

# Framework for Evaluating Energy Efficiency of Access Networks

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**Abstract**— The ever-growing number of Internet users, the introduction of new bandwidth-hungry applications and services as well as the vision of the Internet of Things will set very high requirements on future access networks. Already today there are many different coexisting network technologies and protocols in the access area that have been developed and introduced to fulfill different needs of Internet users and heterogeneous applications. The growing complexity and increasing energy consumption of access networks raise a need for a comprehensive and effective modeling framework that enables a fast projection of energy efficiency of different access network infrastructures. This paper presents a comprehensive framework that joins technological parameters and various configuration options with socio-demographic characteristics and varying user behavior. The modeling framework can be used to evaluate different deployment and migration scenarios for both wireless and wired access networks by means of predicted energy efficiency. Taking into account possible further developments on technology, applications and traffic characteristics, the modeling framework enables predictions on the access related energy demands raised by forecast trends in conjunction with accompanying equipment change options. This modeling framework may serve operators of access networks to select network migration paths that are effective in the short term and efficient in the long term.

**Index Terms**— access networks; energy efficiency; modeling and simulation

## I. INTRODUCTION

THE number of both broadband subscribers and end-user devices has been increasing rapidly in the last decade [1]. This trend is expected to continue in the future. Additionally, introduction and broad use of high-end applications increasingly drive the need for high capacity access networks. The most complex part of today's Internet is the access network area, which also contributes most to the total energy consumption of the global network infrastructure [2],[3]. According to the vision of the "Internet of Things", it is expected that in the foreseeable future, a huge number of smart autonomous devices will communicate via the Internet. All these trends foster the need for more efficient access networks.

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Recently, there has been quite some research on assessing and improving the energy efficiency of access networks [4]-[12]. Most of the works either concentrate on energy-efficient devices and structures or consider only a certain part of the complex and heterogeneous access network infrastructure. In most cases, wired and wireless technologies are treated separately. In this study, we evaluate the energy efficiency of the entire access network infrastructures by considering both wired and wireless access as well as the wireless backhaul used to connect base stations to the backbone. Additionally, we consider the variety of end-user equipment, socio-demographic characteristics and application usage to cover all important aspects needed to appropriately estimate the energy efficiency of access networks concerning possible future developments.

The paper is organized as follows. The next section introduces the modeling framework and describes the structure of the models used to analyze end-user devices, application usage and access network technologies. Section III presents exemplary results obtained by the framework to analyze the energy efficiency of a nation-wide access network infrastructure. Finally, Section IV summarizes the findings and draws conclusions.

## II. MODELING FRAMEWORK

The ultimate aim of the modeling framework presented here is to enable a holistic assessment of access networks and to help understanding complex dependencies among socio-demographic trends, technologies, applications and usage patterns. It could also serve to indicate potentials and risks of different approaches and to assist policy makers in deploying a policy framework towards a sustainable Internet access.

The technical scope of the framework is shown in Fig. 1. The figure illustrates technologies and devices considered in this study. The boundaries of the system under consideration are on one side the interface to the backbone network, i.e. the uplink of the aggregation switch, which is commonly located at network provider premises, and on the other side the customer premises equipment (CPE) used to consume network services. Usually, the aggregation stage is not considered as part of the access network; however, we include it for better comparability of access variants. In the following, we describe three submodels that are used to: i) analyze user behavior and applications, ii) predict trends in the end-user equipment sector and iii) evaluate access networks by means of energy

efficiency. The three submodels joined to obtain an overall representation of the entire system. For example, development of new end-user devices affects both applications and user behavior, while itself is influenced by socio-demographic trends. All these aspects influence the bandwidth demand and the traffic pattern at network terminals, which, on the other hand, have an impact on network design and performance. Similarly, a broad availability of high data access rates and powerful user devices can accelerate the development of new applications and may lead to a notable user behavior change.

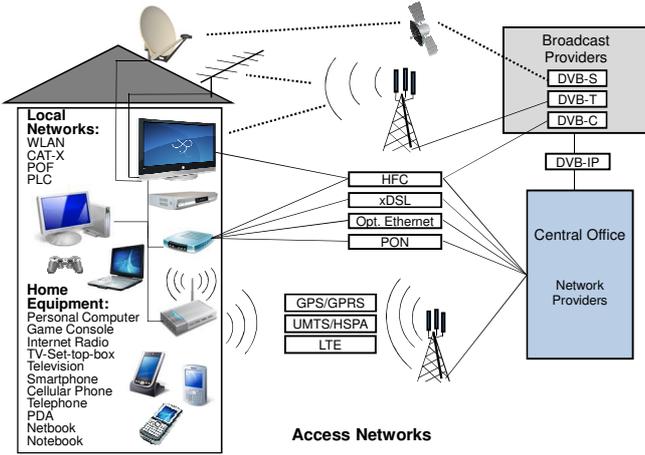


Fig. 1. The scope of the modeling framework.

### A. User Behavior, Applications and Traffic

To assess the energy efficiency of different technologies and deployment scenarios we need to model the traffic that is transported over the provided access capacity. We start with stating the traffic load  $v_a$  caused by typical applications  $a$  while in use (see Table 1). Next we sketch when and for how long an application is commonly used by different user groups. We use five user groups ( $u_1 - u_5$ ), i.e., being children, teenager, young, mature, and the elderly. The usage variation over the time-of-day  $t_d$  is included by normally distributing the usage likelihood across the day to get  $p_{a,u}(t_d)$ :

$$p_{a,u}(t_d) = \frac{1}{d_a(u)\sqrt{2\pi}} e^{-\frac{[t_d - t_a(u)]^2}{2d_a(u)^2}}, \quad (1)$$

where  $t_a(u)$  is the group specific center of the usage period per day and  $d_a(u)$  is halve the time interval during which an application is used per day. The curves express than the usage patterns for each application per user group. Concluding the data base, we rate the popularity of applications for each user group by the parameter  $p_d(u)$ . The application usage  $p_u(a)$  (and thereby application mix) can be changed by adjusting the popularity figures  $p_d(u)$ , while the application consumption patterns (user behaviors) can be changed by adjusting  $p_u(a)$ ,  $t_d(u)$ , and  $d_d(u)$ . The splitting into user groups is essential because it enables us to flexibly consider diverging trends.

TABLE I. TRAFFIC CAUSED BY DIFFERENT APPLICATIONS/SERVICES IN USE.

|       | SERVICES                  | Downlink [MByte/h] | Uplink [MByte/h] | Ref. |
|-------|---------------------------|--------------------|------------------|------|
| Voice | Telephone                 | 28.8               | 28.8             | [13] |
|       | VoIP                      | 28.8               | 28.8             | [13] |
|       | Online Music Streaming    | 72.0               | 1.5              | [13] |
| Video | Videoconference           | 310.5              | 310.5            | [13] |
|       | SDTV (Broadcast)          | 900.0              | 18.0             | [14] |
|       | HDTV (Broadcast)          | 3,600.0            | 75.0             | [*]  |
|       | VoD (Video on demand)     | 900.0              | 16.0             | [14] |
|       | HDoD (HD on Demand)       | 3,600.0            | 70.0             | [*]  |
|       | Online Video Streaming    | 720.0              | 16.0             | [*]  |
| Data  | Classic Internet Services | 12.0               | 3.0              | [*]  |
|       | Online Gaming             | 28.8               | 25.2             | [*]  |
|       | File Sharing              | 52.7               | 47.7             | [*]  |
|       | Home Office via VPN       | 41.9               | 31.4             | [*]  |
|       | Cloud Services            | 21.1               | 9.0              | [15] |
|       | Remote Home Monitoring    | 0.5                | 3.0              | [14] |

[\*] – values obtained by measurements/calculations

To obtain the utilization of wired and wireless access networks, the traffic caused by an average household and an average mobile customer needs to be calculated, respectively. Using the socio-demographic distribution of groups  $p_u$  stated in Fig. 2 we can sum up the popularity weighted usage patterns and get the average demand pattern per application over a day:

$$v_a(t_d) = v_a \sum_u p_u p_{a,u}(t_d). \quad (2)$$

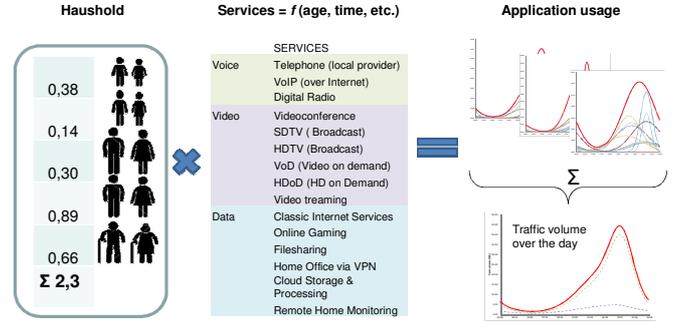


Fig. 2. Access utilization assessment model for an average household.

If the demand exceeds the maximum link capacity provided by a technology, application dependent performance degradation occurs and diminishes the popularity of heavily affected applications. To consider this effect we add a feasibility weighting of applications  $p_d(T)$  per technology and divide the used capacity by the provided capacity  $v_T$  to get the utilization of a technology over a day:

$$e_T(t_d) = \frac{1}{v_T} \sum_a p_a(T) v_a(t_d), \quad (3)$$

which can be used to assess the utilization and, consequently, the energy efficiency of different access technologies. The many degrees of freedom preserved are needed to model socio-economic trends, which are essential for projections.

### B. Model of End-User Equipment

The introduction of new equipment only gradually changes the energy-efficiency over time. The products deployed prior the change will be used in parallel for a potentially long time. Only a negligible percentage of users belong to the early adopters, who get the newest technology just because it is novel. To enable a quick technology adoption new products need to provide essentially demanded features not supported by the current technology. Still, most customers wait until a technology is assumed mature before they even consider to let go of well-tried legacy equipment. Fig. 3a sketches the typical shape of any product sales cycle (upper curve), together with the popularity change over time (lower curve). Note that the sales rise supports wider popularity, and the sales decline lags the popularity because of maintenance and repair demands.

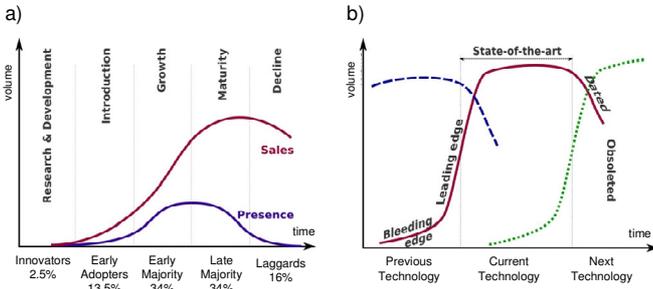


Fig. 3: a) The product life-cycle and b) the technology life-cycle.

Looking back on past major developments we recognize that an IT technology typically dominates the market for approximately ten years, once it takes off (Fig. 3b). Slow changes delay the realization of energy efficiency improvements, but too quick changes cause a strong demand to operate comparable technologies in parallel, which hardly is energy-efficient. Surprising hypes in the popularity and temporary usage of approaching novel applications cannot be excluded, and these may turn the figures dramatically in the mid-term. Such temporary exception can be ignored in the long term, but they heavily influence short term decisions [16]. The most efficient long-term migration path may not be the most economical in the short term. Thus, increasing the energy-efficiency demands changes. If investing in efficiency does not lead to energy savings in the long term, it likely becomes a failure.

The complete product-energy-consumption-cycle, from production to disposal, is here out of the scope, basically because the plurality of devices and manufactures as well as the uncertainties upon future devices hinder a reliable prediction. Our target is to evaluate the operational energy consumption implications of upcoming technology changes, and to identify the long term most efficient. Still, we need a model for the end-user equipment changeover. This we achieve by assuming the 10-years technology-cycle (Fig. 3b), and prognoses on the rise and decline of evaluated technologies:

$$\begin{aligned} d_{bleeding} &= f(\text{marketing, features, novelty}) , \\ d_{edge} &= f(\text{affinity, sales, performance}) , \\ d_{decline} &= f(\text{life-cycle, use-time, competition}) , \end{aligned} \quad (4)$$

which expresses that the duration of phases is influenced by a variety of factors shown in Fig. 4.

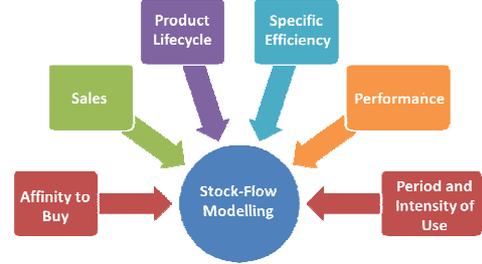


Fig. 4. Exemplary stock-flow model

We skip the first phase  $d_{bleeding}$  prior take off and assume a rise and fall duration of 5 years for the low efficiency scenario, 3 years for the business as usual scenario and no overlap at all for the high efficiency scenario. Basing on these assumptions we obtain trapezoid curves for  $p_T(t_y)$ , the popularity of different technologies over the projection years  $t_y$ . The result of the stock-flow modelling yields the average number of items in operation at customer sites  $n_T(t_y)$ :

$$n_T(t_y) = \int_{t_0}^{t_y} p_T(t_i) - p_T(t_i - t_0 - d_T) dt_i , \quad (5)$$

where  $d_T$  is the average time a device of technology  $T$  remains in use. The numbers  $n_T(t_y)$  yield the technology weighting factors required to correctly merge the utilization curves presented in eq. (3) to state the utilization curves  $e_s(t_y)$  for different scenarios:

$$e_s(t_y) = \frac{1}{24} \sum_T n_T(t_y) \int_{0^h}^{24^h} e_T(t_d) dt_d . \quad (6)$$

Equation (6) provides the base to perform case studies, from which we can predict the change in energy-efficiency that a technology changeover may bring about. In addition, the stock-flow model can be used to analyse which factors most effectively support energy improvements.

### C. Model of Access Networks

A generic representation of the access network model is shown in Fig 5. The user traffic profiles determined by the model described in Section II. A. are used as an input to the model of access networks in order to determine the utilization of network resources.

The access network is first designed according to the requirements on capacity, coverage, number of subscribers and the choice of technology. Various technology and application related parameters need to be taken into account. There are different submodels for wireless and wired parts including the wireless backhaul. The mix of technologies for each submodel is chosen independantly, while the input traffic of the wireless backhaul is determined by the traffic aggregated in the base

stations. In order to keep the complexity of the model at a reasonable level, the model deals with time-of-day dependant average data rates only.

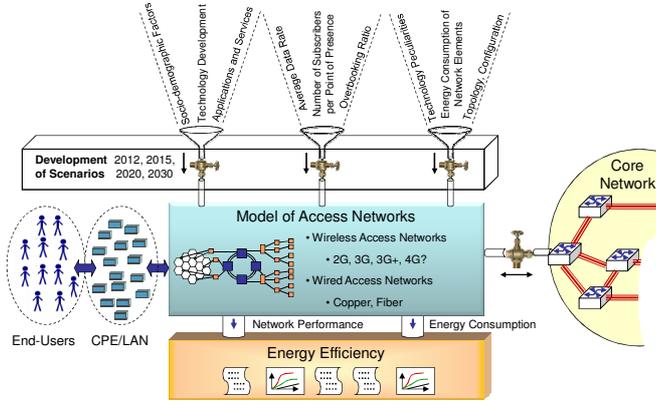


Fig. 5. Generic representation of the access network model.

The finite capacities of both links and nodes are considered by comparing the actual amount of upstream and downstream traffic to the maximum capacity of each network element. The power consumption of network terminals  $P_{C,NT}$  as well as that of network elements in the access  $P_{C,access}$  and the aggregation  $P_{C,aggregation}$  area is determined using the methodology presented in [3], [9], [17]. Together the obtained power consumption and network utilization determine the energy efficiency. The instantaneous total power consumption of the entire access network infrastructure  $P_C(t_d)$  depends on the characteristics and number of active network components. It is the sum over the consumption values of all active elements across all access technologies  $T$  at a particular time  $t_d$ :

$$P_C(t_d) = \sum_T P_{C,NT}(e_T) + \sum_T P_{C,access}(e_T) + \sum_T P_{C,aggregation}(e_T) , \quad (7)$$

Typically more than one network provider acts on the same market, such that coexisting networks serve customers within a region. As a consequence, parallel network infrastructures owned by different network providers need to be taken into account.

### III. CASE STUDY

In this section, we illustrate the use of the framework for evaluating the energy efficiency of access networks based on a notional network infrastructure designed to model the situation in Austria. We apply the approach described above to model the region-specific usage patterns for various end-user equipment and applications. Fig. 7 shows, for example, the energy consumption of different home appliances.

Using the stock flow model and statistical data about sales and the usage of electronic devices in Austria, it is possible to determine the current, country-wide energy consumption caused by each type of device and to predict future trends [18]. These results indicate that most energy is consumed for television in both active and standby mode. The second largest

contributor is the use of personal computers (PCs). Thus, particular attention has to be paid on methods for improving the energy efficiency of the related devices.

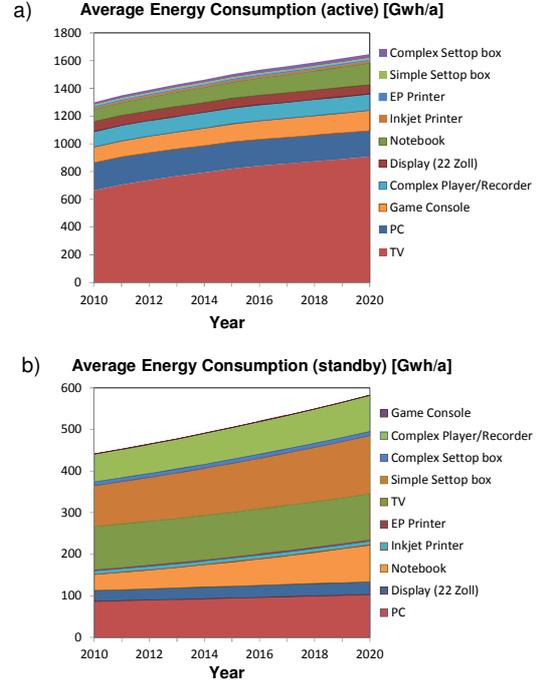


Fig. 7. Projected energy consumption of various home appliances in a) active and b) standby modes in year 2020.

According to statistical data on device, application usage and demography in Austria, we developed traffic profiles for various combinations of services and technologies. The profile that describes the average time dependent traffic demand by a typical user or household is determined using the methodology presented in Section II. A. and illustrated in Fig. 2. Two examples of such traffic profiles for UMTS and xDSL networks are shown in Fig. 8. Note that the profiles are different for users of different technologies and are directly influenced by changes in user behavior (applications usage patterns) and socio-demographic factors such as age distribution, population density, household size and structure.

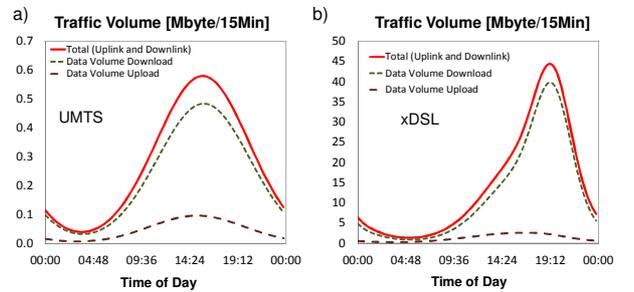


Fig. 8. Exemplary user traffic profiles of a) UMTS users and b) xDSL users.

To evaluate the energy efficiency of the Austrian access network infrastructure we parameterized the framework according to data we obtained from the Statistics Austria, the

Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR), Austrian network operators and the Forum Mobilkommunikation (FMK); particularly, data on technology penetration, market shares and population statistics. First we determined the number of mobile base stations required to achieve the desired coverage using the available data at municipality and federal state level as sketched in Fig. 9 a). There is good coverage by GSM and UMTS networks, especially in urban and suburban areas. LTE is currently deployed in some selected areas for test purposes.

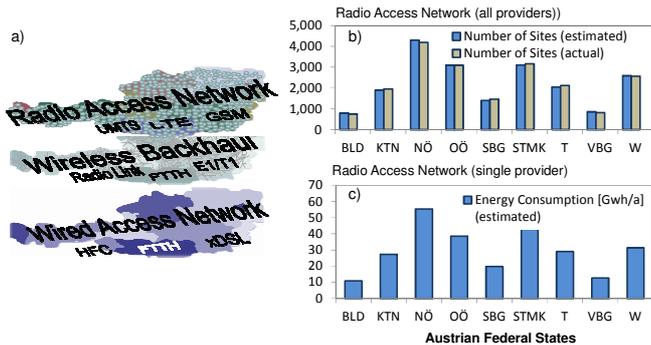


Fig. 9. a) Illustration of the modeling approach for the case of Austrian access networks. The model takes into account both wireless and wired infrastructures and considers the penetration of different technologies. b) Comparison of estimated and actual numbers of base station sites in the Austrian federal states. The maximum relative difference is below 6.4%. c) Estimated yearly energy consumption of a single-operator radio access network in Austria.

The obtained and actual numbers of mobile station sites per federal state is shown in Fig. 9 b). The divergence is mostly below 2% and at most 6.4%. Fig. 9 c) shows the estimated energy consumption of a single radio access network. The variation across the federal states is due to significantly different sizes and population densities. The total energy consumption is estimated to be around 270 GWh/a. Based on the radio access model and considering the current realization of backhaul networks, we design the wireless backhaul to determine its contribution to the power consumption.

The wired access network is designed independent of the requirements for the mobile network. The predominant technology is currently digital subscriber line (DSL) and the second most deployed technology in urban areas is hybrid fiber coax (HFC). According to our results the entire access network infrastructure in Austria, wired and wireless with backhaul, consumes about 1.03 TWh/a. This number includes the consumption of three mobile networks, wireless backhaul and wired networks.

We define three projections (scenarios) for 2020, which imply the implementation of the goals of the Digital Agenda for Europe [19]. This demands among others that the entire European Union (EU) should be covered by broadband above 30 Mbit/s and 50 % of the EU citizens subscribe to broadband above 100 Mbit/s by 2020.

The business-as-usual (BAU) scenario envisages the use and adaption of the current technologies and limited penetration by

new technologies such as LTE and FTTH, predominantly within urban areas.

The hypothetical high energy-efficient scenario assumes that the current network is by 2020 entirely migrated to highly efficient technologies and local regenerative energy supply. LTE becomes predominant for wireless access and FTTH becomes maximally deployed. Parallel infrastructures are minimized and methods for reducing the energy consumption such as low-power and standby modes are widely used.

The hypothetical energy inefficient scenario assumes that new technologies are deployed in a rather energy inefficient manner and that the old technologies are kept in operation together with the existing parallel infrastructures. Energy-efficient devices and approaches for increasing the network energy efficiency are not used.

Fig. 10 presents the estimated energy consumption of the entire Austrian access network infrastructure by 2020. It is evident from the figure that in the BAU scenario the energy consumption increases to 2.9 TWh/a in 2020, which is an increase by a factor of approximately 2.8. In case of an inefficient migration, the energy inefficient scenario, the total energy consumption increases more than 4 times (to 4.4 TWh/a). It is interesting to see that if much attention is paid to energy efficiency and a lot of effort is put into deploying energy efficient components and systems, the high broadband coverage envisaged by the Digital Agenda for Europe could be achieved with almost no increase in energy consumption (at 1.05 TWh/a).

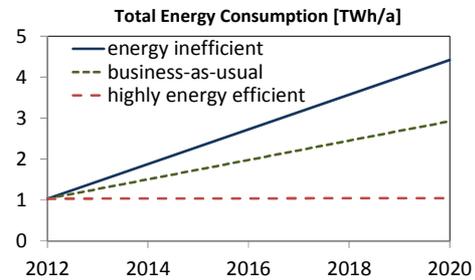


Fig. 10. Prediction of the total energy consumption per year of the overall access network infrastructure in Austria (both wired and wireless networks, multi-provider case). The curves represent two hypothetical scenarios (highly energy efficient and low energy efficient) as well as a prediction of the energy consumption in a business-as-usual case.

#### IV. CONCLUSIONS

We presented a comprehensive framework for evaluating the energy efficiency of access networks. The framework joins technological parameters and different configuration options with socio-demographic characteristics and changing user behaviors. The modeling framework can be used to evaluate different deployment and migration scenarios including both wireless and wired access networks by means of predicted energy efficiency.

In the case study presented, we applied the framework to model the energy efficiency of the Austrian access networks. The results obtained by the model are in good agreement with

the actual data of the networks in operation. We assessed different network deployment options that all achieve a high broadband coverage with at least 30 Mbit/s in 2020. In particular, we designed three scenarios, a business-as-usual (BAU) scenario, a highly efficient scenario and an energy inefficient scenario. The BAU scenario leads to 2.8 times higher energy consumption compared to today's energy demand. The highly inefficient scenario causes an increase by a factor of 4.4. When, however, one concentrates on energy-efficiency and maximally exploits its potentials, it could be possible to achieve an optimized network infrastructure able to provide both, high data rate Internet access to everybody and high energy efficiency, while consuming approximately the same energy as the current access network infrastructure does.

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