Energy Consumption in Wired and Wireless Access Networks

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ABSTRACT

Energy consumption is becoming an increasingly important issue throughout the community. For network operators in particular it is a concern as networks expand to deliver increasing traffic levels to increasing numbers of customers. The majority of the energy used by the Internet today is consumed in the access network, and this will continue to be the case for the short-to-mid-term future. Access technologies should thus be a prime focus for energy use mitigation. In this article, we present a detailed analysis of energy consumption in current and future access networks. We present the energy consumption of DSL, HFC networks, passive optical networks, fiber to the node, point-to-point optical systems, UMTS (W-CDMA), and WiMAX. Optical access networks are the most energy efficient of the available access technologies.

INTRODUCTION

The Internet has revolutionized the way in which we seek and disseminate information, transact business, educate, and entertain. Traffic growth on the consumer Internet has been high and sustained, with growing numbers of Internet customers using increasingly sophisticated applications, and using them more often. The rollout of broadband access networks has both facilitated and been driven by these increasing demands. Service providers and network operators have invested heavily in deploying and upgrading these new access networks, investing as well in large data centers and expanding core network capacity. In general, these investment decisions have been driven by the traditional design metrics of capital cost, operational cost, and capacity requirements. Energy usage has always been considered, but in the context of operational cost rather than as an issue in its own right. In today's world, the traditional network design metrics alone are no longer sustainable, and energy needs to become one of the principal design parameters for future networks and equipment.

It has been estimated that the IT industry today is responsible for a total of 2 percent of the electrical energy consumed in a typical Organization for Economic Cooperation and Development (OECD) country [1]. Within this total, the energy used in the switching, transmission, and access networks delivering the consumer Internet today has been estimated to be approximately 0.5 percent of typical national consumption, with a rising trend as customer traffic levels increase [2, 3]. Moreover, in the short- to medium-term future, the majority of the total network energy will be consumed in the access network.

This article reviews the range of access network technologies that might be used as network operators move to deliver higher-speed customer access, with a special focus on energy usage as average customer data rates increase [4]. Wise technology choices for future access networks will be an important first step in helping our industry to meet its challenges in a more energy-constrained future [5]. We focus here on the energy consumption of digital subscriber line (DSL), hybrid fiber coaxial (HFC) networks, passive optical networks (PONs), fiber to the node (FTTN), point-to-point optical (PtP) systems, WiMAX, and Universal Mobile Telecommunications System (UMTS) using wideband code-division multiple access (W-CDMA). We find that optical access networks are the most energy efficient of the available access technologies.

POWER CONSUMPTION MODEL

In this section we describe an energy model of the access network, and consider the energy consumption of a number of wired and wireless access technologies. There are several different access technologies in use today, and more are in development [4]. Figure 1 is a schematic diagram of the seven access network technologies we consider here. These technologies include DSL and HFC networks as well as a number of high-speed access technologies: PON, FTTN, PtP, WiMAX, and UMTS. In Fig. 1, thin lines indicate optical links while thick lines indicate copper links.

The energy consumption of each access network can be split into three components: the energy consumption in the customer premises equipment (i.e., the modem), the remote node

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or base station (base transceiver station, BTS), and the terminal unit (which is located in the local exchange/central office). The per-customer power consumption P_a of all seven access technologies in Fig. 1 can be expressed in the form

$$P_a = P_{CPE} + \frac{P_{RN}}{N_{RN}} + \frac{1.5 P_{TU}}{N_{TU}}, \quad (1)$$

where P_{CPE}, P_{RN}, and P_{TU} are the powers consumed by the customer premises equipment, remote node or base station (if there is one), and terminal unit, respectively. N_{RN} and N_{TU} are the number of customers or subscribers that share a remote node and the number of customers that share a terminal unit, respectively. The last term on the right side of Eq. 1 includes a factor of 1.5 to account for additional overheads such as external power supplies, electricity distribution losses, and cooling requirements in the building that houses the terminal equipment [6, 7]. The equipment in the remote node and at the customer premises is cooled naturally by the surrounding environment.

In this article, we estimate the energy consumption of a range of access technologies, based on representative data from manufacturers' data sheets for commercial equipment. Table 1 lists commercial equipment for each of the seven access networks. The equipment listed in Table 1 is not necessarily best in class for energy efficiency, but we believe it is representative of 2010-era access network equipment.

Table 2 lists representative values of the parameters in Eq. 1 for each of the access technologies considered here. The number of users per remote node and terminal unit for the two wireless technologies (WiMAX and UMTS) correspond to per-user capacities of 0.25 Mb/s. The number of users per remote node and terminal unit for the wired technologies correspond to configurations where the ports on the remote node equipment and terminal unit are fully occupied. In the following paragraphs we describe each access technology and explain the details of the parameters used in developing an energy model for each access technology.

Digital Subscriber Line

DSL is provided through copper pairs originally installed to deliver a fixed-line telephone service [4]. A DSL modem at each customer home connects via a dedicated copper pair to a DSL access multiplexer (DSLAM) at the nearest central office (telephone exchange).

For the comparison presented here, we consider a modern ADSL2+ access service. This technology can in theory provide maximum speeds of 24 Mb/s downstream to a customer close to the central office and 1 Mb/s upstream. However, to account for the typical degradation in performance due to line length, line loss, crosstalk, and noise, we assume a maximum access rate of 15 Mb/s. We consider a typical DSLAM capable of serving 1008 customers, having a full-duplex switching capacity of 2 Gb/s, and consuming approximately 1.7 kW. The customer modem is modeled as consuming 5 W.

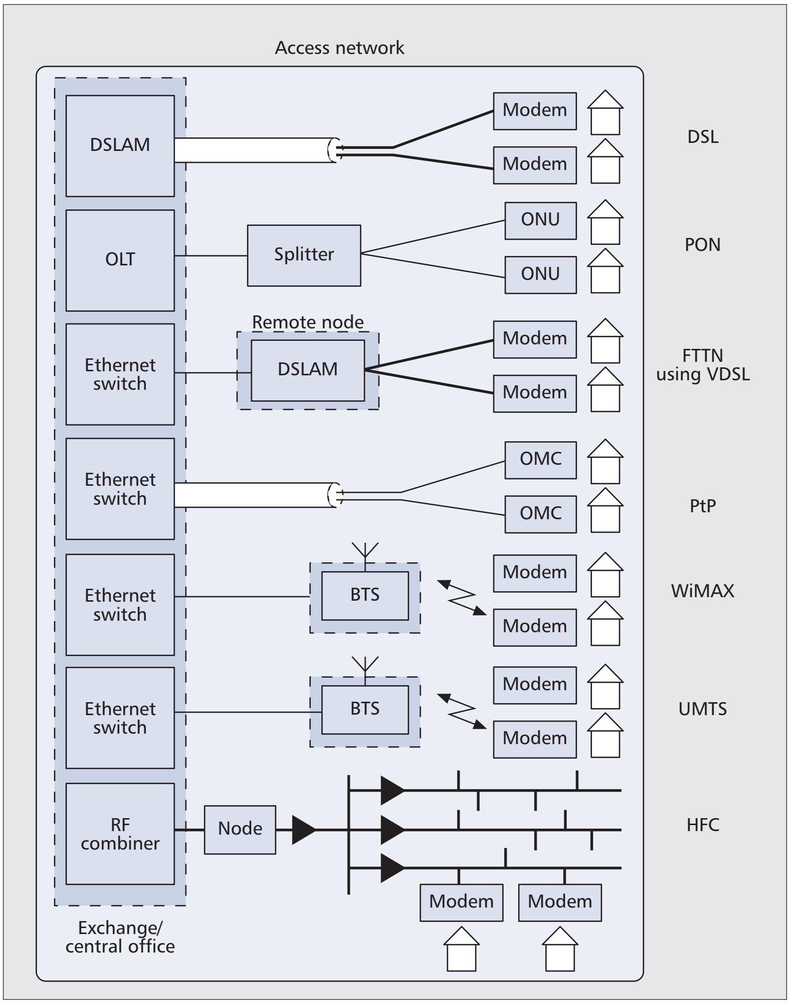

Figure 1. *Schematic of network structure with access network options including digital subscriber line (DSL) and hybrid fiber coaxial (HFC) networks as well as a number of promising candidates for future high speed access technologies - passive optical network (PON), fiber to the node (FTTN), point-to-point optical (PtP), WiMAX and UMTS. Thin lines indicate optical links and thick lines indicate copper links.*

Hybrid Fiber Coaxial Network

Cable distribution networks were initially deployed to deliver television services, and today also deliver Internet and telephony services. Typically, the television program material is compiled from national and regional sources at a headend distribution center in each regional city. This material is distributed on radio frequency (RF) modulated optical carriers through optical fiber to local nodes, where the optical signal is converted into an electrical signal. That electrical signal is then distributed to customers through a tree network of coaxial cables, with electrical amplifiers placed as necessary in the network to maintain signal quality. Hence, these networks are commonly termed hybrid fiber coaxial networks.

The electrical signal sent toward the customer on the coaxial cable includes an array of modulated RF carriers representing the individual television channels, generally extending from either 50 or 65 MHz up to a frequency of 500–900 MHz, depending on the network. A reverse channel to the node or head-end is also provided in the band below 50 MHz. Broadband

Based on the neighborhood topology, the cable is branched, the signal re-amplified, and signals for individual customers tapped off along the route. We allow for four RF carriers to be assigned to convey data signals on each of these coaxial cable links, so that each cable tree supports a total of 152 Mb/s.

	Terminal unit	Remote node	Customer premises equipment
ADSL	Alcatel Stinger FS+	N/A	D-Link DSL502
HFC	Motorola GX2	Motorola SG4000 Quad Node Motorola BLE100 RF Amplifier	Motorola SB6120
PON	Hitachi 1220	N/A	Wave7 ONT-G1000i
FTTN	Hitachi 1220	NEC AM3160	NEC VF200F6
PtP	Cisco 4503	N/A	TC Communications TC3300
WiMAX	Cisco 4503	Motorola WAP 450 Series	Alvarion BreezeMAX USB 200 Zyxel MAX-200M1
UMTS	Cisco 4503	Motorola Horizon 3G-nx	Sierra Wireless AirCard USB 306

Table 1. *Representative equipment used in model of access networks.*

	P_{TU} (kW)	N_{TU}	P_{RN} (W)	N_{RN}	P_{CPE} (W)	Technology limit	Per-user capacity
ADSL	1.7	1008	N/A	N/A	5	15 Mb/s	2 Mb/s
HFC	0.62	480	571	120	6.5	100 Mb/s	0.3 Mb/s
PON	1.34	1024	0	32	5	2.4 Gb/s	16 Mb/s
FTTN	0.47	1792	47	16	10	50 Mb/s	2 Mb/s
PtP	0.47	110	N/A	N/A	4	1 Gb/s	55 Mb/s
WiMAX	0.47	24400	1330	420	5	22 Mb/s	0.25 Mb/s
UMTS	0.47	15300	1500	264	2	20 Mb/s	0.25 Mb/s

Table 2. *Values of access network parameters used.*

Internet access is provided by using one or more of the downstream RF channels to deliver high-speed data, and one or more of the low-frequency reverse channels to send data from the customer into the network (upstream).

Each television customer has a set-top box, which demodulates the incoming signal for display on a television receiver. The data/Internet customer has a cable modem connected to his/her computer or network.

The topology of an HFC network is illustrated in more detail in Fig. 2. As before, thin lines indicate optical links while thick lines indicate copper links. In our model for Internet access via a HFC network, we include:

- "Head-end" equipment, where video RF carriers are combined in a broadband network platform (BNP) with data-supporting RF carriers onto transmission fibers
- Field-deployed node equipment, which converts the optical signals into electrical signals suitable for cable distribution
- A network of electrical RF amplifiers and splitters, so that each node can support a number of customers spread over many streets
- In each customer's premises, a cable modem; Universal Broadband Routers (UBRs) are an essential part of the HFC data network, but in this analysis we focus on the energy consumption of the access network and do not include the energy consumption of UBRs in our calculations.

We model the network using current DOCSIS-based equipment, employing 6 MHz RF channels and 256-quadrature amplitude modulation (QAM) to deliver 38 Mb/s per RF channel. Each node in the cable network receives four sets of RF data carriers on separate fibers and the video program carriers on another fiber. These data carriers are combined with video program carriers and distributed on four lines of coaxial cables. Based on the neighborhood topology, the cable is branched, the signal re-amplified, and signals for individual customers tapped off along the route. We allow for four RF carriers to be assigned to convey data signals on each of these coaxial cable links, so each cable tree supports a total of 152 Mb/s.

In the final distribution network link, we allow 15 customers to be served from a single electrical line amplifier. When the offered capacity per customer is low, the coaxial cable distribution network requires few nodes to support many customers and is highly branched; in such cases we allow one trunk amplifier to support up to eight line amplifiers. Each node requires at least one video and one data port on the BNP that combines the RF signals, and a number of RF data channels from the UBR. When modeling high data loads with low oversubscription, several UBRs may be required in a city.

The BNP consumes 620 W, while serving up to four nodes. The number of customers served by a node depends on the number of RF carriers available for data, in both downstream and upstream directions, and the per-customer traffic level. A quad node consumes 256 W; the trunk and line amplifiers each consume 35 W. In Table 2 the power consumption of the HFC remote node includes the power consumption of the node, trunk amplifier, and necessary electrical amplifiers in a typical installation.

The RF amplifiers, nodes, and head-end RF combining equipment in the HFC network are shared between data and broadcast television services; thus, the energy consumption of this equipment should be shared between the services. On the basis of the subscriber numbers for each service in one provider's network, we allocate 40 percent of energy consumption of this equipment to supporting Internet access.

We have dimensioned the network on the basis of downstream capacity delivered to customers. There are, however, many instances where the upstream capacity of the reverse channels may be limited by high ambient RF noise levels, and this limits the number of customers that can be served from a node and cable network tree. Thus, in assuming a network limited by download capacity, we offer a conservative (i.e., lower) power consumption estimate.

Passive Optical Network (PON)

Fiber to the premises installations most commonly use a PON technology, in which a single fiber from the network node feeds one or more clusters of customers through a passive splitter [4]. An optical line terminal (OLT) is located at the central office, and serves a number of access modems or optical network units (ONUs) located at each customer premises. Each customer ONU in a cluster connects via a fiber to the splitter, and from there shares the same fiber connection to the OLT. ONUs communicate with the OLT in a time multiplexed order, with the OLT assigning time slots to each ONU based on its relative demand.

The number of customers that share a connection to an OLT is generally 32 or 64. For the network energy model, we consider a gigabit PON (GPON) access network, providing asymmetric 2.4 Gb/s downstream, 1.2 Gb/s upstream from the ONU to the OLT and 32 customers sharing a connection to an OLT. The OLT equipment shelf is capable of supporting 32 GPON lines (1024 customers), has a backhaul capacity of 16 Gb/s, and draws 1.34 kW. The splitter is unpowered. The ONU is a basic model providing only data connectivity, and draws 5 W.

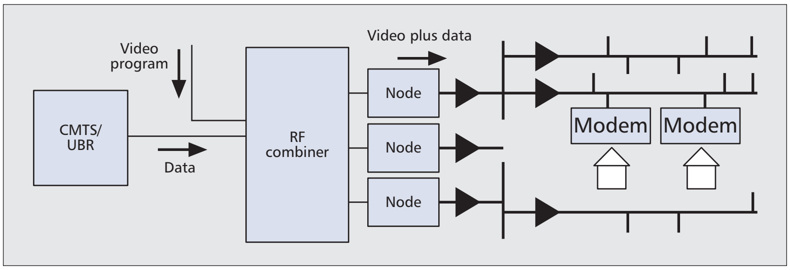

Figure 2. *Layout of an HFC network.*

Fiber to the Node Using VDSL

Fiber-to-the-node (FTTN) technology makes use of existing copper pairs [4]. Dedicated fiber is provided from a network switch to a DSLAM in a street cabinet close to a cluster of customers, and high-speed copper pair cable technologies such as very-high-speed DSL (VDSL) or ADSL2+ are used for the final feed to the customer premises. This accommodates the distance limitations of high-speed pair-cable technologies, and enables high-speed broadband service delivery without the cost of providing new cable entry to the customer premises.

In an FTTN network using VDSL, a remote node houses a VDSL DSLAM which communicates with several homes through the copper wire and connects back to an Ethernet switch in the central office/local exchange through a fiber link. A typical VDSL2 line card supports 16 customers and consumes approximately 42 W. An additional 5 W is consumed for an ONU to link the remote VDSL DLSAM to an OLT back in the central office. The VDSL2 customer modem consumes 10 W and has a peak access rate of 50 Mb/s. The Ethernet switch has 116 optical Gigabit Ethernet ports and 64 Gb/s of switching capacity, with a power consumption of 474 W. For the model, we dimension the fiber backhaul capacity to suit the customer traffic level, but set upper limits on number of customers per Ethernet switch at 1792, and the maximum number of DSLAMs per Ethernet switch at 112. The four remaining ports on the Ethernet switch are used to provide backhaul capacity.

Point-to-Point Access Optical Network

The highest access speed is achieved using a dedicated fiber between each customer premises and the network terminal unit in a PtP configuration [4]. The customer premises employs an optical media converter (OMC) to convert between the electrical signal used inside the home and the optical signal used in the access network.

For typical central office equipment we consider an Ethernet switch providing 116 optical Gigabit Ethernet ports and 64 Gb/s of switching capacity, with a power consumption of 474 W. An OMC at each home converts between the electrical signal used in the home network to an optical signal for transmission over fiber, and consumes 4 W. In this architecture there is no remote node. Each Ethernet switch connects to 110 homes, with the six remaining ports used to provide backhaul capacity.

Although the oversubscription rate applied by network providers is typically much higher for wireless access networks than for wired access networks, to facilitate a fair comparison we model the same across all access networks.

WiMAX

WiMAX is a high-speed wireless access technology. WiMAX was initially designed to provide fixed-point or nomadic wireless access services, but its design standards have since been amended to support full mobility. In our model, we focus on the use of WiMAX in a stationary setting, where each home uses an indoor modem to connect to a base station. The WiMAX base station is remotely located and uses fiber or point-to-point wireless backhauls to connect to the metropolitan and edge network. The area covered by a base station is referred to as a cell, and users in a cell share the total available bandwidth. Per-user bandwidth can be significantly increased by creating multiple sectors in a cell through the use of directional antennas. In a three-sector configuration, each antenna covers a 120° sector.

WiMAX provides access rates of up to 70 Mb/s under ideal conditions. However, typically in urban areas there is not a clear line of sight between the user and the base station, and the combination of reduced signal level and multipath interference limits access speeds to about 35 Mb/s at distances up to about 7 km, with degraded speeds at higher distances.

For the comparison in this article, we model the base station at the remote antenna site as using a point-to-point fiber link to communicate to an upstream Ethernet switch. For the base station we assume a dual-antenna multiple-input multiple-output (MIMO) system with three sectors and mast-mounted power amplifiers. Each sector is modeled as providing 35 Mb/s in total to all users in the sector, and the total base station consumption is 1330 W. The fixed point indoor customer premises unit may be a standalone modem or a USB key style modem. Standalone modems typically achieve higher throughputs than USB modems but also consume more power. We model the home modem as consuming an average of 5 W to account for the diversity of possible devices in a given coverage area.

At low average per-user traffic levels, all users within a cell coverage area will receive adequate service, subject to propagation conditions. At higher average per-user traffic levels, fewer users could be adequately served by each base station sector, and either more sectors or more base stations would be needed. This leads to a rapid increase in the equipment power consumption at higher traffic levels.

UMTS

UMTS is a cellular mobile system that can provide high-speed broadband access capability. It includes radio access to a base station, and from there connections to the core networks for data and voice. For this model we adopt the more commonly used W-CDMA variant, and focus on the broadband data access component of the network. Users may connect to a base station through their mobile phone, USB modem, or standalone modem. The base station is often located remote from its network access controller, and uses fiber or point-to-point wireless backhaul to connect to the controller. Through the radio network controller a mobile user can connect to other mobile phones, the public switched telephone network, or the Internet. As with WiMAX, capacity can be greatly increased through the use of multiple sectors.

The spectral efficiency of UMTS was greatly increased through the introduction of high-speed downlink packet access (HSDPA), high-speed uplink packet access (HSUPA), and, most recently, evolved high-speed packet access (HSPA+). HSPA+ allows for theoretical downlink speeds of 42 Mb/s and uplink speeds of 11 Mb/s. However, typically interference in urban areas limits downlink speeds to about 30 Mb/s and uplink speeds to about 6 Mb/s. For our energy consumption model, the base station connects via Ethernet to an upstream switch, and from there to the radio network controller. A typical outdoor base station consumes 1.5 kW and supports three sectors. Each sector has an average downlink throughput of 22 Mb/s. The user modem is a USB modem that consumes less than 2 W.

Oversubscription

We characterize the capacity available to each customer by the headline access rate advertised and sold to customers by the Internet service provider (ISP). However, backhaul networks connecting the access network to the metropolitan and edge networks are dimensioned by network operators to provide some lower worst-case minimum transmission rate to every customer, taking advantage of the bursty nature of customer Internet traffic. The ratio of the advertised access rate to this minimum per-user rate is referred to as the oversubscription rate. Although the oversubscription rate applied by network providers is typically much higher for wireless access networks than for wired access networks, to facilitate a fair comparison we model the same across all access networks. Note that as the use of the consumer Internet for streaming real-time services increases, high oversubscription ratios will become unsustainable.

We model each access network in terms of a headline access rate of A Mb/s per customer and an oversubscription rate M. During the busiest period of the day, the minimum capacity available to a customer is A/M, the per-user capacity. Statistical multiplexing typically occurs at the DSLAM in ADSL, at the OLT in PON and FTTN, at the UBR in HFC, at the small Ethernet switch in the case of PtP, and at the base station switch for WiMAX and UMTS.

Market Share and Take-Up Rate

In many markets, customers choose from a range of Internet access options; for example, customers may be able to choose between DSL, HFC and UMTS network providers. A network provider, when building an access network, estimates the percentage of households that will buy the service in the short to medium term, referred to as the take-up rate, but will also install additional capacity to cater for future growth in take-up.

In markets with regulated competitive access to infrastructure such as pair cable, a similar but slightly different parameter is market share. Competing ISPs commonly install DSL equipment in the same area, and customers can purchase services from a number of infrastructure-based ISPs, each of which has slightly overprovisioned to cater for future growth.

We combine these factors into one parameter and refer to it as underutilization. The power consumption of current networking equipment does not typically scale with utilization [8]; therefore, underutilization decreases the energy efficiency of equipment. To accommodate underutilization, we increase the power consumption of all access network equipment, except the customer premises equipment, by 25 percent. This increase in power consumption corresponds to network equipment utilization of 80 percent.

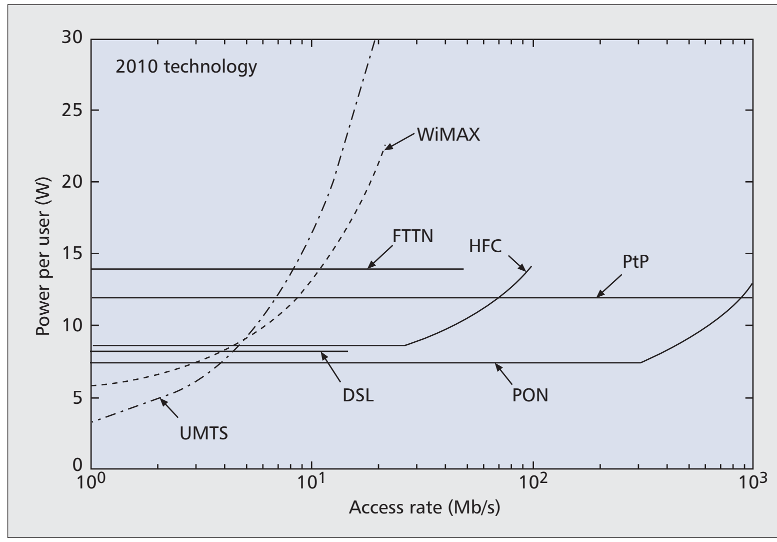

Figure 3. *Power consumption of DSL, HFC, PON, FTTN, PtP, WiMAX, and UMTS as a function of access rate with an oversubscription rate of 20. The technology used is fixed at 2010 vintage for all access rates.*

Energy Consumption

We use the model described earlier to calculate the total per-customer power consumption for typical deployments of each of the seven access networks illustrated in Fig. 1. We also use the model to project the future energy consumption of these access networks. The power consumption of each of the access networks has been calculated for a range of "headline" access service rates, with a constant oversubscription factor of 20. That oversubscription figure is low in situations where customers predominantly use traditional web services such as email and browsing, but could be considered high for future scenarios which include mass use of real-time video on demand services.

For wired access technologies such as ADSL and VDSL, we assume that all customer access ports are fully occupied. For technologies with a shared access resource such as HFC, wireless, and PON, we again assume that all physical ports are utilized, but in addition we share the resource among as many customers as could be served at the particular average service rate and oversubscription factor. As service rates increase, fewer customers can be served, and more equipment (base stations, HFC nodes, PON linecards, etc.) must be provisioned, with an increase in the per-customer power consumption.

Power Consumption Per User

Figure 3 is a plot of the per-customer power consumption of each access technology as a function of the headline access rate. Note here that this access rate is the provisioned per-user capacity multiplied by the oversubscription rate. The technology used in Fig. 3 for all access rates is the 2010-era technology described earlier. From Fig. 3, it is clear that at low access rates (< 1 Mb/s) PON, DSL, and HFC have similar power consumption. At such rates, the overall power consumption is dominated by the consumption of the customer modem. In addition, the power consumption of current networking equipment does not typically scale with utilization [8], resulting in very low efficiencies at low utilization. At an access rate of 1 Mb/s, all five wired access technologies are significantly underutilized. At these low rates, WiMAX and UMTS can flexibly share capacity among a very large number of users, and thus can achieve high efficiency and utilization. Increasing the access rate from 1 to 10 Mb/s increases the power consumption of WiMAX and UMTS by a factor of two and four, respectively, as fewer customers can use a given radio channel or base station and more resources must be provisioned to deliver the service. The power consumption of HFC services increases at a slower rate. At access rates greater than 10 Mb/s, wired access technologies are significantly more energy-efficient than wireless access technologies. HFC, DSL, and FTTN all reach technology limits in the 10–100 Mb/s range. For average service rates of a few to tens of megabits per second envisaged for mass customized streaming services such as high-definition video on demand, the PON has a clear energy advantage.

Comparison of Power Consumption in the Home and the Network

In ADSL, HFC, PON, and FTTN the customer modem or ONU consumes over 65 percent of the total power in the access network. These units would normally operate continuously, but the power consumption of the access network could be significantly reduced through the use of automated sleep modes in customer premises network equipment [9]. Assuming the Internet is used on average 8 h/day, automated sleep modes in customer premises equipment could reduce the energy consumption of the access network by up to 40 percent. Additional savings in power consumption could be realized by fast/micro sleep modes, where customer premises equipment enters a sleep mode during periods of inactivity that are shorter than a second.

	Electronics	Optical interfaces	Power amplifiers	Power conversion
Modem (DSL/HFC)	70%	0%	10%	20%
RF amplifiers	0%	0%	80%	20%
Node (HFC)	0%	20%	60%	20%
BNP	20%	60%	0%	20%
ONU	70%	10%	0%	20%
OMC	50%	30%	0%	20%
Modem (WiMAX/UMTS)	60%	0%	40%	0%
BTS (WiMAX)	69%	0%	11%	20%
BTS (UMTS)	53%	0%	27%	20%

Table 3. *Breakdown of power consumption.*

Improvement in Energy Efficiency with Time

Improvements in complementary metal oxide semiconductor (CMOS) and optical technology should lead to energy efficiency improvements in future generations of network equipment. For example, the energy efficiency improvement rate of Ethernet switches and OLTs is approximately 10 percent per annum [2, 10]. In this section we estimate the overall rate of improvement of each access network technology over time. To estimate this improvement rate we first break down the total power consumption of each item of network equipment into four subsystems: electronic, optical, power amplification, and AC/DC power conversion. We then apply standard estimates of improvement rates (given below) to these subsystems. We calculate the rate of improvement of each item of network equipment as the sum of the improvement rates of its subsystems, weighted by the proportion of total power consumed by that subsystem. This technique of estimating improvement rates is similar to the analysis performed in [10]. Table 3 lists estimates of the breakdown of total power consumption of each item of network equipment into these four subsystems. The per-annum "business as usual" improvement rates for these subsystems are:

- Electronics (26 percent)
- Optical interfaces (5 percent)
- Power conversion (0 percent)
- Power amplifiers (0 percent)

Figure 4 is a plot of the per-customer power consumption for each access technology as a function of time (bottom horizontal axis) and access rate (top horizontal axis). This plot is one scenario for future power consumption of each of the seven access network technologies, using the established "business as usual" efficiency improvement trends outlined in the previous paragraph. For this plot, the access rate is set at 5 Mb/s in 2010 and increases by 42 percent per annum (double every two years), reaching 167 Mb/s in 2020. As before, the oversubscription rate is 20. Although some ISPs today advertise access rates of 100 Mb/s or more, the oversubscription rate used in those networks is typically much greater than 20. The power consumption curves for DSL, HFC, and FTTN cease prior to 2020 because we believe these technologies have a limited ability to scale and meet future increases in bandwidth requirements.

As shown in Fig. 4, we forecast that, if electronics and optics continue to improve at current rates, a lack of improvement in power amplifiers and power conversion subsystems will result in an overall diminishing rate of improvement in all access technologies. The power consumption of HFC and UMTS falls by only 50 percent because the majority of power consumption in these access networks is in power amplifiers, which have limited scope to improve in the future. The results in Fig. 4 suggest that the per-user power consumption of most high-speed access technologies (PON, PtP, FTTN, and WiMAX) should fall by around 70 percent from 2010 to 2020. Wireless technologies will continue to consume at least 10 times more power than wired technologies when providing comparable access rates and traffic volumes. PON will continue to be the most energy-efficient access technology.

Conclusion

We have presented a model of energy consumption of current and future access networks using published specifications of representative commercial equipment. We analyzed the energy consumption of DSL, HFC, PONs, FTTN, point-to-point optical systems, UMTS (W-CDMA), and WiMAX. Passive optical networks and point-to-point optical networks are the most energy-efficient access solutions at high access rates.

Acknowledgement

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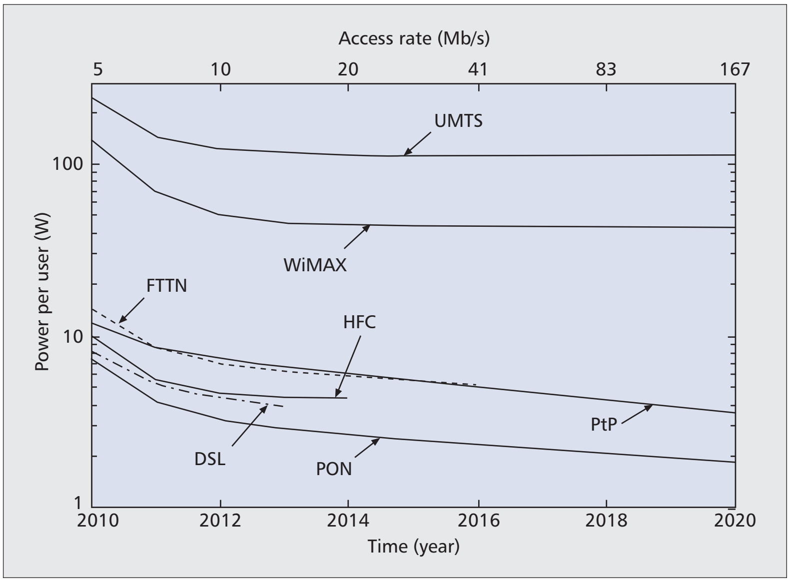

Figure 4. *Expected power consumption of latest generation DSL, HFC, PON, FTTN, PtP, WiMAX and UMTS equipment as a function of the calendar year. The base access rate in 2010 is taken as 5 Mb/s.*

Biographies

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KERRY HINTON received an Honors Bachelor of Engineering in 1978, an Honors Bachelor of Science in 1980, and a Master of Science degree in mathematical sciences in 1982, all from the University of Adelaide. He was awarded a Ph.D. in theoretical physics from the University of Newcastle Upon Tyne, United Kingdom, and a Diploma in industrial relations from the Newcastle Upon Tyne Polytechnic in 1984. In the same year he joined Telstra Research Laboratories (TRL), Victoria, Australia, and worked on analytical and numerical modeling of optical systems and components. His work has focused on optical communications devices and architectures, physical layer issues for automatically switched optical networks (ASONs), and monitoring in all-optical networks. He was also a laser safety expert within Telstra. In 2006 he joined the ARC Special Centre for Ultra-Broadband Information Networks, Australia, at the University of Melbourne, where he is undertaking research into the energy efficiency of the Internet and optical communications technologies.

RODNEY S. TUCKER [S'72, M'75, SM'85, F'90] received his B.E. degree in electrical engineering and Ph.D. degree from the University of Melbourne, Victoria, Australia, in 1969 and 1975, respectively. He is currently a Laureate Professor at the University of Melbourne, where he is director of the Institute for a Broadband-Enabled Society and the Centre for Energy-Efficient Telecommunications. He is a Fellow of the Australian Academy of Science, a Fellow of the Australian Academy of Technological Sciences and Engineering, and a Fellow of the Optical Society of America. In 1975 he was the recipient of a Harkness Fellowship by the Commonwealth Fund, New York. From 1988 to 1990 he was Editor-in-Chief of *IEEE Transactions on Microwave Theory and Techniques*. From 1991 to 1993, he was with the Management Committee of the Australian Telecommunications and Electronics Research Board, and a member of the Australasian Council on Quantum Electronics. From 1995 to 1999 and from 2009 the present, he is a member of the Board of Governors of the IEEE Lasers and Electrooptics Society. In 1995 he was the recipient of the Institution of Engineers, Australia, M. A. Sargent Medal for his contributions to electrical engineering and was named an IEEE Lasers and Electro-optics Society Distinguished Lecturer for the year 1995–1996. In 1997 he was the recipient of the Australia Prize, Australia's premier award for science and technology, for his contributions to telecommunications. From 1997 to 2006 he was an Associate Editor of *IEEE Photonics Technology Letters*. He is currently Vice-President, Publications of the IEEE Photonics Society. In 2007 he was the recipient of the IEEE Lasers and Electro-optics Society Aron Kressel Award for his pioneering contributions to high-speed semiconductor lasers.