Chapter 3:
Green Small-Cell Networks

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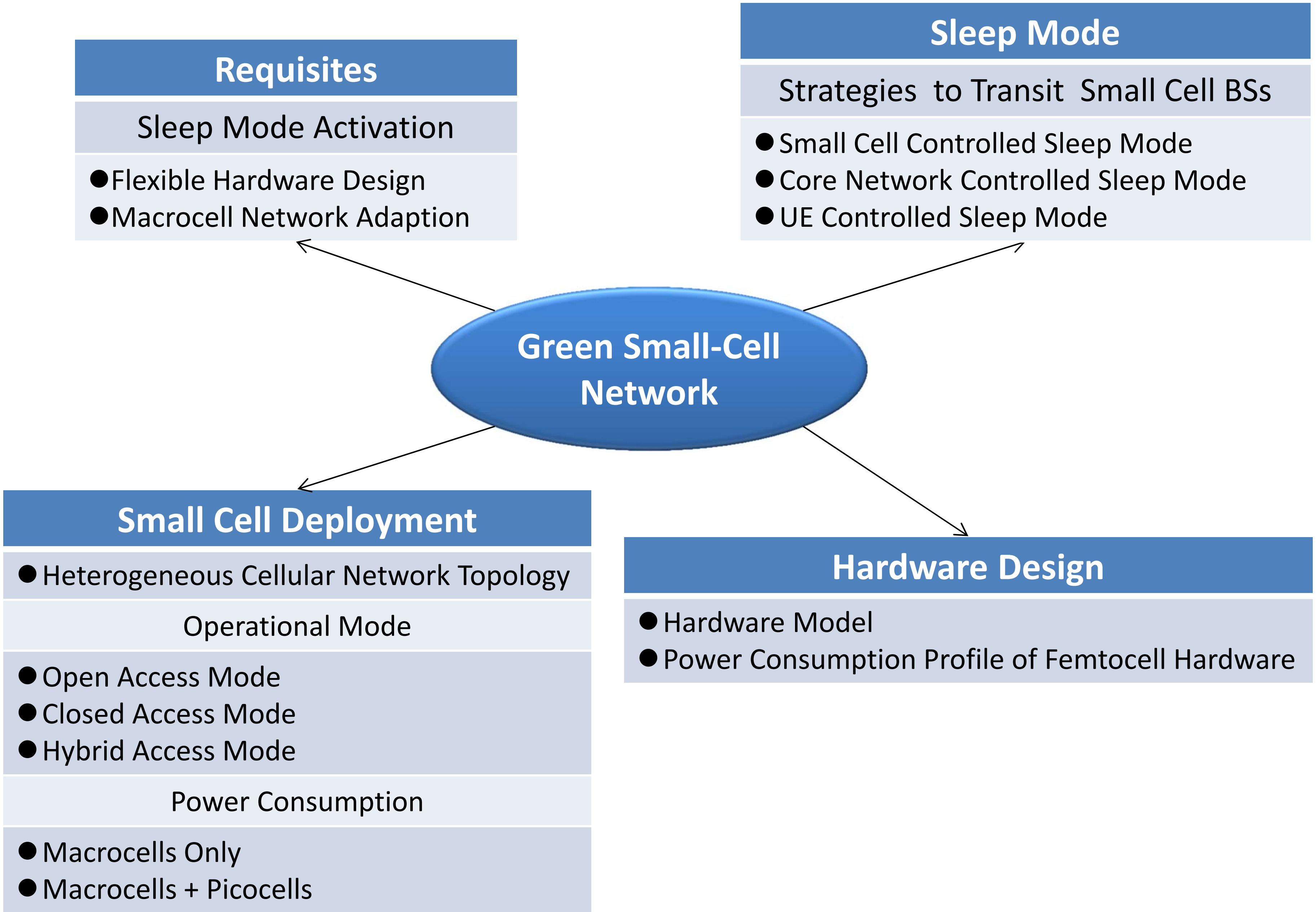
Outline

1. Introduction
2. Small cell deployment in cellular networks
3. Hardware design for small cells
4. Sleep mode procedures for small cells
5. Requisites for sleep mode activation in small cells
6. Concluding remarks

Technical roadmap for Green Small-Cell Networks: A taxonomy graph



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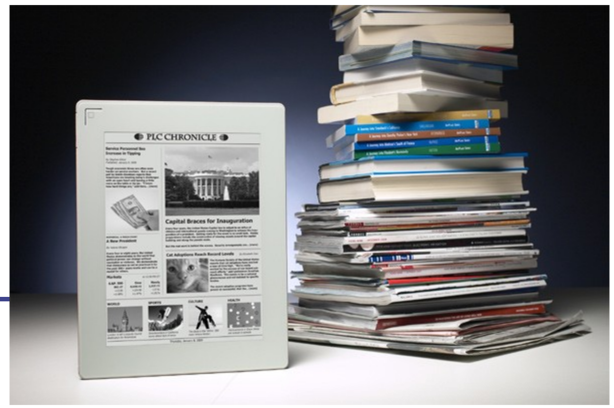
1. Introduction

- Faced with the exponential increase in data traffic, the cellular network operator is confronted with a precarious situation: accommodate the ever increasing traffic growth, yet reduce the costs and consequently increase average revenue per user (ARPU).
- With the electricity bill contributing to 20–30 percent of the network operational expense, the situation does not get any less intricate with the escalating energy costs.
- From another (ecological) perspective, there are concerns about the carbon footprint of the information and communication technology (ICT) industry as a whole.

Cont.

- Although the global ICT industry accounts for a relatively meagre figure of 2% of the global CO_2 emissions.
- It is expected to increase as other industries begin to utilize communication networks to reduce their own carbon footprints.
- Cellular networks take center stage in reducing global ICT emissions, albeit at the expense of a subtle interplay
  - improving revenues
  - reducing costs
  - enabling breakthrough services



Small cell benefit

- The needs of high data throughputs and improved coverage for home and office use, small cells have attracted significant interest in the wireless industry.
- Residential and enterprise small cell BSs provide great leeway to network operators to leverage on their excellent indoor performance, and offer value-added services and applications to end users.
- The upshot is a win-win situation [1]:
  - a higher satisfaction quotient from the subscribers' standpoint,
  - the network operator benefits from **capital expenditure (CAPEX)** reduction
  - macrocell traffic offloading
  - increased revenues

Cont.

- A further knock-on benefit of small cells is their potential to significantly reduce the network energy consumption if integrated with advanced energy saving techniques [2].

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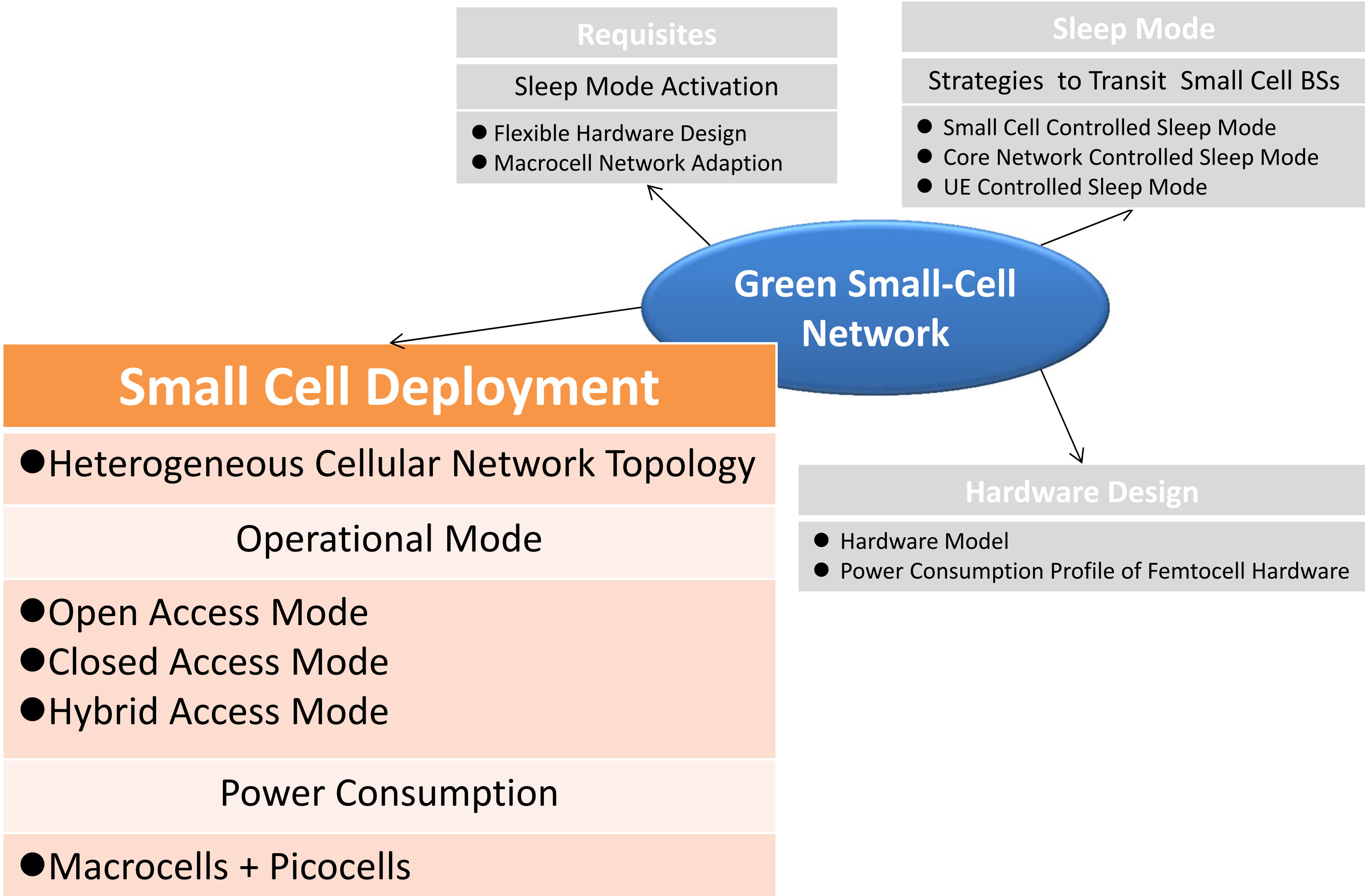

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2. Small cell deployment in cellular networks

- Heterogeneous Cellular Network Topology
- Operational Mode
  - Open Access Mode : the BS allows access to **all users**
  - Closed Access Mode : the BS allows only **registered users**
  - Hybrid Access Mode : limited amount of small cell resources are available to non-registered users
- Power Consumption
  - Macrocells + Picocells

Typical deployment and SLEEP modes

- In this chapter, typical small cell deployment models within cellular networks and discuss their implications on energy-related issues.
- The need for introducing SLEEP modes in small cells is highlighted for a heterogeneous network deployment.

Small cell introduction

- A small cell is a BS
  - low-power
  - low-cost radio
  - self-organizing
  - self-optimization
  - self-configuration
  - primary design objective is to provide superior cellular coverage in residential, enterprise, or hot spot outdoor environments.

The nano3G™ Access Points

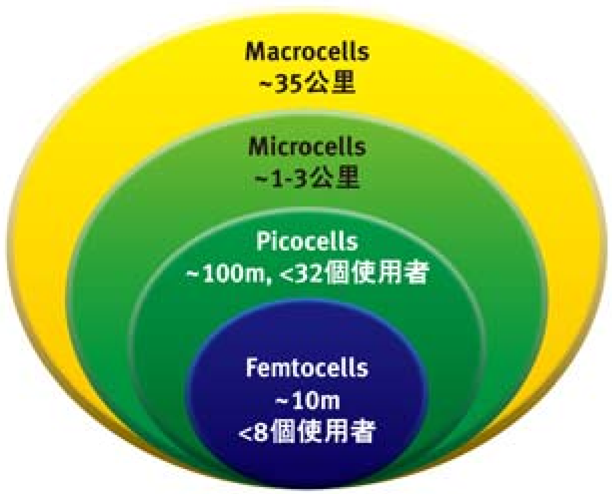
- In order of increasing cell size, small cell include
  - femtocells
  - picocells
  - microcells

3Way HBS(Home Base Station)

AT&T microcells

Microcell / Picocell / Femtocell

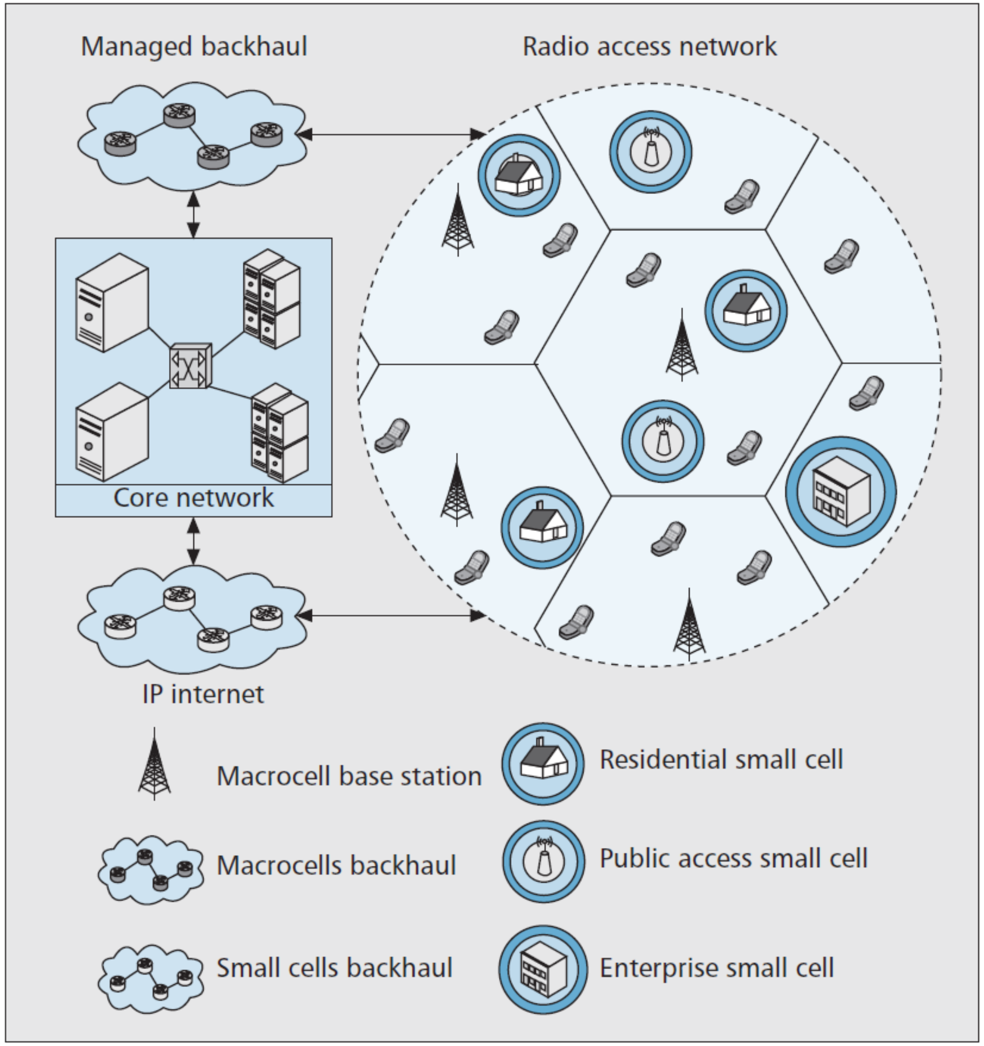
	Microcell	Picocell	Femtocell
Size	Bigger	Medium	Smallest
Coverage	~1 ~ 3Km	~100m	~10m
Users		<32	<8
Position	Outdoor Medium area	Indoor Local area	Indoor Home area
Cost	$US 20,000 and maintain cost	$US 2,000	$US 250
Transmitting Power	~10W	50mW ~ 1W	15mW



Cont.

- **Femtocells**, **picocells** and **microcells** can be interchangeable
  - it is important to focus only on the key commonalities of these smaller sized cells.
- Due to shorter distances between the **transmitter-receiver** pair, the transmit power required to achieve the same quality of service (QoS) scales down significantly in the small cell scenario.
- This transmit power reduction bodes favorably for power requirements of related BS hardware components, and the overall BS power drawn from the socket recedes.

Figure 1. *Heterogeneous cellular network topology incorporating different forms of small cell deployments as an overlay on the macrocell network.*



Small cells may use secure tunnels back to the core network using existing broadband infrastructure.

Small cell characteristic

- An important characteristic of small cell deployment is that it is considerably less **planned** as opposed to typical macrocellular deployments.
- For instance, in the case of residential femtocells, BSs are user-deployed and support plugand-play deployment.
- The same distributed control can be used to invoke SLEEP mode procedures in small cells in a bid to reduce network energy consumption.

Small cell mode

- There are two main operational modes for small cell BSs:
  - ***open access mode*** : the BS allows access to all users of the operator’s network;
  - ***closed access mode*** : allows only registered users to access the small cell.
  - *hybrid access mode* : a limited amount of small cell resources are available to non-registered users, can also be available.
- The energy saving procedures employed in small cell BSs can vary significantly based on the access control mechanism.

Cont.

- In the case of SLEEP mode schemes for closed mode small cells, the BS hardware need to verify whether the subscriber requesting access to resources is registered or not, before switching itself ON.
- User location information, user classification, etc., are also integrated differently in algorithms based on the small cell mode of operation.

Power consumption

Long Term Evolution (LTE) based cellular network	macrocells and picocells
Number of macrocell	η_{macro}
Number of picocell	η_{pico}
Mobile subscribers	40,000 (10,000 outdoor, 30,000 indoor)
Traffic requirements	0.5 Mb/s
Picocel power consumption	12 W and can transmit up to 0.2 W and serve four simultaneous users
Macrocell power consumption	2.7 kW
Average spectral efficiency per macrocell sector	1.7 b/s/Hz
Carrier bandwidth	20 MHz
Total energy consumption per annum	8760 h

$$E_{network} = (\eta_{macro} \cdot P_{macro} + \eta_{pico} \cdot P_{pico}) \cdot 8760, \text{[Watt hours]} \quad (1)$$

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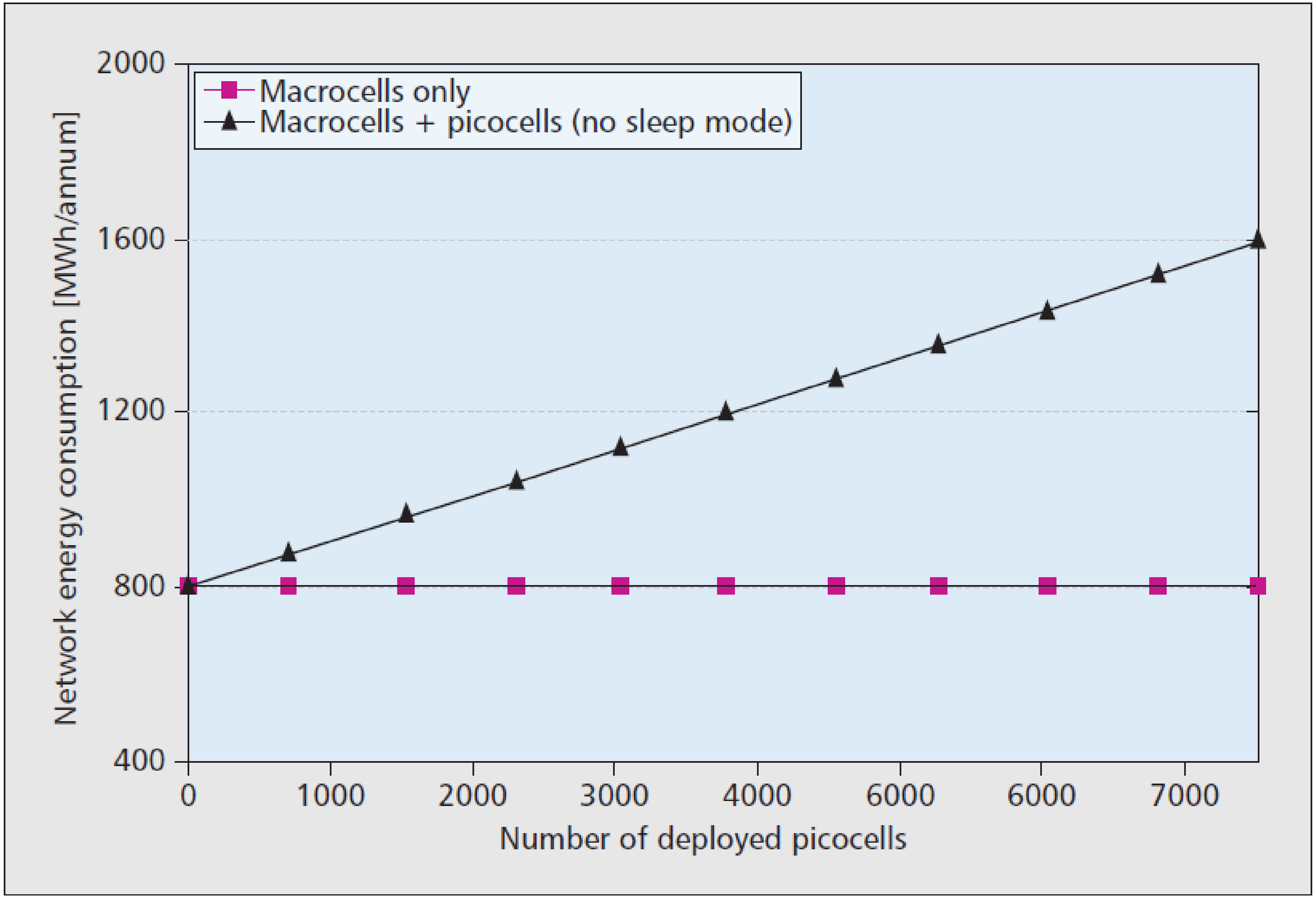
Figure 2. *Energy consumed by radio BSs per annum in dependency of the overlay picocell deployment.*

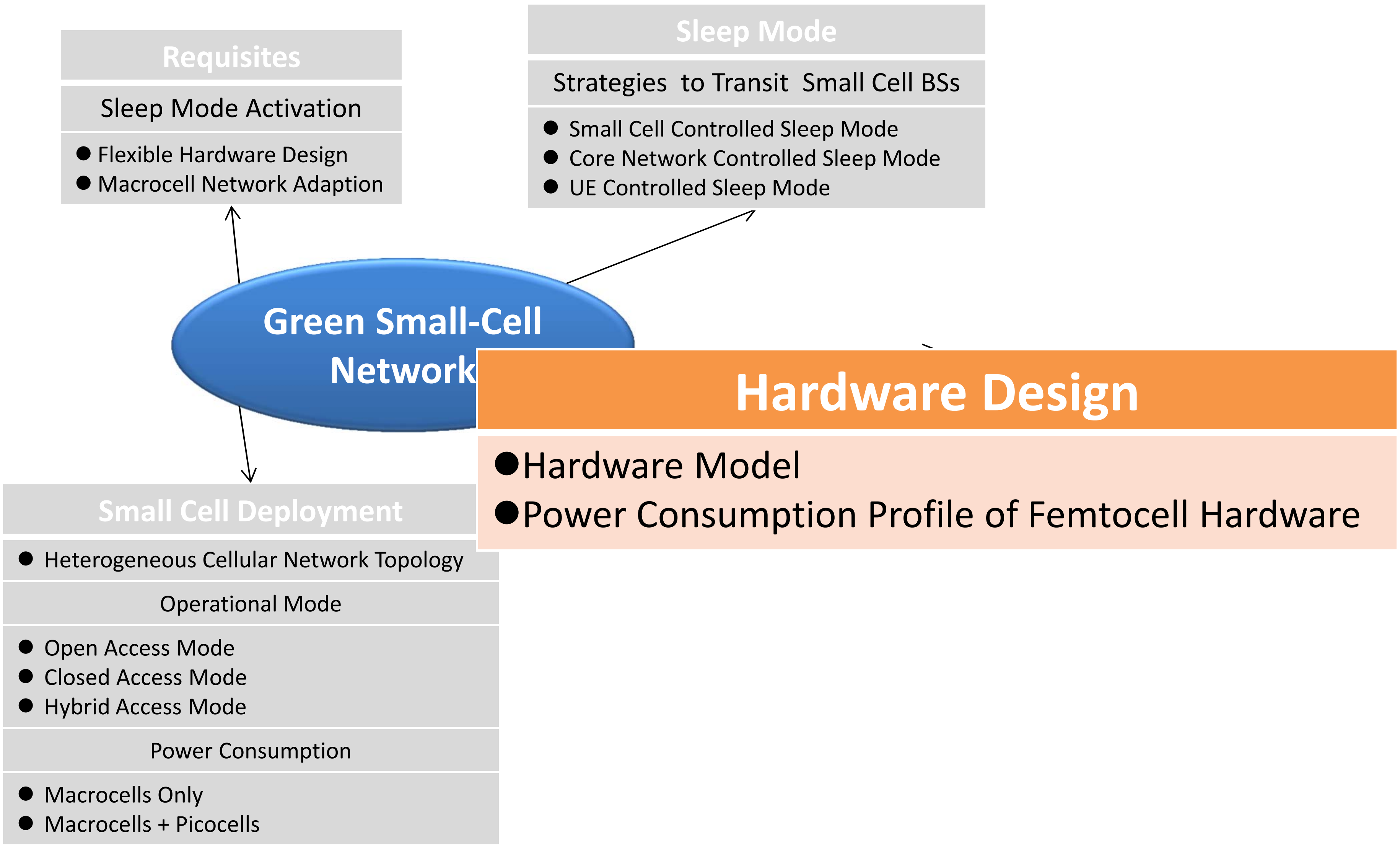


Each macrocell and picocell consume 2.7 kW and 12 W, respectively.

Cont.

- The network gets excessively overprovisioned (in terms of system capacity) as the deployment of picocells scales up, resulting in an increase in the probability of under-utilized BSs.
- This lays strong importance on devising SLEEP mode algorithms for radio BSs in a heterogeneous network setting.
- It will enable an ultra-efficient cellular network
  - substantial user capacity in reserves
  - elegantly provision significant reductions in energy expenditure
  - consequently the energy operating expenditure (OPEX) of the network operator

Technical roadmap for Green Small-Cell Networks: A taxonomy graph



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3. Hardware design for small cells

- Hardware Model
- Power Consumption Profile of Femtocell Hardware

Hardware Model

- The small cell hardware is required to design SLEEP mode algorithms that can utilize the switching off of various hardware components in low traffic conditions.
- It is imperative to scrutinize the limitations of current hardware design in terms of its compatibility with SLEEP mode mechanisms.
- Keeping this view as the backdrop, this chapter elucidates the hardware model for small cell BSs.

Figure 3. *Typical hardware model for a femtocell BS*

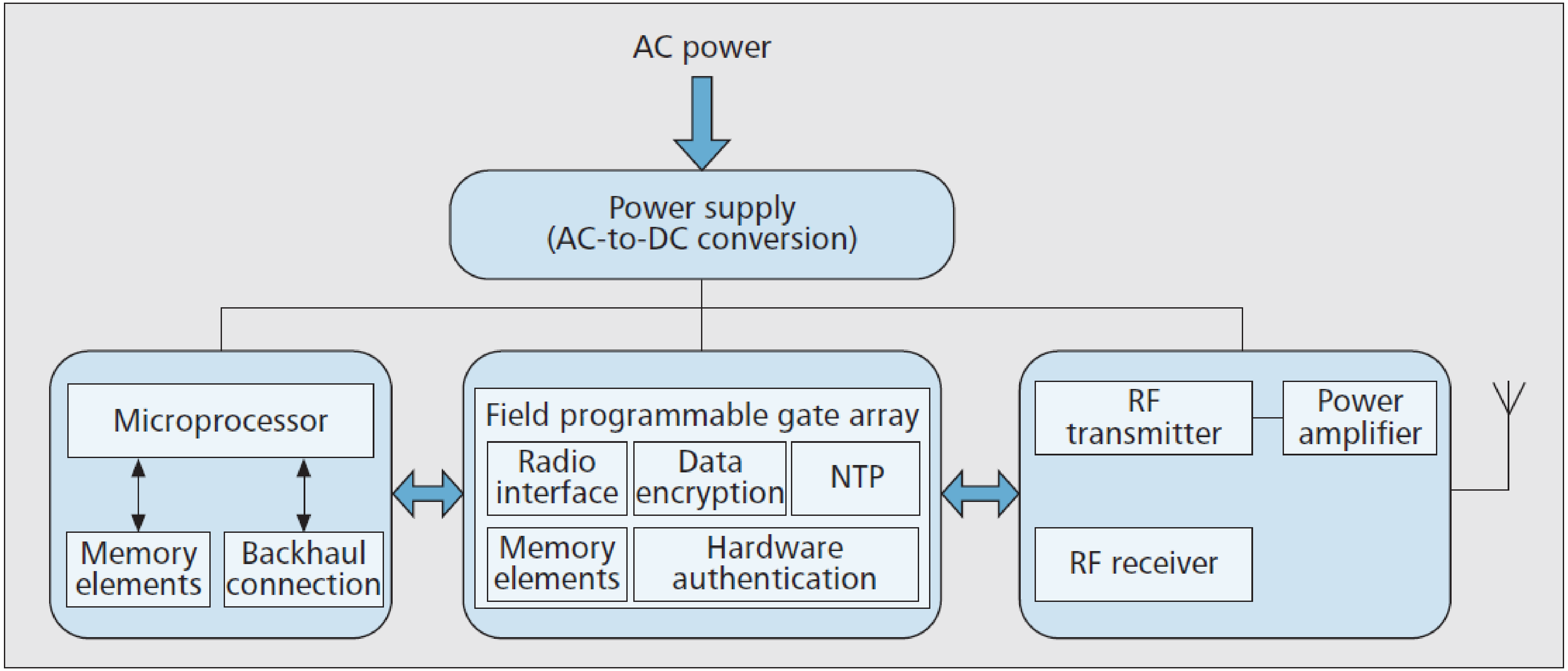

Table 1. *Power consumption profile of femtocell hardware.*

Hardware component	Power consumption (W)
Microprocessor	1.7
Associated memory	0.5
Backhaul circuitry	0.5
FPGA	2.0
Associated memory	0.5
Other hardware functions	1.5
RF transmitter	1.0
RF receiver	0.5
RF power amplifier	2.0

Cont.

- Figure 3 illustrates a high-level schematic representation of a typical femtocell hardware design.
- It comprises
  - a microprocessor that is responsible for implementing
  - managing the standardized radio protocol stack
  - the associated baseband processing
  - administering the backhaul connection to the core network
- This capability is generally implemented as a multicore application-specific integrated circuit (ASIC), which has the added benefit of low power consumption.

Hardware details

- Apart from the on-chip memory, one or more random access memory components are connected to the microprocessor, which are required for various data handling functions and system bootup.
- The design also contains a field-programmable gate array (FPGA) and some other integrated circuitry to implement a host of features, such as data encryption, hardware authentication, and network time protocol (NTP).
- The radio component within the FPGA acts as an interface between the microprocessor and the radio frequency (RF) transceiver.

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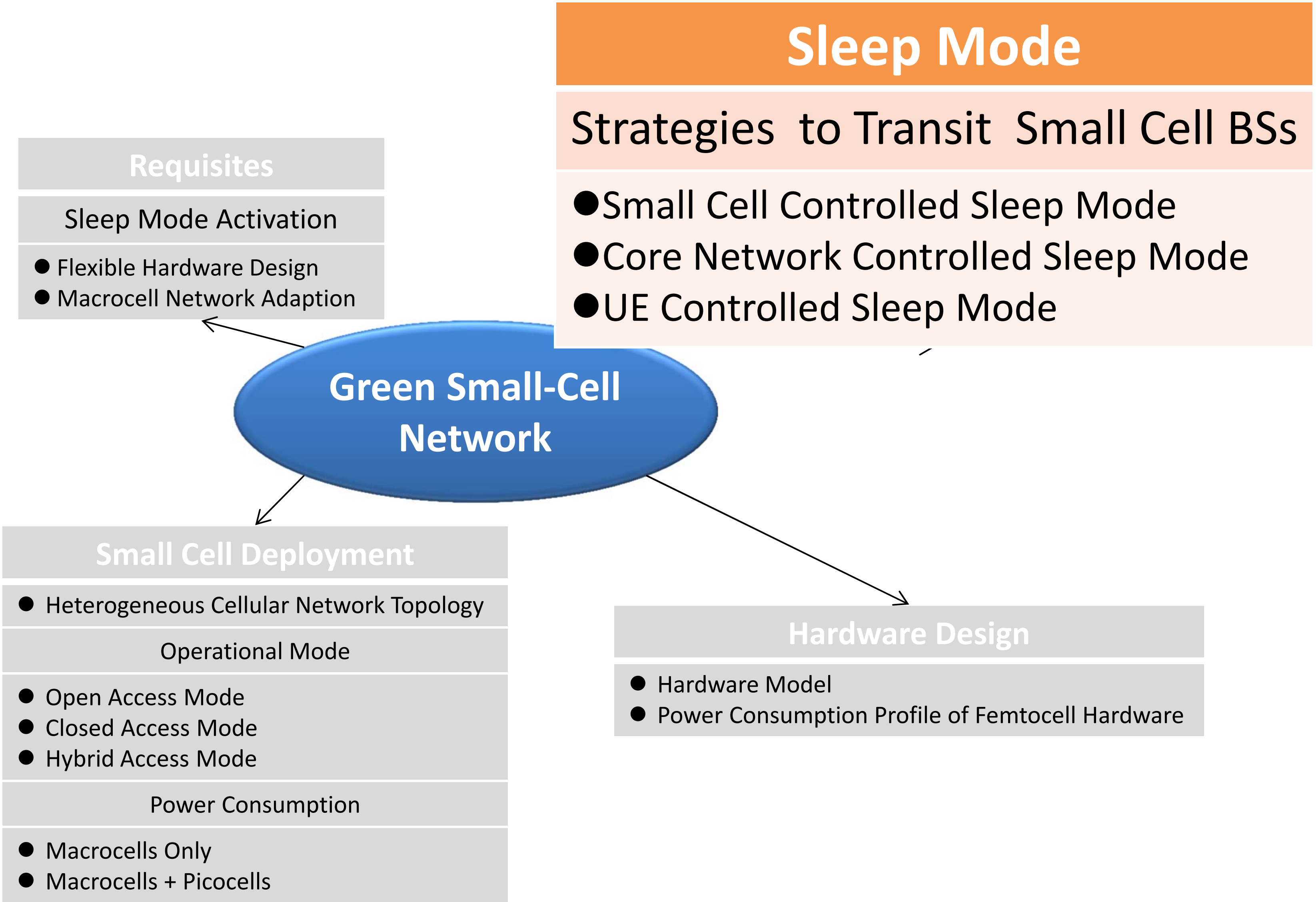

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   1. Small cell controlled sleep mode
   2. Core network controlled sleep mode
   3. UE controlled sleep mode
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4. Sleep mode procedures for small cells

- Femtocell state
  - READY state (RE)
  - SLEEP state (SL)
- Three strategies to transit small cell BSs state
  - Small cell controlled sleep mode
  - Core network controlled sleep mode
  - UE controlled sleep mode

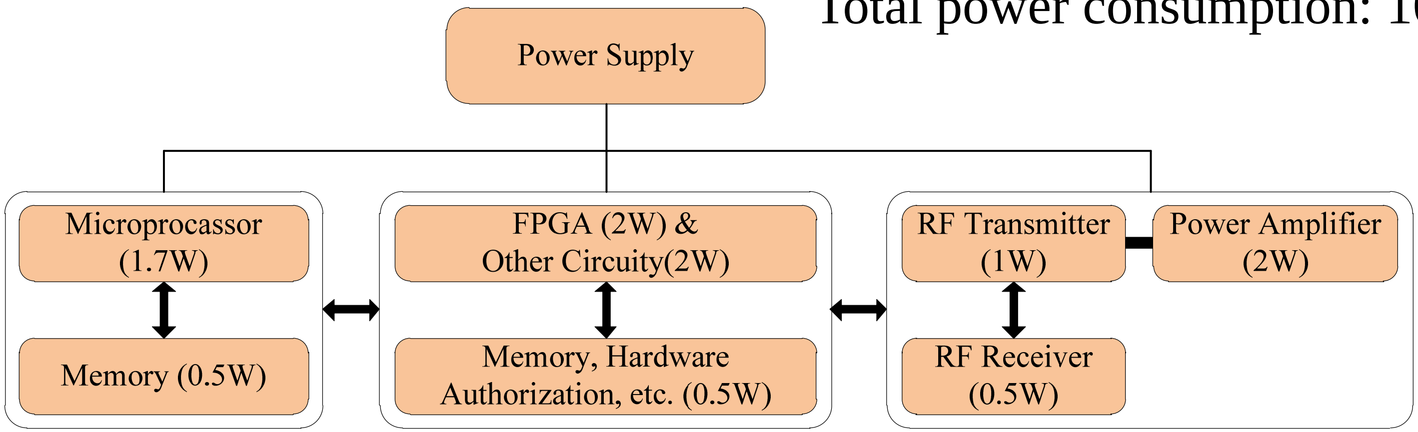
Femtocell state

- The basic idea underpinning SLEEP mode activation in small cell BSs is the introduction of a low-power state in the hardware, referred to as the SLEEP state.
- We assume that the small cell resides in exactly one of the following states at any given time:
  - READY state (RE)
  - SLEEP state (SL)

READY state and SLEEP state

- **READY state (RE):**
  - In this state, all hardware components in the small cell BS are fully switched ON.
  - The pilot channel RF transmissions are carried out to achieve a certain radio coverage area, and all allowed users in the coverage area are served by scheduling radio resources on data channels.
  - All traffic is served under the constraints of the BS's maximum capacity.

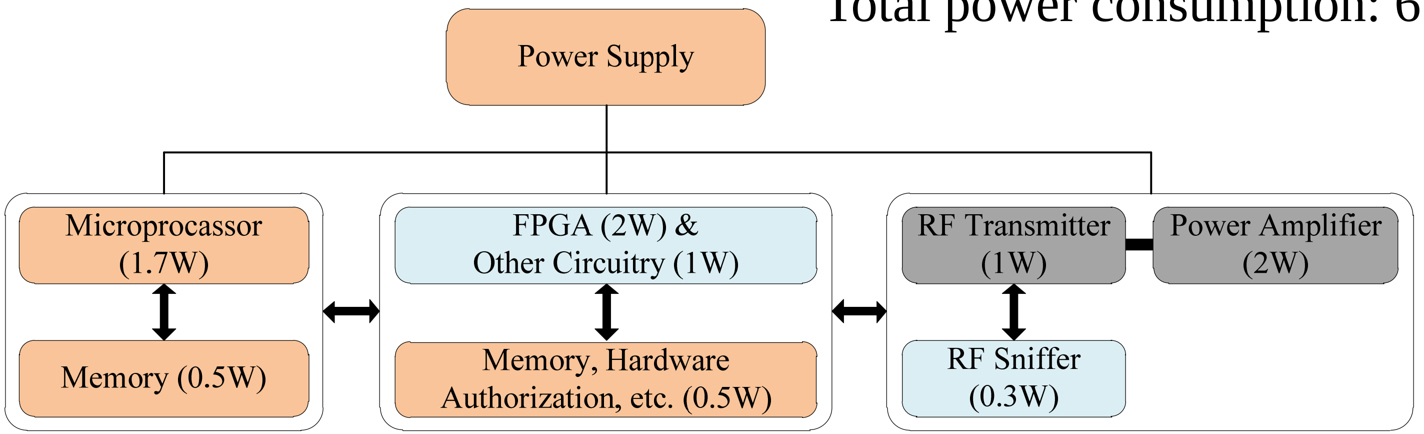
Total power consumption: 10.2W



READY state and SLEEP state

- **SLEEP state (SL):**
  - In this state, some of the hardware components in the small cell BS are either completely switched off or operated in low-power modes.
  - The BS is correspondingly said to reside in SLEEP mode.
  - The exact components to be switched off are a function of the specific hardware architecture and the particular energy saving algorithm.

Total power consumption: 6W



Three strategies to transit small cell BSs state

- Three strategies to enable the transition of small cell BSs between the SL and RE states (i.e., SLEEP mode activation/ deactivation).
- These mechanisms differ fundamentally in terms of the placement of SLEEP mode control in the network, which can be either at the small cell, in the core network, or driven by the user equipment (UE).

Small cell controlled sleep mode

- By leveraging the presence of sufficient underlay macrocell coverage, the small cell hardware can be augmented with a low-power *sniffer* capability
  - allows the detection of an active call from a UE

- The small cell can afford to disable its pilot transmissions and the associated radio processing (SL state) when no active calls are being made by the UE in its coverage area.
- When a UE located inside the sensing range of the small cell sniffer connects to the macrocell, the sniffer detects a rise in the received power on the uplink frequency band.

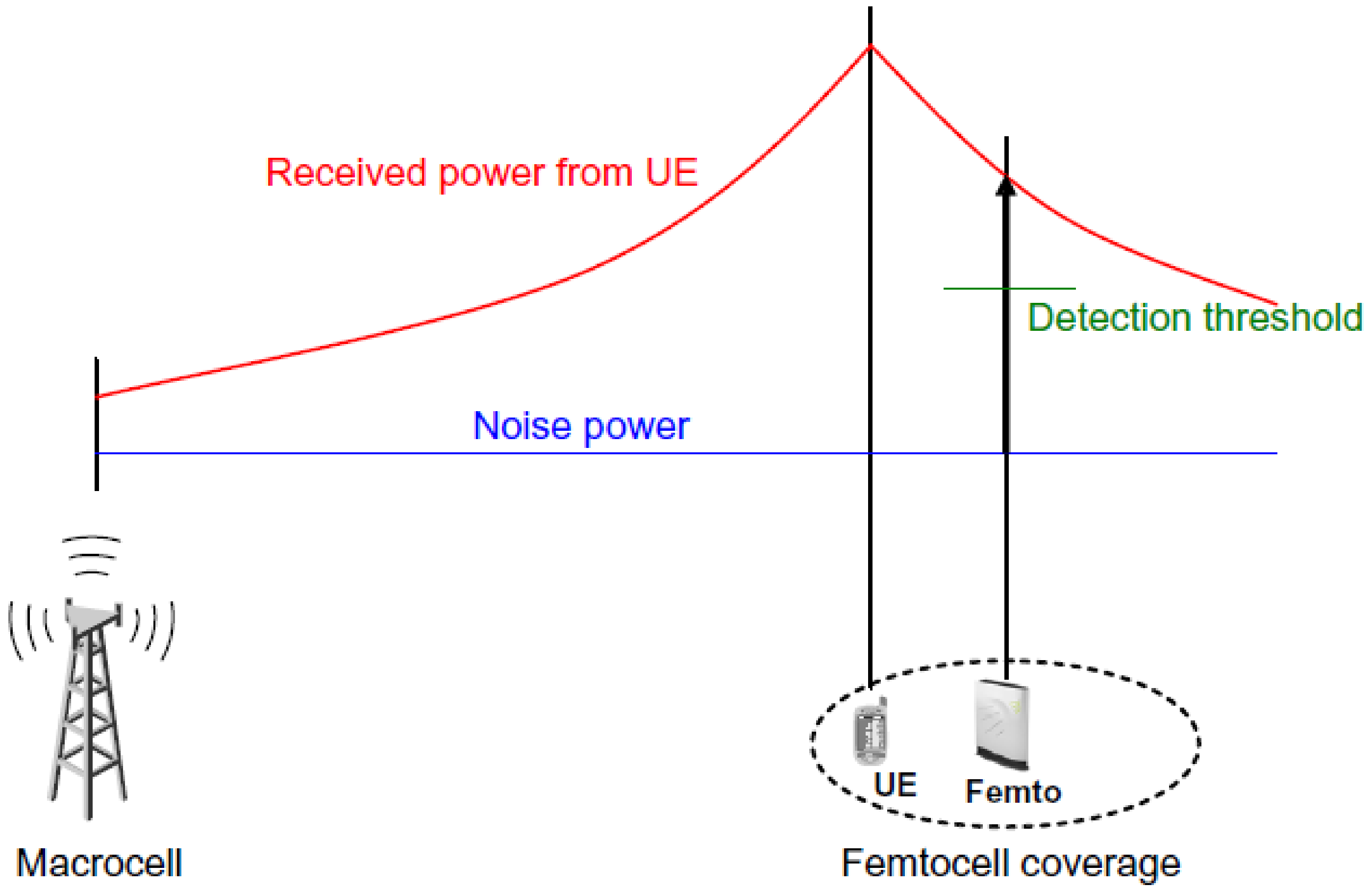
Cont.

- If the received signal strength exceeds a predetermined threshold, the detected UE is deemed close enough to be potentially covered by the small cell.
- At this point, the small cell switches to the RE state and activates its processing and pilot signal transmission.
- If the UE is allowed access to the small cell, the macrocell-to-small cell handover of UE (**inbounded mobility**) will be initiated; otherwise, the small cell can revert to SLEEP mode.
- Upon the completion of the handover process, the small cell serves the UE until its connection is terminated, after which it can switch back to the SLEEP mode.

Cont.

- This procedure requires macrocellular coverage since it relies on detecting transmissions from a UE to a macrocell.
- The sniffer-based SLEEP mode requires one macrocell–small cell handover per connection
- The benefits of reduced mobility events and associated signaling due to switched off pilot transmissions outweigh this [3].

Fig 4. *Noise rise measured at the femtocell, as a result of an active call to the macrocell in vicinity of the femtocell.*



Core network controlled sleep mode

- Different from the proposition above, **Core network controlled sleep mode** does not require the low-power sniffer in the small cell to detect active UE.
- The transition of small cell from SL to RE state is controlled by the core network via the backhaul using a wake-up control message.

Core network controlled procedure

- UE in the downlink or an uplink connection request from the UE is made to the macrocell.
- After a successful connection setup, the appropriate core network element identifies the serving macrocell of the UE and verifies if there is any UE-associated small cell in the same macrocell region.
  - This verification can be performed via the mobility management entity (MME) in LTE, a network element that keeps UE context information.
- The associated small cell BS to which the tagged UE is allowed to connect is then sent a wake-up message via backhaul to transition to the RE state and serve the UE.

Core network controlled sleep mode: Advantage

- The core network controlled solution has the following advantages:
  - The core network driven approach allows the possibility to take a centralized decision, based not only on a particular UE but also taking into account the macrocell traffic load, user’s subscription and traffic behavior, type of service requested, and so on.
  - The core network driven approach allows the exploitation of UE location estimation (or positioning) in order to further improve the decision efficacy.

Core network controlled sleep mode: Drawback

- The core network driven method provides better activation control, it incurs control signaling over the backhaul to wake up small cells.
- A single wake-up control packet could be used to trigger the activation/deactivation of a small cell BS.

UE controlled sleep mode

- Third approach is to place the SLEEP mode control at the UE side, which can broadcast wake-up signals in order to wake up small cell BSs within its range.
- The small cell, when in SL state, retains the capability to receive wake-up signal transmissions from the UE, and any time such signals are received, it transitions to RE state.
- The UE broadcast can also contain identification information such that the closed mode small cell wakes up only to registered UE.

Cont.

- This solution can be implemented in various ways. The UE can broadcast periodic wake-up signals continuously so that any small cells in SL state will transition to RE state when the UE approaches it.
  - UE battery consumption increases due to periodic broadcasts.
- This implementation decreases the amount of energy savings as the small cells would spend more time in RE state actively listening for UE wake-up signals.

An alternative implementation strategy

- The UE to broadcast wake-up signals when required on demand, such as in the absence of sufficient macrocell coverage or for higher data rate requirements.
- The UE can transmit broadcasts to attempt to wake up any small cells within range.
- The UE can also perform these broadcasts prior to establishing a connection with the network.
- This enables the UE to wake up any small cells first and then connect directly through a small cell.
- The ondemand approach can result in better energy savings since the small cell can be in SL state more often, and is only transitioned to the RE state when required.

UE controlled sleep mode: Advantages

- The UE controlled approach does not rely on the need for underlay macrocell coverage to switch ON/OFF small cells.
- This is particularly important as many small cells could be deployed as a means of solving macrocell coverage black spots.
  - Both small cell and core network controlled solutions require sufficient macrocell coverage for the UE in order to enable SLEEP mode activation/deactivation.
- The amount of core network related signaling is reduced.
- The UE makes a call, it does not have to initiate a connection with the macrocell underlay and then get handed over to the small cell after it transitions from SL to RE state.
- The small cell would already be in the RE state at the time of connection establishment allowing the UE to initiate connection directly with it.

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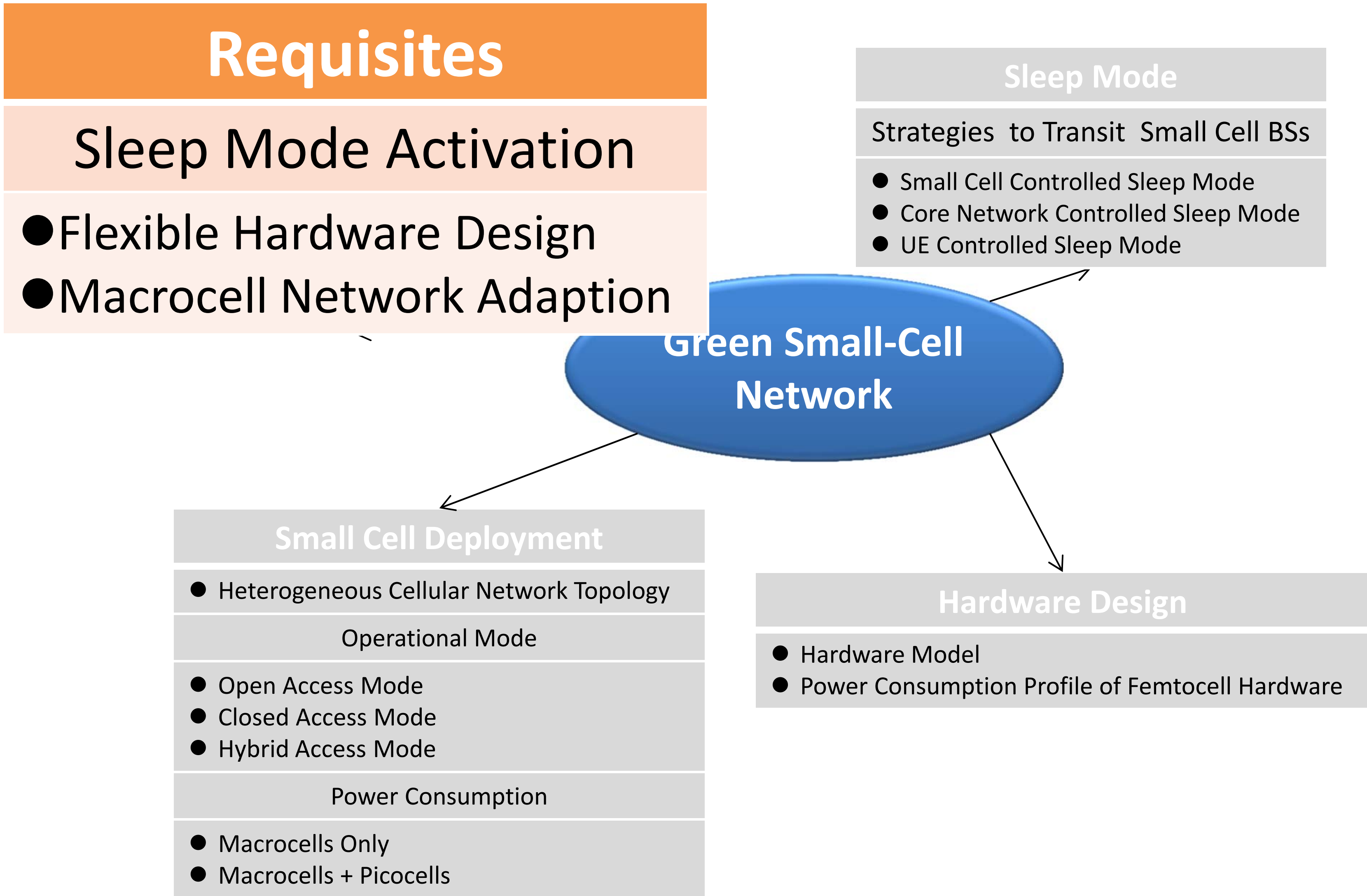

Outline

5. Requisites for sleep mode activation in small cells

- Flexible hardware design
- Macrocell network adaptation

Flexible hardware design

- An obvious drive to reduce the small cell power consumption is to design and produce hardware components that inherently consume less power.
- Substantial energy savings can be achieved by modulating the hardware energy consumption over the traffic load.
- The power drawn by the individual hardware parts should scale with traffic demands, and these should also support ultra-low-power modes in zero load or idle conditions.
- The microprocessor can vary its clock speed depending on the number of UE units served such that the processing power consumption follows user traffic.

Cont.

- Moving on from individual hardware components, the overall hardware design needs to be SLEEP mode aware.
- FPGA acts as a communication interface between the RF transceiver and the microprocessor and cannot be switched off independently.
- A modular hardware design approach, which provides the flexibility of handling components individually, can offer a significant improvement over the current model.

Macrocell network adaptation

- The utilization of macrocells can be reduced due to offloading of user traffic to small cells.
- Small cells are ideal for providing localized high data rate services, while macrocells are better suited for providing coverage over a wide area.
- The joint use of small cell overlays in hotspots to provide additional capacity, with an underlay macrocell for wide area coverage is an efficient way of deploying cellular networks in scenarios where demand for capacity is non-uniformly distributed.

Cont.

- The rewards from such a conjoint arrangement are fully reaped only if the underlay macrocell network is designed to work in tandem with the small cell deployment.
- Various techniques that can be used on the underlay macrocell to maximize the energy efficiency of cellular networks are discussed.

Over-provisioned macrocell

- Consider the scenario where a macrocellular network has been carefully planned, deployed, and provisioned to provide the required coverage and capacity to the existing users.
- With the introduction of small cell overlays, the macrocell network becomes over-provisioned due to the offload of traffic by means of small cells.

Strategy to solve over-provisioned macrocell

- One strategy for the network operator is to keep the existing macrocell BSs as they are, and delay any modifications or capacity upgrades until natural growth in user demand catches up with the spare capacity.
- This approach does not offer the most efficient energy savings since it may take a long time for growth in user demand to increase sufficiently.
- The network operator can re-optimize the existing macrocell network in response to small cell deployment, such as decommissioning sites that are no longer needed.

Cont.

- Performing this optimization can be costly and disruptive in the short-term but will make the overall network more energy-efficient and reduce network OPEX over the long term.

User-deployed small cells

- An interesting scenario is when the small cells are user-deployed, such as residential or enterprise femtocells, where they can be deployed or removed from the network without warning.
- This highly dynamic and unpredictable nature of small cell deployment makes frequent manual re-optimization of the macrocell network impractical.
- It is therefore desirable for the macrocell BS to dynamically scale back its power consumption according to the supported traffic load.

Cont.

- This could be achieved by using various approaches, such as dynamically switching off carriers and traffic modules according to load conditions, and using multistage power amplifiers [5] that allow the transmit powers to be adjusted more efficiently.
- Self-organizing algorithms also allow a BS to reconfigure and compensate when neighboring BSs switch off.

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6. Results

- This chapter introduced a class of energy-efficient SLEEP mode algorithms for small cell base stations.
- The proposed algorithms allow the hardware components in the BS to be astutely switched off in idle conditions, such that the energy consumption is modulated over the variations in traffic load.
- Three different strategies for algorithm control have been discussed, relying on small cell driven, core network driven, and user equipment (UE) driven approaches.
- The importance of macrocell adjustments with small cell deployments has also been discussed.

Cont.

- With small cell deployment, the transmitter-receiver distances are greatly reduced, resulting in reduced transmission power and hence extended battery life for UEs.
- Future studies will take into account these UE aspects, backhaul energy consumption, and non-uniform traffic distribution.

Homework#3

1. Describe the difference between microcell, picocell, and femtocell.
2. Describe the requisites for sleep mode activation.
3. Describe the three strategies of controlling sleep mode.