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ENERGY EFFICIENT RADIO RESOURCE MANAGEMENT FOR GREEN CELLULAR NETWORKS

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Laudato si', mi Signore, per sora nostra matre Terra,
la quale ne sustenta et governa,
et produce diversi fructi con coloriti fior et herba.

Francesco d'Assisi, "Cantico di Frate Sole"

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...angoli del presente che fortunatamente
diventeranno curve nella memoria...

Francesco De Gregori

Tutti gli angoli sono diventati curve di una strada via via sempre più definita. Una strada percorsa con tanti compagni di viaggio, alcuni per pochi passi, altri per chilometri, ma tutti fondamentali per costruirmi come persona e far sì che il mio camminare procedesse nella giusta direzione.

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Abstract

The need of a sustainable economy is driving also communications to be able to provide their services with a low carbon footprint. Focusing on mobile communications, it is expected that the increasing of subscriptions during next year will lead to a growth of energy consumption due to the infrastructure capacity improvement if no action is taken. Therefore researchers and mobile operators are now looking for innovative solution able to cope with this network evolution. The control and the reduction of energy consumption in mobile communications will have two main beneficial effects. First of all environment will benefit because of the concentration decreasing of greenhouses gases that are responsible of the global warming. Then, since energetic bill is one of the main expenditure items of a mobile operator, the introduction of energy saving solution will allow the operators to reduce their operational costs in managing the network. This thesis deals with the radio resource management strategies to reduce the cellular network energy consumption. A forecasting driven solution is introduced to decide how many resources, i.e. active base stations or carriers on air, and their transmission power are enough to satisfy the hourly requested capacity. The use of forecast is justified by the behaviour of cellular traffic and allows to match the daily power figure to the traffic pattern, avoiding the waste due to the overprovisioning. Moreover an optimization framework is introduced to find the optimum network configuration able to minimize the global power consumption for a given number of simultaneous active users. This framework plays with the number of active base stations, the association between users and base stations, the bandwidth allocated to each user and the transmission power at each antenna tower. Finally the focus is moved to private mobile radio and to TETRA system. A TETRA power consumption model is provided and some solutions to reduce the carbon footprint of todayÕs TETRA system are evaluated. Moreover some considerations about the future evolution to a TETRA over LTE system are given taking into account also the energy saving potentials of LTE systems.

Contents

List of Figures

List of Tables

Acronyms

ADC analogic-digital converter.

AMC adaptive modulation and coding.

APC area power consumption.

ASC antenna switching circuit.

AWGN additive white gaussian noise.

BB base band.

BBU baseband unit.

BCCH broadcast control channel.

BS base station.

CA carrier aggregation.

CoMP coordinated multi-point.

CQI channel quality indicator.

DSP digital signal processing.

DTX discontinuous transmission.

ECR energy consumption rating.

EE energy efficiency.

FBSMA forecasting based sleep mode algorithm.

GSM Global System for Mobile communication.

HCS hierarchical cell structure.

HSPA High Speed Packet Access.

HWF Holt-Winter forecast.

ICT information and communications technology.

LTE Long Term Evolution.

MAC medium-access-control layer.

MBSFN multicast broadcast single frequency network.

MCS modulation and coding scheme.

MIMO multiple input multiple output.

OAM operation & maintenance.

OFDM Orthogonal Frequency Division Multiplexing.

OPEX operational expenditures.

PA power amplifier.

PHY physical layer.

PMR professional mobile radio.

PPU power per user.

QoS quality of service.

RFU radio frequency unit.

RRH remote radio head.

RRM radio resource management.

RRU remote radio unit.

RTMSA real time measurements sleep mode algorithm.

SCU site control unit.

SDCCH stand alone control channel.

SE spectrum efficiency.

TCH traffic channel.

TDMA time division multiple access.

TEDS TeTRA enhanced data service.

TeTRA terrestrial trunked radio.

TRX transceiver.

UE user equipment.

UMTS Universal Mobile Telecommunication System.

W-LAN wireless local area network.

W-WAN wireless wide area network.

WCDMA Wideband Code Division Multiple Access.

Chapter 1

Introduction

1.1 Energy efficiency and environment

The world population increase and the economic development are affecting the environment. As a matter of fact energy generation processes, e.g. electricity generation, heating, cooling and motive force for transportation, are polluting and harmful for the ecosystem. Since the beginning of humanity, wood has been burned to obtain the temperature to heating, cooking, melting metals and, afterwards, extracting chemicals and obtaining mechanical power. During burning, the carbon in wood combines with oxygen (O_2) to form carbon dioxide (CO_2) that is then absorbed by plant and converted back to carbon. The industrial revolution in the eighteenth century substituted much of the human labor with machines which required new resources for the production of the needed energy to work. As a consequence, CO_2 concentration in the air increased leading to the beginning of global warming. With the expression "global warming" it is meant the effect associated with the accumulation of a set of particular gases in the atmosphere. Such gases, also known as "greenhouse gas", are CO_2, NO_x, CH_4, CFC, Halons, Ozone and Peroxyacetylmitrate. Greenhouse gases allow solar radiation to penetrate to the Earth's surface while reabsorbing infrared radiation emanating from it, thereby rising the surface temperature, as depicted in Figure 1.1. The surface temperature increased about 0.6℃ over the last century and, as a consequence, the sea level is estimated to have risen by 20 cm. Moreover, the predicted fossil fuel consumption could cause a further increase between 2℃ and 4℃, augmenting the possibility of flooding, reducing the surface of

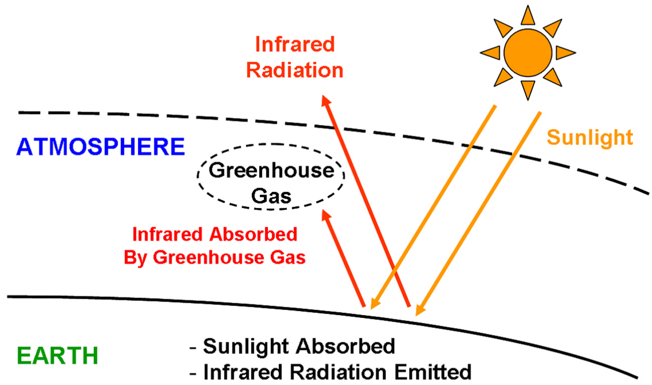


Figure 1.1: Greenhouse effect

fertile zones and the availability of food.

A society seeking sustainable development ideally should utilize only energy sources causing no environmental impact. However all energy source lead to some environmental impact, therefore it is reasonable to suggest that a sustainable development can be supported by increasing the energy efficiency, that is the provisioning of the same services consuming a lower amount of energy, ideally the strict necessary to run such services.

1.2 Energy efficiency and economics

Besides the benefits that energy efficiency could introduce to the environment, also the effect on business and economy should be considered. Actually the concept of "green economy" is high up on the agenda of most governments. The green economy idea starts by considering environment and natural resources a real value which people can invest on and money can be returned from. Green economy can be defined as one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive.

In a green economy, growth in income and employment should be driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services. The concept of a green economy does not replace sustainable development: it is based in the growing recognition that achieving sustainability lies almost entirely upon getting the economy right. From a business point of view there will be both opportunities and challenges from the transition to a green economy and businesses will need to adapt to take advantage of benefits and manage risks. Impacts will be felt by sectors of the economy in different ways and to varying degrees. For example, some sectors will see an increased demand for goods and services; some sectors will need to transform aspects of their business models to reduce their environmental impact, while others will need to manage potential increased input costs or lower or volatile demand.

Considering also the continuous increase of energy costs in the last decade, the green economy issues can be addressed by taking into account energy efficiency policies. Such solution will allow governments and companies to save a considerable amount of money that can be used for new investments, driving the possibility for a new economic growth.

1.3 The environmental impact of mobile cellular networks

The global information and communications technology (ICT) industry is an important and quickly growing contributor to CO_2 emissions and energy consumption. According to the SMART 2020 study [3] it accounted for 830 Megatons each year that is approximately 2% of global human carbon dioxide emissions and about equivalent to those of global aviation [4]. Acknowledging this contribution, the European Union has called on ICT industry to tackle energy efficiency of communication networks and of ICT in general [5] and has been funding related research within the framework program FP7 and Horizon2020. Moreover ICT industry does not have impact only on the environment. As a matter of fact, carbon emissions are the results of the energy absorption process that is about 138 TWh for each year [1]. This energy consumption makes ICT on the same stage of 13 millions of US houses and it is about the same energy provided each year by 18 nuclear

[1]The conversion is done considering that producing 1KWh of electrical energy in a thermoelectric plant is responsible of about 0.8 Kg of CO_2 emissions

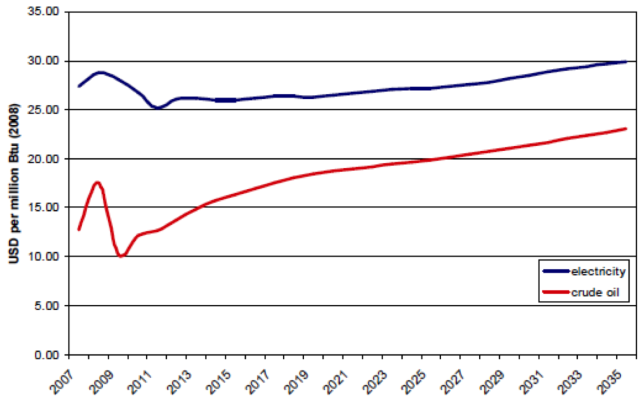


Figure 1.2: Trend of energy cost

reactors [2]. By considering an average energy price of 0.20 €/kWh, the global ICT expenditure for energy supply is about 27000 M€/year. Looking at such simple calculations it is evident the reasons that make the main italian telecommunications company just behind the national railway transportation company in the energy consumers list [6]. Therefore, aiming at increasing the energy efficiency is also a money saving driver for ICT companies and the energy cost trend makes it more and more important for next future, as demonstrated by Figure 1.3, where the growing of energy cost net of local oscillation is reported.

Within ICT, mobile communications networks are the main contributor in term of energy consumption: its contribution is expected to grow up to 178 Megatons of CO_2 in 2020, while in 2002 it was 64 Megatons. Such increasing is justified by the forecasted penetration of mobile subscriptions for next years. As reported in Figure 1.3, the number of mobiles requiring access to the network will increase of about 30% in next five years; moreover such subscriptions will require broadband access following the evolution of cellular technology: in order to fulfill users requirements operators will densify the infrastructure, increasing the global energy costs and their environmental footprint. before, energy consumption and CO_2 emissions of the mobile network infrastructure have received more and more attention in the telecommunications sector lately.

[2] A 1GW nuclear reactor can provide about 8 TWh each year

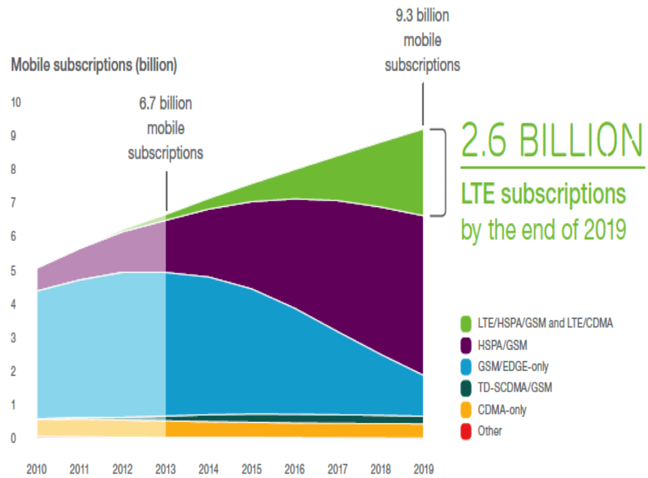


Figure 1.3: Trend of mobile subscriptions

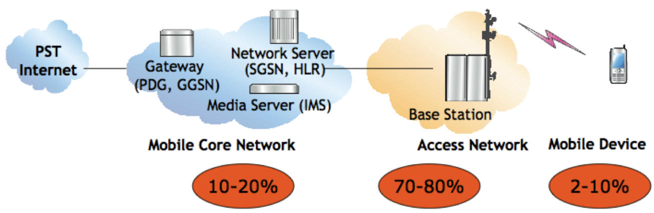


Figure 1.4: Impact on energy consumption of different stages of cellular network

Figure 1.4 shows the impact of each stage of cellular network on global energy consumption. The main contribution is due to radio access network because of the components of radio BS. In particular, BS power consumptions can be subdivided into four main components that are due to power amplifiers (65%), air conditioning and cooling (17.5%), signal processing (10%) and power supply (7.5%). Therefore in order to make greener the cellular network, the starting point is to make more efficient the radio access stage and in particular the BS equipments.

1.4 Objective of the thesis and work organization

Taking into account all of these considerations, the objective of this doctoral thesis is first of all to explore the energy efficiency possibilities for mobile wireless networks, evaluating some innovative solutions for a green radio resource management.

To this aim the work carried out during the three years Ph.D. course can be resumed by the following steps.

- A strong literature review to understand the basis of wireless network energy consumption is provided in Chapter 2. In particular, a power analysis driven by the Shannon's capacity formula is presented highlighting the main trade-off affecting wireless links performance. Then, the focus is set on mobile cellular networks and in particular on radio base station nodes and a detailed evaluation of power usage within such nodes is provided. The importance of such analysis lies in the consequent power consumption model formulation, that is the foundation of every energetic consideration that can be done with the goal of making wireless network more energy efficient. Some energy efficiency metrics are described and the state of the art of solution aiming at maximizing such metrics is discussed, including both deployment and resource management solutions.

- The original work in this thesis is focused on radio resource management strategies enabling cellular network energy saving. In particular the most promising green radio resource management strategy is referred to base station sleep mode, that is the deactivation of base station's radio frequency part for a given time, resulting in a lower site power feeding. The work described in Chapter 3, Chapter 4 and Chapter 5 represents some innovative solution to drive the base station activation or deactivation in order to make the power consumption dependent on the network traffic conditions. In particular:

  - Chapter 3 focus on network traffic forecast to drive the radio resource adaptation. In particular, the solution is presented for different operative conditions: Global System for Mobile communication (GSM), High Speed Packet Access (HSPA) and Long Term

Evolution (LTE) cellular systems. As for GSM, the adaptation concerns activating or deactivating the available carriers, taking as constraint the area coverage. The LTE case represents an example of micro base station sleep mode: small cells are adapted according to the traffic forecast, while the macro cell guarantees the coverage. Finally, in the LTE case the micro cell sleep mode is extended by considering a wider area and increasing the energy saving gain by adapting the maximum transmission power of macro base stations.

– Chapter 4 aims at going deeper into network optimization by proposing a detailed optimization framework. Such formulation takes into account every aspect affecting energy consumption in cellular network, i.e. active base stations, user association, transmission power and bandwidth allocation. The presented work has been carried out in collaboration with Radio System Laboratory of Royal University of Technology (KTH) in Kista (Sweden).

– Chapter 5 considers a specific peculiar topic for wireless cellular network, namely private mobile radio and in particular focuses on TeTRA system. A TeTRA power consumption model has been proposed and the impact of some radio resource management solutions are evaluated for energy efficiency, referring to the actual system and to the future TeTRA over LTE evolution.

Chapter 2

Energy efficient wireless communications

This chapter gives a survey on energy efficient techniques in wireless communications. In particular, the first part introduces the problem that can be solved by such strategies, while the second part provides the power consumption model for cellular base stations. Moreover, the chapter includes a literature review of the energy saving techniques for wireless communications systems giving more attention to cellular networks.

2.1 Green network design

Cellular network design research has been focusing among different trade-offs [7] rising up from the Shannon's capacity formula. Shannon's capacity formula [8] links the maximum achievable datarate R in a point to point additive white gaussian noise (AWGN) channel with the received power P_r and the available bandwidth W. Considering a noise power spectral density N_0, the formula can be written as:

$$R = W \log_2 \left(1 + \frac{P}{WN_0} \right) \tag{2.1}$$

By introducing simple modifications to such formula, the main trade-offs in network design can be dealt with. In particular by introducing the received average energy per bit $E_b^r = P_r/R$, the Equation 2.1 can be written as:

$$\frac{R}{W} = \log_2\left(1 + \frac{R}{W}\frac{E_b^r}{N_0}\right) \tag{2.2}$$

Moreover, by considering the average transmission time per bit $T_b = 1/R$, Equation 2.1 becomes:

$$\frac{1}{T_b} = W\log_2\left(1 + \frac{1}{T_b}\frac{E_b^r}{WN_0}\right) \tag{2.3}$$

Considering P_t, P_r and d respectively the received power, the transmitted power and the distance between transmitter and receiver, the attenuation impact can be introduced by taking into account parameters β and α. Therefore, the received power is $P_r = \beta P_t d^\alpha$ and the Equation 2.1 can be written as:

$$\frac{R}{W} = \log_2\left(1 + \frac{R}{W}\frac{E_b}{N_0}\frac{\beta}{d^\alpha}\right) \tag{2.4}$$

In the following some trade-offs to be considered in the green network design are described and summarized in Figure 2.1.

2.1.1 Spectrum Efficiency-Energy efficiency trade-off

Spectrum efficiency (SE) is a widely accepted criterion for network optimization, defined as the system throughput per bandwidth unit, i.e. bit/s/Hz. On the other hand energy efficiency (EE) is the system throughput per unit of transmitted power, i.e. bit/s/W. Equation 2.2 shows a fundamental trade-off between spectrum and energy efficiency for the same system bandwidth and it can be formulated as:

$$\eta_{EE} = \frac{\eta_{SE}}{\left(2^{\eta_{SE}} - 1\right)N_0} \tag{2.5}$$

The meaning of Equation 2.5 is that increasing the spectral efficiency causes a degradation on energy efficiency, i.e. if $\eta_{SE} \to 0$, then $\eta_{EE} \to \frac{1}{N_0 \log 2}$ and if $\eta_{SE} \to \infty$, then if $\eta_{EE} \to 0$. Note that energy efficiency is calculated considering the received power. In order to consider the transmit power, the channel effect must be included and the Equation 2.5 becomes

$$\eta_{EE} = \frac{\eta_{SE}}{\left(2^{\eta_{SE}} - 1\right)N_0}\frac{\beta}{d^\alpha} \tag{2.6}$$

Some considerations can be done about the SE-EE trade-off and transmission techniques. As a matter of fact, SE is related to the modulation and coding scheme (MCS): the grater the number of bit that can be transmitted in a given time, the better the spectrum efficiency, but, on the other hand, the higher the quality of the signal to be guaranteed and its transmission power. In this scenario Orthogonal Frequency Division Multiplexing (OFDM) systems are able to guarantee better performance looking at the SE-EE tradeoff. OFDM relies on splitting the data flow over a certain number of subcarriers transmitted at the same time on the available bandwidth; each subcarrier uses a portion of the available spectrum. Since channel conditions are homogeneous on entire spectrum, the modulation scheme on each subcarrier can be adapted in order to minimize the energy consumption while the spectrum efficiency is maximized [9]. In a similar way, research is also focusing on SE-EE trade-off in multiple input multiple output (MIMO) systems. Even if the circuitry power consumption increases with the number of antennas, such system allows a better adaptation of the signal to the channel conditions and a consequent power reduction. Moreover a technique has been proposed [10] which adapt the number of active antennas to the effective requirements.

2.1.2 Power-Bandwidth trade-off

The Shannon's capacity formula focus also on the relation between transmit power P_t and bandwidth W, which are limited resources. Fixing the desired datarate R, Equation 2.1 gives:

$$P_t = WN_0 \left(2^{\frac{R}{W}} - 1\right) \frac{\beta}{d^\alpha} \tag{2.7}$$

Such equation says that for a given datarate, a bandwidth expansion allows a lower transmit power, the extreme case is if $W \to \infty$, then $P \to N_0 R \log 2$.

While 2G wireless communications systems, like GSM, do not take advantage from a dynamic bandwidth allocation, the introduction of carrier aggregation technologies in Universal Mobile Telecommunication System (UMTS) and LTE allows more flexibility in managing such resource: particularly, in order to save energy, some bandwidth expansion techniques have been proposed [11]. Moreover, more flexibility can be introduced by the adoption of cognitive radio techniques [12] that could allow, for example, cellular communications, acting as secondary systems, to transmit on the spectrum already licensed to other service acting as primary system, like TV broadcasting [13].

2.1.3 Delay-Power trade-off

One of the most important metric to measure quality of service (QoS) and user experience in packet switching communication is delay. Delay can be defined from different perspectives: at physical layer (PHY) it is the time spent during the physical layer transmission, at the medium-access-control layer (MAC) it is the sum of both PHY and MAC waiting times. Starting from the PHY delay, the relation with the received energy per bit is obtained from Equation 2.3:

$$E_b = N_0 T_b W \left(2^{\frac{1}{T_b W}} - 1\right) \frac{\beta}{d^\alpha} \tag{2.8}$$

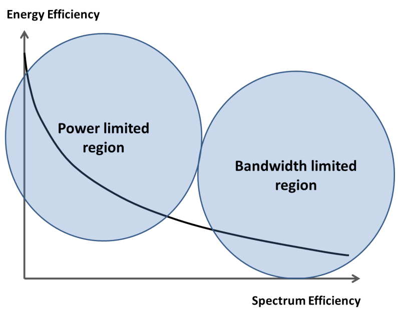
So, there is a monotonically decreasing relation between received energy per bit and PHY delay T_b. The trade-off between power and MAC delay should be investigated taking into account queuing theory since it depends on the traffic statistics. The power-delay trade-off for cellular BS is investigated in [14].

2.2 Power management in cellular base stations and networks

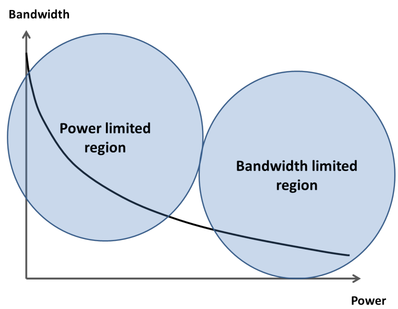
2.2.1 Cell design and base stations technologies

Radio network operators provide service to users by dividing the area in several regions, namely the cells, served by one access point, i.e. the BS. In order to increase the network capacity, smaller cells can overlap to wider cells. Depending on their extension, the cells can be classified as follows:

- Macro cell, which is the basic layer of coverage of a cellular system. Its range is between 1 and 5 Km and, usually, it is used for outdoor coverage.
- Micro cell, which have a range lower than 500 metres. Several micro cell can overlap to one macro cell in order to increase the capacity of a certain area, for example dense urban area.
- Pico cell, which is used inside building, having a range lower than 100 metres.
- Femto cell, providing an indoor home coverage.



(a)



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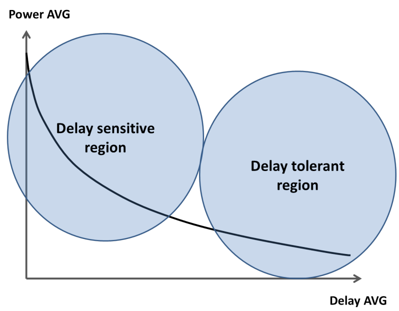


(c)

Figure 2.1: Summary of the fundamental trade-offs rising from Shannon's capacity formula.

The access point related to each kind of cell is characterized by different dimension, cost, maximum transmission power and power consumption profile. Therefore it is possible to have macro-, micro-, pico- and femto-BS.

Moreover, in last years another kind of BS has been used to provide mainly outdoor coverage in macro and micro cell. Such kind of device is remote radio head (RRH), that is a radio transceiver located close to the antenna in order to avoid energy waste due to cooling and cable losses.

In the rest of the section, the main ideas discussed in literature to develop a power consumption model taking into account such differences are presented.

2.2.2 Base station power consumption models

Power consumption model is a very important issue in order to predict the effects due to a modification of the system architecture and configuration and develop energy saving strategies. The widely accepted approach to model BS power consumption has been proposed within the Energy Aware Radio and Network Technologies (EARTH) project [15] and assumes that the power consumption of a BS consists of two parts, namely the static power consumption and the dynamic power consumption. The static power consumption is a power figure that is spent independently by the load status of the BS. On the other hand, the dynamic power consumption is strictly related to the traffic managed instantaneously by the BS. Moreover there is a dependency between power consumption and technology we are referring to. In particular 4G components are more efficient than GSM component because of the electronic technology evolution.

The BS power consumption is composed of two parts [16]:

- static power consumption which describes the consumption that already exists in an empty BS, i.e. when no users are connected;

- dynamic power consumption which depends on the dynamic load conditions.

In the following such components are derived for both macro and micro BS and the main contributors to power consumption are identified.

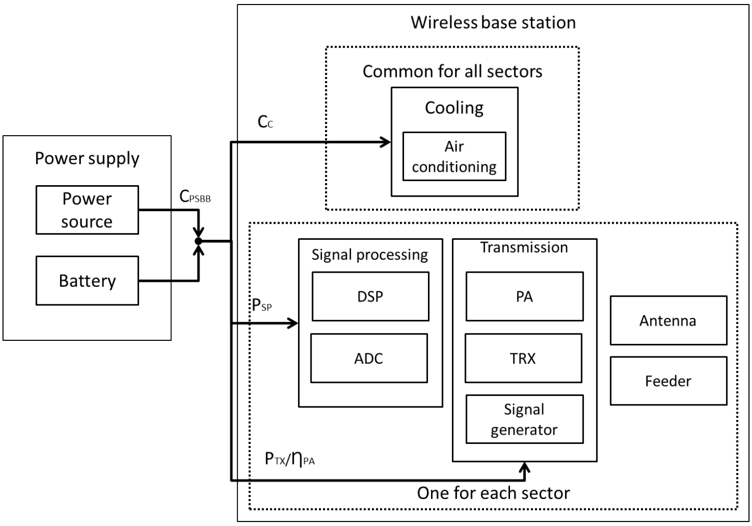


Figure 2.2: Block diagram of a base station.

Base station components included in the model

Referring to Figure 2.2, the power-consuming components of a BS for mobile communications can be identified as:

- Power amplifier (PA) is responsible for amplifying input power.
- The digital signal processing (DSP) is responsible for system processing and coding.
- The analogic-digital converter (ADC) converts an input analog voltage or current to a digital number proportional to the magnitude of the voltage or current.
- The transceiver (TRX) is in charge of receiving and sending the microwave signal to mobile units.
- The signal generator produces a microwave signal.
- The antenna is used to transmit or receive microwave signals.
- The feeder is the component to feed the microwave signal to the rest of the antenna structure.

Table 2.1: Power consumption model parameters

Symbol	**Definition**
N_{Sector}	Number of sectors
N_{PApSec}	Number of PAs per sector
P_{TX}	Transmit power
η_{PA}	PA efficiency
C_C	Cooling loss
P_{SP}	Power consumption for signal processing overhead
C_{PSBB}	Power supply and battery backup loss of macro BS
$P_{m,TX}$	Maximum transmit power per PA
$C_{TX,Static}$	Static transmit power fraction
$P_{SP,Static}$	Power for static signal precessing
C_{PS}	Power supply loss of micro BS
C_{TX,N_L}	Dynamic transmit power per link
P_{SP,N_L}	Dynamic signal processing per link
N_L	Number of active connections

In addiction a BS site, that could be constituted of more than one sector, could be equipped by a cooling device, common to all sectors, which is responsible for dissipating the heat generated by running the components. The cooling power consumption depends mainly on environmental conditions and it is denoted as C_c: its value are typically between zero, i.e. free cooling, and 40% of global power consumption [16].

ADC and DSP are considered together for the power consumption perspective, since ADC is responsible of less than 5% of BS input power. The power consumption of the signal processing part, that could be also indicated as base band (BB) power consumption, is denoted as P_{SP}. PA, TRX and signal generator constitute the transmission part and dissipate globally the power $\frac{P_{TX}}{\eta_{PA}}$. Even if antenna and feeder are included in the transmission part, their power consumption is not computed within $\frac{P_{TX}}{\eta_{PA}}$ since antenna and feeder losses are normally included in the link budget.

Power supply and battery backup component power the BS equipments: their power consumption, denoted as P_{PSBB}, is typically between 10% and 15% depending on the technology employed [16].

Macro BS power consumption model

A macro base station is a BS providing the service over a large coverage area, namely a macrocell. Since measurements have shown that macro BS power consumption variations with load are not significant, it can be described by the only static part. Considering all the different components of a macro BS the parameters reported in Table 2.1, the power consumption can be calculated as follows:

$$P_{BS,Macro} = N_{Sector} \cdot N_{PApSec} \cdot \left(\frac{P_{TX}}{\eta_{PA}} + P_{SP} \right) \cdot (1 + C_C) \cdot (1 + C_{PSBB}) \quad (2.9)$$

Micro BS power consumption model

On the other hand a micro base station provides a coverage over a small area, namely a microcell, in order to increase the capacity for a restricted number of users, i.e. a dense urban area. Micro BS power consumption considers both static and dynamic parts, but battery backup and cooling are not included in the model since they are not needed in running the micro BS devices. Moreover a micro BS is normally composed by only one sector. Such characters and the smaller transmission power result in a smaller consumption compared to macro BS. Following Table 2.1, the power consumption of a micro BS can be modeled as

$$P_{BS,Micro} = P_{Static,Micro} + P_{Dynamic,Micro} \quad (2.10)$$

where

$$P_{Static,Micro} = \left(\frac{P_{m,TX}}{\eta_{PA}} \cdot C_{TX,Static} + P_{SP,Static} \right) \cdot (1 + C_{PS}) \quad (2.11)$$

and

$$P_{Dynamic,Micro} = \left(\frac{P_{m,TX}}{\eta_{PA}} \cdot (1 - C_{TX,Static}) + C_{TX,N_L} + P_{SP,N_L} \right) \cdot (1 + C_{PS}) \cdot N_L \cdot (1 + C_{PS}) \quad (2.12)$$

Table 2.2: Power model parameters

BS type	N_{TRX}	P_{TX} max	a	b	c
macro	6	20 W	4.7	130 W	75 W
RRH	6	20 W	2.8	84 W	56 W
micro	2	6.3 W	2.6	56 W	39 W
pico	2	0.13 W	4.0	6.8 W	4.3 W
femto	2	0.05 W	8.0	4.8 W	2.9 W

EARTH power consumption model

Within the EARTH project activities such model has been extended in order to formulate a parametric model that can be adapted to all kinds of BSs, i.e. femto, pico, RRH, micro and macro. Moreover the EARTH model considers also the possibility to switch off the BS in order to save energy. The resulting model is:

$$P_c = \begin{cases} a \cdot P_{TX} + N_{TRX} \cdot b & \text{if BS is active} \\ N_{TRX} \cdot c & \text{if BS is not active} \end{cases} \tag{2.13}$$

Parameters a, b and c represent respectively the slope of the load dependent power consumption, the power consumption of no RF load and power consumption of sleep mode and they are obtained from measurements for every BS types. Some values are reported in Table 2.2.

Figure 2.3 shows BS power consumption curves for a LTE system with 10 MHz bandwidth and 2x2 MIMO configuration. Three sectors are considered for macro BSs, whereas omni-directional antennas are used for the smaller BS types. While the power consumption is load dependent for macro BSs, and to a lesser extent for micro BSs, there is a negligible load dependency for pico and femto BSs. The reason is that for low power BSs, the impact of the PA is diminishing. In contrast, the share of BB power consumption increases in smaller BS types. Other components hardly scale with the load in a state of the art implementation; although some more innovative designs could lead to an improved power scaling at low loads.

Backhaul effects on power consumption

In mobile networks the backhaul impact to the total power consumption is usually neglected because of its limited contribution. However, due to the

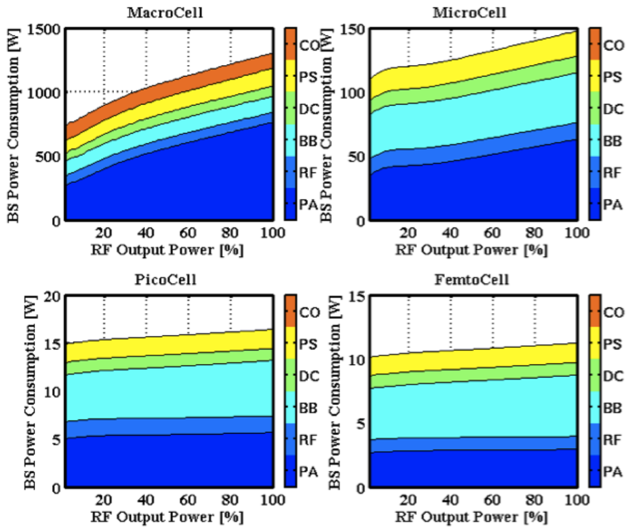


Figure 2.3: Power consumption dependency on RF power load.

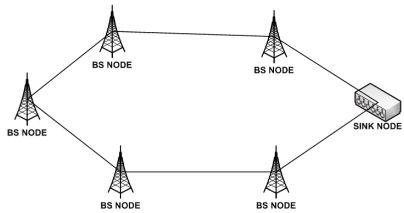
expected densification of small BS in future heterogeneous networks; this impact should be considered in global energy consumption calculation. Backhaul topologies can be classified as ring, star and tree topologies, as depicted in Figure 2.4. In the real world the backhaul networks are more complicated due to base stations positions and link technologies, resulting in a composition of these. The most common linking technologies are microwave radio and optical fiber links.

As reported in [17], a characterization of BS power consumption including backhaul effects can be done by extending the models presented in Section 2.2.2. Power consumption are differentiated for the microwave case and the fiber case.

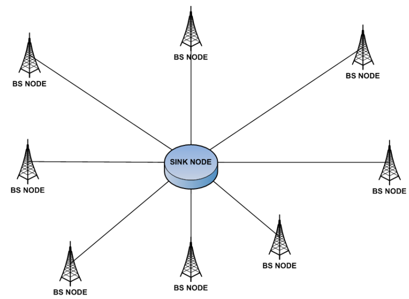
As for the microwave, the total power consumption of a heterogeneous mobile network can be written as

$$P_{tot}^{MW} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{MW} \tag{2.14}$$

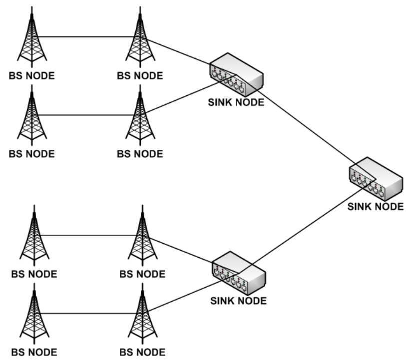
where m is the number of base station types used in the network, N_i is the number of base stations of type i, P_i is the power consumption of a



(a) ring topology



(b) star topology



(c) tree topology

Figure 2.4: Different backhaul topologies

base station of type i calculated as in equation 2.13 and P_{bh}^{MW} is the entire backhaul power consumption which is calculated as follows.

$$P_{bh}^{MW} = P_{sink} + \sum_{j=1}^{N_{BS}} P_j^{MW} \tag{2.15}$$

In equation 2.15 P_{sink} is the power consumption of the area sink node, N_{BS} is the number of base station, regardless their type, and P_j^{MW} is the power consumption associated at the microwave backhaul operations of the j-th base station. By defining C_j the total aggregated capacity that the base station j must manage, such power consumption can be modelled as:

$$P_j^{MW} = P_{j,agg}(C_j) + P_{j,switch}(N_j^{ant}, C_j) \tag{2.16}$$

where

$$P_{j,agg}(C_j) = \begin{cases} P_{low-c} & \text{if } C_j \leq Th_{low-c} \\ P_{high-c} & \text{if } C_j > Th_{low-c} \end{cases} \tag{2.17}$$

and

$$P_{j,switch}(N_j^{ant}, C_j) = \begin{cases} 0 & \text{if } N_j^{ant} = 1 \\ P_S \left\lceil \frac{C_j}{C_{switch}^{MAX}} \right\rceil & \text{otherwise} \end{cases} \tag{2.18}$$

Therefore, equation 2.18 models the power consumption $P_{j,agg}$ associated to transmitting and receiving microwave backhaul traffic to a step function with respect to total capacity C_j. P_{low-c} and P_{high-c} are two power regions defined respectively for low and high capacity traffic. By considering the parameter P_S the power consumption of the switches is taken into account; the number of switches is function of their capacity C_{switch}^{MAX}.

In a similar way the power consumption of a sink node is computed:

$$P_{sink}^{MW} = P_{sink,agg}(C_{sink}) + P_{sink,switch}(N_{sink}^{ant}, C_{sink}) \tag{2.19}$$

where

$$P_{sink,agg}(C_{sink}) = \begin{cases} P_{low-c} & \text{if } C_{sink} \leq Th_{low-c} \\ P_{high-c} & \text{if } C_{sink} > Th_{low-c} \end{cases} \tag{2.20}$$

and

$$P_{sink,switch}(N_{sink}^{ant}, C_j) = \begin{cases} 0 & \text{if } N_{sink}^{ant} = 1 \\ P_S \left\lceil \frac{C_{sink}}{C_{switch}^{MAX}} \right\rceil & \text{otherwise} \end{cases} \tag{2.21}$$

As for the fiber case, the total power consumption of an heterogeneous mobile network including backhaul effects can be written as:

$$P_{tot}^{FIB} = \sum_{i=1}^{m} N_i \left(P_i + c_i\right) + P_{bh}^{FIB} \tag{2.22}$$

and

$$P_{bh}^{FIB} = \left\lceil \frac{1}{max_{dl}} \left(\sum_{i=1}^{m} N_i \right) \right\rceil P_S + \left(\sum_{i=1}^{m} N_i \right) P_{dl} + N_{ul} P_{ul} \tag{2.23}$$

Parameters m, N_i, P_i and P_S are the same as in the microwave case; c_i is an additive factor on the base station power consumption representing the

Table 2.3: Power consumption model parameters in the microwave case

P_{low-c} **[W]**	P_{high-c} **[W]**	Th_{low-c} **[W]**	P_S **[W]**	C_{switch}^{MAX} **[Gbps]**
37	92.5	500	53	36

Table 2.4: Power consumption model parameters in the fiber case

P_{dl} **[W]**	P_{ul} **[W]**	max_{dl} **[W]**	P_S **[W]**	C_{switch}^{MAX} **[Gbps]**
1	2	24	300	24

consumption of the optical interface connecting base station to the aggregation switch at the hub node. P_{dl} is the power consumed by one downlink interface in the aggregation switch, N_{ul} and P_{ul} are respectively the total number of uplink interfaces and the power consumption of each one of them.

Table 2.3 and Table 2.4 report numeric values for the parameters used in the model.

2.2.3 Energy efficiency metrics

The concept of energy efficiency becomes meaningful only if it is measurable. The need of metrics is so justified to quantify and compare the energy consumption performance of different components and systems. Energy efficient metrics can be defined for component, equipment and system levels. While at component level the estimation of energy efficiency is straightforward and most metrics have been well defined, at equipment and system level the definition of metrics is more complicated. As a matter of fact manufacturers implements equipment standards by using competing technologies resulting in different performance. Moreover, telecommunications equipments normally operate at different loads and energy consumption does not scale with load. Since a metric value is the result of a measurement, the measurement method for equipment and system levels, describing setup, environment and procedures, must be standardized for a specific metric.

Metrics for component level

A typical wireless equipment, that is a generic device with air interface, is provided by several building blocks like RF frontend, baseband processor, support systems, power supply and other optional components like climate control. Transmitting and receiving chains compose the RF frontend: the main components of such component are antennas and power amplifiers. The support systems implement some control functions and provide the interface with higher layers. The power source can be alternating current or battery.

As for the RF frontend, the efficiency of an antenna considers the losses that antenna system introduces on the RF signal. In particular antenna efficiency is defined as

$$\eta_{ANT} = \frac{P_{radiated}}{P_{input}} \tag{2.24}$$

On the other hand antenna efficiency can be more oriented to the transmitted power in the maximum radiation direction. In this case the antenna gain is considered:

$$Gain = 4\pi \frac{\text{Radiation intensity}}{P_{input}} \tag{2.25}$$

The antenna gain takes into account the efficiency of the antenna as well its directional capabilities.

The main power consumption contributor in the RF frontend is the power amplifier. The efficiency of a PA is defined as the ratio between output and input power:

$$\eta_{PA} = \frac{P_{output}}{P_{input}} \tag{2.26}$$

Since the power amplifier is responsible of about 60% of global power consumption of a cellular base station, a lot of work has been spent in order to increase its efficiency. Some results have been obtained through Doherty designs which lift efficiency up to 35% from typical 15%. On the other hand Envelope Tracking design ensure efficiency of about 60% by modulating the supply voltage in line with the envelope of the signal. A system level approach is to shut down the power amplifier when the transmitter is idle.

The baseband processor is usually constituted by a DSP. The energy efficiency of a DSP is defined as the number of floating point operation per second with respect to the energy consumed (FLOPS/W). In a similar way also the energy efficiency of support systems is function of performance per unit energy consumption. The energy efficiency metric for support systems are FLOPS/W or MIPS/W which is defined with respect to the number of million of instructions per second (MIPS).

Metrics for equipment level

Equipments can be roughly divided in BS or access point and terminals. The main energy efficiency metric used for BS is the energy consumption rating (ECR) defined as the ratio between power consumption (E) and effective system throughput in bits per second (T):

$$ECR = \frac{E}{T} \tag{2.27}$$

The effective system throughput count the frame overhead from the physical to the link layer.

As for the terminal, since energy consumption depends by communications features as well as running applications, the energy efficiency is evaluated as the talking time and the stand-by time normalized by the capacity of the battery.

Metrics for system level

Energy efficiency at system level is considered as the comparison between energy consumption and some features like coverage area and capacity. One of the most common system level metrics is the APC. Such metric assess the power consumption of the network relative to its extension and it is defined as:

$$APC = \frac{P_c}{A} \quad [W/km^2] \tag{2.28}$$

where P_c is the average power consumed in a reference cell and A is corresponding cell size. APC has been considered to compare the energy efficiency of networks of differing site densities, since increasing distances generate larger coverage areas.

In order to consider also the capacity of the system, energy efficiency can be defined as power per user (PPU):

$$PPU = \frac{P_c}{N_{BH}} \tag{2.29}$$

where N_{BH} is the maximum number of users at busy hour that can be served by the considered cell. However, the most common way to relate the energy consumption to network capacity resorts to the ratio between the total amount of bits delivered and the global power consumption:

$$EE = \frac{T}{P_c} \quad [bit/Joule] \tag{2.30}$$

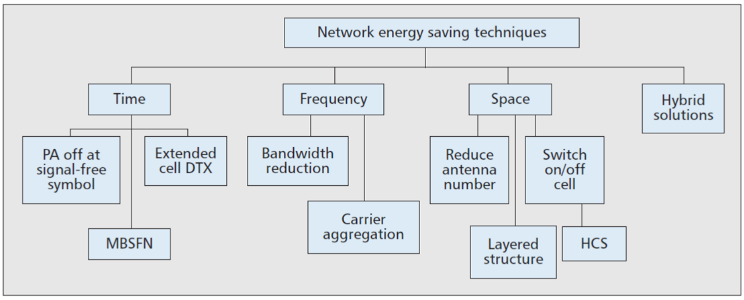


Figure 2.5: Network energy saving radio resource management [1]

where T is the system throughput expressed in bit/s and P_c is the global power consumption expressed in Watt.

2.2.4 Energy efficient radio resource management

Radio resource management (RRM) is one of the effective ways to reduce the energy consumption also for already deployed cellular networks. As a matter of fact, network dimensioning is peak-load oriented and a lot of energy is wasted almost always since the traffic is lower than the peak for the greater part of the day. Therefore the main goal of an energy efficient RRM is to adapt the network energy consumption to the effective daily traffic load. The main idea to adapt radio resources to the effective requests is the introduction of BS sleep mode, that is the possibility to put some devices of a base station in a low power state. Referring to Figure 2.5 [1], sleep mode techniques can be classified as:

- Time domain sleep mode
- Frequency domain sleep mode
- Space domain sleep mode

Time domain sleep mode works putting off the PAs of a base station during time when there is no downlink traffic. Such solution can also identified as cell discontinuous transmission discontinuous transmission (DTX) and can be applied thanks to some features of the LTE frame; for other cellular systems it is not possible or it has a very small impact on energy saving due to signalling transmission also during no traffic time [18]. As reported in [2]

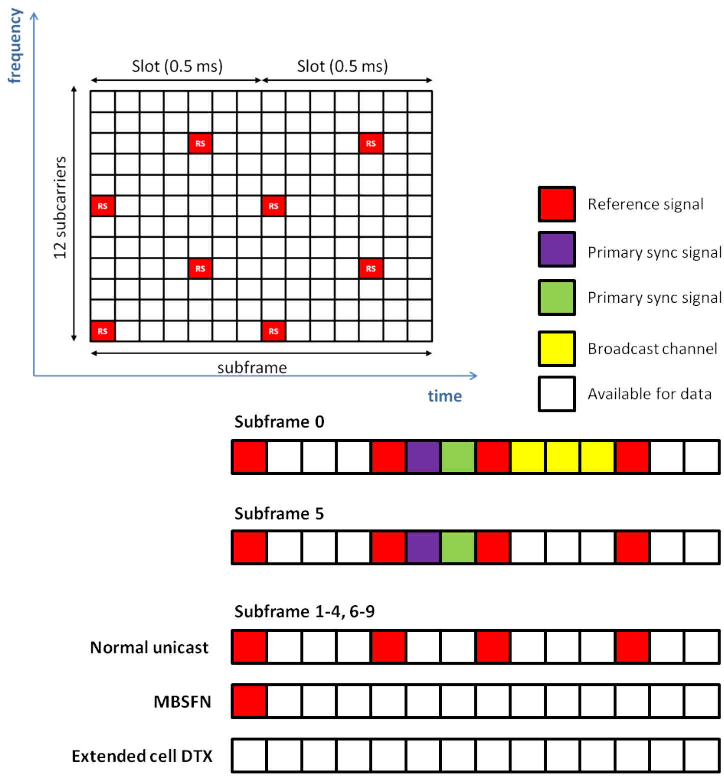
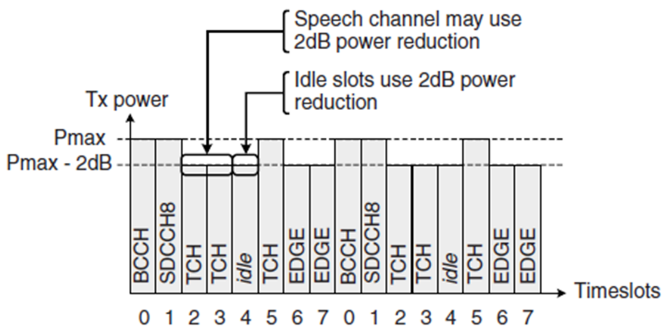


Figure 2.6: LTE frame and cell DTX

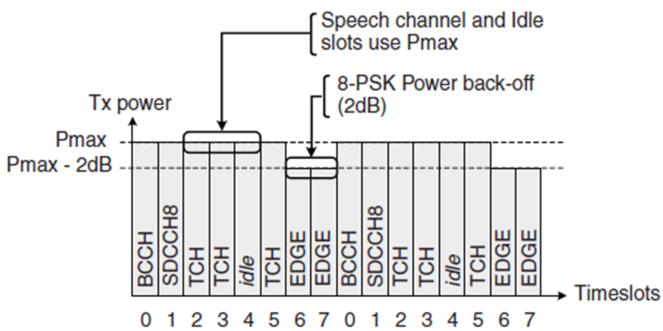
DTX allows to save between 8% and 10% of energy in GSM base stations by putting on sleep mode PAs during time slot allocated for traffic when no activity is detected. As shown in Figure 2.6 only a small fraction of each LTE subframe must be transmitted even if base station is not managing traffic. In a normal LTE frame, which has 7 symbols per slot, 4 symbols in each of subframes 1-4 and 6-9, 9 symbols in subframe 0, and 6 symbols of subframe 5 cannot be signal-free due to the need to transmit reference signals and control signals. In case of no downlink traffic, assuming the PA can be immediately turned off, but it need half of a symbol time to turn on, cell DTX allows PAs to be turned off for at maximum 63% of time. A more aggressive strategy is to use the multicast broadcast single frequency network (MBSFN) subframe to reduce reference signals and increase the potential time a PA can be turned off (at maximum 72% of total time of frame). The upper bound of time domain sleep mode is the introduction of extended cell DTX subframe. Such kind of subframe does not contain reference signals and can be totally put on sleep mode allowing PAs to switch off for at maximum about 92% of time of frame. Even if extended cell DTX seems to enable very high saving, the main problem is that actually it is not part of the standard while MBSFN is part of LTE Rel-8. Energy consumption adaptation to daily traffic variations through cell DTX has been evaluated in [19] where authors also introduce a base station power consumption model including such kind of time domain sleep mode.

Referring to GSM system a similar solution allowing to reduce energy consumption by acting in time domain is the so called power control on broadcast control channel (BCCH) TRXs [2]. BCCH TRXs manage the transmission of broadcast channel, that is the channel containing main information of the cell: the power measured by receiving this channel determines the coverage area. On BCCH TRXs some channel are used for BCCH and other control signals like stand alone control channel (SDCCH), remaining channels can be used as traffic channel (TCH). When a TCH on BCCH TRX is idle, i.e. is not used for traffic, dummy bursts are transmitted in order to maintain the synchronism. In order to save energy it is possible to transmit dummy bursts with a 2 dB power reduction, as depicted in Figure 2.7. Obviously such solution is allowed when traffic is very low and TCHs on BCCH TRX are idle.

As for the frequency domain, there are two main approaches: bandwidth reduction and carrier aggregation. Bandwidth reduction techniques aim at adapting the bandwidth with the downlink traffic load. If downlink traffic is low some PAs can be switched off thanks to a bandwidth reduction that at the same time reduces the reference signals transmission. Moreover, to maintain the same power spectral density, smaller bandwidth requires less radiated power. In the carrier aggregation (CA) approach, it is assumed that in an BS the carriers are aggregated by groups, and each group is served by individual PAs. The idea is to shut down the associated PAs when the corresponding aggregated carriers are not scheduled for the downlink traffic. This approach is only applicable to an BS that has aggregated carriers and separate PAs attached to each group of carriers. In cellular systems different from LTE, like GSM or Wideband Code Division Multiple Access (WCDMA), in order to reduce energy consumption in frequency domain the carrier sleep



(a)



(b)

Figure 2.7: BCCH power control (a) on and (b) off [2]

mode has been evaluated. Such approach allows to switch off PAs associated to a carrier not needed to satisfy downlink traffic demand and signalling. Carrier sleep mode in GSM system has been introduced in [20, 21] where authors focus also on the way to control the sleep mode in order to avoid the *ping-pong* effect, consisting in a continuous activation and deactivation of PAs due to the traffic fluctuations. In order to avoid *ping-pong* the traffic thresholds for carrier activation and deactivation must be carefully set. While time domain and frequency domain solutions refer to a single base station, spatial domain solutions consider a set of base stations and can be extended to heterogeneous networks introducing more flexibility. The main approaches currently used in the spatial domain are reducing antenna number at base station and dynamically configuring cells in a multicell scenario.

Moreover an approach that consider a traffic offloading in a layered structure to reduce energy consumption of the whole network is also possible. The reduction of antenna number when traffic load of a cell is low allows to save energy by the switch off of antennas PAs. It can combine with the bandwidth reduction technique for the low traffic mode of a base station. Since the reduction of antenna branches decreases the total output power and shrinks the cell size, an additional mechanism is needed to maintain the strength of control signals at the cell edge, for example by boosting the power of control signals so as to maintain the cell size. The main problem of this approach is that it may lead to service degradation or interruption as the antenna reconfiguration is needed. In order to not impact the users' behaviour it should be used only in the semi-static load case.

The cell switch-off approach [22–25] is a system-level approach that works in an area covered by multiple cells. When the traffic load in a given area is low, some cells can be shut down, and the served user equipment (UE) units are handed over to the remaining cells. Switching on/off cells can be done following two approaches: signaling directly between base stations or a dedicated control from the operation & maintenance (OAM) layer of the system. The most common cell switch-off approach is related to hierarchical cell structure (HCS) where always-on macrocells are deployed for basic coverage and micro/picocells are used for capacity boost. Capacity cells can be managed in order to follow the daily traffic demand. The main limitations of cell switch-off is that frequently switching on/off cells affects services at users side, so the cell selection decision should be well addressed. Moreover switching off cells may reduce the battery life of mobile terminals as they have to connect with other cells far away. Finally, the switching-off should not lead coverages holes: if active cells need to increase their power to avoid such situation, the energy efficiency gain could be neutralized.

Similarly to heterogeneous networks, a layered structure is a combination of different networks or access technologies to serve same area. Normally, a wireless wide area network (W-WAN) is deployed in one layer, and wireless local area networks (W-LANs) are used in other layers. In order to optimize the use of energy and spectrum, flexible architectures are needed. Layers can be managed to dynamically serve traffic load taking care about energy efficiency constraints, therefore traffic offloading algorithms and mobility management are keys to achieve energy saving in the proposed architecture [26].

2.2.5 Energy efficient deployment

Network deployment is a very important topic for cellular wireless communications. Recently, since energy efficiency become a primary concern, the optimum cell size in terms of energy consumption, the tradeoff between energy efficiency and deployment costs and the impact of heterogeneous networks, relaying and cooperative communications have been considered. In particular, [7, 27, 28] investigate the cell size minimizing the energy consumption taking into account also the deployment expenditures for operators. Moreover [29, 30] evaluate the effects of indoor deployments considering backhaul from both the energy efficiency and the econometric point of view.

The benefit in energy efficiency depending on heterogeneous deployments are discussed in [31] where the potential energy reduction by varying the number of micro sites and macrocell size to achieve the required spectral efficiency at full load is evaluated. The deployment of micro sites enable the reduction of area power consumption while maintaining a target spectral efficiency. Comparing area power consumption an area spectral efficiency for homogeneous micro sites, homogeneous macro sites and heterogenous deployments, as done in [32, 33], highlights the opportunity to use an heterogeneous deployment for higher area throughput targets and higher users densities.

Power consumption can be significantly reduced also considering indoor picocells and femtocells deployments bringing receivers close to the transmitters. In [34] it is stated that the energy consumption of urban areas for high datarate demand can be reduced by up to 60%. Such gain, as reported in [35–37], is due to the smaller pathloss, lower transmit power and lower energy requirement. Same results are confirmed in [38] where the macro only deployment is considered efficient only for very low capacity demands.

An evolution of the heterogeneous network deployment is the coordinated multi-point (CoMP) transmission technology. CoMP divides the traditional base station in two part: the baseband unit (BBU) and the remote radio unit (RRU). The BBU is connected to the RRU via optical fiber and can be placed in a different part with respect to the RRUs it is managing. So, by considering CoMP, the optimal RRU placement can be derived in order to minimize the average transmission power [39].

Chapter 3

Adaptive RRM driven by traffic forecast

This chapter presents some energy saving solutions for cellular networks driven by traffic forecast. Such solution work by playing with sleep mode of carriers or base stations, by adapting power to capacity demands and by join sleep mode and power adaptation. First of all a detailed explanation of the forecasting technique is provided, then the proposed solution is presented for different scenarios depending on the considered cellular system [1].

3.1 Traffic forecast for cellular networks

3.1.1 Traffic forecast: an energy efficiency enabler

Cellular networks are dimensioned according to peak hour traffic that is the maximum expected amount of requests that the system should be able to satisfy. On the other hand traffic profile during days is not flat and the peak hour could never be reached or it could be for a very small fraction of the day. More in details, cellular traffic flow shows three kind of variations:

- daily variations, i.e. the difference between busiest hours and minimum load like night time;

[1] Parts of this chapter have been presented in an international journal [40] and in some international conferences [41–44] focusing on green wireless communications.

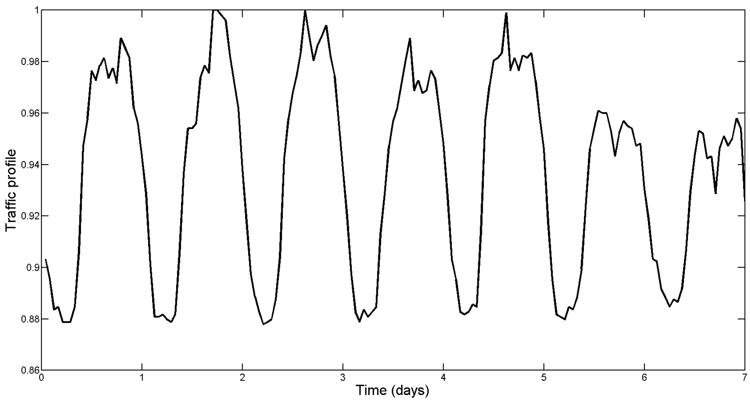


Figure 3.1: Normalized traffic profile during a week for a GSM base station.

- weekly variations, i.e. the difference between average traffic in work days and during weekend;
- incidental variations, i.e. the peak of traffic due to special events

Such variations have different distribution according to the season of the year and the location that are being considered. Figure 3.1 highlights daily and weekly variations: during work days (from Monday to Friday) there is a fraction of time when traffic approaches the maximum peak, during weekend (Saturday and Sunday) the peak traffic is smaller.

By knowing the traffic variations, for instance using a prediction technique, radio resources can be adapted to the effective requests in order to save energy.

Some traffic forecast techniques have been proposed for cellular networks. For example, network dimensioning is done by approximating the traffic volume with a given distribution function. Following this strategy the users arrival is modelled according to a Poisson process while the sojourn time is exponentially distributed [45]. Moreover specific models like Markov chain [46] and regression models [47] can be applied to keep the temporal dynamics. Moreover also a simple solution based on the comparison of very frequent traffic measures with a given threshold [20, 21] imply a prediction because assume that the successive value will be similar to the previous one.

This chapter aims at investigating the energy saving potentials enabled by traffic forecast. In particular the second order exponential smoothing,

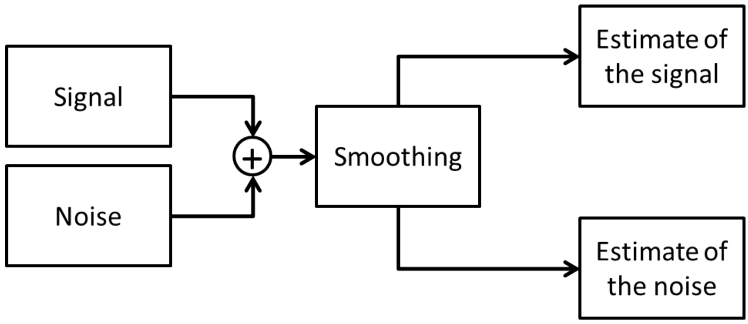


Figure 3.2: Smoothing process.

also known as Holt-Winter forecasting technique, has been considered to perform the prediction. Besides some performance evaluation in terms of switching cost and quality of service are provided.

3.1.2 The exponential smoothing forecasting technique

Time series and smoothing

A time series is a sequence of numerical data points in successive order occurring in uniform intervals. Such data set can be expressed as

$$y_t = \mu + \epsilon_t \tag{3.1}$$

where y_t is an observed value at time t, μ represents the underlying constant level of system response signal and ϵ_t is the noise at time t. The smoothing is a technique aiming at separating signal and noise as much as possible acting as a filter to obtain an estimate of the signal, as depicted in Figure 3.2. Such result is achieved by simply relating the current observation to the previous one. Therefore at time T the observation y_T will be replaced by a combination of observation at and before T.

Theorem 3.1.1. *If the process is constant, the average of previous observed values is the best combination to represent a value at time T.*

Proof. Using the least square criterion, the sum of square errors SS of the constant process is

$$SS = \sum_{t=1}^{T} (y_t - \mu)^2$$

SS is minimized by calculating the derivative with respect to μ and setting it to 0:

$$\frac{\partial SS}{\partial \mu} = -2 \cdot \sum_{t=1}^{T} (y_t - \mu) = 0$$

resulting in

$$\mu = \frac{1}{T} \sum_{t=1}^{T} y_t$$

that is the average of $\{y_t\}_{t=1}^{T}$. □

The constant process is useful to approximate a generic process. In other words, a generic process can be represented by a combination of some constant process, the more is the variability of the process the lower is the number of values to be included in the average calculation of each constant process, i.e. the span of the average. This procedure is called *simple moving average* and its main issue is the choice of the span. As a matter of fact, the variance of the moving average is

$$\sigma_{MA}^2 = \frac{\sigma^2}{N} \tag{3.2}$$

where σ^2 is variance of the uncorrelated observations and N is the span. By decreasing the span, the variance of the moving average increases.

First order exponential smoothing

First order exponential smoothing, also known as Brown's exponential smoothing [48], is an alternative approach to the span variation in order to adapt the smoothing to a variable process. Instead of the simple moving average, the weighted moving average is considered by giving to earlier observations a lower weight than the newest ones. The first order exponential smoothing can be expressed as:

$$s_t = \alpha y_{t-1} + (1 - \alpha) s_{t-1} \tag{3.3}$$

So, performing a forecast, the prediction for time t is the previous forecasted value s_{t-1} corrected by the error between the forecasted and the observed value at time $t - 1$:

$$s_t = \alpha y_{t-1} + (1 - \alpha) s_{t-1} = s_{t-1} + \alpha (y_{t-1} - s_{t-1}) \tag{3.4}$$

α is the smoothing parameter and it is between 0 and 1. The smoothing parameter controls the speed which the updated forecast will adapt to local level of the time series. Note that the m-step ahead forecast will return m equal values.

Second order exponential smoothing

In order to take into account a trend of the time series, the second order exponential smoothing, also known as the Holt's model [49], has been developed. The trend is modeled as a slope component that is itself updated via exponential smoothing. Such component is calculated as:

$$b_t = \beta(s_t - s_{t-1}) + (1 - \beta)b_{t-1} \tag{3.5}$$

while the main component s_t is obtained updating Equation 3.3:

$$s_t = \alpha y_{t-1} + (1 - \alpha)(s_{t-1} - b_{t-1}) \tag{3.6}$$

β is the trend parameter, it is between 0 and 1.

The m-step ahead forecast is calculated as:

$$F_{t+m} = s_t + m \cdot b_t \tag{3.7}$$

Third order exponential smoothing

Third order exponential smoothing has been developed in order to take into account seasonal variations as well. It is also known as Holt-Winter forecast (HWF) model [50]. A season is the period of time before behaviour begins to repeat itself and it can be multiplicative or additive. With respect to the multiplicative or additive nature of the variations, the seasonal component is calculated in different ways. As far the multiplicative seasonality is concerned, the seasonal component is:

$$I_t = \gamma \frac{y_t}{s_t} + (1 - \gamma)I_{t-L} \tag{3.8}$$

and in case of additive seasonality:

$$I_t = \gamma(y_t - s_t) + (1 - \gamma)I_{t-L} \tag{3.9}$$

In the above equations γ is the seasonal parameter, which is comprised between 0 and 1, and L is the length of the season in terms of number of observed values before the seasonal behaviour is repeated.

The m-step ahead forecast is calculated as:

$$F_{t+m} = (s_t + m \cdot b_t) I_{t-L+m} \tag{3.10}$$

The choice of parameters

The values of α, β and γ are very important in order to give the proper importance to earlier observations. As a matter of fact if $\alpha \to 1$, $\beta \to 1$ and $\gamma \to 1$ very small weight is given to historical data. An optimization process is needed to set the right values for such parameters. The optimization can be formulated taking into account the mean square error between forecast and observed values during a training period. The problem is formulated as follows:

$$\begin{aligned} &\textbf{minimize} \quad \sum_{t=a}^{b} (y_t - F_t(\alpha, \beta, \gamma))^2 \\ &\textbf{subject to} \\ &\quad 0 \leq \alpha \leq 1 \\ &\quad 0 \leq \beta \leq 1 \\ &\quad 0 \leq \gamma \leq 1 \end{aligned} \tag{3.11}$$

The training period should be at least one season, but the longer it is the more accurate are the α, β and γ values and consequently the forecast.

Forecasting the cellular traffic through the Holt-Winter technique

Holt-Winter model can be used to forecast the hourly traffic in cellular network [51]. As a matter of fact, traffic in a cell for mobile communications shows a correlation with the hour of the day when it is measured and with the period of the year. Indeed, from the time plots of traffic values in a cell, considering two subsequent working days, the traffic measured at a certain hour of a day is very similar to the traffic measured at the same hour of the previous day. Particularly, each day can be represented as a season that is composed by 24 periods, that is, the hours of a day. Moreover, considering a time plot of traffic values over an entire year, a multiplicative variation of the traffic amplitude in certain months has been observed. For example, in the holiday places during summer, the cellular traffic is higher than during other months. These variations are continuous and distributed over the year and can be modelled as a trend component of the traffic time series.

3.2 Carrier sleep mode in GSM networks

3.2.1 System model

Let be considered a typical GSM deployment which is composed of a three-sector macro-cell, where a two-layer coverage is provided within each sector, as depicted in Figure 3.3. In particular, the basic layer is the GSM900 air interface, whereas the overlay system is the GSM1800 radio technology.

The radio channel is modelled considering the simple pathloss formula:

$$L(d) = c \cdot d^{\alpha} \tag{3.12}$$

By considering Equation 3.12 the pathloss L depends on the distance d between BS and user. The pathloss exponent α is set equal to 4 in order to consider a urban environment. Note that if $\alpha = 2$ the formula models the free-space pathloss, so that $c = \left(\frac{4\pi d}{\lambda}\right)^2$ by considering the carrier wave length λ. The dependency on the wave length motivates the difference between GSM900 and GSM1800 coverage. As a matter of fact a GSM900 carrier ($f_c = 900$ MHz) keeps a lower pathloss and it is able to guarantee a greater coverage range than GSM1800 ($f_c = 1800$ MHz).

As far as the traffic is concerned the Poisson model for the call arrival rate and the exponential distribution for the length of each call have been adopted. In particular each user is able to generate on average 3 calls/hour, i.e. exponentially distributed inter-arrival time with mean value equal to 20 minutes, and exponentially distributed time of service with mean value equal to 3 minutes. Traffic is generated accordingly to the daily profile depicted in Figure 3.4.

The pool of radio resources for each sector is dimensioned taking into account the highest traffic load in a generic day in urban environment. In the GSM system, a radio resource is identified by a time slot on a carrier frequency. The maximum number of time slots on a carrier is equal to eight, so that each transceiver, that is to say each carrier, can support eight channels. All timeslots on each carrier can be used as traffic channels except for the carrier that is used for the broadcast channel and the synchronisation channel so that only six traffic channels can be assigned to the users. The

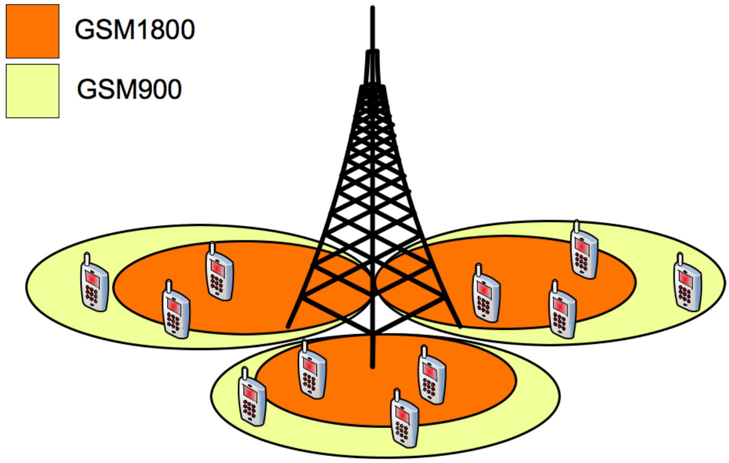


Figure 3.3: GSM deployment.

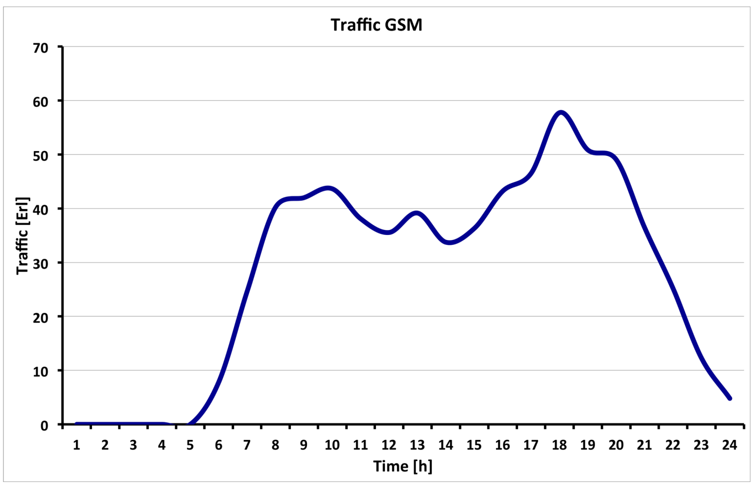


Figure 3.4: GSM daily traffic.

Table 3.1: Simulation parameters for GSM carrier sleep mode

Parameter	value
Transmit power P_{TX}	40 W
Number of TRXs	8 (2 GSM900 + 6 GSM1800)
Call arrival rate	Poisson with mean 3 call/min
Call length	Exponential with mean 180 sec.
Target block probability	0.5%

capacity of a GSM cell can be calculated by the Erlang B formula:

$$P_B(n, A) = \frac{\frac{A^n}{n!}}{\sum_{k=1}^{n} \frac{A}{k!}} \tag{3.13}$$

Equation 3.13 represents the system block probability P_B depending on number of available channels n and expected traffic A. Traffic is measured in Erlang and it is the fraction of time a resource is busy. The Erlang B equation can be expressed in a recursive formulation:

$$P_b(n, A) = \frac{AP_B(n-1, A)}{n + AP_B(n-1, A)} \tag{3.14}$$

All simulation parameter are reported in Table 3.1.

3.2.2 Proposed solution

The proposed solution enabling GSM carrier sleep mode works as follows:

- Each day, a traffic prediction is computed, thanks to the Holt-Winter's procedure.
- Thanks to this prediction and to Equation 3.13, the number of requested channels and, consequently, the number of active transceivers can be computed at a hourly rate.
- The switch off procedure is invoked while

  $$\#\text{requested channels} < (\#\text{TRX} - 1) \cdot \#\text{timeslots}$$

  otherwise, while

  $$\#\text{requested channels} > \#\text{TRX} \cdot \#\text{timeslots}$$

  another TRX is switched on.

The switching off procedure is an issue that needs careful evaluation. As a matter of fact, a carrier transmitted by the transceiver candidate to be switched off could be used by some communications. In order to maintain the requested grade of service, these communications cannot be dropped, but have to be handed over to another carrier. The number of handovers is a key performance indicator of a cellular network: the greater the number of handovers, the greater is the probability that a handover is not correctly performed and, therefore, the system experiences a call drop. Hence, an effective criterion is to choose the transceiver to be switched off as the one with the lowest load. As a result, the switching off procedure is the following:

- Among all the active transceivers of the considered BS, identify the minimum load one.
- If an intracell handover is possible for all the communications that are currently using the transceiver to be switched off, force them to the other carriers of the cell and do not admit any new call on this carrier.
- When the transceiver is empty, switch it off.

3.2.3 Results

The proposed algorithm has been evaluated via software simulations by system level simulator implemented in the OMNeT++ environment. To this aim the framework shown in Figure 3.5 has been considered.

The performance of HWF based algorithm, indicated as forecasting based sleep mode algorithm (FBSMA), is compared with the ones achieved by a simple strategy, which is based on successive measurements and thresholds comparison, indicated as real time measurements sleep mode algorithm (RTMSA). The main goal of the considered algorithm is the adaption of the number of active carriers to the daily traffic profile. By considering that, during the day, the number of active carriers can be kept constant and equal to the needed carriers at the peak hour, a significant energy saving is afforded by FBSMA and RTMSA. As a matter of fact, considering a very low traffic window, as in the night-time, just one carrier is effectively required to guarantee the access to the service. In a similar way, during the other windows of non-peak hours, the algorithm works by simply activating the needed resources. Nonetheless, note that at least one carrier has to be kept active during all the day, in order to maintain the coverage of the considered area.

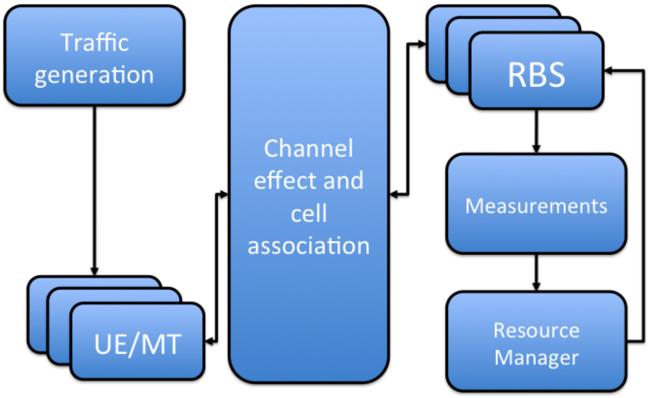


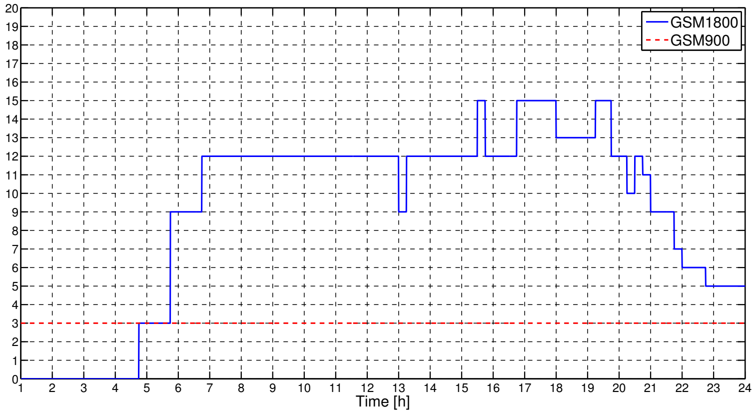
Figure 3.5: Framework for system level simulations.

Figure 3.6 shows how these goals are pursued, by plotting the number of active carriers for each hour during a day. The number of active carriers during the day is shown for FBSMA in Figure 3.6(a) and RTMSA in Figure 3.6(b): it is evident how the technique based on traffic forecast needs a lower number of adaptation actions during the day. Indeed, the main advantage of the forecast approach is to provide the network a rough estimation of the load variations.

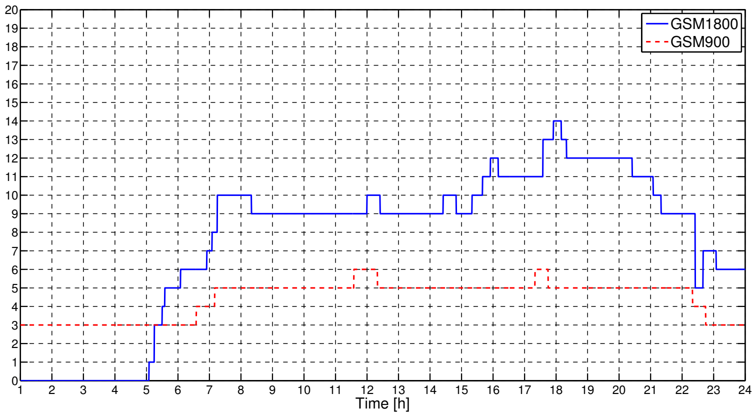
Figure 3.7 and Figure 3.8 show respectively the APC with respect to managed traffic and the energy saving fraction during the day for both FB-SMA and RTMSA compared to the maximum value and the theoretical optimum. The theoretical optimum is obtained by considering the minimum required resources in order to satisfy the traffic demands with no coverage constraint. From these graphs, it is evident that FBSMA performs very similar to RTMSA. The greater savings is obviously during the night-time, when the cell manages the lowest traffic, but good results can be obtained also during the day when traffic requests are far from the peak values.

Figure 3.9 shows the call drop rate behaviour during the day, highlighting that the QoS requirement is satisfied for both considered strategies.

Finally in Figure 3.10 the number of switching actions during the day is plotted for FBSMAand RTMSA. In particular it is shown that RTMSA requires a greater number of switching actions to adapt resources to traffic requests: at the end of the day, while FBSMA performs on average 17



(a) FBSMA



(b) RTMSA

Figure 3.6: Active TRXs during a day for GSM carrier sleep mode

switching actions, RTMSA performs 36.

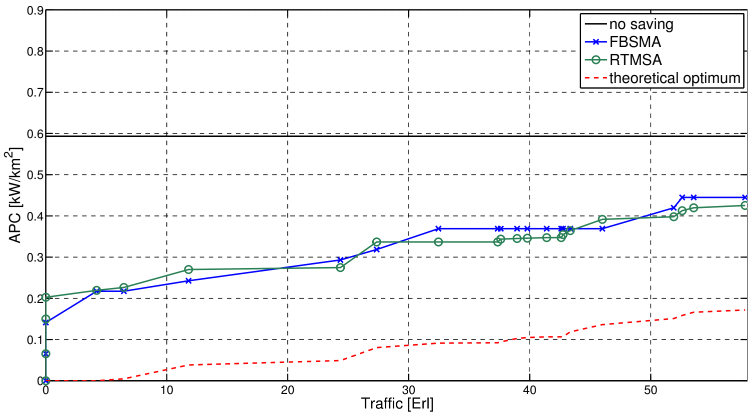


Figure 3.7: APC for GSM carrier sleep mode strategies.

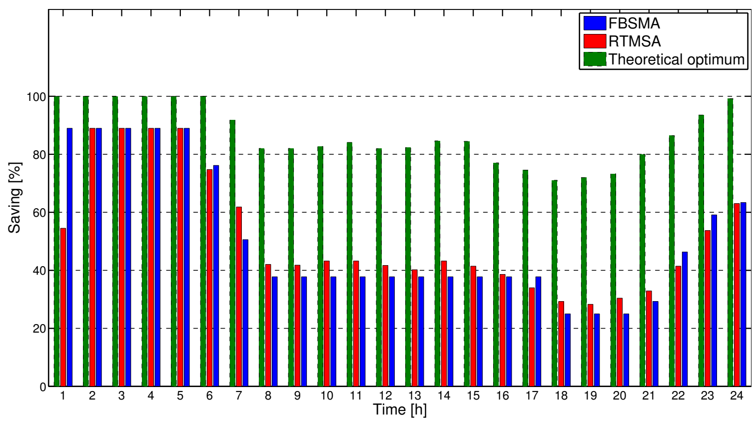


Figure 3.8: Energy saving for GSM carrier sleep mode strategies.

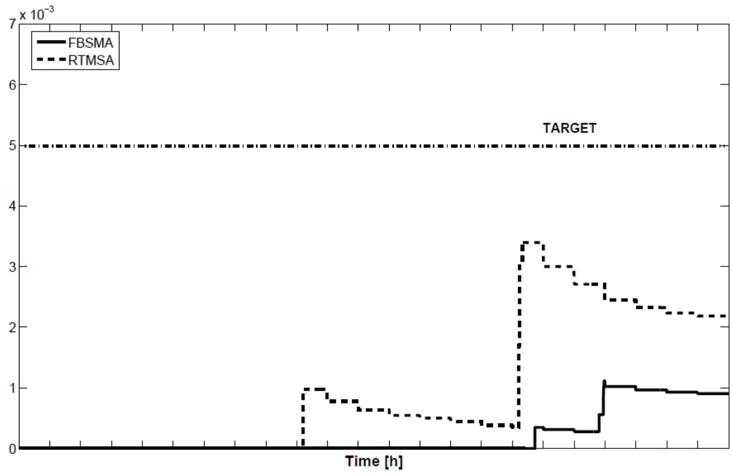


Figure 3.9: Call drop rate for GSM carrier sleep mode strategies.

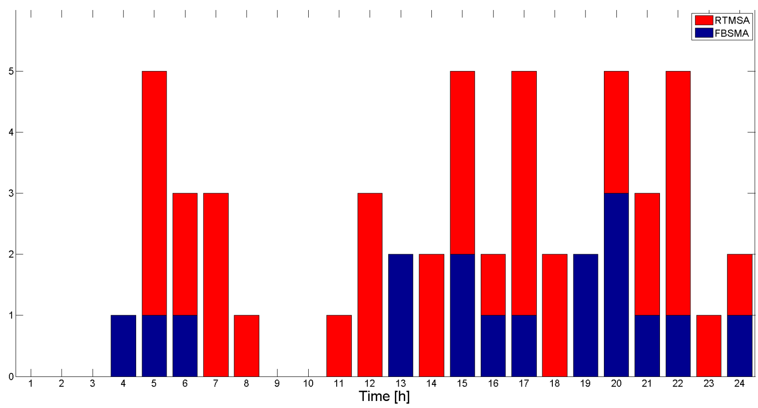


Figure 3.10: Number of switching actions for GSM carrier sleep mode strategies.

3.3 Micro base stations dynamic switch on/off in HSPA netowrks

3.3.1 System model

Let be considered a multi-layer cell deployment for a HSPA system as the one depicted in Figure 3.11: the coverage provided by four micro BSs is overlapped to the coverage area provided by a macro BS. This kind of deployment, which aims at making the radio access closer to the user, is very common when high values of network capacity and, consequently, high data rates have to be guaranteed. The macro BS, which is characterised by a maximum transmission power $P_{TX}^{M} = 43$ dBm, is installed at height $h_M = 30$ m and able to guarantee the coverage for all the considered playground of 1500 m^2 . The micro BSs transmit a maximum power $P_{TX}^{m} = 40$ dBm, whereas their height is $h_M = 15$ m. The path loss has been calculated by means of the Hata model as in Equation 3.15, where R is the distance between transmitter and receiver expressed in km.

$$L_M = 128.1 + 37.6 \log(R) \tag{3.15}$$

HSPA makes use of adaptive modulation and coding (AMC), therefore the downlink maximum capacity depends on the link modulation and coding scheme. In downlink packet QPSK and 16-QAM modulations are adopted. The choice of the modulation is taken by considering channel quality indicator (CQI), which is computed as follows:

$$CQI = \begin{cases} 0 & \gamma \leq -3.96 \\ \lceil \frac{\gamma}{1.02} + 4.81 \rceil & -3.96 < \gamma \leq 26.04 \\ 30 & \gamma > 26.04 \end{cases} \tag{3.16}$$

where γ is the downlink SINR on the link between the $i-$th node B and the $j-$th UE and it is computed as:

$$\begin{aligned} \gamma = SINR_{i,j} = \\ = \frac{SF_{16} P_{i,j}}{(1-\alpha)\sum_{n \neq i} P_{i,n} + \sum_{m \neq j} P_{m,j} + \sigma_n} \end{aligned} \tag{3.17}$$

where SF_{16} is the spreading factor and $\alpha = 0.6$ is the orthogonality factor. The maximum data rate for each user without considering channel coding is

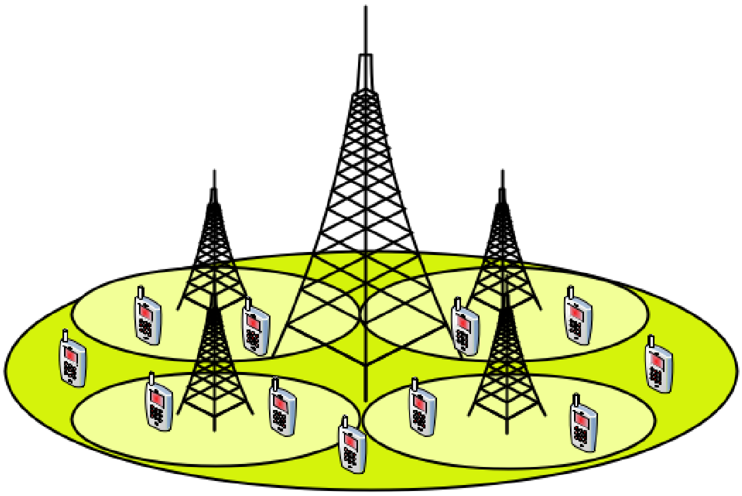


Figure 3.11: Considered HSPA cell deployment.

computed by the following equation:

$$R_{max} = \frac{n_{codes} \cdot W \cdot m}{SF_{16}} \quad (3.18)$$

where n_{codes} is the maximum number of allowed codes, W is the WCDMA chip rate and m is the modulation index. The mapping between CQI, modulation scheme and n_{codes} is reported in Table 3.2.

UEs are uniformly deployed within the macro cell. They require a target datarate of 0.5 Mbps. The traffic is generated following the profile depicted in Figure 3.12. Simulations parameters are reported in Table 3.3.

3.3.2 Proposed solution

Since the coverage of the considered area is guaranteed by the macro BS, the activity of the four micro BSs can be managed so that it is adapted to the traffic profile thanks to the capacity forecast provided by running the HWF.

Similarly to GSM carrier sleep mode, such solution can be described as follows:

- Each day, a hourly data traffic prediction is computed, thanks to HWF.

Table 3.2: CQI table

CQI	**Modulation**	**m**	$\mathbf{n_{codes}}$
1	QPSK	2	1
...	...	...	...
14	QPSK	2	4
15	QPSK	2	5
16	16-QAM	4	5
...	...	...	...
24	16-QAM	4	8
25	16-QAM	4	10

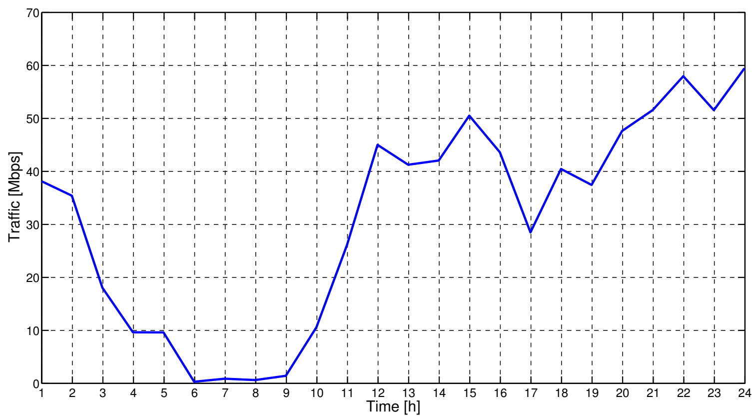


Figure 3.12: Traffic profile in the HSPA scenario.

Table 3.3: HSPA simulation paramters

Parameter	**Value**
Deployment	1 Macro BS + 4 Micro BSs
	1 carrier per BS
Macro transmit power P_{TX}^{M}	43 dBm
Micro transmit power P_{TX}^{m}	40 dBm
Users target rate	0.5 Mbps

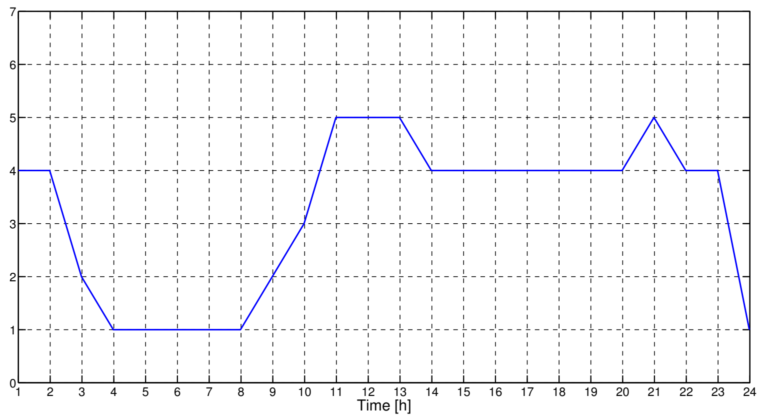
- At each hour, the global required capacity is computed according to the prediction. Starting from this value, the number of needed active BSs can be obtained by taking into account the maximum available capacity of each BS. The maximum capacity is calculated as a fraction of the pole capacity of the considered BS, that is the capacity resulting from Equation 3.18 by using all codes at maximum modulation index. Therefore the downlink pole capacity of an HSPA cell is 14.4 Mbps.
- If the global capacity required by the network cannot be satisfied by the macro cell layer, some micro BSs change to the active state and become available for data traffic load.
- On the other hand, while global capacity of the network is larger than the effective necessity, one micro BS is switched off and UEs managed by such micro BS are offloaded to another micro or to macro BS.

The switching off procedure, that is a crucial point of the proposed solution, is done as follows:

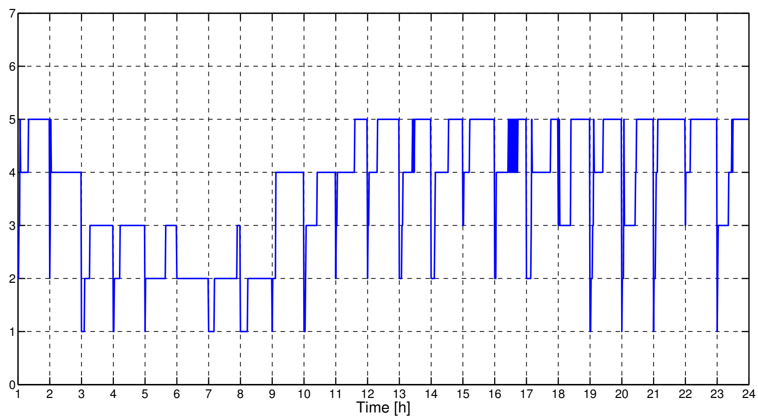
- Among the active micro BSs of the overlapped layer, identify the one with the lowest load in order to minimize the signalling traffic due to handovers.
- Verify if handovers to the macro BS or to the other micro ones is possible for all the communications that exploit the resources of the micro BS to be switched off.
- If handovers are possible, force them from the micro BS to be switched off to the other active ones and do not admit any new request.
- When the micro is empty, switch it off.

3.3.3 Results

Simulations have be done by using the same framework carried out for the GSM carrier sleep mode. Note that in HSPA case the traffic forecast is not in terms of Erlangs, but is referred to the downlink data capacity. Also in this case an output of the simulations is a comparison between the solution based on HWF (FBSMA) and a solution based on frequent measurements (RTMSA).



(a) FBSMA



(b) RTMSA

Figure 3.13: Active BSs during a day for the HSPA sleep mode solution.

Figure 3.13 shows, hour by hour, the number of active HSPA BSs during the day for both FBSMA and RTMSA. As in the GSM case, the main FBSMA advantage is in the lower number of adaptations with respect to RTMSA.

Figure 3.14 and Figure 3.15 show the performance of considered strategies in terms of APC and energy saving. FBSMA and RTMSA have very similar performances, but FBSMA allows a quite greater energy saving especially at low and medium load. Once again, the greater energy saving, which is due to

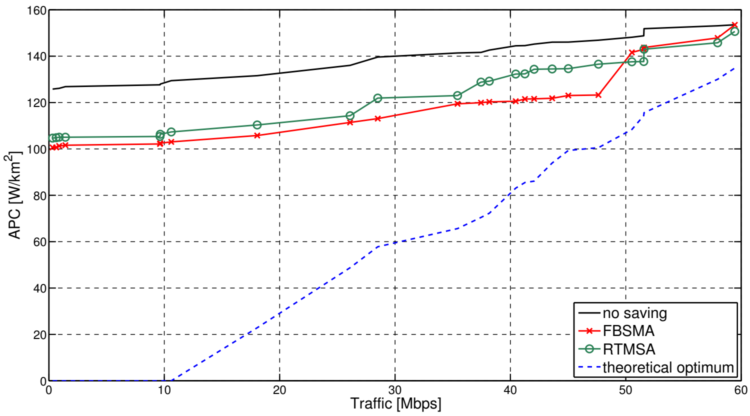


Figure 3.14: APC with respect to managed traffic for the HSPA sleep mode solution.

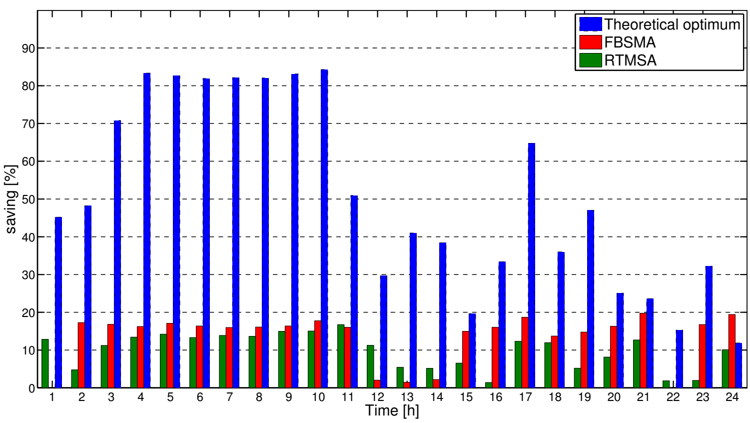


Figure 3.15: Energy saving during the day for the HSPA sleep mode solution.

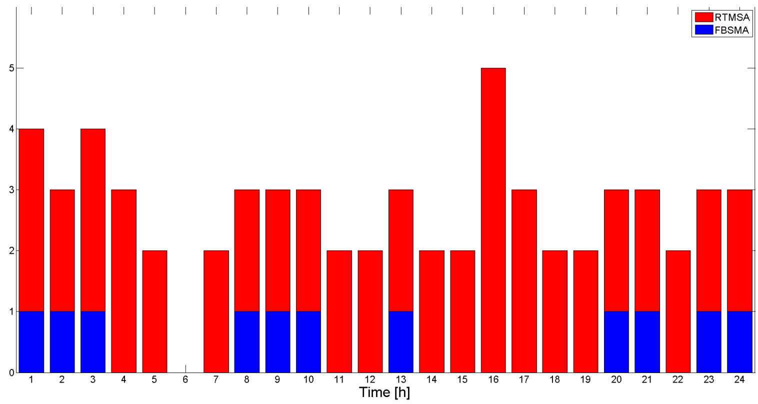


Figure 3.16: Number of switching actions for HSPA cell sleep mode strategies.

both algorithms, is during the night-time. During the other part of the day, a significant result is achieved, thanks to rapid adjustments of resources with respect to real time measurements for RTMSA and to the graceful switch-on of the secondary layer of cells, according to the managed traffic in past days for FBSMA.

Finally in Figure 3.16 the number of switching on/off activity per hour of the day is depicted. FBSMA allows a lower number of switching because the HWF gives a wider vision of the traffic dynamic, on the other hand RTMSA is based on short time measurement and the traffic fluctuations are more influent on cell management. Globally FBSMA requires on average 24 switching actions per day and RTMSA 53.

3.4 Joint power adaptation and sleep mode

3.4.1 System model

A LTE-based network of two different layers of hexagonal cells is considered, as shown in Figure 3.17 and Figure 3.18. The first layer is composed of a set of 19 macro cells: a BS is placed in the center of each cell providing an omnidirectional coverage. The second layer (overlapped to the macro cells coverage area) is formed by 54 micro cells (overlapped to the macro cells) whose BSs are placed in the vertices of each first layer macro cell and are equipped with an omnidirectional antenna. While the first layer of cells aims at providing a global coverage of the selected area, the second one is considered for capacity extension. This deployment scheme represents an effective solution in order to fulfill the users' coverage and capacity requirements in a heterogeneous cellular network [31]: basically, while the macro BSs provide the coverage, the capacity request in the cell edge areas is guaranteed by the micro BSs. We assume that both the macro and the micro BSs are e-NodeBs which resort to the LTE air interface.

In Table 3.4 the parameters to model such systems are reported. The average capacity of each cell is evaluated according to the following formula:

$$C_{avg} = \frac{1}{S} \int_{x_{min}}^{x_{max}} \int_{y_{min}}^{y_{max}} W \log_2(1 + P_{tx} \cdot \Gamma(x, y))\, dxdy \tag{3.19}$$

where W is the system bandwidth, P_{tx} is the power which is transmitted by the BS, S is the considered area and (x,y) are the coordinates of a particular position in S. $\Gamma(x, y)$ is a function that takes into account the effects of pathloss, interference and noise by varying the position of the receiver with respect to the base stationIn particular, for a given position s, it is calculated as follows

$$\Gamma(x, y) = \frac{\sigma(x, y)}{I(x, y) + N} \tag{3.20}$$

where σ(x,y) is the channel gain, I(x,y) the interference received at position (x,y) and N is the noise.

Regarding the traffic generation, a set of active users is considered in the interested area. Each user requests a constant bitrate datastream and the quality of the link is assumed to be acceptable if the datarate is greater than a target value. Users are served by macro and micro base stations in a time sharing way and each of them can be connected to only one base station at a time. To provide equal throughput to all users connected to a BS a Blind Throughput Average scheduler is adopted [52]. This scheduling solution works compensating a weak channel quality by a larger amount of bandwidth. Following EARTH project assumptions [15], the variations of data traffic during the day are modeled with a daily pattern, as the one depicted in Figure 3.19 that considers the fraction of active users during the day with respect to the global number of subscribers in a certain area. Therefore the average number of simultaneous users at busy hour has been fixed and for the other hours it is calculated following this pattern. Following [53], all the considered parameters are resumed in Table 3.4.

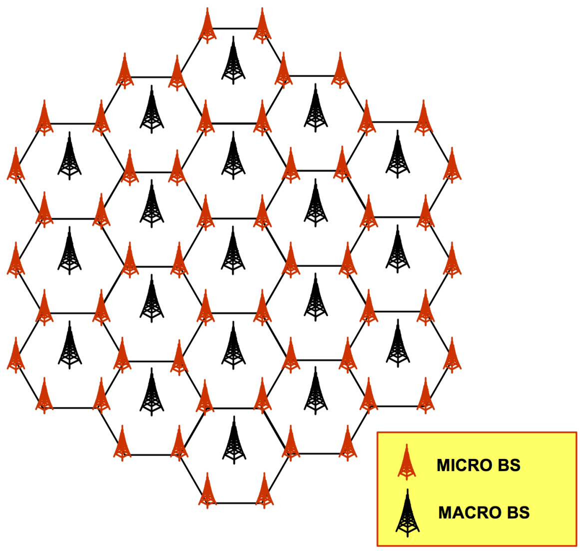


Figure 3.17: The considered heterogeneous deployment.

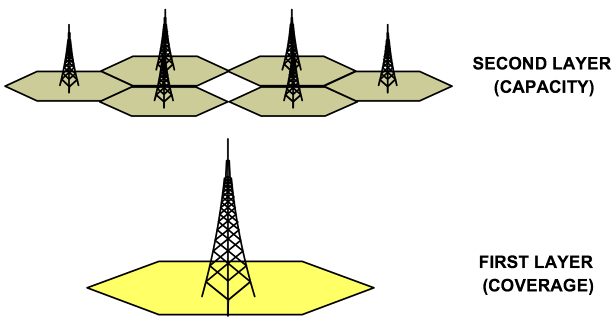


Figure 3.18: Micro and macro coverage.

Table 3.4: System parameters

Basic LTE system parameters	
Carrier frequency	2 GHz
Bandwidth	FDD 10+10 MHz
Available PRBs	50
Base stations parameters	
macro BS transmission power	20 W
micro BS transmission power	5 W
antenna pattern	omnidirectional
macro BS intersite distance	1000 m
micro BS intersite distance	500 m
Link budget parameters	
macro BS-UE pathloss	$128.1 + 37.6 \log(d)$
micro BS-UE pathloss	$140.7 + 36.7 \log(d)$
noise PSD	-174 dBm/Hz
UE receiver sensitivity	-90 dBm
Other parameters	
Datarate target	500 kbps
Scheduling	Blind Average Throughput

3.4.2 The proposed solution

As in previous considered scenarios, that is GSM carrier sleep mode and HSPA cell switch off, also in this case the energy saving solution is driven by a daily traffic forecast that provides at each hour an estimation of the required capacity. The knowledge of this estimation allows to manage the radio resource in order to minimize the energy consumption. In the considered heterogeneous LTE scenario the resource management is done at two domains by adapting the number of active micro BSs and the value of transmit power of macro BSs.

In particular, the proposed algorithm works as in the following. First of all the daily traffic forecast must be performed:

- During the initialization stage, that should be at least one season, the macro BSs record the traffic provided during the time interval by itself and by the micro BSs within its area of coverage and sets up the starting values of the HWF components.

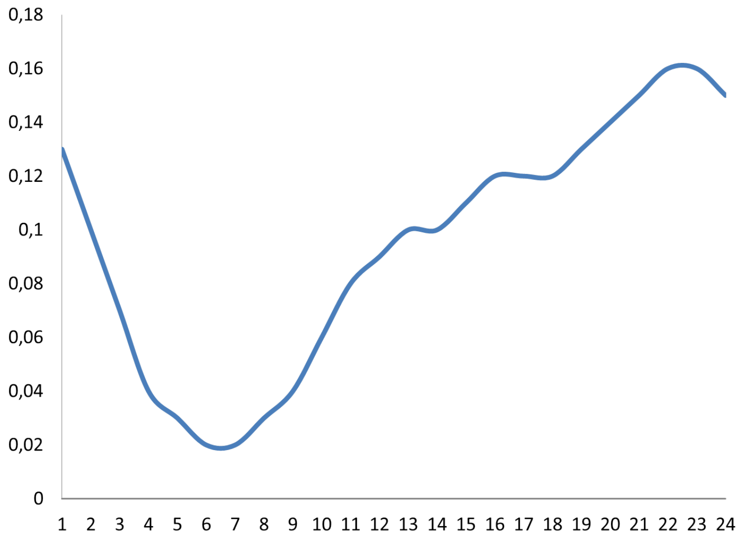


Figure 3.19: The considered traffic pattern.

- After the initialization stage, at each hour the HWF components are updated taking into account the new values of the recorded traffic.
- The forecast is computed at the beginning of each day considering the latest values of the HWF components.

Then, once the traffic forecast is available, the radio resources are managed according to that predicted profile. Therefore if a traffic forecast is available, at each hour the macro BS considers the forecasted values as the reference capacity that has to be provided to its area of coverage for the successive time interval. On the base of this value the capacity is adapted by

- putting in sleep mode or waking up the micro BSs within its area of coverage
- reducing or increasing the transmission power of macro BSs.

Some points have to be clarified. First of all, the set up of the transmission power of a macro BS is driven basically by coverage needs during the network deployment stage. So, acting on this value is possible only if the coverage

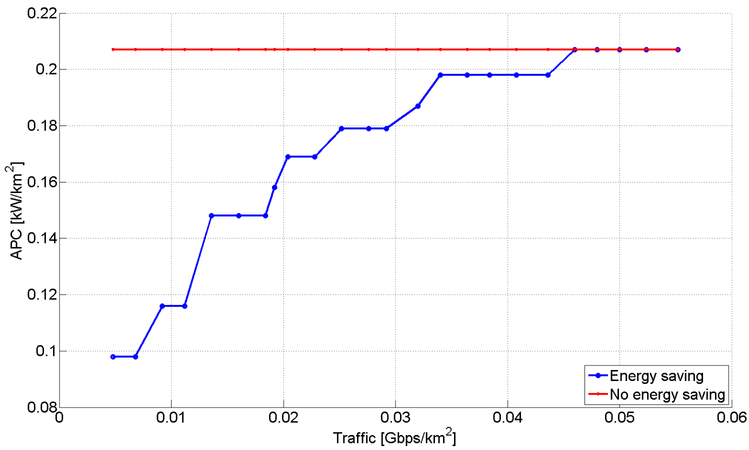


Figure 3.20: APC for joint power adaptation and sleep mode energy saving solution.

area is not modified. For this reason a power range has to be fixed, with the minimum value required to provide the coverage of the area assigned to the cell at the lowest available modulation and coding scheme: this value can be selected as the transmission power lower bound. As for the upper bound, this value is related to the maximum transmission power which is allowed for the BS. The proposed strategy is able to run in a decentralized way at each macro BS of the considered network without any signalling increasing.

3.4.3 Results

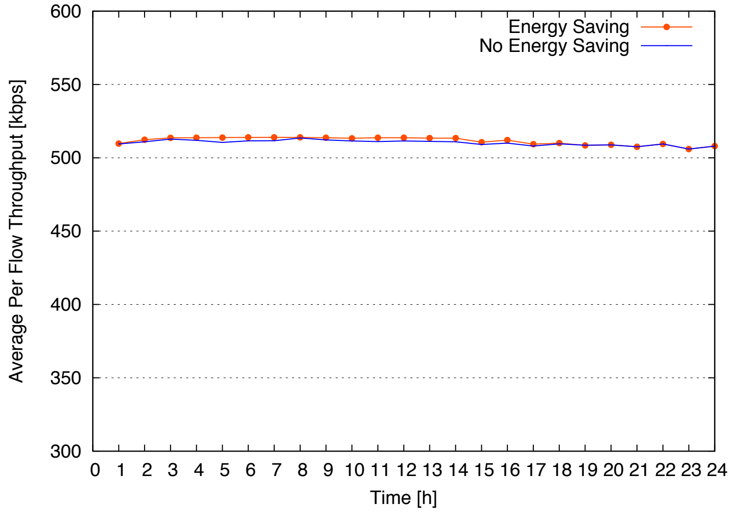
The main effects of the proposed energy saving solution are shown in Figure 3.20 where the APC versus the measured traffic in the whole network is plotted. The chart shows the saving which is caused by the joint adaptation of micro base stations' activity and macro base stations' transmission power with respect to the reference case. In the reference case the APC results constant independently by the number of UEs in the network: this is because all the deployed macro and micro BSs are active at the same time, always transmitting at the maximum power. On the other hand, in the energy saving case, the APC is directly proportional to the traffic load, converging to the reference case when the network is heavily loaded.

The performance of the proposed solution is presented in Figure 3.21

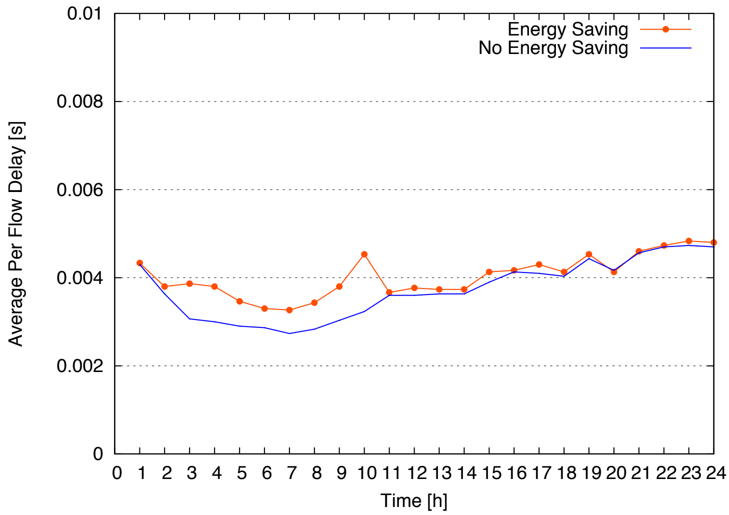
where the average per user throughput and the average per user delay are plotted: these charts show that the implementation of the energy saving solution driven by the traffic forecast does not introduce any performance reduction for the served users. In fact, even though adapting the radio resources, when the load of each cell is low the users can still find a macro BS able to satisfy their needs. In detail Figure 3.21(a) reports the average per user values of throughput experienced during the simulations: it is evident that the energy saving strategy results do not remarkably vary from the values obtained in the no energy saving case. On the other hand Figure 3.21(b) shows that the average per flow delay is marginally affected by the implementation of the energy saving solution when the traffic load is lower, that is when the energy saving is higher. The main contribution affecting this performance metric is the retransmission at the base station side in case of low quality link. As a matter of fact, when some radio resources are not available for the users and the macro base station transmission power is reduced, the quality of each active radio link decreases and some users need more retransmissions with respect to the reference case, where users are connected to the closest macro or micro base station. However, this effect does not significantly reduce the afforded quality of service per user in terms of throughput as shown in Figure 3.21(a).

A detailed evaluation of network performance is presented if Figure 3.22 and 3.23 by considering low, medium and high traffic states. Network is in low traffic state during the hours when traffic is lower than the 30% with respect to the maximum value, medium during the hours when traffic is between 30% and 60%, high when the traffic is greater than 60%. The user throughput CDFs are presented in Figure 3.22. In particular Figure 3.22(a) shows the throughput distribution for low traffic values, Figure 3.22(b) for medium traffic and Figure 3.22(c) for high traffic. It can be observed that when the energy saving strategy is implemented users experiment higher throughput gain in case of low and medium traffic. The reason is that in the reference case, when all radio resources are continuously available, the interference between macro and micro BSs is higher than in the energy saving case.

Similarly in Figure 3.23 the delay performance for low (3.23(a)), medium (3.23(b)) and high traffic values (3.23(c)) are presented. As previously stated the throughput performance in the energy saving case is counterbalanced by higher delays of transmission with low and medium traffic, compared to the

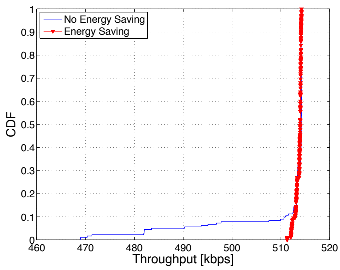


(a) Average per user throughput

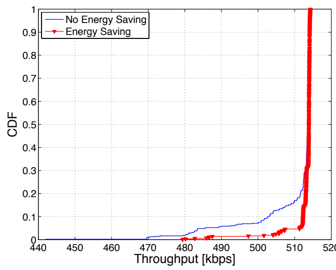


(b) Average per user delay

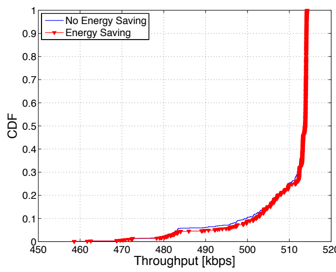
Figure 3.21: QoS evaluation during the day for Joint power adaptation and sleep mode considering average per user throughput and delay.



(a) Low load



(b) Medium load



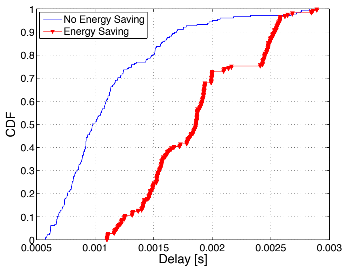
(c) High load

Figure 3.22: CDF of per user throughput for different load cases.

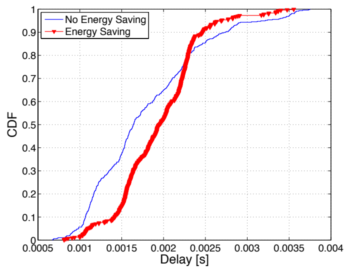
reference case. The user delay and throughput CDFs with high traffic, on the other hand, show a quite similar behaviour for both energy saving and no energy saving cases.

3.5 Conclusion

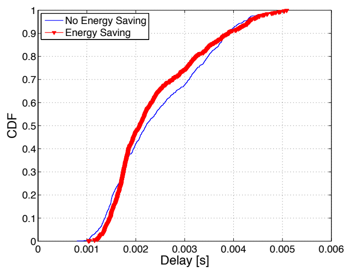
This chapter describes some possibilities to increase the energy efficiency of different cellular systems by taking advantage of traffic forecast. The FB-SMA technique, which resorts in a daily cellular traffic forecast obtained by the HWF technique, has been introduced and tested for different scenarios. In particular the carrier sleep mode for GSM networks, the cell sleep mode for HSPA and a joint technique making use of cell sleep mode and power adaptation in LTE heterogeneous networks. The FBSMA has been compared to another technique based on instantaneous traffic measurements



(a) Low load



(b) Medium load



(c) High load

Figure 3.23: CDF of per user delay for different load cases.

(RTMSA) resulting in a similar power consumption behaviour and in a lower number of switching actions during the day. Note that a higher number of switching actions could result in an increasing of signaling handover traffic and in a reduction of life time of electronic devices. Besides, regarding the joint strategy in LTE heterogeneous networks, a detailed analysis of system performance has been done considering user throughput and delay. Results show the goodness of the forecasting technique and the energy saving introduced by the proposed solution. Moreover the system evaluation shows a negligible reduction of user QoS with respect to the traditional no energy saving radio resource management.

Chapter 4

On the optimum network configuration for energy efficiency

Cellular network energy optimization is driven by different factors, namely base stations transmission power and activity. Quality of Service (QoS) of users cannot be neglected and is driven by received power, interference and bandwidth allocation. In existing studies, such drivers are treated separately, i.e., bandwidth allocation is fixed while power consumption is a variable to be optimized. This chapter proposes a novel optimization framework aimed at minimizing the power consumption in cellular networks while affording a minimum bit rate for each mobile terminal by jointly considering energy consumption and QoS drivers. Mixed Integer Quadratic Programming (MIQP) based optimization framework solves the problems of the determination of the user association, the bandwidth allocation, the identification of the active base stations and their transmission power, guaranteeing also a requested service rate for each user. [1]

[1] Results presented in this chapter have been carried out in collaborations with Communication Systems Department of KTH Royal University of Technology (Kista, Sweden) where Pierpaolo Piunti was visiting student from August 2013 to December 2013 under the supervision of Dr. Cicek Cavdar.

4.1 Introduction

A large number of results have been recently obtained focusing on managing radio resources to obtain an energy efficient cellular network. The bigger impact strategy to cut off wireless systems power consumption is switching off a radio device whenever it is not needed. By this solution the BS activity could be adapted to the real traffic demand avoiding the overprovisioning due to the peak dimensioning [20, 21, 23]. The BS switching off is a critical issue because when a deactivation decision is taken some coverage holes could rise in the area served by that BS. Therefore, in order to keep the energy saving gain of the BS deactivation without affecting the area coverage, a time domain sleep mode has been introduced. Such strategy, identified as cell discontinuous transmission (DTX) [18], is enabled by the particular structure of the LTE frame and allows the transceiver deactivation (sleep mode) during the free data time slots. Thus, the signalling symbols are still transmitted and cell coverage is not affected. Most of work dealing with base station sleep mode techniques do not focus on how the sleep mode decision is taken so limiting to enable sleep mode when the cell load is low [18,54,55]. In order to better adapt the capacity provisioning to real users requests, the association between users and BSs can be considered as an optimization variable to the energy saving goal.

Looking at the Shannon's capacity formula, also bandwidth allocation can play a role in energy efficiency [1]. As a matter of fact, an energy saving gain can be introduced by increasing the bandwidth per user and, consequently, reducing the BS transmission power if the target datarate per user is fixed [11]. Such solution is known as bandwidth expansion mode (BEM) and can be applied when resources usage is light, i.e. in low load case.

Another energy saving RRM solution is the power control which aims at minimizing the BS transmission power with a given QoS target for the served users. Note that the benefit of power control is not only in the energy reduction but also in neighbour cell interference management [56, 57]. In particular, in [56] authors propose an optimization framework to maximize the quantity of transmitted bits per energy unit. Such solution looks at the energy efficiency maximization, but does not consider a QoS target for each user. Moreover, in [57] transmission power for an OFDM communication is minimized without considering any constraint on power model, like a target grade of service per user.

By combining some of these approaches, different optimization solutions have been proposed. A pricing algorithm is evaluated in [58] to solve user association problem and minimize area power consumption, also considering interference: therein, mobile terminal rates are fixed and bandwidth is equally allocated to users regardless of their received signal strength. In [59] power supply per LTE frame is minimized by assigning an opportune transmission power and rate for each link, without considering the mapping problem and a minimum rate value to ensure QoS. Quality of service constraints are considered in [60–62]. In [60] power allocation per user is optimized aiming at energy per bit minimization with a bit error rate constraint to guarantee the QoS. A lower bound on user data rate is set in [61] where BS transmission power and user rate are optimized in order to maximize the "bit per Joule" metric. Such formulations consider a single cell scenario and the effect of neighbouring interference and users mapping are not considered. In [62] a two step algorithm aiming at minimizing energy consumption by opportunely assigning subcarrier and power to users is proposed. Such solution considers a very simple bandwidth division among served users and does not take advantage by the BEM in order to reduce the unfairness in perceived datarate.

In this study a more realistic strategy is taken into account: a given service rate is guaranteed to mobile terminals; if sufficient bandwidth resources are available, mobile users can obtain higher rates than the target value since their received power must be greater than the terminal sensitivity threshold. Moreover, the bandwidth blocks are not uniformly assigned but according to the spectral efficiency of the overall user associations, saving more resources for the users experiencing lower signal quality and including the benefits provided by BEM. Since spectral efficiency depends on the interference as well as on the user associations, the solution of the optimization problem is not trivial. Hence, it is introduced an optimization framework which is based on mixed integer quadratic programming (MIQP): within this framework the user associations are solved, together with the decision variables on the base stations activity; moreover, also the user bandwidth, the rate assignments and the transmit power of each active base station are determined. This approach resorts to a snapshot model where the problem is solved for a given time while all users are transmitting together. Moreover, the cell switch off is possible only if another layer guarantees the coverage of the area. This work focuses on the capacity layer, assuming as verified the hypothesis of a coverage layer. This assumption is justified by the 5G vision that separates control and data layer in cellular networks for green issues [63]. In order to evaluate the performance of the optimization framework, we have used two benchmarking solutions: as an upper bound, a conventional power control algorithm is used whereas, as a lower bound, MIQP model is solved to find minimum power consumption, guaranteeing the requested user rates only if interference between neighbour cells could be neglected. Therefore, in that case, each cell is considered as an independent system.

4.2 MIQP optimization

MIQP is the problem of optimizing a quadratic function over points in a polyhedral set that have some components integer, and others continuous. More formally, a MIQP problem is an optimization problem of the form:

$$\begin{aligned} \textbf{minimize} \quad & x^T\mathbf{H}x + c^Tx \\ \textbf{s.t}: \quad & \mathbf{A}x \leq b \\ & x \in \mathbb{Z}^p \times \mathbb{R}^{n-p} \end{aligned} \tag{4.1}$$

where $\mathbf{H} \in \mathbb{Q}^{n\times n}$ and it is symmetric, $c \in \mathbb{Q}^n$, $\mathbf{A} \in \mathbb{Q}^{n\times m}$ and $b \in \mathbb{Q}^m$. The problem is solved once a solution to $\mathcal{F}(\mathbf{H}, c, d, \mathbf{A}, b)$ have been found. $\mathcal{F}(\mathbf{H}, c, d, \mathbf{A}, b)$ is a set of x satisfying

$$\begin{aligned} & x^T\mathbf{H}x + c^Tx \leq 0 \\ & x \in \mathcal{C} := \{x : \mathbf{A}x \leq b\} \\ & x \in \mathbb{Z}^p \times \mathbb{R}^{n-p} \end{aligned} \tag{4.2}$$

MIQP is a NP problem and can be solved through several solvers. In this work IBM ILOG CPLEX®has been used. The solution is found by applying the Branch and Bound technique. Branch and Bound is an algorithm design paradigm for discrete and combinatorial optimization problems. It consists of a systematic enumeration of candidate solutions by means of state space search: the set of candidate solutions is thought of as forming a rooted tree with the full set at the root. The algorithm explores branches of this tree, which represent subsets of the solution set. Before enumerating the candidate solutions of a branch, the branch is checked against upper and lower estimated bounds on the optimal solution, and is discarded if it cannot produce a better solution than the best one found so far by the algorithm.

4.3 System model and problem formulation

A typical LTE system deployment is considered with a given bandwidth and a set of resource blocks. This study focuses on the capacity layer, assuming that the coverage condition is guaranteed by another layer of the cellular deployment. In the considered deployment a set of omnidirectional BSs provides the radio access to a certain number of UEs. Each base station must allocate the available bandwidth resources among the associated transmitting users by assigning the proper amount of physical resource blocks (PRBs) and guaranteeing their satisfaction in terms of bitrate. UEs request a constant bitrate and will be served at the same time.

Let $\mathcal{B} = \{BS_1, ..., BS_N\}$ and $\mathcal{U} = \{UE_1, ..., UE_M\}$ be respectively the set of N deployed base stations and the set of M users which have to be served. The binary variable x models the association between BSs and UEs, such that:

$$x_{ij} = \begin{cases} 1 & \text{if UE } j \text{ is served by BS } i \\ 0 & \text{otherwise} \end{cases} \qquad i \in \mathcal{B},\, j \in \mathcal{U} \tag{4.3}$$

Assuming π_{ij} the power assigned for transmission between BS i and UE j and w_{ij} the bandwidth assigned by BS i to UE j, the datarate achieved by UE j is:

$$\rho_j = \sum_{i \in \mathcal{B}} x_{ij} w_{ij} \log_2(1 + \gamma_{ij}) \tag{4.4}$$

where γ_{ij} is the SINR between BS i and UE j.

Transmission power of each BS i is

$$P_i = \sum_{i \in \mathcal{B}} \sum_{j \in \mathcal{U}} \pi_{ij} x_{ij} \tag{4.5}$$

Therefore, the SINR γ_{ij} is

$$\gamma_{ij} = \frac{\pi_{ij} \sigma_{ij} x_{ij}}{\frac{w_{ij}}{W} \left(\sum_{k=1}^{N} P_k \sigma_{kj} \zeta_k (1 - x_{kj}) + W N_0 \right)} \tag{4.6}$$

where σ_{ij} is the channel gain between BS i and UE j, W is the total available bandwidth at BS and N_0 is the noise spectral density. Note that in Eqn. 4.6 the received interference is weighted by the effective fraction of bandwidth assigned to UE. Such choice is justified by the need to consider the beneficial effect of allocating different portion of bandwidth to each UE. The activity status of each BS is modelled by the binary variable ζ, such that:

$$\zeta_i = \begin{cases} 1 & \text{if BS } i \text{ is active} \\ 0 & \text{if BS } i \text{ is not active or sleeping} \end{cases} \quad i \in \mathcal{B} \tag{4.7}$$

The power consumption of each BS is modelled following [64]:

$$P_{in} = \begin{cases} aP_{TX} + P_0 & \text{if BS is active} \\ P_{sleep} & \text{if BS is not active or sleeping} \end{cases} \tag{4.8}$$

Given such a system and the data reported in Table 4.1, the problem is to minimize the global power consumption. The global power consumption is derived by Eq. 4.8 and it is calculated as

$$p_c = \sum_{i=1}^{N} [(a \sum_{j=1}^{M} \pi_{ij} x_{ij} + P_0)\zeta_i + (1 - \zeta_i) P_{sleep}] \tag{4.9}$$

So, the optimization problem is formulated as follows.

$$\textbf{minimize } p_c \tag{4.10a}$$

$$\textbf{subject to}:$$

$$\sum_{j=1}^{M} x_{ij} \leq N_p \quad \forall i \in \mathcal{B} \tag{4.10b}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{M} x_{ij} = N \tag{4.10c}$$

$$\sum_{i=1}^{N} x_{ij} = 1 \quad \forall i \in \mathcal{U} \tag{4.10d}$$

$$c_{ij} \leq \frac{\pi_{ij} \cdot \sigma_{ij}}{P_{MINj}} \quad \forall i \in \mathcal{B} \quad \forall j \in \mathcal{U} \tag{4.10e}$$

$$c_{ij} - x_{ij} \geq 0 \quad \forall i \in \mathcal{B} \quad \forall j \in \mathcal{U} \tag{4.10f}$$

$$\zeta_i \leq x_{ij} \quad \forall j \in \mathcal{U} \quad \forall i \in \mathcal{B} \tag{4.10g}$$

$$\sum_{j=1}^{M} \pi_{ij} \leq P_{MAX} \quad \forall i \in \mathcal{B} \tag{4.10h}$$

Constraint (4.10b) is for the BS capacity limitation, while constraints (4.10c) and (4.10d) ensure that each UE must be covered by at least one BS

Table 4.1: Given data for the considered problem

Parameter	**Value**
N	number of deployed base stations
M	number of users
$\mathcal{B} = \{BS_1, ..., BS_N\}$	set of N deployed base stations
$\mathcal{U} = \{UE_1, ..., UE_M\}$	set of M users which have to be served
R_t	datarate target for each UE
P_{MINj}	sensitivity of UE j
P_{MAX}	maximum allowed BS transmission power
N_p	number of available PRBs at BS
W_p	bandwidth of a single PRB
W	total available bandwidth at BS
σ_{ij}	channel gain between BS i and UE j

and can be connected to only one BS at a time. Constraint (4.10e) is the key for assuring the QoS. The binary variable c_{ij} equals to 0 if $\pi_{ij}\sigma_{ij} \leq P_{MINj}$. For a given UE, c_{ij} will define the set of potential BSs that can provide the minimum received power, P_{MINj} . Then, by the help of constraint (4.10f), only one of the BSs in this set is selected. Finally, the activity status of a base station is linked to the user associations by constraint (4.10g).

4.4 Network adaptation solutions

4.4.1 Power control

As already stated, power control is a well known solution to decrease the global energy consumption by acting on the reduction of intercell interference. In this work a modified version of the power control algorithm presented in [65,66] is considered in order to extend its solution to a multichannel scenario with minimum and maximum power constraints [2]. As shown in Algorithm 1, this power control algorithm takes as input a UE-BS association and a bandwidth assignment for each UE and it provides iteratively the optimum BS transmission power able to guarantee the target datarate for each UE. The core of the optimum power control algorithm is to calculate at each

[2] For the proof of convergence in iterative power control algorithm, please see [66], pp. 163-171.

Algorithm 1 Power Control

Given: x_{ij}, w_{ij}, P_{MINj} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$; P_{MAX}; R_t;
Return: P_i $\forall i \in \mathcal{B}$; P_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$;

```
for all i ∈ B do P_i^(0) ← P_MAX
repeat
    for all i ∈ B do
        Calculate π_ij as in Eqns. 4.11 and 4.12 ∀j ∈ U
        P_i ← Σ_{j∈U} π_ij x_ij ∀j ∈ U
    end for
until convergence
Update π_ij as in Eqn.4.12 ∀i ∈ B ∀j ∈ U
Update P_i to the maximum allowed value ∀i ∈ B
```

iteration n the power transmitted by a BS to a certain UE as

$$\pi_{ij}^{(n)} = \frac{w_{ij} 2^{\frac{R_t}{w_{ij}}}}{W \sigma_{ij}} \left(\sum_{k \in \mathcal{B}} P_k^{(n-1)} (1 - x_{kj}) \sigma_{kj} + W N_0 \right) \tag{4.11}$$

where R_t is the target datarate, i.e. the QoS constraint for each UE. The initial condition is such that $\sum_j \pi_{ij}^{(0)} = P_{MAX}$ for all $i \in \mathcal{B}$. Note that the power assigned to a BS P_i cannot be greater than the maximum allowed power P_{MAX}: in that case the power P_{MAX} is divided equally among each UE to indicate the UEs under outage. Moreover the received power for each UE j cannot be smaller than the sensitivity P_{MINj}: in that case the power which is transmitted by a BS to a certain UE is adjusted by the following equation:

$$\pi_{ij} = max \left(\frac{P_{MINj}}{\sigma_{ij}};\ \pi_{ij} \right) \tag{4.12}$$

4.4.2 Bandwidth adaptation

Bandwidth assignment to each served UE is a task that can be solved in different ways by radio network operators (RNOs) depending on their policies. The most simple way to do it is to equally split the cell available bandwidth among all the connected UEs, as in Algorithm 2: by this strategy the UE performance depends only on the signal quality. Moreover, a RNO could give more priority to the UE experimenting the best channel conditions in

Algorithm 2 Equal BW allocation

Given: x_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$

Return: w_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$;

1: $w_{ij} = W_{PRB} \left\lfloor \frac{N_{PRB}}{\sum_{j \in \mathcal{U}} x_{ij}} \right\rfloor$ $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$

order to release the assigned resources in a small time, i.e. proportional fair scheduling. On the other hand, if the RNO would like to serve more UEs as possible at the same time, it could prefer to divide equally the available bandwidth among each UE: in that case UEs could get a very different datarate depending on their channel quality. When a energy saving strategy is applied and the network capacity is reduced with respect to the peak hour dimensioning, a RNO could be aware that each served UE reaches the target QoS. Therefore the fairness between UEs is a key issues. Fairness can be introduced by assigning bandwidth inversely than the proportional fair way, giving more resources to UEs experimenting the worst channel. Such strategy enables the bandwidth expansion mode in order to reduce the BS transmission power and introduce an energy gain. Algorithm 3 and Alg 4 show a possible solution to assign bandwidth in order to have fairness in QoS of served UEs. In particular, Algorithm 3 assigns just the needed amount of bandwidth allowing each UE to reach the target QoS. On the other hand, Algorithm 4 equally splits the residual PRBs in order to increase the UE performance. Note that both algorithms converge to the same behaviour for high number of connected UEs or weak channel quality.

4.4.3 Optimum network management with QoS guarantee

In order to introduce a higher energy saving gain in cellular network, a new optimization strategy is proposed. Such strategy plays with different parameters: association between BS and UE, bandwidth and power allocation. In particular, an opportune BS-UE association allows to save energy by increasing the number of BSs that are not serving traffic and that can be deactivated or put in sleep mode. By bandwidth and power allocation a further gain is introduced by reducing transmission power and decreasing the intercell interference. BSs deactivation and power reduction are allowed only if no outages are introduced, i.e. the target QoS is satisfied for each served UE.

Algorithm 3 Proportional BW allocation (no residuals)

Given: σ_{ij}, P_i, π_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$ **Return**: w_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$;

Set $n_{PRB} = 0$ $\forall j \in \mathcal{U}$
for all $i \in \mathcal{B}$ **do**
  repeat
    for all $j \in \mathcal{U}$ **do**
      Calculate ρ_j as in Eqn. 4.4
      if $x_{ij} = 1$ AND $\rho_j < R_t$ **then**
        increment n_{PRB}
        $w_{ij} = n_{PRB} W_{PRB}$
      end if
    end for
  until all PRBs are assigned or R_t is reached by all served UEs
end for

Algorithm 4 Proportional BW allocation (with residuals)

Given: σ_{ij}, P_i, π_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$ **Return**: w_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$;

Set $n_{PRB} = 0$ $\forall j \in \mathcal{U}$
for all $i \in \mathcal{B}$ **do**
  repeat
    for all $j \in \mathcal{U}$ **do**
      Calculate ρ_j as in Eqn. 4.4
      if $x_{ij} = 1$ AND $\rho_j < R_t$ **then**
        increment n_{PRB}
        $w_{ij} = n_{PRB} W_{PRB}$
      end if
    end for
  until all PRBs are assigned or R_t is reached by all served UEs
end for
if any residual PRB and all UEs are satisfied **then**
  share equally residual PRBs
end if

The optimization framework is composed of (i) MIQP solver to optimize the

UE to BS mapping and the active BSs set, (ii) bandwidth allocation scheme and (iii) power control algorithm which is used to control the feasibility of the UE to BS mapping found in (i) and identify the outages. The MIQP optimization is referred to the problem formulated in Eqns. (4.10a)-(4.10h). The output of this step is the mapping x_{ij} between BSs and UEs, the power transmitted by each BS to each connected UE π_{ij} and the set of active BS ζ_i. Then in the second step the bandwidth is allocated to each UE by the respective serving BSs. The bandwidth allocation is performed following Algorithm 2, Algorithm 3 or Algorithm 4. The MIQP model is solved by IBM ILOG CPLEX®solver. Since the model cannot manage directly the QoS for each UE because of its non-linearity, two approaches are proposed in order to do not introduce any outage. Such approaches are (i) Power consumption minimization assuming a interference controlled scenario (MinPower); (ii) Iterative power consumption minimization to guarantee QoS (MinPower-QoS). The MinPower scenario can be obtained by a good planning or a perfect intercell interference cancellation (ICIC) solution, but it could be also the reference condition for rural areas. In that case the rate of each user is only dependent on the signal to noise ratio (SNR), so the only variable is the power transmitted by the serving BS. If interference cannot be neglected, MinPower algorithm, as shown in Algorithm 5 is not able to detect the quality of service decrease and some outages could rise. For that reason, this algorithm represents an optimum lower bound for the network optimization in terms of global power consumption. In order to avoid the datarate outages the *MinPower-QoS*is introduced.*MinPower-QoS*is presented in Algorithm 6 and combines the optimum power control and the MinPower approaches in an iterative framework. In particular MinPower is executed in order to obtain the optimum set of active BSs, the optimum mapping and the bandwidth assignment and minimize the power consumption, while the feasibility of this solution is controlled by the Power Control as shown in Algorithm 6. If some datarate outages occur, the received power of the users which do not satisfy the target QoS is iteratively increased by a δ value in order to select better mapping and active BSs set.

4.4.4 Results

In order to evaluate the power consumption savings due to the base station sleep mode introduction and the transmission power adaptation, the proposed solution, namely the *MinPower-QoS* is compared to upper bound

Algorithm 5 MinPower

Given: σ_{ij}, P_{MINj} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$; P_{MAX};
Return: x_{ij}, w_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$; ζ_i, P_i $\forall i \in \mathcal{B}$; P_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$

```
Solve MIQP
Solve bandwidth allocation (refers to Algorithm 2, Algorithm 3 or Algorithm 4)
```

Algorithm 6 MinPower-QoS

Given: σ_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$; P_{MAX}; P_{MINj};
Return: x_{ij}, w_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$; ζ_i, P_i $\forall i \in \mathcal{B}$; π_{ij} $\forall i \in \mathcal{B}$, $\forall j \in \mathcal{U}$

```
repeat
    Execute MinPower algorithm (Algorithm 5)
    Execute Optimum power control algorithm (Algorithm 1)
    Datarate (ρ_j) calculation as in Eqn. 4.4 ∀j ∈ U
    for all j ∈ U\satisfied UEs do
        P_MINj ← P_MINj + δ
    end for
until no outages
```

and lower bound solutions. As an upper bound, *Closest BS Map* follows the Algorithm 1 based on power control with closest BS mapping and equal bandwidth assignment to each UE. BSs which are not serving any UE are put on sleep mode. As a lower bound, the optimum solution MinPower is used. Moreover, referring to MinPower-QoS, different bandwidth allocation strategies have been considered in order to show the bandwidth effect on the power optimization. Therefore *MinPower-QoS eq bw* follows the bandwidth allocation solution described in Algorithm 2, i.e. bandwidth equally divided among UEs; *MinPower-QoS no res* follows Algorithm 3, i.e. UEs experimenting worst channel keep more bandwidth, but residual PRBs are not assigned; *MinPower-QoS res* follows Algorithm 4, i.e. residual PRBs are equally split among UEs. Simulations parameters are reported in Table 4.2 [53]. In each iteration of MinPower-QoS, the received power of UEs that are not reaching the datarate target is adapted assuming an increase $\delta = 1$ dB. The number of active UEs that are randomly placed in the considered playground has been set variable from 5 to 230 UEs. The maximum value has been chosen referring to the maximum number of UEs that can be managed by the *Closest BS Map* solution without any capacity outage.

The results that have been obtained by statistical analysis considering 50 simulation runs and a 95% confidence interval are presented: in particular Figure 4.1(a) shows the comparison of the number of active BSs for *MinPower-QoS* with respect to the other solutions, i.e., *Closest BS Map* and MinPower. From the figure the behaviour of proposed solution is evident: if it is feasible, for each number of active UEs the minimum power configuration is selected; note that the number of active BSs is almost linearly dependent on the number of UEs. Because of the QoS requirements, the slope of *MinPower-QoS* is higher than MinPower. Finally, the *MinPower-QoS* converges to*Closest BS Map*when the number of active users increases. This result is enforced by Figure 4.1(b) where total power consumption is depicted versus the number of users. It is interesting to see that in the interference limited scenario under high load, all BSs are activated but *MinPower-QoS* can still have power savings over the *Closest BS Map* algorithm due to its flexibility in user association and bandwidth distribution. Moreover, the performance of *MinPower-QoS* is close to the global optimum which is obtained by the MinPower when the number of users is very low. More in detail, the bandwidth impact in *MinPower-QoS* optimization can be highlighted. The solutions assigning the bandwidth prioritizing UEs with lower signal quality, i.e. *MinPower-QoS no res* and *MinPower-QoS res*, perform better from the power consumption perspective. Such a behaviour can be explained by a more flexible management of the radio resources that allows a lower number of active BSs and a lower transmission power. The assignment of residual PRBs does not provide a significant improvement on power consumption. As shown in Figure 4.1(c), *MinPower-QoS res* needs a bit lower number of iterations to reach the target QoS, but such a behaviour changes for high load because UEs with more bandwidth keep more interference, as shown in Equation 4.6. In Figure 4.1(c) the UE satisfaction rate is depicted starting from optimum MinPower solution as first iteration. From this figure, it is possible to note the impact of the number of active UEs on the number of required iterations to reach 0 outages. Finally, it is possible to see that, while MinPower experiences outages, *MinPower-QoS* converges to 0 outage performance after a certain number of iterations depending on the number of UEs. Moreover, the average transmission power vs the number of iter-

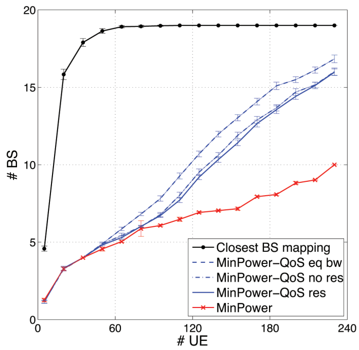
Table 4.2: Simulation parameters

Parameter	**Value**
Deployment	19 BS, hexagonal grid, wrap-around
Intersite distance	500 m
Path loss	$L = 15.3 + 37.6 \log(d)$ (3GPP Typical Urban)
Shadow fading	std dev 8 dB
Indoor loss	20 dB
Bandwidth	5 MHz (25 PRBs)
Carrier frequency	2GHz
Max BS P_{TX}	20 W
UE sensitivity	-90 dBm
Noise PSD	-174 dBm/Hz
Target user datarate	512 Kbps
Power consumption	$a = 4.7$ $P_0 = 130$ W $P_{sleep} = 13$ W

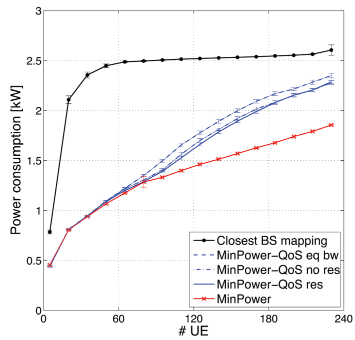
ations is depicted in Figure 4.1(c). All active UEs are satisfied when the mapping and transmission power values allow to minimize the interference: particularly, even if the proper mapping is obtained by increasing the BS transmission powers, this trend can also be harmful for some UEs because of the interference level. Therefore, the BSs can also be switched on so reducing the total power consumption due to interference.

4.5 Conclusion

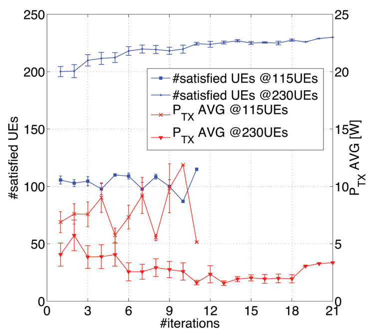
In this chapter, a novel optimization framework is developed which is aimed at minimizing the power consumption with guaranteed QoS. The results for interference limited scenarios and different traffic loads are shown. By putting the cells in sleep mode of operation, up to the 60% power savings can be achieved with respect to the basic scheme especially in low to moderate load scenarios. Moreover, the proposed *MinPower-QoS* methodologies afford performance which are very close to the optimum solution, particularly for low traffic load scenarios.



(a) Active BSs vs number of UEs



(b) Global power consumption vs number of UEs



(c) Satisfied UEs and average transmission power per active BS vs number of iterations in MinPower-QoS

Figure 4.1: Simulation results for the optimization framework.

Chapter 5

Energy efficient design for TeTRA cellular systems

This chapter aims at analyzing the power consumption of TeTRA system by introducing a power consumption model of TeTRA base station. Moreover, some dynamic RRM strategies are presented which can be immediately applied to TeTRA without affecting at all its main features and figures of merits. Finally, the future transition to TeTRA over LTE is evaluated from the energy efficiency point of view [1].

5.1 Introduction

Institutional contexts need radio systems able to provide secure and resilient private radio communications. Such requirements pushed to develop and deploy professional mobile radio (PMR): generally speaking these systems are mainly adopted to provide military and public safety forces a common communication platform, therefore the relative market is mainly reserved to national and regional governments; nonetheless, also some private companies, civil protection and rescue organizations may resort to such systems. Even if the priorities and missions of all these entities are quite different from the ones of the commercial operators and providers, however, in the current scenario of economic crisis and budget cuts the goal of the reduction

[1]Part of this chapter has been presented in [67]

of the energy costs is a general objective of capital importance: as a result, the evaluation of the energy consumption and efficiency and the definition of energy saving strategies becomes a crucial issue also for the PMR systems.

This chapter deals with the energy efficiency of TeTRA cellular system, which is the most common PMR system.

TeTRA [68,69] is a multiple access digital system for secure private radio communications. It allows the transmission of high quality voice and data and it has been proposed mainly for emergency services, public safety and in general for all scenarios where a bounded secure area for communications is needed. It introduces some functionalities that cannot be obtained by commercial cellular systems: these features are motivated by the specific purposes of the secure private radio systems with respect to those pursued by wide spread cellular technologies. In particular, TeTRA offers:

- group calls;
- reduced call setup time (below 300 ms);
- direct mode of operation using other mobile devices as repeater;
- secure data transmission by end-to-end encryption;
- push-to-talk mode.

As depicted in Figure 5.1, the TeTRA architecture shows similarities with the generic cellular network ones and presented the following standard interfaces:

- *Air Interface (AIR I/F)* which ensures the interoperability of terminal equipment of different manufacturers;
- *Terminal Equipment Interface (TEI)* facilitating the indipendent development of mobile data applications;
- *Inter Systems Interface (ISI)* which allows the interconnection between TeTRA networks of different manufacturers;
- *Direct Mode Operation (DMO)* guaranteeing the communication between terminals also beyond network coverage.

Four channels are multiplexed in a time division multiple access (TDMA) 25 kHz bandwidth carrier. In addition the use of $\pi/4$-PSK modulation makes

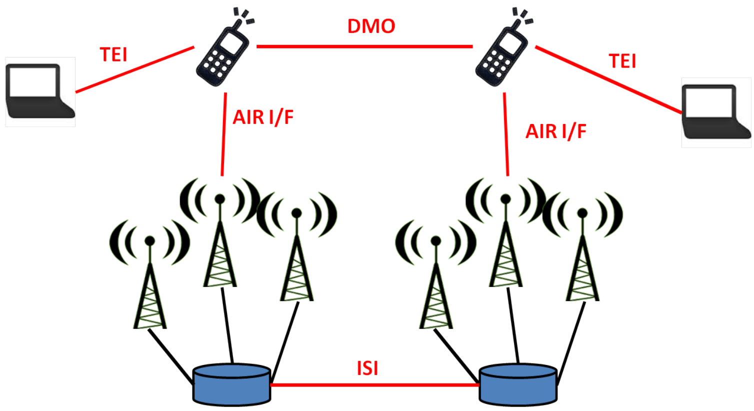


Figure 5.1: TeTRA architecture

the system extremely spectral efficient. Data and control information are mapped into some logical channels which in turn are mapped into physical channels; each physical channel occupies one time slot, i.e. one radio burst, of the downlink radio frame which is described in Figure 5.2. At each base station the first slot of each TDMA frame of one carrier is occupied by the BCCH. The remaining time slots of such carriers and, eventually, all the time slots of other available carriers can be assigned to a TCH. When a channel is idle because it is not assigned to any TCH, a dummy burst is transmitted in order to maintain a continuous bit flow.

The TeTRA first release is able to provide a 28 kbps datarate which allows the voice service, but guarantees only low quality multimedia transmission. Therefore, a second release of standard has been introduced: the TeTRA enhanced data service (TEDS). TEDS uses different channel bandwidths and data-rates for a flexible use of TeTRA bands. In particular, by supporting four different channel bandwidths from 25 kHz to 150 kHz and different modulation schemes ($\pi/4$-DQPSK, $\pi/8$-D8PSK, 4-QAM, 16-QAM and 64-QAM), it enables high speed data transmission of about 500 kbps. Moreover, most TeTRA manufacturers are now looking to the future by implementing a TeTRA over LTE system (TeTRAoLTE) [70]. As described in the previous chapters, LTE will be the widely deployed global mobile broadband standard; it is characterized by an all-IP system architecture that is supported by a flexible radio interface, guaranteing high data rates and low

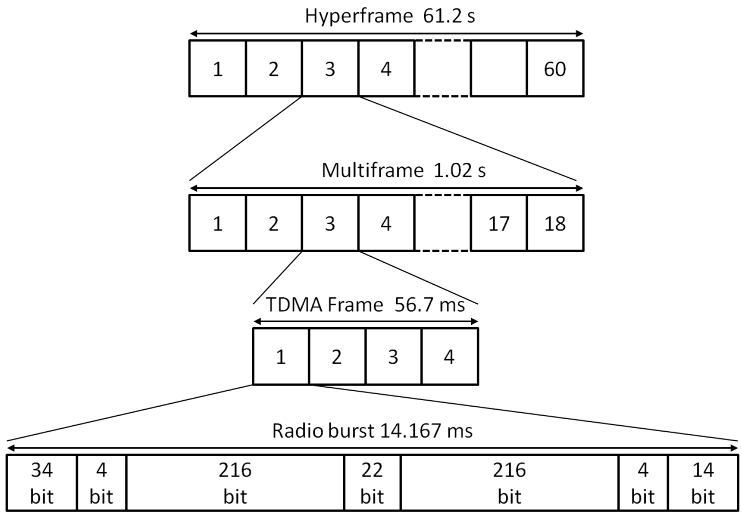


Figure 5.2: TeTRA radio frame

latency. In addition the LTE system provides some features that meet the PMR requirements, like the possibility to deploy heterogeneous networks, the intercell coordination, the interworking with other radio access technology and the unicast and broadcast service support. On the other hand it is important to stress that some challenges are still to be solved before the implementation of a complete TeTRAoLTE system. In particular resilient and highly available infrastructure, reliable and secure communications, direct communications and group communications are not currently provided by the LTE standard. Nonetheless, since the high data rate allowed by LTE is extremely promising for future systems, such challenges are likely to be dealt with by manufacturers and researchers in the next years.

The main contribution of this activity is to analyze the power consumption of TeTRA by introducing a power consumption model of TeTRA base station. Moreover, we present some dynamic RRM strategies that could be immediately applied to TeTRA without affecting at all its main features and figures of merits. Finally, the future transition to TeTRA over LTE is evaluated from the energy efficiency point of view.

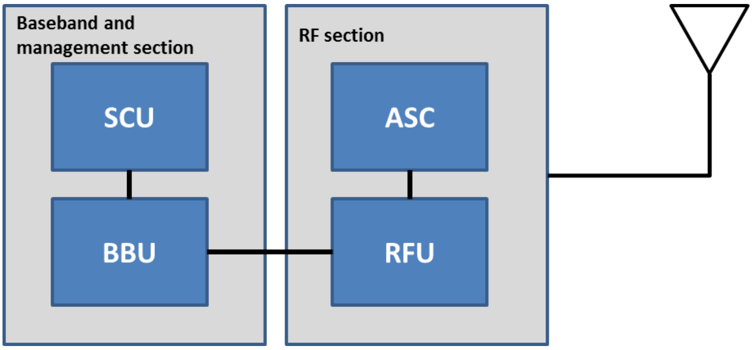


Figure 5.3: TeTRA BS Structure

5.2 TeTRA power consumption model

A TeTRA base station is composed of the different blocks which are depicted in the diagram of Figure 5.3: the site control unit (SCU) and the BBU compose the baseband and management sections while the radio frequency unit (RFU) and the antenna switching circuit (ASC) are dedicated to the radio frequency section: the SCU and BBU are responsible for the management operations of the considered site and for the baseband signal processing operations. The number of SCU and BBU is variable and depends on the desired redundancy level. The RFU controls the RF operations on the transmitted and received signal and the ASC encompasses the circuits which connect the RFU modules to the antenna system. The number of RFU depends on the number of carriers that are available in the site.

A power consumption model for the TeTRA base station can be obtained by properly adapting the models which have been derived for the other commercial cellular systems. In particular, we use as a starting point the linear model which is considered in [64] and also discussed in Equation 2.13. The linear model is composed of a fixed and a variable component. The fixed part models the power consumption that is absorbed independently from the traffic managed by the BTS. The variable part models the RF power consumption and assumes different values depending on the RF power at the antenna port. Such model can be written as follows:

$$P_c = n_{RFU} \cdot P_{RFU} + P_{BBU} + P_{SCU} + P_{ASC} \tag{5.1}$$

where n_{RFU} is the number of Radio Frequency Units (RFU), each one con-

Table 5.1: TeTRA power consumption paramters

$P_{RFU}@20W$	$P_{RFU}@0W$	$P_{BBU} + P_{SCU} + P_{ASC}$
384 W	144 W	130 W

suming P_{RFU} W; P_{BBU}, P_{SCU} and P_{ASC} are respectively the power consumption of BBU, SCU and ASC. In particular, also P_{RFU} contains a fixed and a variable part:

$$P_{RFU} = \alpha \cdot P_{RF}^{in} + P_{RF}^{0} \tag{5.2}$$

where P_{RF}^{in} is the RF power at the antenna port and P_{RF}^{0} is the fixed power consumption that RFU absorbs when there is no power at the antenna port. Hence, a final expression of the power consumption model can be derived as

$$P_c = \alpha \cdot P_{RF}^{in} + P_0 \tag{5.3}$$

Taking into account some manufacturers datasheets, resulting in data reported in Table 5.1, we consider $\alpha = 12$ and $P_0 = 274W$.

5.3 Energy efficiency for current TeTRA systems

5.3.1 Non-BCCH carrier sleep mode

Because of the impact of fixed power consumption, that is the power spent by the base station even for zero transmission power, the most common energy saving strategy proposed for commercial cellular system is the carrier sleep mode. As a matter of fact, in order to improve the capacity, operators could deploy more than one carrier per cell. As explained in Section 5.1, the cell signaling is transmitted just over one carrier, while the other ones only manage the traffic and the dedicated signalling. Therefore carrier sleep mode works automatically deactivating the unused carriers; the only carrier that cannot be ever deactivated is the one carrying the cell signalling in order to maintain the coverage of the area. Deactivating a carrier, or putting it on sleep mode, means putting the carrier in a low power consumption state, so that the base station controller can make it operative again when needed in a very small time.

By adopting the carrier sleep mode, the power consumption model presented in Equation 5.3 can be modified as follows:

$$P_i = \begin{cases} \alpha P_{out} + P_0 & \text{if the } i\text{−th carrier is ON} \\ P_{sleep} & \text{if the } i\text{−th carrier is sleeping} \end{cases} \quad (5.4)$$

where P_{sleep} is the power consumption of the sleep mode state. In this study $P_{sleep} = 140$ W has been assumed; α and P_0 are as in the previous section.

The performance of TeTRA carrier sleep mode is depicted in Figure 5.5, which shows the energy consumption of a TeTRA base station equipped with four carriers as a function of traffic load: the carrier sleep mode, as expected, provides significant energy savings, especially in the case of low traffic load, converging instead to the baseline consumption with peak traffic load.

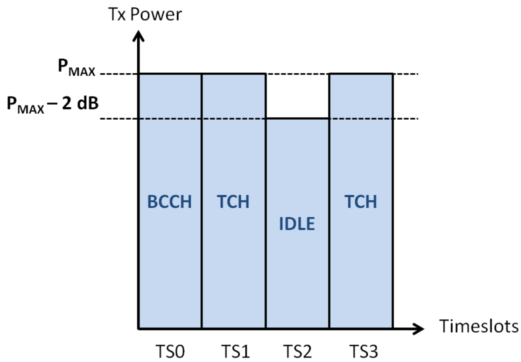
5.3.2 BCCH carrier power reduction

Power Control is a software based solution that allows an energy saving mode on the BCCH transceiver. Such a solution reduces the overall power consumption by transmitting dummy bursts on the idle channels, i.e. on the time slots that are not allocated to a TCH, with a power level lower than the maximum power of the BCCH channel. The behaviour of Power Control is shown in Figure 5.4: note that in our analysis a 2 dB power reduction has been considered. Instead, the BCCH channel is transmitted at full power in order to keep the cell range unaltered. Therefore, the power Control allows to make the power consumption variable according to the served traffic. Figure 5.5 shows the behaviour of TeTRA BS power consumption when Power Control is and is not applied. The highest saving is achievable when the traffic is very low; for higher traffic values the Power Controlled results converge to the baseline solution ones.

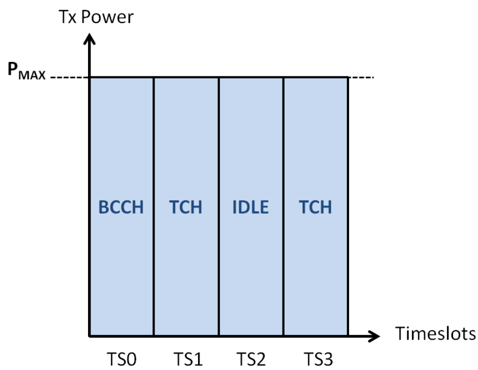
5.4 Energy efficiency of next generation PMR systems

5.4.1 The PMR evolution through the LTE system

Actually most TeTRA manufacturers are now looking to the future by implementing a TETRA over LTE system [70] in order to provide higher data rate and lower latency services.



(a) Power control



(b) No power control

Figure 5.4: Transmitted signals for power control (a) and no power control (b) cases

LTE is the state of the art standard for commercial mobile communications, providing an all-IP connectivity through an infrastructure designed for very high speed services.

Even if LTE has been developed for commercial use, some work groups in 3GPP have been working on the adaptation of such standard to mission critical communications [71]. In particular the following items are currently under investigation:

- Group communication and push-to-talk (PTT)

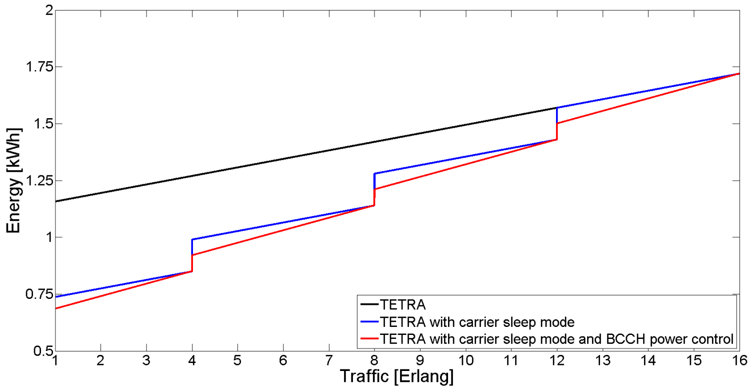


Figure 5.5: BS power consumption versus served traffic for the power control and no power control cases

- Proximity based services
- Network resilience
- High power user equipments
- Enhanced RAN sharing
- Priority and QoS control

More specifically, Group communications, PTT and proximity based services, that enable device-to-device communications (D2D), are the key requirements for public safety mission critical voice services. The work on such subjects has been carrying on within the LTE Release 12 and LTE Release 13 groups [72–74]. Under the same releases domain, also some issues about resilience and RAN sharing are being discussed. For example, in order to face a disaster causing the failure of some devices, any base station should be able to act alone in connecting the served users with the rest of the network [75]. Moreover an enhanced flexibility in sharing network resources could allow the adoption of smart radio resource management strategies between critical and non critical users [76]. As for high power user equipments and priority and QoS control, such features are already provided by the LTE technology and the work that is being carried on is related to future enhancements [77, 78].

Besides the opportunities offered by exploiting the LTE technology for PMR services, the main problem to be solved is related on how such services should be provided. Since there is no commercial interest to develop and integrate all the PMR functionalities over the LTE infrastructure, in particular the ones related to security end encryption operations, only private networks should be preferred. Private networks could be self deployed by the interested organizations for its own activities or provided by a third-party. In both cases, once the LTE system will be compliant with mission critical communications needs, the main open issue will be the actual channelization, since LTE is designed to operate with bandwidths starting from 1.4 MHz. However, the PMR evolution over the LTE system, i.e. TETRAoverLTE, represents a big opportunity for current PMR users to increase the efficiency of their own spectrum usage.

5.4.2 LTE energy efficiency gain

The actual transition from the traditional TeTRA infrastructure to the LTE platform could introduce a significant energy saving gain without considering the adoption of any particular strategy. Referring to the most power consuming stage, that is the RF stage, the main difference between TeTRA and LTE is related to the kind of used modulations. In particular TeTRA, as all systems coming out from 2G cellular technologies, employs constant envelope modulations, which improve the efficiency of power amplifiers thanks to the low peak to average power ratio (PAPR). Recently several techniques have been proposed in order to increase the PA efficiency. In particular, Envelope Tracking has been found to be the most effective one and has been included in the LTE standard. Envelope Tracking dynamically adjusts the supply voltage to the envelope of the RF input, allowing a better efficiency also for high PAPR modulations, like OFDM used in LTE system. Looking at the power consumption model, a comparison could be done considering the LTE system reference case provided by the EARTH project work group [79]. Such reference case has been obtained from the power measurements of a 10 MHz 2x2 LTE base station equipped with 2010 state of the art technology, and, referring to the linear power model in Equation 5.3, $\Delta_p = 4.7$ and $P_0 = 130W$ have been set.

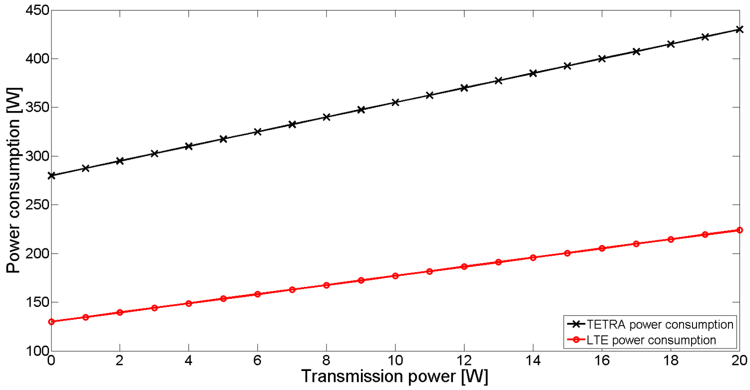


Figure 5.6: Power consumption versus transmission power for TeTRA and LTE

5.4.3 Radio resource management strategies for energy efficiency

Looking at commercial cellular networks, the adoption of efficient radio resource management solutions is one of the most effective ways to reduce the overall energy consumption. As a matter of fact, network dimensioning is peak-load oriented, therefore, since most of the day the traffic is much lower than in peak hours,a lot of energy gets wasted. The main goal of an energy efficient radio resource management scheme is to adapt the network energy consumption to the actual daily traffic load. The main way to adapt the radio resources to the effective requests is the introduction of base station sleep mode, that is the possibility to put some devices of a base station in a low power state. Referring to LTE system, several sleep mode techniques have been proposed [1]. In particular frequency domain, system domain and time domain approaches are currently the focus of the research about green wireless access networks. All the solutions are based on putting the RF power amplifiers on low consumption state. Frequency domain solutions are able to manage the available bandwidth at the base station by putting on sleep mode the relative carrier blocks. In order to maintain the same power spectral density, the reduced bandwidth requires less radiated power. Spatial domain solutions derive from the coexistence of multiple radio access technologies, allowed by the LTE standard: the global network energy efficiency can be improved by introducing cooperation schemes between the available access technologies. Other spatial domain solutions are reducing antenna number at base station and dynamically configuring cells in a multicell scenario. Even if such approaches are an attractive solution for commercial LTE cellular networks, characterized by the densification of base stations and cell layers, they are unsuitable for PMR networks like TeTRA. Therefore, in order to design an energy efficient TETRAoverLTE network, just the time domain approaches should be investigated. The most promising time domain solution is identified as cell discontinuous transmission (cell DTX), that is a new hardware feature, based on the deactivation of some components of a base station when there is no traffic, i.e. during the no transmission time intervals [80]. As we observed before, if a base station with no traffic can be put into sleep mode, then the idle power consumption will be significantly reduced; besides, cell DTX acts only when no data or signalling is transmitted, thereby the cell coverage is not affected. As shown in Figure 5.7 only a small fraction of each subframe must be transmitted even if the base station is not managing any traffic flow. In particular a high cell DTX gain can be obtained using MBSFN or extended cell DTX subframes instead of the normal unicast ones [1].

Unlike long term sleep solutions, cell DTX deactivates only some parts of the base station equipment, to ensure the immediate activation of the base station upon request. This approach hence allows the energy consumption to adapt to the variation of traffic in a very short time scale. The energy per frame of an LTE BS with cell DTX can be calculated as:

$$E_{in} = N_{TRX} T_f (\Delta_p P_{out} \eta + (1-\delta)\eta P_0 + \delta P_0). \tag{5.5}$$

where P_{out} is BS transmission power, Δ_p models the portion of power consumption due to feeder losses and power amplifier, P_0 is the fixed baseline power consumption. The time domain resource usage is modeled by η as

$$\eta = \frac{\sum_{i=1}^{n} t\alpha_i}{T_f} \tag{5.6}$$

where n is the number of time slots in a LTE frame, t is the duration of each time slot, α models the activity, so $\alpha = 1$ if the time slot is used for transmission and $\alpha = 0$ otherwise, T_f is the frame duration. The factor δ is the system DTX capability. It is defined so that $0 < \delta \leq 1$ and it models the fraction of time slots that can be put on sleep mode, depending on the frame composition, i.e. if normal unicast, MBSFN or extended DTX

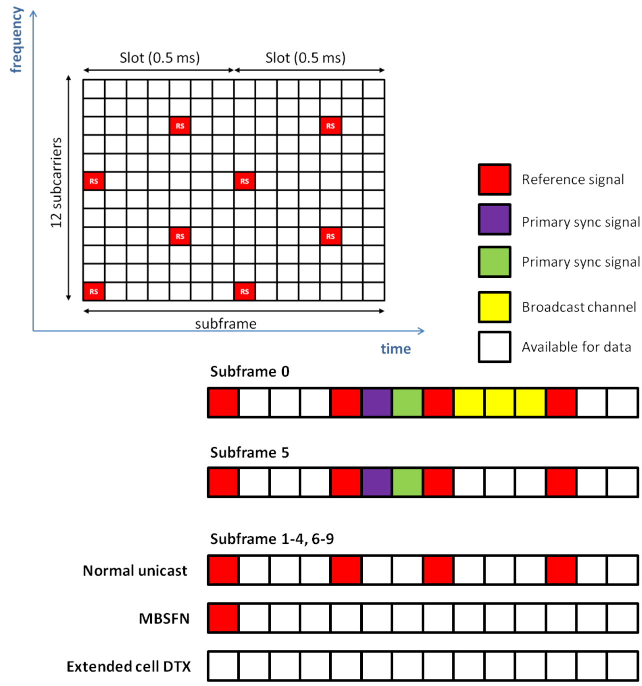


Figure 5.7: Cell DTX: PAs can be put in low power state during the available slots if there is no downlink traffic

subframe are used. Thus, $(1 - \delta)\eta P_0$ is the load dependent baseline power consumption. Note that if $\delta = 1$, i.e. there is no DTX capability, the BS energy consumption model is the same that can be obtained considering the model presented in Equation 2.13.

To compare the energy efficiency performance of the advanced TeTRA systems and the 4G commercial standard LTE, we consider a volume of traffic 100 times greater than the daily average traffic load of a current TeTRA base station. Figure 5.8 displays how the energy efficiency solutions described for TEDS and LTE systems perform, again with respect to the daily energy consumption of a single base station, considering TEDS systems with 50 kHz and 150 kHz bandwidths and assuming $\delta = 0.1$ for the case of LTE with cell DTX. We observe that the combination of carrier sleep mode and power control on BCCH carrier can bring striking energy savings for TeTRA network, although the energy efficiency performance of such systems is very

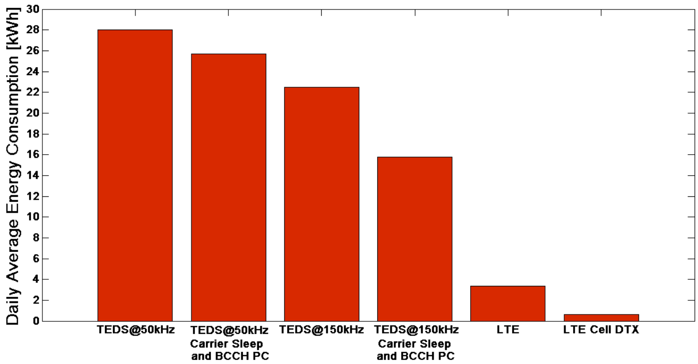


Figure 5.8: Comparison of daily average energy consumption

far from the performance of current LTE commercial standard. Despite the high hardware efficiency of LTE system, the introduction of cell DTX helps to further break down the energy consumption of the network, by significantly reducing the baseline power consumption of the base stations. Looking at the PMR broadband evolution over the LTE system, such a feature represents a very promising energy saving approach, considering the typical low traffic density of PMR systems, compared to cellular public radiotelephone standards. From an economic perspective, the results presented in Figure 5.9 show the impact of the power saving features in terms of annual operational expenditures (OPEX), considering the scenario of a regional network, with 150 base stations, and an energy cost of 0.20 Euros per kWh. Adopting advanced energy efficiency strategies in TETRA network results in significant OPEX savings up to 70 thousand Euros per year of operation, compared to the current standard technology; this positive trend is also considerable with the introduction of highly efficient cell DTX solutions in LTE networks. Regarding the sustainable development of modern communications systems, the overall network energy saving guarantees a remarkable reduction in terms of Carbon emission of CO_2, as depicted in Figure 5.10: considering an average Carbon emission of 525 kg of CO_2 per 1000 kWh, the proposed energy efficiency solutions can save more than 1 ton of CO_2 per year in advanced TeTRA networks. In the case of LTE systems, the adoption of cell DTX has an equally great impact, by granting more than 80% reduction of annual Carbon emission of CO_2, with respect to the standard LTE netwotk configuration.

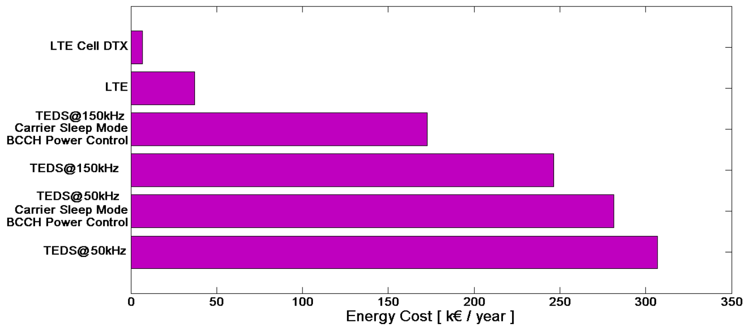


Figure 5.9: Annual energy expenditure for TeTRA and LTE network sustainability in a regional area

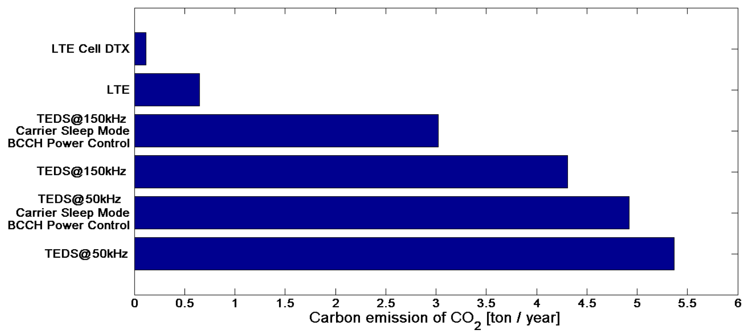


Figure 5.10: Annual Carbon emission of CO_2 for TeTRA and LTE network deployment in a regional area

5.5 Conclusion

In this chapter the energy efficiency of the TeTRA cellular system has been considered. First of all a base station power consumption model has been proposed by considering the modules constituting a generic TeTRA BS. Then, some energy saving solutions have been evaluated. In particular, the BCCH power control allows the reduction of transmitted power during the timeslots when the BS is not transmitting traffic data. The strength of such solutions is to improve the TeTRA energy efficiency without any significant modification in the architecture. Finally, a possible transition to the TeTRA over LTE system has been considered, showing that such solution would increase both the capacity and the energy efficiency because of the effectiveness of both the hardware devices and the radio resource management flexibility. Such improvements must be considered together with the positive impact in terms of OPEX and carbon footprint.

Chapter 6

Conclusion

This chapter summarizes the contribution of the thesis and discusses directions for future research.

6.1 Summary of contribution

With this thesis a step inside the energy efficiency issues of mobile wireless communications has been done. After a detailed statement of the energetic problem and a wide analysis of the literature, including power consumption models and existing approaches to reduce the energetic footprint of mobile communications, some original contributions have been described.

Such work explores the possibility to save energy in cellular networks through resources adaptation to the effective users load. Thereby, power consumption is shaped to the network traffic profile and an important energy saving gain is achieved during low load periods.

Resources adaptation is mainly obtained by putting the base station on sleep mode. The base station sleep mode is a feature of future base stations that allows to switch off the radio frequency stage, in such a way as not power the devices that have the biggest impact on the global power consumption. To a lesser extent a further solution to reduce the energetic impact of a cellular network is to adapt bandwidth and transmission power.

The first of the investigated solutions identifies traffic forecast as the driver for network adaptation. Once a daily traffic forecast is performed through the Holt-Winter's exponential smoothing algorithm, active carrier or base stations or transmission power are adjusted in order to shape the requested capacity. Results show that such solution performs very close to the theoretical optimum, that is the strategy obtained by knowing exactly the instantaneous needed resources, and in terms of number of switch on or switch off. As a matter of fact, an high number of devices activation or deactivations impacts to the network in terms of signaling and handover traffic. Moreover it has been shown that served users keep the same performance as the no saving solution.

Furthermore the work focused on how optimize the network by knowing the number of instantaneous users to be served. The optimization takes into account a set of degree of freedom: UE-BS association, BS activity, bandwidth for each served UE and active BS transmission power. The problem can be formulated as a MIQP. Three main cases have been compared: a baseline solution performing only the cell switch on/off and the transmission power adaptation, an optimum solution based on the proposed framework and a suboptimum one based on the framework, but taking into account also a QoS requirement for the users. Results show that up to the 60% power savings can be achieved with respect to the basic scheme especially in low to moderate load scenarios.

Finally the PMR systems have been addressed. In particular an energy consumption model for TeTRA system has been formulated and some feasible energy saving solution for the today's scenario have been described. Moreover the TeTRA broadband evolution has been focused and some considerations about the energy efficiency of a solution considering the LTE architecture are provided.

6.2 Directions for future work

The work carried out during this doctoral course and summarized through this thesis can be considerated a first step in the energy efficiency issues of wireless communication systems. As a matter of fact the work focuses only on mobile cellular network and considers just singularly the existing technologies. This is a needed simplification in order to formulate solution and test their behaviour though computer simulations. However communications are evolving and more and more services and solutions are rising. If a common today radio base station is explored, it is evident that three radio access technologies are available and with devices configurations, i.e. number of carriers, bandwidth and transmission power, that can be very different for nodes deployed in other regions. Therefore a more detailed analysis must be performed including such diversities and also the effects of the equipments not directly involved by the radio chain, like the impact of cooling in different climate areas.

Moreover the need of ubiquitous wireless access is massively penetrating in the life of developed societies. Fifth generation cellular systems are now in the research stage and it is expected a revolution of the cellular architecture including machine to machine, device to device and millimeter wave communications. It will be really interesting to evaluate an extension to such scenarios of the solutions investigated in this work.

Appendix A

Publications

This research activity has led to several publications in international journals and conferences. These are summarized below.

International Journals

1. S. Morosi, **P. Piunti**, E. Del Re. "Sleep mode management in cellular networks: a traffic based technique enabling energy saving", *Transactions on Emerging Telecommunications Technologies*, vol. 24, iss. 3, pp. 331-341, April 2013. (Special Issue: Quality of Experience in Wireless Multimedia Systems) [DOI:10.1002/ett.2621]
2. E. Del Re, **P. Piunti**, R. Pucci, L.S. Ronga. "Energy Efficient Techniques for Resource Allocation in Cognitive Networks", *Journal of Green Engineering*, vol. 2, iss. 4, pp. 329-346, July 2012.
3. **P. Piunti**, M. Dolfi, S. Morosi, E. Del Re. "Power Consumption Model and Energy Efficiency Perspectives of PMR Cellular Systems", submitted at *IEEE Systems Journal*.

International Conferences and Workshops

1. S. Morosi, **P. Piunti**, E. Del Re. "Traffic based energy saving strategies for green cellular networks", *18th European Wireless Conference*, April 2012.
2. S. Morosi, **P. Piunti**, E. Del Re. "Improving cellular network energy efficiency by joint management of sleep mode and transmission power", *24th Tyrrhenian International Workshop on Digital Communications - Green ICT*, September 2013.

3. S. Morosi, **P. Piunti**, E. Del Re. "A forecasting driven technique enabling power saving in LTE cellular networks", *IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, October 2013.
4. **P. Piunti**, M. Dolfi, S. Morosi, S. Jayousi, E. Del Re. "Performance Evaluation of an Energy Efficient RRM strategy in Heterogeneous Cellular Networks", *IEEE 25th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, September 2014.
5. E. Del Re, S. Morosi, **P. Piunti**, G. Mazzi, O. Gremigni. "Energy Efficient RRM Strategies for Current and Upcoming TeTRA Cellular Systems", *IEEE 10th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, October 2014.
6. **P. Piunti**, C. Cavdar, S. Morosi, K.E. Teka, E. Del Re, J. Zander. "Energy efficient adaptive cellular network configuration with QoS guarantee", sumbitted at *IEEE International Communications Conference (ICC) 2015.*

National Conferences

1. **P. Piunti**, S. Morosi, E. Del Re. "Traffic Forecast and Power Consumption Management in Cellular Networks", in *Riunione annuale GTTI*, Ancona, Italy, June 2013.

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