Reducing the Power Consumption in Wireless Access Networks: Overview and Recommendations

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Abstract

Due to growing importance of wireless access and the steeply growing data volumes being transported, the power consumption of wireless access networks will become an important issue in the coming years. This paper presents a model for this power consumption and investigates three base station types: macrocell, microcell, and femtocell base stations. Based on these models, the coverage effectiveness of the three base station types is compared and the influence of some power reducing techniques such as sleep modes and MIMO (Multiple Input Multiple Output) is evaluated.

I. Introduction

Recent research shows that nowadays the Information and Communication Technologies (ICT) sector is responsible for 2 - 4% of the worldwide carbon emissions which will even double in the next 10 to 15 years if no precautions are made [1]. During the use phase, the ICT equipment causes roughly 40 - 60% of the carbon emissions. A significant amount of these emissions, about one sixth, is caused by the telecommunication networks. Furthermore, the Wireless World Research Forum (WWRF) expects that by 2017 7 billion users are served by 7 trillion wireless devices. Wireless access networks, providing a wireless connection to the subscribers through which they access the internet, will thus become even more important in the future and the existing networks may need to be extended. These wireless access networks are currently responsible for 9% of the ICT power consumption and their power consumption is thus going to become an important issue in the coming years [2].

In wireless access networks, the user connection is provided through a wireless link. The user's devices use radio signals to connect to a base station, which is then further connected to the central office through a backhaul network [3]. A wireless access network typically consists of three different types of base stations: macrocell, microcell, and femtocell (or picocell) base stations. The highest coverage is obtained with a macrocell base station. These base stations are often placed along highways. The microcell base station has a smaller coverage and is often used in densely populated areas such as historical city centres, shopping malls, metro stations, etc. A femtocell base station has the smallest coverage and is often placed in offices and large buildings to provide indoor coverage [4]. To determine the power consumption in a wireless access network, it is important to know how much power each base station type consumes. Therefore, the power consumption for each base station type is modelled and related to its range. Based on this relation, we could evaluate the power consumption per subscriber for the deployment of the base stations in a real-life situation. Furthermore, we indicate where the network could be improved to reduce power consumption and suggest some solutions. The novelty of this paper is thus: (i) comparing the power consumption for three different base station types (i.e., macrocell, microcell, and femtocell base station) and for three different wireless technologies (i.e., LTE (Long Term Evolution) and LTE-Advanced, mobile WiMAX (Worldwide Interoperability for Microwave Access), and HSPA (High Speed Packet Access)), (ii) investigating the influence of introducing sleep modes in the network on the power consumption based on the probability that a high bit rate is needed, also the two layered network proposed in this paper has never been investigated before, and (iii) investigating the influence of MIMO (Multiple Input Multiple Output) on the power consumption for the considered wireless technologies and a realistic number of transmitting and receiving antennas.

Some research has been done about the power consumption of wireless access networks [5], [6], [7], [8], [9], [10], [11]. Mostly, the power consumption is modelled and evaluated for one or two base station types. In [12], four different base station types are investigated, but only LTE is considered as technology. In this paper, three different base station types are studied in a realistic deployment for three different technologies: WiMAX, HSPA, and LTE(-Advanced). In [5], [13], [14], [15], the possibilities of reducing the power consumption of wireless access networks by using sleep modes are investigated. In this paper, sleep modes are also considered, but to the best of our knowledge, our approach with a two layer network where the first layer provides an always-on network with a low bit rate and a second layer with sleeping base stations that provide higher bit rates when needed, has never been investigated before. Also the performance of MIMO is already frequently investigated such as in [16], but its influence is on the energy efficiency is not often considered. This has only been done in [17]. Here, LTE-Advanced is added to the study in [17]. Furthermore, for the number of receiving antennas, only 2 receiving antennas at the mobile device are considered, which is more realistic for the current situation.

The remainder of this paper is organized as follows. Section II gives a short overview of the wireless technologies considered. In Section III, a power consumption model is proposed for the three types of base stations. Section IV evaluates each base station type in a realistic deployment and describes possible solutions for reducing power consumption. In Section V, the conclusions are given.

II. Technologies

The three main emerging wireless technologies considered here are mobile WiMAX, HSPA and LTE(-Advanced). In this section, a short overview of each technology is given.

Mobile WiMAX is based on the IEEE 802.16e-2005 standard [18]. It operates in the 2-6 GHz band and is developed for mobile wireless applications and allows people to communicate while they are moving. The highest supported bit rate is approximately 70 Mbps.

HSPA (Release 4) is the successor of the widely deployed UMTS (Universal Mobile Telecommunications System, also known as 3G) [19]. The end-user experience is further improved by increasing the peak data rates up to 14 Mbps in the downlink. HSPA uses the 2.1 GHz band.

LTE is the newest wireless broadband technology and is marketed as the fourth generation (4G) of radio technologies. Targets for the bit rate are to have peak data rates from 10 Mbps up to 300 Mbps in the downlink. However, in practical implementations 300 Mbps rates have not yet been achieved. LTE uses the 2.6 GHz band. In the future, LTE may be using 800 MHz. Different releases are defined within LTE. Release 8 and 9 are known as LTE, while release 10 is known as LTE Advanced [20], [21], [22]. The four major improvements of LTE Advanced over LTE are: a better support for heterogeneous networks where different base station types (mainly macrocell and femtocell base stations) are mixed in one network, a better support for MIMO (Multiple Input Multiple Output) where multiple antennas are used for sending and receiving of the signals, relaying which allows to reduce the distance between the user and the network, and carrier aggregation which allows to obtain higher bit rates. Note that LTE and LTE Advanced are actually the same technology and thus is LTE Advanced backward compatible with LTE. This means that it is possible for an LTE terminal to connect with an LTE Advanced base station, although it will not be possible for the terminal to use specific LTE Advanced functionalities.

Mobile WiMAX and LTE apply quite similar techniques as they both use SOFDMA (Scalable Orthogonal Frequency Division Multiple Access) as multiple access technique which allows to adaptively change modulation and coding rate to enhance the channel quality.

III. Coverage effectiveness in wireless access networks

Determining which base station type performs better in a deployment is not an easy task. One base station has a high range and a high power consumption, while another can have a lower range but also a lower power consumption, and it is thus not clear which base station is the most energy efficient. To handle this problem, the coverage effectiveness (in m^2/W) is introduced and defined as the ratio of the area covered by the base station to the electrical power consumption P_{el} of that base station. This parameter tells us how much area is covered when 1 W power is consumed. The higher the coverage effectiveness, the better the area covered. A higher value is thus better. Section III-A and III-B discuss how respectively P_{el} and the coverage are determined.

A. *Power consumption in a wireless access network*

In this section, the power consumption for each base station type is determined. These models are developed based on private interviews with an operator and actual power measurements of base stations and reflect thus the situation in current deployed wireless access networks. This situation is used as a reference scenario to investigate the influence of some techniques on the power consumption.

1) Power consumption of a macrocell base station: Looking at the macrocell base station architecture in Fig. 1 shows that a macrocell base station consists of six power-consuming components [23]:

- *Rectifier*: converts alternating current (AC) to direct current (DC), also known as the AC-DC converter.
- *Digital signal processing*: is concerned with the conversion of the signal to a sequence of bits or symbols and the processing of these signals.
- *Transceiver*: is responsible for transmitting and receiving the signals.
- *Power amplifier*: converts the DC input power into a significant radio-frequent (RF) signal.
- *Air conditioning*: regulates the temperature in the base station cabin.
- *Microwave link*: is responsible for the communication with the backhaul network (sometimes replaced by a fiber link).

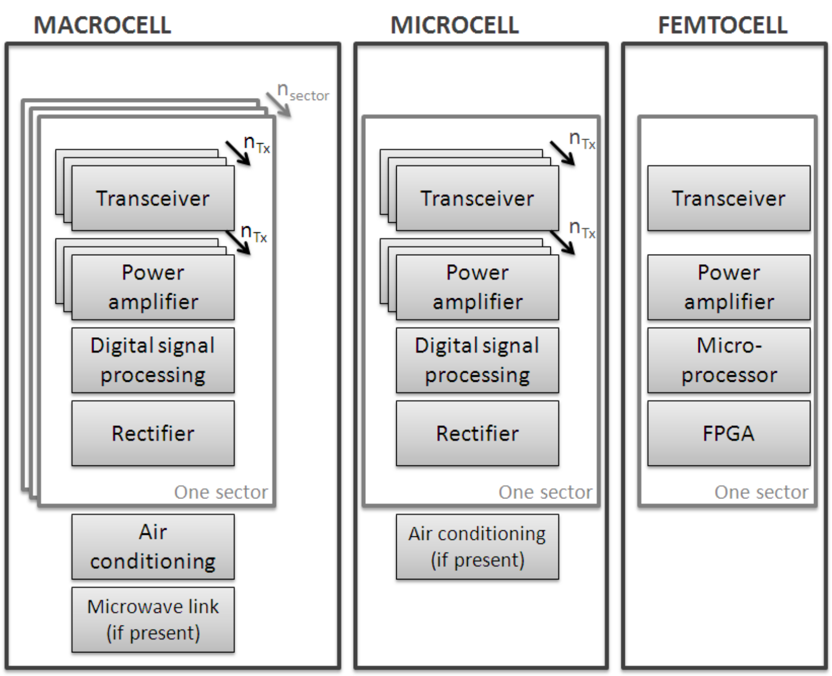

Figure 1. Block diagram of the components of a macrocell, microcell and femtocell base station.

If we take the sum of all those components, we can determine the base station power consumption. However, in Fig. 1, we see that some of the components are used multiple times. The power consumption of these components should thus be multiplied by their number of occurrences to determine the base station power consumption. Which components and how many of them depend on two factors: the number n_{sector} of sectors and the number n_{Tx} of transmitting antennas.

Firstly, we discuss the influence of n_{sector} which determines the number of rectifiers, digital signal processing, transceivers and power amplifiers. The area covered by a base station is called a cell which is further divided into a number n_{sector} of sectors. Each sector is covered by one antenna. For each sector, we need one rectifier, one digital signal processing unit, one transceiver and one power amplifier. The power consumption of these components should thus be multiplied by n_{sector}.
Secondly, we discuss the influence of n_{Tx} on the transceiver and the power amplifier. We mentioned above that each sector is covered by one antenna. However, in the future, it might be possible that multiple transmitting antennas are used per sector. This technique is called Multiple Input Multiple Output (MIMO). For each transmitting antenna, one transceiver and one power amplifier are needed. This means that the power consumption of the transceiver and the power amplifier should not only be multiplied by n_{sector} but also by the number n_{Tx} of transmitting antennas. Unless mentioned otherwise, we assume one transmitting antenna per sector.

Each of the components of the base station has its own typical power consumption which is given in Table I. The power consumption of the microwave link and the rectifier(s) is assumed to be constant throughout time. The power consumption of the air conditioning is not influenced by the time but rather by the temperature inside and outside the base station cabin. It is assumed that the heat generation rate inside the cabin and the temperature outside the cabin is constant, which results in a constant power consumption for the air conditioning.

Component	**Macrocell base station**	**Microcell base station**	**Femtocell base station**
Digital signal processing	100 W	100 W	7.9 W (Microprocessor + FPGA)
Power amplifier	24.7 W (P_{Tx} = 35 dBm) 156.3 W (P_{Tx} = 43 dBm)	16.6 W	2.4 W
Transceiver	100 W	100 W	1.8 W
Rectifier	100 W	100 W	—
Air conditioning	225 W	60 W	—
Microwave link	80 W	—	—

Table I
POWER CONSUMPTION OF THE COMPONENTS OF THE DIFFERENT BASE STATIONS TYPES [7], [17], [23], [24].

The power consumption of the digital signal processing, the transceiver and the power amplifier can fluctuate during time due to variations in load on the base station. The load represents the number of active users and the requirements of the services they use in the base station cell. The higher the load, the higher the power consumption of the base station. To take this into account, we defined the *load factor*. The power consumption of the digital signal processing, the transceiver and the power amplifier should be multiplied by this load factor to determine the base station's power consumption at a certain time of the day. Here, we assume a load factor of 1.0 which corresponds with the maximal power consumption of the base station. The worst case scenario is thus investigated. Furthermore, the power consumption of the power amplifier is also dependent of the input power of the antenna P_{Tx} [23]. For the macrocell base station, mobile WiMAX has a typical P_{Tx} of 35 dBm while HSPA and LTE (Advanced) have a P_{Tx} of 43 dBm. The higher P_{Tx}, the higher the power consumption of the power amplifier.

Based on the discussion above, the following formula is obtain to determine the power consumption of the macrocell base station $P_{el/macro}$ (in Watt) [23]:

$$P_{el/macro} = n_{sector} \cdot (P_{el/rect} + F \cdot (n_{Tx} \cdot (P_{el/amp} + P_{el/trans}) + P_{el/proc}) + P_{el/link} + P_{el/airco} \quad (1)$$

with n_{sector} the number of sectors, F the load factor, n_{Tx} the number of transmitting antennas, and $P_{el/rect}$, $P_{el/amp}$, $P_{el/trans}$, $P_{el/proc}$, $P_{el/link}$, and $P_{el/airco}$ the power consumption (in Watt) of the rectifier, the power amplifier, the transceiver, the digital signal processing, the microwave link, and the air conditioning, respectively.

Taken this into account, we obtained a power consumption of 1279.1 W per base station for mobile WiMAX and 1672.6 W per macrocell base station for HSPA and LTE (Advanced).

2) Power consumption of a microcell base station: Fig. 1 shows that the same components are used for a microcell base station as for a macrocell base station except for the backhauling. The backhauling of a microcell base station is typically established through the overlaying macrocell base station. A microcell base station supports only one sector covered by one antenna. The power consumption of the components are shown in Table I and are similar to those for the macrocell base station except for the power amplifier and the air conditioning. As less devices are present in the base station's cabinet, a less powerful air conditioning with a lower power consumption can be used. Note that the air conditioning is not always necessary in a microcell base station but, as mentioned above, the worst case scenario is investigated so the air conditioning is here included. The power amplifier consumes also less than for the macrocell base station because the input power P_{Tx} of the antenna is 33 dBm for all technologies considered. The value of this input power is typically for microcell base stations. Furthermore, a load factor of 1.0 is again assumed. Although, it is interesting to investigate the power consumption and possible power reduction for lower load factors, the highest load is here considered as we want to determine the maximum power consumption and the maximum possible power reduction. Furthermore, it is assumed that the backhaul connection is through the overlaying macrocell network.

Based on the discussion above, the following formula is obtained for the power consumption of a microcell base station $\mathrm{P}_{el/micro}$ (in Watt) [23]:

$$P_{el/micro} = P_{el/rect} + P_{el/airco} + F \cdot (P_{el/amp} + P_{el/trans} + P_{el/proc}) \quad (2)$$

with F the load factor, and $P_{el/rect}$, $P_{el/airco}$, $P_{el/amp}$, $P_{el/trans}$, and $P_{el/proc}$ the power consumption of the rectifier, the air conditioning, the power amplifier, the transceiver, and the digital signal processing (in Watt), respectively.

This results in a power consumption of 376.6 W per microcell base station for all technologies considered.

3) Power consumption of a femtocell base station: The size of a femtocell base station is much smaller than that of a macrocell and microcell base station and is comparable to that of a WiFi access point. Therefore, the power-consuming components are different from those of a macrocell and microcell base station as shown in Fig. 1. The femtocell base station consists of a microprocessor, a FPGA (Field-Programmable Gate Array), a transceiver and a power amplifier [7]. The microprocessor is responsible for implementing and managing the standardized radio protocol stack and the baseband processing and also takes care of the communication with the backhaul network [7]. The FPGA is responsible for a number of features such as data encryption, hardware authentication, etc. [7]. The power consumption of these components is also listed in Table I. It is assumed that the connection with the backhaul network is done through DSL (Digital Subscriber Line) or cable which is beyond the scope of this paper.

The following formula is obtained to determine the power consumption of the femtocell base station $P_{el/femto}$ (in Watt) [7], [24]:

$$P_{el/femto} = P_{el/mp} + P_{el/FPGA} + P_{el/trans} + P_{el/amp} \quad (3)$$

with $P_{el/mp}$, $P_{el/FGPA}$, $P_{el/trans}$, and $P_{el/amp}$ the power consumption of the microprocessor, the FPGA, the transceiver, and the power amplifier (in Watt), respectively. Taking into account of the values shown in Table I, this results in a femtocell base station power consumption of 12 W per base station.

B. Range of the different base station types

To determine the range of a base station, the maximum allowable path loss PL_{max} needs to be calculated. Path loss is the ratio of the transmitted power to the received power of the signal. PL_{max} is then the maximum allowable path loss which a transmitted signal can be subjected to while still being detectable at the receiver and includes all of the possible elements of loss associated between the propagating wave and any objects between the transmitter and receiver.

Based on PL_{max}, we can determine the range by using a propagation model which describes the relation between path loss and range. We are obliged to use a different propagation model for each type of base station as the circumstances for each base station type are different. For example, the femtocell base station is placed indoor while the macrocell and microcell base station is outdoor, the macrocell base station has a height of 30 m while the antenna height for a microcell base station is 6 m. The following propagation models were used: Erceg C for the macrocell base station [25], Walfisch-Ikegami for the microcell base station [26], and the ITU-R P.1238 model for the femtocell base station [27].

An important parameter when determining the range is the receiver Signal-to-Noise Ratio (SNR), which represents the SNR at the receiver for a certain Bit Error Rate (BER) and depends on the modulation scheme and coding rate used. For wireless communication, the binary bit stream has first to be translated into an analogue signal which can be done by using a modulation scheme such as QPSK (Quadrature Phase Shifting Keying) and 16- or 64-QAM (Quadrature Amplitude Modulation). The coding rate is used for Forward Error Correction (FEC) which is responsible for the correction of errors occurred. The coding rate indicates how many redundant bits will be added per number of information bits. The modulation scheme and the coding rate determine the physical bit rate, which is the total number of physically transferred bits per second including useful data as well as the protocol overhead. The higher the bit rate, the higher the receiver SNR and the lower the range.

The receiver SNR is also a determining factor for the required signal power which indicates what the signal power level is for just acceptable communication quality. A lower required signal power corresponds with a higher range. The required signal power is also determined by the channel bandwidth. The lower the channel bandwidth, the lower the required signal power and the higher the range.

IV. Deployment of base stations

In this section, a comparison is made between the energy efficiency of the considered wireless technologies and two wired technologies. Furthermore, the influence of some power-reducing techniques such as sleep modes and MIMO is investigated.

A. Always-on deployment

In the previous section, we have seen that the range of a base station is dependent on the channel bandwidth and the modulation scheme. This results in different ranges for different bit rates. A higher channel bandwidth allows higher bit rates to be transmitted, but reduces the range due to a higher required signal power. A larger number of symbols in a modulation scheme increases the bit rate, but reduces the range due to higher noise sensitivity. These considerations lead to an availability of higher bit rates closer to a base station, whereas lower bit rates allow a larger reach of the base station.

For the deployment of base stations in a real-life situation, this means that the bit rate we want to make available to our users is a determining factor in the power consumption of our mobile access network. The higher the bit rate we want to make available to the users in the entire area covered by the network, the more base stations we need to deploy and the higher the power consumption of our access network becomes.

Thus, we can evaluate the power consumption per subscriber in relation to the access bit rate offered to a subscriber. The power consumption per subscriber ($W/subs$) is calculated by dividing the above described coverage effectiveness (W/km^2) by the considered user density ($subs/km^2$). We assume a user density of approximately 300 $subs./km^2$ which is common for suburban areas. Fig. 2 gives an overview of the access bit rate (in Mbps) versus the power consumption per subscriber (in $W/subs$) which is a typical metric used for comparing energy efficiency in wired and wireless access networks [3], [28]. To obtain these results, the power consumption for the macrocell, microcell, and femtocell base station is determined by using equations (1), (2), and (3), respectively. For the range calculations, the approach discussed in Section III-B is used. Finally, the bit rate is determined by taking into account a number of parameters such as the number of carriers for user data, the total number of carriers, the bandwidth, modulation scheme, coding rate, etc. Note that the bit rates that are indicated as LTE can be obtained by both LTE (Release 8 and 9) and LTE Advanced (Release 10), while the bit rates indicated as LTE Advanced are only applicable to Release 10. For LTE Advanced, only the highest bit rates are considered (i.e., 5 carriers of the same bandwidth are aggregated). The faces in Fig. 2 indicate which points belong to which technology.

We see that, due to the high availability of different channel bandwidths and modulation schemes, a wide range of bit rates is available for different technologies. This variety is the largest in LTE Advanced and the smallest in HSPA. We also see that for mobile WiMAX and LTE (Advanced) the femtocell base stations are more power efficient, whereas for HSPA the macrocell base stations are more power efficient. In all technologies, the microcell base stations are the least power efficient.

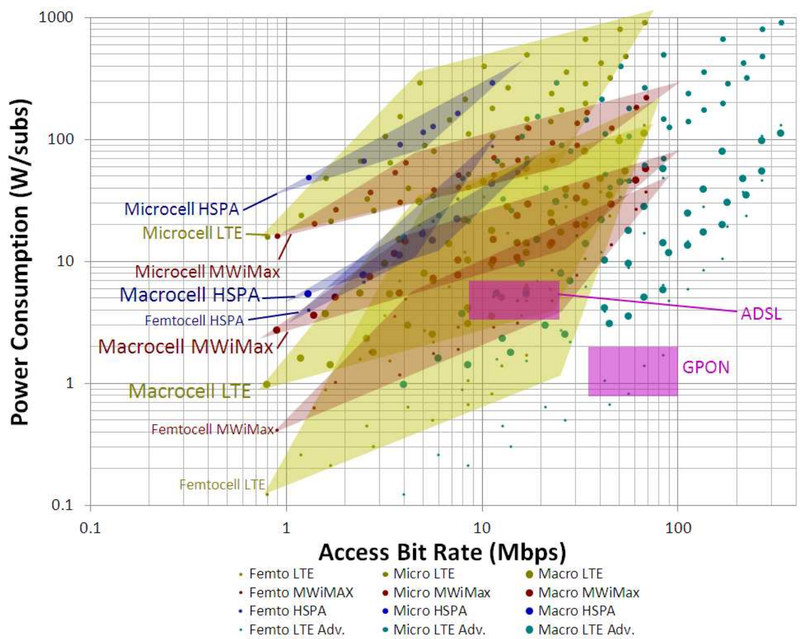

Figure 2. Power Consumption per Subscriber versus Bit Rate for mobile WiMAX (black x), LTE (black circle), HSPA (grey +), and LTE Advanced (grey diamond) and femto- (•), micro- (●) and macrocells (●).

The high number of available bit rates is entangled with a large variation in power consumption per subscriber. For LTE Advanced femtocell base stations, the lowest power consumption is 0.12 $W/subs$ at an access bit rate of 4.0 Mbps, whereas the access bit rate of 338.0 Mbps corresponds with a power consumption of 130.99 $W/subs$. A higher bit rate corresponds thus with a lower power efficiency. These high bit rates are unsustainable, and lead to a high environmental footprint of the access network, as well as a large operational cost for the network operator.

For comparison, in Fig. 2, we also displayed the power consumption and access bit rates of ADSL (Assymetric Digital Subscriber Line) and GPON (Gigabit Passive Optical Network) technologies [3]. In terms of power efficiency and access bit rates GPON technologies are clearly superior to mobile WiMAX, HSPA, and LTE. LTE Advanced supports bit rates similar to the GPON technologies for a similar power consumption. It even supports higher bit rates but then the power consumption is also higher. The performance of ADSL technologies is comparable to LTE and mobile WiMAX femtocell base station.

Note that these numbers are dependent on the users density. For a user density of 150 $subs./km^2$ all the power consumption numbers for the mobile access networks will double.

In conclusion we see that for low bit rates femtocell and macrocell networks can be deployed with a rather low power consumption per subscriber. However, the high bit rates these technologies were designed for have a too low reach to allow a power efficient deployment in an always-on scenario.

B. Introduction of sleep modes

Since the higher bit rates are only available near the base stations and a simple roll-out of a high bit rate mobile access network appears unsustainable, we need to find a way to reduce the power consumption of these high bit rate access networks. Therefore, we reconsider the suggested scenario. When offering high bit rates to a user, we assume that these high bit rates are requested on rare occasions. There is a difference between the peak bit rate and the average bit rate a user requires. In fixed line access networks, this is used to allow traffic aggregation and reduce the requirements on intermediary nodes. In this situation, we can use this difference to introduce *sleep modes* in the mobile access network.

When we take a closer look at an LTE Advanced femtocell base station architecture we see bit rates up to 338 Mbps are available as well as bit rates of 4.0 Mbps (or even 0.8 Mbps when the LTE bit rates are also considered). The coverage for the higher bit rates is only required when the user is requesting these higher bit rates. Therefore, we can design the access network in such a way that we cover the entire area with a low bit rate. These base stations are always-on. The higher bit rate coverage is provided with a second layer of deployment, to cover for higher bit rates, but these base stations are in a sleep mode and consuming less power. Only when a user requests a higher bit rate and is not close enough to the base station to receive this higher bit rate, a base station of the second layer is activated. The introduction of sleep modes allows the power consumption of this access network to be reduced.

The success of this method is dependent on the probability P that a subscriber needs the high bit rate. We have modelled this scenario and in Fig. 3 we displayed the power consumption of such a network as a function of the probability that a high bit rate is required P[High Bit Rate]. Assuming that P[High Bit Rate] = p (with $0 \leq$ p ≤ 1, p = probability), the power consumption per subscriber P_U is determined as follows (in Watt/subs):

$$P_U = \frac{(1 + (\frac{A_{min}}{A_{max}} - 1) \cdot (1 - (1-p)^{U/A_{max}})) \cdot P_{el}}{A_{min} \cdot U} \tag{4}$$

with A_{min} the base station's coverage for the lowest bit rate (in km^2), A_{max} the base station's coverage for the highest bit rate (in km^2), U the number of subscribers per km^2, and P_{el} the base station's power consumption (in Watt). Note that when it is certain that a high bit rate is needed i.e., P[High Bit Rate] = 1, eq. (4) simplifies to:

$$P_U = \frac{P_{el}}{U \cdot A_{max}} \tag{5}$$

because it is certain that a high bit rate is needed (p = 1) and thus it is certain that the second layer of base stations, which support the high bit rate as discussed above, is activated. Analogously, when it is certain that a high bit rate is not needed i.e., P[High Bit Rate] = 0, eq. (4) simplifies to:

$$P_U = \frac{P_{el}}{U \cdot A_{min}} \tag{6}$$

because it is certain that a high bit rate is not needed (p = 0) and thus the second layer of base stations will certainly not be activated. For all the other values of P[High Bit Rate] between 0 and 1 (boundaries not included) P_U is properly scaled between $\frac{P_{el}}{U \cdot A_{min}}$ and $\frac{P_{el}}{U \cdot A_{max}}$ depending on the probability that a high bit rate is needed. Fig. 3 shows that the LTE (Advanced) femtocell base stations are again the most power efficient (lowest power per subscriber in Fig. 3). Moreover, the reduction due to sleep modes becomes apparent more quickly for femtocell technologies. This is due to the smaller cell sizes. Since there are less users in a cell, the probability of a user requiring a peak bit rate being present in a cell is lower for femtocell base stations compared to macrocell base stations.

In this graph, we see that for $P < 0.001$ the power consumption converges to the minimal power consumption for most technologies. This corresponds with approximately 1.5 minutes of peak bit rate use per user per day. Moreover, since the peak bit rate requirements of the user will not always correspond to the maximum bit rate, these numbers can in reality be lower. On the other hand, we assumed no power consumption for the nodes in sleep mode. However, in reality some power will always be consumed in sleep mode for example for receiving wake-up signals.

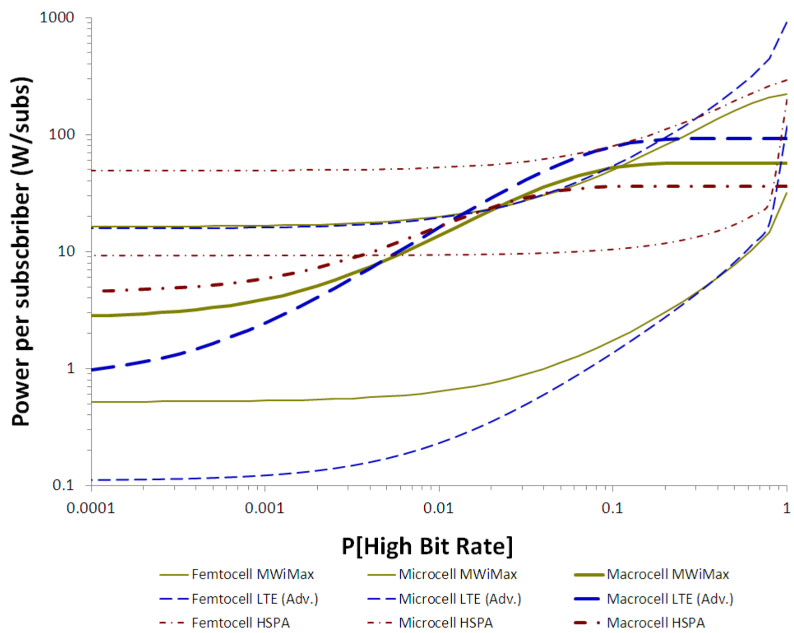

Figure 3. Power Consumption for mobile access networks with sleep modes.

C. *Introduction of MIMO*

In the previous section, we explained how the power efficiency of especially the femtocell base stations can be further increased by introducing sleep modes. In this section, the influence of MIMO on the coverage effectiveness is investigated. Nowadays, a macrocell base station uses mostly only one antenna, the transmitting antenna, to cover one sector. The user device uses also one antenna, the receiving antenna. This current situation is known as SISO (Single Input Single Output). In the future, both the base station and the user device may use multiple antennas which is called a MIMO (Multiple Input Multiple Output) system. A prefix is added to indicate how much transmitting and receiving antennas are used. For example, a 3x2 MIMO system is a MIMO system with 3 transmitting antennas and 2 receiving antennas. Although MIMO is not seen as a power reducing technique, it is still interesting to investigate if the introduction of MIMO results in a lower power consumption and/or higher coverage effectiveness.
MIMO can be introduced in three ways: spatial diversity, spatial multiplexing, and beamforming. Spatial diversity means that the receiver SNR is improved in order to increase the quality at the receiver side. In this way, higher ranges can also be achieved. By spatial multiplexing, the capacity for sending data is increased instead of improving the receiver SNR. Finally, when beamforming is applied, the directivity in the direction of the receiver is increased. In this study, spatial diversity is assumed as it will first be used in the near future.

The introduction of MIMO influences the coverage effectiveness as both the power consumption and the range are effected by MIMO. In Section III-A, we established that just as much power amplifiers and transceivers are needed as transmitting antennas of the base station. Clearly, this will influence the power consumption. As more components become active, the power consumption of a single base station will thus increase. For the range, an extra gain, the so-called MIMO gain, needs to be taken into account [17]. Due to this gain, a higher range is obtained.

Fig. 4 gives an overview of the coverage effectiveness for all MIMO systems supported by the technologies considered. Furthermore, for each MIMO system the coverage effectiveness gain (CEG) is indicated. This coverage effectiveness gain tells us how much the coverage effectiveness is increased (positive percentage) or decreased (negative percentage) for the MIMO system considered compared to the SISO system and is determined by using the definition of [17]. Note that in LTE Advanced, the MIMO support is improved and even up to 8 transmitting and receiving antennas are supported. However, in this study, the number of transmitting and receiving antennas is restricted to 4 and 2, respectively, which is more representative for the current situation. Fig. 4 confirms that the coverage effectiveness increases when MIMO is introduced. The highest CEG is obtained with a 3x2 MIMO system (CEG of 136.6%, 209.1%, and 209.2% for mobile WiMAX, HSPA, and LTE, respectively). A higher MIMO system (i.e., more transmitting and receiving antennas) thus not always results in a higher CEG. However, it is obvious that MIMO is a very promising technique to reduce the power consumption in future wireless access networks.

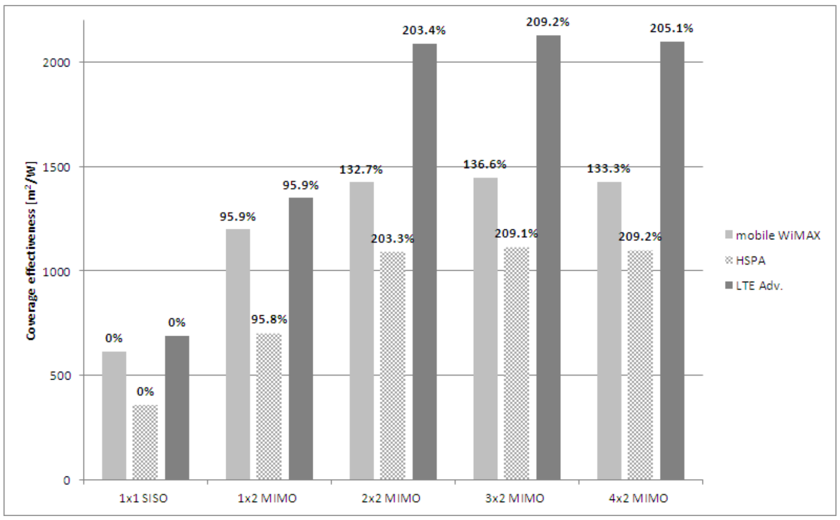

Figure 4. Coverage effectiveness and coverage effectiveness gain (in %) for different MIMO systems.

V. Conclusions

Nowadays, wireless access networks consume already high amounts of power and are thus large contributors to CO_2 emissions. As increasingly more devices are equipped with wireless interfaces, new networks have to be designed and the existing networks need expansion. Therefore, it is important to get a good view of the power consumption of the different elements of the wireless access network. Based on these views, recommendations and guidelines for the design of future wireless access networks can be formulated.

In the current wireless access networks, the bit rate we want to make available to our users is the determining factor in the power consumption of the network. The higher the available bit rate in the entire area covered by the network, the more base stations we need to deploy and the higher the power consumption of the network becomes. Furthermore, a higher bit rate corresponds with a lower power efficiency of the base station.

A wireless access network has typically three types of base stations: macrocell, microcell, and femtocell base stations. Depending on the technology considered, the macrocell and the femtocell base stations are the most power efficient. The power efficiency and access bit rates of the mobile WiMAX and LTE femtocell base station are comparable to that of ADSL technologies, while LTE Advanced is for some bit rates comparable to GPON access networks. However, for higher bit rates, GPON is superior in terms of energy efficiency. A reduction of the power consumption in wireless access networks is thus clearly needed.

One way to do this is by introducing sleep modes. Nowadays, the wireless access network is always-on. When sleep modes are supported, a first layer of base stations covers the entire area with a low bit rate and is always-on. A second layer is responsible for the coverage for higher bit rates and is only activated when higher bit rates are requested by the users. Sleep modes are a very promising reduction strategy especially for the femtocell base stations.

A second way to reduce power consumption is the introduction of MIMO where multiple transmitting and receiving antennas are used. The coverage effectiveness increases with a factor 2 to 3 when introducing MIMO compared to single antenna technologies.

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