Gearbox RF - the Backbone of Privacy and Energy Efficiency in 6G?

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***Abstract*— This paper introduces a reconfigurable Gearbox transceiver architecture to address the heterogeneous requirements of sixth generation (6G) networks. Current designs are tailored for peak-performance use cases, and they lead to increased energy costs in low-data-rate scenarios that dominate cellular traffic. To overcome this inefficiency, we propose an adaptive radio frequency (RF) front-end in line with the previously established Gearbox physical layer (PHY) concept. The resulting system is designed to switch between high-performance and energy-efficient modes, reducing power consumption while supporting both communication and sensing services. Furthermore, the hardware's reconfigurability allows for privacy-preserving operation by enabling controlled resource allocation. By jointly targeting energy efficiency, sensing capabilities, and privacy, this approach provides a promising foundation for sustainable and resilient 6G hardware design.**

***Keywords*— 6G, RF, Energy Efficiency, Gearbox, PHY.**

I. Introduction

While the vision for sixth generation (6G) networks and their potential applications are still being discussed in worldwide forums and standardization bodies, there is a consensus that 6G will connect a broader range of devices and support more diverse use cases than fifth generation (5G) networks. Consumer demands are expected to drive the adoption of connected robots, connected cars, and other internet of things (IoT) devices alongside traditional devices, with the growing need for a single device to support multiple applications. However, such a network vision may be challenged by its diverging requirements on radio frequency (RF) hardware, which in turn reduces its scope with respect to energy and practical usage. A potential solution lies in the Gearbox physical layer (PHY) concept [1], which envisions using multiple front-ends, each tailored for a specific requirement scenario. Although advances in packaging technologies will make it easier to integrate multiple chips within a single platform, manufacturing yields and supply-chain complexity render such solutions expensive. A single-chip, multi-mode RF hardware designed for a Gearbox PHY can be key to a sustainable 6G adoption and deployment.

Today's mobile communication networks consume approximately 161 TWh of electricity annually, corresponding to about 0.7 % of global electricity demand [2], which leads to three major challenges. First, the associated electricity generation results in considerable greenhouse gas emissions. Second, by 2021, energy expenditures already accounted for 20 % to 40 % of the operational costs of a typical mobile network operator, with this share expected to rise in the coming years [3]. Finally, such energy intensity limits the deployment of innovative low-power solutions, such as energy-harvesting devices and wireless sensor networks, thus restricting new services and revenue streams. A closer look at the distribution of energy consumption reveals that the radio access network is the dominant contributor, responsible for about 73 % of a network operator's total energy use [4], with the majority attributed to RF hardware. Consequently, addressing the *energy challenge* at the RF front-end is the most promising strategy. Yet, as discussed, this is non-trivial due to diverging requirements from the use cases. The front-end is therefore designed to support the most demanding use case, typically requiring high linearity for high data rates, which inevitably limits energy efficiency in less demanding use cases. The discussed trends, implications, challenges and solution are represented in Fig. 1.

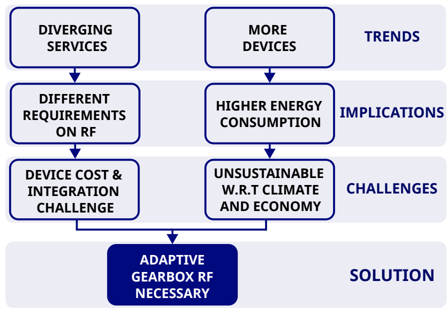


Fig. 1. Drivers necessitating an adaptive Gearbox RF.

Apart from energy consumption aspects, in recent years, the addition of active radio sensing to traditional communication platforms is also envisioned in the paradigm of integrated sensing and communication (ISAC) usecases, along with embedded artificial Intelligence (AI). An ISAC approach can also make overall systems more energy-efficient by bringing context awareness into communications. However, this also leads to privacy issues, as discussed in [5]. In this paper, we mitigate the privacy issues using the Gearbox approach to add user-driven and network-driven (e.g. base station) privacy control features. The Gearbox architecture discussed is scalable from a single antenna single front-end system to a multi-antenna multiple-input multiple-output (MIMO) system. The contributions are summarized below:

- To envision future RF systems addressing multiple applications in a scalable chip development

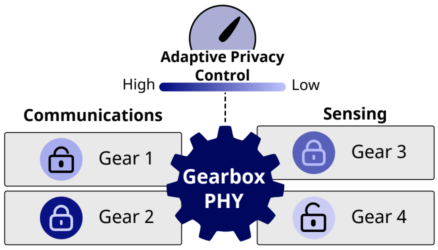


Fig. 2. Gearbox PHY and RF concept with communications and sensing gears under variable, per-gear privacy control.

- To use the Gearbox approach to address the energy efficiency, functionality and privacy aspects in a trustworthy-by-design framework.

Section II will cover the Gearbox approach with energy efficiency and privacy aspects. Section III will report initial results and validation aspects. Section IV concludes the paper.

II. Gearbox Approach - Potential in 6G

Future systems need to provide MIMO and beamforming capability. They need to address the different requirements of communication and sensing services with analog as well as digital controls to adjust the energy consumption based on various key performance indicators (KPIs). However, such a system needs to address bandwidth and energy tradeoffs, while meeting diverse receiver dynamic range and transmitter output power requirements for different applications. A Gearbox front-end should be able to change one or multiple transceiver (Trx) KPIs, namely, transmitter output 1-dB compression point (OP1dB), power amplifier class or efficiency, transmitter and receiver linearity, bandwidth, etc. Only then, the antennas can be shared. However, the best performance mode and the best energy-efficient mode may share antennas but may not be integrated in the same transmitter (Tx) and receiver (Rx). These different modes are shown in Fig. 2. The availability of gears in communication and sensing modes allows the system to control the privacy KPI, as described in Subsection IIB.

A. Energy Efficiency Aspects of Gearbox Approach

The Gearbox PHY concept [1], which employs multiple front-ends together with modulation schemes and algorithms, is ideal for reducing energy consumption by tailoring each operational mode to specific data rate regimes and services. Studies demonstrated that the Gearbox PHY approach can reduce the energy consumption per bit by up to three orders of magnitude in low-data-rate scenarios [6]. Particularly, the "low gears," characterized by spectrally inefficient but energy-efficient operation, were identified as crucial for sustainable operation at low data rates, challenging the assumption that high spectral efficiency leads to increased energy efficiency. While promising, deploying multiple dedicated front-ends, as assumed in [1], [6] increases capital expenditure and carbon footprint due to larger silicon area. In digital circuits, chip area typically scales with algorithmic complexity and target data rates, implying that adding "low gears" for low-rate scenarios only modestly enlarges the overall digital footprint. This scaling property, however, does not extend to the RF domain, where additional front-ends significantly inflate hardware size and energy overhead. Therefore, it is highly desirable to develop adaptive RF components capable of switching between operational modes, thereby preserving the energy-saving benefits of the Gearbox PHY paradigm without necessitating fully parallel hardware implementations.

B. Privacy aspects of Gearbox Approach

The information about the context/environment can significantly reduce the energy footprint with the embedded sensing functionality. But, it can also lead to vulnerability in terms of privacy and security. Without a trustworthy-by-design approach, sensing functionality could be the biggest threat to privacy and digital sovereignty. Privacy in this case refers to individual's right and obligations to control personally identifiable information (PII) including collection, use, retention, disclosure and disposal of such data. For communication systems, low latency, low bit error rate (BER), high signal-to-noise ratio (SNR) along with high usable bandwidth (BW) increases the data throughput. For radar sensing, high SNR and high BW help with several detection KPIs, namely range resolution, detection accuracy etc. However, these capabilities may also reveal more PII, essential for the applications, e.g., biometric data, behavioral patterns, movements, locations. A context-aware system needs to be designed with trustworthiness as a requirement for secure deployment.

In a system of connected devices, one unsafe system can lead to data leakage leading to a compromised network. A Gearbox approach with Tx and Rx controls can provide user based privacy control [5]. It is also the lowest layer and if limited, can restrict recovery of PII by a malicious entity. In general privacy KPIs and hardware KPIs are contrary to each other. As mentioned in [5], bandwidth, linearity and noise in the systems using secure digital control paths along with physical switches, can bring the control of information in the hand of users. A Gearbox RF can enable such control features, as shown in Fig. 2. An example of such privacy control using analog circuits is described in the next section.

III. Initial Results and Validation

In this section, we are primarily considering aspects of a Gearbox Rx as a building block of a Gearbox RF. In commercial systems, there is usually more flexibility in receiver design whereas transmitter properties are more regulated by standardization. The Rx tunability can be achieved in terms of gain, linearity, frequency and bandwidth. Conventional receivers employ reconfigurability in terms of gain and linearity by means of variable gain amplifiers (VGAs) in the baseband. The low noise amplifier (LNA) and down-conversion mixer can also be made tunable in terms frequency, gain and linearity while the baseband amplifier is tunable in terms of gain and bandwidth. This way, the gain controllability can be distributed across the receiver chain. With reconfigurability embedded in the basic front-end components like LNAs and mixers, it would also be possible to switch from a high performance to an energy efficient mode. Such a tunable front-end architecture is shown in Fig. 3. For evaluation, 22nm Fully Depleted Silicon on Insulator (FDSOI) process from GlobalFoundries is used.

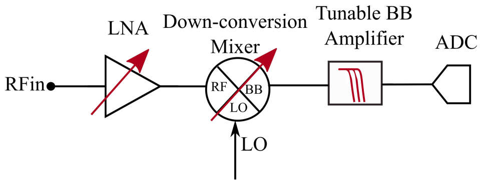
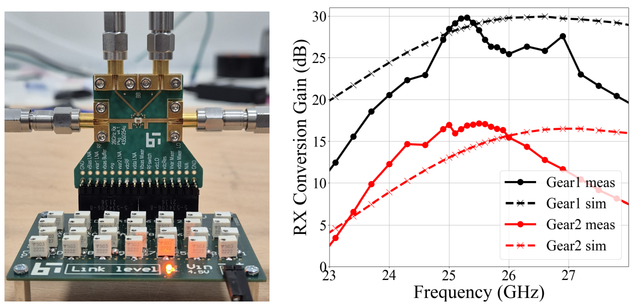


Fig. 3. Reconfigurable receiver front-end.

A multi-mode receiver at $25.5\,\mathrm{GHz}$ was presented in [7], where a tunable front-end with LNA and mixer achieved a gain of $29.9\,\mathrm{dB}$ with input 1-dB compression point (IP1dB) of $-34\,\mathrm{dBm}$, while consuming a power of $30\,\mathrm{mW}$ in the high gain mode. In the high linearity mode, the receiver achieves a gain of $16.8\,\mathrm{dB}$ with and IP1dB of $-17.5\,\mathrm{dBm}$ and consumes a total power of $19\,\mathrm{mW}$. The receiver was prototyped on a printed circuit board (PCB) and is shown in Fig. 4a along with the multi-mode results in Fig. 4b. Such a receiver will be able to dynamically change modes based on the requirements from the Gearbox PHY.



(a) (b)

Fig. 4. (a) Rx PCB with DC supply board ; (b) Receiver characteristics: Rx conversion gain Vs RF frequency at BB $300\,\mathrm{MHz}$.

The operating frequency can be made tunable in the RF domain, while the bandwidth is tunable in the baseband domain. Bandwidth is usually made tunable to cater to the different bandwidth requirements [8] or to address different applications, for instance in an ISAC receiver to meet the bandwidth requirements of radar and communication [9]. A bandwidth tunable low pass filter (LPF) is shown in Fig. 5. This structure uses the Butterworth structures with tunable switched capacitors and varactors. The capacitor values can be made different in each stage to achieve the desired cut-off frequency. The switch selects between the high-bandwidth and low-bandwidth outputs and can be incorporated along with the privacy control feature from the Gearbox PHY. Measurement results show that it is possible to attain a difference of $28\,\mathrm{dB}$ in signal strength between $100\,\mathrm{MHz}$ and $1\,\mathrm{GHz}$ with the utilization of the variable capacitors and the control switch. Bandwidth is a key component that can restrict the range resolution in time-bound system and, thus, can significantly reduce the estimation of PII. While digital bandwidth control can also be used to enforce privacy KPIs, it remains vulnerable if the digital PHY controls are compromised by a malicious entity. In such cases, specific analog controls, such as those illustrated in Fig. 5, can be provided through a secure control box to ensure trustworthiness.

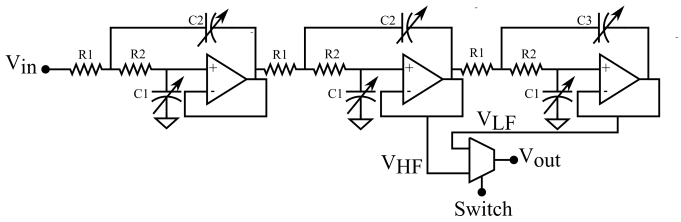


Fig. 5. Reconfigurable LPF.

IV. Conclusion

This paper has highlighted the need to rethink RF architecture design by leveraging advances in semiconductor technologies, making reconfigurability a necessity rather than an option. While partial integration into 5G is possible, looking ahead to 6G, with the emergence of ISAC and diverse new applications, the Gearbox PHY paradigm has the potential to become a game changer in terms of energy efficiency, privacy, cost, and scalability. Future work will compare the energy consumption across different gears and provide a detailed energy–area–performance evaluation.

Acknowledgment

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