An RF-to-DC energy harvester for co-integration in a low-power 2.4 GHz transceiver frontend

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***Abstract*—A 2.4 GHz energy harvester for co-integration into a low-power transceiver (TRx) operating at the same frequency is presented. An RF switch decouples the harvester from the TRx and keeps the performance degradation of the TRx low, i.e. 0.2 dB reduced output power in Tx-mode and 0.4 dB reduced sensitivity in Rx-mode. In order to enable the harvester to operate without a DC power supply, an RF switch is used that is passively turned on. The circuit is implemented in a 130 nm CMOS process, and requires a minimum input RF power of -10 dBm. Based on post-layout simulation results the proposed energy harvester achieves a peak efficiency of 22.7% at an input power level of -3 dBm.**

I. Introduction

Wireless sensors for Body Area Networks (BAN) are expected to allow for many new applications, for example in the health care and fitness environment. Apart from minimizing the power consumption of the wireless transceiver, recent research also focuses on how to supply the sensor using energy harvesting techniques and render an internal power supply unnecessary [1]. One popular technique converts received radio frequency (RF) power from the antenna to store it in a capacitor or battery [2], [3].

Charging a battery or supercapacitor requires a minimum DC power on the order of 25 μW [3] and, therefore, an incident RF power of about 100 μW (-10 dBm) is needed for RF energy harvesting if conversion losses are taken into account [2]. Based on these parameters, the resulting maximum distance from a 100 mW transmitter is approximately 30 cm, assuming isotropic antennas and taking into account the free-space path loss at 2.4 GHz.

RF-DC conversion may be incorporated into a wireless sensor by adding a dedicated antenna [2] or, more elegantly, by re-using the antenna of the transceiver, as shown in Fig. 1. The latter facilitates the miniaturization of the wireless sensor but requires some kind of decoupling between the RF-DC conversion stage and the transceiver. This can be accomplished by using two different carrier frequencies and a dual-band antenna [4]. In this case the input matching networks of RF-DC and transceiver provide decoupling by presenting a high impedance to the antenna at the carrier frequency of the respective other functional unit.

This paper presents an energy harvester implemented into a low power transceiver of a previous work [5] where both the harvester and the transceiver operate at the same carrier frequency of 2.4 GHz and share a single antenna. This allows to use typical BAN protocols such as Bluetooth low energy or ZigBee and harvest RF energy from emissions of wireless local area network (WLAN) routers. The main design goal is to maximize the power conversion efficiency (PCE) of the energy harvester while keeping the performance degradation of the transceiver low. A key element in this design is the RF switch at the input of the harvester as it needs to be activated, i.e. turned on, without any DC supply voltage. After reviewing different alternatives, section II describes the proposed solution based on the use of a simple NMOS transistor driven by a start-up rectifier. This solution is not only very area-efficient but also keeps the degradation of the transceiver performance below 0.5 dB. Then, section III describes the circuit design of the energy harvester and section IV presents post-layout simulation results. An overall peak efficiency of 22.7% is achieved at an input power level of -3 dBm. Finally, concluding remarks are given in section V.

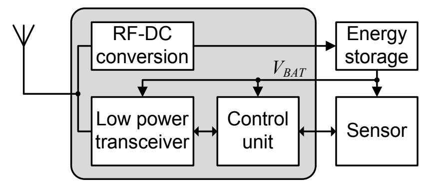


Figure 1. Architecture of the wireless sensor node with RF energy harvesting.

II. RF switch for the harvester

The frontend of the harvesting transceiver has to support three modes of operation, namely data transmission (Tx), data reception (Rx) and energy harvesting. The three modes are multiplexed such that only one is active at a time and the remaining two functional units are disconnected from the antenna by means of switches, as illustrated in Fig. 2. However, different supply voltage conditions apply for the three switches. Closing (turning on) the Tx- or Rx-switch only makes sense when the supply voltage is sufficiently high to operate Tx or Rx, respectively. On the other hand, the switch for the harvester should be closed even if no supply voltage is available, i.e. if the energy storage of the wireless sensor is completely discharged.

In standard CMOS technologies the required functionality of the Tx- and Rx-switches can be easily implemented by means of enhancement-mode transistors [6]. The harvesting

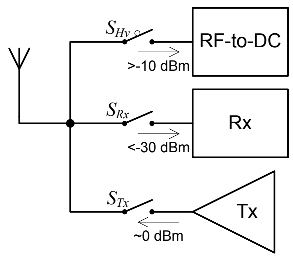
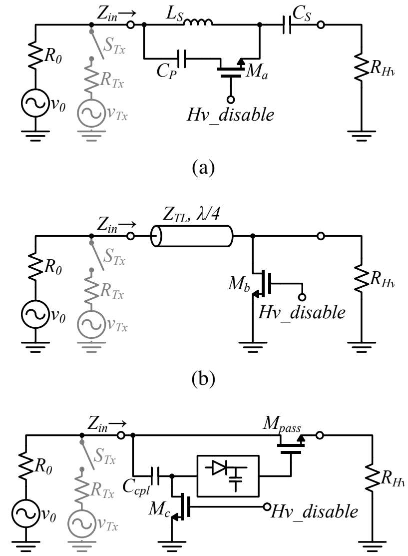


Figure 2. RF switches



(c)

Figure 3. Alternatives for a single-ended active-low RF switch to connect the antenna (modeled as v_0 and R_0) to the harvester (R_{Hv}): with LC-resonator (a), with $\lambda/4$-transmission line (b) and with start-up rectifier (c). To illustrate how the de-activated switch impairs the Tx-performance the transmitter is shown in gray (v_{Tx} and R_{Tx} with an ideal switch S_{Tx}).

switch S_{Hv}, however, requires active-low behavior as exhibited by depletion-mode NMOS transistors which are able to form conducting channels even with negative gate-source voltages. As depletion-mode devices are not available in standard CMOS technologies [7], three different alternatives are discussed in the following.

A. LC-resonator

One possibility to implement an active-low RF switch with an inherently active-high device, such as e.g. an enhancement-mode NMOS transistor, is by using resonators [8]. In the simple model shown in Fig. 3(a) the antenna is represented by a voltage source v_0 and a real impedance R_0. With the digital control voltage $HV\_disable$ being low, the transistor M_a is an open switch and the load R_{Hv} is connected in series to the antenna through L_S and C_S, which ideally act as a short-circuit at resonance. When $HV\_disable$ is high, a parallel resonance circuit is formed by L_S and C_P, providing an ideally infinite input impedance Z_{in} at resonance.

Let us assume the harvester is active and the switch is characterized by its insertion loss factor ILF, defined as the ratio of the available power from the antenna to the power delivered to the load R_{Hv}. Then, assuming matched source and load impedances ($R_{Hv} = R_0$), the required quality factor of the series resonance circuit Q_S can be expressed as

$$Q_S = \frac{2\pi f_0 \cdot L_S}{2R_0 \cdot (\sqrt{ILF} - 1)} \tag{1}$$

where f_0 represents the resonance frequency. The de-activated switch may be assessed by quantifying how much the power transfer from the antenna to the Rx, or equivalently from the Tx to the antenna, is impaired due to leakage through the deactivated S_{Hv} switch. As before, let us define the switch-induced degradation factor DGF as the ratio of available power from the source v_{Tx} with its impedance R_{Tx} to the power delivered to R_0. Then, assuming again matched conditions ($R_{Tx} = R_0$), the required quality factor of the parallel resonance circuit Q_P can be expressed as

$$Q_P = \frac{R_0}{4\pi f_0 \cdot L_S} \cdot \left(\frac{1}{\sqrt{DGF} - 1} - 2 \right). \tag{2}$$

If we further assume equal quality factors of the serial and parallel resonators, then they may be expressed as a function of the switch requirements.

$$Q_S = Q_P = \frac{1}{2} \cdot \sqrt{\frac{1}{\sqrt{ILF} - 1} \cdot \left(\frac{1}{\sqrt{DGF} - 1} - 2 \right)} \tag{3}$$

As an example, for an insertion loss of 1 dB (ILF=1.26) and Tx/Rx-degradation of 0.5 dB (DGF=1.12), the required quality factor of the resonators would be 5.5.

B. $\lambda/4$-transmission line

A second possibility to implement the active-low RF switch with an NMOS transistor is based on a $\lambda/4$-transmission line as shown in Fig. 3(b). With $HV\_disable$=0 the load impedance is connected to the antenna through an ideally lossless transmission line with a characteristic impedance Z_{TL} equal to load and source impedance (Z_{TL}=R_{Hv}=R_0). When $HV\_disable$ is pulled high, the transistor M_b grounds the output of the transmission line which rotates this short-circuit one semi-circle across the Smith chart to an open-circuit. Hence, Z_{in} would ideally be infinite but in practice depends on the on-resistance $R_{DS,on}$ of the transistor [9].

$$Z_{in} = \frac{Z_{TL}^2}{R_{DS,on} || R_{Rect}} \approx \frac{Z_{TL}^2}{R_{DS,on}\,(M_b)} \tag{4}$$

C. Start-up rectifier

A third option for the active-low RF switch is to use an NMOS transistor as a pass device and generate the required positive gate-source voltage by means of a start-up rectifier, as shown in Fig. 3(c). The start-up rectifier can have very small dimensions and does not require an outstanding efficiency because it is loaded only capacitively by the gate of the pass transistor M_{pass}. However, in this concept the input power has to exceed a certain level given by the required turn-on voltage swing of the start-up rectifier. In order to de-activate the RF switch, the input of the rectifier is tied to ground by the transistor M_c and the antenna is mainly loaded capacitively by the coupling C_{cpl}.

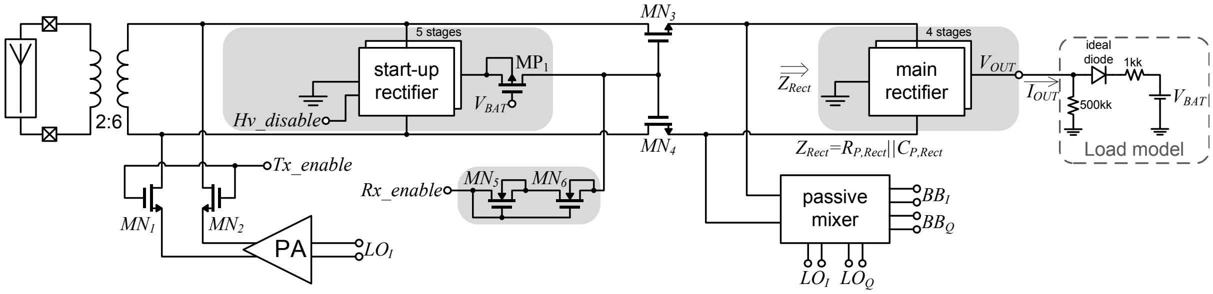


Figure 4. Frontend of the transceiver with energy harvester. The parts on gray background are added to the previous work to allow for RF-DC conversion.

D. Topology selection

For selecting the most suitable topology, the transceiver frontend that will be used for co-integrating the RF-DC conversion has to be taken into account. We use a previously designed 2.4 GHz low power transceiver frontend [5] which up-converts the antenna impedance to an internal RF impedance of about 1 kΩ in order to allow for an efficient low-output power transmitter [10]. Impedance up-transformation also provides passive voltage gain for the receiver and is expected to allow for an efficient RF-DC conversion since the rectifier performance usually improves for a higher input voltage swing [11].

The high RF impedance level (R_0=1 kΩ) excludes the LC-resonator approach in a fully-integrated solution as the required inductance would be approximately 90 nH according to (2) for DGF=1.12, Q_P=5.5 and f_0=2.4 GHz. Also the transmission line approach cannot be integrated into silicon as the $\lambda/4$-transmission line would be about 16 mm long at 2.4 GHz [9].

The solution with the start-up rectifier can be very area-efficient as no inductors or transmission lines are needed but it does not work for small signal levels because rectification relies on the non-linear large-signal characteristics of a diode. Anyhow, this is still a valid option for the given application if we keep in mind that we want to harvest RF energy only if the incoming power level is at least -10 dBm. This yields an input amplitude of at least 250 mV (R_0=1 kΩ) and, hence, large enough to drive the start-up rectifier [2].

III. Circuit design

The schematic of the 2.4 GHz transceiver frontend is shown in Fig. 4 where the circuits that have been added for the energy harvesting functionality are highlighted. At the antenna interface a transformer up-converts the antenna impedance to a differential internal impedance of 1 kΩ. The differential power amplifier (PA) connects to the transformer through $MN_{1/2}$ that act as the Tx-switch. NMOS transistors $MN_{3/4}$ operate as the shared switches for both the receiver and the energy harvester.

In order to generate a sufficient overdrive voltage at the gates of $MN_{3/4}$ in the harvesting mode, a 5-stage start-up rectifier has been implemented. The individual stages (Fig. 5) are based on the cross-coupled differential 4-transistor cell [11]. However, for this application a fifth transistor M_{Off} has been added that acts as the off-switch. Pulling $HV\_disable$

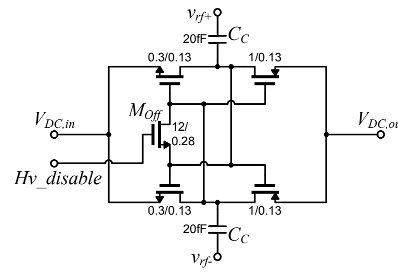


Figure 5. Differential implementation of the start-up rectifier with coupling capacitors and off-switch M_{Off}.

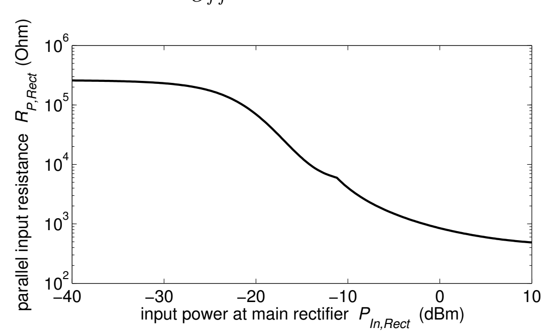


Figure 6. Parallel input resistance of the main rectifier $R_{P,Rect}$ versus rectifier input power $P_{in,Rect}$ from a 1kΩ-source (load condition: V_{BAT}=1.0 V).

high effectively short-circuits the two internal nodes and creates a virtual ground here. Then, the RF input impedance of the disabled rectifier is mainly the series connection of the two coupling capacitors C_C and the on-resistance of M_{Off}. The resistive part of this impedance has to be minimized in order to prevent RF power dissipation in the start-up rectifier when the transmitter is active. The coupling capacitors and the rectifying transistors are close to the minimum size in order to keep the loading of the RF nodes as low as possible.

The main rectifier employs the conventional 4-transistor rectifier cell for its good power conversion efficiency [11], i.e. the topology shown in Fig. 5 but without M_{Off}. The transistors widths are 4 times larger compared to the start-up rectifier and the coupling capacitances are 250 fF each. These dimensions have been selected in order to obtain the peak efficiency at around -5 dBm considering the parallel input resistance of the rectifier $R_{P,Rect}$, shown in Fig. 6. The peak PCE occurs when the rectifier is matched to the source impedance, i.e. where $R_{P,Rect}$ is about 1 kΩ.

The characteristic of $R_{P,Rect}$ versus input power also allows to place the main rectifier directly in parallel to the input of

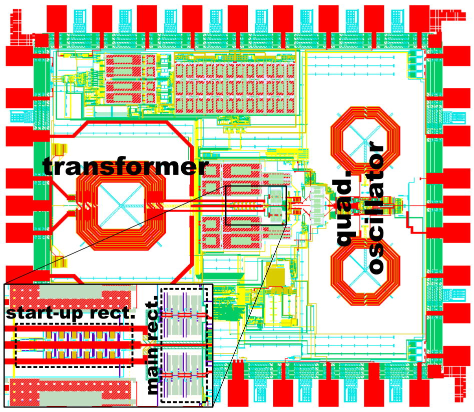


Figure 7. Layout of the transceiver frontend with the energy harvester shown in the inset. The total die size is 1.6mm by 1.3mm.

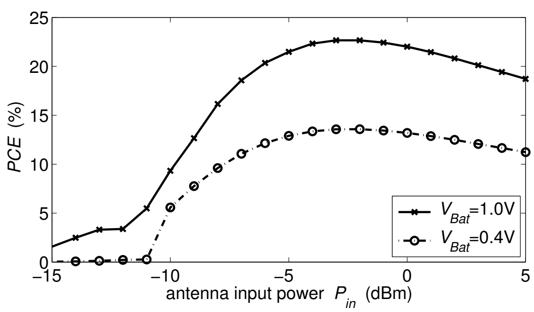


Figure 8. Post-layout power conversion efficiency PCE versus antenna input power P_{in} for different load and supply conditions.

the receiver without further decoupling. Fig. 6 shows that the small-signal $R_{P,Rect}$ is well above 100 kΩ and hence hardly affects the sensitivity of the receiver. On the other hand, in the energy harvesting mode the local oscillator inputs $LO_{I/Q}$ are grounded, leading to a high input impedance of the passive mixer because all its internal switches are off [5].

IV. Post-Layout Simulation Results

The transceiver frontend with the harvester has been implemented in a 130 nm standard CMOS technology. A layout plot of the frontend is shown in Fig. 7 with the internal transformer port on the left. The occupied area of the start-up rectifier and main rectifier is 2100 μm² and 4400 μm², respectively.

The simulated power conversion efficiency (PCE) is shown in Fig. 8 for two different supply conditions. The first scenario with V_{BAT}=1.0 V represents the nominal operation condition of the transceiver and achieves the maximum PCE of 22.7% (8.7% higher than reported in [4]). The second scenario with V_{BAT}=0.4 V represents the case when the battery is almost empty. In this scenario, the turn-on threshold of the RF switch of about -10 dBm can be observed together with a generally lower PCE because the RF voltage swing is reduced by the different load condition of the main rectifier. In both cases, the peak PCE is achieved around -3 dBm where the main rectifier is well matched to the internal RF impedance of 1 kΩ (Fig. 6). The main losses occur in the transformer (≈2 dB) and the Rx/Hv-switch (≈1 dB).

The degradation of the Tx- and Rx-performance of the transceiver has been estimated by simulating the frontend with and without the two rectifiers of the energy harvester. The output power of the transmitter is reduced by only 0.2 dB with the energy harvester. The degradation is mainly caused by power dissipation in the de-activated start-up rectifier due to a non-zero $R_{DS,on}$ of M_{Off}. In the Rx-mode, the received signal power is reduced by approximately 0.4 dB and, hence, the noise figure is increased by the same amount. In this case the degradation is mainly caused by an increased mismatch due to the added capacitive loading of the RF nodes.

V. Conclusions

An energy harvester frontend has been proposed to be integrated into a 2.4 GHz transceiver. The key element of the harvester is an active-low RF switch that decouples the harvester from the antenna when the transmitter is active but still allows energy harvesting without any power supply, i.e. when the battery is empty. In this case, a small start-up rectifier ensures that the switch at the harvester is activated. The harvester achieves a peak power conversion efficiency of 22.7% and degrades the Tx- and Rx-performance by only 0.2 dB and 0.4 dB, respectively. The area occupation of the harvester is less than 0.01 mm² and hence negligible.

Acknowledgment

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