Telecommunication Networks as Smart Energy Consumers in Space and Time

C. Lange[1,*], R. Schlenk[2], M. Schlosser[3], F. Pfeuffer[4], I. Gamrath[4], A. Werner[4], D. Kosiankowski[1], A. Betker[1], D. Prantl[5] and H. Lehmann[1]

[1]*Deutsche Telekom, Telekom Innovation Laboratories, Winterfeldtstraße 21, 10781 Berlin, Germany*
[2]*Alcatel-Lucent Deutschland AG, Thurn-und-Taxis-Straße 10, 90411 Nürnberg, Germany*
[3]*Berlin Institute for Software Defined Networks (BISDN), Christburger Straße 45, 10405 Berlin, Germany*
[4]*Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB), Takustraße 7, 14195 Berlin, Germany*
[5]*Cisco GmbH, Friedrich-Ebert-Straße 35, 34117 Kassel, Germany*
[*]*Corresponding Author: christoph.lange@telekom.de*

Received 1 June 2016; Accepted 27 July 2016;
Publication 4 October 2016

Abstract

Telecommunication networks and power grids are parallel hierarchical maintenance structures with system-wide reach. National telecommunication carriers figure among the top energy consumers in developed national economies and, thus, it is important to improve the network energy efficiency – in particular in the light of the increasing user and usage demands. One promising option is to exploit traffic dynamics by introducing load-adaptive operation modes leading – besides internal energy efficiency improvements – to a systemic electricity consumer with spatially and temporally fluctuating electricity demands.

New ways of coupling both of the two network types open up the possibility of an optimized joint control of the 'energy' and 'transport' dimensions of the telecommunication network. Due to the high overall electricity demands of

Journal of Green Engineering, Vol. 6, 1–22.
doi: 10.13052/jge1904-4720.621

telecommunication networks, their new flexibility can be assumed to be of a relevant scale, leading to optimized overall energy consumption. To fill out such a role, networks have to be made amenable to control signals of different nature. Thus, the hitherto static and unidirectional powering of the telecommunication network is replaced by feedback options and overall load variability in space and time.

In the project DESI, funded by a German federal grant and conducted by a topically wide-ranging consortium, the different coupling mechanisms such as load-adaptive network operation mode or distributed energy storage capability were studied in detail along the entire information and communication technology services delivery chain. This article summarizes theoretical and practical project results and gives insights on their expected future relevance. Project results showed that the coupling and joint optimization leads to an overall optimized energy efficient and reliable telecommunication network operation at the same time offering valuable stability services to power grids.

Keywords: Telecommunication network, energy efficiency, network topology and traffic model, network optimization, smart grid, controllable load, demand-side management.

1 Introduction

Telecommunication networks and power grids are designed to follow human activity patterns. As a consequence, the *spatial* hierarchical organization of both network structures mirrors the average population density distribution. The *temporal* network traffic load follows diurnal, weekly and seasonal variations of human behavior and increasingly machine activity.

In this article we investigate how the two parallel network structures are coupled and what options arise thereof against the background of rising user and usage demands in information and communication technology (ICT) networks and the trend towards an increased utilization of renewable energies in electrical power generation. Historically, this coupling was established in a unidirectional way, in the sense that the technical equipment of the telecommunication network needed powering and was, thus, connected to the power grid in a suitable way. Nowadays, however, the telecommunication network acquires the ability to act back onto the power grid: several different mechanisms lead to the electrical load of the communication network becoming variable in space and time. These mechanisms of introducing adjusting screws into the telecommunication network will be studied with respect to their drivers, their leverage and their realization specifics.

This article gives an overview over intentions, approaches, and major results of the DESI project ("Durchgängig Energie-Sensible IKT-Produktion", Pervasively Energy-Efficient ICT Production).

Based on Figure 1 the leitmotifs and the approaches of the DESI project are illustrated:

1. Depending on temporal and spatial characteristics, the demand for data transport capacity in the telecommunication networks varies.
2. The network is rendered responsive to these signals and adapts its transport capacity.
3. Overall energy savings may be registered, the energy provision burden is lightened during low-demand times.
4. The generation side in the energy provisioning system – when integrating renewable energy sources – fluctuates uncontrollably due to variations in solar and wind power.
5. Buffer capacity in the power installations of the telecommunication network (uninterruptable power supply systems, UPS) is utilized to react to load shifting demands of the power grid.

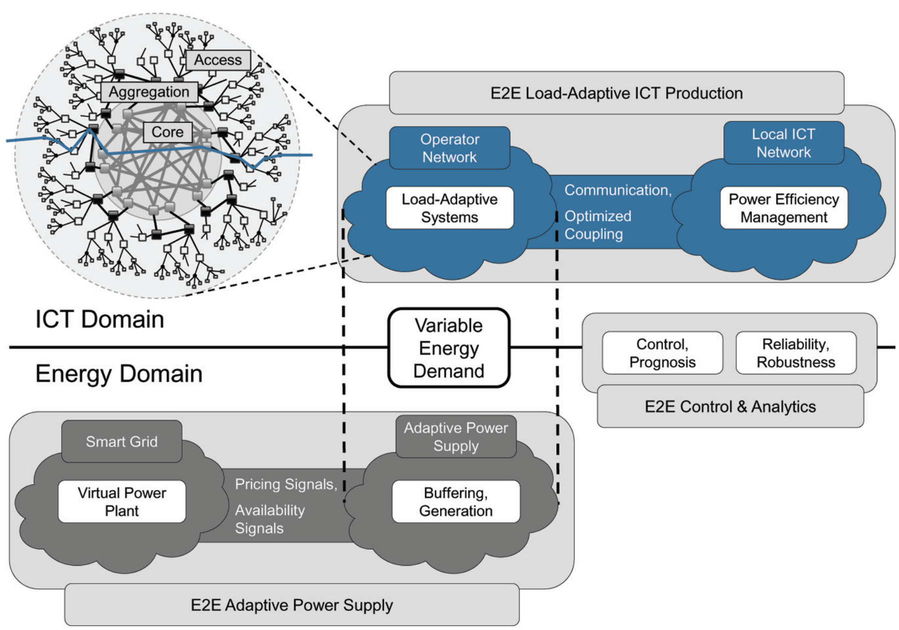

Figure 1 Overview of the principle telecommunication network and power grid structural interplay.

6. The telecommunication network as a whole is transformed into a DSM-ready (demand side management) consumer.

The principal advances that are reported in this article are, thus, concerned with rendering the ICT network flexible in two dimensions:

- adaptability of the data transport capacity to varying traffic demand,
- adaptability of the telecommunication network's energy consumption to power grid signals (i.e. capability of load-shifting in the telecommunication network domain to follow power grid demands and price signals).

These two new degrees of freedom for the telecommunication network may be utilized simultaneously in respective use cases. Therefore, a unified control plane for the actual traffic processing and transport and its powering infrastructure is needed.

For the clearness of argument, we structure this article according to the degrees of freedom cited above: In the second section we explain how the telecommunication network is made responsive to temporally varying traffic demands by introducing load-adaptive regimes. The third section discusses the energy load-shifting properties of the telecommunication network. In the fourth section, the interplay between the telecommunication network as systemic electricity consumer with spatial-temporally varying demands and load-shifting capability and the power grid is analyzed. In section five the main results are summarized and their practical relevance is discussed.

2 The Demand-Driven Telecommunication Network

Typically, telecommunication networks are catered in design and operation to traffic loads they have to transport. Thus, their dimensioning and operation relies on inherited principles from an era in which telecommunication networks were operated statically based on peak-load demands and therefore they were monolithic power consumers. However, caused by the need to operate telecommunication networks efficiently and because of sustainability reasons, in the recent past load-adaptive operation modes have been developed in that respect, e.g. [1, 2]. At first sight, such modes allow for significant efficiency improvements – resulting in lowered operational expenses. When looking deeper into the coupling options between telecommunication network and power grid, this, in addition, provides a degree of flexibility that can be exploited for the benefits of the energy provisioning system – as discussed in sections three and four.

2.1 Network Topology and Traffic Modelling

The network for end-to-end ICT service delivery is composed of local customer networks and the broadband operator network. In an inset in Figure 1 an exemplary end-to-end connection is shown over the different domains (access, aggregation, core) of the operator network. In principle, load-adaptive operation can be applied to all network segments. As typically there is no direct control of the local customer network by the operator, a coupling has to be established technically – by communication – or economically – by a tariff design containing suitable incentives.

The operator network model presented here is hypothetical, but closely based on a realistic nationwide German fixed communications network, comprising the aggregation and core sections and the supporting optical transport network. Figure 2(b) shows the core IP network part of the model. In this network section, the total number of devices, power consumption and costs can be reduced by routing, multiplexing and grooming the number of necessary links. By using Cisco's Visual Networking Index 2014–2019 [9] and internal forecasts of a large telecommunication provider, the peak data flow in Germany was approximated to be 10 Tb/s in 2012. This traffic volume was generated from approximately 36 million private households, 25 million business computers, 62 million mobile users of radio networks [10] and core transit traffic between public Internet exchange points (IXP). Data centers were assumed to be located at the IXP locations. An important

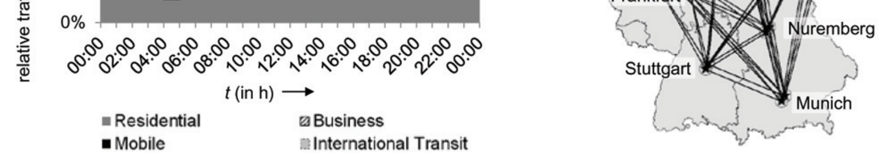

Figure 2 a) Temporal operator network traffic characteristics, b) national operator IP core network topology.

objective of this model is the structural assessment of this traffic flow. Internal measurements within an operator's network, plus other regional non-public measurements returned different residential and business traffic flows over a 24-hour time period Figure 2(a) shows an exemplary diurnal working day traffic curve. While the traffic shares change between an average working day and an average weekend day, the size and the shape of the daily traffic does not vary significantly between the different days of the week [7]. Every network node's traffic is obtained as the total traffic from the flow curve at the specified time, scaled with the relative number of users at the considered node. The resulting traffic curve is the basis for obtaining temporally varying traffic demands between all network nodes. The core network demand matrix contains the total demand between all core network node pairs – consisting of residential, business, mobile, and international traffic. These matrices are the starting points for the network optimization discussed below.

2.2 Traffic-Load Adaptive Network Elements

To operate telecommunication networks load-adaptively, first of all its individual components have to be prepared for dynamic operation and adaptation, e.g. [3]. Depending on the network segment, different approaches are required: Power efficiency management solutions enable the monitoring and control of *local networks* at the customer's premises. These systems manage the energy consumption of all IP-connected devices on the local network (computers, phones, etc.) including distributed office and data center equipment as well as facility devices. For instance, the entire desktop/mobile compute environment, including displays, can be integrated by connecting to appropriate software control solutions, such as e.g. Microsoft Active Directory, within an enterprise, which provides a list of all known computers. These are then polled using, e.g., the Windows Management Instrumentation (WMI) protocol to gather information about the systems, including hardware setup and utilization. Using this information the current energy consumption of these devices is modelled and updated periodically. To mitigate energy waste, policies are implemented that shut down devices that are currently not used.

In the DESI project, this solution was enhanced towards networking devices, such as Ethernet Local Area Network (LAN) switches. Control mechanisms include coordination of standby modes and lowering the traffic bandwidth towards the operator's network.

The operator's access networks are typically designed as star-likes structures with Digital Subscriber Line Access Multiplexers (DSLAMs), Optical

Line Terminals (OLTs) or Long-Term Evolution (LTE) base stations as central nodes and the customers as end points. In this topology, there are no alternative transmission paths, thus load adaptive operation are negotiated (autonomously) between central node and end point. Examples of standardized and commercially available (load-adaptive) power management features include DSL L2/L3 mode, Energy Efficient Ethernet (EEE) Low Power Idle (LPI) [4], and LTE power amplifier control [5]. The inset in Figure 1 sketches the principle characteristic network structure explained here.

In contrast, aggregation and core networks are partly or fully meshed with (additional) redundant resources that are activated in case of failures. Moreover, the architecture is split into an optical transport layer and an Internet Protocol/Multi-Protocol Label Switching (IP/MPLS) routing layer [6]. In principle, load-adaptive power management could be controlled by autonomous protocols. However, the lack of interoperability and standardization in conjunction with strict traffic outage requirements call for a central control function. In the meshed and redundant topology of these network segments, this control function enables new energy saving strategies, e.g., by re-routing traffic and partially shutting down network elements.

As today's heterogeneous aggregation/core networks are not operated load-adaptively yet, the effort of transforming a commercially available core network switch into a load-adaptive network element was taken. By choosing a high-capacity Optical Transport Network (OTN) platform that natively switches wavelengths, Optical Data Units (ODUs), and packets, it has been made sure that results of the investigations can be applied to network elements of similar design as well, such as IP routers. To this end, a generic network element model was developed (Figure 3(a)) that can be parameterized for any

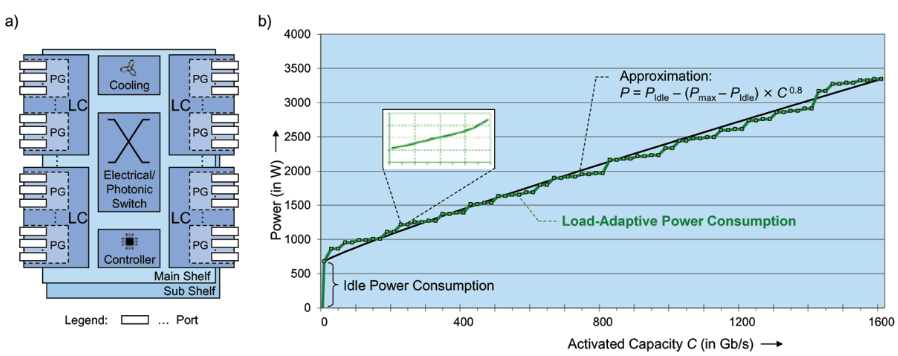

Figure 3 a) Generic network element model, b) measured/approximated power consumption characteristic as a function of activated capacity.

chassis-based network node in the access, aggregation, or core network. Such a modular network element consists of one or more chassis managed by a system controller. Each of these shelves is composed of common equipment (controller cards, switch fabric, internal cooling, and power supplies) as well as transmission line cards (LC) with port groups (PG) and ports (P).

While common equipment typically exhibits a low load-adaptiveness and thus determines the idle power consumption of a system, dynamic power management for individual transmission ports can be controlled much better. Also because network providers deploy partially loaded systems initially and then fill up ports over time, power consumption needs to be optimized for the idle case nevertheless. In the DESI project, the basic power-save techniques rate adaptation and sleeping were applied to various components and subsystems of the network switch. Load-adaptive power management features were implemented, such as capacity- and temperature-adaptive fan speed control, sleep modes for ports, port groups and entire line cards, serializer-deserializer (serdes) power-save, RAM cell microsleep, and adaptive voltage scaling for the switch fabric. The load-adaptive power consumption for a configuration of 80×10 Gb/s Ethernet over 40 Gb/s OTU3 wavelength-division multiplexing (WDM) transport was measured: Power over activated capacity yields a remarkably load-proportional curve (Figure 3(b)). Taking into account the optimizations for near-idle configurations, in simulations it can be approximated by a power-law characteristic with an exponent smaller than 1 [14].

In a second step, the activation/deactivation behavior of these power-save modes was analyzed: Depending on port data rate, power-save modes with wake-up times in the order of microseconds are controlled autonomously in an opportunistic manner if data is buffered locally. If wake-up takes longer, typically an additional signal is required between sender and receiver in order to activate the receiving side early enough.

Savings of almost 100% were achieved by powering down complete entities such as line cards (in terms of the incorporated individual components) – with the drawback of relatively long activation times, however. Despite efforts within the project of reducing these to a minimum, they remain in the two-digit seconds range. As buffering over these timescales is not feasible, an overarching control function needs to orchestrate the wake-up between the client and optical transport layers.

The DESI project work indicates that load-adaptive networking is already possible with existing (albeit slightly modified) network elements. This is an important result, because today's network equipment will stay in the field for the next 10–15 years, while the still-to-be-developed control plane functions can be added later through software updates.

2.3 Energy-Efficiency Related Telecommunication Network Optimization

Based on a given telecommunication network structure and expected traffic demands, an optimization of utilized network configurations can be performed to ensure a least possible consumption of energy in the operation of the telecommunication network. For the core network, the potential for energy savings is substantial, due to the wide choice of alternative routes for transported traffic. The computation of a power-minimized configuration that uses a suitable routing for a traffic situation at a fixed point in time can be done with the help of an Integer Linear Programming Model (see [7, 8] for details). From this, we can conclude that at times of low traffic demand the instantaneous power consumption could, in principle, be reduced by about 70% in the core network, and by about 4% in the metro or aggregation network sections, where re-routing of traffic is not possible due to their unique non-meshed structure. This exhibits the principal potential for power savings.

Focusing on the energy consumption, this implies that almost 28% of the energy spent in the core network can be saved. To realize this, however, a reconfiguration of the complete core network would be necessary every half hour, which is hardly applicable in practice. Hence, a more realistic question is: How much energy can be saved if only a limited number of reconfigurations is allowed per day or each configuration is required to run for a minimal amount of time once it is activated – or both. In other words, a feasible set of network configurations has to be found that covers all occurring traffic situations and yields minimal total energy consumption. This problem is solved by a graph-theoretical approach; see [7]. Figure 4 shows the power consumption and the corresponding energy used over one day for a maximal number of six reconfigurations with no restriction on the minimal running time of each configuration. It is apparent that a considerable part of the maximally possible energy savings can already be achieved with only six reconfigurations per day.

All results apply to 100-Gb/s-transponder technology with link-protection in the optical layer. Different prerequisites and other practice-oriented side constraints can be taken into account [7, 8]).

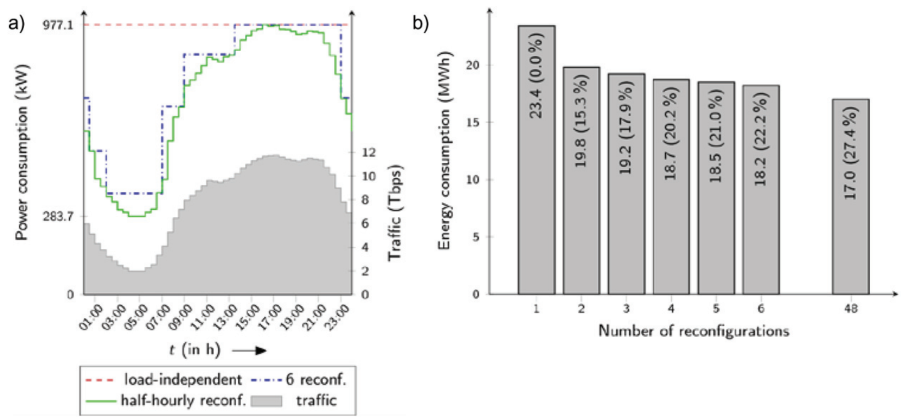

Figure 4 Telecommunication network optimization results for different exemplary switching regimes in the core network: a) diurnal traffic and power functions and b) corresponding diurnal energy consumption results and associated energy savings' percentages.

3 The Energy Load-Shifting Network

In the classical power provisioning paradigm, powerful point sources feed into the higher voltage layer of a hierarchically structured grid, whence the power is cascaded down to the low-voltage distribution layer to the points of consumption. At any given point in time, generation and consumption have to be exactly balanced in order to keep the system stable. The principal lever for this balance is generation control. With the advent of renewable energy sources which come to a large extent as low-intensity area sources, this unidirectional and hierarchical provisioning pattern is disturbed. Furthermore, the generation cannot be controlled but is essentially dependent on stochastic variables such as sunshine or wind intensity. Hence, the balancing activity shifts to the consumption side. In such a situation the existence of a system-wide energy consumer with a potentially controllable spatially resolved electrical load would be a powerful systemic stabilizer.

Telecommunication networks range among the strongest energy consumers in developed economies. A huge – and increasing – number of network nodes and a growing energy demand for network-integrated data centers cover the entire system and present a meaningful power amplitude.

3.1 Telecommunication Network Infrastructure Characteristics

Telecommunication network nodes can be hierarchically classified: from a few core sites with an electrical load in the megawatt class down to a long tail of access sites with electrical loads of a couple of dozen kilowatts. For Germany, the total number of network production sites of the incumbent operator's fixed network is in the order of 8.000. Figure 5(a) shows the principle of the power supply chain of telecommunication network equipment: Usually telecommunication operators' central offices are provided by low-voltage Alternating Current (AC) mains from the Distribution Grid Operator (DGO). To feed the telecommunication equipment and supporting machines for heating, ventilation and air conditioning with appropriate Direct Current (DC) voltage, a rectifier in combination with large battery cascades provides uninterruptible power supply (UPS).

To harden the critical infrastructure "telecommunication" against disasters and attacks, these sites are equipped with technical means to uphold functionality even when the powering grid breaks down: in the more important network sites – besides the above mentioned large battery banks –, additional emergency Diesel generator sets are available. Viewed from the *Energiewende* (the German term for "energy turnaround") perspective, these security measures are seen as decentralized storage and recovery functionalities and provide

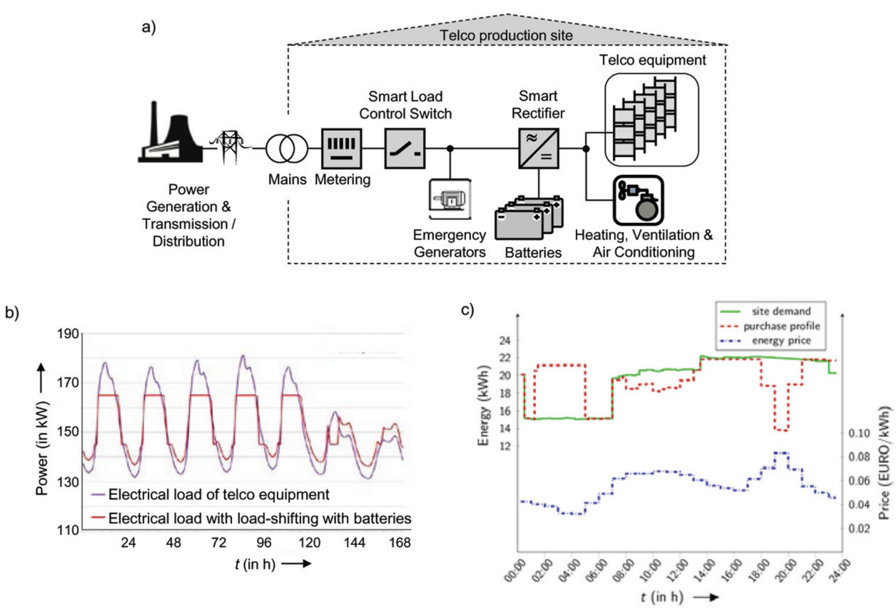

Figure 5 a) Principle structure of telecommunication network equipment power supply, b) general effect of load-shifting with batteries on a weekly basis, c) effects of the battery optimization for a typical day.

the spatially resolved flexibility potential mentioned above. Here, a general approach to utilize this potential for smart energy services is presented while upholding its primary purpose of securing the network operation. In order to not compromise this primary purpose of the UPS batteries, only a fraction of their electrical capacity – in the order of 20–30% – is used for load-shifting: This is possible due to the inherited over-dimensioning of the batteries' capacity compared to the network equipment's electrical load – as replacement cycles of battery banks are by far larger than those of telecommunication equipment that in turn benefits several times from technology progress within the batteries' life time, usually reducing its electrical load.

To offer the telecommunication equipment's electrical load in central offices as controllable load to the grid, a smart load-control switch (see Figure 5(a)) is added and the rectifiers operate with smart functionalities. Then the telecommunication equipment can be switched off from mains and is served completely from the batteries although no power outage occurred. The smart rectifier controls the charging/discharging current for the batteries (to limit the overall load and provide battery health improvements) and can feed the telecommunication equipment with a mixture of power from mains *and* battery. With these control options, the ability arises to shift loads and to change load-curves over time (Figure 5(b)). A normal electrical load profile over a week is shown with the typical daily ups and downs. With smart load-control switching enabled, peak electrical loads can be cut by shifting the battery loading timeslots to low traffic-load time periods. The result is a "smoothed" electrical load profile curve.

3.2 Network Demand Side Management

The infrastructure characteristics of a national carrier described in the preceding paragraph may now, from the power grid perspective, be regarded as a huge potential with respect to the newly arising power balancing demand mentioned above. Several principal properties have to be pointed out:

"Lazy Assets": The energy game change in developed economies brings with it a severe capital expenditures' problem – new generation machinery, new devices and new grid lines have to be funded. In this situation any existing resource (storage capacity, given grid connection points, completed approval procedures etc.) that may be enabled to contribute to the new system is valuable.

Ubiquity: It is a quasi-natural property of former national telecommunication networks to cover the entire system in question. Therefore, a high probability is given that the described technical properties are available at concrete places where they may contribute to desired systemic services.

Flexibility: The storage capacity in the network's UPS systems provides the opportunity to decouple the simultaneousness of energy generation and consumption. Furthermore, the telecommunication network's ability to channel data traffic via different routes from A to B generates a spatial flexibility. Finally, the option of a backend aggregation of the distributed resources (aka Virtual Power Plant) presents a scale flexibility: whereas a single site may have a load-shifting potential of a mere several dozen kilowatts, concerted action of sites easily enters the megawatt class.

Putting these properties together, it is immediately obvious that the telecommunication network as a whole has the potential to be turned into a grid-serving consumer. Section four describes in detail the control architecture that has to be put into place to leverage this potential.

3.3 Optimization of Network Site's Battery Load Schedules

The computation of optimal load schedules for batteries to enable demand side management at an ICT network equipment site follows a typical smart grid scenario: Optimal times for charging the battery by purchasing energy or discharging it to power the local equipment have to be determined, depending on the prices at the energy stock market, relevant technical and operative constraints, and a forecast of the site's power consumption. This coupling of network and energy domain is a step towards the inter-domain optimization of the network site.

The battery load schedules are computed for a certain optimization horizon (typically 6 to 30 hours), which usually corresponds to the availability of input data and is longer than the actual decision horizon (typically 15 minutes); a re-optimization takes place each time the decision horizon has passed, to account for unpredicted changes in the input data (see [15] for more details).

The problem is solved using a Mixed Integer Nonlinear Programming Model that takes the physical properties of the battery into account by appropriately mathematically modelling the batteries' charging and discharging processes (e.g. by using C-rates). Furthermore, the model incorporates cost effects that originate from the charging and discharging processes and their impact on battery life time. The characteristics of the energy losses while discharging the battery lead to nonlinearities in the model, which are tackled by using problem-specific heuristics and piecewise linear approximations. In contrast, previously used models did either not consider losses at all [11] or only constant losses [12]. One of several objective functions can be chosen: Minimization of energy expenses, minimization of the peak power transmission rate, or approximation of a given purchase profile.

In Figure 5(c), the purchase profile (red) shows the effects resulting from the optimization of the battery schedule for a typical day. During low-price times (blue curve) the battery is charged, while energy stored in the battery is used for supplying the site at high-price times. The energy consumption of the site (green) shows the effects of the network optimization: During low-traffic times, network equipment is switched to power-save. A further benefit is the reduction of the peak power transmission rate (at 1:30 pm), which, without optimized battery usage, would result in a higher system usage fee. The total savings (energy costs plus usage fee) add up to 11.3% in the shown example.

Within the DESI project, we implemented the optimization of battery load schedules and applied it to a network production site in a setting as shown in Figure 5(a) The optimized battery schedules were integrated into regular operation procedures and proved to be applicable in real-world usage. In another exemplary production site deployment, the smart load control is used to provide flexibility to power utility companies: The AC frequency is controlled by dynamically changing the demand side at the telecommunication production site. Also here, an operational deployment has been proven applicable to real-world usage.

4 Piecing It Together: Unified Control Architecture

4.1 General Control Approach

To operate a network according to the DESI approach a suitable control architecture was developed, see Figure 6. The main component is the Control Layer, split into two function blocks: One controls the network part and manages the routing decisions for both the IP and the OTN layers. The other controls the energy part, i.e., the batteries. The network controller consists of two modules for Traffic Monitoring and Traffic Routing. These are supported by the Energy Aware Optimization modules from the Application Layer.

4.2 Smart Power Supply Enhanced Demonstrator Network

A four-node demonstrator network was realized with IP and OTN network elements to demonstrate the DESI approach. The IP layer was fully and the OTN layer partly meshed. An energy-aware control plane was implemented

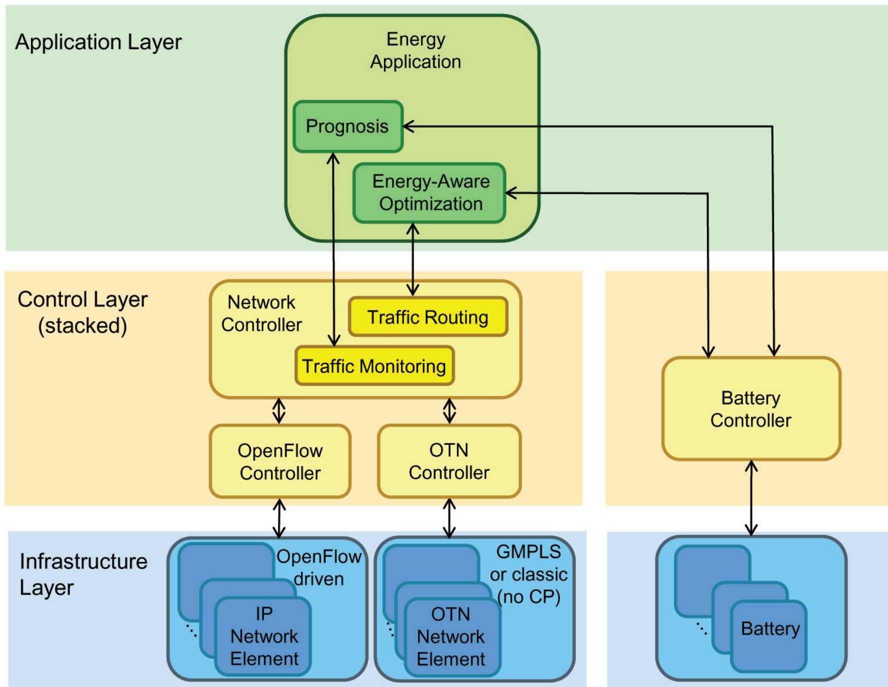

Figure 6 Energy control plane architecture.

that provisions the IP routers and the optical transport network. All IP routers are located on an IP evaluation system, each with the OpenFlow [13] protocol as control channel. The optical transport network is controlled via the Transaction Language 1 (TL/1) protocol.

The controller is continuously querying the network load in the IP router and checking the power consumption of the network elements. The network load is retrieved using the flow statistics provided by OpenFlow and then transformed to demand matrices. The queried information is used in the controller's Prognosis and Optimization module to calculate the most energy efficient network topology according to the current measurement.

The network controller maps the network topology provided by the optimization module to the current network, following the "make before break" principle, i.e., creating all physical links before using them and removing links only after all traffic is moved to other links. The current optimization is based on an offline calculated superset of network topologies. Based on the findings from Section 2.3, the number was limited to three, namely, a peak-load scenario, an average day scenario and a night scenario.

In the demonstrator setup, we measured a reduction in energy consumption of 15–30% (depending on the network node) between a non-optimized and an optimized "night" configuration. For a more realistic nationwide core network with its greater scope for reconfigurations, an overall reduction of 25% for a complete business day was *simulated.*

In the accompanying pilot installation in a central office (see Section 3.3) of a real telecommunication network, the energy controller *optimizes* the charging/discharging cycles of UPS batteries based on continuous power measurements from the network, in addition to demand forecasts, and price signals from the power supply grid. This pilot installation has proven the technical feasibility in a real-world network environment.

Finally, it could be shown that traffic load-adaptive network operation will result in extended switching options for the energy storage equipment – not only because of lower energy consumption in off-peak times but also because additional UPS batteries become available for energy load-shifting purposes.

5 Relevance and Conclusion

The DESI project's main focus was set on the optimization of load-adaptive operation approaches over the entire ICT services delivery chain as well as on approaches to exploit the structural characteristics of the two system-covering infrastructures telecommunication network and power grid in a suitable interplay. The results are very promising with respect to both domains:

- Important network element characteristics have been improved that now allow for traffic load-adaptive operation in optical networks and the calculations and optimizations suggest significant energy efficiency improvement potential. Due to replacement cycles of network equipment the introduction in real operator networks will not be immediate, but such kind of network elements will contribute to improved sustainability of ICT services production in the future. The DESI demonstrator network proved the feasibility and the improvement potential.
- The energy load-shifting capabilities of the telecommunication operator network have been investigated and its flexibility potential has been attested. Battery scheduling capabilities have been economically evaluated and the battery and load shifting control has been deployed

exemplarily in a real-world operational network production site. However, the environments may differ significantly in different countries, in particular with regard to energy prices and regulation – requiring thorough assessment of possible solutions.

Smart and load-adaptive telecommunication networks allow, on the one hand, for a more efficient operation of the telecommunication network itself targeting at savings of operational expenditures. As they are system-covering like the energy grid, on the other hand, they can be seen as a flexible and controllable spatially distributed electrical load that allows for offering flexibility and stability services to energy grid operators. Thus, such a coupling and interplay between telecommunication networks and energy grids, essentially paralleling each other spatially, creates a symbiosis employing mutual advantages.

Acknowledgments

The project DESI (http://www.desi-it2green.de/) has received public funding from the German Federal Ministry of Economics and Energy (Bundesministerium für Wirtschaft und Energie) through the IT2Green program (http://www.it2green.de/en/index.php).

The authors would like to thank all contributing members of the project staff, the project sponsor and the accompanying research as well as all supporters and benevolent stakeholders of the DESI project.

References

[1] Lange, C., Kosiankowski, D., Betker, A., Simon, H., Bayer, N., Hugo, D. v., Lehmann, H., and Gladisch, A. (2014). Energy efficiency of load-adaptively operated telecommunication networks. *IEEE/OSA J. Lightw. Technol.* 32, 571–590.

[2] Bolla, R., Bruschi, R., Davoli, F., and Cucchietti, F. (2011). Energy efficiency of the future internet: a survey of existing approaches and trends in energy-aware fixed network infrastructures. IEEE *Commun. Surveys. Tuts*. 13, 223–244.

[3] Mahadevan, P., Sharma, P., Banerjee, S., and Ranganathan, P. (2009). A power benchmarking framework for network devices. *Lect. Notes Comput Sci*. 5550, 795–808.

[4] Christensen, K., Reviriego, P., Nordman, B., Bennett, M., Mostowfi, M., and Maestro, J. A. (2010). IEEE 802.3az: the road to energy efficient ethernet. *IEEE Commun. Mag*. 48, 50–56.
[5] Chen, T., Yang, Y., Zhang, H., Kim, H., and Horneman, K. (2011). Network energy saving technologies for green wireless access networks. *IEEE Wireless Commun. Feature Topics Issue Green Radio Commun. Netw*. 18, 30–38.
[6] Idzikowski, F., Orlowski, S., Raack, C., Woesner, H., Wolisz, A. (2011). Dynamic routing at different layers in IP-over-WDM networks — Maximizing energy savings. *Opt. Switch. Netw*. 8, 181–200.
[7] Betker, A., Gamrath, I., Kosiankowski, D., Lange, C., Lehmann, H., Pfeuffer, F., Simon, F., Werner, A. (2014). Comprehensive topology and traffic model of a nationwide telecommunication network. *J Opt. Commun. Netw.* 6, 1038–1047.
[8] Betker, A., Kosiankowski, D., Lange, C., Pfeuffer, F., Raack, C., Werner, A. (2012). Energy efficiency in extensive IP-over-WDM networks with protection. *Operat. Res. Proc.*, 93–99.
[9] Cisco Systems. (2016). *Visual Networking Index: Forecast and Methodology 2014–2019*. Available at http://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/vni-forecast.html
[10] Hintemann, R. (2014). *Entwicklung der Computernutzung in Haushalten, Unternehmen und Behörden im Jahr 2014*. Berlin: Borderstep Institut.
[11] Barbato, A., Carpentieri, G. (2012). "Model and algorithms for the real time management of residential electricity demand," in *IEEE Energy Conference and Exhibition (ENERGYCON)*, pp. 701–706.
[12] Fischetti, M., Sartor, G., Zanette, A. (2013). A MIP-and-refine matheuristic for smart grid energy management. *Int. Trans. Operat. Res*.
[13] Open Networking Foundation. (2011). *OpenFlow Switch Specification, Version 1.2 (Wire Protocol 0x03)*.
[14] Schlenk, R., Lange, C., Lehmann, H., Vleugel, R. (2013). "Taxonomy of dynamic power saving techniques in fixed broadband networks," in *14 ITG Symposium Photonic Networks*, Vol. 241, ITG (Ed.) Offenbach: VDE-Verlag, pp. 30–37.
[15] Draegert, A. Eisenblätter, A., Gamrath, I., and Werner, A. (2016). "Optimal battery control for smart grid nodes," in *Optimization in the Real World – Towards Solving Real-World Optimization Problems*, K. Fujisawa, Y. Shinano, and H. Waki (eds.), Berlin: Springer.

Biographies

C. Lange (christoph.lange@telekom.de) received the Dipl.-Ing. degree (diploma) in electrical engineering and the Dr.-Ing. degree (doctorate) in communications engineering from the University of Rostock, Germany, in 1998 and 2003, respectively.

From 1998 to 2006 he was with the Institute of Communications Engineering of the University of Rostock, where his research interests included the equalization and optimization of wired and wireless communication systems with an emphasis on multicarrier and multichannel communication.

In 2006, he joined T-Systems as part of the Deutsche Telekom group. Since 2009, he has been with Telekom Innovation Laboratories, the central research and innovation (R&I) department of Deutsche Telekom AG, in Berlin, Germany. Currently, his work is focused on strategies for the future development of broadband communication networks – concentrating on the energy efficiency and sustainability of telecommunication networks as well as on access network evolution topics.

Dr. Lange has published extensively on communication engineering and networking topics.

R. Schlenk (ralph.schlenk@nokia.com) received the Dipl.-Ing. (M. Sc.) degree in electrical engineering from University of Erlangen, Germany, in 2000. In the same year he joined Lucent Technologies' Optical Networking Group in Nürnberg, Germany. Since then, his work has spanned the areas of optical transmission simulation, prototyping of electronic and optical equalizers for long-haul transmission systems, embedded software development for packet switching, and system architecture definition. He is currently managing software development for optical transport switches at Alcatel-Lucent.

Mr. Schlenk has authored/co-authored various technical conference papers and holds patents for mobile and optical transmission networks.

M. Schlosser (michael.schlosser@bisdn.de) received the Diploma in Computer Science in 2001 from the Technical University of Berlin, Germany. His diploma thesis was done at the Institute for Software Engineering and Theoretical Computer Science. From 2001–2015 he was with the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institute, in Berlin, Germany, as a research assistant in the Photonic Networks and Systems department. In 2016 he joined Berlin Institute for Software Defined Networks, Berlin, Germany.

His current research interests include optical core and access networks. He has been involved in various national and international research projects. He has authored/co-authored various scientific publications.

F. Pfeuffer (pfeuffer@zib.de) received the Dipl.-Math. degree in mathematics from University of Erlangen, Germany, in 2006 and the Dr. rer. nat. degree in mathematics from the University of Magdeburg, Germany, in 2012.

From 2008 to 2011 he was a Research Assistant with the Institute of Mathematical Optimization of the University of Magdeburg and from 2008 to 2012 a Ph.D. Student of the International Max Planck Research School for Analysis, Design and Optimization in Chemical and Biochemical Process Engineering. Since 2012 he has been a Postdoctoral Fellow with the Working Group Telecommunications at Zuse Institute Berlin, Germany. His current research interests include mathematical methods for the design and operation of telecommunication networks.

I. Gamrath (inken.gamrath@zib.de) received the Dipl.-Math. degree in mathematics from Technical University Berlin, Germany, in 2012.

She is currently pursuing the Ph.D. degree in mathematics at Technical University Berlin. Since 2012 she is a Research Assistant with the Department Optimization at Zuse Institute Berlin, Germany.

Her research interests include mathematical methods for nonlinear optimization problems, in particular for energy optimization.

A. Werner (werner@zib.de) received the Dipl.-Math. degree (M.S.) from University of Würzburg, Germany in 2002 and the Dr. rer. nat degree (Ph.D.) in mathematics from Technical University Berlin, Germany in 2009.

From 2003 to 2009 he was a Research and Teaching Assistant with TU Berlin, after which he joined Zuse Institute Berlin (ZIB) as a Postdoctoral Fellow, since 2011 as Head of the Working Group Telecommunications within the Department Optimization at ZIB. His research interests include mathematical models and algorithms, in particular for telecommunication networks.

Dr. Werner has authored/coauthored various papers in mathematical journals and conference proceedings and is a member of the DFG Research Center Matheon.

D. Kosiankowski (dirk.kosiankowski@telekom.de) studied micro-electronics and holds a graduate engineer certificate (Dipl.-Ing.) which he received in 1995 from Technical University of Dresden, Germany. He has over 15 years of experience in the field of copper and optical telecommunication networks.

Since 1995 he has been with Deutsche Telekom in different R&D departments and subsidiaries. In 2009 he joined Telekom Innovation Laboratories in Berlin. His current activities are focused on strategies and forward looking work about the ongoing development of transport network architectures and especially the future of next generation network architectures within Deutsche Telekom.

Mr. Kosiankowski has authored or co-authored several national and international technical conference or journal papers.

A. Betker (andreas.betker@telekom.de) received the Dipl.-Ing. degree (diploma) in electronics technology and precision engineering from the Technical University of Dresden in 1982. He has been with Deutsche Post/ Deutsche Telekom since 1982 and has been active in different fields of research and development like concept and design of hybrid circuits, fiber-laser coupling and special measurement on fiber optics. Since 2009 he is with Telekom Innovation Laboratories in Berlin, Germany.

Currently, his work is focused on design and optimization of existing and future optical transport network architecture.

D. Prantl (dprantl@cisco.com) received the Dipl.-Phys. (M. Sc.) degree in physics from the Technical University of Kaiserslautern, Germany in 2003. He joined Cisco with the acquisition of JouleX in 2013. Before that he was part of the JouleX founding Team in 2009 with more than 12 years of experience in the networking and information security areas of IT. He is the Lead Architect of Cisco Energywise Management. He works with major partners including Rockwell, Schneider Electrics and Johnson Control to jointly create industry leading solutions for Cisco's global customers. He leads research activities with some of the company's largest partners including Deutsche Telekom to further enhance Cisco's capabilities.

Mr. Prantl has authored/co-authored various technical conference papers.

H. Lehmann (h-lehmann@telekom.de) received the diploma degree in Physics in 1988 and a PhD in Theoretical Physics in 1992, both from Humboldt University Berlin, Germany, respectively. Following postdoctoral academic work at Oxford University and the German National Society for Mathematics and Informatics, he joined the telematics subsidiary of Volkswagen Group in 1999 where he held the position of Innovation Manager. In 2006, he joined Telekom Innovation Laboratories, the central R&I unit of Deutsche Telekom, where he is Research and Innovation Director for Smart Energy responsible for a portfolio of innovation projects.

His principal scientific and innovation interests are self-organization, complex systems and optimization in a wide variety of application areas.

Dr. Lehmann was founding Thematic Area Leader for "Smart Energy" at the European Institute of Technology and Innovation in 2010 where he remains an advisor. He is a member of several national and international industrial, academic and administrative bodies and discussion groups. Dr. Lehmann has published extensively in theoretical physics, informatics, engineering and business topics.