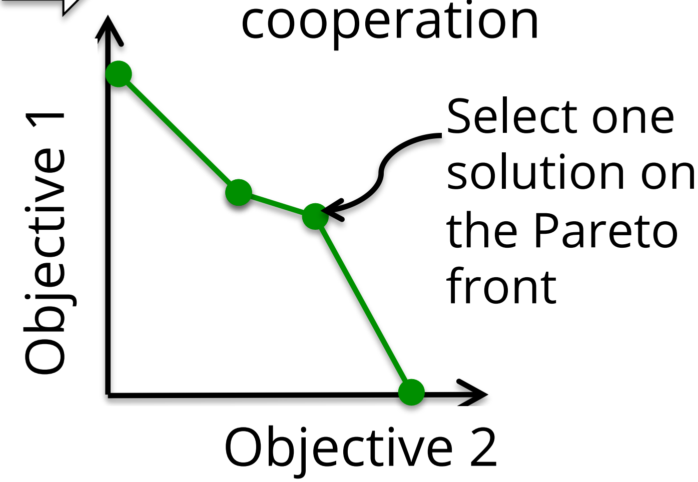
System state
- Sensing duration
- Sensing reliability
- Social tie

PU constraint
- Pd > 0.9

Objective
1) Maximize throughput
2) Maximize trust of the collaborators

Cooperator selection algorithm

Who this CR asks for cooperation



- No malicious users: EMOA, 90% of the optimal throughput
- Malicious users (SSDF): Robust and significant performance difference

Why social?

Context

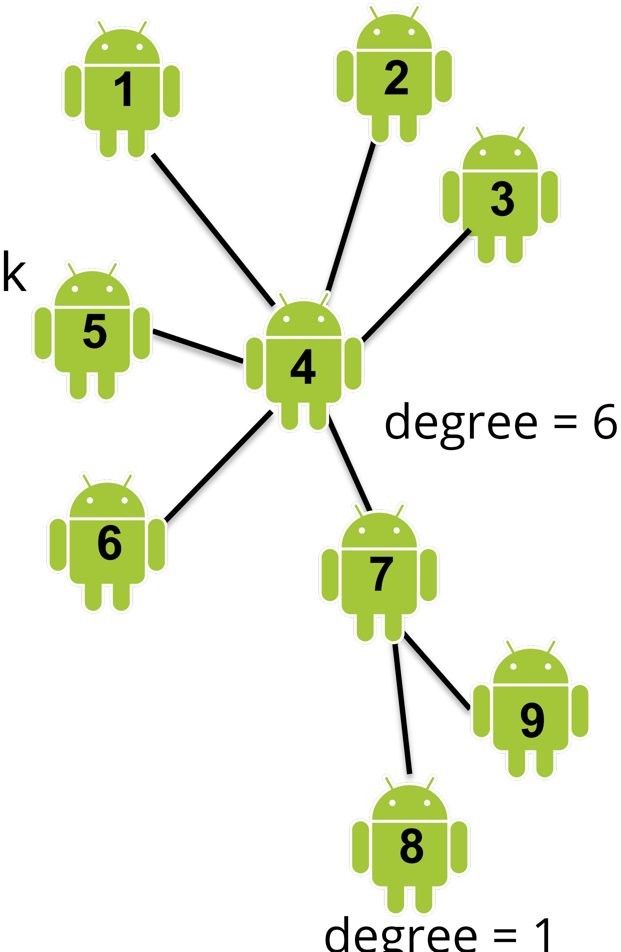
Realistic protocol design

Wisdom of crowds

Be Cognitive!

Collective learning

- Use the wisdom of crowds
  - Learning everything from scratch, very resource-consuming (energy and computing)
  - Exchange knowledge, like human beings, ask for recommendations
- How this knowledge propagates?
  - Epidemic propagation modeling in social networks
    - Husheng Li *et al.*, Behavior Propagation CRNs: A Social Network Approach, IEEE TWC, 2014.
- Whose knowledge may be more accurate?
  - CR 4 or CR 8?



Why social?

Context

Realistic protocol design

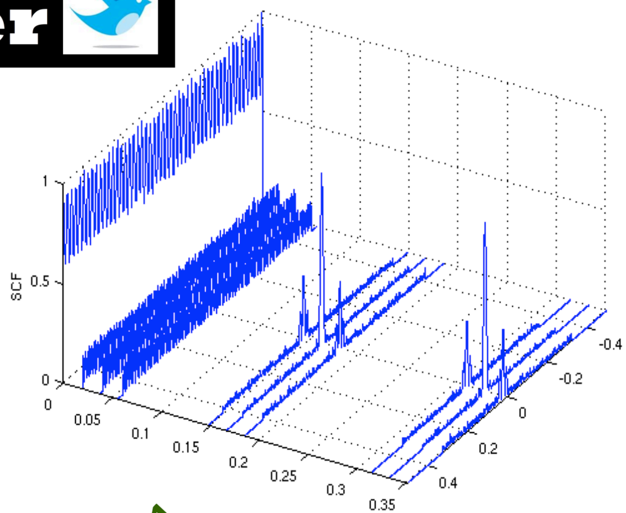
Wisdom of crowds

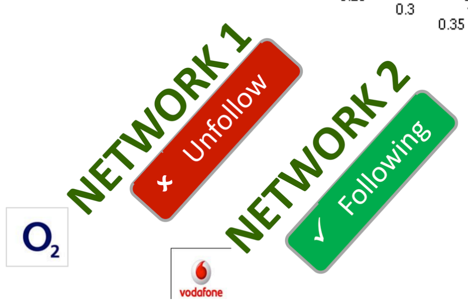
Be Cognitive!

“Maybe being cognitive means doing things like humans...”

Linda Doyle’s keynote on *The Social Life of CRs*

flitter





Timeline

voda_dynamic
Just moved to 1.85GHz – lots of space – 20 MHz bandwidth

02moves
The 2.34 GHz band is still the place to be!

CTVR
squatting in 1.25 Ghz – nice!

CTVR
Very busy have to move 1.48 GHz now

CTVR
Just scavenged – 2.80 GHz

voda_dynamic
900 MHz place to be ... looks like I will be here for a while

02moves
The 2.34 GHz band is the place to be!

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
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idea teknoloji çözümleri

PROVUS A MasterCard Company

Cost of being social-aware and research directions

- **Processing and communication overhead**
  - Manual one-time or periodic settings of the social parameters
  - Global vs. ego-network (accuracy traded-off for cost)
- **Privacy vs. awareness tradeoff**
  - Metrics for awareness
  - Privacy-preserving information exchange
- **Energy-aware techniques for social-awareness**
  - Remaining energy can be another factor affecting CR cooperation behavior
  - EE vs. awareness tradeoff

EE implications of social-awareness

Tx Power	**Interference**	**Spectrum efficiency**	**Effective tx time**	**Energy consumption (Misc)**

- Increased environment awareness
- Decreased cost of collaboration (implies more time for transmission)
- Avoiding the effects of malicious users (implies higher spectrum efficiency)
- Increased energy consumption for social-awareness

- Can exploit CRs similarity to deliver content
- Can increase users incentives for collaboration, e.g., sensing, relaying, D2D mode transmission (social-aware D2D)

(Human) Mobility modeling

Why relevant for CR research?

- Short-range communications
- How network topology changes
  - Wireless connectivity layer
- How likely two nodes interact and where they interact
  - Social connectivity layer
- Realistic large-scale, e.g. urban-scale, networks

Research on mobility modeling

- Complex systems (Macro-mobility)
- Urban planning and transportation (Macro-mobility)
- Spread of diseases (Macro-mobility and micro-mobility)
- Opportunistic networks (micro-mobility)

Mobile call detail records	Social network data	GPS	Sensor readings (Bluetooth, AP signals)

Image from http://www.dotherightmix.eu/

Is your mobility **predictable** on a <week, day, hour> granularity?

How is it affected by your **social ties**?

95% predictable whereabouts, [Lu *et al* 2013]

20% all trips taken for social purposes [Toole *et al* 2015]

Tools for realistic mobility models

- Models that can represent patterns in human mobility
  - GeoSim: “the movement of people in cities taking individual and social preferences into account.” , [Toole *et al* 2015]
  - Musolesi et al. "Designing mobility models based on social network theory." ACM SIGMOBILE MCR, 2007.

- Publicly available mobility traces
  - CRAWDAD http://www.crawdad.org/

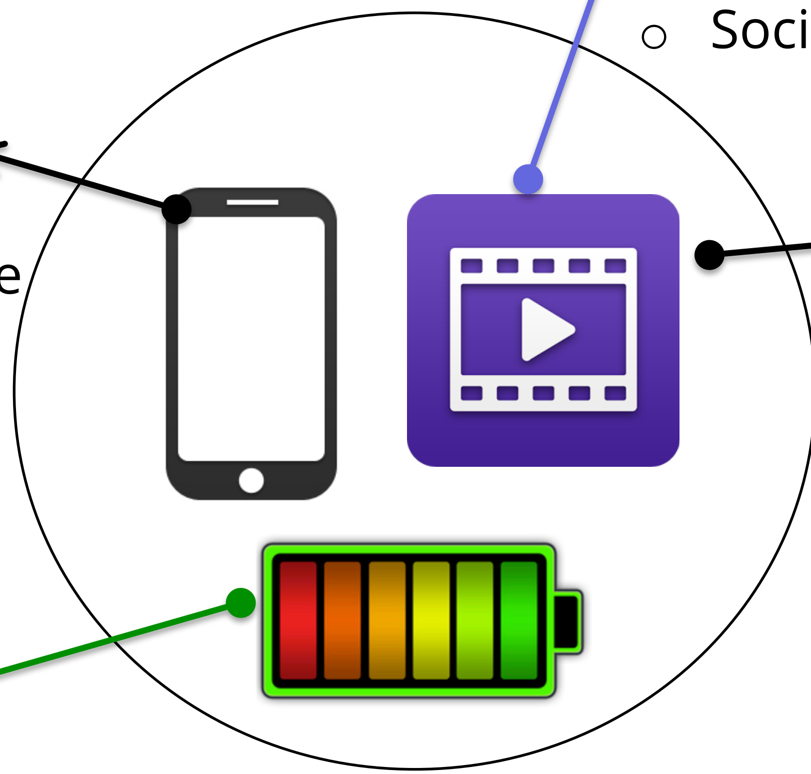
How mobility modeling can help CRNs

- Select better relays among contacted nodes
  - 🙂 More efficient routing
- Determine spectrum based on the route’s spectrum availability
  - 🙂 Decreased cost for spectrum switching
- Sensing data pre-fetched from WSDBs depending on the predicted mobility
  - 🙂 Smooth spectrum mobility
- Caching based on mobility and spectrum availability of the route
  - 🙂 Less effort to access data

Summary

Content centric
- Caching close to edge
- Short-range
- Social-awareness

Device centric
- Short-range
- Mobility
- Social-awareness



How to manage CR functionalities?
- Spectrum discovery
- Spectrum mobility

Energy efficiency

Many research questions to explore further.

Thank you

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5. CRAWDAD: http://crawdad.cs.dartmouth.edu/
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7. GeoSim: http://humnetlab.mit.edu/wordpress/downloads/

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