Comparison of power consumption of mobile WiMAX, HSPA and LTE access networks

Margot Deruyck, Willem Vereecken, Emmeric Tanghe, Wout Joseph, Mario Pickavet, Luc Martens, and Piet Demeester

***Abstract*—Nowadays, wireless access networks are a large contributor to the CO_2 emissions of ICT. Today, ICT is responsible for 4 % of the annual energy consumption and this number is expected to grow drastically in the coming years. The power consumption of these wireless access networks will thus become an important issue in the coming years. In this paper, the power consumption of wireless base stations for mobile WiMAX, HSPA and LTE is modelled and compared for a future scenario.**
For our research, we assume a suburban area and a physical bit rate of 10 Mbps. We compare the wireless technologies for a SISO and three MIMO systems. For each case, we give a ranking of the wireless technologies as a function of their power consumption, range and energy efficiency. Based on these results, we cover a specified area with each technology and determine which technology is the best solution for the specified area. We also compare the power consumption of the wireless access networks with the power consumption of the wired access networks.

***Index Terms*—base station, coverage, MIMO, power consumption**

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. Currently the transmitted data volume in communication networks doubles every five years. Moreover, the WWRF (Wireless World Research Forum) [2] has a vision of 7 trillion wireless devices serving 7 billion users by 2017. Furthermore, the radio access networks are large contributors to the CO_2 emissions of ICT [1], [3], [4]. This indicates that the power consumption of wireless access networks, and more in particulary the power consumption of the base stations, is going to become an important issue in the coming years. Nowadays, the base stations are responsible for roughly two-thirds of the total CO_2 emissions of the wireless access networks. [4] 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 network of about 1:150. The energy consumption of the terminals is thus negligible with respect to the energy consumption of the networks. Therefore, it is clear that one 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 purpose of this research is to model the power consumption of base stations of various wireless technologies. This power consumption is related to the coverage. Based on these characteristics we compare the different wireless technologies for a current and future scenario. Furthermore, we are able to compare the power consumption of the wireless access networks with the power consumption of the wired (or fixed) access networks.

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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), HSPA (High Speed Packet Access), and LTE (Long Term Evolution). For the wired access networks, the following technologies are considered: ADSL2 (Asymmetric Digital Subscriber Loop 2), VDSL2 (Very high speed Digital Subscriber Line 2), PtP fibre (1 Gbps) and GPON (Gigabit-capable Passive Optical Network).

The outline of the paper is as follows: in section II the considered technical scenarios are discussed and a theoretical power consumption model for wireless access networks is proposed. Section III provides the power efficiency versus the coverage of the considered wireless technologies using the model of Section II. These results are used in Section IV to determine the total power consumption in a suburban area for different wireless and wired technologies. In Section V conclusions are presented.

II. Method

A. Scenarios

In this investigation, we consider an indoor residential configuration in a suburban environment with a WNIC (Wireless Network Interface Card) for a laptop for the three technologies. Table I summarizes the configuration parameters for all technologies of Section I. We also define two technical scenarios for the outdoor base stations: a *basic reference scenario* and a *future scenario*. In the reference scenario, one receiving (Rx) and one transmitting (Tx) antenna is considered i.e., a SISO system. In the reference scenario, both the base station and the receiver have multiple antennas i.e., a MIMO system. We consider a 2x1 MIMO system, a 2x2 MIMO system and a 4x4 MIMO system.

B. Global

In general a communication network consists of three different components: the home network also referred to as the CPE (Customer Premises Equipment), the access network and the core network. CPE is defined as any terminal equipment which resides at the customer's site, e.g. a WNIC is considered to

Parameter	Value	Unit
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 I
CONFIGURATION TABLE.

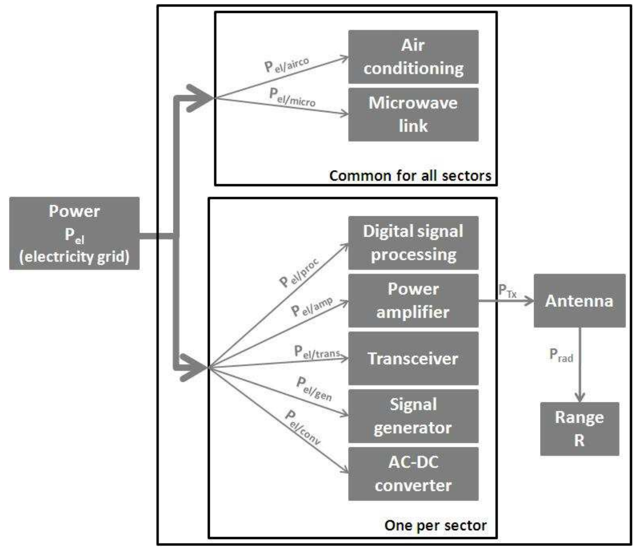

Fig. 1. Block diagram of the base station equipment

be CPE for the wireless technologies. For the fixed technologies a home gateway is used at the customer premises. The CPE is connected with the core network through the access network. The access network is that part of a communication network which connects subscribers to their immediate service provider.

To compare the different technologies we define the total power consumption P^u_{tot} per user (in Watt):

$$P^u_{tot} = P^u_{home} + P^u_{access} + P^u_{core} \tag{1}$$

with P^u_{home} the power consumption of the CPE (Customer Premises Equipment) (in Watt), P^u_{access} the power consumption of the access network (in Watt) and P^u_{core} the power consumption in the core network (in Watt). The wireless access network usually consists of base stations. The DSLAM (Digital Subscriber Line Access Multiplexer) and OLT (Optical Line Termination) are part of the access network for respectively the ADSL and VDSL technologies and the PtP optical networks and PON networks i.e., the fixed technologies. The core network is the central part of a telecommunication network that provides various services to customers who are connected by the access networks. The purpose of the core network is to interconnect several network sites or subnetworks. The main functionality of a core network is performed by routers.

C. Theoretical model for wireless access

In this section the model for determination of the power consumption P^u_{access} for wireless technologies is presented. The power consumption of a base station is evaluated. Based on this evaluation, we relate the power consumption of the base station to the wireless coverage range.

1) Power consumption of a base station: A base station is here defined as the equipment needed to communicate with the mobile stations and with the backhaul network. A base station typically consists of several power consuming components. Fig. 1 gives an overview of these components. Some equipment 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 and the AC-DC converter. Furthermore, a base station contains equipment that is common for all the sectors such as the air conditioning and the microwave link (responsible for communication with the backhaul network). In Fig. 1, the equipment of the base station and the different notations for the power consumption P_{el} of the different parts are indicated.

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 P_{Tx} of the antenna. The power consumption $P_{el/amp}$ of the power amplifier (in Watt) is determined as follows [10]:

$$P_{el/amp} = \frac{P_{Tx}}{\eta} \tag{2}$$

with P_{Tx} the input power of the antenna (in Watt) and η the efficiency of the power amplifier which is the ratio of RF power $P_{out/amp}$ (in Watt) to the electrical input power $P_{el/amp}$ of the power amplifier (in Watt) [11].

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

$$\begin{aligned} P_{el} \quad = \quad & n_{sector} \cdot (n_{Tx} \cdot P_{el/amp} + P_{el/trans} + P_{el/proc} \\ & + P_{el/conv} + P_{el/gen}) + P_{el/micro} + P_{el/airco} \end{aligned} \tag{3}$$

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. Furthermore, n_{Tx} is the number of transmitting antennas per sector. Table II summarises the power consumption of the different components of a base station for the considered technologies. These values are retrieved from data sheets of various manufacturers of network equipment.

2) Calculation of the 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

Equipment		Mobile WiMAX	HSPA	LTE
Digital signal processing	$P_{el/proc}$	100 W	100 W	100 W
Power amplifier SISO (1x1)	$P_{el/amp}$	100 W	300 W	350 W
	η	10 %	6.67 %	6.3 %
	RF_{out}	40 dBm	43 dBm	43 dBm
Power amplifier MIMO	$P_{el/amp}$	10.4 W	10.4 W	10.4 W
	η	11.54 %	11.54 %	11.54 %
	RF_{out}	30 dBm	30 dBm	30 dBm
Transceiver	$P_{el/trans}$	100 W	100 W	100 W
Signal generator	$P_{el/gen}$	384 W	384 W	384 W
AC-DC converter	$P_{el/conv}$	100 W	100 W	100 W
Air conditioning	$P_{el/airco}$	690 W	690 W	690 W
Microwave link	$P_{el/micro}$	80 W	80 W	80 W

TABLE II
POWER CONSUMPTION OF THE DIFFERENT PARTS OF THE WIRELESS BASE STATIONS.

ratio of the radiated power to the received power of the signal [12]. To determine the maximum path loss PL_{max} we need to take the parameters of Table III into account. Table III gives an overview of all the gains and losses that occur. These parameters are retrieved from the specifications and/or are typical values proposed by the operators self in order to make a fair comparison between the considered technologies. Furthermore, it is important to remark, 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 $\eta \cdot P_{el/amp}$.

Parameter	Mobile WiMAX	HSPA	LTE
Frequency [MHz]	2500	2100	2600
Maximum input power of base station [dBm]	35	24.7	43
Antenna gain of base station [dBi]	16	17.4	18
Antenna gain of mobile station [dBi]	2	0	0
Number of MIMO Tx antennas	1, 2, 4		
Number of MIMO Rx antennas	1, 2, 4		
MIMO gain [dB]	1x1: 0, 2x1: 3, 2x2: 6, 4x4: 12		
Cyclic combining gain of base station [dB]	3		
Soft handover gain [dB]	0	1.5	0
Feeder loss of base station [dB]	0.5	0	2
Feeder loss of mobile station [dB]	0		
Fade margin [dB]	10		
Cell interference margin [dB]	2		
User speed [km/h]	0		
Bandwidth [MHz]	5	5	3
Receiver SNR [dB]	15 [1]	15.6 [2]	29.4 [3]
Number of used subcarriers	360	1	151
Number of total subcarriers	512	1	256
Noise figure of mobile station [dB]	7	9	8
Implementation loss of mobile station [dB]	2	0	0
Duplexing	TDD		
Building penetration loss [dB] [20]	8.1		

(1) 3/4 16-QAM, (2) 3/4 64-QAM, (3) 2/3 64-QAM

TABLE III
LINK BUDGET TABLE FOR THE WIRELESS TECHNOLOGIES.

Once we know the maximum path loss PL_{max}, we can determine the maximum range R (in metres) we can reach with the base station of a certain technology [10]:

$$R = g^{-1}(PL_{max} - SM|f, h_{BS}, h_{MS}) \quad (4)$$

with PL_{max} the maximum path loss (in dB), SM the shadowing margin (in dB), f the frequency (in Hz), h_{BS} the height of the base station (in metres) and h_{MS} the height of the mobile station (in metres). The shadowing margin 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 other parameters can be found in Table I. The function $g(.)$ depends on the used path loss model e.g., the HATA model and the Erceg model [13], [14]. In this paper, we use the Erceg C model. The quantity before the ”|” in (4) is a variable and varies over a continuous interval, while the quantities after the ”|” in (4) are parameters which take only one discrete known value.

III. NUMERICAL ESTIMATIONS

A. Comparison of the wireless technologies

In this section, we compare the following wireless technologies: mobile WiMAX, HSPA and LTE. We compare these technologies at a certain bit rate to make a fair comparison. Here, we define a bit rate of 10 Mbps. The parameters given in Tables I, I and III are used. For mobile WiMAX we used the 3/4 16-QAM constellation.

Fig. 2 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 values for P_{el}, R and PC_{opp} for the different technologies. PC_{opp} presents the power consumption per covered area (in W/m^2) [10]:

$$PC_{opp} = \frac{P_{el}}{\pi \cdot R^2} \quad (5)$$

The lower PC_{opp}, the more energy-efficient the technology is.

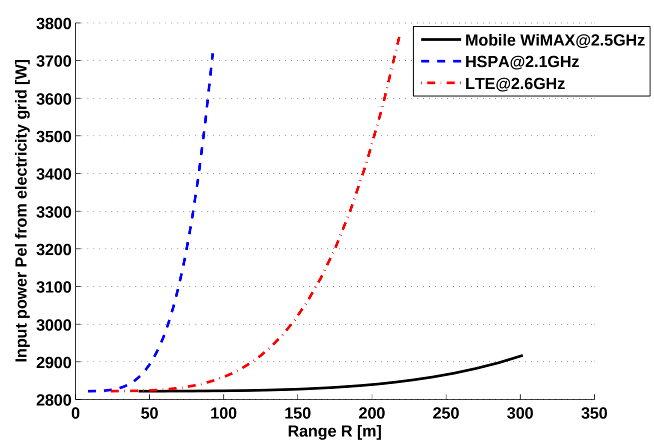

Fig. 2. Comparison of the technologies for a bit rate of approximately 10 Mbps

Fig. 2 and Table IV show that mobile WiMAX has the lowest power consumption, 2916.9 W, and the highest range, 301.7 m, resulting in the lowest value for PC_{opp} i.e.,

	Mobile WiMAX	HSPA	LTE
P_{el} [W]	2916.9	3719.4	3772.1
R [m]	301.7	92.6	218.9
Bit rate [Mbps]	11.5	11.3	10.20
PC_{opp} [mW/m^2]	10.2	138.07	25.06

TABLE IV
COMPARISON OF THE WIRELESS TECHNOLOGIES FOR A BIT RATE OF APPROXIMATELY 10 MBPS

10.2 mW/m^2 which makes mobile WiMAX the most energy-efficient. HSPA has a power consumption (3719.4 W) that is 27.5 % higher than the power consumption of mobile WiMAX, caused by the low efficiency (6.67 %) and the higher power consumption (300 W) of the power amplifier. Based on equation (2), one can see that a power amplifier with a higher efficiency consumes less power for the same P_{Tx}. For this power consumption, HSPA has a range of only 92.6 m. This range is 69.3 % lower than for mobile WiMAX because the input power of the HSPA base station (24.7 dBm) is lower than for the WiMAX base station (35 dBm). The higher the input power of the base station is, the higher the reached range will be. Furthermore, mobile WiMAX has an antenna gain of 2 dBi for the mobile station, while HSPA has no antenna gain at all. The high power consumption and the low range obtained with HSPA leads to a high value of PC_{opp}, 138.07 mW/m^2, which makes HSPA the least energy-efficient technology for this scenario. The power consumption of LTE (3772.1 W) is the highest of all technologies and is 29.3 % higher than for mobile WiMAX. This high power consumption is again caused by the low efficiency (6.3 %) and the high power consumption (350 W) of the power amplifier. The input power of the LTE base station (43 dBm) is also higher than the input power for the WiMAX base station (35 dBm). Equation (2) shows that there is a direct connection between the input power and the power consumption of the base station. The higher the input power of the base station, the higher the power consumption of the base station. However, LTE reaches a range (218.9 m) which is 27.4 % lower than the range obtained with mobile WiMAX. This range is lower because LTE works at a higher frequency (2.6 GHz) than mobile WiMAX (2.5 GHz) and because the required receiver SNR of LTE (29.4 dB) is very high compared to mobile WiMAX (15 dB) as shown in Table III.

For this scenario, we conclude that mobile WiMAX has the highest range and the lowest power consumption and is thus the most energy-efficient of the considered technologies. Furthermore, Table IV shows that mobile WiMAX has also the highest bit rate, 11.5 Mbps, for this scenario. Here, mobile WiMAX is definitely the best solution.

B. *Influence of MIMO*

In this section, we investigate the influence of MIMO on the power consumption and the range and compare the results with those of the 1x1 SISO system. We consider three MIMO systems: 2x1 MIMO (2 Tx and 1 Rx antenna), 2x2 MIMO (2 Tx and 2 Rx antennas) and 4x4 MIMO (4 Tx and 4 Rx antennas). For the 2x1 MIMO system we consider a bit rate of approximately 10 Mbps, for the 2x2 MIMO system a bit rate of approximately 20 Mbps and for the 4x4 MIMO system a bit rate of approximately 40 Mbps. The settings can be found in Tables I, II and III.

Table V summarizes the results for the 2x1, 2x2 and 4x4 MIMO system. Table V shows for mobile WiMAX the highest ranges (422.3 m, 499.7 m and 699.8 m for a 2x1, 2x2 and 4x4 MIMO system, respectively) and the lowest power consumptions (2986.4 W for 2x1 and 2x2 MIMO system and 3150.8 W for a 4x4 MIMO system), resulting in low values for PC_{opp} (5.33 mW/m^2, 3.81 mW/m^2 and 2.05 mW/m^2 for a 2x1, 2x2 and 4x4 MIMO system, respectively). Mobile WiMAX is thus the most energy-efficient technology and has the highest bit rates of all the considered technologies (Table V). The least energy-efficient technology is HSPA. HSPA has the same power consumption as LTE but ranges that are much lower than for LTE leading to higher values for PC_{opp} (Table V).

2x1 MIMO	**Mobile WiMAX**	**HSPA**	**LTE**
P_{el} [W]	2986.4	3859.4	3859.4
R [m]	422.3	129.6	306.4
Bit rate [Mbps]	11.5	11.3	10.20
PC_{opp} [mW/m^2]	5.33	73.14	13.09
2x2 MIMO	**Mobile WiMAX**	**HSPA**	**LTE**
P_{el} [W]	2986.4	3859.4	3859.4
R [m]	499.7	153.3	362.6
Bit rate [Mbps]	23	22.6	20.40
PC_{opp} [mW/m^2]	3.81	52.27	9.34
4x4 MIMO	**Mobile WiMAX**	**HSPA**	**LTE**
P_{el} [W]	3150.8	4896.8	4896.8
R [m]	699.8	214.7	507.8
Bit rate [Mbps]	46	45.2	40.8
PC_{opp} [mW/m^2]	2.05	33.81	6.05

TABLE V
COMPARISON OF THE WIRELESS TECHNOLOGIES FOR 2X1, 2X2 AND 4X4 MIMO SYSTEM

In general, one can state that the energy efficiency increases when more receiving and transmitting antennas are used. The range increases with 40 %, 66 % and 132 % for respectively a 2x1, 2x2 and 4x4 MIMO system compared to a 1x1 SISO system, while the power consumption increases with only 2 to 4 % for a 2x1 and 2x2 MIMO system compared to a 1x1 SISO system. From equation (3) one can see that only the Tx antennas are taken into account. For a 4x4 MIMO system the power consumption increases with only 8 % for mobile WiMAX and 30 to 32 % for HSPA and LTE compared to the 1x1 SISO system. The highest energy efficiency is reached with a 4x4 MIMO system.

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 each technology. 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 II gives an overview of the most important characteristics of the base stations. The other settings can be found in Tables I and III.

We calculate how much base stations $\#BS$ we need as follows [10]:

$$\#BS = \left\lceil \frac{S}{\pi \cdot R^2} \right\rceil \quad (6)$$

with R the range of the base station (in metres) and $\lceil . \rceil$ the ceil function. Table VI lists the results for a 4x4 MIMO system. P_{tot} (in kW) gives an estimation of the power consumption of all the required base stations.

	$\#BS$	P_{tot} [kW]
Mobile WiMAX	65	204.8
HSPA	205	1003.8
LTE	124	607.2

TABLE VI
COMPARISON OF THE WIRELESS TECHNOLOGIES FOR THE COVERAGE OF AN AREA WITH A 4X4 MIMO SYSTEM

From Table VI, we conclude that mobile WiMAX is the best solution. Mobile WiMAX needs only 65 base stations and has a total power consumption of 204.8 kW. This is self-evident because in Section III-B we saw that the WiMAX base station has the highest range and the lowest power consumption. Furthermore, we conclude that HSPA is not a good solution to cover the area. HSPA needs the highest number of base stations and has thus a high total power consumption (Table VI).

IV. COMPARATIVE EVALUATION

We now compare the power consumption of the different wireless access technologies with the power consumption of the wireline access technologies. Therefore, we determine P^u_{tot}, defined in equation (1), for each technology. We assume a rollout in a suburban area of 100 km^2 with 300 subscribers/km^2.

A. Power consumption P^u_{home} of the home networks

For the customer premises equipment, power consumption values per user are found in [15] for each technology. These values are listed in Table VII. 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 the wireless technologies, we consider mobile applications. The CPE for mobile applications is typically designed to have a low power consumption in order to allow long autonomy times. The CPE can come in many forms but in this work we consider a USB modem. Based on the specifications of several commercial devices, the power consumption of USB modems is estimated at 2.5 W. In applications where the wireless technology is used to simply replace the fixed line technology (e.g. fixed WiMAX) the home equipment has higher power consumptions typically in the range between 5 and 10 W. In this work we do not elaborate on this case but generally one can say that this application will consume more power than the mobile application. Note on the other hand, that for the home network we only consider the device which allows the customer to connect to the access network. PCs, televisions, settop-boxes, etc. have not been accounted for both the wireless and the wired case.

B. Power consumption P^u_{access} of the access networks

For the wireless technologies, we define the power consumption per user P^u_{access} (in Watt) as follows [10]:

$$P^u_{access} = \frac{PC_{opp}}{N} \quad (7)$$

with PC_{opp} the power consumption per area (in W/km^2) and N the number of subscribers per km^2. Table VII shows the results for P^u_{access} obtained with equation (7) and the values for PC_{opp} retrieved from Table IV.

The power consumption for ADSL2 and VDSL2 access network devices is approximately 1.95 and 3.0 W per user, respectively [15]. 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. Note that VDSL2 offers higher bit rates than ADSL2, but at lower distances between the user and the DSLAM. At 26 Mbps the range is about 1 km and whereas for bit rates up to 100 Mbps the range is smaller than 300 m. For PtP optical networks, the power consumption of access network devices is between 4.5 and 7.5 W per user at 1 Gbps [15]. 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[1] . Although the capacity of the optical fiber is shared over multiple users in GPON, the architecture allows for peak bit rates comparable to PtP due to the traffic aggregation on the shared medium. 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 [16] 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.

C. Power consumption P^u_{core} of the core networks

For the core networks, we assume the same network for all the considered wireless and wired technologies i.e., a DSL network. In [17], it is estimated that $P^u_{core} = 11\ \% \cdot P^u_{access}$. We will consider this estimation for the power consumption values of the DSL core networks. We found a P^u_{access} between 1.3 - 2.0 W for the DSL access networks, which results in a P^u_{core} of approximately 0.14 - 0.22 W for the core network [15]. Note that these numbers do not include the power consumption of cooling which we did consider when modelling the wireless access networks. In order to incorporate

[1]Point to point technologies allow ranges up to 60 km. GPON technologies allow ranges between 10 km (split ratio 64) and 20 km (split ratio 32)

	P^u_{home} [W]	P^u_{access} [W]	P^u_{core} [W]	P^u_{tot} [W]
Mobile WiMAX	2.5	34.0	0.28 – 0.44	36.78 – 36.94
HSPA	2.5	462.3	0.28 – 0.44	465.08 – 465.24
LTE	2.5	83.5	0.28 – 0.44	86.28 – 86.44
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 VII
COMPARISON OF THE POWER CONSUMPTION PER USER FOR THE DIFFERENT TECHNOLOGIES

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 [18]. For the core networks a PUE of 2 is assumed which is typical for data centers.

D. Comparison of the different technologies

Table VII summarizes the power consumption per user for the considered technologies. For the wireless technologies, one can see that mobile WiMAX is the best solution. For mobile WiMAX the lowest values for P^u_{tot} (36.78-36.94 W) are obtained, which is evident because mobile WiMAX has the lowest value for P^u_{access} (34.0 W). P^u_{home} and P^u_{core} are the same for all the wireless technologies because they can use the same CPE and we considered the same core network for the different technologies. Furthermore, we can conclude that HSPA performs worst of all the technologies because of the high power consumption of the access network.

For the wired technologies, Table VII shows that ADSL2 is the best solution. ADSL2 has a P^u_{tot} of 6.03-7.39 W which is the lowest value for P^u_{tot} because both P^u_{home} (3.8-5.0 W) and P^u_{access} (1.95 W) are the lowest for ADSL2. If we compare ADSL2 with mobile WiMAX, we see that ADSL2 performs better. Although mobile WiMAX has the lowest P^u_{home}, P^u_{access} is higher than ADSL2. The higher P^u_{access} for mobile WiMAX is caused by the power consumption of the WiMAX base station.

Fig. 3 gives an overview of the contribution of each part of the network to the total power consumption. For the wireless technologies, it is clear that the access network contributes the most to the total power consumption. For wired technologies, in contrary, the home network is the largest contributor. We conclude that the wireless access networks are consuming significantly more power consumption than the wired access networks. This result is an 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.

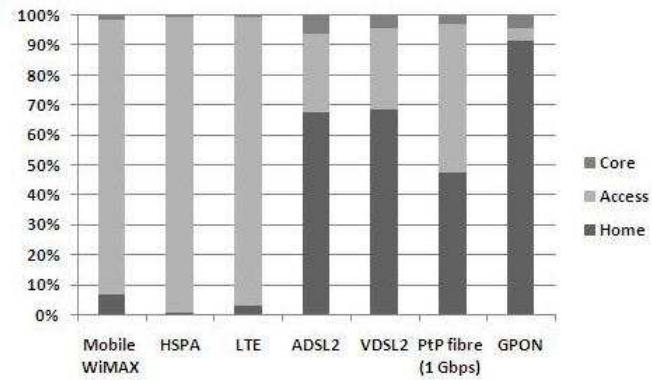

Fig. 3. Comparison of the power consumption per user for different technologies

V. CONCLUSIONS

In this paper, the power consumption for three different wireless technologies, namely mobile WiMAX, HSPA and LTE, is investigated. This power consumption is related to the coverage of their outdoor base stations. For the mobile stations, we considered an indoor residential scenario with a WNIC for all the considered technologies. With a pre-defined bit rate of 10 Mbps, we found that mobile WiMAX is the most energy-efficient solution. LTE has a power consumption that is 29 % higher and a range that is 27 % lower than mobile WiMAX. HSPA is the least energy-efficient and has a range that is 69 % lower than for mobile WiMAX while the power consumption is 28 % higher.

When MIMO is introduced, we concluded that each technology becomes more energy-efficient. When we compare a 4x4 MIMO system with a 1x1 SISO system, the range increases with 132 %, while the power consumption increases with only 8 % for mobile WiMAX and 30 to 32 % for HSPA and LTE. The 4x4 MIMO system is for each technology the most energy-efficient. Mobile WiMAX is the best solution for this future scenario.

Also for the coverage of a suburban area of 100 km^2 mobile WiMAX is a good solution. It needs the lowest number of base stations (65) and has the lowest total power consumption (P_{tot} = 204.8 kW) of all considered technologies.

The power consumption per user is also investigated in this paper. For the wireless access network, the best solution is again mobile WiMAX with a total power consumption per user P^u_{tot} of 37 W. The best solution of all the considered wireless and wired technologies is ADSL2 which has a P^u_{tot} that is 81 % lower than the P^u_{tot} of mobile WiMAX. Furthermore, we concluded that for the wireless technologies, the access network is the largest contributor to P^u_{tot}. In order to make wireless and wired technologies competitive in terms of energy efficiency, this result shows that it is interesting to investigate how the power consumption of the base stations of the wireless technologies can be reduced.

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