D2.5 Final report for the IRA 2.2 'On/off strategies for energy saving and transparent connectivity in WLAN access points, cellular femtocells and Base stations'

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Abstract:

This deliverable presents the activities within IRA 2.2 of the TREND NoE. The document describes the different activities and main results concerning the algorithms to switch on/off Base Stations, Access Points and Femtocells. The document also describes the main purpose of the implementation of such management schemes, trying to present the big picture behind self-adaptable base station operation, in terms of energy savings/efficiency. The results are then presented in terms of technical achievements and collaborations.

Keyword list:

Switch on/off base station management in cellular networks, access points switch on/off schemes, self optimized energy efficient networks, renewable energy sources and telecommunication networks, access networks.

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1. Executive Summary

IRA 2.2 of NoE TREND refers to 'On/off strategies for energy saving and transparent connectivity in WLAN access points, cellular femtocells and base stations' and is based on joint research activities between TREND partners. This report explores techniques that are used for base station (BS), access point (AP) and femtocell management under switch on/off strategies. Switch on/off strategies provide the required degrees of freedom to the network operator so as to reduce energy consumption of network nodes when necessary. Switch on/off management of network nodes is important since they can provide traffic proportional network power consumption and can enable efficient penetration of renewable energy sources (RES) as a potential power source in the network.

The first part of the report presents the main scope behind the investigation of switch on/off strategies and their importance in the Future Internet. In this section a holistic view of the applicability of switch on/off schemes in the network, focusing on future network architectures, is presented. The second part of the report presents the work that has been performed by the partners. The work is categorized in different sections each providing the description of the work, the results and the applicability of the solution in real scenarios. The sections introduce the problem of planning and management of BSs (Section 3.1), the effect of femotcell layer in BS management schemes (Section 3.2), the need for on/off strategies so as to provide island model operation of the network assuming RES, but also to provide an active role of the operator to the energy market (Section 3.3), energy savings in femtocell networks (section 3.4), the effect of on/off schemes on QoS (section 3.5), energy savings in WLAN networks (Section 3.6) and the prototype 3G femtocell that can support on/off management schemes (Section 3.7).

The third part of the deliverable introduces a review based research among most of TREND partners that will be part of the TREND white paper.

The last part presents the outcome of the research in terms of mobility actions and publications.

2. Introduction/ The Scope behind Switch on/off Infrastructure Schemes

Power Consumption of Current Networks and Network Nodes
Current cellular networks suffer from great energy waste especially during off peak hours when data traffic is low and network power consumption presents small sensitivity with regards to network traffic. One important issue that has attracted the concern of regulatory and standardization bodies such as 3GPP and IEEE is to increase the traffic proportional network power consumption characteristics.

The reason behind the great energy waste (especially during off peak hours) is that telecommunication nodes (BSs, APs, Femtocells) incorporate two types of losses. The no load losses (parameter b of equation below) and the IT losses. No load losses exist even when there is no traffic served by the IT equipment. No load losses hold a great portion of the total power consumption of the node and are usually related to network critical physical infrastructure (NCPI) such as cooling and power units, fans, etc. This causes a large amount of energy to be wasted during off-peak hours, and makes it important to switch off unnecessary nodes in the network in order to save energy and provide traffic-proportional network power consumption.

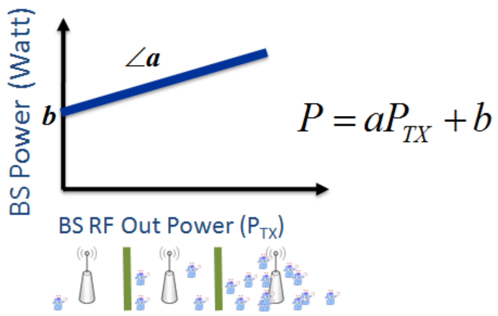

Figure 2.1. Power consumption versus RF out power of typical BSs

On the other hand, network traffic presents a high daily variation that in some occasions can yield traffic variations during the day with peak-to-average ratio greater than 3. This is also met in business districts where traffic during the day can be more than 7 times larger than traffic during the night. Unfortunately, network power consumption does not present such a high correlation with traffic, due to the existence of no load losses and low proportionality characteristics at the hardware of the network nodes.

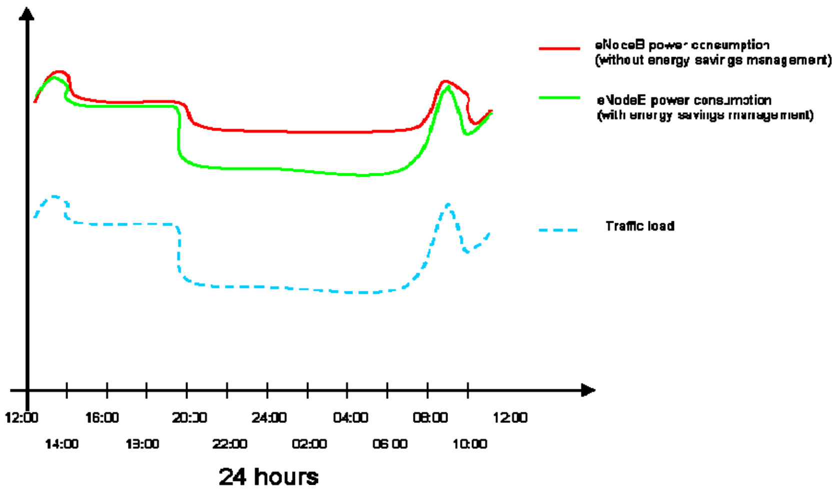

Figure 2.2. Traffic variation and eNodeB power consumption with and without energy saving modes

One approach to overcome this situation is to provide switch on/off schemes at the network nodes when necessary and thus ‘force’ a higher proportionality to traffic, as shown in Figure 2.2.

The Future Internet Characteristics

The future internet network must be a smart network that is flexible, robust and cost effective. This is included in the 5G infrastructure report, that was recently published as a joint academic and industrial guideline. A lot of research interest is placed upon energy efficient networking techniques, green Service Level Agreements (SLAs) and penetration of RES in the network, that offer free energy that can fulfill the cost-effective characteristic of the future internet. The flexibility refers to adaptation to external conditions and also the support of different types of data (low data rate for M2M communications and high data rates for UHDTV).

Focusing on the cost effectiveness part, and more precisely on the operational expenses (OPEX) of the network that are mainly related to energy consumption, it is expected to observe in the 5G network, a saving up to 90% of today per service provided. The most important already existing technologies to support such a radical reduction are base station switch on/off schemes that are already incorporated in 3GPP plans, multipath TCP, and multi RAT access, that provide resource management-offloading, task migration and allocation strategies over virtualization schemes, and green SLAs that can provide adaptable network operation.

Furthermore, the external conditions that characterize the flexible operation of 5G networks can be context-based, traffic-based or even characterized by the available energy that is supplied by the power grid network. This is discussed in the next section.

The Future Energy Issues

Together with the need for energy saving during off-peak hours, there is one more important characteristic that needs to be considered in future networks. It becomes a global trend to supply off grid BSs or even a subset of the network with renewable energy sources (RES). The main constraint of RES is that they provide a limited and time variant power capacity that should not be exceeded if anyone wants to operate the network in island mode (net zero operation with no import of energy). To achieve this target it is important for the telecommunication provider to have the ability to provide load (power) control in the network.

Furthermore, with the development of smart grid networks and the open/competitive energy market that will support real time (dynamic) electricity pricing schemes, the network should be able to support load control and demand response (DR) commands in order to reduce consumption during high electricity price hours. In that case cooperation and offloading to other networks (WiFi or femtocells) is of major importance. Adaptation to real time electricity prices is also important for the cost-effective characteristic of the future internet.

Our Contribution

Within this report we present switch on/off techniques that can collaborate with other heterogeneous networks (WiFi or femtocell) and thus enable load migration and adaptable power consumption at the administrative domain of the mobile operator when necessary (during high traffic hours too). The presented techniques cover BS, AP and femtocell networks and provide acceptable QoS with an important reduction of energy and power when necessary.

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3. On/off strategies for energy saving and transparent connectivity in WLAN access points, cellular femtocells and Base stations

3.1 Planning and Management of Cellular Networks

Summary: The algorithms and techniques used in this scientific domain explore centralized, distributed and pseudo-distributed control architectures. In addition, the effect of planning of the cellular network is investigated upon switch on/off savings and sleep mode intervals.

Results/Papers:

1. L. Chiaraviglio, D. Ciullo, G. Koutitas, M. Meo, L. Tassiulas, 'Energy-Efficient Planning and Management of Cellular Networks', IEEE Wireless on demand Network Systems and Services (WONS) 2012
2. S. Kokkinogenis and G. Koutitas, 'Dynamic and Static Base Station Management Schemes for Cellular Networks', IEEE GlobeCom, Anaheim, USA, 2012
3. G. Koutitas, A. Karousos, L. Tassiulas, 'Deployment Strategies and Energy Efficiency of Cellular Networks', IEEE Transactions on Wireless Communications, vol. 7, no.11, pp. 2252-2563, 2012
4. M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, Multiple Daily Base Station Switch-Offs in Cellular Networks, 4th International Conference on Communications and Electronics (ICCE 2012), Hue, Vietnam, August 2012

Reason for Research: To provide traffic proportional network power consumption by setting BS to sleep mode.

Contributing partner(s): PoliTO, UTH

3.1.1 Introduction

We study base stations energy-efficient management algorithms in a cellular access network taking into account different planning strategies. To provide energy savings, sleep modes are adopted at the Base Stations (BSs). We first consider three network planning strategies: the first one minimizes the number of transmitters, the second one minimizes the power consumption, while the third one is a combination between the previous two strategies. Specifically, we focus on a real urban environment in the center of London and we leverage on genetic algorithms to find deployments for each of the considered network planning strategies. For the purpose of our investigation we investigate three planning strategies:

• minimum transmitters (TX)
• minimum power consumption (MP)
• hybrid network (H)

TX strategy corresponds to the typical mobile operator's strategy for low CAPEX (CAPital EXpenditure); the objective is to minimize the number of deployed base stations and provide

Quality of Service (QoS) over a predefined area. The MP strategy corresponds to energy efficiency and low OPEX (OPerating EXpense) imposed to the administrative domain of the mobile operator; the objective is to minimize the total energy consumption and provide QoS over the examined area and it can be considered as a minimum Joule/bit strategy. The hybrid strategy is a combination of the above.

Furthermore, we introduce algorithms for BS management that are responsible to switch on/off the BSs in the network topology according to traffic conditions. In this way, traffic proportional network power consumption is achieved following recent 3GPP and IEEE standards and recommendations. Centralized and distributed management schemes are explored and a new pseudo-distributed management scheme is proposed. In that case a set of critical BSs are distinguished and used for the coverage in the area. The rest of BSs are named as flexible BSs and are assigned in the administrative domain of the critical stations according to cell overlap criteria

3.1.2 General System Model and Description

We assumed a real urban district in central London. The channel model used is based on a 2D ray tracing code that computes multipaths according to the basic propagation mechanisms of reflection, diffraction and combination of the above. The planning of BSs in the area of interest was performed using a genetic algorithm (GA) optimization technique that had as objective function the planning strategies (MP, TX and H). The planning was performed for the maximum capacity scenario. In order to compute the required number of BSs for the minimum traffic period (and thus know the required BS for the coverage umbrella) we performed upon the planning strategies a GA technique where the objective was to minimize the BSs from the set of BS defined in MP, TX, H. In that case we distinguish two sets of BS. One set that is the required BSs in the network to fulfill coverage and capacity issues and the second set that consist of BS that are required only for coverage.

To support BS management algorithm we considered

- Centralized algorithm
- Distributed algorithm
- Pseudo distributed algorithm

For the pseudo-distributed case we distinguish two types of BSs in the network. The critical BSs (CBS) that are the BS obtained for the coverage only of the network and the flexible BS that fall under the administrative domain of CBS according to cell overlap criteria (Figure 3.1.1). The decision of which BSs to switch on/off is based on a pseudo real time dynamic management algorithm where we assume that the traffic per one hour interval is almost static and thus we divide the day in 24 time periods. Each period contains a collecting data stage where the BS monitors the traffic in the cell. If the traffic is higher than a predefined threshold then the BS decides to switch on. In other case is set in sleep mode. This procedure is given in the Figure 3.1.2.

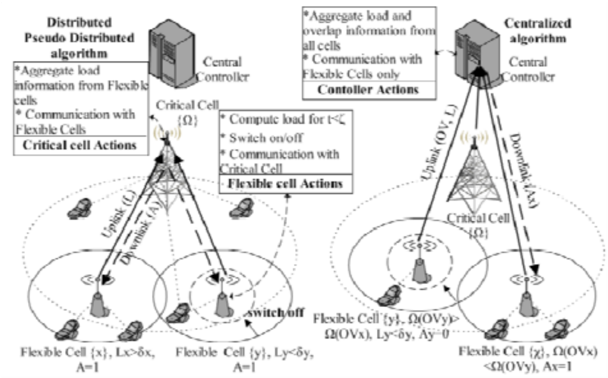

Figure 3.1.1: Control Architecture

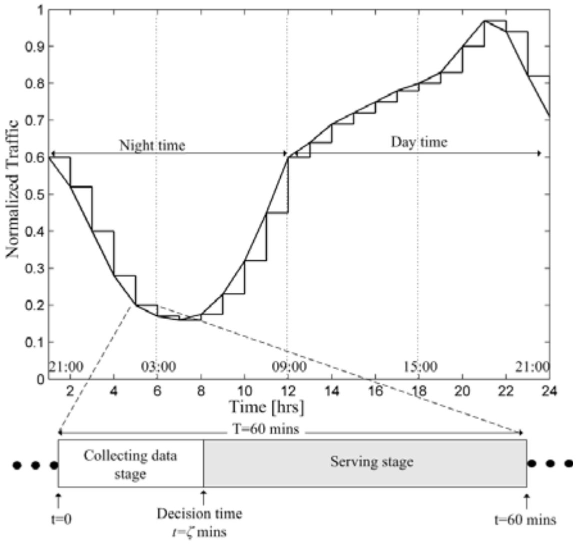

Figure 3.1.2: BS management architecture

3.1.3 Results

Given the generated deployments, we evaluate the energy savings achievable when sleep modes are implemented and users traffic varies over time. Our aim is to find the minimum set of BSs to be powered on to satisfy a given traffic demand. We apply different heuristic algorithms for deciding which BSs to be switched off, based on the cell load (LL algorithm) or the cell overlap (OV algorithm). We apply the presented strategies considering two operational states of the network, corresponding to peak traffic and off-peak traffic. The intuition is to provide to the BS management algorithm the deployment computed for the peak traffic. The algorithm then switches off some BSs according to the current traffic. However, we provide also to the management algorithm the set of BSs that has to be always powered on to guarantee a minimal QoS, computed for the off-peak traffic.

It is shown that the power consumption of the Always-On scheme (labels ’AO’) and the power consumption of the LL strategy versus the fraction of active users. When sleep modes are adopted the power consumption of the network is reduced with respect to an Always-On scheme for all the deployments. In particular, the savings achievable with sleep mode become significant when the fraction of active users is lower than the peak, namely about 0.42, 0.8 and 0.58 for deployments TX, MP and H, respectively. As expected, the highest energy saving is obtained with the hybrid deployment H, since it is designed to be a combination between the minimum transmitter and the energy-efficient deployments. Interestingly, the power consumption of the sleep mode scheme is higher than the Always-On scheme when TX is deployed and the percentage of active users is larger than 60%. This is due to the transmission power increase of the BSs that have to remain active and have to cover the users left by the BSs switched-off. These are presented in Figure 3.1.3. In Figure 3.1.4 we present energy savings with pseudodistributed management for different traffic threshold criteria.

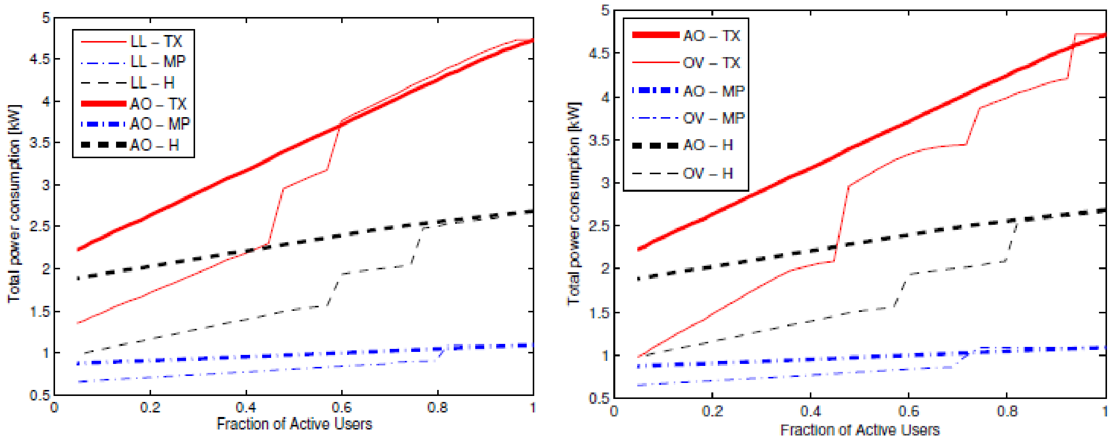

Figure 3.1.3: Power consumption of the network for LL and OV schemes

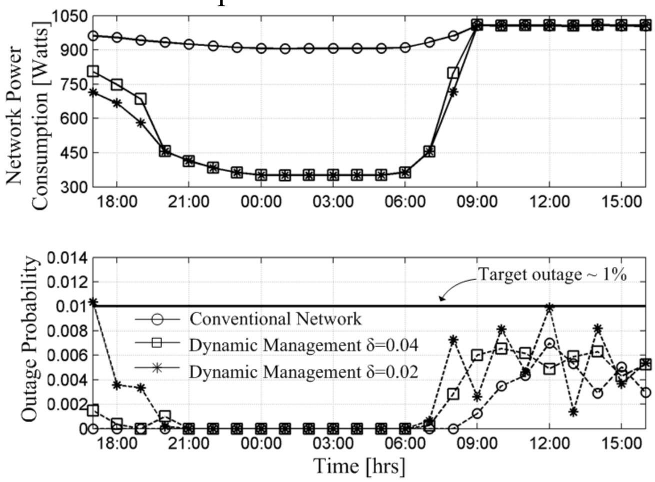

Figure 3.1.4: Power consumption and QoS for pseudo distributed management schemes.

3.1.4 Practical Applicability (pros and cons)

The advantages of implementing the proposed on/off schemes concern the reduction of energy waste of the network especially during low traffic periods. The negative issue is that QoS is reduced and this is a function of the traffic threshold where decision to switch on/off is taken. From our observations we observed that the best tradeoff between energy saving and QoS is achieved by the pseudodistributed management scheme.

3.1.5 Conclusions

We explored different planning strategies combined with BS management schemes. It was found that energy savings of the order of 20-30% can be achieved when BS switch on/off schemes are introduced in the network. From our observations we observed that the best tradeoff between energy saving and QoS is achieved by the pseudo-distributed management scheme.

3.2 Self Optimized Energy Efficient Operation of Cellular Networks with the Effect of Femtocell Layer

Summary: Following the algorithms found in 3.1 here we explore the effect of external networks (femtocell) to BS switch on/off schemes. In addition, we explore the energy savings without BS management schemes when traffic is offloaded in the femtocell layer

Results/Papers: One paper is under preparation following revisions from a first submission.

Reason for Research: To provide load control even when traffic is high. Femtocell layer is important to absorb traffic when necessary and enable BS management.

References

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Contributing partner(s): UTH-PoliTO, EPFL

3.2.1 Introduction

In this section we consider as the most practical BS management scheme the dynamic pseudo distributed scheme that was presented in Section 3.1. In addition, we explore the Hybrid network topology and we observe the effect of the opportunistic femtocell layer on the offered degrees of freedom upon the switch on/off states of the flexible stations. To capture the potential gains from the femto layer, two user-to-femto association rules are explored assuming open loop access. The user association rules are

- Femto priority: if the user can detect a femtocell then it is automatically assigned to it
- No priority: the femtos are treated as common BS in the network and the user is assigned to a node according to best server criteria.

In addition, we explore the energy saving when femtocell is offloaded in the femtocell layer without using BS management. We study the energy savings due to the deployment of femto base stations by using a simulation (based on data obtained from an operator) of a plausible LTE deployment in a mid-size metropolitan area, and by using detailed models of heterogeneous devices, traffic, and physical layers. We compare the energy consumption of two strategies that increase the capacity of LTE macro networks:

- **Macro-micro deployment** is the deployment of redundant macro and micro base stations by operators at locations where the traffic load is heavy. Specifically, we consider the deployment of 10 macro and micro base stations whose positions are determined from the operator data.

- **Femto deployment** is the deployment of publicly accessible femto base stations by home users to supplement the capacity of the macro network as proposed in [1]. We consider different number of deployed femto base stations.

We quantify energy consumptions and capacity enhancements of two deployment strategies through simulation. The metrics of interest are operator-energy-consumption/total-energy-consumption per unit of network capacity

3.2.2 General System Model and Description (UTH-PoliTO)

The same model as explained in Section 3.1 was consider. Two additional features exist in order to model the effect of the femtocell layer in the BS management scheme. The first concerns the user association rule. As explained before two user to femto association rules were considered and these are the femto priority and the no priority as shown in Figure 3.2.1.

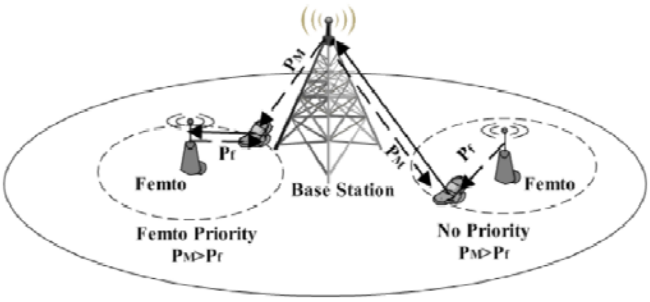

Figure 3.2.1: User to femto association rules. PM denotes received power from mobile BS and Pf denots received power from femtocell.

The other feature concerns the channel model used to model the wireless link between user-femtocell. An empirical model was considered and this is the Keenan-Motley formula.

3.2.3 General System Model and Description (EPFL)

To understand the performance of each of the two above-mentioned strategies better, based on data obtained from an operator, we simulate a plausible LTE deployment in a mid-size metropolitan area. We consider a heterogeneous network - a co-channel deployment of macro, micro and femto base stations. To the best of our knowledge, there are no representative operational data from the commercial LTE networks available; hence, some assumptions need to be made, as will be explained in this section.

In our network model, apart from femto base stations we have two classes of base stations:

-Class A (non-redundant) base stations: These are non-redundant macro and micro base stations that provide full coverage to the user. We cannot remove or switch off a class A base station without losing coverage to some users in the region.

-Class B (redundant) base stations: These redundant base stations are deployed to increase the capacity of the network. Class B base stations do not contribute to the coverage of class A base stations and are deployed by the operator at locations where traffic density is high.

Figure 3.2.2 depicts network topology we used in our simulations. In grey we see the coverage area of class A (non-redundant) base station. On the left-hand side we see, in color, coverage area of class B (redundant) base station. These positions are based on the data obtained from an operator. On the right-hand side se see coverage areas of femto base stations.

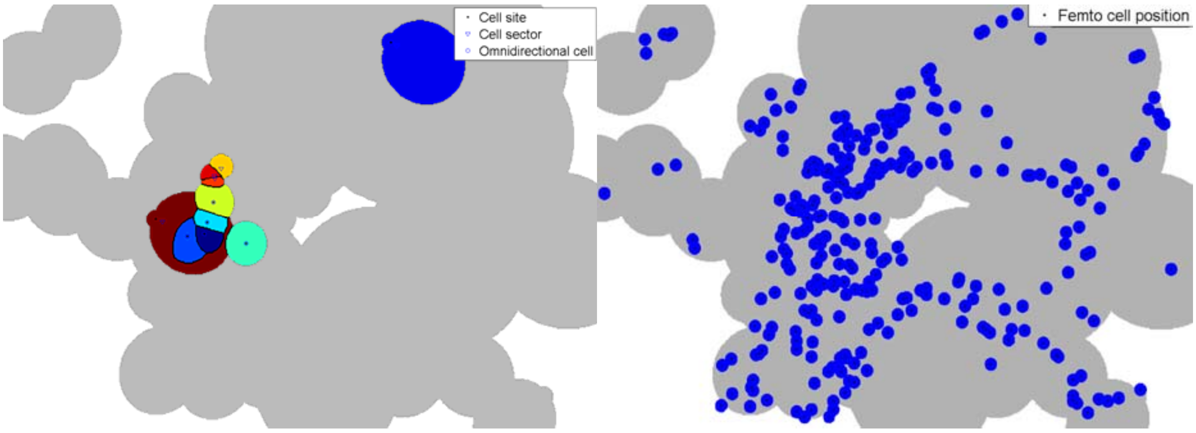

Figure 3.2.2. Coverage areas of the three types of base stations (class A, class B, femto)

We extrapolate our traffic model from an operator trace file with traffic data in the observed network segment. It contains the activity type (call or SMS), time and serving sector. Every trace-file entry represents an arrival generating one session - we replicate this session-arrival sequence exactly in the simulation.

To position a user within the serving sector in a realistic way, we split the whole region into four different areas based on the expected level of traffic (Figure 3.2.3). In the rural areas, the expected level of traffic is low, on the city outskirts it is medium, in the city center it is high, and the highest expected level of traffic is in the vicinity of buildings. We assign probabilities, proportional to the expected level of traffic, for the position of a user in each of these areas inside the observed sector of a base station.

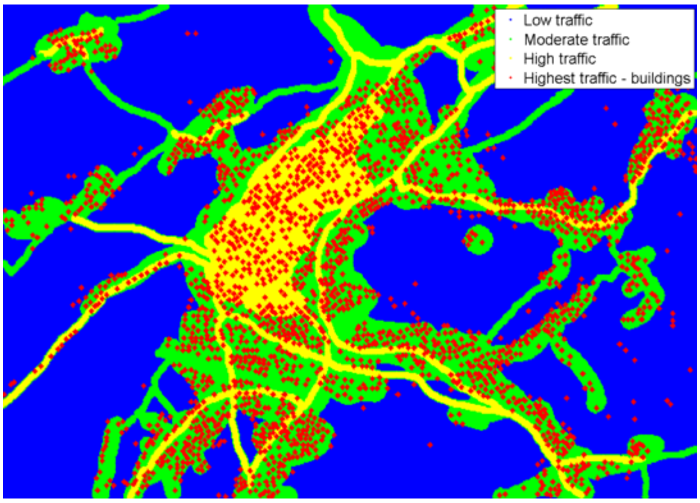

Figure 3.2.3 – Region separated into areas with different traffic intensities

Calculation of the signal level received from a base station is done based on the relevant 3GPP and other specifications and models [2], [3], [4]. The same method is also used to calculate coverage regions depicted in Figure 3.2.2.

The user association policy is defined such that a user will not experience a large service-delay as discussed in the published paper. For modeling device power-consumption, we use empirical models observed in the literature ([1], [5], [6], [7]) where we capture the dependency of power consumption on an immediate traffic load.
Several performance metrics are used to compare add-micro and add-femto methods:

- Total energy consumption, E_T,
- Operator energy consumption, E_O.
- Fraction of blocked sessions, B.
- Operator-energy-consumption/total-energy-consumption per unit of capacity, E_{CO}/E_{CT}:

3.2.4 Results (UTH-PoliTO)

The following critical observations were derived when traffic was offloaded from the mobile Macro-Micro network to the femtocell layer

1. Energy savings during the day are increased for approximately 20-30% and this is a function of the number of femtocells in the network
2. The time interval that the Flexible BSs could be in sleep modes was increased
3. The QoS was increased compared to the case where no femtocell layer was examined
4. The femtocell layer could provide load control in the network power consumption a characteristic that finds application when RES are used in the network (see Section 3.3)

The effect of the femtoccell layer upon energy savings, traffic proportional power consumption and load control is presented in Figure 3.2.2.

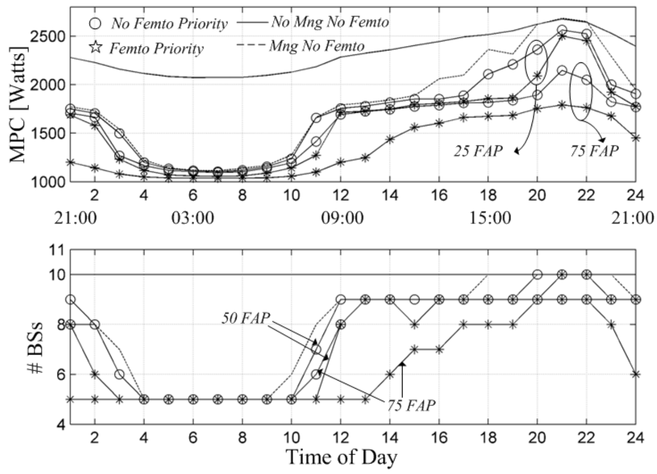

Figure 3.2.4: Daily power consumption assuming BS pseudordistributed management and femtocell effect.

3.2.5 Results (EPFL)

We observe:

- Network capacity where only class A base stations are deployed is β = 39.9 kbps.
- The capacity of the network is increased by 19% by deployment of class B base stations. A similar capacity gain can be achieved by deployment of 300 femto base stations in the network.
- There is no significant difference between operator energy consumption of femto and macro-micro deployment strategies. Even in the worst case the difference is less than 7%. This differs from the previous findings in [1], which compares these capacity adding strategies, and finds that femto deployment is considerably more energy efficient. Note that to calculate E_O, we ignore the energy consumption of femto base stations where femto deployment strategy is applied. However, the power consumption of class B base stations is included in EO when macro-micro deployment strategy is used.

Figure 3.2.5 - left compares the operator-energy-consumption per unit of capacity for macro-micro and femto deployment strategies. We observe that, for all energy models, using femto base stations is around 7% more energy efficient compared to the macro-micro deployment. We consider these savings as negligible, keeping in mind that operators would prefer to have a smaller number of class B base stations under their direct control rather than a large number of unreliable femto base stations (users could turn them off anytime). Figure 3.2.5 – right compares the total-energy-consumption per unit of capacity for macro-micro and femto deployment strategies. Here we observe that, from the point of view of society, macro-micro deployment is even more energy efficient in some cases. Femto deployment is advantageous only in very energy proportional energy models that are unrealistic, but even in this case the gain is negligible.

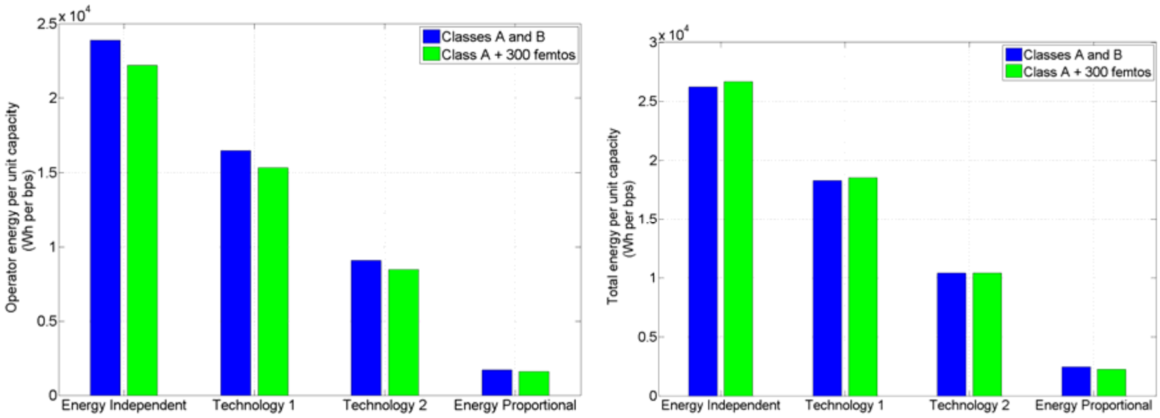

Figure 3.2.5. E_{CO} (left) and E_{CT} (right) for two described scenarios (macro-micro deployment and femto deployment) and for four different energy models

3.2.6 Practical Applicability (pros and cons)

The application of the proposed solution is important when the network is power supplied by renewable energy sources and load control and higher energy savings are required compared to conventional BS only management schemes. The complexity of the proposed architecture arises from the fact that if the user does not have by default the femtocell in open access then management of femtocells by the mobile operator is required.

3.2.7 Conclusion

It was observed that when the number of femtocells in open loop access increases then the energy savings and the level of power reduction (during also high traffic periods) increases. It can be concluded that the femtocell layer can provide off loading from the macro-micro network that is related to the OPEX of the mobile operator and thus increase the time interval that BSs are is sleep mode. It should be mentioned that the the offloading to femtocells layer does not increase electricity costs at the user (femto owner) side since its power consumption is flat and almost independent to traffic served.

On the other hand when no BS management is performed then the energy savings by the offloading to femto layer is small.

3.3 Penetration of Renewable Energy Sources

Summary:	To explore combined RES and BS management schemes for autonomous and green operation. PoliTO explores the case of dimensioning of RES in each BS. UTH explores how new smart grid concepts can be applied on cellular networks to enable active role of mobile provider in the energy market.
Results/Papers:	1. Marco Ajmone Marsan, Giuseppina Bucalo, Alfonso Di Caro, Michela Meo, Yi Zhang, "Towards Zero Grid Electricity Networking: Powering BSs with Renewable Energy Sources," IEEE International Conference on Communications 2013: IEEE ICC'13 - Workshop on Green Broadband access, Budapest, June 2013. 2. G. Koutitas and L. Tassiulas, 'Smart Grid Concepts for the Future Internet', IEEE Communication Magazine, under review
Reason for Research:	Reduce OPEX of mobile operator, increase profit by enabling the provider to play an active role in the energy market
References:	[1] M.Ajmone Marsan, G.Bucalo, A.Di Caro, M.Meo, Y.Zhang, "Towards Zero Grid Electricity Networking: Powering BSs with Renewable Energy Sources," IEEE International Conference on Communications 2013: IEEE ICC'13 - Workshop on Green Broadband access, Budapest, June 2013. [2] http://rredc.nrel.gov/solar/calculators/pvwatts/version1/. [3] S. Zhou, J. Gong, Z. Yang, Z. Niu, and P. Yang, Green mobile access network with dynamic base station energy saving, in Proc. of ACM MobiCom, Beijing, China, Sep. 20-25, 2009, pp. 13. [4] E. Oh and B. Krishnamachari, Energy savings through dynamic base station switching in cellular wireless access networks, in Proc. IEEE Globecom, Miami, FL, December 2010
Contributing partner(s):	UTH, PoliTO

3.3.1 Introduction

Renewable energy is utilized worldwide to solve the problem of shortage of traditional fossil energy and Green House Gas (GHG) emission. We tackle problems which are at the root of carrier-grade cellular networking approaches that solely rely on renewable energy or virtually rely on RES that can be placed in different geographical areas and be a distributed generation (DG) for a subset of BSs of the network. We focus on the problem of dimensioning the renewable energy sources (RES) powering system for a typical LTE BS. We start by discussing the BS energy need, that depends on both the BS consumption model and the BS traffic profiles. Focusing then on some specific locations, we consider the use of photovoltaic (PV) panels, and dimension them based on the daily energy need of the BS and on typical radiative power of sun in the considered locations. Once the PV system has been dimensioned, we also evaluate the energy storage capacity that is needed to absorb energy

production variability due to both daily and seasonal radiative power variations. Finally, we investigate the effectiveness of integrating the PV system with wind turbines, as well as the benefit induced on the system by base station sleep modes [1].
For the future smart grid network we also explore how smart grid concepts can be applied in telecommunication network and provide the ability to the mobile operator to support Demand Response (DR) algorithm in a dynamic electricity prize market. We explore the case of virtual island mode operation of the network but also load control according to real time pricing signals. The greatest benefit behind this scheme is that mobile operator can hold an active role in the energy market since he can adapt consumption (even during high traffic periods) when electricity is high. To achieve this we combine BS and femtocell cooperation as a medium to support DR events.

3.3.2 General System Model and Description (RES dimensioning-PoliTO)

Photovoltaic (PV) modules can be used to convert solar radiation into electricity. The output power of a PV module is directly proportional to the solar radiation. A set of modules forms a PV panel. A set of panels forms a PV system, which is characterized by a peak power expressed in peak kW (denoted by kWp). Approximately 1 kWp is obtained with a panel of about 5 m2 for a typical commercial solar panel model. For a detailed estimation of the energy production of a PV system, we have used the data of the PVWatts simulator [2]. The inputs to be given to PVWatts are: i) geographic position, ii) peak power in kW, iii) DC-AC loss factor (including all losses in the conversion chain), iv) panel tilt and azimuth. The simulator outputs the hourly power generation, exploiting the internally stored historical data about solar radiation in the Typical Meteorological Year (TMY) for the chosen location. In our study we considered 3 locations: Torino and Palermo in Italy, and Aswan in Egypt, so as to investigate the viability of the approach in both southern Europe and North Africa, and in locations with quite different solar radiation.
Electricity can be generated also from wind by using turbines, which convert the kinetic energy of the air flow into electricity. Wind has the characteristic of being much more variable than sunlight, but this variability brings with itself the advantage of not being constrained to daytime periods, and to specific seasons. Since precise data about the daily wind force in given locations are not available, we account for the average annual wind speed in the three locations.
Batteries are needed to store energy so as to power the BS when the production from the PV panels or wind turbine is low or null. We consider simple 12 V lead-acid batteries with capacity 200 Ah, which are often used in conjunction with PV panels. The choice of the number of batteries required for a smooth operation of the BS must account for: i) the characteristics of the periods of high energy production and periods of low or no production; ii) the limits on the Depth of Discharge (DoD) of batteries, i.e., the minimum charge level (usually 30%) required not to damage the batteries; iii) the battery efficiency η_b, which reflects the fact that not all energy input in the battery can be extracted; normally the value of η_b is around 85%.
In traditional deployments, BS equipment is located far from the antenna, so that long feeder cables are necessary, which induce high power losses. In the case of LTE BSs, quite often the RF and PA components can be located close to the antenna, so as to eliminate the feeder cable losses. This layout is called Remote Radio Unit (RRU) or Remote Radio Head. An additional advantage of the RRU layout is that in some cases cooling becomes unnecessary. In this work we investigate these two technologies, i.e., with/without RRU.

3.3.3 General System Model and Description (Smart Grid Concepts-UTH)

In this work we present the smart radio and datacenter network based on concepts and algorithms applied on smart grids. We explore the case of a cellular network comprising macrocells, microcells and femtocells and are powered by renewable energy sources. We observe the effect of the prosumer in the network that is considered as a femto owner in the radio network. In addition, we explore a datacenter network that incorporates renewable energy sources. The main outcome of the research is to apply smart grid algorithms such as demand response and supply load control in a smart telecommunication networks and achieve net zero operation or carbon free service delivery. In addition, the role of the telecommunication operator to the energy market is examined. We distinguish the following entities in the smart radio network (we don't analyse here the datacenter network since it falls out of the scope of the WP2 of TREND).

Radio Microgrid: The radio microgrid is a portion of the telecommunication network that incorporates CBSs and FBSs which are powered by a DG with a certain power capacity, P(t). The DG might not be directly connected to the base stations but it can be deployed in a different geographical area with attractive energy selling prices that aims to virtually feed with power the base stations. The DG, the CBSs and FBSs are assumed to have controllers that process critical data and can support base station management schemes in a self optimized approach to achieve island mode operation.

Virtual Radio Plant (VRP): The VRP is a cluster of prosumer cells that fall within the administrative domain of a CBS from which they can be coordinated (Fig. 2). When necessary, the VRP can support a femtocell or relay priority user association rule, independent of the received signal strength from the macro/micro layer in order to absorb traffic and relieve the operator's power consumption.

Radio Demand Response (RDR): The scope of the RDR is to equalize the load created by the active base stations of the network b(t), with the available DG capacity, P(t) and enable an island mode (net zero) operation. It can also be considered as a mechanism to reduce costs when real time electricity pricing is available under DR signal reception. The RDR renders the network power consumption proportional to the available DG energy in contrast to traditional base station management schemes that aim to provide traffic proportional power consumption characteristics.

Radio Supply Load Control (RSLC): RSLC is an optimization mechanism that is performed within the controller of the DG and aims to optimize the use of the available multiple energy sources while keeping the grid imported energy to the minimum possible levels. RSLC and RDR are in strong collaboration. A characteristic example is a base station that is supplied with wind and solar energy that is also connected to a battery bank.

The general system architecture is presented in Figure 3.3.1.

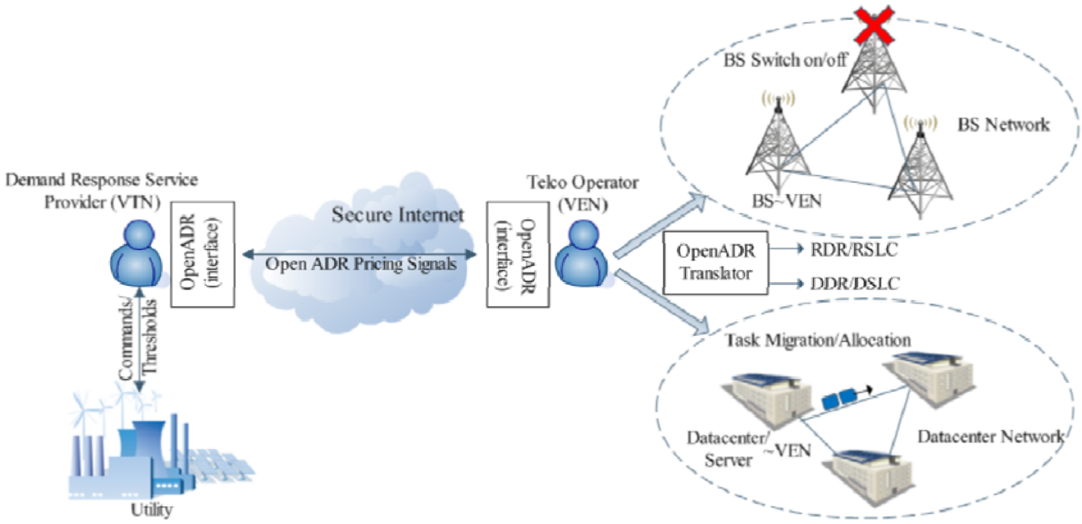

Figure 3.3.1. Architecture to support DR standards for the telecommunication network.

3.3.4 Results (RES dimensioning-PoliTO)

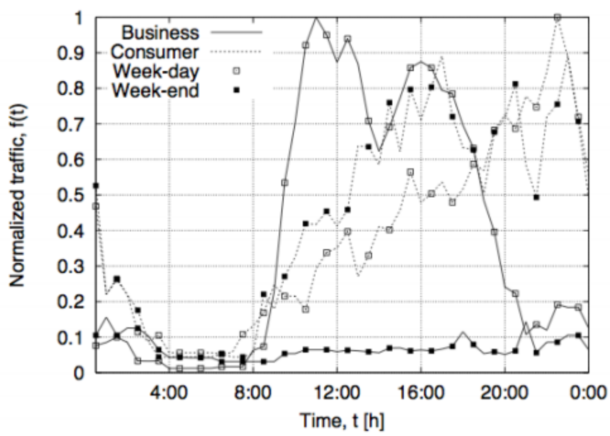

Fig. 3.3.2 Daily traffic profiles for a cell in a business area and a cell in a consumer area, week-day and week-end profiles measured in a network in operation.

To account for the variability of the BS power consumption with traffic, we need to consider realistic traffic profiles. To this end we use results of measurements in an operational network leading to the traffic profiles shown in Fig. 3.3.3. The traffic values are the result of measures on a cell in a business area and a cell in a residential area; the solid markers identify the profile of a week-day. Traffic values are obtained by averaging the measurements collected during a week, and are then normalized to the peak traffic value in the cell.

A) Dimensioning with PV panels

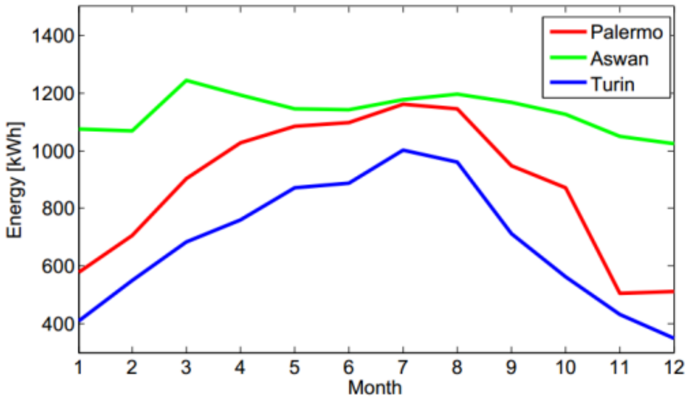

Fig. 3.3.3 Monthly energy production of a 8 kW peak power PV plant in the three considered locations.

Fig. 3.3.3 shows the average monthly energy production in kWh for the three locations, as predicted by PVWatts in the case of a system with 8 kW peak power. It can be noted that the PV system in Aswan has a much more constant energy production with respect to both Palermo and Torino; overall, the Aswan system generates 66% more energy with respect to the one in Torino.

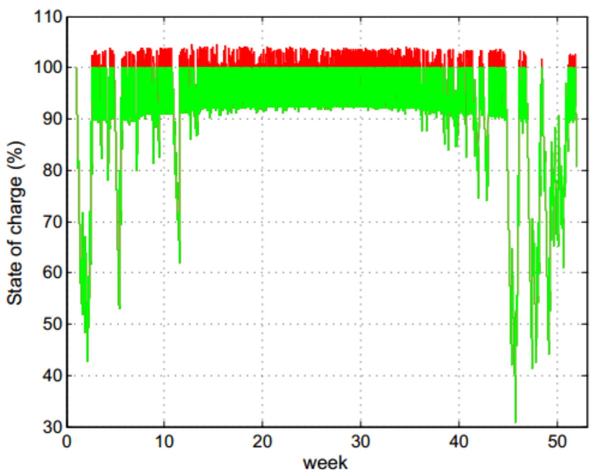

Fig. 3.3.4 Simulation of batteries charge levels, for the case of a residential area in Torino.

The yearly behaviors of the charge level of batteries for a BS in a residential area for Torino in Fig. 3.3.4. We show the residential area case, which is more critical, since the traffic load is similar for weekdays and weekends; the business area case instead can take advantage of the fact that during weekends traffic is very low, and so is energy consumption, thus batteries can be more easily recharged. The red portions of the curves correspond to energy generated by the PV system which is lost, because the battery is already fully charged. The green portions of the curves show the charge level, when lower than 100%. As can be seen, the battery charge level never drops below 30%, as desired (note that total battery discharge is still possible, due to meteorological deviations from the TMY). This is achieved for a minimum amount of energy storage, which corresponds to the battery dimensioning for the BS.
Table 4.3.1 Whole PV System dimensioning, residential area

Location	No RRU			With RRU		
	Size [kWp]	No. batt.	Panel area [m^2]	Size [kWp]	No. batt.	Panel area [m^2]
Torino	20	75	97.8	14	45	68.5
Palermo	16	50	78.2	10	32	48.9
Aswan	8	30	39.1	6	16	29.3

The results of the simulations led us to the dimensioning of the peak power of the PV system, and of the number of batteries. Results are reported in Table 4.3.1. The conclusions that can be drawn from the results heavily depend on the BS location and type. In the case of a BS with RRU located in Aswan, a 6x5 m PV system is necessary, with 16 batteries. This seems not very convenient, but doable. On the contrary, a BS with no RRU located in Torino requires a 10x10 m PV system, with 75 batteries.

B) Dimensioning with PV panels + wind turbines

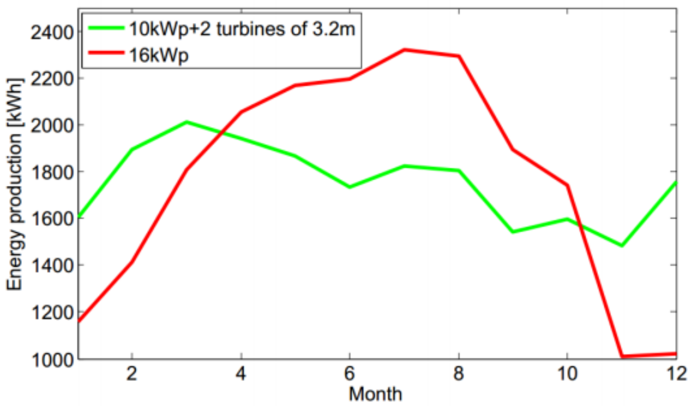

Fig. 3.3.5 Production of a purely PV system and an hybrid PV/wind system in Palermo

Fig. 3.3.5 compares the energy production of the 16~kWp PV system with the one of a hybrid system comprising a 10kWp PV system and two wind turbines with 3.2m diameter. The production curve of the hybrid system is flatter; this is a very good result, since it implies that the energy needs of the BS are satisfied all year, with limited excess generation, contrary to the case of a pure PV system, which is correctly dimensioned for the winter months, but results largely overdimensioned in summer.

C) Impact of BS sleep modes

Sleep modes are today considered as one of the most promising approaches to reduce the power consumption of cellular networks. Indeed, while all the BSs of a cellular network are normally necessary to provide the desired QoS to end users during periods of high traffic, in periods of low traffic only a fraction of the BSs is sufficient to provide the same services, and some BSs can enter low-power sleep modes.

Sleep modes can be of different sorts, depending on the portions of the BS equipment that is switched off [3-4]. In the case of partial switch-off, the BS can be switched on again very rapidly, in the order of fractions of seconds, but the power consumption remains non-negligible, around 30% of the power consumption at full load. In the case of total switch-off, the power consumption goes down to almost zero, but the switch-on time is of the order of minutes. The power consumed by a BS in the case of partial switch-off in our study is assumed to be 450 W in the case without RRU, and 336 W with RRU.

Table 4.3.2 PV system dimensioning with no sleep, partial sleep and deep sleep mode:

	No sleep		Partial sleep		Deep sleep	
	kWp	No. batt.	kWp	No. batt.	kWp	No. batt.
Torino	20	75	18	61	12	42
Palermo	16	50	12	40	8	28
Aswan	8	30	6	23	4	19

By repeating the PV system dimensioning, as in the previous sections, for the case in which half the BSs can go to sleep mode when the traffic is below 50% of peak, we obtain the results of Table 4.3.2, that refers to the consumer traffic profile and the case of no RRU, that are the most consuming cases considered so far. With a partial BS switch-off, peak powers of the powering system decrease by 2 to 4 kWp, corresponding to a reduction of the PV panels area of 10 to 20 m2. Instead, with a total switch-off, peak powers decrease by 4 to 8 kWp, corresponding to a reduction of PV panels area of 20 to 40m2. The number of batteries reduces also, becoming almost half in some cases. Of course, this reduction only applies to half the BS, those that are put to sleep.

3.3.5 Results (Smart Grid Concepts-UTH)

The results show that a network that is powered by renewable energy sources can sustain net zero operation even in the case where the available energy is not sufficient to satisfy the demand. By proper control algorithms and participation of prosumers in the network the network power consumption can be traffic proportional but also proportional to the produced RES energy.

More discussion and results will be presented in a future deliverable of WP2 after the journal publication that is under submission process is finally accepted

3.3.6 Practical Applicability (pros and cons)

The renewable energy system for powering the BSs can be practically deployed especially in the area where there is abundant solar and wind energy production. For example: The solar radiation in Aswan is high all the year round, and Palermo is windy in most of the seasons. In this areas, renewable energy could be effectively utilized to reduce the Green House Gas emission. In addition, in some rural areas, e.g. countryside of Africa, the price of electricity from the Power Grids is extremely high and some places do not even have an access to the Power Grids. In those areas, people use diesel generator to generate power. In this case, using renewable energy is not only green, but also cost-efficient than using diesel generator or buying energy from the Power Grids. In future work we will investigate the CapEx and OpEx of different power supply system, e.g. renewable energy, diesel generator, Power Grids, etc.
If the LTE macro BSs are solely powered by the PV, the size of the solar panels and the number of batteries are quite large because there is a bottleneck of energy production during the winter, especially in Europe such as Italy, where the solar radiation varies a lot during the year. So in these areas, it is possibly a better way to combine the renewable energy and the electricity Grids to power the BSs in winter season in order to reduce the dimension of solar system. In future work we will investigate this approach.

Besides, micro base stations are increasingly deployed these days in urban areas in order to improve the capacity of the cellular networks. The energy consumption of micro base station is much smaller than the macro one, correspondingly the dimension of the PV system for powering them is smaller than the one for the macro base stations. Therefore, the smaller size solar system can be more conveniently utilized on micro base stations in urban areas. In future work we will analyze this problem.

Regarding the application of smart grid concepts in radio networks it is observed that load (power) reduction can be achieved during high traffic hours (or high electricity price hours) with the cooperation of BS management schemes and external networks such as femtocells, relay stations or even other multi RATs. As mentioned before the main constraint in this situation is the complexity added in the system since the mobile operator will require to manage smaller cells in the network. On the other hand, this condition is expected to be transparent in 5G networks and is included within the main objective of future internet.

3.3.7 Conclusions

We have looked into the feasibility of LTE cellular access networks which solely rely on renewable energy sources. We have dimensioned PV panels (and wind turbines, in some cases) together with their associated energy storage systems, so that an LTE macro BS can operate off-grid. With current technology, the size of the renewable energy power system is challenging, but the use of BS sleep modes can provide a significant reduction of the system size. In addition, we have shown that autonomous (island mode operation) or cost effective operation of radio networks can be achieved assuming a DG virtually supply a network nodes. In future dynamic electricity price market this will have a significant effect in the OPEX of the network.

3.4 Energy Savings in Femtocell Networks using Sleep Modes in the Base Stations – heuristic for introducing sleep modes and the effect of variable wake up times

Summary:	To improve the energy efficiency of femtocell networks, the introduction of sleep modes in the base stations is essential. We derived a heuristic which allows establishing a baseline of active base station fractions. We also studied the effect of variable wake up times on the power consumption of a femtocell network.
Results/papers:	Journal Papers [1] W. Vereecken (IBBT), M. Deruyck (IBBT), D. Colle (IBBT), W. Joseph (IBBT), M. Pickavet (IBBT), L. Martens (IBBT), P. Demeester (IBBT), Evaluation of the Potential for Energy Saving in Macrocell and Femtocell Networks using a Heuristic Introducing Sleep Modes in Base Stations, EURASIP Journal onWireless Communications and Networking, Vol. 2012, No. 170, 10.1186/1687-1499-2012-170, May 2012. Conference papers [1] W. Vereecken (IBBT), I. Haratcherev (A-LBLF), M. Deruyck (IBBT), W. Joseph (IBBT), M. Pickavet (IBBT), L. Martens (IBBT), P. Demeester (IBBT), The Effect of Variable Wake Up Time on the Utilization of Sleep Modes in Femtocell Mobile Access Networks., Wireless On-demand Network Systems and Services (WONS), 2012 9th Annual Conference on , No. 9-11 Jan 2012, pp. 63-66, Courmayeur, Italy, January 2012
Reason for Research:	Enable femtocell switch on/off and reduce waste in indoor network.
References	The contribution is published in the two mentioned papers, and we refer to these paper for the used references
Contributing partner(s):	iMINDS-ALBLF

3.4.1 Introduction

In order to improve the energy efficiency of dense mobile access networks, like femtocells, the introduction of sleep modes is required. We derived a heuristic which allows establishing a baseline of active base station fractions in order to be able to evaluate mobile access network designs.

In order to maximize the energy saving effect of sleep modes, it is important to reduce the power consumption of the sleep modes as well as increase the speed of taking a femtocell out of sleep mode. We evaluated the power reduction and wake up time of different sleep modes and demonstrated that fast wake up times and low power sleep modes are essential in order to make femtocells a viable technology for mobile access networks.

3.4.2 General System Model and Description

Please refer to the published papers.

3.4.3 Results

Heuristic for introducing sleep modes

We designed a heuristic to find a best-effort distribution of base stations to be put to sleep mode in order to minimize power consumption. Based on the information about the number of base stations that can serve a certain user and the number of users potentially connecting to a base station, we can iteratively switch on base stations until all users are connected. The heuristic requires information on both the exact location of the base stations and the users, as well as the bit rate requirement of the users. Note that in practical deployments, the user information will not be readily available, will only be valid at a certain moment in time and will be subject to changes due to movement and varying bit rate requirements. However, the heuristic does provide a near-optimal solution for putting deployed base stations in a sleep mode, and hence, it provides a baseline for practical implementations of sleep mode algorithms. Also, during the design of a mobile access network, it can provide useful information on the suitability of a topology for the introduction of sleep modes.

To determine the potential of sleep modes, we evaluated the heuristic in a theoretical base station topology with hexagonal cells. We defined a user density and distributed the users, requiring different bit rates, randomly in the area covered by the base stations until the required user density is reached. In order to model the different bit rates, we used an exponential distribution representing the probability a user requires a certain bit rate. Typically the base stations closest to the users with high demand are switched on and already provide a good coverage for the users with lower requirements. Additionally, some coverage holes for low bit rates need to be eliminated, leading to the optimal active base station distribution. In practical deployments, where the distribution of base stations is suboptimal compared to a hexagonal grid deployment, the introduction of sleep modes helps in optimising the use of the base stations and reduces the effects of increased power consumption due to this suboptimal deployment.

We especially evaluated the active base station fraction for a femtocell network by varying the bit rate requirements, and we also did the same exercise for a macro cell network. When using femtocells even in cases with a large preference for high bit rates, the active basis station fraction is lower than the theoretical maximum corresponding to the user density. For low bit rates, additional savings in the order of 85% to 95% compared to the theoretical maximum are possible. If we use macrocells, it is also possible to save energy by using sleep modes, especially in the case where lower bit rates are preferred. Active basis station fractions of e.g. 15 - 25% can lead to significant reductions in power consumption although values in the order of 50 - 75% seem more realistic. Due to the small cell size, femtocell access networks appear to be better suitable than macrocell networks for introducing sleep modes. The influence of the user density was also evaluated, and although the theoretical limit is increasing with increasing user density, the simulations result in a slower increase of active base stations. It could be concluded that at user densities between 100 and 1000 users the optimal active base station fraction for high bit rate networks is below 20%. Thus, covering areas for high bit rates with sleep-enabled femtocells has a high potential for being less power consuming than using macrocells. However, also in macrocell networks there are opportunities for introducing sleep modes, especially when users have a preference for lower bit rates.

Different sleep modes in femtocells and the influence of the wake-up times

In the previous section, we only differentiated between switching on or switching off a femtocell. However, different sleep modes can be introduced depending on the components that are switched off. The largest part of the power consumed in a femtocell is related to the RF front-end (45%) and the TCXO heater (7%). Hence, switching these components off reduces the consumed power by more than 50%. At the same time, waking up the RF is in the order of few hundred of miliseconds. The TCXO will indeed take some time to heat back up, but our tests show that apart from some induced clock drift, there will be no disruption of femtocell operation.

Based on test results and simulation, we defined some power-save modes, ordered by ‘depth’. The deeper a sleep mode is, the more power is saved, but the more the cost of that mode is - i.e. it takes the femtocell additional time to wake-up.

- On: The femtocell is in full operation, and is consuming maximum power. Depending on the design that power is typically between 8 and 15 Watts.
- Stand-by: The femtocell is in ‘light’ sleep and can wakeup quickly (0.5 s). The RF and the TCXO heater are switched off, leading to a reduced power consumption of 50%.
- Sleep: The femtocell is in ‘deep’ sleep and needs some time to wake up (10 s). In this mode only the power supply, the backend connection and the generic CPU core remain active, leading to a reduced power consumption of only 15%.
- Offline: The femtocell is off and consumes no power, but a wake-up time of ca. 30 s is needed..

The calculation of the optimal distribution of active femtocells in the previous discussion does not take into account any time constraints. If waking up and handing over to a different cell would happen instantaneously, this would not matter. However, the different possible sleep modes require a certain wake up time.

An important factor to take into account is the moving speed of the users. If a user moves out of range of a cell before the next cell can wake up, there is a problem. We defined a maximal speed of a user in the network and varied this speed between 0 and 3 m/s, corresponding to the speed of a running person. Based on the distance a user can travel in order to wake up from sleep or off mode, the right sleep mode needs to be defined for neighbouring cells. We simulated active base station distributions with a varying user speed and it is clear that, due to the variation of active base stations and the variation in the distribution, the exact number of base stations in a certain mode will be difficult to predict. We can see from the fraction of offline base stations compared to online base stations, there are almost no offline base stations at a user speed above 1 m/s. Hence, the entire mobile access network is filled with base stations in sleep mode.
It is demonstrated that the power consumption of the different sleep modes (offline, sleeping and stand-by) has a large impact on the mobile access network power consumption. It is important to both reduce the power consumption of the sleep modes as well as increase the speed of taking a femtocell out of sleep mode in order to maximize the energy saving effect of sleep modes

3.4.4 Practical Applicability (pros and cons)

Please refer to the published papers

3.4.5 Conclusions

Please refer to the published papers

3.5 Bounds on QoS-Constrained Energy Savings in Cellular Access Networks with Sleep Modes

Summary:	Bounds on QoS-Constrained Energy Savings in Cellular Access Networks with Sleep Modes.
Results/papers:	Conference paper B. Rengarajan, G. Rizzo, M. Ajmone Marsan, Bounds on QoS-Constrained Energy Savings in Cellular Access Networks with Sleep Modes, The 23rd International Teletraffic Congress (ITC 2011), San Francisco, USA, September 2011 (won the ITC 2011 best paper award).
Reason for Research:	To define the bounds between QoS and energy savings and thus quantify the degradation of services
References	
Contributing partner(s):	PoliTO-IMDEA

3.5.1 Introduction

In this work we characterize the maximum energy saving that can be achieved in a cellular wireless access network under a given performance constraint. In particular, our approach allows the derivation of realistic estimates of the energy-optimal density of base stations corresponding to a given user density, under a fixed performance constraint.

3.5.2 General System Model and Description

Please refer to the published papers.

3.5.3 Results

Our contributions are as follows:

- For a given base station topology, we develop a method for estimating the density of base stations that minimizes energy consumption and which is sufficient to serve a given set of active users, with fixed performance guarantees.

- For base stations whose power consumption is independent of load, we derive a topology-independent lower bound on the density of base stations required to support a particular user density and thus an upper bound on energy savings.

- Through numerical evaluation and simulations, we compute bounds on the maximum energy saving and illustrate the impact of various system parameters. We demonstrate that even with highly energy efficient hardware, system level techniques are crucial to minimizing energy consumption.

3.5.4 Conclusions

Please refer to the published papers.

3.6 Energy savings in WLANs networks

Summary:	Energy Savings in Cell Overlap and dense WLANS
Results/papers:	Journal paper [1] A. P. Couto da Silva, M. Meo, M. Ajmone Marsan, Energy-Performance Trade-off in Dense WLANs: a Queuing Study, Elsevier Computer Networks, in press. Conference paper under preparation: F.Ganji, Ł.Budzisz, and A.Wolisz, "Assessment of the power saving potential in dense enterprise WLANs" to be submitted to IEEE Wireless Communications and Networking Conference (WCNC) 2013
Reason for Research:	To reduce energy waste in dense WLAN networks that are underutilized during off peak hours
Contributing partner(s):	PoliTO/Federal University of Juiz de For a, TUB

3.6.1 Introduction

PoliTO

We consider a portion of adense WLAN system, where many APs are deployed to provide sufficient capacity to serve a large number of active users during peak traffic hours. To provide large capacity, a number of APs are colocated in the same position and provide identical coverage; we say that these APs belong to the same group, and they serve users in the same area. The areas covered by different groups only partially overlap, so that some active users can only be served by a group of APs, but a fraction of active users can be served by several groups. Due to daily variations of the number of active users accessing the WLAN, some APs can be switched off to save energy when not all the capacity is needed. The main focus of our study is the investigation of the type of algorithm that should be used for the association of active users with APs in order to increase the amount of saved energy in dense WLANs.

TUB

Focusing on the problem of excessive amount of power consumption in dense WLANs we investigate purely WLAN-based approaches and propose a promising solution to aggressively reduce the density of APs in such a network and thus reduce its power footprint. While purely WLAN-based approaches proposed so far in the literature cannot reduce the density of APs as aggressively as these solutions that rely on availability and coverage of another wireless technology (heterogeneous solutions), our approach exhibits not only a significant amount of power saving, but also represent less complex deployment requirements.

3.6.2 General System Model and Description (PoliTO)

Please refer to the published papers.

3.6.3 General System Model and Description (TUB)

The scenario under consideration is a dense high-capacity WLAN deployed in an university campus or an enterprise, i.e., we assume that the available APs are dense enough to assure the required high capacity, as opposed to the density needed just for the coverage of a given area. It is also assumed that all the APs are powered by Power over Ethernet (PoE).

To achieve power-efficient operation of the system described above we develop a policy for aggressive reduction of WLANs APs activity. In that we make the following observation: to assure that the permitted waiting time for a user connection establishment is not exceeded, it is not necessary to keep alive APs providing coverage over the entire target area with the desired bit-rate. We need only to detect the user connection initiation, and switch the appropriate APs on within a desired time. In order to determine the reduced set of APs, we define a detection coverage of an AP as an area where the transmission (with low bit rate!) is detectable but, due to the high error rate, the connectivity cannot be established. The proposed strategy yields extremely reduced set of APs that are still able to provide the coverage (in the entire are)a that is sufficient to detect an incoming user and power on additional APs to fulfill the capacity requirements.

3.6.4 Results

PoliTO

Results show that when some system state information is available, such as the number of users associated with each AP, the energy consumption can decrease up to 20%. Furthermore, our study gives comprehensive insights on the trade-off between the opposite needs to save energy and provide quality of service to the users.

TUB

We show, analytically and by means of simulations, that significant amount of power can be saved in dense WLAN scenarios by providing coverage with the lowest possible bit rate. Furthermore, we show that additional, slight increase in power saving can be achieved for a given detection probability while the user-tolerable connection delay is increased. Last but not least, we address the impact of the coverage percentage decline on the number of APs required to detect the user with given probability of detection and tolerable delay. Our results show that the proposed strategy leads to considerable decrease in number of APs and consequently decreases the power consumption.

3.6.5 Practical Applicability (pros and cons)

Practical applicability of the proposed solution can be considered twofold: first, application of the proposed strategy in the simplest form, namely the detection coverage of an AP is defined as the coverage area with the slowest possible data rate, and, second, in order to increase the power saving potential the detection coverage may be extended to the area in which an APs is still able to distinguish user connectivity attempts (Probe Requests) from the noise floor although it is not able to correctly decode the frames. As for the first approach, it can be immediately deployed with out-of-the-shelf equipment without posing any further requirements. The only limitation is the time it takes for an AP to transit from the off state to the fully operational state.

In the latter case however, a more precise experimental study most follow to determine how much the coverage area can be extended with a regular WLAN APs. This is currently the subject of a joint work between PoliTO and TUB within WP4.

3.6.6 Conclusions

This novel, purely WLAN-based and very aggressive strategy to reduce the density of WLAN APs may result in switching off up to 98 % of the inactive APs in campus and enterprise environments.

3.7 3G femtocell on/off – Joint work on the Prototype

Summary:	In this work ALBLF realized an in-depth (component level) study of the energy consumption of a 3G femtocell and designed a novel active-standby mode with associated wake-up procedure. A prototype has been developed (in the frame of TREND WP4) starting from a real commercial product.

Results/papers:	**Results summary**:
	- Component-level analysis of the energy consumption of a 3G femtocell
	- Real-values of energy consumption from measurements
	- Femtocell on/off design guidelines
	- Prototyping (TREND WP4)
	  - Operational prototype offering full cellular (3G) service (UE attachment, core network connection, calls) into a residential scenario
	  - Operational dynamic standby mode: RF part shout-down when no UE to serve
	  - Operational wake-up through secondary "presence detection" channel (based on an additional WiFi module)
	- Experimental results on energy gain, sleep/wake-up times… (TREND WP4)
	Papers:
	- I. Haratcherev, A. Conte, "Practical energy-saving in 3G femtocells"- ICC 2013 Workshop "Green Broadband Access: energy efficient wireless and wired network solutions", Jun 2013
	- A. Conte, "Power consumption of base stations", presented at the TREND Open workshop in Ghent, February 2012

Reason for Research:	Better understand the reality of commercial equipments in order to: - provide realistic values to be injected in models and simulations - move from theoretical studies to real implementations
References	I. Haratcherev, A. Conte, "Practical energy-saving in 3G femtocells"- ICC 2013 Workshop "Green Broadband Access: energy efficient wireless and wired network solutions", Jun 2013 II. W. Vereecken, I. Haratcherev, M. Deruyck, W. Joseph, M. Pickavet, L. Martens and P. Demeester, "The Effect of Variable Wake Up Time on the Utilization of Sleep Modes in Femtocell Mobile Access Networks", Coneference on Wireless On-demand Network Systems and Services (WONS), January 2012 III. A. Conte, "Power consumption of base stations", presented at the TREND Open workshop in Ghent, February 2012
Contributing partner(s):	ALBLF

3.7.1 Introduction

From the analysis of several base station data sheets (and literature) it is possible to derive a model of the power consumption of a base station as function of the traffic load (power profile). Depending on the type of Base Station (i.e. macro, micro, femto) the energy consumption is more or less dependent of the load. But in any case, there is a big offset at 0% load. This is due to what is called *coverage tax*: Base Stations permanently advertise their presence and availability by broadcasting pilots and signaling, even when no user needs connectivity. The equivalent RF power used is ~10%-15% of max RF power, which unfortunately translate to almost 50% of power consumption are electrical plug, at zero load. The following Figure 3.7.1 presents the concept.

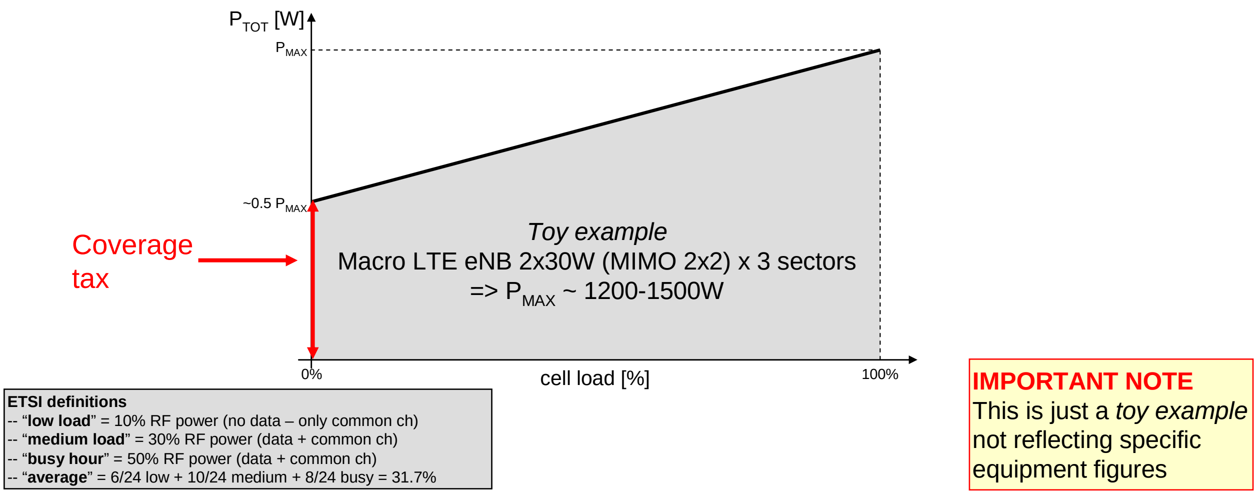

Figure 3.7.1. BS power consumption as function of traffic load

From this profile it is possible to show where the commonly studied techniques to improve energy efficiency apply, summarized in 3.7.2.

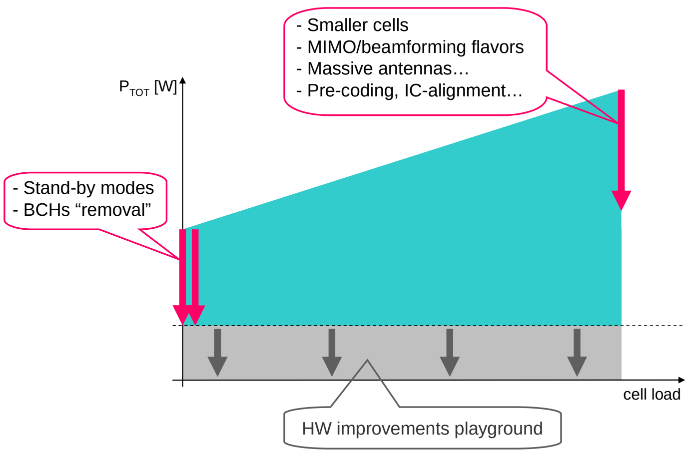

Figure 3.7.2. Ideas to improve efficiency

Cell stand-by is broadly considered as one of the most promising techniques to reduce the energy consumption of base station, especially at low loads. And this is particularly true in case of femtocells. In fact femtocells are often not used during very long periods (e.g. during night, or working/school time). During such time the deployed femtocell becomes unnecessary and can enter some low-consumption mode. A lot of literature exists on the subject, from performance (savings) evaluation over different scenarios, to algorithms for selecting the best cells to keep active.

Unfortunately very few information exists on actual energy-consumption figures of real equipments and on practical implementation of such low-power modes. It is our belief that realistic measurements on achievable gains and wake-up delays are necessary to validate (or infirm) algorithms and performance estimations. For example, solutions based on immediate wake-up are not realistic.

In this work we analyzed the energy consumption of a 3G femtocell at component level, we derived guidelines for the design of active/standby modes and we moved from theory to practice by implementing an operational standby mode with associated wake-up procedure on a commercial 3G femtocell.

The details can be found in the paper published at the Green Broadband Access Workshop associated to IEE ICC 2013.

The experimental part has been conducted within TREND WP4, but based on the studies performed within IRA 2.1 and IRA 2.2 of WP2.

3.7.2 General System Model and Description

A typical generic architecture of a 3G femto BS (a femtocell, or just femto) is shown on **Errore. L'origine riferimento non è stata trovata.**.7.3. Most of the elements can be found in any embedded system. In particular the architecture is quite close to that of a Wi-Fi Access Point.

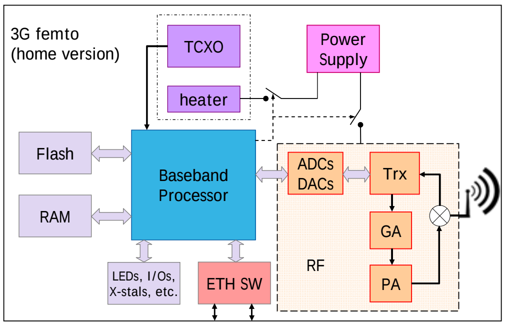

Figure.3.7.3. 3G Femto block diagram

The heart of the device is the Baseband processor, which implements most of the required functionalities. It contains (not exhaustive list) a generic application CPU, a 3G modem, HW accelerators, and peripherals to support HSPA functionality.

The second major subsystem is the Radio Frequency (RF) module. Its main parts are: ADCs+DACs (often referred to as mixed signal frontend), a transceiver (Trx), pre-amplifier (also called Gain Block or Gain Amplifier – GA), and a power amplifier (PA).

These two subsystems are responsible of the majority of the overall power consumption. Other parts are present (e.g. master clock). The detailed analysis can be found in [1].

3.7.3 Results

Power consumption and component level

The power consumption of a typical modern 3G femto is about 8-14 Watts. The figure does not include the external power supply efficiency (usually between 80% and 90%). Since losses in internal DC/DC converters (ranging from 5% to 10%) are proportional to the load, those losses have been implicitly added to components/subsystems consumption figures. The consumption split per component/subsystem (in %) is shown in **Errore. L'origine riferimento non è stata trovata.**.

Component / Subsystem	Power share, %	RF power share, %
BB processor	25	
ETH switch	15	
MEM Avg.	5	
Radio (incl. DC/DC)	45	
ADC/DAC		20
Trx		25
PreAmp (GA)		20
PA		30
Other		5
Osc. Heater Avg.	9	
Other	1	

Stand-by mode specification guidelines

A stand-by mode can be implemented by turning-off some subsystems or components of the femto. Turning-off a component brings a cost (or penalty) and benefit (or gain) to the system's power-save mode. The cost can be the time that is added to the wake-up delay of the femto, or how important/necessary it is the component to still remain switched on in a particular power-saving mode. According to their gain/cost femto components/subsystems can be classified as:

1) Good candidates to be switched off in power-saving modes:
   - Radio: high power savings (45%), low wakeup delay (<0.5s).
   - TCXO heater: medium power savings (9% in steady state), negligible cost: does not influence the wakeup delay of the femto, and has no short-term importance.
2) Average candidates to be switched off in power-saving modes:
   - Baseband processor: high power savings (25%), but high costs as well: considerable (>10s) wakeup delay due to power-up sequences and context restoring; huge software redesign effort (available firmware is typically written with no power-saving in mind).
   - ETH switch: high power savings (15%), but high cost: necessary to maintain backhaul connectivity for a) link with the core nw, and for b) waking-up femto wake-up.
3) Bad candidates to be switched off in power-saving modes:
   - Memory: medium-to-low power savings (5%), high cost: Flash is always necessary when BB processor is on, and RAM is necessary for all modes except off.
   - Logic ICs and oscillators: very low power-savings (<2%), medium to high cost.
   - DC/DC converters: very low power-savings, high cost (most of the time used).

Based on the above classification, and on estimation and experimentation, we determined that a good balance between granularity and complexity/effort would be to define four distinct operational (power) modes: Active, Standby, Sleep, Off. They are summarized in **Errore. L'origine riferimento non è stata trovata.**.

		Power-Save mode			
		Active	*Standby*	*Sleep*	*Off*
Wakeup time, s		NA	0.5	< 10	90-130
Total power consumption, %		100	45-66	< 20	0
Components' state	BB proc.	**On**	**On**	**Power-save**	**Off**
	ETH switch	**On**	**On**	**Power-save**	**Off**
	RAM	**On**	**On**	**Power-save**	**Off**
	Flash	**On**	**On**	**Off**	**Off**
	Radio (supply)	**On**	**Optional off**	**Off**	**Off**

	ADC/DAC	On	Optional off	Off	Off
	Trx	On	Optional off	Off	Off
	PreAmp (GA)	On	Off	Off	Off
	PA	On	Off	Off	Off
	Other	On	Optional off	Off	Off
	TCXO Heater	On	Off	Off	Off
	Other	On	On	On	Off

Additional details, including an analysis of wake-up techniques can be found in [1].

Prototyping

An operation Standby mode can be implemented on today equipments, and energy savings can be achieved by exploiting periods of inactivity. A companion wake-up procedure is mandatory to re-activate the femtocell when needed. Wake-up requires a mechanism to detect the presence of a UE in the proximity of the femtocell.

We showed that the choice of internal circuits to turn-off during standby mode is crucial to balance energy consumption reduction and wake-up delay. Savings in the order of 33-55% can be obtained while still ensuring rapid wake-up (<1 second). Higher savings come at price of much longer wakeup time (tens to hundreds of seconds).

For the wake-up we leverage on a collocated WiFi AP in charge of detecting the proximity of UEs. We use the standard 802.11 PROBE Req/Rsp to request trigger the femtocell wake-up (see **Errore. L'origine riferimento non è stata trovata.**). Since our femto did not include a native WiFi interface, we added an external WiFi Access Point linked to the 3G femtocell via the Ethernet connection. The operational behavior exploits the following ideas:

- when femtocell (3G) in standby, broadcast a special "3G_green_femto" SSID in the WiFi beacon to signal the availability of the 3G connection via wake-up
- use WiFi to detect the presence of a UE in the close area of the dormant femtocell
- exploit the WiFi probe request from the UE to trigger the 3G femto wake-up

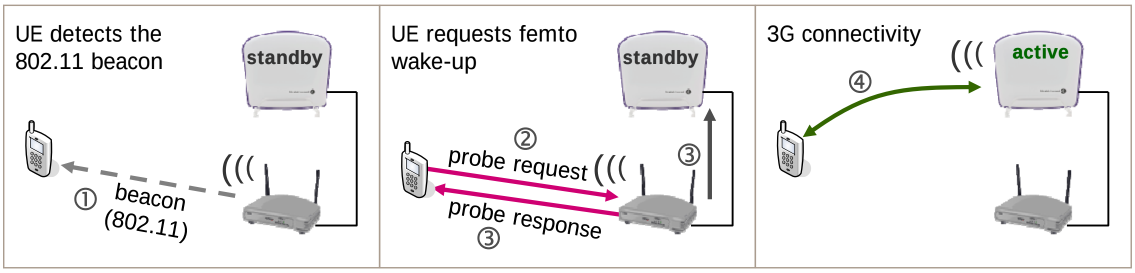

Figure 3.7.4. Prototype

In this setting UEs need to be dual-mode (3G+WiFi).

A complete description of the prototype, experimental test-bed, tests and measurements results will be provided by WP4.

4. Review and Holistic Presentation of BS/AP management Schemes

Summary:	In this work all partners are working in the area of BS and AP management schemes to give an in depth literature review but also a holistic view of the approach of BS and AP management.
Results/papers:	White paper/under preparation - Lectures at the PhD school in Torino, July 2013
Reason for Research:	To present a review of existing algorithms and techniques and highlight their applicability in real scenarios
Contributing partner(s):	UTH, TUB, IMDEA, TUB, ALBLF, iMINDS

4.1.1 Introduction

The proposed paper will combine all algorithms, techniques and lessons learned in the area of BS and AP management schemes. As a result of joint work a journal paper, a big portion of the TREND white paper and lecture notes for TREND PhD school will be provided.

4.1.2 General Architecture of White Paper

The following outline of the journal paper has been agreed among the partners.
Section 1 will cover introduction to the problem of BS/AP management in WiFi, Femtocell and cellular environments. Section 2 will provide a detailed description of the technical evolution that facilitates BS/AP management techniques. Section 3 will provide a definition and detailed description of the taxonomy, based on which the evaluation will be made. Next, in Section 4 a detailed survey of cellular BS management techniques as well as WLAN APs will follow. In that section also a comparison of mechanism developed for different networks will be given. Section 5 will provide a long term view on the performance of proposed energy saving schemes. And finally Section 6 will bring the conclusions and summarize lessons learned in IRA 2.2.

A review paper is under preparation so more details will be provided in the final deliverable of TREND.

5. Conclusions

In this deliverable we presented the work of TREND partners in the area of BS switch on/off schemes under the IRA 2.2 'On/off strategies for energy saving and transparent connectivity in WLAN access points, cellular femtocells and base stations'. The work presented in the deliverable consists of joint activities between the partners but also on individual work on related subjects that shall yield to joint publications and research in the immediate future. Within the report we first presented why IRA 2.2 is important for the future internet network. This was followed by different sections describing the work in more detail. In the first section we presented the case of BS management. We explored almost all possible control configurations (centralized, distributed, pseudo-distributed) in an offline and online approach. The next section introduces how BS management can be achieved with a cooperation with external networks. We explored the case of femtocell networks as a potential medium to offload traffic and increase sleep mode time intervals at the BSs. Furthermore within this section we explored how much energy can be saved when femtocell is used for offloading but without having BS management implementation in the network. The next section described the case of implementing BS management for net zero operation of the network (assuming a proper dimensioning of RES at BS level) but also we explored the case of a Distributed Generation (DG) approach to a subset of the network taking into account smart grid concepts with a proper translation to telecommunication networks. We proposed that OpenADR standard can be implemented in telecommunication network by enabling BS management and cooperation with external networks (multi RAT, femtocell, etc..) In that case the telecommunication provider can hold an active role to energy market and obey to pricing signals. The next section described the case of implementing switch on/off schemes in a femtocell network. QoS issues are explored in the section followed whereas Access Points in WiFi networks switch on/off schemes are explored in 3.6. To present the applicability of switch on/off schemes, the section 3.7 presents the 3G femto prototype that can support such functionalities. Finally, the last section gives a short description of the joint work that is under research that targets to give a holistic review of BS/AP switch on off schemes. This work will be part of the TREND white paper.

As a general conclusion we can state that switch on/off management of network nodes is crucial to support traffic proportional power consumption of the network but also provide the ability for load (power) control in the grid network.

6. Summary of the papers and mobility actions

6.1 Published/submitted papers

Involved partners/Collaborating Institutions	**Authors**	**Title**	**Conf/journal**	**Date of presentation/ publication**
PoliTO-UTH	L. Charaviglio, D. Ciullio, G. Koutitas, M. Meo, L. Tassiulas	Energy-Efficient Planning and Management of Cellular Networks	Conf/IEEE Wireless on demand Network Systems and Services (WONS)	2012
UTH	S. Kokkinogenis and G. Koutitas	Dynamic and Static Base Station Management Schemes for Cellular Networks	Conf/IEEE GlobeCom, Anaheim, USA,	2012
PoliTO	M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo	Multiple Daily Base Station Switch-Offs in Cellular Networks	Conf/ 4th International Conference on Communications and Electronics (ICCE 2012), Hue, Vietnam,	2012
UTH-IHU	G. Koutitas, A. Karousos, L. Tassiulas	Deployment Strategies and Energy Efficiency of Cellular Networks	Journal/ IEEE Transactions on Wireless Communications, vol. 7, no.11, pp. 2252-2563	2012
EPFL	K. Dufkova, M. Popovic, R. Khalili, J.-Y. Le Boudec and M. Bjelica et al.	Energy Consumption Comparison Between Macro-Micro and Public Femto Deployment in a Plausible LTE Network	Conf/ e-Energy	2011
PoliTO	Marco Ajmone Marsan, Giuseppina Bucalo, Alfonso Di Caro, Michela Meo, Yi Zhang	Towards Zero Grid Electricity Networking: Powering BSs with Renewable Energy Sources	Conf/IEEE International Conference on Communications 2013: IEEE ICC'13 - Workshop on Green Broadband access, Budapest,	2013
UTH-IHU	G. Koutitas and L. Tassiulas	Smart Grid Concepts for the Future Internet	IEEE Communication Magazine, under review	Under review
iMINDS	W. Vereecken , M. Deruyck , D. Colle , W. Joseph, M. Pickavet, L. Martens, P. Demeester,	Evaluation of the Potential for Energy Saving in Macrocell and Femtocell Networks using a Heuristic Introducing Sleep Modes in Base Stations	Journal/EURASIP Journal onWireless Communications and Networking, Vol. 2012, No. 170, 10.1186/1687-1499-2012-170,	2012
iMINDS-ALBLF	W. Vereecken, I. Haratcherev, M. Deruyck, W. Joseph , M. Pickavet , L. Martens , P. Demeester	The Effect of Variable Wake Up Time on the Utilization of Sleep Modes in Femtocell Mobile Access Networks	Conf/Wireless On-demand Network Systems and Services (WONS), 2012 9th Annual Conference on , No. 9-11 Jan 2012, pp. 63-66, Courmayeur, Italy,	2012
IMDEA-PoliTO	B. Rengarajan, G. Rizzo, M. Ajmone Marsan	Bounds on QoS-Constrained Energy Savings in Cellular Access Networks with Sleep Modes	Conf/The 23rd International Teletraffic Congress (ITC 2011), San Francisco, USA (won the ITC 2011 best paper award)	2011

PoliTO	A. P. Couto da Silva, M. Meo, M. Ajmone Marsan	Energy-Performance Trade-off in Dense WLANs: a Queuing Study	Journal/Elsevier Computer Networks	2012
TUB	F.Ganji, Ł.Budzisz, and A.Wolisz	Assessment of the power saving potential in dense enterprise WLANs	Conf/IEEE Wireless Communications and Networking Conference	2013
ALBLF	I. Haratcherev, A. Conte	Practical energy-saving in 3G femtocells	Conf/ICC 2013 Workshop "Green Broadband Access: energy efficient wireless and wired network solutions",	2013
ALBLF	A. Conte	Power consumption of base stations	Conf/presented at the TREND Open workshop in Ghent	2012
ALBLF	IH. Hou, and C. S. Chen	An Energy-Aware Protocol for Self-Organizing Heterogeneous LTE Systems	Journal/ IEEE Journal on Selected Areas in Communications	2013

6.2 Planned papers

Involved partners	**Topic**	**Targeted conf/journal**	**Planned date**
UTH-PoliTO	Self-Optimized Energy-Efficient Cellular Networks: The Effect of Planning, Management and Femto Layers	Journal	2013
UTH-PoliTO-IMDEA-iMINDS-ALBLF-TUB	Review of BS management schemes (white paper WP2)	Journal	2013

6.3 Mobility actions

Involved partners	**Person**	**Topic**	**Period**
PoliTO-INRIA	Dellia Ciullo	Energy-efficient cellular networks: the effect of planning, management and femto layers	23/07/2012 to 27/07/2012
PoliTO-ALBLF	Delia Ciullo, Post-Doc at PoliTO, hosted by A-LBLF	*Sleep modes adoption for base stations in cellular access networks*	from 28/02/2011 to 28/02/2011
UTH-PoliTO	George Koutitas, Research Associate at UTH, hosted by PoliTO	*Energy Management of Base Stations in Deterministic Cellular Networks*	06/06/2011 to 10/06/2011
INRIA-PoliTO	Delia Ciullo, Post-Doc at INRIA, hosted by PoliTO	*Energy-efficient cellular networks: the effect of planning, management and femto layers*	from 23/07/2012 to 27/07/2012
INRIA-EPFL	Delia Ciullo, Post-Doc at INRIA,	*Energy optimization in sustainable wireless networks*	from 05/11/2012 to 09/11/2012

	hosted by EPFL		
PoliTO-IMDEA	Balaji Rengarajan, Staff Researcher at IMDEA, hosted by PoliTO	*Quantifying and optimizing energy consumption in wireless access networks*	from 24/11/2012 to 29/11/2012
PoliTO-IMDEA	Gianluca Rizzo, staff researcher at IMDEA, hosted by PoliTO	*Quantifying and optimizing energy consumption in wireless access networks*	from 24/11/2012 to 29/11/2012
TUB-PoliTO	Fatemeh Ganji, PhD Student at TUB, hosted by PoliTO	*Collection of WLAN traces in dense WLAN to verify on/off strategies proposed in WP2*	from 21/05/2013 to 31/05/2013

7. References

References are provided in each subsection of the document