Design of RF energy harvesting platforms for power management unit with start-up circuits

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Abstract. In this contribution we discuss an unconventional rectifier design dedicated to RF energy harvesting from ultra-low sources, such as ambient RF sources which are typically of the order of few to few tens of μW. In such conditions unsuccessful results may occur if the rectenna is directly connected to its actual load since either the minimum power or the minimum activation voltage may not be simultaneously available. For this reason a double-branch rectifier topology is considered for the power management unit (PMU), instead of traditional single-branch one. The new PMU, interposed between the rectenna and application circuits, allows the system to operate with significantly lower input power with respect to the traditional solution, while preserving efficiency during steady-state power conversion.

1. Introduction
In those situations where available RF energy in the ambient is the only source the systems autonomy by energy scavenging is almost impractical, even for typical distributed embedded systems activities, such as sensors read out, which usually operate at very low duty-cycles, This is due to low available DC voltages or power, with respect to the minimum requirements.

For this reason a PMU is typically adopted between the rectenna and the actual user [1], [2], to provide the rectenna with the maximum power point (MPP) tracking condition. But a traditional solution with single rectifier designed and optimized for a single specific load condition is not able to ensure minimum supply voltage of PMU. Therefore we propose a new rectifier design approach to reach this goal.

The scenario we refer to is schematically depicted in Figure 1.

Figure 1. Block diagram of an energy autonomous system wirelessly powered by randomly distributed RF sources
For the entire system to be energetically autonomous, the PMU is equipped with a start-up stage, slow and less efficient, designed to consume few µW and to activate a more efficient boost converter stage with maximum power point tracking (MPPT) capabilities, with higher operating voltages and power consumptions requirements. These two stages provide two highly different loading conditions to the RF rectifier, namely the start-up impedance and the optimum load, whose operations require two different rectifier designs as well. In turn they represent two different source impedances for the base-band operation of the PMU, due to the nonlinear nature of the RF rectifiers. Therefore a joint RF/base-band design of the nonlinear rectifiers and of the two PMU sub-systems, is recommended to preserve the overall system efficiency maximization. The latter can be computed with reference to the schematic block diagram of Fig. 1, by considering the power quantities at the interconnecting sections:

$$\eta_{EH} = \eta_{TX-RX} \cdot \eta_{RX-DC} \cdot \eta_{DC-DC} = \frac{P_{RX}}{P_{TX}} \cdot \frac{P_{RECT}}{P_{RX}} \cdot \frac{P_{HARV}}{P_{RECT}}$$ (1)

The first factor, is dependent on the radio channel and is highly variable due to the unknown source location and to fading effects, especially significant in indoor environments. It can be accurately evaluated by resorting to the reciprocity theorem as in [3], but is not a concern of the present paper.

The second and third factors are strictly interdependent. In fact $\eta_{RF-DC}$ is the RF-to-DC rectifier conversion efficiency with $P_{RECT}$ being the RF power at the rectifier output port, which is strongly dependent on the rectifier load. The latter consists of the PMU input impedance, which varies whether the start-up or the boost stages are operating. Similarly the third factor in (1) is the DC-DC converter efficiency which is a function of the rectenna output impedance.

We thus design a parallel connection of two different rectifier/matching network assemblies to operate alternatively during the start-up and the boost converter operations.

2. The switched-load rectifier

The block representation of the new subsystem is shown in Fig. 2.

Two identical rectifiers, consisting of a traditional voltage doubler topology, are used in the two branches of the new proposed topology. One is designed together with the rectenna optimum load to reach the maximum RF-to-DC power conversion efficiency, thus allowing the DC-DC converter to dynamically provide the rectenna MPP condition. The other one is designed for a fixed load, namely the converter start-up circuit input impedance ($\approx 200$ kΩ), to provide the DC voltage and power needed for an autonomous start-up operation. The switching between the two arrangements is controlled at the load side by dynamically driving a couple of mutually exclusive field-effect transistors by acting on the CTRL signal (inset of Fig. 1). This way the selection of two separate antenna matching networks is possible: when CTRL is low, the lower branch is active and the upper one is shorted to ground; when CTRL is high the role of the branches is flipped. In this way the actual nonlinear behavior of the rectenna in the time-domain design of the PMU is rigorously accounted for. Similarly the rectenna regime in its actual loading conditions can be optimized.
In Fig. 3 the final layout of the optimized double branch matching network in microstrip technology is reported, with the two networks put into evidence: double-stub and single-stub solutions are adopted for the boost converter and the start-up branches, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Distributed layout of the double-branch matching network.}
\end{figure}

2.1. Simulation results
The system operation is demonstrated by numerical simulation based on the nonlinear/electromagnetic (EM) co-design in the 900-MHz band, where RF sources are commonly available. Some significant results are plotted in Fig 4: the optimized rectenna efficiencies and output DC voltages as a function of the load current consumption, (for $P_{RF} = -15$ dBm) are plotted for the start-up (Fig. 4(a)) and boost (Fig. 4(b)) operating conditions: a higher DC voltage (> 1V) is reached when the start-up is loading; conversely at the MPP the best RF-to-DC efficiency is realized with the rectifier loaded by the boost, but the corresponding DC voltage is significantly lower (< 0.5 V).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Efficiency and output DC voltage for the rectifier loaded by the start-up (almost open-circuit load) (a) and the boost (optimum load) (b).}
\end{figure}

This situation is of course strongly dependent on the level of the incoming RF signal ($P_{RX}$). In order to show this dependence results similar to the previous ones are plotted in Fig. 5, where the DC voltage (Fig. 5(a)) and the efficiency (Fig. 5(b)) are given as a function of $P_{RX}$, focusing on low power levels, typical of harvesting scenarios.
The lower efficiency values pertaining to the start-up phase (active for low $P_{RX}$ levels) are not a concern, since in this phase we are interested in having high DC voltage values (which are more than twice the corresponding values obtained in the boost phase again for low $P_{RX}$ levels) (Fig. 5(a)). Once the wake-up of the system is guaranteed by the start-up, the convenience in switching to the boost phase is demonstrated by Fig. 5(b) where the higher efficiency of the boost rectifier is the desired target.

Finally, in Fig. 6, the effectiveness of the proposed approach is demonstrated by the time-domain simulation of the entire system loaded by a DC-DC converter, during the converter start-up phase. An input power $P_{RX} = -15.5$ dBm allows to reach an output voltage ($V_{ST}$ of Fig. 2) equal to 2 V in a charging time of almost 20 s. This roughly corresponds to an average rectified power (lower than the corresponding instantaneous value $P_{RECT}$) of about 3 $\mu$W, evaluated as the energy stored in the storage capacitor ($C_{ST}$ of Fig. 2) of 33 $\mu$F in the charging period. These results show that by the present solution half the RF power needed by standard rectifier design (for optimum load) is required with the new two-branch solution.

References
[1] T. Paing, E. A. Falkenstein, R. Zane, and Z. Popovic, “Custom IC for Ultralow Power RF Energy Scavenging,” IEEE Transactions on Power Electronics, vol. 26, no. 6, pp. 1620–1626, 2011.

[2] A. Costanzo, A. Romani, D. Masotti, N. Arbizzani, and V. Rizzoli, “RF/baseband co-design of switching receivers for multiband microwave energy harvesting,” Sensors and Actuators A: Physical, vol. 179, pp. 158–168, Jun. 2012.

[3] V. Rizzoli, A. Costanzo, D. Masotti, F. Donzelli, "Integration of numerical and field-theoretical techniques in the design of single- and multi-band rectennas for micro-power generation," EuMA Int. J. of Microw. and Wirel. Tech. vol. 2, no. 3-4, pp. 293-303, July 2010.