The Impact of Waveform on the Efficiency of RF to DC Conversion Using Prefabricated Energy Harvesting Device

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Abstract—**This paper is dedicated to the investigation of the influence of different waveforms on the efficiency of radio frequency (RF) to direct current (DC) conversion in wireless power transfer (WPT) systems. Single-tone, multi-tone, random and chaotic signals are used and compared as waveforms for wireless power transfer. The influence of peak-to-average power ratio (PAPR) and average input power of the waveform on the efficiency of RF-to-DC conversion is measured in laboratory conditions and studied. A commercially available RF energy harvesting device – Powercast P2110B is used as RF-to-DC conversion circuitry.**

I. Introduction

Wireless sensor networks (WSNs) have become the object of intensive research during several last decades. While presenting flexible solutions for many previously unsolved problems [1], [2], [3], [4], WSNs themselves pose plenty of design challenges. One of the main issues of WSN nodes is the strong dependence on the power provided by an attached energy source, leading to limitations of usability. Promising solutions for the development of autonomous WSN nodes based on ambient energy harvesting as well as dedicated wireless power transfer (WPT) [5], [6], [7] have appeared during the last decade. The latter technique allows providing a stable, predictable amount of radio frequency (RF) energy to the WSN node that is responsible for the conversion of the received signal to direct current (DC) as well as for matching it to the properties of the load.

The maximum amount of energy that can be transmitted without a licence, generally expressed in the form of Equivalent Isotropically Radiated Power (EIRP), is limited by international standards [8]. Thus, within the mentioned power constraints, solutions should be found in order to boost the power transfer and conversion efficiency. One approach is based on the optimization of the hardware part of the transmitter and receiver: increasing the number of antennas and changing their size and shape [9], [10]; creating antenna arrays [11]; modifying the rectification schemes [12], [13], etc.

However, all the mentioned solutions lead to more complex, space and cost demanding implementations of wireless sensor nodes. Another promising solution, proved to be quite acceptable, is the deliberate selection of waveforms used for WPT.

Researchers propose and examine different signal waveforms that could potentially increase the efficiency of WPT as well as RF-to-DC conversion [14], [15], [16]. The proposed signals can be classified as narrowband and wideband [17], single-tone and multi-tone [18], [19], as well as deterministic and random [20], adaptive and non-adaptive [21], [22]. Besides, the evaluation of efficiency of power conversion can be done using a linear or non-linear receiver circuit model [23], [24]. Different channel models are used with and without known channel state information (CSI) [25] to investigate WPT and predict power conversion efficiency. Different types of WPT are proposed and compared: single-input single-output (SISO) [26], multiple-input multiple-output (MIMO) [27], multiple-input single-output (MISO) [28].

A very limited number of comercially available solutions for WPT are available on the market. One of them is the RF energy harvesting device Powercast P2110B [29] – an energy receiver which is optimized for the operation in 902 MHz to 928 MHz frequency band and which provides efficiency of up to 50%. At the same time, the dependence of efficiency on the incoming signal frequency for this energy harvesting device demonstrates acceptable characteristics for the broader 800 MHz to 1000 MHz RF band.

Thus, on the one hand, researchers provide a variety of solutions for enhancing the efficiency of WPT and RF-to-DC conversion, which are proved to be effective in quite artificial laboratory environment under certain (sometimes rather unpractical) assumptions. On the other hand, engineers should comply with some restrictions imposed by the frequency band and EIRP (set by corresponding regulatory agencies), as well as with practical limitations of industrially manufactured solutions for wireless power conversion.

This article is devoted to the investigation of the influence of different waveforms on the power conversion efficiency of a chosen industrially manufactured energy harvesting device. The paper is organized as follows. Section II presents the main properties of waveforms selected for WPT within the study. Section III describes the experimental setup used for evaluation of the proposed signals. Section IV provides the results of RF-to-DC conversion efficiency for different waveforms, power levels and bands. Last but not least, the conclusion section V presents an overview of the obtained results and

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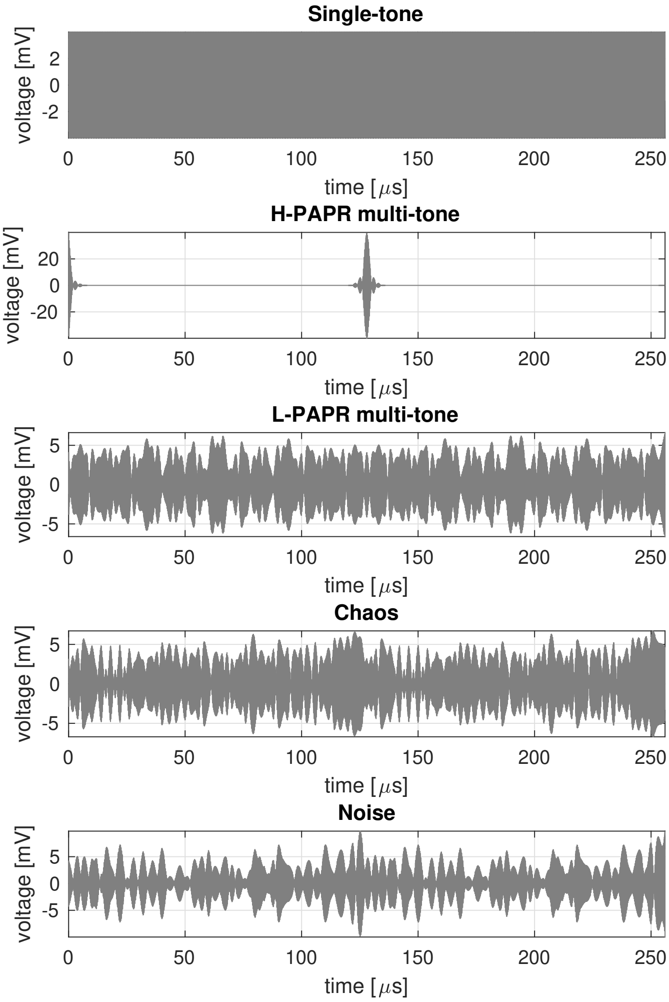

Fig. 1. Simulated time-domain signals

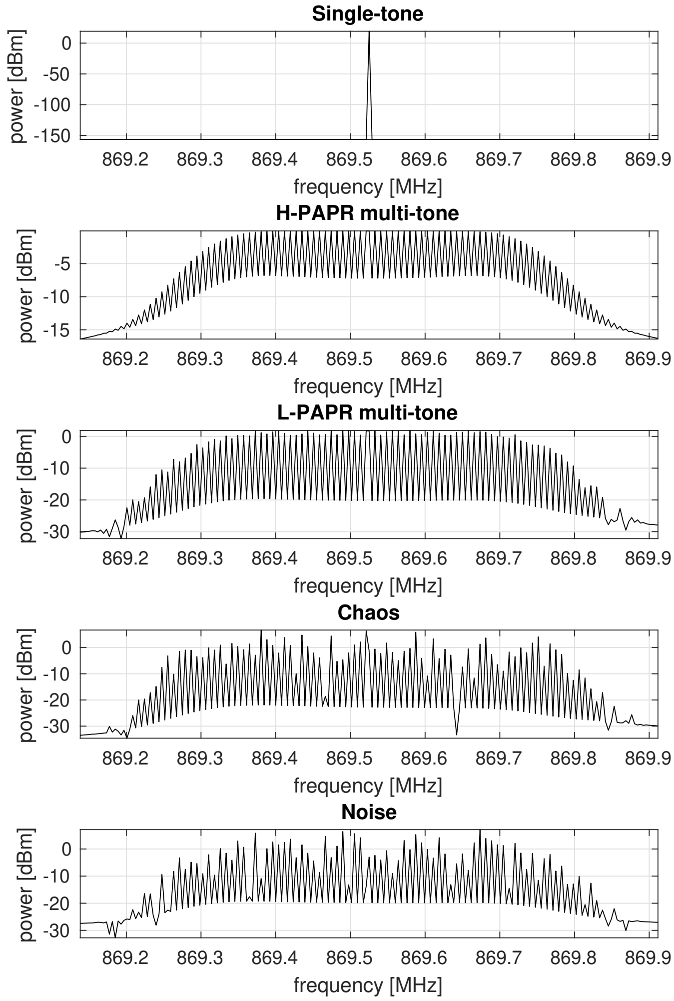

Fig. 2. Simulated power spectral density (PSD) of the proposed signals

addresses the next research steps.

II. Waveform Selection

This section presents the main characteristics of the waveforms selected for WPT: single-tone, multi-tone, random and chaotic signals as well as the means of their generation. For the study of RF energy conversion efficiency, two types of signals are used: a narrowband signal occupying $869.4\,\mathrm{MHz}$ to $869.65\,\mathrm{MHz}$ with center frequency of $869.525\,\mathrm{MHz}$, and a wideband signal occupying $863\,\mathrm{MHz}$ to $868\,\mathrm{MHz}$ with $865.5\,\mathrm{MHz}$ center frequency. The bandwidths of all examined signals are limited to $250\,\mathrm{kHz}$ in narrowband mode or $5\,\mathrm{MHz}$ in broadband mode. It is important to notice all considered waveforms have equal average power during the measurement.

RF signals are generated using Universal Software Radio Peripheral (USRP) software-defined radio (SDR) connected to a personal computer (PC) running Simulink. The bandwidth of the generated signals is controlled by an appropriate setup of USRP. Namely, the combination of interpolation factor and master lock rate of USRP determines the maximum bandwidth of the signal.

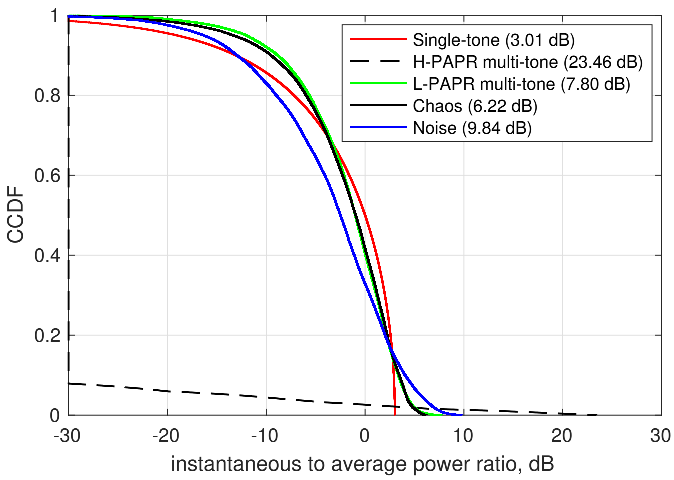

Fig. 3. Simulated CCDF functions of instantaneous power

Fig.1 illustrates the proposed waveforms with a carrier frequency of $869.525\,\mathrm{MHz}$ and a bandwidth of $250\,\mathrm{kHz}$ and Fig.2 shows their power spectral densities. In addition, the complementary cumulative distribution function (CCDF) functions of instantaneous power are presented in Fig. 3. H-PAPR and L-PAPR stand for a multi-tone signal with high peak-to-average power ratio (PAPR) and low PAPR, respectively.

A. Single-tone

The most popular waveform for WPT is a sinusoidal signal. Mathematically it is expressed as follows:

$$s(t) = S_m \cos(2\pi f t) \tag{1}$$

where S_m is the amplitude, and f is the frequency. The main advantage of a single-tone signal is a low PAPR level and a simple generation scheme, since the envelope of the signal is constant. In the present case, generation of a single-tone RF signal is performed by sending constant samples to the digital input of USRP.

B. Multi-tone with a high PAPR

According to [30], it is potentially much more efficient to use signals with a high PAPR for RF-to-DC conversion compared to single-tone signals. Therefore, in this paper we will pay attention to several modulated multi-tone and band-limited random waveforms.

The simplest multi-tone signal with a high PAPR can be obtained by modulating a high frequency carrier and using, accordingly, a filtered discrete time unit impulse function $u(n)$:

$$u(n) = \begin{cases} 1, & \text{if } n = 0 \\ 0, & \text{if } n > 0 \end{cases} \tag{2}$$

In our experiments, 64-sample discrete time unit impulse functions (2) were sent to the digital input of USRP working at the master clock rate of 50 MHz and two different interpolation factors 200 and 10. In such a way, 250 kHz and 5 MHz, respectively, wide multi-tone signals with 64 subcarriers having equal zero phase were generated.

This signal can be produced also by inverse fast Fourier transform (IFFT) from the vector of all ones, which represent amplitudes and phases of subcarriers. Since all subcarriers have the same phase and amplitude, this signal has a very high PAPR level, namely, more than 23 dB.

C. Multi-tone with a low PAPR

If a digital signal at the input of USRP is produced by IFFT from the Zadoff-Chu sequence [31], the resulting time-domain multi-carrier signal has a much lower PAPR compared to the case with the same phase multi-carrier signal described in Subsection II-B. This is because the Zadoff-Chu sequence has a unit magnitude and a pseudo-random phase. The PAPR level for this signal is less than 8 dB.

D. Random

Another waveform for wireless power transmission, widely mentioned in the literature, is a band-limited random signal. This signal can be generated by sending random normally-distributed complex samples to the digital input of USRP. The PAPR level of the signal generated in a such manner is approximately 10 dB.

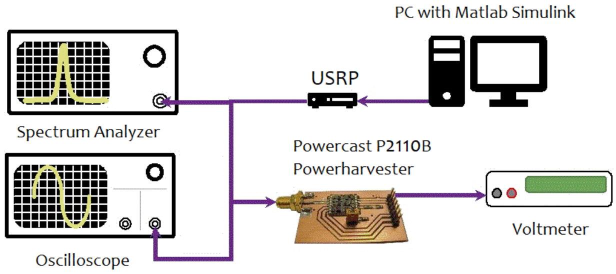

Fig. 4. Block diagram of experimental setup

E. Chaotic

In researches [20], [30], chaotic signals are proposed for WPT. To test the efficiency of RF-to-DC energy conversion in the case of a band-limited chaotic signal, the simplest and most popular 1-D chaotic map generation algorithm - logistic map [32] has been employed. The I and Q components of the baseband signal are generated using the logistic map with two different initial conditions. Moreover, the values of chaotic samples are adjusted in order to obtain sequences with zero mean. The generated chaotic signal has a relatively low 6.22 dB PAPR level.

III. Description of Experimental Setup

The block diagram of experimental setup is shown in Fig.4. The complex envelope of RF signal is calculated by Simulink software and sent as digital samples via Universal Serial Bus (USB) port to the USRP, which performs upsampling, digital-to-analog conversion and up-conversion to the carrier frequency. The USRP is able to generate an RF signal with an average power of up to +20 dBm. Moreover, the average power of the generated waveforms is being monitored by a digital oscilloscope and maintained equal during the RF-to-DC conversion measurements. The average input power levels for narrowband and wideband modes of the transmission should differ. According to [8], for 869.4 MHz to 869.65 MHz band up to 500 mW are allowed on the output of transmitter, whereas, for 863 MHz to 868 MHz band only 25 mW are allowed. Therefore, in the first case, the average power at the input of the Powercast P2110B Powerharvester device is attenuated down to 35 μW, and in the second case it is lowered to 1.5 μW to measure the efficiency when low-power wideband input signals are used.

The Powercast P2110B Powerharvester device [29] is chosen as commercially available module with potential to be implemented in wireless sensor node design. The essential part of the module is the RF-to-DC converter. Its performance determines the amount of energy that can be delivered to the load, and so it is the main contributor to the overall module efficiency. The P2110B is soldered on printed circuit board (PCB) with FR4 material that is designed to enable all the necessary connections and measurements. The matching parameter $s11$ is measured at the RF input SubMiniature

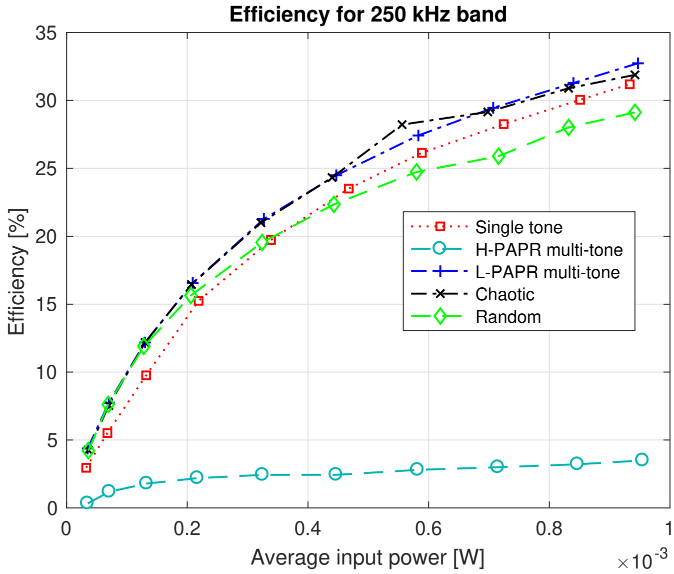

Fig. 5. Efficiency of RF-to-DC conversion in 250 kHz bandwidth mode

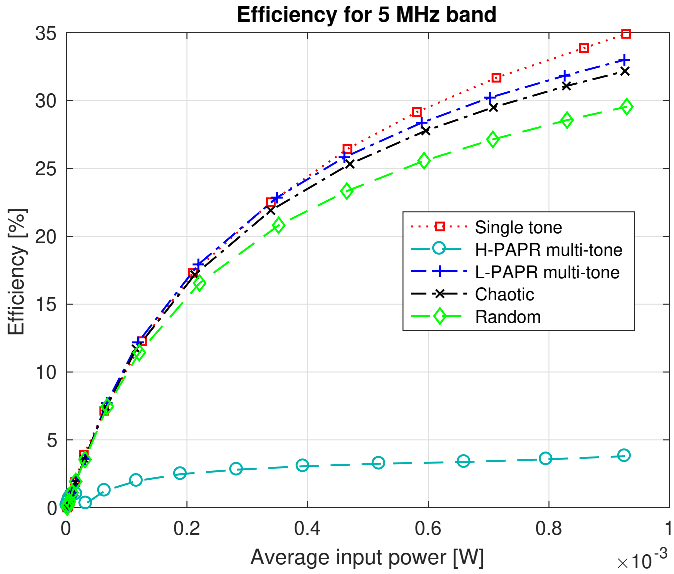

Fig. 6. Efficiency of RF-to-DC conversion in 5MHz bandwidth mode

version A (SMA) connector and it does not exceed -15 dB in frequency band from 800 MHz to 1 GHz [33]. Although it is declared in the data sheet [29] that the optimal operating frequency of the P2110B is 915 MHz, experimental verification revealed acceptable performance also in the frequency band of research interest – from 850 MHz to 900 MHz.

The P2110B module also includes a boost converter, which makes it possible to achieve up to 5.5 V regulated output voltage. However, in this experiment only the performance of the RF-to-DC converter was evaluated. This is because only the input phase deals with a signal obtained from the antenna and different waveform shapes can influence the rectified voltage level and subsequently – the efficiency. The P2110B module has received signal strength indicator (RSSI) output to allow measurements of the received signal level. In RSSI measurement mode the output of the rectifier is connected to the internal sense resistor. The measured value of the sense resistor is 287.8 Ω. During the experiments, the DC voltage on that sense resistor was recorded for different input RF signals.

IV. Measurements of RF-to-DC conversion efficiency

The efficiency of RF power conversion into DC was studied and measured for single-tone, multi-tone with high and low PAPR level, random and chaotic signals. The narrowband (250 kHz) and wideband (5 MHz) signals were tested.

The dependence of efficiency on the average input power level for RF-to-DC power conversion using Powercast P2110B Powerharvester device in narrowband mode is presented in Fig.5. The level of average input power is changed from 35 µW to 950 µW. The obtained efficiency range for observed average input power levels and waveforms is 0.3 – 33%. Higher efficiency results are shown by a chaotic signal and a multi-tone signal with a low PAPR level. The results for both waveforms are very close to each other. For average input power levels less than 400 µW, a random signal shows higher efficiency than a single-tone, but if the average input power is higher, then a single-tone demonstrates higher efficiency than a random signal. For the observed average input power levels, the efficiency of single-tone, multi-tone with a low PAPR, chaotic and random signals grows from 3–4.5 % up to 29–33%, in such a way showing a quite similar performance and correspondence to the specification of Powercast P2110B Powerharvester device [29]. However, a multi-tone signal with a high PAPR level behaves differently. In case of multi-tone waveform with a high PAPR level, the efficiency grows from 0.3% to just 3.5%, presenting the lowest efficiency of RF-to-DC conversion for the observed waveforms. It could be

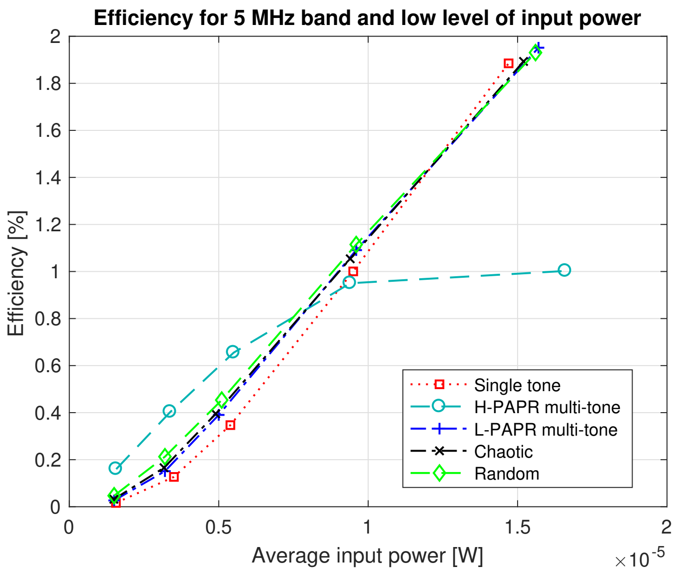

Fig. 7. Zoomed part of low average input power in the graph of efficiency of RF-to-DC conversion in 5 MHz bandwidth mode

explained as follows: at certain level the instantaneous input power becomes larger than the dynamic range of Powercast P2110B Powerharvester device and the conversion efficiency rapidly decreases.

The efficiency measurements for 5 MHz bandwidth are shown in Fig.6. In addition, Fig.7 displays the conversion efficiency in the case of low average input power levels. In Fig.6 the level of average input power is changed from $1.5\,\mu\text{W}$ to $950\,\mu\text{W}$ and the obtained efficiency ranges from 0.02% to 33%. In Fig. 7 are shown low average input power levels up to $16\,\mu\text{W}$ and the range of efficiency is 0.02 – 1.95%. As in case of 250 kHz bandwidth, the dynamics of efficiency growth are quite similar for single-tone, multi-tone with a low PAPR, chaotic and random signals and correspond to the specification of Powercast P2110B Powerharvester device. But a multi-tone signal with a high PAPR level has a very slow growing dynamic of the RF-to-DC conversion efficiency. It is worth to notice that, for average input power levels less than $8\,\mu\text{W}$, a waveform with a high PAPR shows much higher efficiency results (0.16% – 3.8%) compared to the other waveforms. For average input power levels $1.5\,\mu\text{W}$ to $300\,\mu\text{W}$, single-tone, multi-tone with a low PAPR, chaotic and random signals show quite similar efficiency results, except for the range from $1.5\,\mu\text{W}$ to $12\,\mu\text{W}$, where a single-tone waveform demonstrates lower efficiency levels. For the average input power ranging from $200\,\mu\text{W}$ to $950\,\mu\text{W}$, highest efficiency levels are shown by a single-tone signal, then following by a multi-tone with a low PAPR and a chaotic signal, and a random signal demonstrating a slightly lower efficiency. During the measurements, the maximal obtained RF-to-DC conversion efficiency for a single-tone waveform was 35%, for a multi-tone with a low PAPR and a chaotic signal 33% and 32.2%, respectively, and for a random signal it was 29.5%. The difference in dynamics and levels of efficiency among single-tone, multi-tone with a low PAPR, chaotic and random signals is small and the obtained results are very similar to those of the 250 kHz bandwidth case.

V. Conclusions

This research is devoted to the study of waveform influence on the efficiency of radio frequency (RF) to direct current (DC) power conversion performed by the industrially manufactured energy harvesting device Powercast P2110B. Several waveforms were proposed and compared: single-tone, multi-tone with high and low peak-to-average power ratio (PAPR) level, random and chaotic signals. Two bandwidths according to the harvesting device specification and restrictions of International Telecommunication Union (ITU) were selected for the study of RF power conversion efficiency: 869.4 MHz to 869.65 MHz narrowband and 863 MHz to 868 MHz wideband. The proposed waveforms were generated by the Universal Software Radio Peripheral (USRP) device, which was connected to a PC. The generated RF signal from the USRP module was transmitted via cable to the Powercast P2110B Powerharvester device. A digital oscilloscope measured the average power at the input of RF-to-DC converter in order to ensure equal average power of all transmitted waveforms. The influence of average input power level on the conversion efficiency was measured by monitoring the voltage at the output of RF-to-DC converter.

The measurements showed quite similar efficiency levels for single-tone, multi-tone with a low PAPR level, random and chaotic signals in the tested wide- and narrowband modes. When the average input power was higher than $8\,\mu\text{W}$, the efficiency levels were much higher than the efficiency in the case of a multi-tone signal with a high PAPR. In the case of weak input signals with average power below $8\,\mu\text{W}$, the efficiency of a high PAPR signal was higher than for the other waveforms. This noticeable difference between the efficiency results can be explained by an insufficiently high dynamic range of particular energy harvesting device. On other hand, it means that a multi-tone signal with a high PAPR can be beneficial for energy transfer to the low-power devices.

In narrowband mode, a multi-tone with a low PAPR level and a chaotic signal demonstrated slightly better results than the other waveforms, whereas in wideband mode, if the average input power is higher than $300\,\mu\text{W}$, a single-tone waveform showed a bit higher efficiency. It could be explained by the non-uniform efficiency of the Powercast P2110B Powerharvester device in the frequency domain.

It should be noted that, during real wireless power transfer (WPT), the frequency response of the wireless channel is non-uniform and influences the waveform and the average power of the received signal, therefore, influencing the conversion efficiency. In such a way, wideband signals can achieve higher efficiency for WPT in channels with deep fading.

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