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Green Circular Economy Design Aspects for 6G Wireless Millimeter-Wave Transceivers

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Abstract

Application specific integrated circuits (ASICs) operating at millimeter-wave (MW) frequencies (30 to 300 GHz) are of key importance for future wireless communications. At present, MW transceivers are mainly optimized for high performance leading to a large DC power (P_{DC}). In this paper, we propose a holistic design paradigm for wireless MW transceivers taking into account a wide range of green circular economy aspects. We discuss concepts to decrease P_{DC} in operation and resource consumption in fabrication. We further discuss how to avoid toxicity and allow for a longer lifetime, DC supply via energy harvesting, battery-less operation and recycling. To demonstrate the feasibility of several of these concepts, we present the first self-sufficient supply of a 60 GHz CMOS on/off keying (OOK) data transmitter (TX) ASIC with highly-adaptive duty-cycling. Since the required active solar cell area is only 4.5 mm^2, the way is paved for significantly advanced levels of miniaturization and resource saving for self-supplying MW-TX.

1. Introduction

Our society faces significant challenges related to climate change, scarcity of raw materials, growing volumes of electronic waste and inefficient use of resources. These challenges must be considered in the design of future sixth generation (6G) communication systems, where the increasing hunger for data speed will be solved by MW transceivers. On the one hand, MW transceivers have a great potential to enable large bandwidths (BWs) of tens of GHz, data rates (DRs) of ≈ 100 Gb/s and heterogenous functionalities using the same hardware e.g. for high resolution radar sensors [1]. Further advantages are more compact implementations and energy savings by high-performance applications such as high-resolution-video-conferencing, which reduces the necessity to travel [2]. On the other hand, MW ASICs come with additional sustainability challenges beyond those of standard electronics, e.g. to reach sufficient gain and communication range. If existing techniques are just mapped to higher frequencies, P_{DC} would increase and thus shorten the device lifetime due to stronger self-heating.

Until today, if considered at all, the traditional design of active MW circuits has only taken into account circular economy aspects related to energy consumption during operation. However, it becomes increasingly apparent that the design of MW ASICs has to be rethought considering the complete range of circular economy aspects. The consideration of such approaches for electronics operating at lower frequencies are investigated e.g. in [3]. Aspects of sustainable eco-friendly manufacturing, energy harvesting and wireless connectivity for next-generation IoT-devices are described in [4]. Design strategies for radio frequency integrated circuits (RFICs) are proposed in [5] to minimize not only P_{DC} during operation but also the chip area.

2. Review of state-of-the-art MW transceivers

There are two possibilities to increase the achievable DRs, which can be combined. First, by increasing the spectral efficiencies via high order modulation schemes such as quadrature amplitude modulation (QAM). However, this requires a high amplitude resolution and hence generally higher peak amplitudes and thus very power consuming analogue-to-digital converters (ADCs). Second, by increasing the BW requiring higher operation frequencies as reflected in the Shannon theorem. Increasing the operating frequency f unfortunately reduces the received power P_r as it is shown by the equation of Friis:

$$P_r = P_t \frac{G_t G_r c^2}{\left(4\pi r f\right)^2}, \quad (1)$$

where P_t is the transmitted signal power, G_t and G_r are the antenna gains of the TX and the receiver (RX), respectively, c is the speed of light and r is the achievable communication distance between TX and RX. Since the relation is quadratic, e.g. a four times higher frequency decreases the available P_r by a factor of 1/16. In practice, this strongly reduces the possible r. This effect can be partly mitigated by the fact that for the same area, higher frequencies allow higher G_t and G_r, because the antennas are much smaller enabling complex antenna arrays and beam steering.

Table 1 summarizes the performance of leading-edge MW transceiver frontends. The lowest P_{DC} is only 154 mW. The highest EpB is 3.85 pJ/bit [6]. The largest r of 850 m by

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using external horn antennas with very high gain is demonstrated in [7], albeit at the expense of bulky system dimensions and high P_{DC}. The highest DR reported to date is 200 Gb/s at P_{DC} = 4.1 W and r = 15 cm [8].

Most of the energy of the MW frontends is consumed by the power amplifiers (PAs) and the ADCs. SiGe PAs with leading-edge BW of 80 GHz around 180 GHz, 19 dB gain and 15 dBm saturated P_t were demonstrated. However, with P_{DC} = 830 mW, the power added efficiency is only 3.5% [9]. The latest 7-bit SAR ADC shows at 1.7 GS/s a very low P_{DC} of only 1.38 mW and 8.85 fJ/conversion-step in 22 nm CMOS (complementary metal oxide semi-conductor) FDSOI (fully depleted silicon on insulator) [10]. The sampling rate can be increased by parallel time interleaving paths, but this significantly increases P_{DC}.

Table 1. Leading-edge MW transceiver frontends

Reference	[6]	[7]	[8]
Antenna gain/dBi	Bondwire 5	External horn 55	Lens + beam 11 + 26
P_t/dBm	-6	-4.5	-8
r/cm	2	**85000**	15
Modulation	BPSK	QPSK/8PSK	32 QAM
f/GHz	190	240	140
BW/GHz	40	n.a.	80
DR/(Gb/s)	40	64	**200**
P_{DC}/mW	**154**	n.a., very high	4100
EpB/(pJ/bit)	**3.85**		20,5
Technology	130 nm SiGe	GaAs HEMT	130 nm SiGe
Advantages	Lowest P_{DC} + EpB	Largest com. distance	Highest DR

EpB: Energy per bit, SiGe: Silicon Germanium, GaAs: Gallium Arsenide, HEMT: Hetero Mobility Transistor

3. Green design approaches and challenges

This section discusses novel design paradigms for MW transceivers and ASICs considering a wide range of green circular economy aspects as well as the specific challenges and opportunities for MW systems.

3.1 Minimization of DC power in operation

According to [11], Information and communication technologies (ICT) consumes around 9% of the total energy in 2023, which will increase to around 21% in 2030. By using also MWs, P_{DC} may further increase. This can and has to be circumvented by the following approaches.

Adaptive duty cycling (AdDuCy): The peak DRs of MW transceivers, which can go up to several tens of Gb/s or even higher, are typically only required during a fraction of time. By smart AdDuCy, large amounts of energy can be saved at lower DRs [12]. The decrease of P_{DC} is limited by the circuit leakage currents in off-mode. The 22 nm FDSOI CMOS technology of GlobalFoundries allows for mode optimization by means of the available backgate bias.

Sleep modes: Efficient sleep modes are important. However, to enable real-time wake-up, the RC (resistor capacitor) constants at the control nodes must be small. This challenges good RF grounds needed to avoid stability problems associated with parasitic loop currents.

OOK: Allows for simple transceiver architectures. Data reception based on windowed energy detection without the need for complex phase locked loops and ADCs is possible. A non-coherent 60 GHz 19 Gb/s OOK demodulator in 22 nm FDSOI draws only 5.7 mW P_{DC} [13].

Spike based communication: The complexity and P_{DC} of transceivers can be further decreased by spike-based communications [14], where optimized architectures ensure that energy is almost exclusively consumed in all circuits only during a short pulse duration. This principle is also attractive for MWs enabling ultra-short pulses.

Super-regenerative receivers: A major challenge at MWs is to get enough signal gain, since at MW frequencies, the gain is significantly decreased by parasitic low pass filters as e.g. inherent in transistors. This problem can be solved by super-regenerative approaches applying positive feedback enabling a high large-signal-gain event at MW frequencies, e.g. 58 dB at 180 GHz [15].

Time-to-digital converters: In case that ADCs are required for sampling, a low P_{DC} is possible by changing from power-hungry amplitude level to time domain detection by time-to-digital converters. At only 16 mW, resolutions of 250 ns were demonstrated in CMOS [16].

3.2 Minimization of resources required for fabrication

For typical mobile base stations, most of the DC energy is consumed in operation. For the mobile terminals, a significant share of energy is consumed by device fabrication. Resources can be reduced by decreasing areas and volumes. Antennas consume the biggest area fraction. Bond-wire antennas are an interesting option, because they can be ultra-compact at MWs and avoid connection losses as well as the large chip-areas of on-chip antennas. A bond-wire antenna with only 435 µm length providing a BW from 140 to 220 GHz and 4.9 dBi gain is presented in [17]. To minimize the chip area, inductive elements should be avoided wherever possible. An example is the pulse CMOS generator published in [18], which does not require narrowband LC filters for the generation of narrow band pulses. Instead, delayed parallel gates are used to generate pulses with a BW of 3.8 to 8.8 GHz at 4 pJ/pulse.

At MWs, multiple amplifier stages increase the area. This can be circumvented by super-regenerative amplifiers enabling high large-signal-gain with just one stage [15].

3.3 Reduction of toxic materials

Toxic materials should be avoided as much as possible. In this context the European REACH regulation must be taken into account that classifies semiconductors. The major area consumption in electronic systems is attributed to printed circuit boards and in many instances to external antennas. For these passive devices environmentally friendly materials such as PLA and PEDOT:PPS are well suited even for high frequencies as demonstrated in [4]. Standard batteries contain toxic materials. Hence, where possible, it is helpful to avoid the need for batteries as proposed in Section 3.5.

3.4 DC-supply of devices via energy harvesting

Given that future MW circuits enable very low energy consumption, the DC-supply via compact distributed local energy harvesters is very promising. This can e.g. be based on miniature solar cells, movement or vibration harvesting, or thermal harvesting exploiting e.g. the temperature difference between humans or machines and the air. A solar-powered RF oscillator with 18.7 dB gain for ZigBee is presented in [19].

3.5 Battery-less operation

For energy harvesting, an energy storage is typically needed to provide enough energy for a certain time frame. Batteries or accumulators constitute a significant environmental load, because of the high level of toxic materials and the limited life-time. (Super)-capacitors are an interesting option for systems operating with ultra-low power and consequently needing only a very small temporary energy storage. Green ceramic caps are noncritical from an environmental perspective and enable an almost unlimited number of charging cycles. A battery-free communication using caps with only 47 µF was successfully shown for frequencies around 2 GHz [20]. This is only possible by aggressive duty-cycling. However, the big challenge is the efficient supply synchronization of the different communication nodes. The devices must be on at the same time considering that typically only some milliseconds per second are available for the data transfer.

3.6 Improvement of reliability and life-time

High temperatures degrade the reliability [21] and hence the life-time of electronics. If the P_{DC} at MWs is higher than at lower frequencies, the temperature increases and consequently the life-time decreases. This further motivates the low-power concepts discussed in Section 3.1.

3.7 Improvement of ability for recycling

The ability to recycle can be improved by smart choices and placement of all components already in the design, e.g. by placing the same type of materials close together. Also the number of different materials should be reduced. Bio-compatible and recycling-friendly printed RF antennas, based on cellulosic materials are discussed in [22].

4. MW transmitter supplied by mini solar cell

To show the feasibility of several of the afore mentioned concepts, we designed a performance-adaptive, 60 GHz OOK-TX-ASIC with very low P_{DC} in 22 nm FDSOI CMOS and fabricated it together with a 1.2 mm bond-wire antenna, see Fig. 1. We plan to publish details of this TX chip in [23]. At a *DR* of 2 Gb/s, the TX consumes 11.7 mW. With dynamic AdDuCy, P_{DC} can be reduced when the communication load is low, as plotted in Fig. 2. Hence, at 100 kb/s, the P_{DC} can be reduced to only 1.5 µW. We experimentally demonstrated the transmission of 23 Mb/s over a 35 cm wireless link when the TX is fully supplied by a perovskite solar cell with a total active area of only 4.5 mm^2. The measurement setup is sketched in Fig. 3. Fig 4 shows the solar cell. One cell can generate up to 600 µW P_{DC} at 1 sun. For the experiment, we used a halogen lamp to light the solar cell resulting in 450 µW P_{DC} before the power management unit (PMU) and low dropout regulator (LDO). Such high efficiency solar cells are fabricated using simple solution-processing at low temperature ($<100^0$C) [24], making them very interesting for sustainable energy supply of MW circuits.

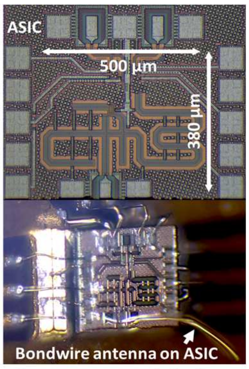

Figure 1 TX ASIC

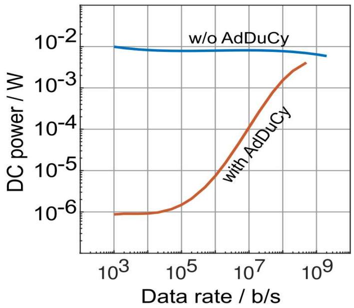

Figure 2 P_{DC} of TX with and without adaptive duty-cycling

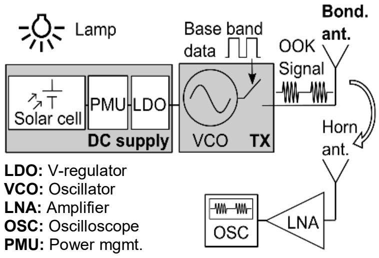

Figure 3 Measurement setup

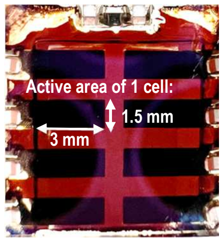

Figure 4 Perovskite solar cell module with 8 cells

5. Conclusions

In this paper, we proposed a novel holistic design paradigm for future 6G MW transceiver and RFICs combining a wide range of green circular economy aspects. Approaches are discussed enabling corresponding improvements regarding energy consumption in operation, resource consumption in fabrication, toxicology, life-time, supply via energy harvesting up to battery-less operation and recycling.
To show the feasibility of several of these concepts, we designed a compact, energy efficient MW-TX-ASIC that can be self-supplied by an emerging small-area solar cell.
To the best of our knowledge, for the first time, the following combined green-design approaches were shown by experiment: TX at 60 GHz with bond-wire antenna to minimize dimensions, OOK and circuit adaptivity with aggressive AdDuCy to save P_{DC} and self-sufficient supply by a perovskite solar cell fabricated at low temperature.
With only 4.5 mm^2 active solar cell area, significantly advanced levels of miniaturization and resource saving were demonstrated for self-sufficient 6G MW transmitters.

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