Thesis Title
second line of title

Author Name

THE UNIVERSITY *of* EDINBURGH

Thesis submitted in fulfilment of

the requirements for the degree of

Doctor of Philosophy

to the

University of Edinburgh — 20xx

Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, either in whole or in part, in any previous application for a degree. Except where otherwise acknowledged, the work presented is entirely my own.

Hauke Andreas Holtkamp

October 2013

Abstract

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Acknowledgements

Thanks...

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List of Acronyms

AA Antenna Adaptation

AC Alternating Current

BB Baseband

BS Base Station

DC Direct Current

DTX Discontinuous Transmission

EARTH Energy Aware Radio and neTwork tecHnologies

GSM Global System for Mobile communications

LTE Long Term Evolution

PA Power Amplifier

PC Power Control

PRAIS Power and Resource Allocation Including Sleep

RAPS Resource allocation using Antenna adaptation, Power control and Sleep modes

RF Radio Frequency

RRM Radio Resource Management

TDMA Time Division Multiple Access

UMTS Universal Mobile Telecommunications System

Nomenclature

Q	Ranking tuple, time slots in order of capacity, page 18
Q_0	Time slot with highest virtual capacity, page 18
V	Priority tuple, time slots in order of score, page 18
$\Upsilon_{\mathrm{u}}, \Upsilon_{\mathrm{uu}}$	Set of used/unused time slots, respectively, page 18
ψ	Scoring map, assigning scores to users, page 18
$\psi_{\mathrm{ul}}, \psi_{\mathrm{ll}}$	Upper/lower limit of score, respectively, page 18

Chapter 1

Introduction

1.1 Overview

This chapter...

1.2 Thesis Context

Since the emergence of mobile communications...

1.3 Thesis Contributions

This thesis contributes t...

1.4 Thesis Structure

Chapter 2 ...

Chapter 2

Motivation and Background

2.1 Overview

This chapter first...

2.2 Energy Efficient Base Stations

A sample figure.

2.3 Quantifying Energy Efficiency

Enhancing the energy efficiency of communication networks has led to a field of research popularly labelled *Green Radio*...

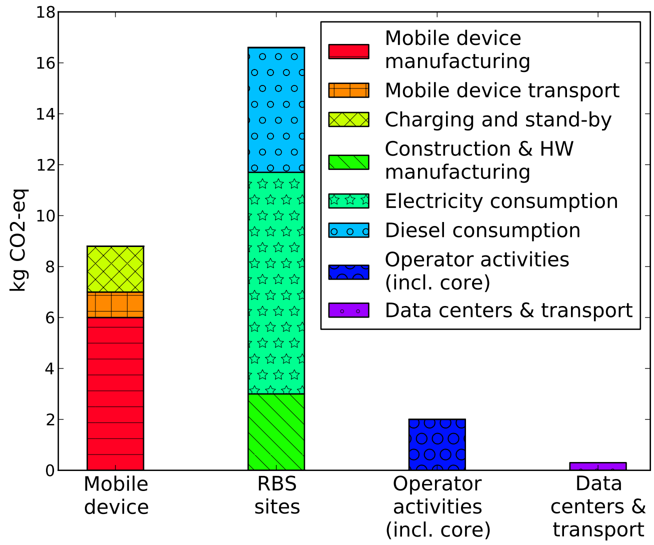

Figure 2.1: The carbon footprint (CO_2-equivalent emissions, see Section 2.3) for an average subscriber in 2007 [1].

2.4 Green Radio in Literature

Historically, ...

2.5 Technical Background

The following sections outline some fundamental concepts ...

2.5.1 Long Term Evolution (LTE)

LTE [2] is a wireless access standard superseding the Global System for Mobile communications (GSM) and Universal Mobile Telecommunications System (UMTS) for increased network capacities.

2.5.2 Multi-carrier Technology

The wireless medium is inherently shared...

2.5.3 Network Simulation

For many problems in communications research...

2.6 Summary

This chapter served to provide ...

Chapter 3

Power Saving on the Device Level

3.1 Overview

Power models describe ...

3.2 Challenges in Power Modeling

Generic modeling of Base Station (BS) power consumption is not a trivial task for multiple reasons...

3.3 Existing Power Models

In literature, three distinct power models for wireless transmitters are proposed and applied...

3.4 The Component Power Model

Before the description of the model, it is necessary to make some introductory remarks.

3.4.1 Remarks

First, ...

3.4.2 The Components of a BS

The modelled Long Term Evolution (LTE) macro BS consists of ...

Antenna Interface

This passive component is ...

Power Amplifier (PA)

The PA amplifies ...

Radio Frequency (RF) Transceiver

The RF transceiver provides the signal conversion ...

Baseband (BB) Unit

The BB unit generates ...

Direct Current (DC)-DC-Conversion

To supply the required DC voltages ...

Mains Supply/Alternating Current (AC)-DC-Conversion

Power from the the AC mains grid is converted to DC by the mains power supply unit...

Cooling

Macro BSs are typically housed in a cooled cabinet...

3.4.3 BS Power Consumption

The power consumption...

3.5 The Parameterized Power Model

The power model described above is ...

$P_{\mathrm{PA,limit}}$ /W	$\eta_{\mathrm{PA,max}}$	θ	P_{BB} /W	P_{RF} /W	σ_{feed}	σ_{DC}	σ_{COOL}	σ_{AC}	M_{Sec}
80.00	0.36	0.15	29.4	12.9	0.5	0.075	0.1	0.09	3

P_{max} /W	P_1 /W	Δ_{p} *10 MHz	$P_{\mathrm{S,0}}$ /W
40.00	460.4	4.2	324.0

Table 3.1: Parameter breakdown.

3.6 The Affine Power Model

In preparation for the following chapters of this thesis...

3.7 Summary

In this chapter, ...

Chapter 4

Power Saving on the Cell Level

4.1 Overview

As introduced in Chapter 2...

4.2 Power-saving Radio Resource Management (RRM) in Literature

In literature, ...

4.3 Power Control (PC) and TDMA

When the number of bits transmitted ...

Equation example

$$A + B = C \tag{4.1}$$

Subequation example

$$\underset{\mu,\nu}{\text{minimize}} \quad P_{\text{supply}}(\overline{R}_k) = \left[\sum_{k=1}^{K} \mu_k \left(P_0 + \Delta_{\text{p}} \frac{P_{\text{N}}}{G_k}\left(2^{\frac{\overline{R}_k}{W\mu_k}} - 1\right)\right)\right] + \nu P_{\text{S}} \tag{4.2a}$$

$$\text{subject to} \quad \sum_{k=1}^{K} \mu_k + \nu = 1\,, \tag{4.2b}$$

$$\nu \geq 0, \tag{4.2c}$$

$$\mu_k \geq 0 \quad \forall\, k, \tag{4.2d}$$

$$0 \leq P_k = \frac{P_{\text{N}}}{G_k}\left(2^{\frac{\overline{R}_k}{W\mu_k}} - 1\right) \leq P_{\max} \quad \forall\, k. \tag{4.2e}$$

Power allocation on the link level

It follows a derivation of ...

Power allocation on the cell level

Next, an optimization problem is proposed which ...

Evaluation

Next, the affine power model is taken into account...

4.4 Power and Resource Allocation Including Sleep (PRAIS)

This section introduces the ...

Joint PC and Discontinuous Transmission (DTX)

When employing DTX individually ...

Problem formulation

This section proceeds to ...

Evaluation

For the numerical analysis, ...

4.5 Resource allocation using Antenna adaptation, Power control and Sleep modes (RAPS)

To extend the previous analytical work ...

4.5.1 Problem Formulation

The global problem statement ...

Complexity

Dynamic subcarrier allocation ...

4.5.2 Step 1: Antenna Adaptation (AA), DTX and Resource Allocation

...

4.5.3 Step 2: Subcarrier and Power Allocation

This section ...

4.5.4 Results

...

Benchmarks

The following transmission strategies are evaluated ...

Performance Analysis

The channel value selection in ...

4.6 Summary

Starting with the Shannon limit, ...

Chapter 5

Power Saving on the Network Level

5.1 Overview

Chapter 4 proposed ...

5.2 Channel Allocation in Literature

Generally, ...

5.3 System Model and Problem Formulation

The network is considered as follows...

5.4 Discontinuous Transmission (DTX) Alignment Strategies

In this section, ...

5.4.1 Sequential Alignment

In *sequential alignment*, ...

5.4.2 Random Alignment

Random alignment ...

5.4.3 P-persistent Ranking

The synchronous alignment of uncoordinated Base Stations (BSs) can lead to instabilities...

5.4.4 Distributed DTX Alignment with Memory

Sample algorithm

5.5 Results

This section ...

Algorithm 1 Distributed DTX alignment with memory

Ensure: $\psi, \Upsilon_{\mathrm{u}}$

$Q \leftarrow$sort-desc-by-capacity(Υ)
for all υ in Υ_{u} **do**
    if $\psi(\upsilon) < \psi_{\mathrm{ul}}$ **then**
        $\psi(\upsilon) \leftarrow \psi(\upsilon) + 1$
    end if
end for
for all υ in $\Upsilon_{\mathrm{uu}} \backslash \{Q_0\}$ **do**
    if $\psi(\upsilon) > \psi_{\mathrm{ll}}$ **then**
        $\psi(\upsilon) \leftarrow \psi(\upsilon) - 1$
    end if
end for
$\psi(Q_0) \leftarrow \psi(Q_0) + 1$
$V \leftarrow$ sort-desc-by-score(Q, ψ, Υ)
return $\psi, V, \Upsilon_{\mathrm{u}}$

Simulation Environment and Resource Block Scheduling

The four strategies were tested ...

Power Consumption

To assess ...

Convergence

Another relevant aspect is ...

Reliability

An important aspect ...

Complexity

With regard to complexity...

Interpretation

...

5.6 Summary

In this chapter, ...

Chapter 6

Conclusions, Limitations and Future Work

6.1 Summary and Conclusions

In this thesis, ...

6.2 Limitations and Future Work

The most important limitation to the techniques proposed in this thesis ...

Appendix A

Appendix

A.1 Proof of Convexity for Problem (4.1)

This proof shows that ...

A.2 Proof of Convexity for Problem (4.2)

This proof shows that...

Appendix B

List of Publications

This chapter contains a list of publications related to this thesis ordered by academic publication status (published, accepted, submitted) and other type (project reports and book contributions).

B.1 Published

- Gunther Auer and István Gódor and László Hévizi and Muhammad Ali Imran and Jens Malmodin and Péter Fasekas and Gergely Biczók and **Hauke Holtkamp** and Dietrich Zeller and Oliver Blume and Rahim Tafazolli, "Enablers for Energy Efficient Wireless Networks", *Proceedings of the IEEE Vehicular Technology Conference (VTC) Fall-2010*, 2010 [a]

- **Hauke Holtkamp** and Gunther Auer, "Fundamental Limits of Energy-Efficient Resource Sharing, Power Control and Discontinuous Transmission", *Proceedings of the Future Network & Mobile Summit 2011*, 2011 [b]

- **Hauke Holtkamp** and Gunther Auer and Harald Haas, "Minimal Average

Consumption Downlink Base Station Power Control Strategy", *Proceedings of the 2011 IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, 2011 [c]

- **Hauke Holtkamp** and Gunther Auer and Harald Haas, "On Minimizing Base Station Power Consumption", *Proceedings of the Vehicular Technology Conference (VTC) Fall-2011*, 2011 [d]

- Claude Desset and Björn Debaillie and Vito Giannini and Albrecht Fehske and Gunther Auer and **Hauke Holtkamp** and Wieslawa Wajda and Dario Sabella and Fred Richter and Manuel Gonzalez and Henrik Klessig and István Gódor and Per Skillermark and Magnus Olsson and Muhammad Ali Imran and Anton Ambrosy and Oliver Blume, "Flexible Power Modeling of LTE Base Stations", *Proceedings of the 2012 IEEE Wireless Communications and Networking Conference:*, 2012 [e]

- **Hauke Holtkamp** and Gunther Auer and Samer Bazzi and Harald Haas, "Minimizing Base Station Power Consumption", *IEEE Journal on Selected Areas in Communications*, 2014 [j]

B.2 Accepted

- **Hauke Holtkamp** and Gunther Auer and Vito Giannini and Harald Haas, "A Parameterized Base Station Power Model", *IEEE Communications Letters*, 2013 [h]

- **Hauke Holtkamp** and Harald Haas, "OFDMA Base Station Power-saving Via Joint Power Control and DTX in Cellular Systems", *Proceedings of the Vehicular Technology Conference (VTC) Fall-2013*, 2013 [i]

B.3 Submitted

- **Hauke Holtkamp** and Guido Dietl and Harald Haas, "Distributed DTX Alignment with Memory", *Proceedings of the 2014 IEEE International Conference on Communications (ICC)*, 2014 [k]

B.4 Project Reports

- EARTH Project Work Package 2, "Deliverable D2.2: Reference Systems and Scenarios", 2012 [f]
- EARTH Project Work Package 3, "Deliverable D3.3: Green Network Technologies", 2012 [g]

B.5 Contributions

- Jinsong Wu and Sundeep Rangan and Honggang Zhang, "Green Communications: Theoretical Fundamentals, Algorithms and Applications", *Taylor & Francis Group*, 2012 [l]

Appendix C

Attached Publications

This chapter contains all work either published or submitted for publication to academic conferences or journals. For brevity, Energy Aware Radio and neTwork tecHnologies (EARTH) project deliverables [g, f] and a book chapter [l] are not listed here.

A Parameterized Base Station Power Model

Hauke Holtkamp, *Member, IEEE,* Gunther Auer, *Member, IEEE,* Vito Giannini, *Member, IEEE,*
Harald Haas, *Member, IEEE*

***Abstract*—Power models are needed to assess the power consumption of cellular base stations (BSs) on an abstract level. Currently available models are either too simplified to cover necessary aspects or overly complex. We provide a parameterized linear power model which covers the individual aspects of a BS which are relevant for a power consumption analysis, especially the transmission bandwidth and the number of radio chains. Details reflecting the underlying architecture are abstracted in favor of simplicity and applicability. We identify current power-saving techniques of cellular networks for which this model can be used. Furthermore, the parameter set of typical commercial BSs is provided and compared to the underlying complex model. The complex model is well approximated while only using a fraction of the input parameters.**

I. Introduction

Recently, the power consumption of cellular networks has become a point of interest in research and even been taken into consideration for the standardization of future cellular networks like Long Term Evolution (LTE)-Advanced [1]. It was found in [2] that in cellular networks the element which causes the largest share of overall consumption is the base station (BS). Numerous techniques have consequently been proposed by which the power consumption of BSs can be reduced [3]–[8]. Some of these techniques only consider transmission power while others take into consideration that the generation of the radio signal also consumes power in circuitry by employing power models. Such power models describe abstractly how much power a transmitter consumes and how this consumption depends on operating parameters. In the past, the modelling of BS power consumption often had to be based on intuition until the first power models were published [9]–[13]. Simple models like [9], [10] allow computing the power consumption of a BS for specific configurations. In contrast, the non-linear complex model described by Desset *et al.* [13] is derived from the combination of each of a BS' subcomponents. This allows inspecting the power consumption to such detailed level as the effect of giga operations per second or transistor gate lengths, but is unwieldy to apply. In this paper, we extend the work in [11], [12] by maintaining simplicity while integrating two relevant operating variables into the model, namely the power amplifier (PA)'s output range and the transmission bandwidth. The proposed model allows assessing the power consumption of all techniques that are currently employed to reduce the power consumption of BS while conserving simplicity.

H. Holtkamp is with DOCOMO Euro-Labs, Munich, Germany, e-mail: holtkamp@docomolab-euro.com

G. Auer was with DOCOMO Euro-Labs when this work was carried out. He is now with Ericsson AB, Stockholm, Sweden.

V. Giannini is with IMEC, Leuven, Belgium, e-mail: vito@imec.be

H. Haas is with the University of Edinburgh, UK, e-mail: h.haas@ed.ac.uk

The scope of the model is described in Section II. The model is subsequently presented in Section III. In Section IV, it is discussed and compared to the complex model. The paper is concluded in Section V.

II. Power Model Scope

Power saving techniques in literature can be generally divided into design changes and operating approaches. Design changes affect the layout of the network or the hardware architecture. For example, in [14] it is proposed that the use of heterogeneous networks will positively affect the network power consumption under certain conditions. Cui *et al.* [4] show how adjusting the number of antennas affects power consumption. In contrast to design changes, operating approaches manipulate the functionality of a BS during operation. Here, proposed techniques are the reduction of transmission power [5], the deactivation of unneeded antennas [6], the adaptation of the transmission bandwidth [7] and the use of low power consumption sleep modes of varied durations [8].

The model presented in this paper encompasses all of these approaches to allow for a direct comparison while abstracting parameters which can either be assumed to be constant or have been shown to have little effect in the studied scenarios, such as modulation and coding settings, equipment manufacturing details and leakage powers [13]. To this extent, the following is covered in the proposed model:

- The different BS types of a heterogeneous network are modelled by applying different parameter sets to the same model equations.
- The number of transmission antennas and radio chains affects consumption during design and operation.
- The same holds true for transmission power, which affects the design indirectly by choice of a suitable power amplifier as well as the operation directly.
- Also, transmission bandwidth and sleep modes are modelled in their effect on BS power consumption.

III. Base Station Power Model

It was found in [11] that the supply power consumption of a BS can be approximated as an affine function of transmission power. In other words, the consumption can be represented by a static (load-independent) share, P_0, with an added load-dependent share that increases linearly by a power gradient, Δ_p. The maximum supply power consumption, P_1, is reached when transmitting at maximum total transmission power, P_max. Furthermore, a BS may enter a sleep mode with lowered consumption, P_sleep, when it is not transmitting. Fig. 1 shows an illustration. Total power consumption considering the

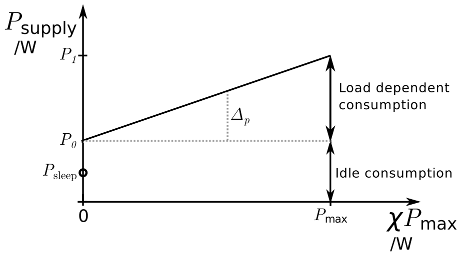

Fig. 1. Load-dependent power model for an LTE BS.

number of sectors, M_{sec}, is then formulated as

$$P_{\text{supply}}(\chi) = \begin{cases} M_{\text{sec}}\left(P_1 + \Delta_{\text{p}} P_{\max}(\chi - 1)\right) & \text{if } 0 < \chi \leq 1 \\ M_{\text{sec}} P_{\text{sleep}} & \text{if } \chi = 0, \end{cases} \tag{1}$$

where $P_1 = P_0 + \Delta_{\text{p}} P_{\max}$. The scaling parameter χ is the load share, where $\chi = 1$ indicates a fully loaded system, *e.g.* transmitting at full power and full bandwidth, and $\chi = 0$ indicates an idle system. To further understand the contribution of different parameters on this basic model, we parameterize the maximum supply power consumption, P_1. We first establish how power consumption scales with the transmission bandwidth in Hz, W, the number of BS radio chains/antennas, D, and the maximum transmission power in W, $P_{\max}$. This requires to consider the main units of a BS: PA, radio frequency (RF) small-signal transceiver, baseband (BB) engine, direct-current (DC)-DC converter, active cooling and mains supply (MS). The dependence of the BS units on W, D and $P_{\max}$ can be approximated as follows [13]:

- Both the power consumptions of BB and RF, P_{BB} and P_{RF}, respectively, scale linearly with bandwidth, W, in and the number of BS antennas D. For some basic consumptions, P'_{BB} and P'_{RF}, we thus define

$$P_{\text{BB}} = D \frac{W}{10 \text{ MHz}} P'_{\text{BB}} \tag{2}$$

  and

$$P_{\text{RF}} = D \frac{W}{10 \text{ MHz}} P'_{\text{RF}}. \tag{3}$$

- The PA power consumption P_{PA} depends on the maximum transmission power per antenna $P_{\max}/D$ and the PA efficiency η_{PA}. Also, possible feeder cable losses, σ_{feed}, have to be accounted for:

$$P_{\text{PA}} = \frac{P_{\max}}{D \eta_{\text{PA}}(1-\sigma_{\text{feed}})}. \tag{4}$$

- Losses incurred by DC-DC conversion, MS and active cooling scale linearly with the power consumption of other components and may be approximated by the loss factors σ_{DC}, σ_{MS}, and σ_{cool}, respectively. These losses are included in the model as losses of a total according to [11]. Active cooling is typically only applied in Macro type BSs.

These assumptions are combined to calculate the maximum power consumption of a BS sector,

$$P_1 = \frac{P_{\text{BB}} + P_{\text{RF}} + P_{\text{PA}}}{(1-\sigma_{\text{DC}})(1-\sigma_{\text{MS}})(1-\sigma_{\text{cool}})} \tag{5a}$$

$$= \frac{D \frac{W}{10 \text{ MHz}} \left(P'_{\text{BB}} + P'_{\text{RF}}\right) + \frac{P_{\max}}{D \eta_{\text{PA}}(1-\sigma_{\text{feed}})}}{(1-\sigma_{\text{DC}})(1-\sigma_{\text{MS}})(1-\sigma_{\text{cool}})}. \tag{5b}$$

An important characteristic of a PA is that operation at lower transmit powers reduces the efficiency of the PA and that, consequently, power consumption is not a linear function of the PA output power. This is resolved by taking into account the ratio of maximum transmission power of the PA from the data sheet, $P_{\text{PA,limit}}$ to the maximum transmission power of the PA during operation $\frac{P_{\max}}{D}$. The current transmission power can be adjusted by adapting the DC supply voltage, which impacts the offset power of the PA. The efficiency is assumed to decrease by a factor of γ for each halving of the transmission power. The efficiency is thus maximal when $P_{\max} = P_{\text{PA,limit}}$ in single antenna transmission and was heuristically found to be well-described by

$$\eta_{\text{PA}} = \eta_{\text{PA,max}} \left[1 - \gamma \log_2 \left(\frac{P_{\text{PA,limit}}}{P_{\max}/D}\right)\right], \tag{6}$$

where $\eta_{\text{PA,max}}$ is the maximum PA efficiency.

The reduction of power consumption during sleep modes is achieved by powering off PAs and reduced computations necessary in the BB engine. For simplicity, we only model the dependence on D as each PA is powered off. Thus, P_{sleep}, is approximated as

$$P_{\text{sleep}} = D P_{\text{sleep},0}, \tag{7}$$

where $P_{\text{sleep},0}$ is a reference value for the single antenna BS chosen such that P_{sleep} matches the complex model value for two antennas.

IV. Results and Discussion

The parameterized power model is applied to approximate the consumption of the Macro, Pico and Femto BSs which are described in the complex model. Parameters are chosen where possible according to [11], such as losses, efficiencies and power limits. The remaining parameters are adapted such that a closer match to the complex model could be achieved. The resulting parameter breakdown is provided in Table I. The proposed and the complex power models are compared for a bandwidth sweep with a varying number of transmit antennas in Fig. 2, Fig. 3, and Fig. 4, for a Macro, a Pico and a Femto station, respectively. Although two parameters, the bandwidth and the number of BS antennas, are varied, the parameterized model can be seen to closely approximate the complex model for all BS types. The largest deviation of the parameterized model from the complex model occurs when modeling four transmit antennas. This is caused by the fact that the parameterized model considers a constant slope, Δ_{p}, which is independent of D. In contrast, the PA efficiency in the complex model decreases with rising D, leading to an increasing slope which can not be matched by a constant slope. This deviation is a trade-off between simplicity and model accuracy.

BS type	$P_{\text{PA,limit}}$ /W	$\eta_{\text{PA,max}}$	γ	P'_{BB} /W	P'_{RF} /W	σ_{feed}	σ_{DC}	σ_{cool}	σ_{MS}	M_{Sec}	$P_{\max}$ /W	P_1 /W	Δ_{p} *10 MHz	$P_{\text{sleep,0}}$ /W
Macro	80.00	0.36	0.15	29.4	12.9	0.5	0.075	0.1	0.09	3	40.00	460.4	4.2	324.0
Pico	0.25	0.08	0.20	4.0	1.2	0.0	0.09	0.0	0.11	1	0.25	17.4	4.0	4.9
Femto	0.10	0.05	0.10	2.5	0.6	0.0	0.09	0.0	0.11	1	0.10	12.0	4.0	3.3

TABLE I
PARAMETER BREAKDOWN.

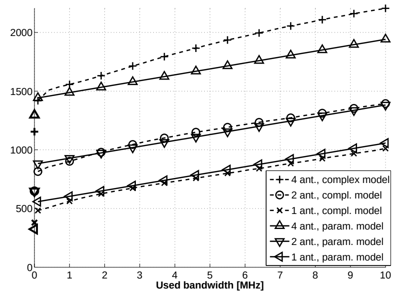

Fig. 2. Comparison of the parameterized with the complex model [13] power models for the Macro BS type with 40 W transmission power.

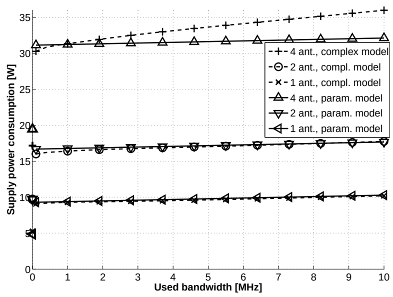

Fig. 3. Comparison of the parameterized with the complex model [13] power models for the Pico BS type with 0.25 W transmission power.

In addition to providing a solid reference, the model and the parameters can provide a basis for exploration. Individual parameters can be changed to observe the resulting variation in power consumption. With regard to the number of antennas, the parameterized model can only be verified up to four antennas, which is the extent of the complex model. Extending the system bandwidth, for example to 20 MHz, is expected to increase the BB and RF power consumption. The other parameters such as the transmission power and losses are expected to remain unaffected by different system bandwidths. Adapting the design maximum transmission power, $P_{\max}$, affects the PA efficiencies, which decrease with $P_{\max}$.

V. Conclusion and remarks

In this paper, we have provided a parameterized power model which allows calculating the power consumption of a modern BS based on important design and operation parameters. The model is much simpler and more applicable than the model it was derived from. A comparison of the parameterized model with the source model is provided.

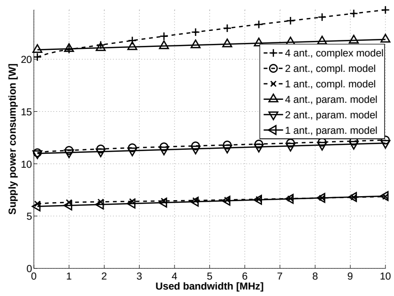

Fig. 4. Comparison of the parameterized with the complex model [13] power models for the Femto BS type with 0.1 W transmission power.

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