Optimal Waveforms for Efficient Wireless Power Transmission

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***Abstract*—This work shows how using specifically selected or designed waveforms in wireless power transfer (WPT) systems can lead to improved RF to dc conversion efficiency in rectifier circuits in the receiving end of these systems. Signals with different time domain waveforms are considered such as OFDM, white noise and chaotic waveforms, and the performance of a rectifier circuit operating at 433 MHz is evaluated when using these signals in comparison to a single carrier constant envelope signal. The performed experiments show that selecting high peak to average power ratio (PAPR) signals lead to improved RF-DC conversion efficiency in rectifier circuits.**

***Index Terms*—Energy harvesting, rectifier, rectenna, wireless power transmission.**

I. Introduction

THE increasing interest for the concepts of Smart Cities, Smart Buildings and the Internet of Things where a large amount of devices need to be powered up has increased the demand for solutions that provide autonomy to these devices. Energy harvesting solutions, where energy from a selected source such as solar, electromagnetic (EM), thermal, or kinetic is captured and converted to dc power has had a great development in the last years [1], [2]. Among the energy harvesting alternatives, electromagnetic energy harvesting has received a lot of attention. However the main drawback in EM energy harvesting is that the amount of available energy from the surrounding EM sources is variable and unpredictable. This uncertainty leads to reduced RF-DC conversion efficiency in EM energy harvesters.

As an alternative, wireless power transmission (WPT) uses an intentional EM signal, transmitted at a certain frequency and with a certain amount of average power to power up devices up to large distances [3]. In WPT the amount of transmitted power is known and usually constant, which allows performing optimized design of the rectifier circuits in the receiving end towards maximizing the RF to dc conversion efficiency. Several works have proposed to improve the RF-DC conversion efficiency of rectifier circuits by selecting the most adequate waveform for the transmitted EM signal. In [4]–[11] the use of multitone signals and chaotic signals were explored to improve the conversion efficiency in WPT systems. These works have shown that signals with a time varying envelope can provide improved conversion efficiency as they are capable to activate the rectifying devices for lower average input power levels, compared to signals of constant envelope and the same average power.

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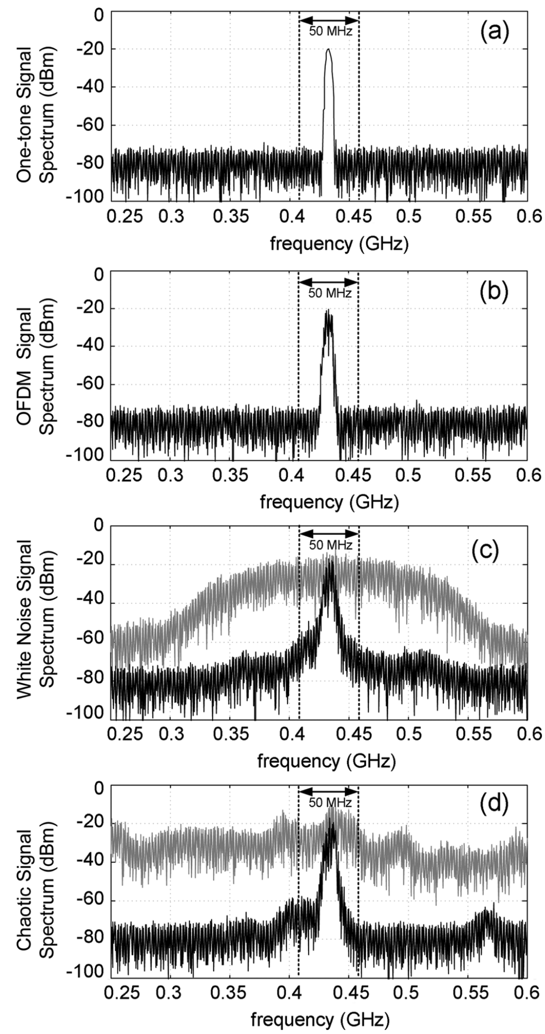

Fig. 1. Signal output spectrum (a) single carrier signal (b) OFDM signal (c) white noise signal (d) chaotic signal.

In this letter the optimum signal waveform to be used in WPT systems is investigated. The use of white noise and OFDM signals is explored and the results obtained in terms of RF-DC conversion efficiency are compared to the ones obtained when using single carrier and chaotic waveforms.

II. Waveform Selection for WPT

When using high PAPR signals in WPT systems, the main objective is to overcome the limitations imposed by the threshold voltage of the rectifying devices in the receiving end, by maximizing the peak voltage that reaches them. In the case of using

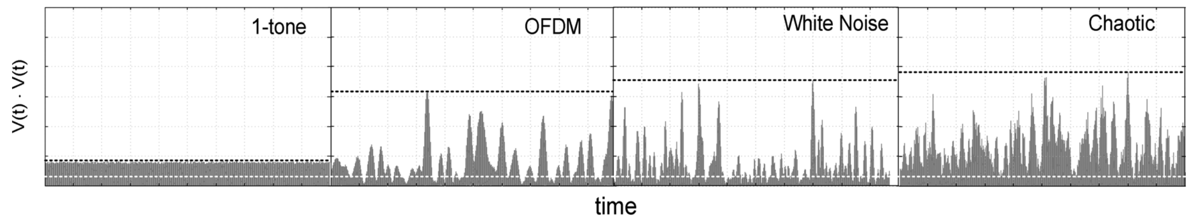

Fig. 2. Instantaneous power of the different types of test signals. Dashed-white line indicates the average power that is the same for all the signals. Dashed-black line indicates the peak power value.

Schottky diodes as rectifying devices, for the same total average power of the input signal, high PAPR signals will turn on the diode for lower input power levels.

There are several types of signals that can present high PAPR, such as OFDM signals, white noise or chaotic signals. Potentially all of these signals can lead to improved performance of rectifier circuits. A comparison, attending to the improvement obtained in the RF-DC efficiency of rectifiers when using these signals in comparison to a one tone signal [Fig. 1(a)], will be shown next. In order to use these type of signals in WPT systems it is mandatory to limit them to a certain bandwidth, which imposes their filtering.

The PAPR (dB) of a waveform can be defined as

$$\mathrm{PAPR} = 10\log_{10}\left(\frac{\max[x(t)^2]}{\langle x(t)^2\rangle}\right) \tag{1}$$

where $x(t)$ is the time domain waveform of the signal of interest and $\langle\rangle$ refers to the time average operator.

The PAPR can also be defined with respect to the envelope of the signal $e(t)$, using the so called envelope approach [12]. The PAPR of the signal envelope is related to the PAPR of the signal through (2) [12]

$$\mathrm{PAPR}(x(t)) \sim \mathrm{PAPR}(e(t)) + 3\ \mathrm{dB}. \tag{2}$$

Attending to this definition the PAPR of the envelope of a one tone signal is 0 dB.

Here, the Complementary Cumulative Distribution Function (CCDF) of the PAPR of the envelope is used to evaluate the different signals used for the experiment [12]. The CCDF curve is obtained using the Agilent Vector Signal Analyzer (VSA) software. The CCDF curve indicates the probability that the PAPR of the signal envelope be above a certain threshold γ, and at the same time it provides an estimate of the frequency of the peaks in the time domain waveforms. The maximum value of γ in the CCDF curve indicates the maximum PAPR of the signal envelope $e(t)$. The maximum PAPR of the signal $x(t)$ can be estimated adding 3 dB to the PAPR of the signal envelope [12].

A. OFDM Signal

OFDM signals present high PAPR due to the used multi carrier aggregation scheme. Depending on the number of used subcarriers (N), the maximum theoretical PAPR of an OFDM signal can equal N as long as all the sub-carriers add up in phase. However, as the sub-carriers of the OFDM signal are not modulated equally, the in-phase condition is not reached which prevents obtaining the maximum theoretical PAPR. The selected OFDM signal to be used in the experiment is an LTE FDD downlink OFDM signal with 301 occupied sub-carriers modulated using QPSK, 5 MHz bandwidth and a PAPR of 12 dB (Fig. 3). The frequency spectrum of this signal is shown in Fig. 1(b) and its time domain waveform in Fig. 2(b).

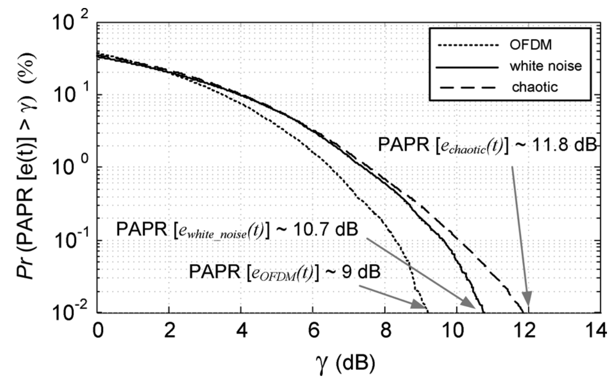

Fig. 3. CCDF of the envelope of the test signals.

B. White Noise Signal

A band limited white noise signal around 433 MHz is synthesized using a single carrier modulated by a Gaussian white noise signal provided by an arbitrary waveform generator Agilent 33250A source. The baseband noise signal had 1 V_{pp} amplitude. White noise presents a flat power spectral density and high PAPR which makes it suitable for its use in WPT systems. In order to compare the various signals used in this work within a given limited bandwidth, both for practical purposes as well as due to the limited bandwidth of the rectifier used, it is necessary to filter the noise signal. For this specific work a commercial 433 MHz band-pass surface acoustic wave (SAW) filter with a 3 dB-bandwidth of 6 MHz was used. The original and filtered frequency spectrum can be seen in Fig. 1(c). The time domain waveform is shown in Fig. 2(c). The filtered white noise signal in Fig. 1(c) presents a PAPR of 13.7 dB (Fig. 3).

C. Chaotic Signal

The used chaotic generator at 433 MHz uses a Colpitts based topology, where the values of C_1, C_2 and L are calculated to obtain the desired chaotic behavior [7]. It can be seen that with a single transistor circuit it is possible to design a chaotic generator which makes it quite easy to implement and use in WPT transmitters [7], [13].

Chaotic signals present a continuous frequency spectrum, which makes it necessary to also introduce a filtering mechanism in order to limit them to a certain frequency bandwidth. The same filter used for the white noise signal is used here. Original and filtered frequency spectrum can be seen in Fig. 1(d). The time domain waveform is shown in Fig. 2(d). The synthesized chaotic signal has a PAPR of 14.8 dB (Fig. 3).

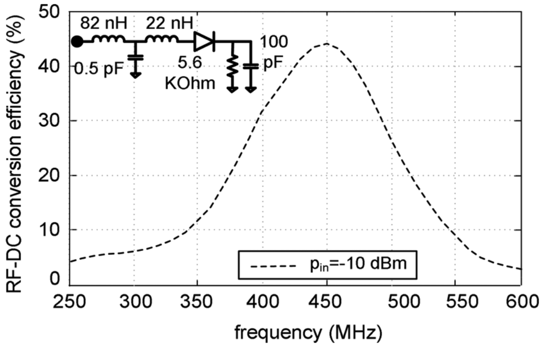

Fig. 4. RF-DC conversion efficiency of the rectifier circuit.

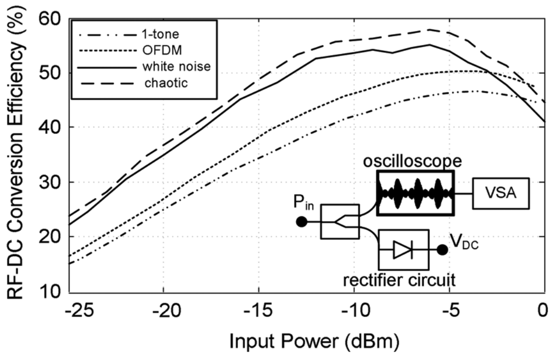

Fig. 5. RF-DC conversion efficiency of the rectifier circuit versus total input power for different test signals.

III. RF TO DC CONVERSION EFFICIENCY EVALUATION

In order to compare the performance of a WPT system when using different types of high PAPR signals, a rectifier circuit based on a single series Schottky diode is used. The rectifier operates at 433 MHz and uses as rectifying device the Skyworks SMS7630-02LF that can function with turn on voltages as low as 0.06 V for 0.1 mA of current and an output load of 5.6 KΩ (Fig. 4). A T-type matching network is used to match the rectifier circuit input to 50 Ω [7]. The measured RF-DC conversion efficiency for an input power of -10 dBm is shown in Fig. 4.

The performed experiments evaluate the RF-DC conversion efficiency in the rectifier circuit using (3). The different test signals of Fig. 1 are used to operate the designed rectifier. All the signals have the same average power but different PAPR (Fig. 1). The signal power is evaluated as the total (average) power in a 50 MHz bandwidth around the carrier (Fig. 1) and it is measured using a VSA software together with the Agilent Infiniium DSO81004A oscilloscope (Fig. 5) [7]

$$\eta = \frac{P_{\mathrm{out\_DC}}}{P_{\mathrm{in\_RF}}} = \frac{V^2_{\mathrm{out\_DC}}/R_L}{P_{\mathrm{in\_RF}}}. \tag{3}$$

Fig. 5 shows the RF-DC conversion efficiency versus the total signal power for the different type of signals. Fig. 5 shows that the chaotic signal leads to the higher RF-DC conversion efficiency. This fact is attributed to the PAPR of the chaotic signal (14.8 dB), which is higher than the maximum PAPR of the rest of the test signals. The white noise and the OFDM signals have a PAPR of approximately 13.7 dB and 12 dB, respectively, so even though these signals also lead to improved efficiency when compared to a one-tone signal, this improvement is less than the one obtained with the chaotic signal. In addition to the high PAPR, the characteristics of the time domain waveform together with the selected rectifier RC filter (Fig. 4) also affect the RF-DC efficiency. Similar results have been obtained when using multi-sine signals where all the sines combine in phase and create high PAPR waveforms [4]–[6], [8]–[10]. The drop observed in the RF-DC conversion efficiency (Fig. 5) occurs when reaching the breakdown voltage of the selected diode.

It has to be noted that even though high PAPR signals are not desired in communication systems due to the distortion that these signals suffer when amplified in the transmitter, in WPT systems high PAPR signals are desired towards improving the RF-DC conversion efficiency of the rectifiers.

IV. CONCLUSION

This work has shown how properly selecting the waveform of the signals in wireless power transmission (WPT) can lead to improved performance in these systems. This fact has been verified by testing several types of signals such as white noise, OFDM and chaotic signals showing that the RF to dc conversion efficiency increases when using high PAPR signals.

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