HANDBOOK ON GREEN INFORMATION AND COMMUNICATION SYSTEMS

Cognitive Strategies for Green Two-Tier Cellular Networks: A Critical Overview

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Presentation Outline

- ☆Introduction
- ☆Femtocell Networks
- ☆Cognitive Radio
- ☆Cognitive Femtocell Networks
- ☆Conclusion
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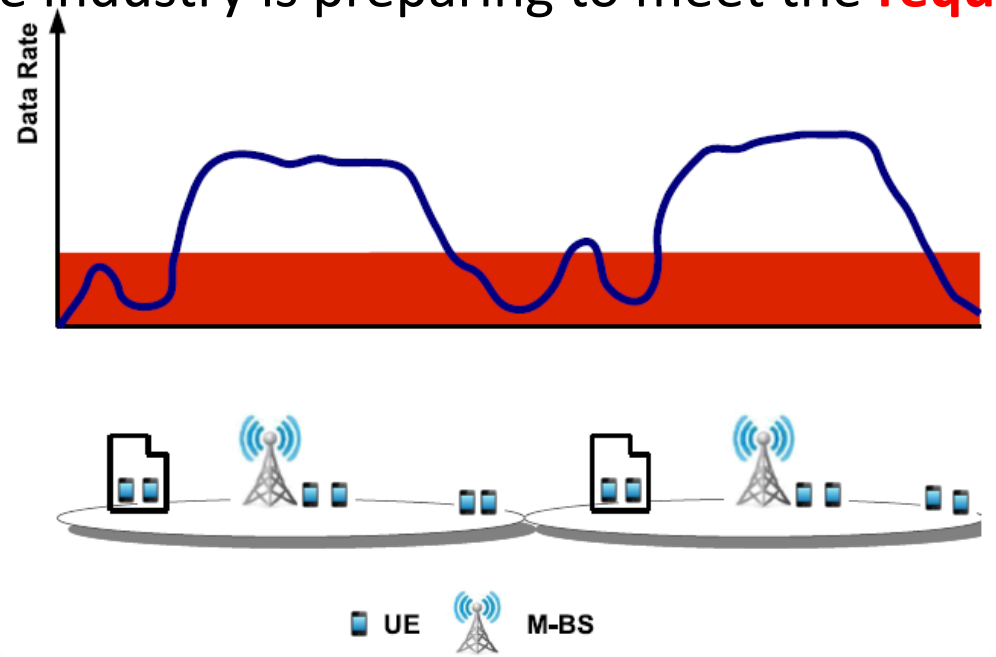
Open Challenges in Future Cellular Networks (1/2)

- Traffic figures are expected to double annually over the next five years [Ercsn10]
- The smartphone will generate 1 GB of traffic per user per month in 2015 [Cisco10]
- Indoor and cell edge UEs still experience very poor performance due to propagation losses and interference

➢ The mobile industry is preparing to meet the **requirement** of **traffic** and **coverage**.



Open Challenges in Future Cellular Networks (1/2)

- Operators need to ameliorate their infrastructure to satisfy rate demand and data services
- Forecasts indicate that expenditure related to future requirements may lead to negative cash flow for western operators [Mclaughlin11]
- Energy consumption will cause an increase of CO_2 and impose challenging operational cost for operators

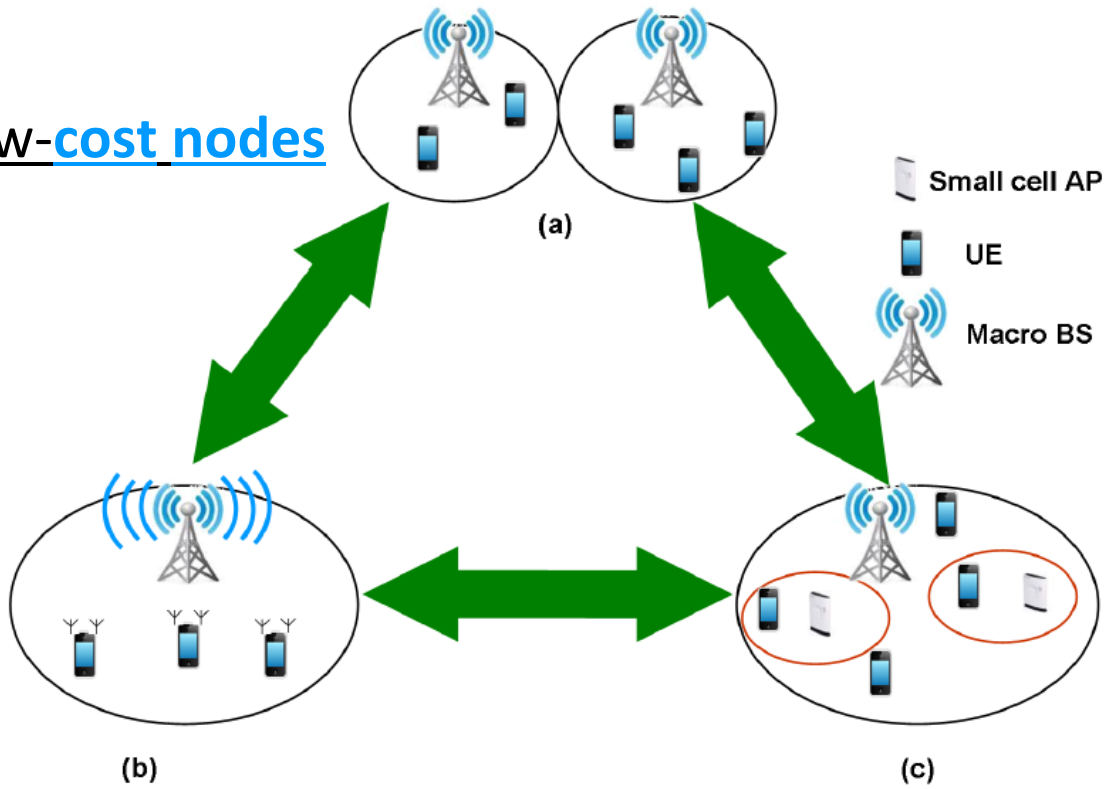
  - **Energy Efficiency** is an alarming **bottleneck**!!

Approaches for a Uniform Broadband Wireless Service in Cellular Networks

a) **Densifying** the **homogeneous** cellular network

b) **Upgrading** the radio **access**

c) Deploying **low-power** low-**cost nodes**



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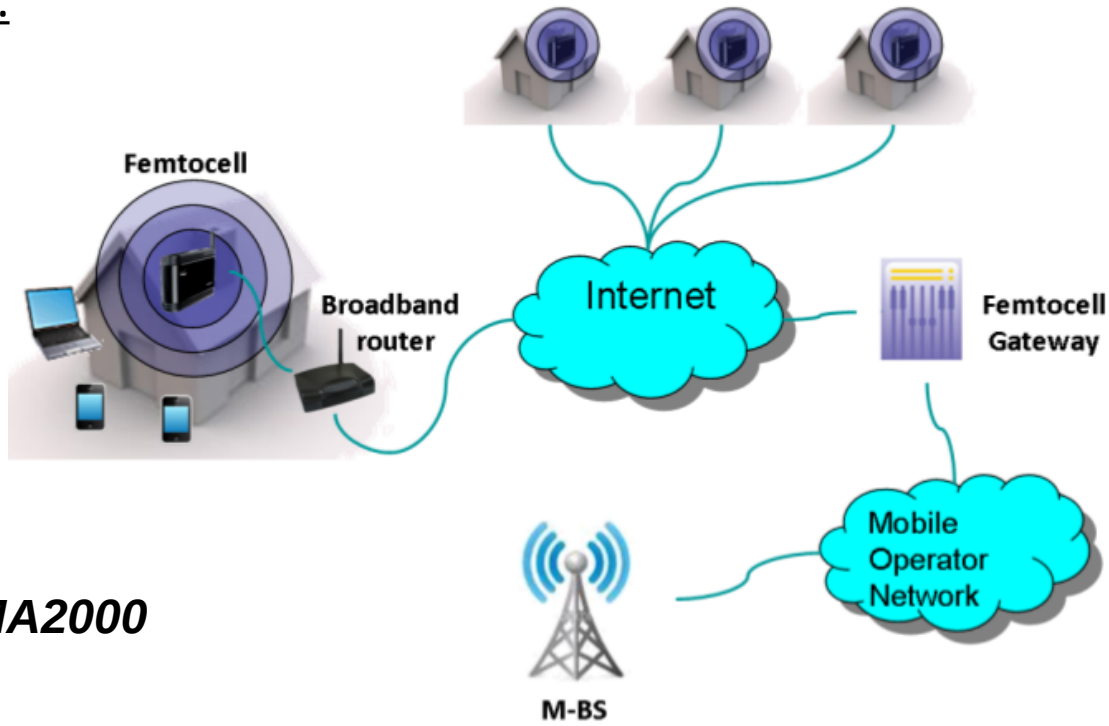
Femtocell Networks

Recent studies indicate that more than 60% of mobile traffic is generated indoors [Informa08]

In order to improve indoor coverage, cellular networks have integrated **Femtocell Access Points (FAPs)** [Chandrasekhar08]

Main characteristics of FAPs:

I. **Low power**
II. **Low cost**
III. **Few UEs/cell**
IV. **IP-based backhaul**
V. **Limited coverage**



lte™ wimax ***CDMA2000***

Main advantages of femtocell deployment

At customers' side:

I. **Larger coverage**

II. **Higher** data **rate** services

III. **Increased battery** life of devices

These advantages comes from the **reduced distance** between **terminal and FAP**

At the operator's side:

I. Higher consumers' **satisfaction**

II. Lower **CAPEX** and **OPEX**

III. Network **Offload**

Interference in two-tier cellular networks (1/3)

Macro and femtocells share the same spectrum in a given area as a ***two-tier network***

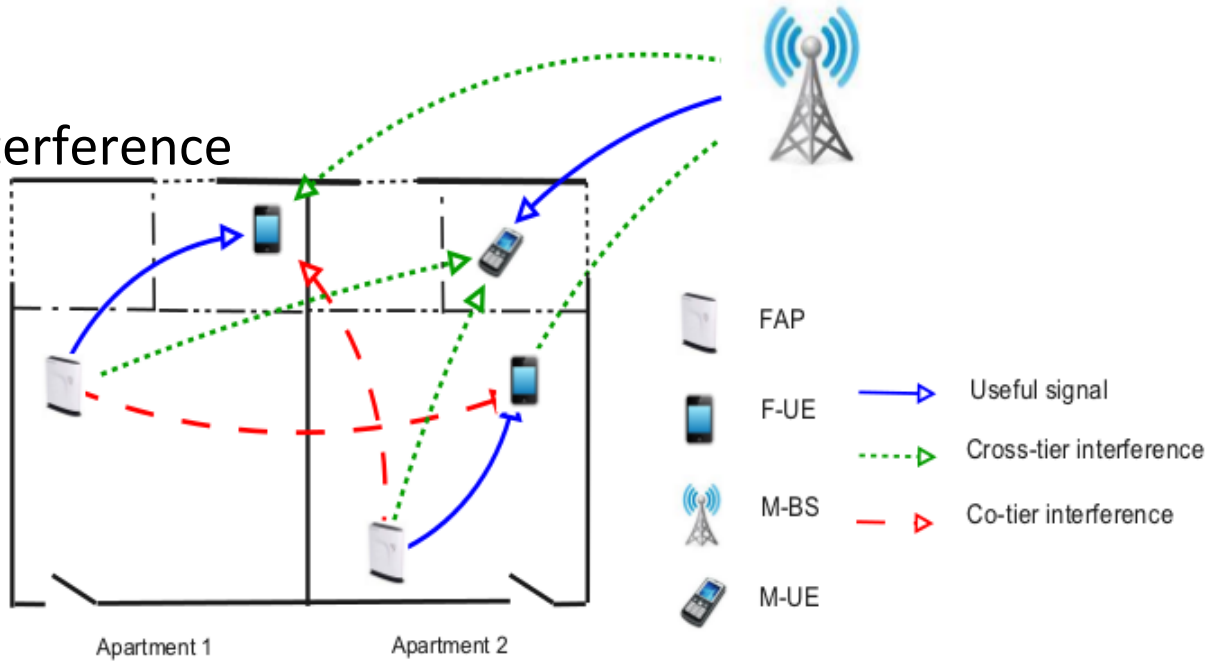
Cross-tier interference

- Femto-to-Macro Interference
- Macro-to-Femto Interference

FAPs belonging to same operators interfere with each other

Co-tier interference

- Femto-to-Femto Interference

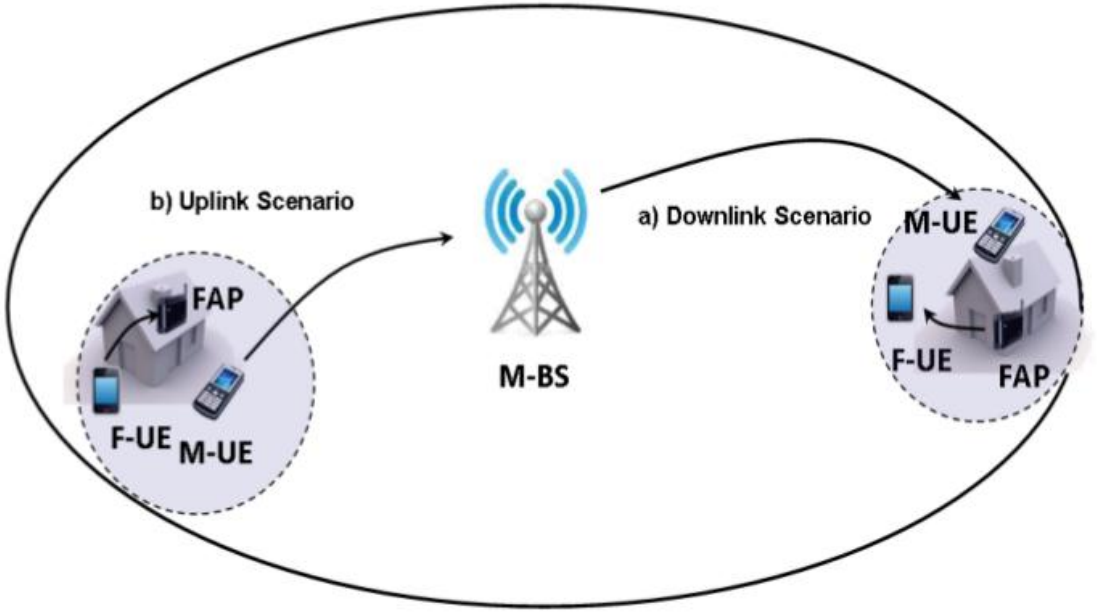


Interference in two-tier cellular networks (2/3)

Cross-tier interference joint with the near-far effect create *dead zones* around the interfered receiver

There is no direct connection amongst FAPs and M-BSs

- Inter-cell Interference Coordination (ICIC) is complex
- FAPs backhaul is characterized by limited rate and notable latency
- FAPs need to be more autonomous and self-adaptive



Interference in a two-tier cellular network (3/3)

In the downlink scenario

- F-UEs nearby the M-BS are affected by strong macro-to-femto interference
- Indoor M-UEs located nearby the FAP are affected by strong femto-to-macro interference

In the uplink scenario

- Indoor M-UEs located at the cell edge generate strong Macro-to-femto interference towards neighboring FAPs

The strength of the femto-to-femto interference depends on the density of the femtocell deployment

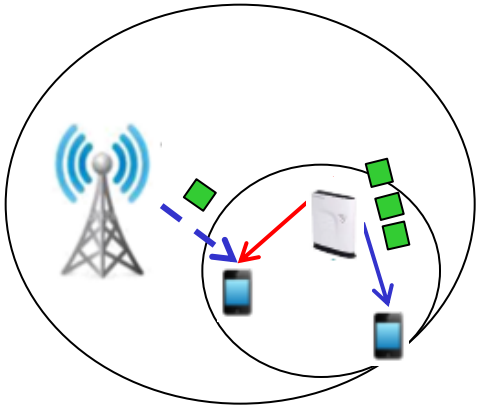
Access schemes in femtocell networks (1/2)

The impact of interference is related to FAPs access control mechanism [delaRoche10]

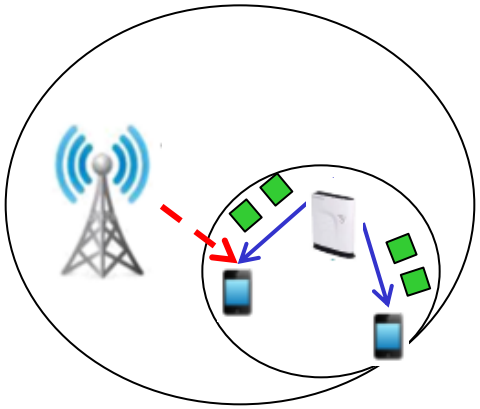
a) **Closed Access**: only a restricted set of users is allowed to connect

b) **Open Access**: always permit a subscriber to access

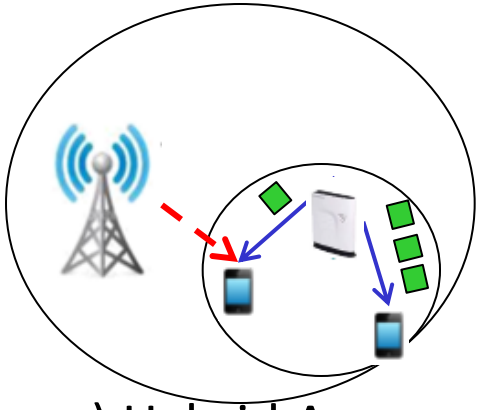
c) **Hybrid Access**: allow the access to all UEs but certain subscribers maintain higher priority



a) Closed Access



b) Open Access



c) Hybrid Access

Data — Strong Interference — Weak Interference — Strong Signal — Weak Signal

Access schemes in femtocell networks (2/2)

a) **Closed Access**

- Higher femto-to-macro interference
- Will be mainly used for residential usage
- Co-tier interference can be an issue in dense deployment scenarios

b) **Open Access**

- Lower interference
- Will be mainly used for business usage
- X2 interface may be available
- Security and handover can be relevant issues

c) **Hybrid Access**

- A compromise amongst advantages and drawbacks
- A new business model may be required

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Cognitive Radio

The term Cognitive Radio was coined by J. Mitola in an article published in 1999 [Mitola99]

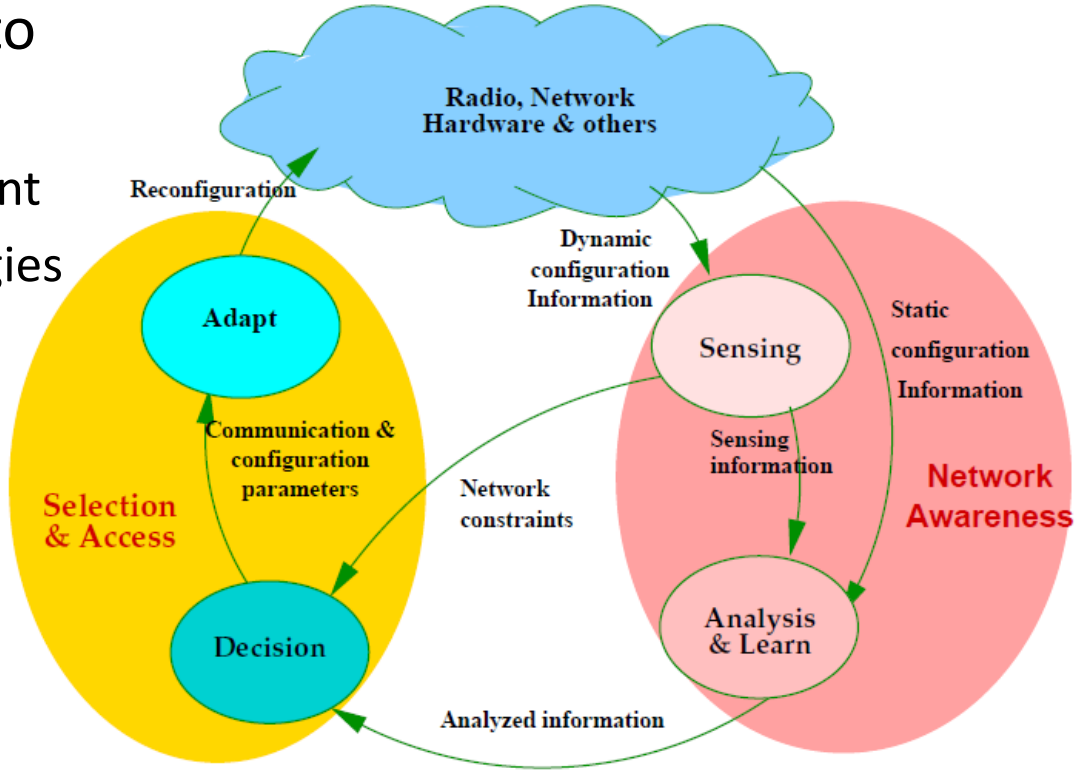
The cognitive radio, built on a software-defined radio, is defined as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli, with two primary objectives in mind [Haykin05]:

- Highly reliable **communication whenever** and **wherever** needed
- **Efficient** utilization of the radio **resources**

The Cognitive Cycle

A Cognitive Radio is capable to

- **Observe:** sensing its environment
- **Plan:** construct different strategies
- **Decide:** select the best action
- **Learn:** evolve its behaviour
- **Act:** establish a communication



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Cognitive Femtocell Networks

Merging cognitive principles in two-tier networks can permit the successful and cost-effective deployment of femtocells

1. **Network Awareness**
2. **Agile Radio Resource Management**
3. **Spectrum Sharing**

represent the natural answer to issues that rely on ad-hoc nature of FAPs

Network Awareness (1/3)

Enable a wide **consciousness** at both UEs and APs

- Network topology
- Traffic characteristics and constraints
- Network load
- UEs and BSs position
- Available Radio Access Technologies (RATs)

Challenges:

1. Which are the most useful types of information ?
2. Which bands should be sensed?
3. How to limit overhead?
4. Which sources of information are reliable?

Network Awareness (2/3): Victim detection

M-BS allocates all frequency resources in highly loaded scenarios.

A sensing analysis based on the classic ***energy detection*** [Urkowitz67] may detect few spectrum opportunities

Channels associated to far away M-UEs can be effectively reused at femtocells

PicoChip and Kyocera propose a method where FAPs determine the presence of a M-UE by detecting its uplink reference signal [Pccp10]

A **M-UE is easy to detect** because it transmits with high power due to the experienced attenuation.

Agile Radio Resource Management (1/2)

Orthogonal usage of spectrum amongst M-BS and FAPs can avoid cross-tier interference

Drawback: Notable reduction of overall network's spectral efficiency, co-tier interference is still present

A cognitive FAP, based on

1. the **sensing** outcome
2. and the **transmission strategy**,

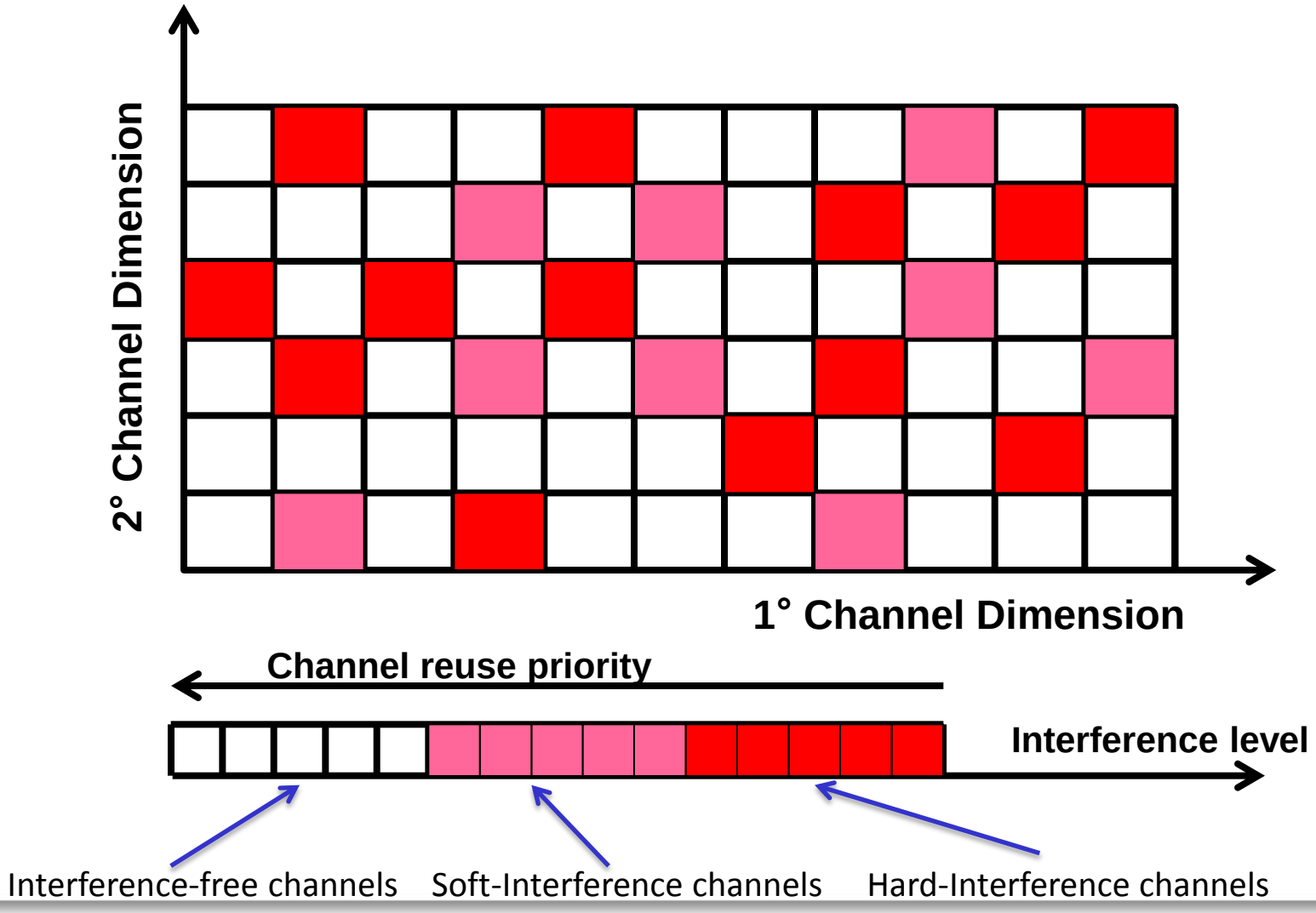
dynamically assigns available **channels** to contending users

- by attempting to maximize a utility function

This function is often made up of two components: a reward and a price

- The reward describes the gain achieved by a certain UE when choosing a particular channel (i.e., the data rate)
- The price represents the cost that this choice implies for the overall network (such as the interference)

Agile Radio Resource Management (2/2)
Ex: [LI09]



Spectrum Sharing (1/2)

In two-tier network scenarios we can identify two classes of UEs:

1. M-UEs that generally experience low performance due to propagation losses and interference
2. F-UEs that likely experience high quality signal due to the limited distance between the AP and the user-terminal

- The macrocell network has not specific functionalities to coexist with the femtocell network
- Femtocells have to avoid interference with both M-UEs and neighboring FAPs

The spectrum sharing functionalities face the problem of coexistence between heterogeneous users accessing the radio resource.

Spectrum Sharing (2/2)

Three different cognitive transmission access paradigms are presented in literature: **underlay, overlay, and interweave** [Goldsmith09]

1. **Interweave**: Cognitive users/APs transmit only in **spectrum holes**; if during in-band sensing a cognitive user detects a legacy user, it vacates its channel to **avoid interference**

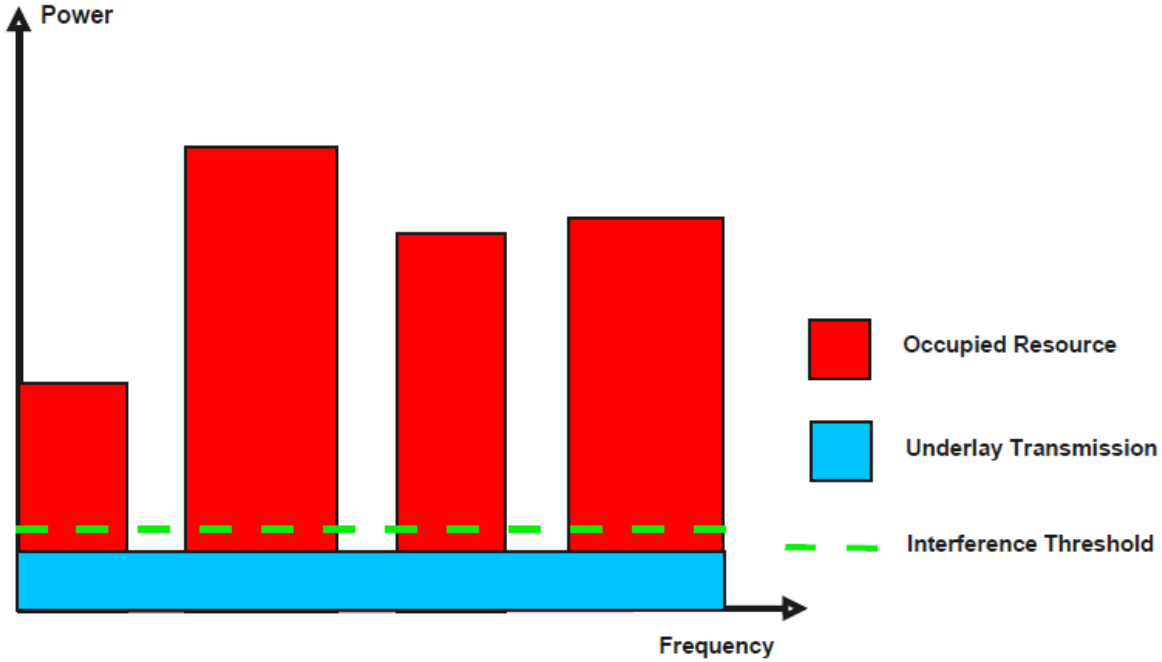
2. **Underlay**: Cognitive users are allowed to operate in the band of the legacy system while generated interference **stays below a given threshold**

3. **Overlay**: Cognitive users exploit some specific information to either **cancel or mitigate** perceived/generated **interference**

Underlay Spectrum Access (1/2)

SUEs are allowed to operate while generated interference stays below a given threshold

Due to such constraint, the underlay technique is mainly useful in **short range communications** [Srinivasa07]



Underlay Spectrum Access (2/2)

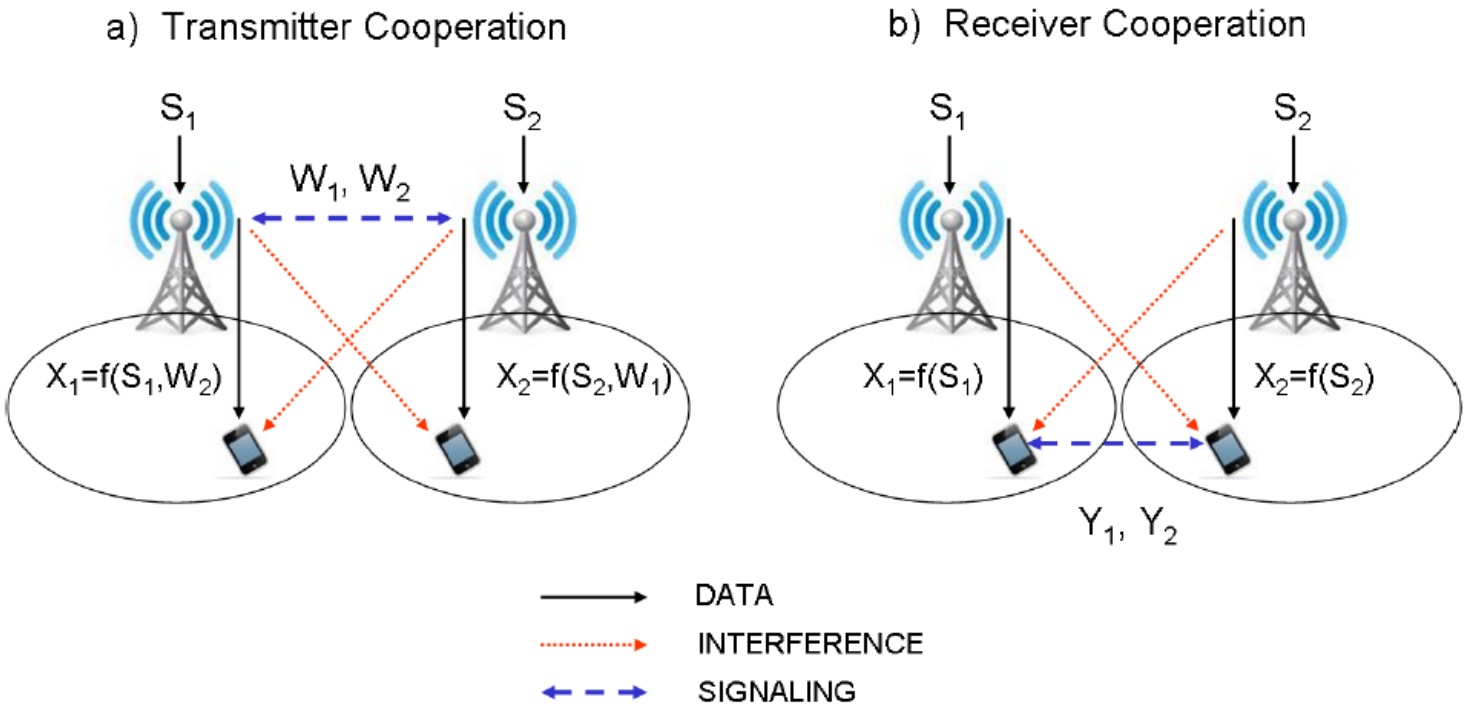
In 2003 the FCC defined the *interference temperature* as a way to measure and limit the interference perceived at legacy users [FCC-03-289]

This limit is hard to estimate and depends on the relative position between the cognitive transmitter and interfered receiver

However, according to recent studies implementation of this model results in poor performance compared to the amount of generated interference it can cause to the legacy users.

Hence, this model has been abandoned by the FCC in 2007 [Clancy09]

Overlay Spectrum Access



a) The two BSs exchange information in order to acquire a-priori knowledge about concurrent transmissions. Such information is then exploited to either cancel or mitigate mutual interference

b) The two UEs jointly process received signals to correctly decode desired information.

Interweave Spectrum Access

Due to the lack of information on the legacy system, most of cognitive radio strategies are developed according to the interweave approach.

Cognitive users avoid contention with incumbent legacy users by performing periodic sensing on occupied channels.

When an incumbent is detected, the channel is vacated, transmission is interrupted, and a communication link is set up on a different channel.

Recent investigations show that underlay and overlay approaches can result in better SE than the interweave scheme [Cheng10]

However, former mechanisms require a better awareness of the network state and higher level information (such as the position of neighbor licensee users, scheduling information, and channel gains).

Spectrum Leasing: a cooperative spectrum sharing mechanism [Pantisano12]

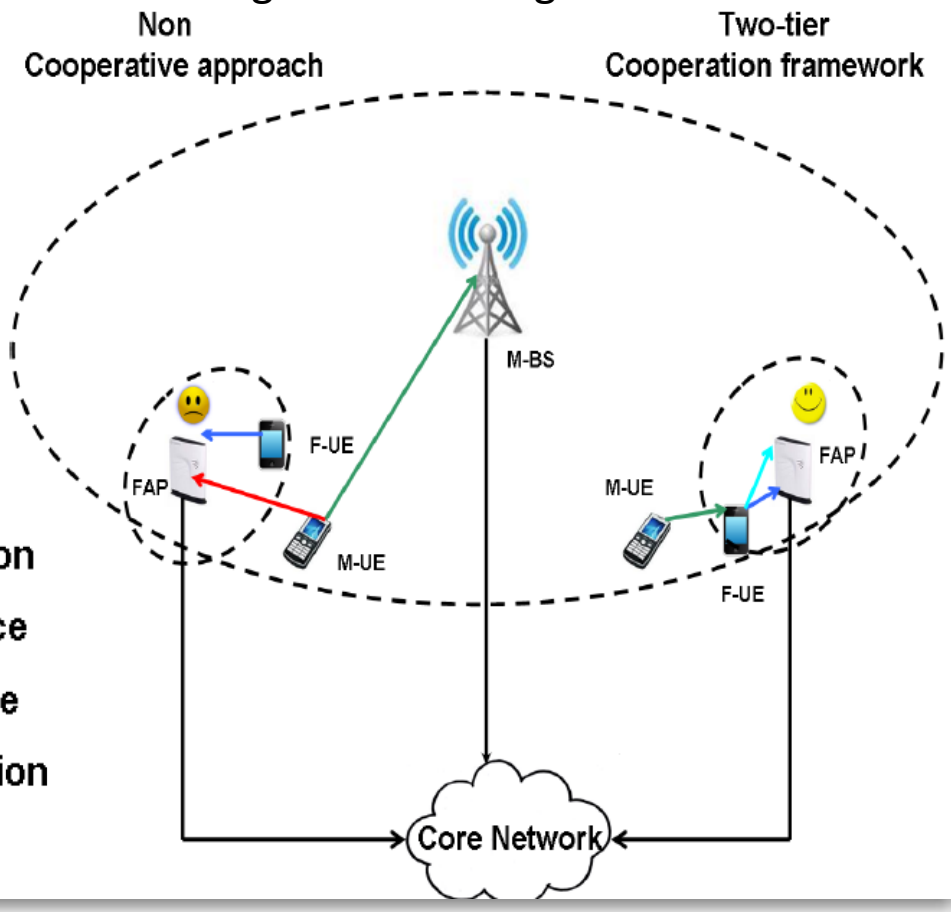
M-UEs can *lease* its allotted bandwidth to neighboring F-UUs

F-UEs uses

- the first part of the band to forward the M-UE's message to its serving FAP
- the second part of the band to transmit its own traffic

Such an approach has 3 main advantages:

1. It avoids excessive retransmissions (i.e., latency)
2. It reduces cross-tier interference
3. It limits uplink power consumption at M-UEs (prolonged battery life)



Energy Efficiency in Two-Tier Cellular Networks

Issues:

With **dense** and **uncoordinated** FemtoCells **deployment**:

1. **Excess of offered capacity**:

   → offered **capacity** may **exceeds** momentary local service **request**

2. **Overlaying coverage**:

   → several APs can accommodate same user

3. **Traffic** load **fluctuates** in time, space & frequency

   → FemtoCells' **resources** are often locally **under-utilized**

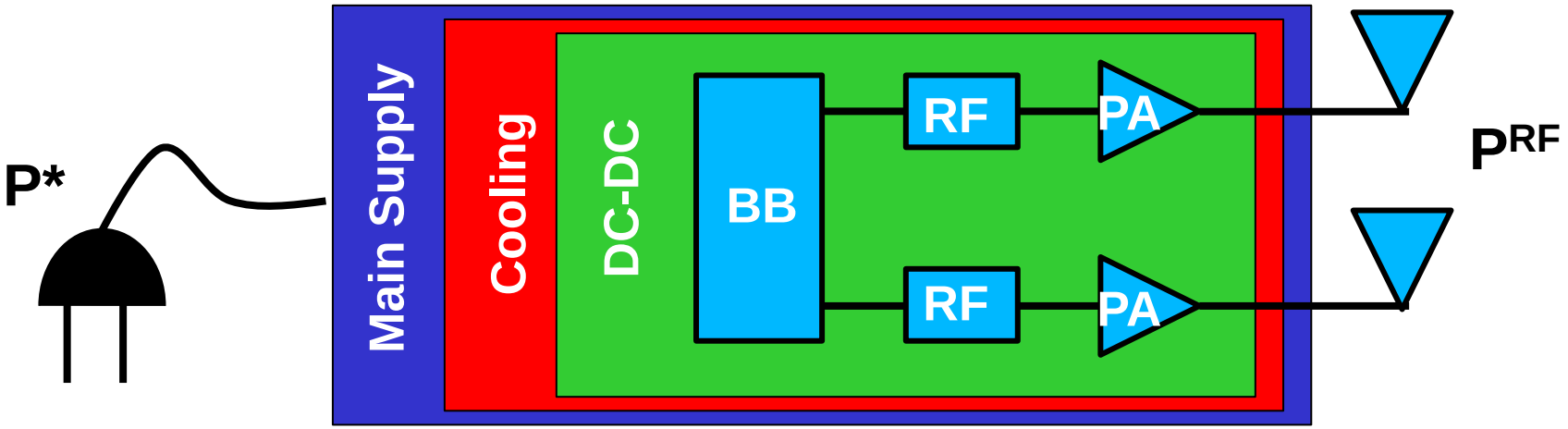
Drawback: Potential large Energy Wastage!

EARTH Energy Efficiency Evaluation Framework (E^3F)

The **EARTH E^3F** maps the radiated RF power to the power supply of a BS site and underlines the relationship between the BS load and its power consumption [Auer11]

The effect of the various components of the BS transceivers is considered

Allows to quantify improvements on components (e.g., power amplifier) at system level



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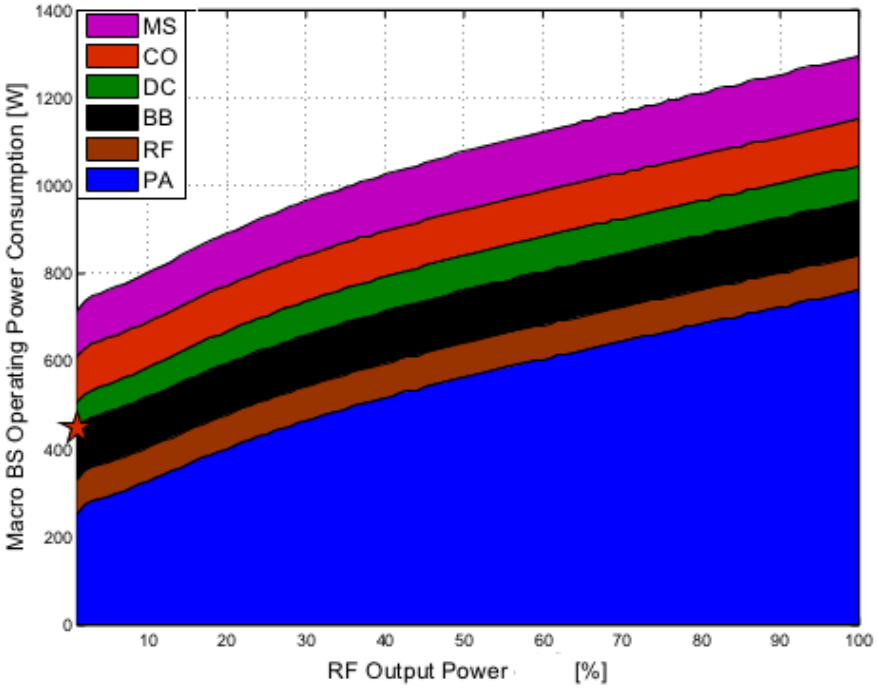
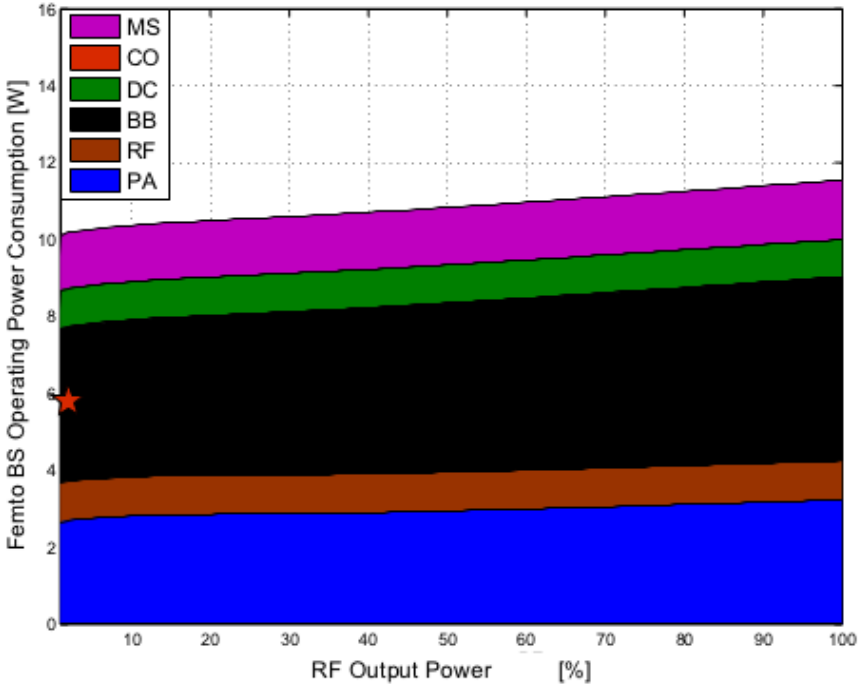




- M-BS power consumption is fairly related to the load
- FAP power consumption slightly vary with the load
- Macro offloading via FAPs deployment can greatly enhance the EE
- Poor EE in lightly load scenarios
- Cell switch-off can adapt cells activity to the load and save energy
- Low cost PAs that scale their power consumption with the load could improve the EE of femtocells

EARTH Energy Efficiency Evaluation Framework (E^3F)

The EARTH E^3F also introduces a linear power consumption model that approximates the dependency of the BS power consumption to the cell load

$$P^* = \begin{cases} P_0 + \Delta_p P^{RF}, & 0 < P^{RF} \leq P_{max}; \\ P_{sleep}, & P_{out} = 0. \end{cases}$$

where P* is the BS input power require to generate the irradiated P^{RF} power and Δ_p is the slope of the load dependent power consumption.

P_{max}, P_0, and P_{sleep} indicate the RF output power at maximum load, minimum load, and in sleep mode, respectively.

TABLE I

BS POWER MODEL PARAMETERS

BS type	P_{max} [W]	P_0 [W]	Δ_p
M-BS	40	712	14.5
FAP	0.01	10.1	15

Agile FAP switch off/on

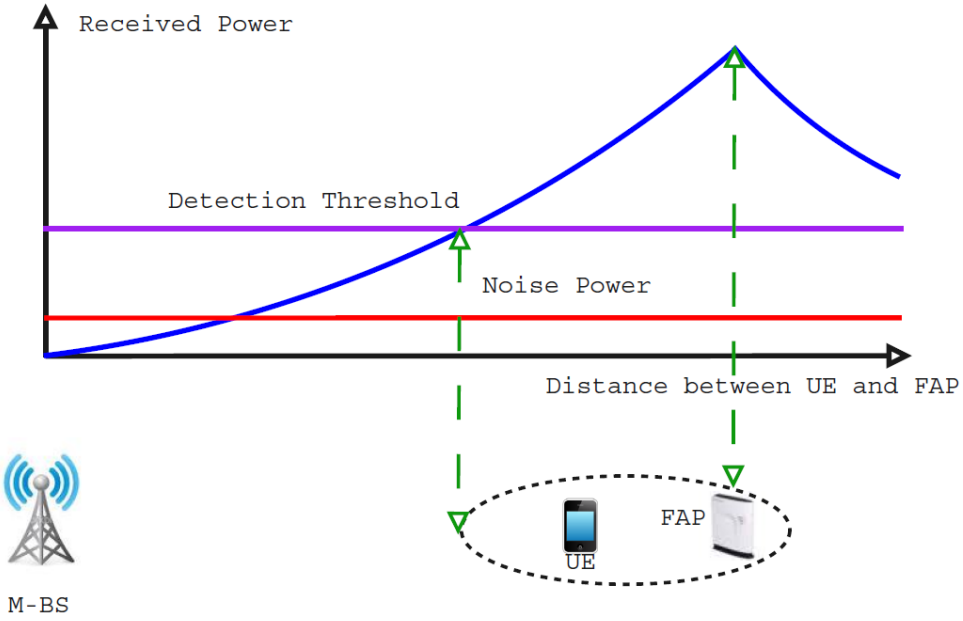
High Energy Efficiency can be achieved by dynamically switching off idle FAPs

This approach disable pilot transmission and associated radio processing

How to self-switch on??

FAPs can be equipped with an **energy detector** to ***sniff*** the presence of a nearby M-UEs

- An indoor M-UE, transmits with high power, hence, it is easy to detect it [Ashraf11]



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Conclusion

The success of cellular networks has resulted in proliferation of ubiquitous ultra-broadband data services

This is imposing new challenges to both industrial and research communities in terms of coverage, spectral efficiency, and energy efficiency

Femtocells have been recently captured a worldwide attention as a technical solution to deal with this problems.

However, interference, ad-hoc deployment, and limited backhaul are notable issues.

Moreover, cognitive mechanisms are required to manage FAPs activity and avoid that uncoordinated operation and massive deployment results in excessive power consumption

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