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Chapter 4: Green Wireless Communication via Cognitive Dimension

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Outline

- Abstract
- Background
- Benefits of Cognitive Radios for Green Wireless Communications
- Conclusion
- Reference

Chapter 4: Green Wireless Communication via Cognitive Dimension

Issue

- Intelligence support for energy efficiency functionalities
- Energy savings via duty-cycle optimization and robustness in ad hoc settings
- Network layer capabilities
- Cross-layer optimizations
- Enabler for ubiquitous efficiency optimizations
- Physical layer capabilities
- Bandwidth-energy trade-offs
- Simpler and more efficient evolution paths
- Smaller impact on human health

Benefits of Cognitive Radios for Green Wireless Communications

- Cognitive cycle

Green Cognitive Radio

Green Communication and Cognitive Networks

- Features

Cognitive Femtocell Networks

- Architecture
- Access modes and networks matrix

Abstract

- There are two fundamental aspects of cognitive radios in the green communications context: **leveraging CRs for energy efficiency** and **operation of CRs with energy efficiency**.
- These two objectives overlap since the improvement of energy efficiency with CRs require efficient CRs, whereas efficient wireless communications require cognitive abilities at different network components and protocols.
  - There are high challenges such as hardware complexity, algorithmic problems, and design trade-offs.
- This chapter discuss these issues to highlight the case of **CRs** for green wireless communication systems.

Dr. Honggang Zhang said that [1]

- The whole world of telecommunications and information communities is facing a more and more serious challenge, namely on one side the transmitted multimedia-rich data are exploding at an astonishing speed and on the other side the total energy consumption by the communication and networking devices and the relevant global **CO_2** emission are terribly increasing.

Dr. Honggang Zhang said that [1]

- The emerging *Cognitive Radio* (CR) system and technology are potentially capable of contributing to solve the abovementioned problem for realizing "**Green Communications**".
- Cognitive Radio is characterized of an adaptive, multi-dimensionally aware, autonomous radio system empowered by advanced intelligent functionality, which interacts with its operating environment and learns from its experiences to reason, plan, and decide future actions to meet various needs.
- This approach can lead to a significant increase in radio resource (spectrum) efficiency, networking efficiency as well as energy efficiency.

Dr. Honggang Zhang said that [1]

- A number of CR-enabled key advantages will be addressed in detail, including energy-efficient network architecture & protocols, energy-efficient CR transmission techniques (e.g., reduced transmission power & reduced radiation), cross-layer optimization methods, and opportunistic spectrum sharing without causing harmful interference pollution (i.e. **Green Spectrum**).

Backgroup

- **Telecommunications data volume** increases approximately by an order of **10** every 5 years, which results in an increase of the associated energy consumption by approximately 16–20 percent per annum [1].
- For instance, in Japan**, network power consumption** in 2025 is predicted to be **13** times the 2006 level, especially due to the anticipated increase in traffic volume with **broadband services** and **machine-to-machine** bursty traffic originating from **cloud computing** [2].

Cont.

- While the use of **information and communications technology** (**ICT**) is considered to be a facilitator for global energy savings (**teleworking**, **smart logistics**, **smart buildings**, etc.), the volume of network traffic will also increase, which leads to a challenging trade-off.
- Computing and communication systems are regarded as key components for reducing the environmental footprint in other environments such as *utility grids* and *transportation systems*, and also for *greening services* and *utilities*.
- It was estimated (2008 figures) that 3 percent of worldwide energy consumption was caused by the ICT infrastructure that generated about 2 percent of the worldwide CO2 emissions [3].

Cont.

- A major portion of this expanding traffic has been migrating to **mobile networks** and **systems**.
- Optimizing the energy efficiency of wireless communications not only reduces environmental impact, but also cuts overall network costs and helps make communication more practical and affordable in a pervasive setting.
  - For instance, in many portable devices, 30 percent of the energy consumption is due to wireless network interfaces [4].
- With the expanding domination of **multimedia services/traffic in wireless networks**, the spectrum requirements and computational burden on these mobile devices are also toughening in contrast to the perpetual trend of equipment miniaturization.

Cont.

- **Energywise optimization** of all aspects of wireless communications, ranging from equipment manufacturing to core functionalities, is paramount.
- **Green networks and communications** approaches, which call for holistic energy-wise optimization of communication systems, have spurred a substantial stream of new research activity.
- **Cognitive radio (CR)** is a promising paradigm proposed to cope with the spectrum scarcity problem that has emerged as a result of increased need for anytime anywhere connectivity [5].

Cont.

- CR (also called *smart radio) is defined as a wireless* radio device that can **adapt to its operating environment** via **sensing in order to facilitate efficient communications** [6].
- A CR, with its built-in intelligence and cognitive capabilities, can sense the radio spectrum, locate spectrum holes, and opportunistically access them as long as the licensed users (also called *primary users, PUs) do not use the band.*
- It can facilitate multimode radio interfaces that can operate in multiple standards with its adaptation property.
- Detecting spectrum holes reliably and vacating the spectrum bands immediately as a PU appears in the CR band are difficult problems.

Cont.

- CRs open up new control dimensions for **green** wireless communications with their **agility** and **adaptation** properties.
- Cognitive abilities that refer to a wide range of properties, from spectrum sensing to learning-empowered adaptive transmission in wireless network nodes, are beneficial for leveraging intricate trade-offs between energy efficiency, performance, and practicality.
- Nodes coupled with these cognitive functionalities, known as *cognitive nodes, can improve* network performance by **environment-aware** and **self-aware operation** capabilities.

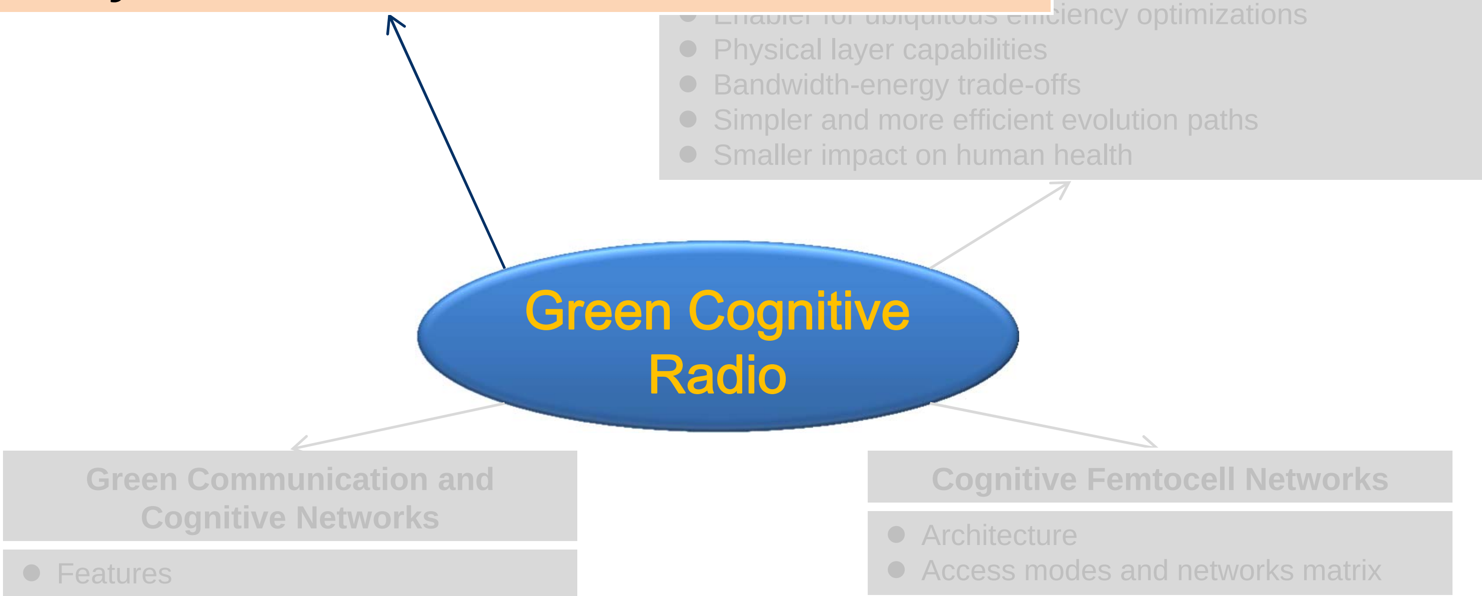
Cont.

- There are many challenges such as hardware complexity, algorithmic problems, and design trade-offs.
- These issues can be classified into two broad groups: ***CR inherent problems***, *e.g.* efficient sensing and spectrum access, and ***interworking*** issues entailing communications networks themselves and other infrastructural segments such as smart grids [1].
- It is envisaged that **adaptive** and **optima**l operation via **cognitive nodes** will benefit the **overall ICT** and the **relevant interconnected systems**.
- In this chapter, we present and discuss these points to highlight the case of CRs for green wireless communication systems.

Benefits of Cognitive Radios for Green Wireless Communications

Benefits of Cognitive Radios for Green Wireless Communications

- Cognitive cycle



Benefits of Cognitive Radios for Green Wireless Communications

- According to the FCC (FCC NPRM, Dec 17, 2003, ET-03-108), "***A cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates***."
- This interaction may involve active negotiation or communications with other spectrum users and/or passive sensing and decision making within the radio.
- To this end, a CR is supposed to perform an envisaged cognitive operational cycle shown in Fig. 4.

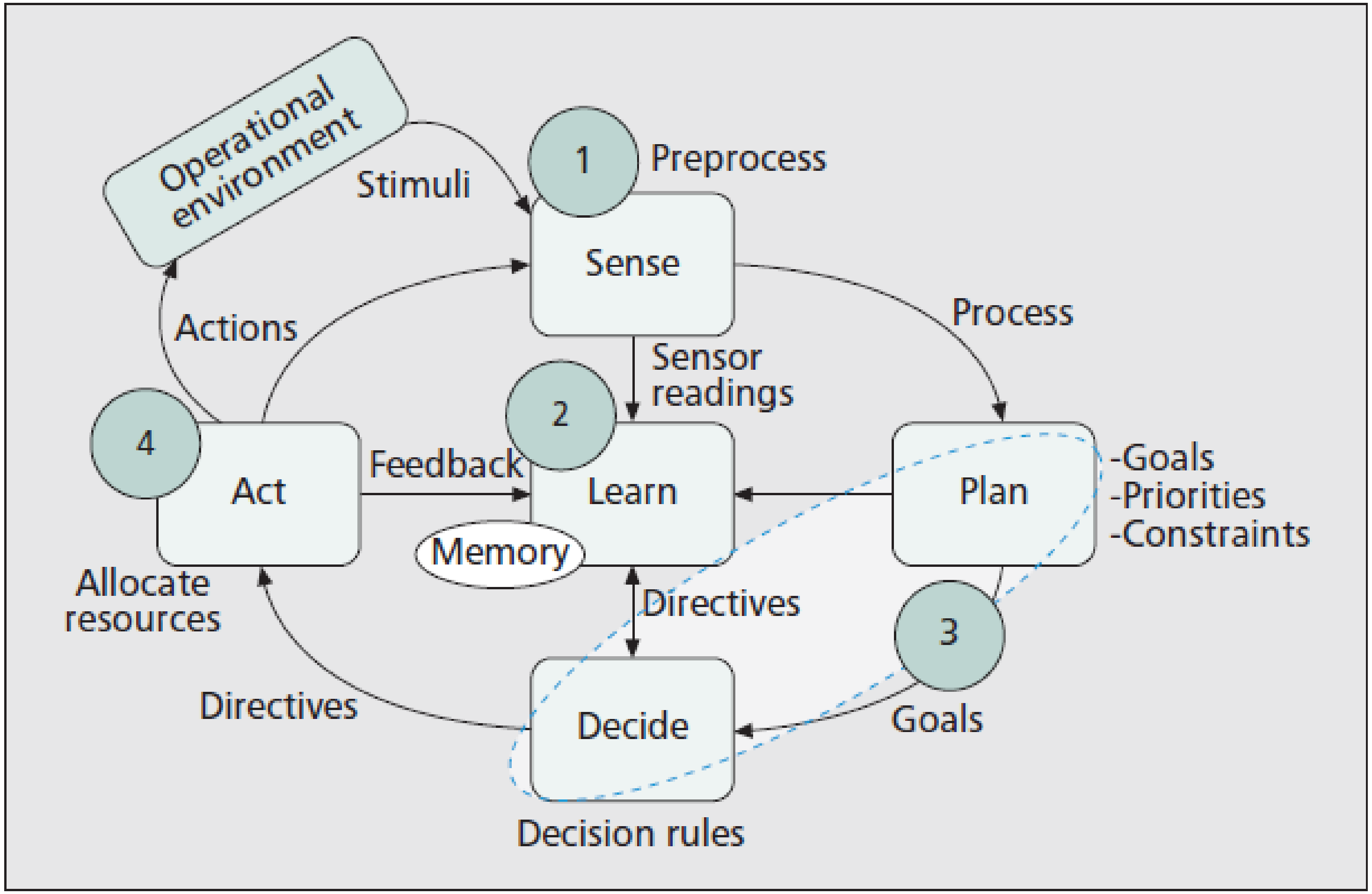


Figure 4. *Cognition cycle: CR is an active entity performing a cognition cycle entailing actions such as sense, act and decide which can be utilized for energy efficiency in networks.*

Cont.

- CR *senses its electromagnetic* operational environment by its sensors.
- After processing these sensory readings that represent the state of the environment, CR *plans and decides on its actions considering* its goals, priorities and constraints.
- With these self awareness and environment-awareness capabilities, a CR can select the best strategy meeting its goals.
- Upon deciding on the most appropriate strategy, CR *acts accordingly.*
- *All steps* interact with the embedded learning module.

Cont.

- A CR *learns from its experiences which also makes it smart.*
- **The energy efficiency related functionalities should be embedded in these flows**, and also these processes themselves should be made energy-efficient.
- CR has been proposed as a general approach for higher efficiency in wireless communication systems.
- From the green perspective, spectrum is a natural resource which should not be wasted but be shared.
- CRs enable this paradigm with smart operation and agile spectrum access. They also have to be optimized on the way to green communications.

Cont.

- There are two related aspects of CRs from the green networks perspective: **achieving energy efficiency in CR** (this paradigm enables a more prevalent optimization) and **energy efficiency via cognitive radio** (capabilities.)
- The energy management problem, in its most general formulation, is a multidimensional optimization problem, which consists of dynamically controlling the system to minimize the average energy consumption under some performance constraint(s) [18].
- In general, the related objective of energy efficiency can be measured as number of transmitted data bits per Joule of energy.

Cont.

- Since CRs mostly apply a **periodic sensing scheme** in order to evade any interruptions to the reappearing PUs, each frame is divided into two main parts: sensing and transmission.
- In general, the longer the sensing duration, the better the sensing accuracy. However, it shortens the duration available to transmission. Sensing and transmission scheduling should be performed providing a balance between the sensing accuracy and transmission efficiency.
- Taking this issue from the energy perspective, especially for battery-limited CRs, CRs can decide on the best sensing and transmission duration considering this problem as an energy efficiency maximization problem subject to PU interference restrictions.

Cont.

- Power allocation over a number of channels can improve the energy-efficiency in multi-channel CRs.
- A CR with a limited power budget can allocate its restricted resources considering the energy-efficiency of each channel [19].
- The evolution and interaction of **green** communications and the cognitive networks are shown in Fig. 5.

Green Communication and Cognitive Networks

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Cognitive Femtocell Networks

- Architecture
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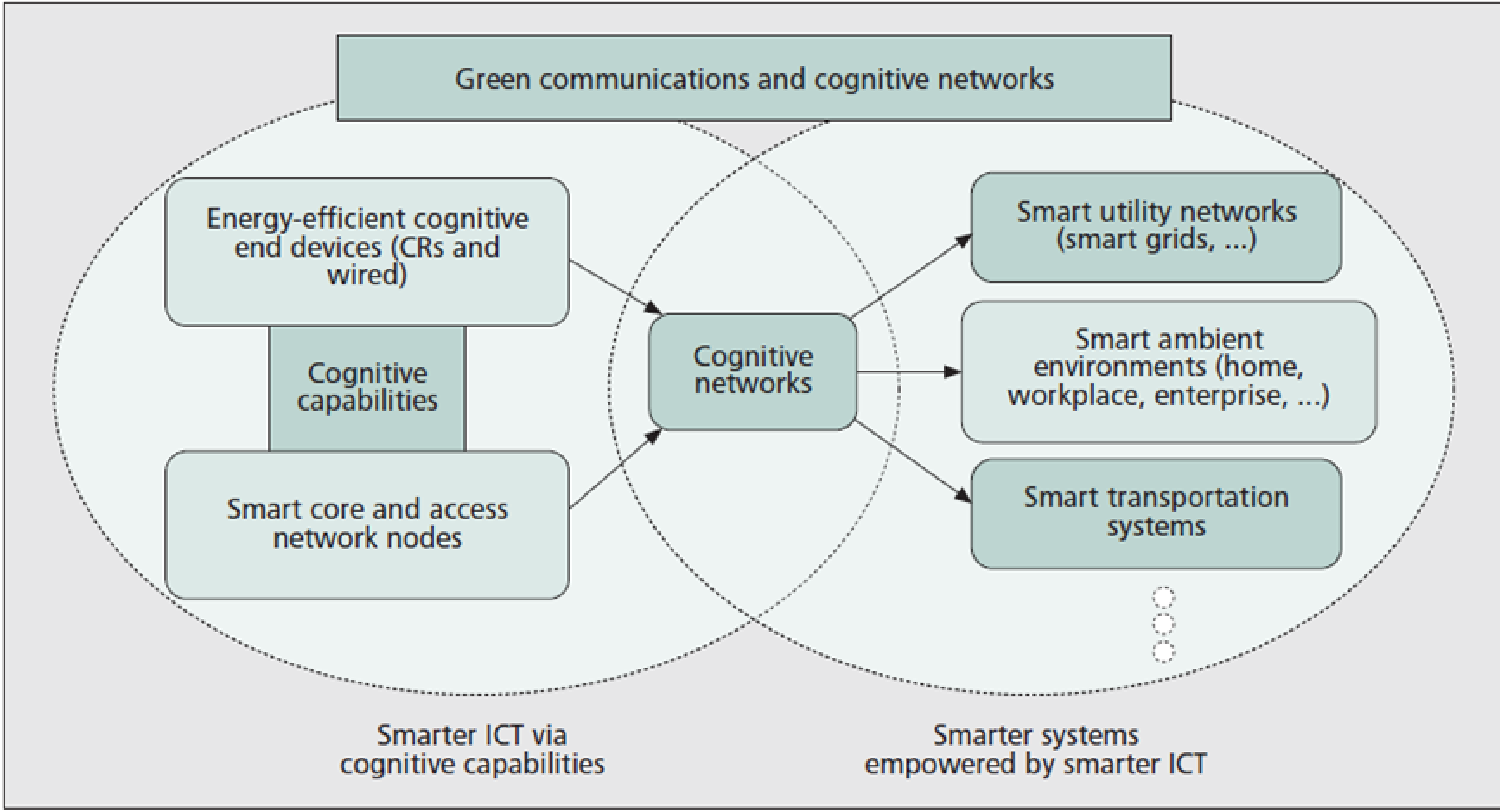

Cont.

- The advent of cognitive end devices (CRs and wired nodes) and smart core/access network nodes such as **cognitive femtocells** constitute a meta-infrastructure forming smarter ICT via cognitive capabilities, which can be denoted as *cognitive networks.*
- This interconnected structure provides a pervasive enabler for green systems and services such as smart utility networks (e.g., smart grids), smart ambient environments (home, workplace, enterprise, etc.), and smart transportation systems.
  - In this chapter, we focus on the general optimization problem of operational consumption after the wireless communication system is deployed, but not the entire system life cycle of manufacturing, deployment, and operations as the green networks approach considers.

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Figure. Cognitive Femtocell Architecture

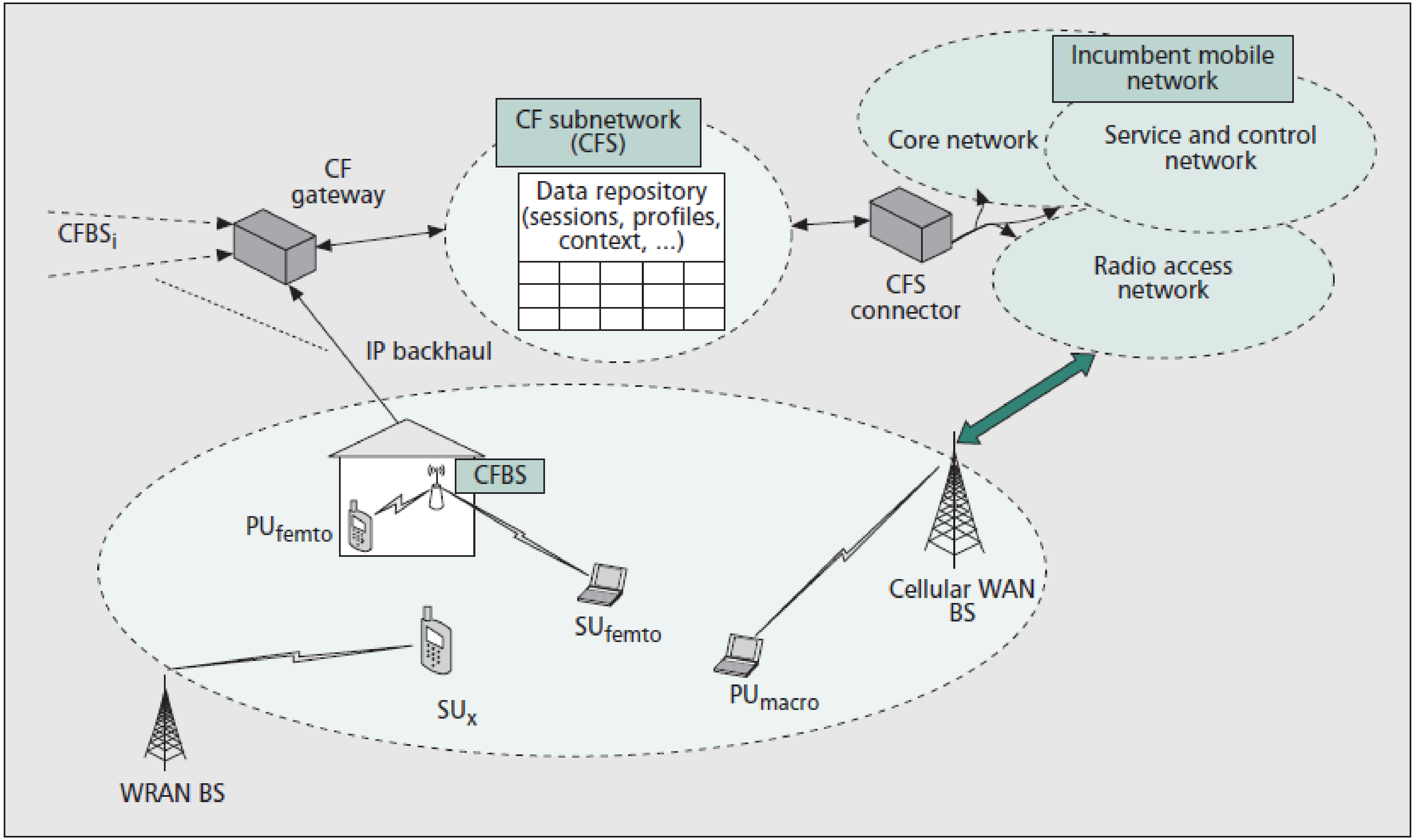

Figure 1. *Cognitive femtocell network architecture with network subsystems, SUs and PUs (femtocell and macrocell) having various access modes.*

Cognitive Femtocell Networks

- In this setting the standard indoor coverage expansion idea for a femtocell is still intact and operational.
- We use the term *cognitive femtocell base station (CFBS) for the device, which is a simplified* low-power network entity that utilizes broadband cellular technology (3G LTE/WiMAX) with IP backhaul through a local broadband connection, such as DSL, cable, or fiber [9].
- It is coupled with relevant CR capabilities such as spectrum sensing, interference management, and efficient resource allocation via learning and adapting to the operating environment.

Cognitive Femtocell Networks

- A CFBS acts as a conventional femtocell base station (FBS) that provides backhauling services to the users in its coverage region.
- A CFBS accesses the operator's network via wired broadband IP connection.
- The wide area network used for cognitive exploitation is assumed to be 3G LTE or IEEE 802.16 WiMAX.
- A CFBS is responsible for local sensing and is connected to a separate cognitive femtocell subnetwork (CFS) for infrastructure resident functionalities such as user rights, service provisioning, profile management, and charging in the cognitive domain.

Figure. Access modes and networks matrix

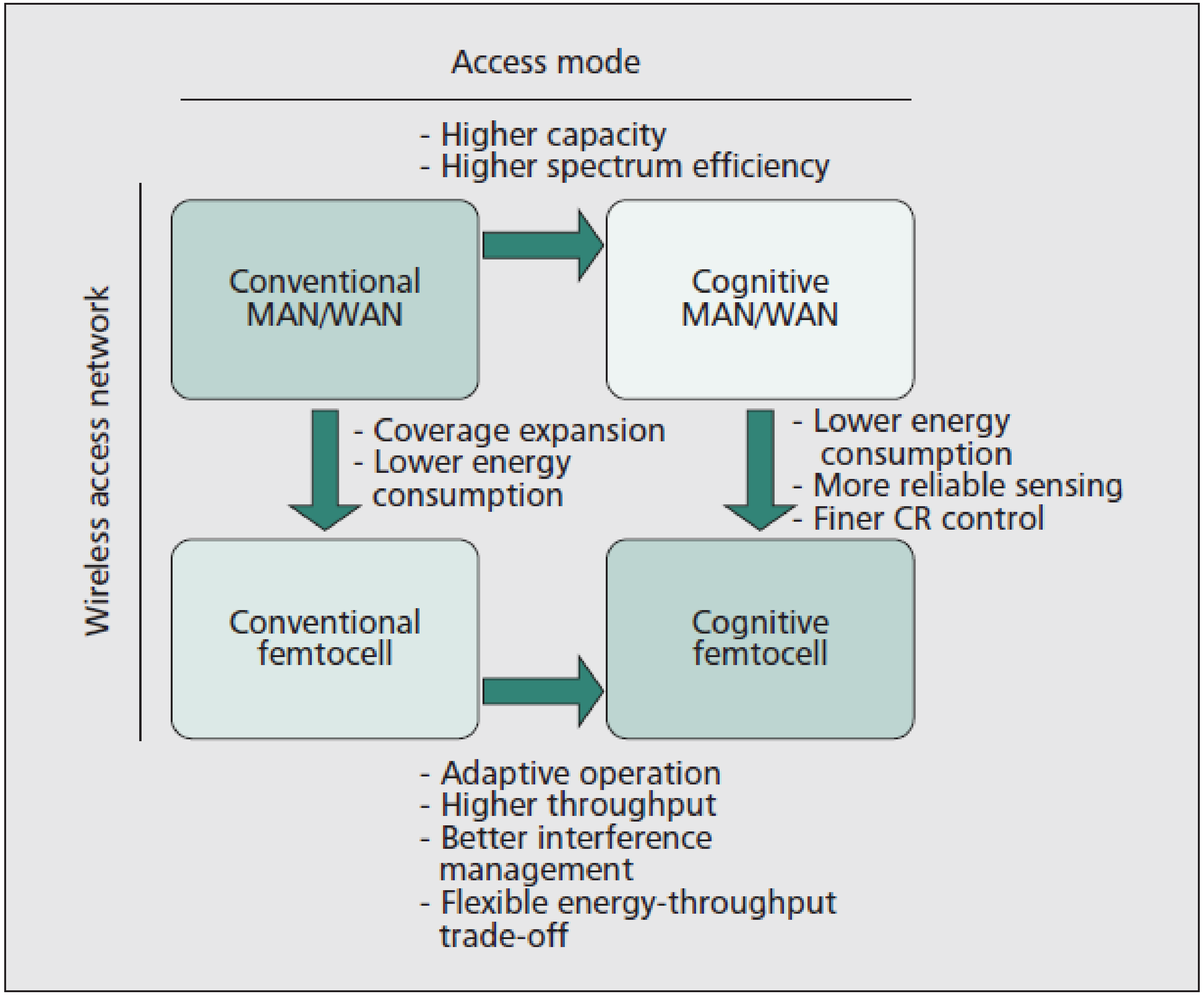

Figure 2. *Access modes and networks matrix.*

Cont.

- To that end, the capabilities of CRs enable a diverse set of energy efficiency optimizations in different communication settings:

Issue

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Benefits of Cognitive [partially hidden] Green Wireless Comm[partially hidden]

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1. Intelligence support for energy efficiency functionalities

- Models for energy consumption estimation require sensory data and computational schemes based on learning for accurate operation.
- Sophisticated middleware support for energy management and measurement, and profiling of energy consumption in wireless networks are crucial for attaining energy efficiency.
- Power supply and energy efficiency awareness is possible with CRs since the CR knows the **source of its power supply**, the **remaining battery life**, and **the energy efficiency** of alternative adaptation schemes [20].
- CRs encompass the sensor and computational infrastructure for enabling these capacities.

2. Energy savings via duty-cycle optimization and robustness in ad hoc settings

- For mobile ad hoc networks, the infrastructure-less and mobile system setup leads to rapid changes in the network topology and thus causes the issue of constantly forming and breaking communication links.
- This difficulty is also critical for the lifetime of the network since mobile ad hoc networks comprise energy-limited nodes [21].
- **Dynamic spectrum access** in CRs can alleviate this problem via various mechanisms such **as switching to the backup channels**, **estimation of the further link qualities**, and acting accordingly, since it is inherently designed with these considerations.

Cont.

- CRs may be subject to link disruptions due to unexpected PU appearance in the transmission band.
- **The service disruptions due to spectrum unavailability should be minimized** since the constant cost of having the system ready for communication can be eliminated and longer sleep opportunities can be created for network devices.
- CRs facilitate **duty-cycle optimization** since they perform agile spectrum access.

3. Network layer capabilities

- CRs can utilize **energy-aware vertical and horizontal handovers** with support from the access infrastructure.
- They can select the most appropriate network not just according to the physical layer conditions and available bandwidth, but also with consideration of **energy cost**.
- For instance, in the mesh mode, they can optimize routing and switching for energy efficiency.

4. Cross-layer optimizations

- The energy management problem lends itself to a **cross-layer solution** approach, as measuring performance requires taking into account the characteristics of the protocol stack, whereas optimizing energy expenditure relies on the detailed knowledge of **the low level radio hardware** [18].
- Cognitive network devices with their assumed machine learning and control frameworks are inherently more apt to **cross-layer optimizations** since these functionalities have to interact with different layers of the system.
- These communication systems will operate in dynamic environments where a single energy management solution is not sufficient. Thus, flexible cross-layer solutions are necessary [4].

Cont.

- The applications in cognitive networks will be able to interact with the radio for more flexible and adaptive operation.
- This enables context aware operation in the lower layers under application-driven smart schemes.
- On the infrastructure side, network nodes with cognitive capabilities may optimize their energy efficiency using different control dimensions such as switching to different network interfaces, **adaptive sleep cycles**, application-specific policies, and class based policies to avoid sacrificing the quality of service (QoS) of important users (Fig. 3).

Figure.

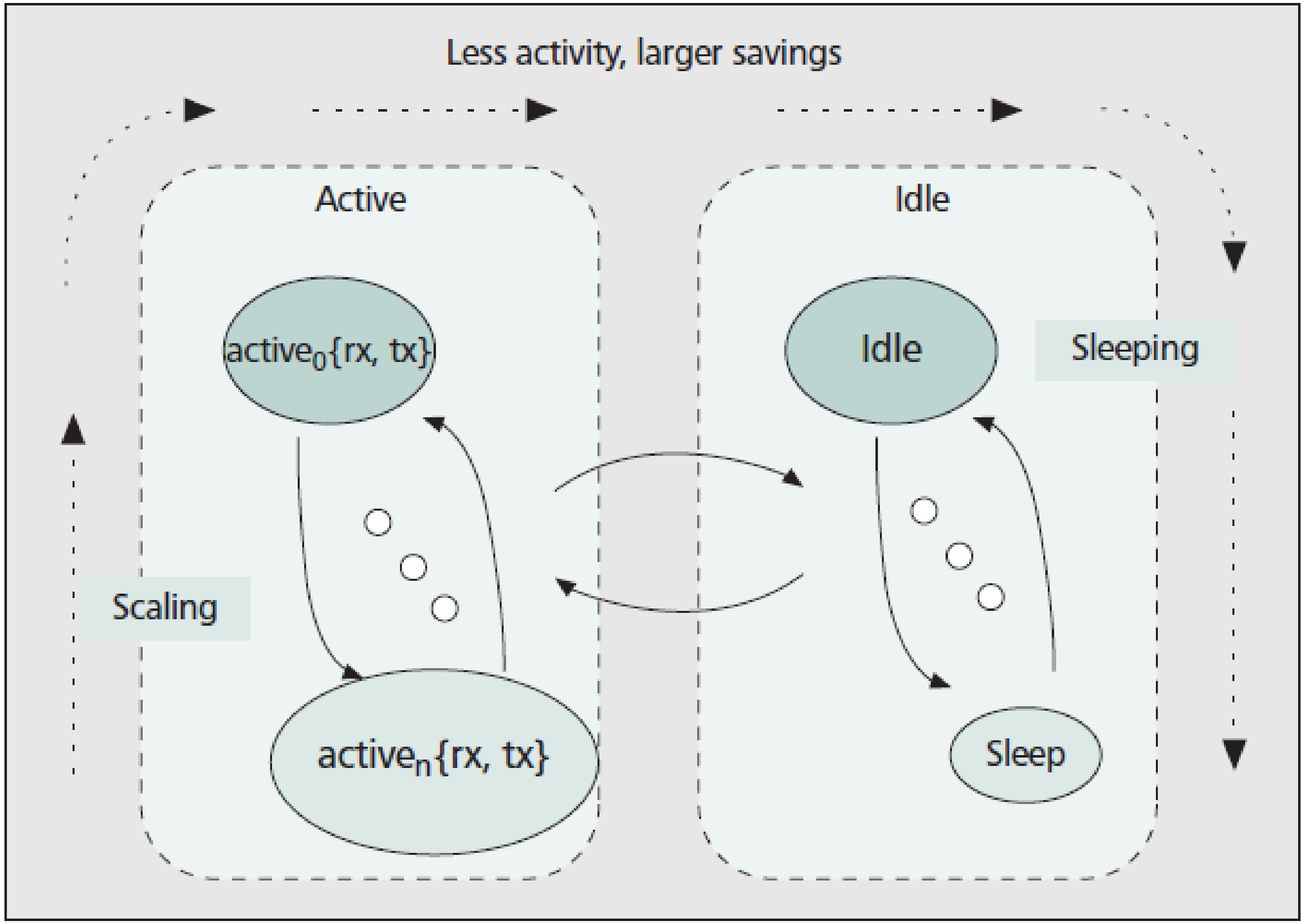

Figure 3. *Adaptive sleep and active modes for network nodes. The wireless node can utilize dynamic voltage scaling for transmit (tx) and receive (rx) interfaces in active mode. It can also adapt to different activity levels while being idle.*

5. Enabler for ubiquitous efficiency optimizations

- The interaction with other utility networks such as endpoints for “**smart grids**” and “**smart transportation systems**” will provide new opportunities for optimization of these networks.
  - A typical example is distributed power generation and consumption, which will become more common with the proliferation of home fuel cells, small-scale renewable energy sources, and high peak-to-average resource demands such as in **electrical grids** when plug-in hybrids and **electric vehicles (EVs)** are charged overnight [1].
- CRs can provide support for twoway information flows in the next-generation grids. For these grids**, smart meters** that provide accurate real-time information on consumption to the user and utility company are critical.

Cont.

- Distributed and micro-scale power generation infrastructure requires **pervasive** networking for control and monitoring. Various communication standards such as Zigbee have been considered for communication among these elements in the **home** network and **WAN** (toward the grid operator).
- These systems generally face two main issues: *coverage and interference* [22]. Using cognitive networks such as TV white space (TVWS)-based IEEE 802.22 can provide a feasible solution to these issues.

Cont.

- In particular, given the relatively low data rates involved in smart metering communications within each home, a single (or even a small subchannel) TVWS channel could be assigned for such applications in order to provide whole-home coverage. Moreover, they can support wider area communication between smart meters, microgrids and utility control centers.

6. Physical layer capabilities

- In the physical layer, beamforming (exploiting antenna directionality) for reducing power requirement and interference for a given range and data rate is possible.
  - An example in that regard is the major issue of the PAPR of the transmitted signal in multicarrier transmission schemes such as OFDM.
- CR sensors provide data support for power-efficient PAPR reduction techniques.
- Cognitive mobile devices will have the intelligence to select the **most energy-efficient PHY profiles** based on the present channel state via **learning** and **estimatio**n.
- This requires hardware support with more complex signal processing and comes with some typical issues such as the hidden node problem and MAC design [23].

7. Bandwidth-energy trade-offs

- According to Shannon's law, there is a direct trade-off between **bandwidth** and **power** efficiency.
- With agile spectrum access and smart operation, CRs may prefer bandwidth expansion to minimize power consumption in valid operational opportunities **without sacrificing throughput**.
- These communication theoretic tradeoffs provide tools to mitigate energy consumption.

8. Simpler and more efficient evolution paths

- The **software defined nature** of CR allows the **modification** of energy saving schemes in operation (runtime) **much more easily** (e.g., novel sleep mechanisms, operational profile mappings computed offline and updated [4]).
- This also enables more **autonomous** operation and **self configuration** for network nodes.
- This is in line with the fourth generation (4G) evolution path where the flat network architecture incurs a paradigm shift toward an **intelligent radio access network**.

9. Smaller impact on human health

- The increase in the number of wireless infrastructure nodes such as BSs and mobile terminals has increased public awareness of EM radiation.
- Avoiding EM pollution via the proper use and sharing of spectrum resources for protecting human health [24] addresses public health concerns due to EM radiation originating from wireless systems.

Conclusion

- The benefits of green wireless communications outweigh the drawbacks for the mobile operators. The research for green communications is an interdisciplinary field since it depends on advances in myriad areas from computer architecture to networking/communications standards.
- It requires the parallel effort of optimizing cognitive networks and optimization of other systems via cognitive networks and cognitive capabilities in general.
- CRs are supposed to couple energy efficiency with efficient spectrum usage for supporting green communications. The vast applicability of CR based optimization in home, enterprise and data center environments brings up many opportunities as well as challenges and open problems towards these goals.

Conclusion

- It should be noted that "**to consume only when necessary**" (spectrum, energy, hardware) is in contrast with the consumer society tendencies promoted by the cultural logic of late capitalism.

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Homework#4:

1. What is the cognition cycle for green wireless communications ?
2. What is the architecture of cognitive femtocell network ?
3. What are the features of green communication and cognitive Networks ?