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with a Gearbox Physical Layer**

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Optimizing Transceiver Energy Efficiency with a Gearbox Physical Layer

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der Fakultät Elektrotechnik und Informationstechnik
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zur Erlangung des akademischen Grades
Doktoringenieur
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genehmigte Dissertation

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Abstract

With their rapidly increasing energy demands, mobile communications networks present significant economic and environmental challenges. Their high energy consumption results in significant greenhouse gas emissions and substantial operational costs for network providers. Given the projected increase in data traffic, it is crucial to implement energy-efficient solutions to mitigate this trend.

Analyses by network providers identify the analog front end as the dominant contributor to overall energy consumption, making it the central focus of this thesis. In this regard, we investigate the Gearbox-PHY, a dynamic physical layer approach designed to reduce energy consumption by switching between multiple modulation schemes and their corresponding radio front ends. This work aims to evaluate its energy-saving potential and identify the key components influencing its efficiency.

We first analyze the data rate requirements in mobile networks and demonstrate that low data rates occur most frequently, while peak rates remain rare events. We then explain the Gearbox-PHY in more detail, express the concept as a mathematical optimization problem, and integrate models and literature-based measurements for all major analog front end components to quantify the energy consumption per bit across various system configurations. Starting with generalized modulation schemes, we progressively extend our analysis to practical modulation schemes and ultimately incorporate hardware impairments, gradually refining our model to capture practical aspects of mobile communications systems.

Our findings demonstrate that the Gearbox-PHY has significant potential to reduce energy consumption in future mobile networks, achieving energy savings of up to two orders of magnitude at low data rates and high carrier frequencies. These results show that the Gearbox-PHY is a strong candidate for next-generation mobile networks, offering a promising path toward reducing energy consumption and enhancing the sustainability of wireless communications.

Kurzfassung

Mit ihrem rasant steigenden Energiebedarf stellen mobile Kommunikationsnetze erhebliche wirtschaftliche und ökologische Herausforderungen dar. Ihr hoher Energieverbrauch führt zu erheblichen Treibhausgasemissionen und enormen Betriebskosten für Netzbetreiber. Angesichts des prognostizierten Anstiegs des Datenverkehrs ist die Implementierung energieeffizienter Lösungen entscheidend.

Analysen von Netzbetreibern zeigen, dass das analoge Front End den größten Beitrag zur Gesamtleistungsaufnahme bildet, was es zum zentralen Fokus dieser Arbeit macht. In diesem Zusammenhang untersuchen wir das Gearbox-PHY Konzept, einen Ansatz, der darauf ausgelegt ist, den Energieverbrauch von Kommunikationsnetzen durch das Umschalten zwischen Modulationsschemata und dazugehörigen Front Ends zu reduzieren. Diese Arbeit analysiert das Energieeinsparpotenzial des Gearbox-PHY und identifiziert die Schlüsselkomponenten, die die Effizienz beeinflussen.

Zunächst analysieren wir dafür die Datenratenanforderungen eines Mobilfunknetzes und zeigen, dass niedrige Datenraten am häufigsten auftreten, während Spitzendatenraten seltene Ereignisse bleiben. Anschließend erläutern wir das Gearbox-PHY genauer, formulieren das Konzept als mathematisches Optimierungsproblem und integrieren Modelle sowie literaturbasierte Messwerte für die Leistungsaufnahme aller wesentlichen Komponenten des analogen Front Ends, um den Energieverbrauch pro übertragenem Bit in verschiedenen Systemkonfigurationen zu quantifizieren. Ausgehend von verallgemeinerten Modulationsschemata erweitern wir unsere Analyse schrittweise auf praktische Modulationsschemata und beziehen schließlich Hardware-Beeinträchtigungen mit ein, wodurch unser Modell zunehmend die realen Herausforderungen mobiler Kommunikationssysteme widerspiegelt.

Unsere Ergebnisse zeigen, dass das Gearbox-PHY Konzept ein erhebliches Potenzial zur Reduzierung des Energieverbrauchs in zukünftigen Kommunikationsetzwerken bietet. Insbesondere bei niedrigen Datenraten und hohen Trägerfrequenzen kann der Energieverbrauch um bis zu zwei Größenordnungen gesenkt werden. Diese Erkenntnisse belegen, dass das Gearbox-PHY Konzept ein vielversprechender Kandidat für die nächste Generation mobiler Kommunikationsetzwerke ist und einen effizienten Ansatz zur Senkung des Energieverbrauchs und zur Förderung nachhaltiger drahtloser Kommunikation darstellt.

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The author used ChatGPT to check and improve the spelling and grammar of parts of this manuscript.

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1.1 Energy-Efficient Mobile Networks

Six years after the first large-scale rollout of the fifth generation (5G) of mobile networks [Wik24a], academia and industry are shifting focus onto the successor, the sixth generation (6G). The details of 6G remain uncertain, as its exact characteristics and objectives are still being defined. This has led to extensive discussions about the key priorities that should shape its development. While initial thoughts and early visions have emerged [Hua21], a fixed set of key performance indicators (KPIs) has yet to be established. As research progresses, various perspectives on potential performance metrics are being proposed. But rather than focusing on specific KPIs, this thesis aims to follow a broader strategic direction. In this context, we focus on three key drivers identified in [NGM21a], which the evolution of mobile networks, i.e., 6G, must address to achieve meaningful advancements for both industry and society.

1. **Societal Goals** in terms of addressing the United Nations sustainable development goals (SDG)
2. **Operational Necessities** in terms of more efficient systems and system management
3. **Market Expectations** in terms of enabling new services and capabilities in a cost-effective way

In this thesis, we want to focus on one fundamental aspect that is essential for all three mentioned drivers: **Energy Efficiency**. In the following, we explain how each of these three drivers benefits from improved energy efficiency.

1.1.1 Why do we need energy efficiency for 6G?

Energy-Efficient Networks Decrease Environmental Impact Regarding the first driver *Societal Goals*, energy efficiency directly influences the 13th goal of the United Nations SDG: "climate action". The need to address the environmental footprint of all sectors of industry and society is critical in our collective efforts to mitigate climate change and protect the planet for future generations. As mobile networks contribute

to greenhouse gas emissions, primarily through electricity consumption and equipment manufacturing, the mobile network industry, with its various operators and manufacturers, is no exception in this effort.

In 2015, the electricity consumption of mobile networks worldwide, excluding user devices, was estimated to be approximately 137 TWh, accounting for about 0.6% of global electricity usage [ML18; GSM]. However, this consumption has shown a significant upward trend, increasing by nearly 61% over a five-year period, corresponding to an average annual growth rate of approximately 10% [ML18]. Similar trends have been observed in Germany, where mobile network energy consumption is projected to grow by 12% annually until 2030 [Sto23]. This substantial consumption of energy results in considerable greenhouse gas emissions. Global network operations in 2015 accounted for approximately 100 MtCO_{2e} (carbon dioxide equivalent) [ML18]. When emissions from user devices are included, this figure doubles to around 200 MtCO_{2e}, representing about 0.4% of global emissions as of 2015 [GSM]. In 2021, the GSMA reported comparable figures, with total emissions from the mobile sector reaching 220 MtCO_{2e}, more than half of it originating from network operations [GSM21a].

Economic Reasons to Reduce Energy Consumption The need to reduce electricity consumption aligns with the second mentioned key driver "operational necessities", as the high electricity consumption also entails high costs for mobile network operators. As of 2021, energy expenditures accounted for approximately 20% to 40% of the operational expenses for a typical mobile network operator, with these costs projected to increase in the coming years [GSM21c]. Since the operational expenses account for roughly 37% of the total cost of ownership [GSM19, Section 4.6.2], energy-related expenses represent between 7.4% and 14.8% of the total cost of ownership. Consequently, efforts to reduce energy consumption not only enhance the environmental sustainability of mobile networks but also yield substantial economic benefits by lowering operational costs.

Energy Efficiency as an Application Enabler Energy efficiency is a key focus for all battery-powered devices. For consumer electronics, improved energy efficiency enhances the user experience by reducing the need for frequent recharging. However, in the context of wireless sensor networks, energy efficiency becomes even more critical, as frequent battery replacements can severely limit their operational feasibility and scalability [SBB13]. Energy-efficient wireless sensor networks might be deployed in remote, inaccessible, or hazardous environments where manual

battery replacement is impractical or costly. As a result, extending battery life or eliminating the need for external power sources is a key design challenge.

Beyond traditional battery-powered devices, extreme energy efficiency is essential for systems that rely on energy harvesting, where power is generated from external sources such as radio frequency energy. The demand for such ultra-low-power technologies is increasing, particularly in applications like environmental monitoring.

1.1.2 Where can we save energy?

Achieving the substantial energy savings required in mobile communications networks necessitates a detailed analysis of the main energy consumers in a mobile network. Data from [GSM21b] and [NGM21b], visualized in Fig. 1.1, reveal that most of the energy is consumed in the radio access network (RAN), mainly due to radio frequency (RF) components, with the power amplifier (PA) being the primary contributor. Furthermore, the significant energy demand of RF components necessitates extensive cooling systems, which account for 29% of the total energy consumption. As mobile network operators collectively account for 0.6% of global electricity use [GSM], this implies that approximately 0.2% of global electricity consumption is dedicated solely to cooling base stations, which is a striking figure.

Given that energy consumption is predominantly concentrated within the physical layer (PHY), specifically in RF components, addressing the escalating power demands requires targeting these areas. Consequently, this thesis focuses on these critical components, aiming to analyze an energy-efficient PHY.

1.1.3 How can we save energy?

To meet the growing traffic demands of customers, network capacity must increase substantially. Estimates for the required scale of this increase vary, ranging from a tenfold rise every decade [Eri24] to a tenfold increase every five years [FB21]. However, as noted in [MLM24] "network power consumption is related to the capacity of the network equipment", which presents a significant challenge: how can network capacity be scaled to meet user data rate requirements without a corresponding increase in power consumption?

A promising solution lies in dynamically adapting the network's operational capacity. By partitioning the network into segments with varying capacities, energy efficiency can be maximized in low data rate scenarios by utilizing low-capability

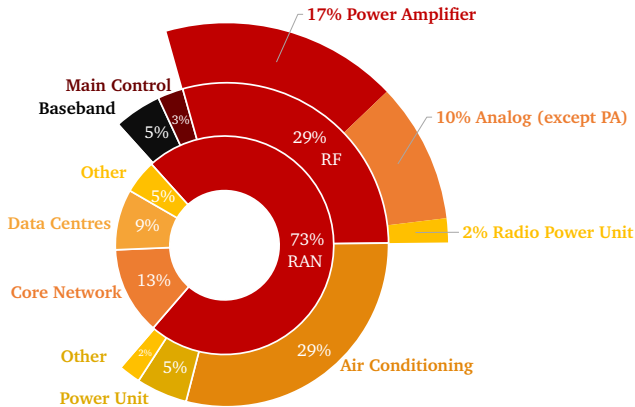


Fig. 1.1: Energy consumption breakdown of a "typical" mobile operator (data from [GSM21b] and [NGM21b]) (©IEEE 2026).

equipment. Conversely, when high data rates are required, the system switches to high-capacity equipment, sacrificing energy efficiency temporarily to meet performance demands.

This concept was first introduced in [FB21] and was termed the **Gearbox-PHY**. Like the gearbox in a car, which switches between gears depending on the speed of the vehicle, the proposed PHY in [FB21] dynamically switches between modulation schemes and their corresponding analog front ends based on data rate requirements and spectral availability. For example, in scenarios with abundant spectral resources (e.g., at sub-THz frequencies) and low spectral efficiency requirements (e.g., approximately 0.1bit/s/Hz or lower), impulse radio modulation with specialized hardware can provide the most energy-efficient solution [Mel+24]. When higher spectral efficiency is necessary, alternative modulation schemes, such as zero-crossing modulation (ZXM), may outperform impulse modulation in terms of energy efficiency. For even greater spectral efficiency demands, QAM may be the most suitable option. This exemplary selection of *gears*, i.e., modulation schemes and corresponding front ends, for different spectral availability regimes is outlined in Table 1.1.

Given the typical ten-year rollout cycle of mobile network generations and the anticipated 10- to 100-fold increase in data rates over this period [Eri24; FB21], 6G must achieve a proportional improvement in energy efficiency. Hence, 6G needs to achieve a 10 to 100 times more energy-efficient transmission per bit than 5G just to sustain a comparable absolute energy consumption level during its deployment phase.

Spectral Availability	Abundant	High	Medium	Low
Exemplary PHY/ <i>gear</i>	Impulse Radio	ZXM	MIMO-OFDM	MIMO-OFDM or OTFS or WH-OFDM

Tab. 1.1: Exemplary Gearbox-PHY [FB21]

This thesis investigates the feasibility of the Gearbox-PHY approach proposed in [FB21] as a potential solution to this challenge. Specifically, we conduct a detailed analysis of the Gearbox-PHY concept, estimating its energy-saving potential and identifying the key system components that will be critical to its successful implementation.

1.2 Outline and Main Contributions

Chapter 2: As mentioned above, the Gearbox-PHY aims at reducing energy consumption by switching between different modulation schemes and front ends depending on the data rate required and the available resources. Thus, in the sense of [MLM24] it temporarily reduces the capacity to save energy. How often such a reduction can take place is determined by the statistical properties of the network traffic. For major energy savings, the Gearbox-PHY would require peak data rates to be rare events. As such, in Chapter 2, we derive a spatio-temporal model of data rates based on existing research and mathematical concepts including correlations in time and space for mobile network. Further, based on the model, we derive the probability distribution of data rates occurring in mobile networks.

While there are existing models describing correlation of data rates in space, temporal correlation has not been considered so far and was only incorporated in terms of temporal *load curves*, i.e., the overall traffic of the considered network changing over time. In this work, we integrate both temporal and spatial correlation into a unified model. To parameterize and validate our approach, we use data from *Twitter*, which has been shown to be highly correlated to cellular data [Kle+17]. While the fit using *Twitter* data does not allow for exact predictions of the probability of certain data rates in a network, the high correlation between *Twitter* and cellular data allows to observe trends and validate the wide-spread assumption that "peak rates are rare events" and that in most cases low data rates are sufficient to meet user requirements.

Chapter 3: We then continue to formulate the Gearbox-PHY concept in more detail, refining and generalizing the initial idea presented in [FB21] by formulating its core principles while also addressing its key limitations. To establish the foundation for our analysis, we introduce relevant frequency bands and a suitable path loss model. Following this, we present the system model, which serves as the structural framework for our study. The central aspect of this chapter is the formalization of the Gearbox-PHY as a constrained optimization problem, which forms the basis for the remainder of this thesis. From this point forward, our primary objective is to minimize energy consumption per successfully transmitted bit.

Chapter 4: Building on the formulated optimization problem, we conduct an initial estimation of the potential energy savings enabled by the Gearbox-PHY using generalized linear modulation schemes. By using generalized schemes, we aim to derive deeper theoretical insights while avoiding a focus on the specific characteristics of concrete modulation schemes. For this purpose we model the achievable spectral efficiencies based on the Shannon-Hartley theorem and a limited ADC and DAC resolution.

To account for practical hardware power consumption, we incorporate models and literature-based measurements for the main components in the analog front end, i.e., DAC, mixer, local oscillator (LO), PA, low noise amplifier (LNA), and ADC. Analyzing the resulting expressions shows that using only linear modulation schemes can lead to energy savings solely in the mid-data rate regime. Additionally, the results highlight the importance of the power consumption of LO and mixer, which dominate the overall power consumption at low data rates. Finally, our findings confirm that high spectral efficiency is only energy-optimal at peak rates, challenging the assumption that maximizing spectral efficiency inherently improves energy efficiency.

Chapter 5: Motivated by the findings in Chapter 4, we extend our analysis to a more diverse set of modulation schemes within the Gearbox-PHY framework. Specifically, we consider a Gearbox-PHY employing QAM with varying constellation sizes, ZXM, a modulation scheme designed for 1-bit ADCs, and two different variants of impulse radio. To correctly model the energy consumption of these schemes, we refine the hardware power model to accurately represent the required front ends for each modulation type. We then evaluate the achievable spectral efficiencies and solve the Gearbox-PHY optimization problem for this extended set of modulation schemes.

Our results demonstrate that impulse radio without phase information is energy-optimal at low data rates, irrespective of the carrier frequency. ZXM emerges as the most energy-efficient option at medium data rates and higher carrier frequencies, whereas QAM remains optimal at peak rates and for low carrier frequencies. By comparing the achievable energy per bit of the Gearbox-PHY approach with a single-gear approach, we show energy efficiency gains of more than one order of magnitude for high carrier frequencies. Our evaluation further reinforces the conclusion that receiver downconversion, particularly the LO and mixer, is the dominant power consumer at low data rates, emphasizing the need for hardware-aware energy optimization in this regime.

Chapter 6: In the final technical chapter of this thesis, we evaluate the Gearbox-PHY in a more practical context, incorporating hardware impairments to assess its feasibility under realistic conditions. Since our previous analyses identified the receiver downconversion stage as the dominant power consumer at low data rates, which are the most frequently occurring rates as per Chapter 2, we refine our model by including phase noise as the primary hardware impairment affecting this stage.

To achieve this, we combine a mathematical phase noise model with a hardware-focused model, enabling us to define the "power consumption – phase noise trade-off" for local oscillators. We then investigate phase noise tracking mechanisms to determine their effectiveness in mitigating performance degradation and demonstrate that phase noise tracking remains feasible even for 1-bit quantized ADCs.

Following this, we analyze the achievable spectral efficiency under phase noise for the three modulation families introduced in Chapter 5, showing that modulation schemes exhibit significantly different sensitivities to phase noise. We then incorporate the "power consumption – phase noise trade-off" into the Gearbox-PHY optimization, evaluating two scenarios. First, a fully adaptive system design, and second, a constrained system design where each gear operates with a single fixed front end, requiring certain hardware parameters to be non-adaptive. Despite these restrictions, our results confirm that limiting adaptivity to a single front end per gear still enables significant energy savings. In this context, we demonstrate that considering LO phase noise as an exemplary hardware impairment does not reduce the Gearbox-PHY's energy-saving potential, but rather improves it, yielding energy savings of up to three orders of magnitude. Finally, we extend our analysis to a cellular setting, assuming a uniform user distribution within a circular cell, and show that energy savings in the range of one to two orders of magnitude remain achievable at high carrier frequencies across various cell sizes.

Chapter 7: Finally, we conclude this thesis. We summarize the key learnings and give an outlook on open topics and future research.

1.3 Related Works

The Gearbox-PHY was first introduced in [FB21], where the concept underlying this work was initially proposed. The original study [FB21] laid the foundation to the concept and is the main motivation for this thesis. The present thesis expands on [FB21] by strengthening some assumptions, like the distribution of data rates, quantifying the energy-saving potential for various settings, and deriving detailed insights for its implementation.

Beyond this, our research contributes to the broader field of joint waveform and analog front end optimization, which has been explored in various other works. A similar energy efficiency analysis, though with a different scope and modeling approach, was conducted in [MN11]. There, the energy per bit is minimized for a given minimum target area spectral efficiency (expressed in bit/s/Hz/m^2), optimizing key hardware parameters such as ADC resolution and PA backoff. In contrast, our approach maintains a fixed data rate rather than a fixed spectral efficiency, allowing for energy efficiency optimization via bandwidth adaptation, which is central to the Gearbox-PHY concept. Another closely related study is [CGB05], which focuses on minimizing energy per bit for a sensor network, considering both the transmitter and receiver – an approach that aligns with our methodology. However, different to our study, [CGB05] primarily investigates the trade-off between coded and uncoded transmission, analyzing blocklength and demonstrating that longer blocklengths do not always lead to lower energy per bit. Additionally, this work incorporates variable ADC and DAC resolution, which is also an essential aspect of our framework. Further contributions in this domain include [BN15], which examines the optimal number of ADC bits for multi-antenna systems. While this study provides valuable insights into quantization efficiency, our research takes a broader approach by integrating multiple hardware components and modulation strategies into a unified energy optimization framework.

An important and related concept is adaptive coded modulation (ACM), as studied in [GC98]. ACM jointly optimizes the modulation order of QAM and error correction codes, leveraging SNR advantages to improve energy efficiency. However, ACM operates entirely in the digital domain, leaving the analog front end largely unmodified, whereas the Gearbox-PHY seeks to adapt the digital and analog transceiver

design. A further related work in a similar direction as ACM is presented in [Sch06], which investigates energy-efficient modulation, transmission, and error correction schemes for wireless sensor networks. The work in [Sch06] focuses primarily on optimizing digital control parameters, such as duty cycling, modulation scheme selection, and automatic repeat requests, within a fixed hardware context based on ZigBee transceivers. Its scope remains largely within the digital and protocol domain, assuming a static analog front end. In contrast, our work extends to adaptive hardware, dynamically selecting modulation schemes and reconfigurable analog front ends to optimize system-level energy efficiency.

While numerous works focus on energy efficiency, they typically fall into two distinct categories: waveform optimization or analog circuit design improvements. The Gearbox-PHY approach, however, requires bridging these two domains, integrating both waveform adaptation and front end architecture considerations into a system-level optimization framework.

Beyond waveform and hardware optimization, our work also examines the statistical properties of data rates in a network to identify the primary operational regimes where the Gearbox-PHY optimization should focus on to maximize energy efficiency. The statistical properties of data rates have been widely studied from various perspectives. For instance, the variability of network load over time is a well-documented phenomenon, extensively studied in works such as [AQC99]. In addition to these temporal dynamics, numerous studies have shown that time-aggregated data rates approximately follow a log-normal distribution over space [GR98; Lee+14; MRM11]. Furthermore, the spatial correlation of data rates has been investigated in several works, including [Lee+14] and [Zho+15]. However, the joint probability distribution of data rate occurrences over both time and space remains an open question, which we cover in our work.

While there are many models exploring spatio-temporal data rate distributions, they primarily describe time-dependent load variations without integrating actual temporal correlation between data rates. In contrast, our work provides well-defined mathematical framework, explicitly capturing both spatial and temporal dependencies for a more accurate and interpretable representation of data rate dynamics. To the best of our knowledge, this is the first academic work to explicitly model and incorporate temporal correlation in data rate distributions.

1.4 Notation

In this thesis, we describe random quantities as uppercase sans serif letters, e.g., H describes a random scalar. The corresponding realization of the random variable is denoted in serif letters, e.g., H is a realization of H . Matrices are denoted using bold letters, e.g., \mathbf{H} is a matrix and $[\mathbf{H}]_{i,j}$ describes the element in the i -th row and j -th column of the matrix \mathbf{H} .

1.5 Key Insights

The key insights of this chapter are as follows.

- Mobile communication networks account for more than 0.6% of global electricity consumption, with an annual growth rate of around 10%.
- The physical layer, particularly the radio front end, is the primary source of network energy consumption.
- To mitigate the expected $10 - 100\times$ increase in traffic, the energy consumed per transmitted bit must be reduced by an even larger factor to achieve an absolute reduction in energy use.
- The Gearbox-PHY was proposed as a dynamic transceiver architecture that adapts modulation schemes and analog front ends to data rate demands and spectral availability, promising the substantial energy savings required for future networks.

This thesis evaluates the energy-saving potential of the Gearbox-PHY and demonstrates that it can enable substantial reductions in energy consumption across a wide range of operating conditions, thus, offering a promising approach for future energy-efficient physical layer architectures.