Power consumption in wireless access networks

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***Abstract*—The power consumption of wireless access networks will become an important issue in the coming years. In this paper the power consumption of base stations for mobile WiMAX, fixed WiMAX and UMTS is modelled. This power consumption is evaluated in relation to the coverage. For a physical bit rate of 2 Mbps, a power consumption of approximately 5600 W and a range of 1 km is obtained with UMTS. Fixed WiMAX covers 70 % and mobile WiMAX only 40 % of this range. However, fixed and mobile WiMAX consume roughly 50 % less than UMTS. In a suburban area and for a physical bitrate of 2 Mbps, fixed WiMAX base stations consume approximately 6 W per user, mobile WiMAX base stations 17 W per user, and UMTS base stations 5 W per user . The power consumption of these wireless access networks is compared with other access network technologies and research challenges concerning these access networks are presented.**

I. Introduction

Recent studies have shown that the power consumption of ICT is approximately 4% of the annual energy production [1]. More importantly, this number is expected to grow drastically in the coming years. The Internet traffic has a compound annual growth rate of 40 % i.e., doubling every two years [2]. Moreover, the wireless world research forum (WWRF) [3] has a vision of 7 trillion wireless devices serving 7 billion users by 2017. This indicates that the power consumption of wireless access networks is going to become an important issue in the coming years.

Earlier work showed that the radio access network is a large contributor to CO_2 emissions [4], [1], [5]. Particularly, the base stations are responsible for roughly two-thirds of the total CO_2 emissions [4] of these radio access networks. NTT DoCoMo states that the daily energy consumption per customer is 0.83 Wh for a terminal and 120 Wh for the mobile network, which is a consumption ratio of terminal versus networks of about 1:150 [5]. The energy consumption of the terminals is thus negligible with respect to the energy consumption of the networks. Therefore, it is clear that we should focus on the base stations in the wireless access networks in order to reduce the energy consumption as the terminals are already optimized in terms of energy consumption because they work on batteries.

The outline of the paper is as follows: in section III we give a short overview of the considered technologies. In Section IV the power consumption of a base station is modelled and related to the coverage. Section V gives for the three wireless technologies some results obtained with the model from Section IV. These results will be used in Section VI to determine the P^u_{access} of the wireless technologies. We also determine P^u_{access}, P^u_{home} and P^u_{core} for all the considered technologies. Based on these values, we compare the power consumption P^u_{tot} per user for the considered technologies. Section VII gives an overview of future work and in Section VIII we give our final conclusions.

II. General approach

The total power consumption P^u_{tot} per user can be expressed as follows:

$$P^u_{tot} = P^u_{home} + P^u_{access} + P^u_{core} \quad (1)$$

with P^u_{home} the power consumption of the customer premises, e.g. a residential gateway or a WNIC (Wireless Network Interface Card), P^u_{access} the power consumption of the access network and P^u_{core} the power consumption of the core network.

For the wireless access networks, we investigate the power consumption of outdoor base stations for three different wireless technologies: mobile WiMAX (Worldwide Interoperability for Microwave Access), fixed WiMAX and UMTS (Universal Mobile Telecommunications System). For a fair comparison with the wired technologies, we consider an indoor residential scenario for the mobile stations. For mobile WiMAX and UMTS we consider a WNIC for a laptop and for fixed WiMAX a residential gateway. The following wired access technologies will be considered: ADSL (Asymmetric Digital Subscriber Line) and VDSL (Very high bitrate Digital Subscriber Line), PtP (Point-to-Point) optical fibre and GPON (Gigabit Passive Optical network).

III. Technology

For wireless access networks we investigate the power consumption of outdoor base stations for three different wireless technologies: mobile WiMAX, fixed WiMAX and UMTS. WiMAX is a wireless technology for broadband communication based on the IEEE 802.16 standard [6]. For fixed WiMAX, we analyse the IEEE 802.16-2004 interface, operating in the 2-11 GHz band which is developed for fixed wireless applications. For mobile WiMAX, we analyse the IEEE 802.16e interface, operating in the 2-6 GHz band which is developed for mobile wireless applications and lets people communicate while they are moving. UMTS is developed by ETSI (European Telecommunications Standardisation Institute) and operates in the 2.1 GHz band [7]. UMTS has been specified as an integrated solution for mobile voice and data. It offers mobile operators significant capacity and broadband capabilities to support more voice and data customers, especially in urban centres.

One of the largest differences between these technologies is the multiple access technique they use. Fixed WiMAX uses OFDMA (Open Frequency Division Multiple Access). Mobile WiMAX employs the novel SOFDMA (Scalable Open Frequency Division Multiple Access) technique which is derived from OFDMA and supports a wide range of channel band widths to flexibly address the need for various spectrum allocation and application requirements. UMTS uses W-CDMA (Wideband Code Division Multiple Access).

For the wired access technologies, the connection to the customer premises is made with a DSLAM (Digital Subscriber Line Access Multiplexer) for ADSL and VDSL technologies. For PtP Optical Networks and PON networks the connection is made with an OLT (Optical Line Termination). These are the devices we will consider for estimating the power consumption in wired access networks. At the customer premises we consider for wired technologies a home gateway to connect the users devices to the access network.

The purpose of the core network is to interconnect several network sites or subnetworks. Core networks exist on different levels, varying from a metropolitan area (where they are sometimes referred to as Metropolitan Area Network) to a worldwide network. The main functionality of a core network is performed by routers.

IV. Method

Firstly, we evaluate the power consumption of the base stations. Based on this evaluation, we will relate the power consumption of the base station to the wireless coverage range. The base stations are placed outdoor. For the mobile stations, we consider an indoor residential scenario.

A. Power consumption of a base station

In this section, we focus on the power consumption of base stations in wireless access networks. In a base station we typically find several power consuming components. Figure 1 gives an overview of these components. We define a base station as the equipment needed to communicate with the mobile stations and with the backhaul network. A base station contains equipment that occurs per sector (then n_{sector} times for all sectors) such as digital signal processing (responsible for system processing and coding), power amplifier, transceiver (responsible for receiving and sending of signals to the mobile stations), signal generator, AC-DC converter. Furthermore a base station contains equipment that occurs only once such as the air conditioning and the microwave link (responsible for communication with the backhaul network). In Figure 1, the equipment of the base station and the different notations for the power consumption P_{el} of the different parts are indicated.

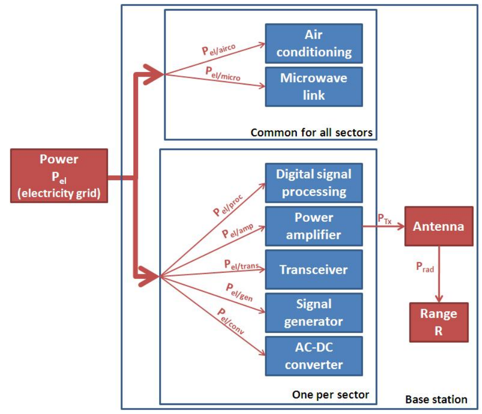

Fig. 1. Block diagram of the base station equipment.

Once we know the power consumption of the different components of the base stations, we can calculate the power consumption P_{el} of the entire base station (in Watt):

$$P_{el} = n_{sector} \cdot (n_{Tx} \cdot P_{el/amp} + P_{el/trans} + P_{el/proc} + P_{el/conv} + P_{el/gen}) + P_{el/micro} + P_{el/airco} \quad (2)$$

with n_{sector} the number of sectors in the cell, $P_{el/amp}$, $P_{el/trans}$, $P_{el/proc}$, $P_{el/conv}$, $P_{el/gen}$, $P_{el/micro}$ and $P_{el/airco}$ are the power consumptions of the power amplifier, the transceiver, the digital signal processing, the AC-DC converter, the generator, the microwave link and the air conditioning, respectively. Table I shows the values that we consider here for the power consumption of this equipment for the considered technologies. These values are retrieved from data sheets of various manufacturers of network equipment. In this investigation, we use cells with three sectors (thus n_{sector} is 3). Furthermore, n_{Tx} is the number of transmitting antennas per sector. In the most simple situation, which is called a SISO (Single Input Single Output) system, the base station uses only one antenna for transmission and the mobile station uses only one antenna for receiving. In this case the parameter n_{Tx} is 1. When a MIMO (Multiple Input Multiple Output) system is considered where the base station uses two transmitting antennas and the mobile station one or two receiving antennas, the n_{Tx} parameter is 2. For each transmitting antenna of the base station we need one power amplifier. So we have to take the power consumption of the power amplifier into account several times according to the number of transmitting antennas that are used in one sector.

The power consumption of each part of the base station is a constant value (in Watt), except for the power amplifier. The power consumption of the power amplifier depends on the required input power of the antenna. To model the power consumption of the power amplifier we need to define the efficiency η of the power amplifier. The efficiency η of the power amplifier is the ratio of RF output power $P_{out/amp}$ (in Watt) to the electrical input power $P_{el/amp}$ of the power amplifier (in Watt):

Equipment		**Mobile WiMAX**	**Fixed WiMAX**	**UMTS**
Digital signal processing	$P_{el/proc}$	100 W	100 W	100 W
Power amplifier	$P_{el/amp}$	100 W	100 W	400 W
	Efficiency η	9 %	9 %	3.75 %
Transceiver	$P_{el/trans}$	100 W	100 W	100 W
Signal generator	$P_{el/gen}$	384 W	384 W	144 W
AC-DC converter	$P_{el/conv}$	100 W	100 W	100 W
Air conditioning	$P_{el/airco}$	690 W	690 W	2590 W
Microwave link	$P_{el/micro}$	80 W	80 W	80 W

TABLE I
POWER CONSUMPTION OF THE DIFFERENT PARTS FOR THE CONSIDERED TECHNOLOGIES.

$$\eta = \frac{P_{out/amp}}{P_{el/amp}} \tag{3}$$

In Figure 1, $P_{out/amp}$ corresponds to the input power P_{Tx} of the one sector antenna. The maximum value of P_{Tx} is often regulated. The maximum input power P_{Tx} for an antenna for fixed WiMAX at a frequency of 3.5 GHz is 35 dBm. Based on P_{Tx} we can calculate the power consumption $P_{el/amp}$ of the power amplifier (in Watt) as follows:

$$P_{el/amp} = \frac{P_{Tx}}{\eta} \tag{4}$$

B. Calculation of range R

In this section, we want to relate the power consumption P_{el} of the base station to the wireless range R. For this, we have to set up a link budget. A link budget takes all of the gains and losses of the transmitter through the medium to the receiver into account. Firstly, we need to calculate the maximum path loss PL_{max} (in dB) to which a transmitted signal can be subjected while still being detectable at the receiver. The path loss is the ratio of the radiated power to the received power of the signal [8]. To determine the maximum path loss PL_{max} we need to take the parameters of Table II into account [9], [10], [11], [7]. Table II gives an overview of all the gains and losses that occur. It is important to note that PL_{max} is dependent of the input power P_{Tx} of the antenna and thus dependent of the output power of the power amplifier which is $\eta \cdot P_{el/amp}$.

Once we know the maximum path loss PL_{max}, we can determine the range R (in metres) by using a path loss model. We first give a general path loss PL_{med} function:

$$PL_{med} = g(d|f, h_{BS}, h_{MS}) \tag{5}$$

PL_{med} is a function $g(.)$ of the distance d (in metres), the frequency f, the height h_{BS} of the base station and the height h_{MS} of the mobile station. The quantity before the $|$ is a variable and varies over a continuous interval while the quantities after the $|$ are parameters which take only one discrete know value. The function $g(.)$ depends on the used path loss model e.g. , the HATA model and the Erceg model [14], [15]. In this paper we will use the Erceg C model.
To determine the distance d we take the inverted function of equation (5):

$$d = g^{-1}(PL_{med}|f, h_{BS}, h_{MS}) \tag{6}$$

Parameter	**Mobile WiMAX**	**Fixed WiMAX**	**UMTS**	**Unit**
Frequency	2500	3500	2100	MHz
Area type	Suburban			—
n_{sector}	3			—
Height of base station	30			m
Height of mobile station	1.5			m
Coverage requirement	90%			—
Shadowing margin	13.2			dB

TABLE III
SCENARIO TABLE FOR DIFFERENT TECHNOLOGIES.

Based on equation (6) we can determine the maximum range R (in metres) we can reach with the base station of a certain technology:

$$R = g^{-1}(PL_{max} - SM|f, h_{BS}, h_{MS}) \tag{7}$$

with SM the shadowing margin which depends on the standard deviation of the path loss model, the coverage percentage and the outdoor standard deviation. Here we consider a coverage percentage of 90 %. The values for the parameters for the different technologies can be found in Table III [9], [10], [11], [7].

V. NUMERICAL ESTIMATIONS

A. Influence of the modulation scheme and coding rate

In this section, we investigate the influence of the modulation scheme and the coding rate on the power consumption and the range of the base station. We explain this using mobile WiMAX here. The configuration of the WiMAX base station can be found in Table I. The link budget and scenario parameters can be found in Table II and Table III, respectively. Figure 2 shows the power consumption P_{el} from the electricity grid (in Watt) as a function of the range R (in metres). The corresponding bit rates for the different modulation schemes and coding rates are also indicated on the figure.

Figure 2 shows that the electrical power consumption P_{el} of the base station depends on the range we want to reach and varies from 2822.0 W with a range of 57.3 m up to 2927.4 W with a maximum range of 406.1 m. The power consumption at the maximum range is thus higher than the

Parameter	Mobile WiMAX	Fixed WiMAX	UMTS	Unit
Maximum input power of base station	35	35	33.6	dBm
Antenna gain of base station	16	17	17.4	dBi
Antenna gain of mobile station	2	8	0	dBi
Number of MIMO Tx antennas of base station	1	1	1	—
Number of MIMO Rx antennas of mobile station	1	1	1	—
Cyclic combining gain of base station	3	3	3	dB
Number of antenna elements of antenna array base station	1	1	1	—
Soft handover gain of mobile station	0	0	1.5	dB
Feeder (cable) loss of base station	0.5	0.5	2	dB
Feeder (cable) loss of mobile station	0	0	0	dB
Fade margin	10	10	10	dB
Cell interference margin	2	0	0	dB
Building penetration loss	0	0	0	dB
Vehicle penetration loss [12]	13.7	13.7	13.7	dB
User speed	0	0	0	km/h
Bandwidth	10	3.5	5	MHz
Receiver SNR	[6 8.5 11.5 15 19 21][1]	[6.4 9.4 11.2 16.4 18.2 22.7 24.4][2]	5.5	dB
Number of used subcarriers	841	201	1	—
Number of total subcarriers	1024	256	1	—
Noise figure of mobile station	7	4.6	8	dB
Implementation loss of mobile station	2	0	0	dB
Guard period	—	—	0.15	—
Target load	—	—	0.75	—
Number of users	—	—	16	—
Duplexing	TDD			—
Building penetration loss [13]	8.1			dB

(1) format: [1/2 QPSK, 3/4 QPSK, 1/2 16-QAM, 3/4 16-QAM, 2/3 64-QAM, 3/4 64-QAM]
(2) format: [1/2 BPSK, 1/2 QPSK, 3/4 QPSK, 1/2 16-QAM, 3/4 16-QAM, 2/3 64-QAM, 3/4 64-QAM]

TABLE II
LINK BUDGET TABLE FOR DIFFERENT TECHNOLOGIES.

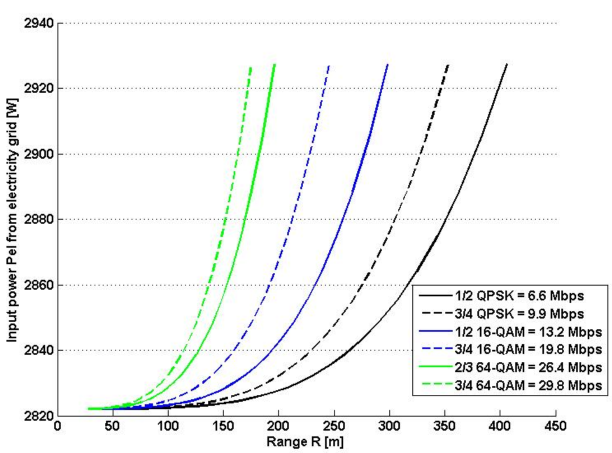

Fig. 2. Influence of modulation scheme and coding rate.

power consumption at the minimum range. This is self-evident because if one wants to obtain a higher range, one needs a larger P_{Tx}. Based on equation (4), we know that the power amplifier will consume more electrical power for a larger P_{Tx} and thus for higher ranges.

Figure 2 also shows that a lower constellation corresponds to a higher range for the same power consumption. For example, the 1/2 QPSK constellation has a higher range than the 1/2 16-QAM constellation. The maximum range for the 1/2 QPSK constellation is 406.1 m and for the 1/2 16-QAM constellation 298.6 m. The power consumption at maximum range is for both cases 2927.4 W. The reason for this difference in range can be found in the receiver SNR (Signal-to-Noise Ratio) which is lower for lower constellations: the receiver SNR for 1/2 QPSK is 6 dB versus 11.5 dB for 1/2 16-QAM (see Table II). In order to obtain a higher physical bit rate for the same range, one needs more electrical power.
The same thing is true for the coding rate: a lower coding rate corresponds with a higher range for the same power consumption. For example, the QPSK constellation, it can be noticed that a coding rate of 1/2 corresponds with a higher range (maximum 406.1 m) than the 3/4 coding rate (maximum 353.1 m) for the same power consumption of 2927.4 W.

B. Comparison of different technologies

1) Maximum range for a pre-defined bit rate: We will now compare the three different wireless technologies: mobile WiMAX, fixed WiMAX and UMTS. For a fair comparison, we define a bit rate, which is 2 Mbps. For mobile WiMAX we will use a bandwidth of 1.25 MHz with 85 used subcarriers and a total of 128 subcarriers. The 3/4 16-QAM modulation is used for mobile WiMAX and 1/2 QPSK is used for fixed WiMAX. The other parameters remain the same. The configuration of

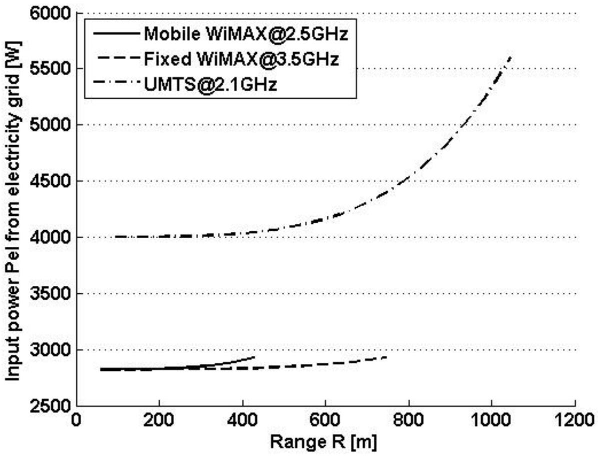

Fig. 3. Comparison of mobile, fixed WiMAX and UMTS.

	Mobile WiMAX	Fixed WiMAX	UMTS	Unit
Frequency	2.5	3.5	2.1	GHz
Bit rate	2.0	2.8	2	Mbps
Rx SNR	15	9.4	5.5	dB
Range	0.428	0.746	1.047	km
P_{el}	2927.4	2927.4	5598.2	W
P_{Tx}	3.2	3.2	20	W
P_{rad}	125.9	158.5	1096.5	W
PC_{opp}	5.09	1.67	1.63	mW/m^2

TABLE IV
COMPARISON OF THE WIRELESS TECHNOLOGIES FOR A BIT RATE OF 2 MBPS.

the different base stations can be found in Table I.
Figure 3 shows the power P_{el} needed from the electricity grid (in Watt) as a function of the range R (in metres) for the three different technologies. Table IV lists the results for the defined case. We define P_{rad} as the radiated power of one sector antenna (in Watt) and PC_{opp} as the power consumption per covered area (in W/m^2):

$$PC_{opp} = \frac{P_{el}}{\pi R^2} \tag{8}$$

The lower PC$_{opp}$, the more energy-efficient the considered technology is.

Figure 3 and Table IV show that mobile and fixed WiMAX have the lowest power consumption. This power consumption is 2927.4 W. The power consumption of both technologies is the same because we can use the same equipment for mobile as for fixed WiMAX as shown in Table I. However, mobile WiMAX has a lower maximum range, 428.4 m, than fixed WiMAX which has a maximum range of 745.9 m for the same power consumption. The range for mobile WiMAX is lower because the receiver SNR of mobile WiMAX is much higher (15 dB) than for fixed WiMAX (9.4 dB). We already mentioned that a high receiver SNR corresponds to a low range. Furthermore, fixed WiMAX has a higher gain (8 dBi) than mobile WiMAX (2 dBi) which also contributes to the higher range reached by fixed WiMAX.

The maximum range for UMTS is 1046.7 m with a power consumption of 5598.2 W. The power consumption of UMTS is higher than for mobile and fixed WiMAX. There are two components of the UMTS base station that contribute to this high power consumption. The first one is the power amplifier. If we look at Table I we see that the power amplifier for UMTS has an efficiency of 3.75%. The power amplifier for mobile and fixed WiMAX has an efficiency of 9%. From equations (3) and (4), it is clear that a power amplifier with a higher efficiency consumes less power for the same P_{Tx}. The second component is the air conditioning. $P_{el/air}$ is 2590 W for UMTS, while only 690 W for fixed WiMAX (see Table I). We need a larger air conditioning because the power amplifier is charged with a higher load than for WiMAX.
Despite the high power consumption, UMTS has the largest range (1046.7 m) of the three technologies. The reason is again the receiver SNR. UMTS has a receiver SNR of only 5.5 dB, where the receiver SNR of mobile and fixed WiMAX are definitely higher (see Table IV). Furthermore, UMTS has the lowest frequency (2.1 GHz) which also contributes to the high range reached by UMTS.

From the values of PC_{opp} in Table IV, we can conclude that UMTS is the best solution because it has the lowest value of 1.63 W/m^2. This is consistent with equation (8), UMTS has a high power consumption but also a large range which still results in a low value for PC_{opp}.

C. Coverage of an area

In this section we investigate how much electrical power we need to cover a pre-defined area with the base stations of the different technologies. Important to remark is that we only use one technology at a time. The surface S of the suburban area we want to cover is 100 km^2. We define three types of base stations according to the used technology. Table IV gives an overview of the most important characteristics of the base stations. The other parameters and the different components of the base stations can be found in Tables I, II and III.

First we define the covered area $covered\_area_{1BS}$ of one base station (in km^2) as:

$$covered\_area_{1BS} = \pi R^2 \tag{9}$$

with R the range of the base station (in metres). Here, we assume that the covered area is a circle. Based on equation (9) we can calculate how much base stations $\#BS$ we need for a certain area with surface S:

$$\#BS = \left\lceil \frac{S}{covered\_area_{1BS}} \right\rceil \tag{10}$$

with $\lceil . \rceil$ the ceil function. Table V gives an overview of the results.

	Mobile WiMAX	Fixed WiMAX	UMTS	Unit
$\#BS$	174	58	30	
Power consumption	509.4	170.0	87.8	kW

TABLE V
COMPARISON TECHNOLOGIES IN COVERAGE OF AN AREA.

The best solution to cover the considered area is UMTS. We need only 30 UMTS base stations and both the total power consumption and PC_{opp} are the lowest for UMTS. From Table IV it can be seen that the UMTS base station has the highest range which means that we need the lowest number of base stations to cover the area. The power consumption for a UMTS base station is the highest of all the three base stations. However, because of the large range of one base station we need just a few base stations to cover the area. Mobile and fixed WiMAX have a lower power consumption but also a lower range. We need a lot more base stations to cover the area. This results in a higher total power consumption than when we cover the area with UMTS base stations.

VI. COMPARATIVE EVALUATION

We compare the power consumption of the different wireless technologies with the power consumption of wireline access technologies, core network power consumption and power consumption of customer premises equipment. We assume a rollout in a suburban area, with 300 subscribers/km^2.

For the wireless technologies, we define the power consumption per user (in W/user) as follows:

$$\frac{PC_{opp}}{subs} \tag{11}$$

with PC_{opp} the power consumption per covered area (in W/km^2) and $subs$ the number of subscribers per km^2.

Based on the results shown in Table IV and our assumption of $subs$ = 300 we find for mobile WiMAX:

$$\frac{PC_{opp}}{subs} = \frac{5.09 \cdot 10^{-3} \cdot 1000000}{300} = 16.97\ W/user \tag{12}$$

Furthermore we find for fixed WiMAX 5.57 W/user and 5.43 W/user for UMTS. Although UMTS base stations have a significantly higher power consumption, UMTS consumes less power per subscriber than both fixed and mobile WiMAX due to the large obtained range. Note also that the derived numbers are based on a theoretical modelling and not a real access network design.

A. Access Network and Customer Premises Equipment

For the customer premises equipment, power consumption values per user are found in [16] for each access technology. These values are listed in Table VI. It is noted that the power consumption of the fixed WiMAX home equipment (between 10.6 and 11.0 W) is greater than the power consumption of the access network. For the fixed line technologies, ADSL2 home equipment consumes between 3.8 and 5.0 W, VDSL2 between 6.0 and 7.5 W, PtP optical between 5.6 and 7.1 W, and GPON home devices between 7.7 and 9.7 W. For mobile WiMAX and UMTS, the home equipment typically consists of a USB modem. Based on the specifications of several commercial devices, the power consumption of a USB modems is estimated at 2.5 W for both mobile WiMAX and UMTS.

The power consumption for ADSL2 and VDSL2 access network devices is approximately 1.95 and 3.0 W per user, respectively. Note that for VDSL2 networks, the maximum distance between the user and the DSLAM is about 300 m. On the other hand, VDSL2 enables access rates of 100 Mbps. For PtP optical networks, the power consumption of access network devices is between 4.5 and 7.5 W per user at 1 Gbps. For GPON devices, for which we assume a distribution ratio of 64 users per port, the power consumption is 0.35 to 0.47 W per user.

It is important to note that although optical networks have a much lower power consumption compared to the wireless access networks, they have a much higher cost rolling them out. In [17] an analysis was performed and it was shown that the cost of keeping an optical access network up and running is only 10 % of the investment in a roll-out. This indicates that when making a fair comparison between the different technologies concerning power consumption and carbon footprint, life cycle assessment is required. This is however out of the scope for this paper.

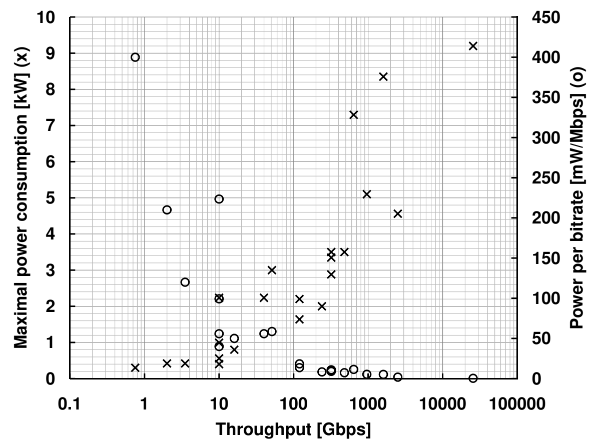

Fig. 4. Maximal Power Consumption (×) and Power per bit rate (o) of Routers versus the Maximal Throughput

B. Core Network

In order to evaluate the core network we compare the maximal power consumption with the maximal throughput of the routers [18]. These values are a good indicator for the actual power consumption in a router. Note however that the power consumption values on data sheets [18] are often higher than the actual power consumption. Additionally, the routers often do not operate at their maximal throughput value.

Figure 4 shows the maximal power consumption (×) and the power per bit rate (o) versus their maximal throughput. For higher bit rates the power consumption increases. However, when evaluating the power per bit rate, higher capacity routers are preferable over low capacity routers. Typically, one can state that the higher the capacity of the router the deeper the router is in the network. The routers with the lowest throughput are typically used at the edge of the core, and sometimes even in access networks.

In this paper we have not specified the average bit rate consumption of the user. It is also not in scope of this paper to determine how much traffic will be transferred through a core network. Based on the results derived in [18], we derive that $P^u_{core} = 11\% P^u_{access}$ for DSL technologies. In [16], we found a P^u_{access} between 1.3 - 2.0 W/user for the DSL access networks, which results in a P^u_{core} of approximately 0.14 - 0.22 W/user for the core network.

C. Summary

Table VI summarizes the power consumption per user for the considered technologies. The determination of the values for P^u_{access} of the wireless technologies is presented in the above sections. For P^u_{home} we used the values from [16]. For the other technologies, we also used the values from [16] for both P^u_{home} and P^u_{access}. Note that the numbers for the wired technologies do not include the power consumption of cooling which we did consider when modelling the wireless access networks. In order to incorporate this power consumption we will multiply the values with a Power Usage Effectiveness (PUE) which expresses the overall power consumption divided by the ICT device power consumption [19]. In the wired access networks, we assume a PUE of 1.5. For the core networks we assume a PUE of 2 which is typical for data centers.

Table VI shows that UMTS is clearly the best solution of the three wireless technologies. UMTS has the lowest value for P^u_{tot} because both P^u_{access} and P^u_{home} are low. We explained earlier (Section V-B) why UMTS has a lower PC_{opp} and thus a lower power consumption per user than both mobile and fixed WiMAX. Furthermore, the P^u_{home} is lower for UMTS because it uses a WNIC which consumes less power in comparison to the residential gateway used by fixed WiMAX. If we compare mobile and fixed WiMAX, we see that mobile WiMAX has a lower P^u_{home} because it also uses a WNIC and fixed WiMAX a residential gateway. Despite the low P^u_{home}, mobile WiMAX has a high P^u_{access} which results in a higher P^u_{tot} than for fixed WiMAX. We explained earlier why the P^u_{access} is higher for mobile WiMAX than for fixed WiMAX.

For the considered wired technologies, Table VI shows that ADSL2 is the best solution. Both P^u_{home} and P^u_{access} are the lowest for ADSL2. If we compare ADSL2 with UMTS, we see that ADSL2 has the lowest P^u_{tot}. Although, UMTS has the lowest P^u_{home}, the P^u_{access} for UMTS is higher than ADSL2. The higher P^u_{access} for UMTS is mainly caused by the high power consumption of the UMTS base station.

If we only compare P^u_{access} between the different technologies, we see that the wireless access technologies are consuming significantly more power than the wired access technologies. This result is a obvious motive to reduce the power consumption of the base stations in order to make wireless and wired access networks competitive in terms of power consumption per user.

VII. Future Work

In the previous section, we saw that the wireless access technologies have a high power consumption per user in comparison to the wired access technologies. In this section we project some research challenges to tackle this power consumption.

A. Optimization of individual base stations

First of all the individual base station can be optimized. Multiple Input Multiple Output (MIMO) techniques can be used where there is more than one receiving and sending antenna on the base station. Formula (2) takes MIMO already into account.

Beamforming is a different technique which could lead to a power consumption reduction. In beamforming adaptive antennas are used where the radiated power of the antenna is concentrated in the direction of the receiver. This allows for a lower requirements for the output power of the base station.

We also note that the power consumption of a base station is not very load dependent. This is largely due to the fact that many components are not designed to adapt their power consumption. The best example is the air conditioning which is typically sized for maximal power consumption of the other equipment. It would be interesting to introduce dependencies of the power consumption on the base station load in order to reduce the base station power consumption.

B. Optimization of the overall network

Next to optimizing the individual devices it is also necessary to optimize the access network as a whole. In section VI-C sleep modes are not considered yet. Sleep modes are used to lower the power consumption of a network. In wired access networks the connection speed is lowered when the user is not active which allows both the customer premises equipment and the access network equipment to consume less power. When the user becomes active, a wake-up signal is sent over the connection to increase the connection speed.

Wireless access networks could be optimized by adapting the coverage and capacity to the required load. By combining different types of base stations (large coverage and low per user bitrate capacity versus base stations with small coverage and high per user bitrate capacity, i.e., so called microcells, picocells and femtocells) one could allow to introduce sleep modes in the network and a more load-dependent power consumption.

When designing these networks it is also important to design proper management algorithms for these access networks. Roughly there are two approaches for introducing sleep states in the network. Firstly, one can introduce managed sleep where the traffic on the entire network is monitored and a central system decides whether or not to wake up nodes in the network. Secondly, one can use autonomous sleep where

	$\mathbf{P^u_{home}}$	$\mathbf{P^u_{access}}$	$\mathbf{P^u_{core}}$	$\mathbf{P^u_{tot}}$
Fixed WiMAX	10.6 – 11.0	5.57	0.28 – 0.44	16.45 – 17.01
Mobile WiMAX	2.5	16.97	0.28 – 0.44	19.75 – 19.91
UMTS	2.5	5.43	0.28 – 0.44	8.21 – 8.37
ADSL2	3.8 – 5.0	1.95	0.28 – 0.44	6.03 – 7.39
VDSL2	6.0 – 7.5	3.0	0.28 – 0.44	9.28 – 10.94
PtP fibre (1 Gbps)	5.6 – 7.1	4.5 – 7.5	0.28 – 0.44	10.38 – 15.04
GPON	7.7 – 9.7	0.35 – 0.47	0.28 – 0.44	8.33 – 10.61

TABLE VI
PER USER POWER CONSUMPTION (W/USER) FOR DIFFERENT TECHNOLOGIES

the devices monitor their own activity and based on this information decides to go to sleep or to wake up.

Table VI shows that it is also important to lower the power consumption of the customer premises equipment as well. The introduction of sleep modes in the access network should be done while taking the customer premises equipment into consideration in order to achieve maximal power saving.

VIII. CONCLUSIONS

In this paper, the power consumption for three different wireless technologies, namely fixed WiMAX, mobile WiMAX and UMTS, is investigated. This power consumption is related to the coverage of their base stations. We considered an indoor residential scenario with a residential gateway for fixed WiMAX and a WNIC for mobile WiMAX and UMTS. With a pre-defined bit rate of 2 Mbps, the power consumption is the same (circa 2900 W) for fixed and mobile WiMAX. Both technologies have the same power consumption because we can use the same equipment for the base stations. The power consumption for a UMTS base station is roughly 90 % higher than the power consumption of the WiMAX base stations. This high power consumption is mainly caused by the high power consumption of both the air conditioning and the power amplifier. For the mentioned power consumptions, the highest range (circa 1 km) is reached with a UMTS base station. Fixed WiMAX covers about 70 % of the UMTS range and mobile WiMAX only 40 %.

The power consumption per user is also investigated in this paper. For the wireless access networks and for a physical bitrate of 2 Mbps, a power consumption of 17 W/user is obtained for mobile WiMAX. Fixed WiMAX has a P^u_{access} of 6 W/user and UMTS has the lowest P^u_{access} of the considered wireless technologies, namely 5 W/user. The P^u_{access} of the best solution of all considered technologies (i.e. the wireless or wired technology with the lowest P^u_{tot}) is 64 % lower than the P^u_{access} of UMTS. This result shows that it's interesting to investigate the base stations of the wireless access technologies in order to reduce their power consumption.

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