D2.6 Final WP2 technical report on "Energy Efficiency in Access and Home Networks"

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Abstract:
This report is the final deliverable of TREND NoE and presents the aggregated activities in the area of energy efficiency in access and home networks. The report describes the approach that was followed by TREND partners in the direction of energy management and energy efficiency in access networks. The big picture emerging from the obtained results includes network adaptation in terms of energy saving under switch on/off schemes of the critical nodes, energy efficient data transmission over wireless and wired access networks, and efficient integration of the access network to renewable energy sources. The results are presented in terms of technical achievement and collaborations.

Keyword list:
Resource allocation, algorithms for base station management in cellular networks, self optimized energy-efficient networks, renewable energy sources and telecommunication

networks, smart-grids, access networks, energy-efficient hardware equipment, energy measurements from ICT equipment, dense WLANs.

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1. Executive Summary

The access sector is the most energy demanding part of telecommunication networks, because of the very large number of end-user equipment. In addition, the demand for high data rates and large traffic volumes, which continue experiencing an exponential growth, drive telecommunication operators to deploy ever more access nodes in their networks. This has a direct effect on the forecasted energy consumption of the access network, which is expected to soon become a relevant issue for the operators' OPEX and for the cost of services for end users. In this context, the objective of WP2 is to coordinate the efforts of partners in the area of energy-efficient access and home networks, and develop solutions and techniques which can reduce the overall energy footprint of the sector. To achieve this target, WP2 has focused on four technical domains.

In the first technical domain TD2.1, 'Redesign the home equipment for energy-efficient communications', WP2 investigates energy-efficient techniques for home network equipment, such as femtocells and WiFi access points, to provide energy proportionality with actual utilization. In addition, the concept of energy management of home appliances, within the smart grid environment, is introduced and explored in terms of scheduling algorithms and control schemes for the demand response problem. Within this technical domain falls the Integrated Research Activity (IRA 2.1) 'Low energy solutions directly applicable to user premises'.

In the second technical domain TD2.2, 'Network access architecture and management: optimizing power usage one step away from the end user' WP2 investigates techniques and protocol design for achieving energy efficiency at the access network, specializing in fixed and wireless access.

In the third technical domain TD2.3, 'Organize the flying bits: saving energy on wireless access' WP2 investigates energy saving techniques by changing the way that the mobile devices access the wireless medium.

In the fourth technical domain TD2.4, 'Green protocols for handling wireless access from the network view', WP2 investigates energy management and radio planning techniques responsible for energy savings in cellular systems (Base Stations, WiFi access points, Femtocells). Within this technical domain falls the Integrated Research Activity (IRA 2.2) 'On/off strategies for energy saving and transparent connectivity in WLAN access points, cellular femtocells and base stations'.

The studies presented in this document have already resulted in more than 77 papers, of which 22 publications appeared in journals, magazines and book chapters, and about 50 are included in international conference proceeding. More than 31 papers are joint publications. Within WP2, 21 mobility actions were organized, to enhance the interaction among TREND partners. Finally, one proposal was submitted to the ITN Marie Curie on November 2012 in the domain of demand response in telecommunication networks by WP2 TREND partners with additional external institutions; since the proposal was not successful, a resubmission is under consideration. Other project proposals in the framework of Horizon 2020 are in preparation..

This document presents the results obtained by partners during the TREND project, based on the activity plan defined at the beginning of 2011.

2. Introduction

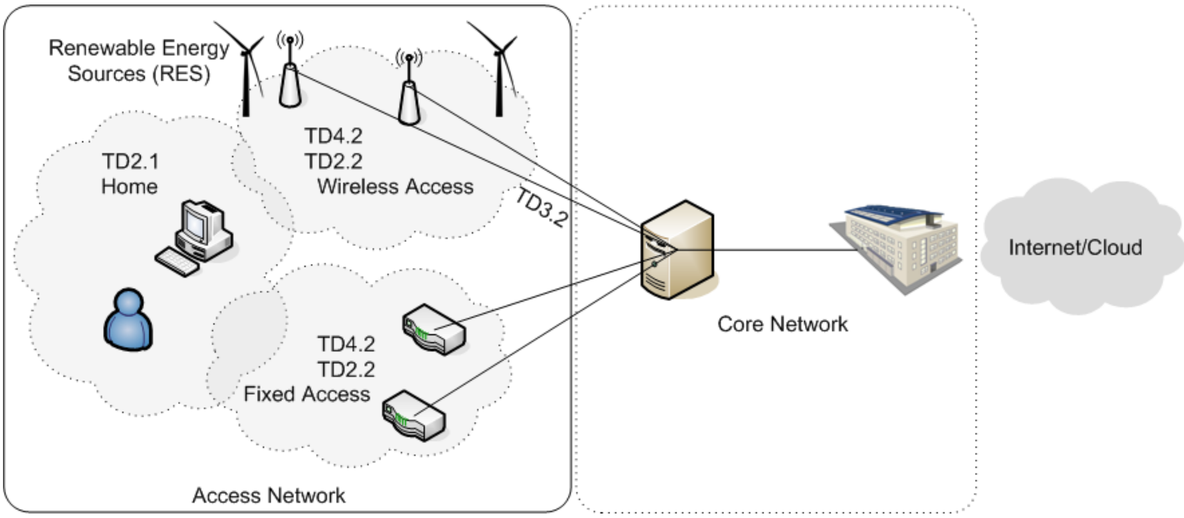

Figure 1 – Network Access and domains studied within TREND. The frame represents the segment covered in this report.

The access part of modern cellular systems is the most energy demanding part of the network. It incorporates network nodes, such as base stations (macrocells, microcells, picocells and femtocells), as well as access points, such as DSL routers and WiFi APs, as shown in Figure 1. Despite the fact that the power needs and energy consumption of the individual nodes is small, their large number in the network yields to enormous energy demands.

The need for high data rates and large data volumes from non-human centric data (Advanced Metering Infrastructures-AMI and Internet of Things-IoT) that are expected in the future, will drive the number of access nodes and thus their aggregated energy consumption to enormous values. This condition has a direct effect on the OPEX of the operator and the cost of services. Within WP2, TREND has focused on the development of sophisticated solutions and techniques that enable energy saving in the access network or even exploitation of renewable energy sources (RES) to reduce the costs and energy waste of the sector. In the introductory part of the report, WP2 presents a map of the most critical points of interest as well as the main achievements in terms of energy saving.

Power Consumption of Modern Networks and Network Nodes

Modern cellular networks suffer from great energy waste, especially during off-peak hours, when data traffic is low, because the network equipment power consumption presents small sensitivity with respect 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 huge 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 the equation below) and the IT losses. No-load losses exist even when there is no traffic served by the IT equipment. No-load losses account for 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 has the consequence of great amounts of energy wasted during off-peak hours, and thus it is important to switch off unnecessary nodes in the network in order to save energy and provide traffic-proportional network power consumption. A typical dependency of BS or AP power consumption with traffic is given in Figure 2.

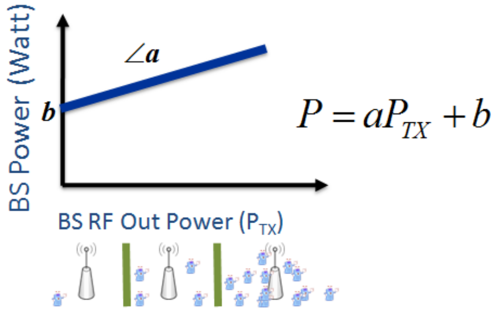

Figure 2. Power consumption versus RF out power of typical BSs and APs

On the other hand, network traffic presents a high daily variation that in some occasions can yield to 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 in the hardware of the network nodes. 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 with traffic.

The Future Internet Characteristics

The future Internet 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. Much research interest is presently focusing upon energy-efficient networking techniques, green Service Level Agreements (SLAs) and penetration of RES (renewable energy sources) 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 support of different types of data (low data rate for M2M communications, and high data rates for UHDTV).

Focusing on the cost-effective part, and more precisely on the operational expenses (OPEX) of the network, which is mainly related to energy consumption, it is expected to observe in the 5G network a saving up to 90% with respect to the situation of today, per unit of service provided. The most important already existing technologies to support such a radical reduction are: i) base station switch on/off schemes, that are already incorporated in 3GPP plans, and that were investigated in detail within TREND, ii) multipath TCP, and iii) multi RAT access, that provide resource management-offloading, iv) task migration and allocation strategies over virtualization schemes, and v) 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 another important characteristic that needs to be considered in future networks. It is becoming a global trend to install off-grid BSs, or even to power 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 the network must operate in island mode (net-zero operation with no import of energy). To achieve this target, it is important that the telecommunication network operator has the ability to provide load (power) control in the network.

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

The objective of this deliverable is to provide the TREND big picture on energy-efficient access networks, capable of sustaining traffic growth with reduced energy consumption. The results obtained within TREND show that it is possible to achieve large savings (of the order of 20-40%) already with the network of today. Moreover, the proposed solutions put the basis for the design of sustainable future networks. The main message that can be achieved through the TREND research is that the future network should become dynamically adaptive to the traffic demand and user capacity need, by exploiting and involving a wide set of possible resources, that includes nodes with their various sleep modes, heterogeneous devices, different kinds of energy, and possibly also resources from other networks.

In Section 3 we focus on home networks, in Section 4 we focus on wireless access, and in Section 5 we focus on wired access. We conclude the report with a discussion and a wrap-up of the potential savings (Section 6). Each section contains a list of references of TREND publications with detailed descriptions of the proposed solutions. The reader is referred to such publications for a more careful assessment of the TREND contributions.

The partners that contributed to this document are listed below:

Partner short name
PoliTO
EPFL
A-LBLF
UC3M
IMINDS
TID
TUB
IMDEA
UTH
FT
TUD
CNIT
INRIA
IHU

3. Energy efficiency in home networks

When focusing on home networks and equipment, two main issues should be considered. The first one is the energy efficiency of home telecommunication equipment itself; the second is the possibility to use telecommunication networks to enable a smarter energy management of home appliances. TREND has contributed to both these themes. As a case of telecommunication equipment in the home, TREND has considered femtocells, prototyping efficient femtocells that use sleep modes when capacity is not needed, and developing algorithms and protocols to coordinate femtocells sleep modes when more devices are in use. For what concerns energy management of smart home appliances, some algorithms have been proposed.

3.1 Energy-Efficiency in home telecommunication equipment

The work that is presented in this section describes research performed by TREND partners to provide solutions for energy saving in the telecommunication equipments in home area networks (HAN). The main research focus is on femtocells.

3.1.1 Prototype 3G WiFi Femtocell with sleep modes

Cell stand-by is broadly considered as one of the most promising techniques to reduce the energy consumption of residential femtocells. It exploits the fact that, in residential scenarios, 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 vast 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 practical implementations 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 moved from theory to practice by implementing an operational standby mode with associated wake-up procedure on a commercial 3G femtocell.

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 trigger the femtocell wake-up. 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 the femtocell (3G) is in standby mode, 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 proximity of the dormant femtocell
- exploit the WiFi probe request from the UE to trigger the 3G femto wake-up

In this setting UEs need to be dual-mode (3G+WiFi). A specific Connection Manager has been developed for the terminal side. An HTC Desire 2 with Android 2.3.7 with API 10 is used as platform for the development of the application. Android was selected considering its increasing presence into the market of mobile operating systems, the availability of terminals supporting it, and the facility provided with the SDK. The new Connection Manager allows to manually turn-on/off WiFi in order to trigger the femtocell wake-up process. The result of this activity is presented in the reference below.

[1] I. Haratcherev, A. Conte, "Practical energy efficiency in 3G femtocells"- International Conference INFOCOM, 2013

3.1.2 *Switch of Radio Sections of Femtocells*

In a typical femtocell network deployment, there is no hierarchical relationship among femtonodes. Femtonodes are located with the aim to cover a whole area (a building, for example) with no coverage holes, and all of them continuously radiate, even if there are no users in active or idle mode. Besides, additional femtonodes may be deployed in order to cope with traffic peaks due to an unequal distribution of the users in time and space. This may be the case, for example, of an auditorium or meeting hall. In this scenario, though one femtonode could cover the whole area, due to capacity issues additional femtonodes would be necessary to serve all the users during some periods of time.

In order to avoid the unnecessary waste of energy and minimize the interference generation, we propose to build groups or clusters of femtonodes with a certain hierarchical relation between them having the possibility of switching off the RF transceiver of those nodes that are not essential for a correct service when the load conditions permit it.

The basic concept consists of providing to the femtonodes in an enterprise deployment (or similar scenarios where there is an infrastructure that can support the communication between femtonodes, like an Ethernet LAN), a mechanism to disable the RF sub-system of some femtonodes during certain periods of time. The mechanism is based on a master/slave communication through the communications infrastructure (e.g. a LAN) used as backhaul of the femtonodes, for the interchange of simple messages related with the traffic load of the deployment. The messages interchange could be supported by means of a specific communications interface for those femtonodes compliant with 3GPP releases previous to release 10, or could be supported by the so-called X2 interface for 3GPP release 10 and later versions.

The main objective of the proposed procedure is to decrease the energy consumption and minimize the interference level on the deployment where the femtonodes implement this mechanism. In short, we propose a mechanism for the deactivation of the RF sub-system of the slave femtonodes according to a certain algorithm, so that the service is correctly attended while an important energy saving is achieved, and the interference level is decreased. The intention is always to solve the technical challenge without any external human control in enterprise scenarios, where a number of femtonodes could be deployed, that collaborate with each other in order to provide the best coverage with the best quality of service. The result of this activity is presented in [2]. Further investigations regarding AP management is presented in Chapter 4.

[2] Patent Application P201130693, "Master/Slave Coordination Mechanism for Hierarchical Femtocells".

3.2 Energy efficiency at Home appliances using ICT infrastructure

The work that is presented in this section describes work performed by TREND partners to provide solutions for energy savings in the user premises by utilizing management of home appliances connected to HAN. The research falls under the general topic of smart grids and demand side management (DSM) or else demand response (DR).

3.2.1 *Algorithms for Energy Management of Smart Home Appliances*

We explore algorithms for energy management and load control in the smart grid. More precisely we investigate devices that can be externally controlled in the smart home and provide the degrees of freedom for energy management and load control. These types of devices are related to non emergency power tasks (washing machine) and thermostatic loads (air conditioning units, water heaters, etc.). We explore the following problems:

1. Algorithms for scheduling non emergency power tasks to meet load control in the smart grid. The optimization is based upon the duration of the power tasks, the associated power level and the deadline of the execution of the task [3-5].

2. Algorithms for controlling thermostatic loads (flexible devices). The control problem is based upon the ratio Tmin/Tmax where Tmin indicates the minimum duration the device is on to achieve a predefined comfort value and Tmax the maximum duration the device can be switched off to reach the maximum discomfort value set by the user.

3. Algorithms for shifting the phase of periodic loads to achieve load control in the smart grid. It is shown that many devices create periodic pulse shape power loads and thus we implement a gradient descent algorithm to define the phase delay of the devices and achieve a first stage of optimization in the smart grid that does not enforce devices to switch off for long time periods, but instead 'play' with their phases by implementing a small time shift of their duty cycle.

[3] Iordanis Koutsopoulos and Leandros Tassiulas, 'Challenges in demand load control for the smart grid', IEEE Networks, vol. 15, no. 5, 2011

[4] I. Koutsopoulos and L. Tassiulas, 'Optimal control policies for power demand scheduling in the smart grid', IEEE Selected Areas on Communic., vol. 30, no.6 ,pp. 1049-1060, 2012

[5] Iordanis Koutspoulos and Leandros Tassiulas 'Optimization and Control meet the Smart Power Grid', e Energy 2011 (New York)

[6] G. Koutitas (UTH), Control of Flexible Smart Devices in the Smart Grid, IEEE Transactions Smart Grids, Vol. 3, No. 3, pp. 1333- 1343, September 2012

[7] G. Koutitas (UTH), L. Tassiulas (UTH), A delay based optimization scheme for peak load reduction in the smart grid, Future Energy Systems: Where Energy, Computing and

Communication Meet (e-Energy), Third International Conference on, pp. 1-4, Spain, May 2012.

[8] G. Koutitas (UTH), L. Tassiulas (UTH), Periodic Flexible Demand: Optimization and Phase Management in the Smart Grid, IEEE Transactions Smart Grids, Vol. 4, No. 3, pp. 1305- 1313, September 2013.

4. Energy Efficiency in Wireless Access

As mentioned above, wireless access networks are among the largest contributor to energy consumption in the telecommunication networks. TREND has deeply investigated the issues related to this network segment, by proposing a number of solutions that include new architectures and planning techniques, efficient transmission techniques, algorithm to dynamically exploit the network node sleep modes.

4.1 Network access architecture and management

The work that is presented in this section describes work performed by TREND partners to provide solutions for energy saving at the access network. The main research focused on the offloading techniques, self optimized network operation, radio network planning.

4.1.1 Offloading techniques

TCP packet flows are usually routed via a single default path in the Internet. This limits the bandwidth of the TCP connection by the capacity of the bottleneck link on the single path. Instead, TCP traffic could be carried over multiple paths. However, TCP performance decreases when multiple paths are used to carry TCP segments (e.g., because of out-of-order packet arrivals caused by path delay differences). Thus, solutions are needed that eliminate side effects of multipath usage.

End-host based solutions suffer from deployment issues. Even if multiple interfaces are available on the TCP end-points, their use is limited by factors like high energy consumption. That is, the use of multiple interfaces drastically increases the power consumption and thus decreases the battery lifetime. Therefore, we suggest using proxy-based transparent multipath TCP (MPTCP) solutions instead of end-host based solutions. The work in this area described a Splitter/Combiner Architecture (SCA) to develop transparent TCP over multiple paths proxies. SCA is presented in a recent IETF draft. TREND partners worked on the development of transparent proxies that are based on the SCA.

Furthermore, MPTCP has been proposed as a mechanism to support transparently multiple connections at the application layer and is under discussion at the IETF. Using MPTCP, a mobile user would mainly use the less congested access point, e.g. WiFi, but would also maintain a second connection to a more congested network, e.g. LTE. The new idea is that both connections would be active and would be used in parallel. Ideally, the most congested connection would not be used unless necessary. In principle, the less congested access points are LTE micro base stations or WiFi access points as they cover smaller area and are closer to users. Moreover, it is well-known that they are more energy efficient than LTE or WiMax macro base stations. Therefore, using MPTCP, we can smartly offload the traffic to more energy efficient access points without degrading the coverage and QoS of users. Also, MPTCP has the benefit of avoiding complex and delay/energy expensive handover, and would adapt to rapidly changing conditions.

However, we show by measurements over a testbed and analytically, that the current MPTCP implementation suffers from performance issues: i) upgrading some TCP users to MPTCP can reduce the throughput of others without any benefit to the upgraded users, which is a symptom of non- Pareto optimality; ii) MPTCP users could be excessively aggressive towards TCP users. Hence, using the current MPTCP implementation, unnecessary traffic would be transmitted over the congested path. This increases the energy cost without any benefit (in terms of throughput) for anybody. The work in this direction is presented in [10-13].

Finally, Offloading data traffic to IEEE 802.11 hotspots is one of the key techniques with which mobile operators aim at dealing with the increasing traffic demand of their users in cellular networks. Usually, these offloads are simply conducted once an end-device has WLAN connectivity. This work identifies gains if the decisions for accommodating certain traffic flows in WLAN consider the characteristics of this technology, i.e., the suitability of traffic being offloaded in terms of occupation of the channel and MAC overhead as result of contention, interference, and fluctuating channels. The contribution of this work is twofold: A performance evaluation compares the novel scheme with common received-signal-strength-based decisions as well as with simpler randomized choices for offloading particular traffic flows. Our scheme, consisting of the two different flavors "Inefficiency" and "Equal Weight", shows substantial improvements over a broad range of factors. Lastly, the results identify operational points of the WLAN cell allowing operators to dynamically choose the mix of the offloaded traffic according to their requirements.

[9] T. Ayar, B. Rathke, Ł. Budzisz, and A. Wolisz, ”A Transparent Performance Enhancing Proxy Architecture To Enable TCP over Multiple Paths for Single-Homed Hosts,” draft-ayar-transparent-sca-proxy-00 (http://tools.ietf.org/html/draft-ayar-transparent-sca-proxy-00.txt), work in progress, February 2012.

[10] R. Khalili (EPFL), N. Gast (EPFL), M. Popovic (EPFL), J. Le Boudec (EPFL), MPTCP Is Not Pareto-Optimal: Performance Issues and a Possible Solution, IEEE/ACM TRANSACTIONS ON NETWORKING, vol 21., no. 5, 2012.

[11] R. Khalili (EPFL), N. Gast (EPFL), M. Popovic (EPFL), J. Le Boudec (EPFL), Performance Issues with MPTCP, INTERNET-DRAFT, MPTCP working group, July 2012.

[12] R. Khalili (EPFL), N. Gast (EPFL), M. Popovic (EPFL), U. Upadhyay (EPFL), J. Le Boudec (EPFL), MPTCP is not Pareto-Optimal: Performance Issues and a Possible Solution, ACM CoNEXT 2012, December 2012.

[13] R. Khalili (EPFL), N. Gast (EPFL), M. Popovic (EPFL), J. Le Boudec (EPFL), Opportunistic Linked-Increases Congestion Control Algorithm for MPTCP, INTERNET-DRAFT, MPTCP working group, February 2013

[14] S. Wiethölter (TUB), M. Emmelmann (Fraunhofer FOKUS, Berlin), R. Andersson (TUB), A. Wolisz (TUB), Performance evaluation of selection schemes for offloading traffic to IEEE 802.11 hotspots, Proc. of IEEE ICC 2012 - Wireless Networks Symposium, Ottawa, Canada, June 2012.

4.1.2 Planning, management of Base Station and Real implementation

Base Stations are the most energy-hungry elements in a cellular network. For this reason, it is of the utmost importance to study how to reduce their consumption. This section describes real implementation aspects of BS power consumption modeling, self optimized LTE network operation towards energy savings and network planning of BS for energy efficiency.

In the first case, we study actual Base Stations data sheets and derived a generic (yet realistic) power profile as function of the load. In addition, we performed extensive real-time measurements of power consumption at component level on our experimental platform composed of a 3G femtocell enhanced with standby mode and wake-up procedures. The work is reported in the references below [15].

For the LTE Self Optimized Management, we propose a model that jointly considers several important characteristics of heterogeneous LTE system, including the usage of orthogonal frequency division multiple access (OFDMA), the frequency selective fading for each link, the interference among different links, and the different transmission capabilities of different types of base stations. We also consider the cost of energy by taking into account the power consumption, including that for wireless transmission and that for operation, of base stations and the price of energy [16].

For BS planning and management, we examined energy efficient planning of cellular networks. The investigation focused on the deployment strategies a mobile network operator can follow and their effects on energy consumption. The study focused on minimum power consumption strategy, that yield to a network consisting of a large number of small cells, the minimum transmitter strategy that yields to a network consisting of a small number of large cells and a hybrid approach. In addition, the effect of the femtocell upon the energy consumption of the network is investigated. The results of this activity are presented in the following papers [17-20].

[15] I. Haratcherev (A-LBLF), A. Conte (A-LBLF), Practical energy-saving in 3G femtocells, IEEE ICC'13 - Workshop on Green Broadband access, to be published.

[16] C. S. Chen (A-LBLF), An Energy-Aware Protocol for Self-Organizing Heterogeneous LTE Systems, IEEE Journal on Selected Areas in Communications (JSAC), to be published.

[17] G. Koutitas (UTH), A. Karousos (Aircom), L. Tassiulas (UTH), Deployment strategies and energy efficiency of cellular networks, IEEE Transactions Wireless Communications, Vol. 11, No. 7, pp. 2552- 2563, July 2012.

[18] T. T. Tesfay (EPFL), R. Khalili (EPFL), J. Y. Le Boudec (EPFL), F. Richter (TUD), A. J. Fehske (TUD), Energy Saving and Capacity Gain of Micro Sites in Regular LTE Networks: Downlink Traffic Layer Analysis, 6-th ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks, October 2011.

[19] K. Dufkova (Czech Technical University in Prague), M. Popovic (EPFL), R. Khalili (EPFL), J. Y. Le Boudec (EPFL), M. Bjelica (Faculty of Electrical Engineering, University of Belgrade), L. Kencl (Czech Technical University in Prague), Energy Consumption Comparison Between Macro-Micro and Public Femto Deployment in a

Plausible LTE Network, e-Energy 2011: 2nd International Conference on Energy-Efficient Computing and Networking 2011, June 2011.

[20] G. Koutitas, L. Chiaraviglio, D. Ciullo, M. Meo, and L. Tassiulas, 'Energy-Aware Base Stations: the Effect of Planning, Management and Femto Layers', Int. Journal of Electrical Engineering, Hindawi, accepted (minor revisions), 2013.

4.2 Saving energy on wireless transmission

The work that is presented in this section describes work performed by TREND partners to provide solutions for energy savings wireless transmissions.

4.2.1 *Energy-efficient Power Control for MIMO channels with partial or full CSI*

In a multiple-input-multiple-output (MIMO) downlink channel, the impact of line-of-sight, out-of-cell interferers and of antenna correlation on the energy efficiency (EE) of the communication is discussed. With reference to a power budget model reflecting the power expenditure of a base station (BS) together with the power employed for training, we provide analytical insights for power control policies either designed in presence of full channel state information (CSI) availability at the transmitter or under the assumption that power allocation does not adapt to channel state dynamically. The maximization of EE has been carried out in the literature under either the assumption of adaptation of the transmitted power to the channel state, or in the static case, where the power is just allocated once, and the transmitter has only access to the statistics of the channel. The work is presented in the references below.

[21] G. Alfano (PoliTO), Z. Chong (TUD), E. Jorswieck (TUD) Energy-efficient Power Control for MIMO channels with partial or full CSI, IEEE/ITG WSA 2012, Dresden, Germany, March 7,8 2012.

[22] A. Zappone (TUD), G. Alfano (PoliTO), S. Buzzi (CNIT), M. Meo (PoliTO), Distributed energy-aware resource allocation in multi-antenna multi-carrier interference networks with statistical CSI, EURASIP Journal on Wireless Communications and Networking, Vol. 2013, to be published

4.2.2 *On the analysis of WiFi communication and WiMAX network entry over single radios*

Future wireless mobile devices will have to support a variety of heterogeneous access technologies while having a limited number of transceiver chains. One of the most challenging tasks remains how to support wireless access in one of the technologies, while preparing a “smooth transition” to another, especially to technologies with a lengthy network entry such as WiMAX. This work proposes an efficient way to organize a WiMAX network entry process while continuing a communication session with stringent QoS requirements via WLAN. We advocate the prioritization of the strict WiMAX timing over the contention-based WLAN channel access. Our results show the applicability of this approach over a wide range of mobile WiMAX parameters, i.e., for different mobile profiles of the WiMAX forum, and identify bounds on the WiMAX downlink load for which the WiFi communication does not suffer quality distortions. The work is presented in the references below.

[23] S. Wiethölter, M. Emmelmann, R. Andersson, and A. Wolisz, "On the analysis of WiFi communication and WiMAX network entry over single radios", in the Proc. of CONWIRE workshop (co-located with IEEE ICC conference), Ottawa, Canada, June 2012.

4.2.3 *Energy-Efficient QoS-constrained ARQ protocols*

The focus of this activity is the definition of a cross-layer approach for the transmission of multiplexed rate-controlled multimedia streams over wireless channels. The idea is to exploit the correlation properties of the wireless channel to reduce the energy consumption due to ARQ retransmissions, while trading off energy-saving with QoS.

The ARQ protocol retransmits every unacknowledged packet either until the packet is correctly received by the next hop, or until the maximum number of retransmission is reached. However, due to the wireless transmission channel correlation properties, bursts of retransmission failures can be present during time interval characterized by high bit error rate. Therefore, if a transmission has failed, it is highly likely that an immediately successive attempt will follow the same sort. Starting from this consideration, the idea is to use a retransmission policy where the transmission is attempted with a probability depending on the number of previous attempts. In such a way, the sender deduces the state of the channel and transmits more rarely when the channel is considered bad. Of course, the choice of the retransmission policy is expected to have a big impact on the effective transmission bandwidth, so affecting the performance in terms of perceived QoS at destination. For this reason, the energy-efficient ARQ protocol is coupled with a source Rate-Controller with the aim of compensating the transmission bandwidth reduction due to the energy saving policies.

In order to evaluate performance in terms of both energy-saving and QoS, a custom simulator has been developed and an analytical model of the whole system is under definition. Preliminary results have been collected, for several retransmission policies in different scenarios, and demonstrate that great energy-saving can be achieved while guarantying network performance. However a deeper analysis is still needed in order to provide guidelines for the design of the configuration parameters.

[24] A. Lombardo (CNIT), C. Panarello (CNIT), G. Schembra (CNIT), EE-ARQ: a Green ARQ-Based Algorithm for the Transmission of Video Streams on Noise Wireless Channels, Network Protocols and Algorithms, Vol. 5, No. 1, March 2013.

[25] A. Lombardo (CNIT), C. Panarello (CNIT), G. Schembra (CNIT), An Adaptive Cross-Layer Approach for Energy-Efficient and QoS-Constrained Multimedia Transmission over Wireless Channels, The Second International Conference on Green Communications and Networking (GreeNets 2012), Gandia, Spain, October 2012.

[26] A. Lombardo (CNIT), C. Panarello (CNIT), G. Schembra (CNIT), Analytically Evaluating the Impact of Wireless Channel Behavior on an Energy-Efficient Rate-Controlled Video Transmission System, SustainIT 2013, October 2013

4.2.4 *Energy efficiency in OFDMA interference wireless networks*

First of all, it should be mentioned that this scenario is very general, and includes as special cases several instances of communication networks, such as multi-cell and femto-cell OFDMA networks, peer-to-peer OFDMA networks, and OFDMA-based multi-tier networks.

In this general scenario, the issues of competitive subcarrier assignment and power control for energy efficiency optimization have been investigated. Here, the energy-efficiency has been defined as the ratio between the achieved throughput and the consumed power. Both the transmit power and the circuit power required to operate the devices has been considered.

The problem has been formulated as a non-cooperative game and employing the tool of Potential Games, non-cooperative games that are guaranteed to admit Nash equilibria have been devised. Moreover, best-response-based algorithms for subcarrier and power allocation have been derived, which are guaranteed to converge to an NE of the considered non-cooperative game.

The derived results have been also extended to the multiple-antenna OFDMA interference networks and to the case in which only statistical CSI at the transmitters is available, In both cases, the asymptotic scenario of a large networks in which the number of users and of deployed receive antennas grow large with a fixed ratio has been analyzed, too.

[27] Zappone, G. Alfano, S. Buzzi, and M. Meo, “Energy-Efficient Non- cooperative Resource Allocation in Multi-Cell OFDMA Systems with Multiple Base Station Antennas”, IEEE Online Green Communications Conference, Greencom 2011, September 26-29, 2011.

[28] Zappone, G. Alfano, S. Buzzi, and M. Meo, “Impact of Incomplete CSI on Energy Efficiency for Multi-cell OFDMA Wireless Uplink”, 17th Workshop on Energy-aware communications, EUNICE 2011, September 5-7, 2011, Dresden.

[29] A. Zappone, G. Alfano, S. Buzzi, and M. Meo, “Non-cooperative Resource Allocation in Multi-Cell OFDMA Systems with Multiple Base Station Antennas”, 8-th International Symposium on Wireless Communication Systems, ISWCS 2011, November 6-9, 2011, Aachen.

[30] L. Venturino (CNIT), C. Risi (CNIT), A. Zappone (TUD), S. Buzzi (CNIT), Energy efficient coordinated user scheduling and power control in downlink multicell ofdma networks, Proceedings of PIMRC 2013, pp. 1 - 5, September 2013

[31] S. Buzzi (CNIT), G. Colavolpe (University of Parma), D. Saturnino (Scuola Sant'Anna di Pisa), A. Zappone (CNIT), Potential Games for Energy-Efficient Power Control and Subcarrier Allocation in Uplink Multicell OFDMA Systems, IEEE Journal of Selected Topics in Signal Processing, Vol. 6, No. 2, pp. 89 - 103, USA, April 2012

[32] S. Buzzi (CNIT), G. Colavolpe (University of Parma), D. Saturnino (Scuola Superiore Sant'Anna di Pisa), A. Zappone (CNIT), Potential Games for Power Control and Subcarrier Allocation in Uplink Multicell OFDMA Systems, 2nd International ICST Conference on Game Theory for Networks, pp. 1 - 8, April 2011

[33] Zappone (CNIT), G. Alfano (PoliTO), S. Buzzi (CNIT), M. Meo (PoliTO), Energy-efficient non-cooperative resource allocation in multicell OFDMA systems with multiple base station antennas and MRC combining, Annual Meeting of the Italian Telecommunication Group, pp. 8, June 2011

4.2.5 *Energy Efficiency in multiple-access relay-assisted wireless DS/CDMA channels*

The issue of energy efficiency in DS/CDMA relay-assisted multiple-access channels has been considered. Amplify-and-forward relaying has been considered and the energy-efficiency has been defined as the ratio between the achieved throughput and the consumed power.

The competitive resource allocation problem has been modeled as a non-cooperative game with the mobile terminals as players and algorithms for transmit power, relay amplification factor, and receiver structure design have been obtained. Moreover, the performance of the derived algorithms have been contrasted against cooperative benchmarks in which the resources are centrally optimized. The best performance is obtained with the MMSE receiver, whereas the MF receiver performs poorly as the number of users grows. As for the ZF receiver, it is seen that it performs similarly to the MMSE receiver, unless the number of users approaches the processing gain N, due to the well-known noise-enhancement phenomenon.

[34] A. Zappone and E. Jorswieck, "Resource Allocation in Amplify-and-Forward Relay-Assisted DS/CDMA Channels," IEEE Transactions on Wireless Communications, Vol. 11, pp. 1271-1276, April 2012

[35] A. Zappone, S. Buzzi, and E. Jorswieck, "Green Power Control and Receiver Design in Relay-Assisted Interference Channel Wireless Networks: A Game-Theoretic Approach", 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies, ISABEL 2011, October 26-29, 2011, Barcelona.

[36] S. Buzzi (CNIT), A. Zappone (TUD), Potential games for energy-efficient resource allocation in multipoint-to-multipoint CDMA wireless data networks, Physical Communication, Vol. 7, pp. 1 - 13, June 2013.

[37] S. Buzzi (CNIT), H. V. Poor (Princeton University), A. Zappone (CNIT), Transmitter waveform and widely linear receiver design: noncooperative games for wireless multiple-access networks, IEEE Transactions on Information Theory, Vol. 56, No. 10, pp. 4874 - 4892, USA, October 2010

4.2.6 *Energy Efficiency in relay-assisted wireless interference networks*

The exponential increase in the use of mobile communication devices poses challenges to operators to meet rising demands for higher data rates and coverage. A solution to this problem includes a denser deployment of base stations so that more users per area may be served with the desired QoS. However, this implies more interference in transmission streams, which causes a higher power consumption for each terminal of the network, if appropriate measures are not taken. As a consequence, mobile users will have to recharge their devices more frequently. In order to improve the situation, studies have been done for finding methods to enhance the energy efficiency (EE) of communication devices and base stations.

The first and most widely used metric to mathematically express the EE of a given terminal has been the ratio between the throughput and the consumed power. Another proposed metric uses the outage probability in place of the throughput. As far as the computation of the consumed power is concerned, however, only the transmit power is considered, whereas the power that is dissipated in the electronic circuitry of each terminal in order to keep the terminal active is neglected. More recently, this assumption has been relaxed, and several papers have begun to address this issue by defining the consumed power as the sum of the transmit power plus a constant term independent of the transmit power, which models the circuit power needed for operating the terminal. Very often, one-hop systems are considered. However, in order to support cell-edge users with high-data rate services under agile frequency reuse, a well established strategy is to install relay stations at certain points in the existing cellular infrastructure. Besides, the use of relays is necessary to overcome shadowing effects due to natural obstacles and buildings, and to improve the network's reliability and throughput. Moreover, employing relays provides a promising addition in enhancing the EE in cellular networks and has recently attracted attention in research.

In this line of research we employ a game-theoretic approach to investigate the issue of EE maximization in an amplify-and-forward (AF) relay-assisted interference channels, accounting for the circuit power dissipated in each terminal. A novel non-cooperative power control game for EE maximization is derived and the following contributions are made.

1) It is shown that the considered non-cooperative game admits a unique Nash equilibrium (NE).

2) It is proved that the best response dynamics (BRD) associated to the game always converges to the unique NE.

3) A cooperative, centralized power control algorithm is derived. This will also serve as a benchmark for the efficiency of the NE of the non-cooperative game.

The power dissipated in the transmitters' electronic circuitry has been set to Pc = 10dBm, and the average EE achieved at the NE of the proposed non-cooperative power control game is benchmarked against that achieved by the proposed cooperative power control with a fairness constraint. Moreover, the initial average EE resulting from a random power allocation, namely the energy efficiency before the resource allocation algorithms come into play, has been reported. The results indicate that the proposed non-cooperative algorithm achieves an EE significantly larger than the initial energy-efficiency. Moreover, when the network is not heavily loaded, the gap with respect to the cooperative approach is limited. Of course, such a gap increases as the number of active users K grows.

[38] A. Zappone, Z. Chong, E. Jorswieck, and S. Buzzi, "Green Resource Allocation in Relay-Assisted Multicarrier IC Networks Considering Circuit Dissipated Power," Third International Conference on Future Energy Systems, e-Energy 2012, 9-11 May, 2012, Madrid.

[39] A. Zappone, Z. Chong, E. Jorswieck, and S. Buzzi,"Energy-Efficient Non-cooperative Power Control in Relay-Assisted Interference Channels Considering Circuit Dissipated Power," IEEE International Conference on Communications ICC 2012, 10-15 June 2012, Ottawa.

[40] A. Zappone, Z. Chong, E. Jorswieck, and S. Buzzi, "Energy-Aware Non-Cooperative Resource Allocation in Relay-Assisted MIMO IC Considering Circuit Dissipated Power," Future Network and Mobile Summit, 4-6 July 2012, Berlin.

[41] A. Zappone, Z. Chong, F. Shen, E. Jorswieck, and S .Buzzi, “Energy-Aware Competitive Resource Allocation in Relay-Assisted Interference Channels,” to be presented at the Ninth International Symposium on Wireless Communication Systems, ISWCS 2012, 28-31 August 2012, Paris.

[42] A. Zappone (TUD), S. Buzzi (CNIT), E. Jorswieck (TUD), M. Meo (PoliTO), A survey on game-theoretic approaches to energy-efficient relay-assisted communications, Proc. of the 24th Tyrrhenian International Workshop on Digital Communications (TIWDC 2013), Italy, September 2013.

[43] A. Zappone (TUD), E. Jorswieck (TUD), S. Buzzi (CNIT), Competitive Energy-Aware Power Control in Relay-Assisted Interference Channels Considering Circuit Dissipated Power, 2013 IEEE 77th Vehicular Technology Conference, June 2013

[44] A. Zappone (TUD), Z. Chong (TUD), E. Jorswieck (TUD), S. Buzzi (CNIT), Energy-aware competitive power control in relay-assisted interference wireless networks, IEEE Transactions on Wireless Communications, Vol. 12, pp. 1860 - 1861, USA, April 2013

[45] A. Zappone (CNIT), Z. Chong (TUD), F. Shen (TUD), E. Jorswieck (TUD), S. Buzzi (CNIT), Energy-aware competitive resource allocation in relay-assisted interference channels, Proc. of the 9th International Symposium on Wireless Communication Systems (ISWCS 2012), August 2012

[46] A. Zappone (CNIT), E. Jorswieck (TUD), Resource Allocation in Amplify-and-Forward Relay-Assisted DS/CDMA Systems, IEEE Transactions on Wireless Communications, Vol. 11, No. 4, pp. 1271 - 1276, USA, April 2012

[47] A. Zappone (CNIT), S. Buzzi (CNIT), E. Jorswieck (TUD), Green power control and receiver design in relay-assisted interference channel wireless networks: A game-theoretic approach, Proc. of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2011), Barcelona, October 2011.

4.3 *Wireless Network Nodes Management*

This section describes management techniques (switch on/off schemes) of wireless nodes. The investigation focuses on WiFi, APs and BSs. Furthermore, the section presents integration of the management techniques to RES for autonomous (net zero) operation. Finally, the management techniques are implemented on a game theoretic investigation for Mobile Network Operators (MNO) cooperation. The investigation covers non cooperative and cooperative theoretical analysis based on classical game theory. The majority of the activities of this part of the TREND project are integrated in two review papers that give the big picture of access network management, as listed below. The investigation of the MNO cooperation is given in a joint paper that is under preparation and is reported in detail within WP1. One can refer to those papers to extract analytical descriptions.

[48] Y. Zhang (PoliTO), L. Budzisz (TUB), M. Meo (PoliTO), A. Conte (A-LBLF), I. Haratcherev (A-LBLF), G. Koutitas (UTH), L. Tassiulas (UTH), M. A. Marsan (PoliTO), S. Lambert (iMinds), An Overview of Energy-efficient Base Station Management Techniques, 24th Tyrrhenian International Workshop on Digital Communications (TIWDC'13), Genoa, Italy, September 2013

[49] L. Budzisz (TUB), Ganji Fatemeh, G. Rizzo, B. Lanoo, Mario Pickavet, Y. Zhang (PoliTO), M. Meo (PoliTO), A. Conte (A-LBLF), I. Haratcherev (A-LBLF), G. Koutitas (UTH), L. Tassiulas (UTH), M. A. Marsan (PoliTO), S. Lambert (iMinds), 'Dynamic Resource Provisioning for Energy Efficiency in Wireless Access Networks: a Survey and an Outlook', IEEE Communications Surveys and Tutorials, at the second review stage (major corrections), 2013.

4.3.1 Base Station management

The papers cited in this section describe techniques for BS management. The main research activities concern the development of centralized, distributed and pseudodistributed control schemes that can be implemented in an online and offline fashion. The investigation further comprises the case of cooperation between two mobile network operators, a scheme that can provide dramatic energy savings. Finally, a combination of network planning and BS management is also examined.

[50] 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.

[51] S. Kokkinogenis and G. Koutitas, 'Base station management schemes in Cellular networks', IEEE Globecom, Aneheim, USA, 2012.

[52] L. Chiaraviglio, D. Ciullo, G. Koutitas, M. Meo, L. Tassiulas, Energy-Efficient Planning and Management of Cellular Networks, 9th International Conference on Wireless On-demand Network Systems and Services (WONS), Courmayeur, Italy, January 2012.

[53] 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

[54] M. Ajmone Marsan (PoliTO), L. Chiaraviglio (PoliTO), D. Ciullo (PoliTO), M. Meo (PoliTO), Multiple Daily Base Station Switch-Offs in Cellular Networks, 4th International Conference on Communications and Electronics (ICCE 2012), Hue, Vietnam, August 2012

[55] A. Conte (A-LBLF), A. Feki (A-LBLF), L. Chiaraviglio (PoliTO), D. Ciullo (PoliTO), M. Meo (PoliTO), M. Ajmone Marsan (PoliTO), Cell Wilting and Blossoming for Energy Efficiency, IEEE Wireless Communications Magazine, Vol. 18, No. 5, pp. 50-57, IEEE Communications Society, October 2011

[56] M. Ajmone Marsan (PoliTO), L. Chiaraviglio (PoliTO), D. Ciullo (PoliTO), M. Meo (PoliTO), Switch-Off Transients in Cellular Access Networks with Sleep Modes, 4th IEEE ICC 2011 Workshop on Green Communications (GreenComm4), Kyoto, Japan , June 2011

[57] M. Ajmone Marsan (PoliTO), M. Meo (PoliTO), Green Wireless Networking: Three Questions, he 10th IEEE IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net 2011), Favignana island, Sicily, Italy, June 2011.

[58] M. Ajmone Marsan (PoliTO), M. Meo (PoliTO), Energy efficient wireless Internet access with cooperative cellular networks, Computer Networks Journal, Special Issue: Wireless for the Future Internet, Vol. 55, No. 2, February 2011.

4.3.2 *Access Point management*

The papers cited in this section describe similar activities focused on the case of indoor networks. The main activities are presented in the references below. The research evaluated the potential for energy saving by use of sleep modes in various types of small-cell networks, and the impact of energy saving strategies on network performance.

[59] W. Vereecken (IBBT/iMinds), M. Deruyck (IBBT/iMinds), D. Colle (IBBT/iMinds), W. Joseph (IBBT/iMinds), M. Pickavet (IBBT/iMinds), L. Martens (IBBT/iMinds), P. Demeester (IBBT/iMinds), 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.

[60] 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.

[61] F. Ganji (TUB), L. Budzisz (TUB), A. Wolisz (TUB), Assessment of the Power Saving Potential in Dense Enterprise WLANs, 24th annual IEEE Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'13), pp. 2835 – 2840, London, Great Britain, September 2013.

[62] S. Chiaravalloti (TUB), F. Idzikowski (TUB), L. Budzisz (TUB), Power consumption of WLAN network elements, TKN Technical Reports Series, Vol. TKN-11-002, Berlin, Germany, August 2011

[63] A. P. Couto da Silva (Federal University of Juiz de Fora), M. Meo (PoliTO), M. Ajmone Marsan (PoliTO), Energy-Performance Trade-off in Dense WLANs: a Queuing Study, Elsevier Computer Networks, Vol. 56, No. 10, pp. 2522–2537, Elsevier Computer Networks, June 2012.

4.3.3 *Integration of Renewable Energy Sources*

In this section we consider smart radio and datacenter networks based on concepts and algorithms applied on smart grids. We explore the case of a cellular network comprising macrocells, microcells and femtocells that 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 network and achieve net zero operation or carbon free service delivery. In addition, the role of the telecommunication operator to the energy market is examined.

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.

[64] G. Koutitas (IHU), L. Tassiulas (UTH), Smart Grid Technologies for Future Radio and Data Centre Networks, IEEE Communications Magazine, Vol. in press, No. in press, to be published.

4.3.4 Mobile Network Operators cooperation

This work is mainly part of WP1, but there was a strong collaboration between WP2 and WP1 towards the realization of the final target. In this work we developed a game theoretic approach to study MNO cooperation. The investigation covers the case of two and three MNOs that provide coverage and QoS in a specific geographical area. The scope is to keep QoS at same standards while reducing the number of MNOs that have their BSs in on mode. With this approach great energy savings are observed for the network as a whole. The investigation gives a holistic view of the problem, since it covers the case of non cooperative game and cooperative game. The overall savings and the roaming costs for the MNO cooperation are also computed as a function of the technology of the BSs that can be described by parameters a and b. Parameter a presents the proportionality factor of BS power consumption according to traffic whereas parameter b models the no load losses of the BS due to the operation of cooling and in general the network critical physical infrastructure. The linear relationship between the BS power consumption (P) and the traffic (L) is given by $P=a*L+b$. It is shown the cooperation strategy and the overall gains do not depend on the parameter a but they are very sensitive to b.

[65] G. Koutitas (UTH), G. Iossifidis (UTH), B. Lanoo (iMINDS), M. Tahon (iMINDS), S. Verbrugge (iMINDS), P. Ziridis (IHU), L. Budzisz (TUB), M. Meo (PoliTO), M. Marsan (PoliTO), L. Tassiulas (UTH), A Game Theoretic Approach for Mobile Network Operators Cooperation, to be submitted Journal, 2013.

5. Energy Efficiency in Wired Access

5.1 Network access architecture and management

The work that is presented in this section describes work performed by TREND partners to provide solutions for energy saving at the wired network access. The main research focused on the NGPON architectures, energy efficiency in file/content distribution systems and gateway virtualization.

5.1.1 Comparison of NG-PON architectures

2nd generation NG-PON (NG-PON2) technologies are still under discussion for standardization within FSAN/ITU-T groups. In this work, the energy efficiency of the main NG-PON2 candidates has been analyzed. XGPON1 and GPON have also been considered as a reference.

For each candidate technology, the bandwidth capacity per user and the physical reach of the fiber infrastructure were determined for various degrees of equipment sharing. The degree of equipment sharing is influenced by changing the split ratio, i.e. the number of connected households per feeder fiber. Various user demand scenarios were considered, and the network was dimensioned for optimal energy efficiency in each case. The model parameters, relations between them and their values have been identified. Increasing user demands imply less potential for equipment sharing; the extent to which this impacts the energy consumption, depends on the chosen NG-PON2 architecture.

Using the developed model and the performance parameters, the TNP (Total Network Power) consumption can be obtained for each solution in order to obtain an energy efficiency comparison and optimization in an NG-PON2 simulation scenario. A first estimation of the OLT cards and ONTs consumption for each solution has been obtained and communicated in Trend Work Package WP1.

Furthermore, the work was responsible to calculate the TNP consumption of a realistic massive deployment scenario using NG-PON2 technologies. In collaboration with the PP7-ACCORDANCE Project, a techno-economic model was acquired, comprising experimental information on the different geotypes present in a large city deployment. A techno-economic tool decides on central office locations, in a main central area with dense urban geotype and three outer rings of less populated areas. A deployment model focused on energy consumption is being considered, using a green field approach to calculate the total equipment count and resulting power consumption per user of each NG-PON2 approach in the realistic massive deployment scenario. The work is reported in the references below.

[66] S. Lambert (iMinds), B. Lannoo (iMinds), D. Colle (iMinds), M. Pickavet (iMinds), J. Montalvo (TID), J. Torrijos (TID), P. Vetter (Alcatel-Lucent, Murray Hill, NJ, US), Power Consumption Evaluation for Next-Generation Passive Optical Networks, 24th

Tyrrhenian International Workshop on Digital Communications (TIWDC '13), Genoa, Italy, September 2013.

[67] S. Lambert (iMinds), J. Montalvo (TID), J. Torrijos (TID), B. Lannoo (iMinds), D. Colle (iMinds), M. Pickavet (iMinds), Energy efficiency analysis of next-generation passive optical network (NG-PON) technologies in a major city network, International Conference on Transparent Optical Networks (ICTON 2013), Cartagena, Spain, June 2013.

[68] S. Lambert (iMinds), J. Montalvo (TID), J. Torrijos (TID), B. Lannoo (iMinds), D. Colle (iMinds), M. Pickavet (iMinds), Energy Demand of High-Speed Connectivity Services in NG-PON Massive Deployments, 39th European Conference and Exhibition on Optical Communication (ECOC 2013), London, United Kingdom, September 2013

[69] S. Lambert (iMinds), B. Lannoo (iMinds), D. Colle (iMinds), M. Pickavet (iMinds), J. Montalvo (TID), J. Torrijos (TID), P. Vetter (Alcatel-Lucent, Murray Hill, NJ, US), Energy Efficient High Speed Triple-Play Services in a Major City PON Deployment, IEEE Journal of Selected Areas in Communications (JSAC), under review, 2014

5.1.2 *Theoretical Study of Energy Consumption in the File/Content Distribution Processes*

The proposed approaches in the field of energy efficient networking at either the device level (e.g. new hardware design or the system level (energy efficient routing or sleep modes in wired and wireless networks, aim to achieve an "energy proportional" network. This is, making the energy consumed by the network proportional to its traffic load. Specifically, hosts servers and user terminals) are responsible of the major portion of the whole Internet power consumption. Current energy efficient strategies in this domain aim at making the energy consumed proportional to the level of CPU or network activity of hosts, and often imply switching off or to a low power mode the devices when not active. However, energy proportionality of hardware does not suffice to define a complete energy efficient framework for end users hosts. Indeed, new solutions must be found that implement energy efficient services (e.g. file sharing, web browsing, etc.) to optimize the utilization of hosts and network resources.

In this work, we focus on the file distribution service, which is one of the most widespread services on the Internet. Indeed, some of the existing file distribution services, such as peer-to-peer (p2p), one-click-hosting (OCH), software release, etc., represent a major fraction of current Internet traffic. Despite of the importance of these services, to the best of the authors' knowledge, little effort has been dedicated to understanding and achieving energy-efficiency in the context of file distribution applications. In addition, within the context of corporate/LAN networks, other operations such as software updates are also file distribution processes. All this makes essential to deeply investigate energy-efficiency in file distribution, in order achieve a truly Green Internet.

[70] K. Verma (IMDEA), G. Rizzo (IMDEA), A. Fernandez-Anta (IMDEA), R. Cuevas-Rumin (UC3M), A. Azcorra (UC3M), Greening the Internet: Energy-Optimal File Distribution, 2012 IEEE 11th International Symposium on Network Computing and Applications, August 2012.

5.1.3 *Energy savings by Residential Gateway (RG) virtualization*

Hardware decomposition and power consumption breakdown of regular Residential Gateways has been analyzed. Functionalities suitable for being translated into the operator's network have been studied.

By translating most of CPU functions to the operators network, a rough reduction up to 43%/56% of energy saving could be achieved in the customer premises in ON and idle states, respectively. Nevertheless, a more detailed analysis of CPU power reduction related to L3 and management functions is required.

[71] J. Montalvo (TID), J. Torrijos (TID), J. Xia (HWDU), Y. Ye (HWDU), Energy Efficiency in PON Home Network Scenarios With Network Enhanced Residential Gateways, IEEE Conference of Networking, Sensing and Control, to be published.

6. Conclusions

6.1 Summary

This section presents the aggregated achievements of WP2 TREND in each technical domain (TD). The reader can refer to Figure 1 that provides the mapping of activities. Within TREND project what was achieved is:

Table 1. WP2 Mapping of Achievements

Technical Domain	**Network Map**	**Main Topics of Interest**	**Energy Savings**
TD2.1	Home and wireless access	• Prototype 3G WiFi femtocell with sleep modes • Femtocell management schemes • Smart grid algorithms for energy savings at home appliances	• Approx. 70% according to user activity in the house • Approx. 20% • Approx. 20%
TD2.2	Wireless and fixed access	• NGPON network power consumption analysis • Residential gateway virtualization for energy savings • Multipath TCP energy savings and offloading • Energy Consumption in File/Content Distribution Processes	• Depends on architecture. Approx 10% • The energy that is saved is equal to the difference in energy consumption when a user is served by LTE base station and when he is served by WiFi base station.
TD2.3	Wireless and Fixed access	• Resource allocation MIMO • Resource allocation in relay assisted networks • Resource allocation in OFDM networks • Energy-Efficient QoS-constrained ARQ protocols	• Up to 20% • Up to 20% • Up to 20% • Up to 10%

TD 2.4	Wireless Access	• Energy efficient network planning	• Approx. 60% (prefer small cells)
		• Base station and access point switch on/off schemes	• Up to 40% and extra 25% if offloading to femtocell layer is used
		• Integration with renewable energy sources	• Theoretical net zero operation
		• MNO cooperation	• Up to 40%

The schemes proposed in this report could lead to the (estimated) energy consumption reductions summarized in Table 1. These numbers are provided only as purely indicative ones (according to corresponding references), since their relative impact on the global picture depends on the consumption of the segment they address and the considered network scenario. However, these figures show that much saving (roughly between 20 and 40%) can be achieved at the access network by adopting energy efficient techniques.

6.2 *WP2 Integration*

This section describes the integration of WP2 TREND partners. It presents the mobility actions that were performed during TREND in order to achieve the joint publications and results of WP2. It is mentioned that the graph presented below does not include collaborations over teleconference meetings but includes only mobility actions in the form of real travels. The total number of mobility actions was 21.

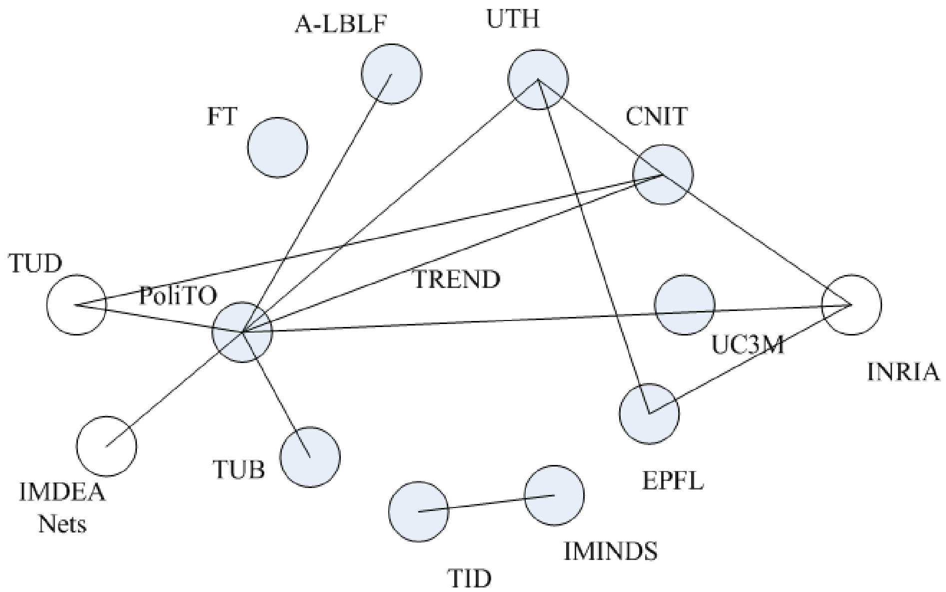

Figure 4. Mobility actions of WP2 TREND. 21 mobility actions. Non colored circles indicate collaborating institutions.

6.3 WP2 TREND Beneficiaries

WP2 of TREND developed techniques and solutions that can be applied by third parties in order to achieve energy efficiency and dynamic energy management. The main beneficiaries of the WP2 TREND solutions are presented in the following table.

Table 2. Beneficiaries of WP2 TREND

Name of Beneficiary	WP2 TREND Result
End User	• Developed a WiFi-3G femtocell prototype that incorporates sleep modes • Developed solutions to manage WiFi Access Points and femtocells • Developed smart grid (demand response) algorithms to manage energy at households • Multipath TCO for offloading
Network Operator	• Developed startegies for energy efficient planning of BSs • Developed BS and WLAN APs on/off schemes (centralized, distributed, pseudo-distributed) • Energy efficient transmission techinques (MIMO, power control, OFDM) • Cooperation schemes for relay networks • Multipath TCP for offloading • Autonomous networking including RES and BS operation
Internet Provider	• Developed resource management algorithms in internet nodes • Developed techniques to reduce the number of Optical Line Terminals (OLTs) equipment • Developed theoretical approximations to allocate power consumption to file/content distribution processes

6.4 Recommendations and perspective

Regulation and incentives towards energy efficiency

Improving power efficiency is certainly under the responsibility of equipment vendors, but incentives are to be initiated from the operator side, with requests and specifications. Improved power efficiency requires new technologies or new network architectures. It is then an operator decision to upgrade its network or change its architecture. Cost savings generated by energy consumption reduction are already an incentive for network operators. Regulations also play an important role as an incentive toward vendors and operators to meet certain standards. As an example, due to the free-market, the publication of the power consumption values could be a positive trigger for vendors to make their equipment more energy-efficient. Regulation though may also have negative impact on the total network power consumption, for instance when it leads to the deployment of multiple infrastructures or equipments to avoid a dominant position of an operator.

Keeping a global vision

Energy consumption reduction should be thought beyond the actors' own equipment keeping in mind that savings on one part of the networks may result in an increase in other parts. End-to-end vision is inevitable to make the most of the solutions. And it is also a must to make the solution compatible with operators' requirements. QoS is a good example.

One of the most critical aspects of access networks is that they guarantee coverage of the service area. Thus, the possible trade-off between QoS and energy savings should be evaluated with respect to the possible impact on failure rates of network devices, on network resilience and on possible service disruption due to the energy efficient mechanisms.

7. List of Acronyms

ADSL	Asymmetrical Digital Subscriber Line
AP	Access Point
ARQ	Automatic Repeat Request
BS	Base Station
DSM	Demand Side Management
DR	Demand Response
FTTH	Fiber To The Home
GA	Genetic Algorithm
HAN	Home Area Network
ICT	Information and communication technologies
IP	Internet Protocol
IRA	Integrated Research Action
ISP	Internet Service Provider
MTCP	Multipath TCP
NGPON	Next Generation Passive Optical Network
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditure
RES	Renewable Energy Sources
SLA	Service Level Agreement
UHDTV	Ultra High Definition Digital Television
TD	Technical Domain
QoS	Quality of Service
WP	Work Package