RF Energy Harvester Circuits Supplied with Multi-sine Signals

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***Abstract*—Radio frequency (RF) harvesting is showed to be a feasible technique to power energy neutral devices, providing a flexible solution to exchange small amounts of energy. The rectifier, used to convert RF to direct current (DC), introduces non-linearities, degrading the efficiency of the RF harvester. Different techniques are studied in literature to address this challenge, e.g., by using high peak-to-average power ratio (PAPR) signals. This research presents several *PySpice* rectifier models to evaluate the efficiency of different signal waveforms and RF harvester architectures. In this work, these models are utilized to assess the energy-efficiency gain of high PAPR signals with respect to single tone signals. As resulted from this work, we concluded that the gains of high PAPR signals depend strongly on the rectifier circuit, even having an adverse effect in case of a voltage doubler.**

Originally, a lot of attention has been spent on the improvement of the power conversion efficiency of rectifier circuits in order to increase the overall harvesting efficiency. However, recently, it has been shown that waveform design also affects the energy harvester efficiency [1]–[3]. The RF-to-DC efficiency of the harvester can be improved by waveform types with high peak-to-average power ratio (PAPR) signals. As the term explains, the signal power level will fluctuate and peaks of higher radiated power will occur periodically. At non-peak times, the transmitted power is significantly lower than the average radiated power. The reason why this method is being studied, is due to the restrictions in radiated power. Searching for techniques where the average radiated power of the transmitted signals remains the same, yet causes higher efficiency gains in the harvester, is therefore worth considering. In this study, the harvester performance supplied with a single tone signal is compared with multi-sine signals. To make a fair comparison, the generated waveforms should have the same average power than a single tone signal. While many research papers have shown that the RF-to-DC efficiency can be increased by applying high PAPR signals, it turns out that these signals are not always beneficial for the harvester performance. [4] has described this phenomenon more in detail specifically for a voltage doubler rectifier.

In this comparative study, the full harvester efficiency is considered, including matching losses and consequently reflections. Due to the nonlinear model of a diode, it is challenging to match a rectifier circuit. Usually, the input impedance is determined by simulations or measured with a vector network analyzer (VNA). Based on the obtained complex input impedance and using the Smith chart, an appropriate matching network is proposed. The nonlinear model of the diode causes an additional input power dependency, in addition to the frequency dependency. This additional dependency means that the matching circuit cannot ensure a perfect match over the entire input power range. A matching circuit between the antenna impedance of typically $50\,\Omega$ and the rectifier circuit is proposed for each considered harvester. Unfortunately, this matching circuit provides only one optimal situation with small losses and reflections for a well-defined frequency and input power level. In practise, reflections will cause additional losses due to a fluctuating input power. This study considers two rectifier circuits constructed with a single diode rectifier and a voltage doubler rectifier.

The results show that for a single diode rectifier, the power conversion efficiency increases with an increasing number of frequency components. However, with a voltage doubler, the opposite effect is stated. It appears that the voltage doubler performance decreases with increasing frequency components in the multi-sine signal. This latter rectifier circuit no longer works as a true doubler. Furthermore, the simulations show that efficiency gains can be validated with low complex PySpice scripts. Implementation and design effort can be improved by first modelling and simulating the desired rectifier circuit with corresponding matching circuits, and then supply them with the desired waveform input signals. Sweeps over the entire input power range (e.g. $-20\,\mathrm{dBm}$ up to $10\,\mathrm{dBm}$) for multiple input signals provides a good estimate of the potential efficiency gains.

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