Efficiency–Throughput Trade-off of Pulsed RF Waveforms in Simultaneous Wireless Information and Power Transfer

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***Abstract*—We study the receiver efficiency–throughput trade-off in a realistic radio frequency (RF) simultaneous wireless information and power transfer (SWIPT) system. Based on the energy harvesting receiver characteristics, we propose a continuously phase-modulated pulsed RF waveform to achieve maximum receiver efficiency at any input RF power level. We study the impact of varying the duty cycle of a pulsed RF waveform on the receiver efficiency of wireless power transfer along with the throughput of information transfer, and the trade-off thereof. The experiments confirm that a phase-shift keying (PSK) modulated pulsed RF waveform yields superior receiver efficiency than other digital baseband modulations as well as multisine signals despite they are designed particularly for power transfer. However, the optimal efficiency is attained at the expense of a significant loss in throughput due to pulsed transmission, depending on the average input RF power level.**

***Index Terms*—Continuous phase modulation, wireless power transfer, efficiency–throughput trade-off, pulsed RF, simultaneous wireless information and power transfer.**

I. INTRODUCTION

Far-field radio frequency (RF) simultaneous wireless information and power transfer (SWIPT) has received significant research interest [1] due to its potential applications in consumer and industrial Internet-of-Things (IoT). While RF wireless power transfer (WPT) envisions providing IoT sensors a replenishable energy source, the true technical challenge lies in utilizing the same RF spectrum for delivering both information and power to receivers.

The RF energy harvesting (EH) receiver and the information receiver can either be co-located or separate (*cf.* Fig. 1) depending on the network configuration, device complexity and intended application. The concept of RF SWIPT can also be extended to the networking paradigms of wireless powered communication and backscatter networking. In these networks, the energy is harvested in the downlink, stored momentarily and then utilized to transmit information in the uplink [2].

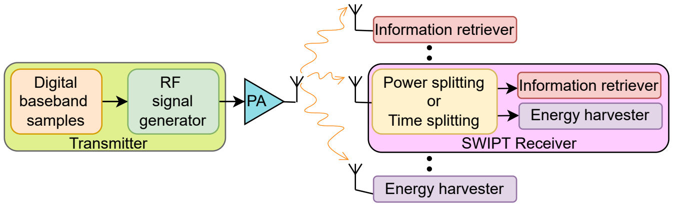

Fig. 1: Block diagram of a typical RF SWIPT system.

While the transmitter side of an RF SWIPT system is similar to that of an RF WPT system, the receiver architecture is different and it plays a crucial role in the overall performance of an RF SWIPT system. A SWIPT receiver with a co-located information receiver and RF energy harvester employs either power-splitting (PS) or time-splitting (TS) technique to direct the received RF signal to the nodes (*cf.* Fig. 1). In PS approach, a fraction (say α) of the total received RF power is directed towards the RF energy harvester, whereas the remaining $1-\alpha$ portion of the power is supplied to the information retriever. In this way, both the nodes can simultaneously access the incoming RF signal. A power splitter is utilized to distribute the incident RF power. In TS approach, the RF EH receiver gets complete access to the incoming RF signal for a part (say τ) of the total transmission time (T), while the communication node receives the incident RF signal for the remaining $T-\tau$ time duration. In practice, an RF switch is employed to implement TS. These two schemes were experimentally compared in [3] and the PS scheme was found to be superior in the input power range relevant to RF EH.

Moving on to SWIPT test-beds, one based on software-defined radios was presented in [3] to study the rate–energy trade-off, while employing a multisine signal for WPT and an orthogonal frequency-division modulation (OFDM) signal for information transfer, which were superimposed by TS and PS schemes. A SWIPT test-bed to evaluate the performance of multitone frequency-shift keying signals was showcased in [4], where the frequency spacing between the tones encodes the information. More such test-beds are reviewed in [2].

In this paper, we explore the use of a single waveform, a phase modulated pulsed RF signal, for both WPT and information transfer, and study the efficiency–throughput trade-off thereof. To the best of authors' knowledge, this is the first work in this regard.

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II. Pulsed RF Modulation for RF SWIPT

In this section, we first present an overview of an RF SWIPT system along with some eminent experimental observations. Later, we study the performance of a digitally modulated pulsed RF waveform for RF SWIPT and focus on the impact of varying the duty cycle of the pulsed RF signal on the power transfer efficiency of an RF EH receiver.

A. A Practical RF SWIPT System

A realistic RF SWIPT system consists of a digital transmitter, an external power amplifier (PA) and the receiver side comprising a communication node and an RF energy harvester. Depending on the network configuration, the communication node and the RF energy harvester could be co-located or separate. Likewise, the network may contain multiple such transmitters and/or receivers. We consider a generic single-input multiple-output system, as depicted in Fig. 1, with atleast one receiver capable of information retrieval as well as RF EH. Nonetheless, the analysis in the sequel holds for any RF SWIPT network configuration.

At the transmitter, the digital baseband samples are converted to an analog signal to modulate an RF carrier. The internal amplification of the RF signal generator is insufficient for wireless transmission, and thus an external PA is required. The amplified signal is then propagated wirelessly through an antenna. At the receiver, the signal captured by the antenna is available either for information decoding or RF EH, or both, based on the PS or TS receiver architecture. The efficiency of RF WPT is determined in terms of the RF-to-direct current (DC) efficiency of the receiver while the efficacy of information transfer is evaluated in terms of the transmission bit-rate (ρ), the receiver bit error rate (BER) and the corresponding throughput (Γ), which is defined as

$$\Gamma = \rho \times (1 - \text{BER}) \tag{1}$$

In practice, the receiver sensitivity of a communication node is much lower (< -80 dBm) than an RF EH receiver (-30 to -15 dBm for commercial energy harvesters) [3], [5], [6]. Consequently, in the power range that is relevant to RF EH (even with the PS scheme), the BER for a communication receiver is practically zero [3]. We confirmed the same through wireless measurements for varying transmitter–receiver separation relevant to RF SWIPT. Thus, the throughput in (1) is effectively equal to ρ. This implies that Γ in RF SWIPT could be maximized by transmitting an information carrying waveform.

Therefore, we shall next focus on determining the information carrying waveforms that can maximize the receiver RF WPT efficiency (η) as well.

B. Continuous Phase-Modulated Pulsed RF Waveform

Let us examine the receiver RF EH efficiency while employing only an information carrying signal, instead of using separate signals for RF WPT and information transfer. We do so by employing the test-bed shown in Fig. 2.

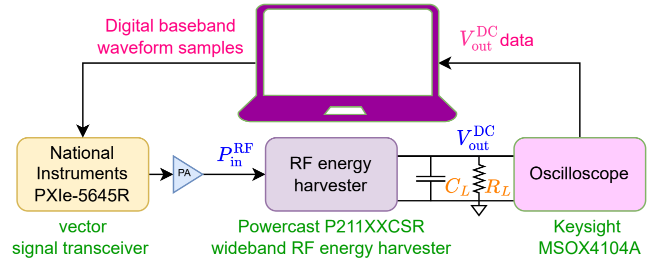

Fig. 2: Block diagram of the RF WPT test-bed utilized for evaluating the receiver efficiency for varying $P_{\text{in}}^{\text{RF}}$.

1) Test-bed: The test-bed is similar to the RF EH part of the RF SWIPT block diagram in Fig. 1, with the exception that here we use a wired medium to have a precise control over the average RF input power ($P_{\text{in}}^{\text{RF}}$) at the input port of the RF energy harvester. This allows us to determine η accurately at each $P_{\text{in}}^{\text{RF}}$. Here, a computer generates the digital baseband waveform samples and sends it to a vector signal transceiver for analog RF transmission. The RF signal, on amplification by an external PA, is transmitted towards the RF energy harvester, comprising a matching network and a diode-based rectifier network. The oscilloscope measures the DC root mean square voltage ($V_{\text{out}}^{\text{DC}}$) across a load capacitor C_{L} and a load resistor R_{L}. The computer retrieves the $V_{\text{out}}^{\text{DC}}$ value from the oscilloscope and computes the average harvested DC power ($P_{\text{out}}^{\text{DC}}$) and the corresponding η, which is given as

$$\eta = \frac{P_{\text{out}}^{\text{DC}}}{P_{\text{in}}^{\text{RF}}} = \frac{(V_{\text{out}}^{\text{DC}})^2}{R_{\text{L}}\, P_{\text{in}}^{\text{RF}}} \tag{2}$$

2) Proposition: We begin by experimentally evaluating η for a continuous wave (CW). In accordance with the observation in [7], our measurements reveal that an M-level phase-shift keying (PSK) modulated RF waveform ($M = 2^n$, $n \in \mathbb{P}$) yields the same η as a CW. This result can be attributed to the fact that an M-PSK modulated RF signal is still a CW, with phase transitions at symbol rate. The aforementioned experimental observation can be further extended to any continuously phase-modulated RF signal, where the envelope of the RF signal does not change with time. We further improvise this concept and apply it to a pulsed RF signal with duty cycle δ. We propose that: *given a continuously phase-modulated RF signal ($\delta = 1$) with $P_{in}^{RF} = \bar{P}_{\text{in}}^{\text{RF}}$ and corresponding receiver efficiency η, a continuous phase modulated pulsed RF signal with duty cycle δ achieves the same η, albeit at a lower $P_{in}^{RF} = \delta\, \bar{P}_{\text{in}}^{\text{RF}}$*. The reasoning is as follows. A pulsed RF signal with duty cycle δ and input power $\delta\, \bar{P}_{\text{in}}^{\text{RF}}$ has the same amplitude as a CW with input power $\bar{P}_{\text{in}}^{\text{RF}}$. Consequently, the pulsed wave signal, during its absolute pulse duration, attains the same $V_{\text{out}}^{\text{DC}}$ as a CW, at a lower $P_{\text{in}}^{\text{RF}}$. As a result, the pulsed signal yields the same efficiency as a CW, at a lower $P_{\text{in}}^{\text{RF}}$ depending on its duty cycle δ.

The primary advantage of adopting a phase-modulated pulsed RF signal is that the RF EH receiver could be operated at the maximum η for any given $P_{\text{in}}^{\text{RF}}$, by varying just δ of

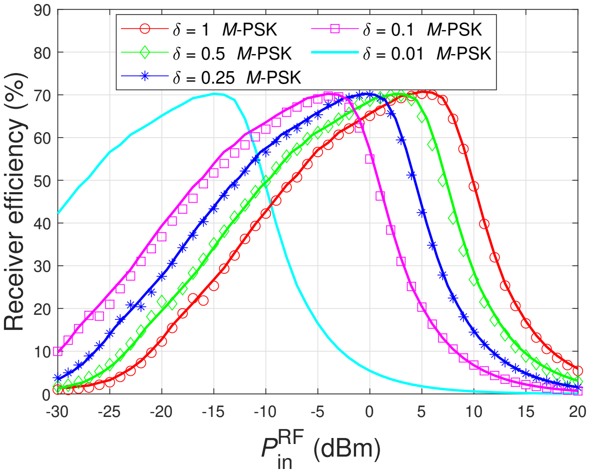

Fig. 3: Receiver efficiency of the RF energy harvester for M-PSK modulated RF signal and phased RF signals, for varying $P_{\text{in}}^{\text{RF}}$ and different duty cycles, with $R_{\text{L}} = 10\ \text{k}\Omega$. The solid lines represent the predictions of the proposition, while the markers represent measurements. The discontinuities in the measurements at low $P_{\text{in}}^{\text{RF}}$ are due to resolution limitations of the oscilloscope.

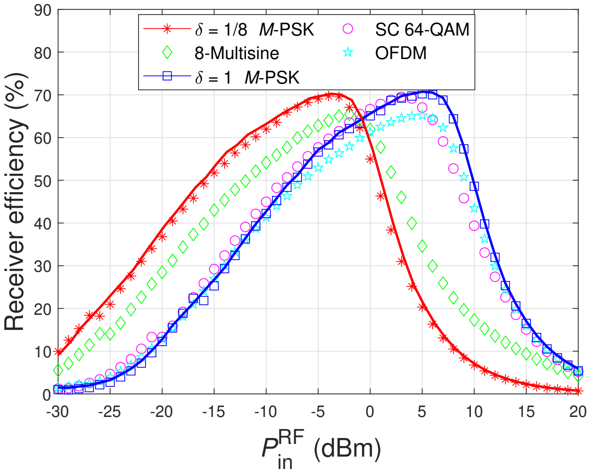

Fig. 4: Comparison of receiver efficiency of a M-PSK modulated pulsed RF signal with a WPT-specific multisine signal and other information carrying signals, for varying $P_{\text{in}}^{\text{RF}}$ and $R_{\text{L}} = 10\ \text{k}\Omega$. The markers represent measurements, while the solid lines represent estimates based on the proposition for the continuously phase-modulated pulsed waveforms.

the transmitted pulsed wave. The benefit of operating at an enhanced η, however, comes with an efficiency–throughput trade-off. We present these in more detail in the next section.

III. MEASUREMENT RESULTS AND DISCUSSION

In this section, we first present measurement results that corroborate the proposition in Section II-B2 and also compare the performance of a phase-modulated pulsed RF signal with other RF WPT and information transfer signals. Later, we discuss the associated efficiency–throughput trade-off.

We evaluated the BER using Universal Software Radio Peripheral (USRP) transceivers at 915 MHz and 2.45 GHz in the ISM and WiFi frequency bands, respectively and found the BER to be effectively zero at $P_{\text{in}}^{\text{RF}}$ levels relevant to RF WPT. The BER of phase-modulated pulsed RF signals would, thus, also be zero since for a given $P_{\text{in}}^{\text{RF}}$, the pulsed RF signals have higher amplitude, and therefore higher signal-to-noise ratio. Next, the hardware configuration of the test-bed utilized to determine η is depicted in Fig. 2. The oscilloscope probes with ≈ 15 pF capacitance act as C_{L} without an external capacitor, while we employ external $3.3\ \text{k}\Omega$ and $10\ \text{k}\Omega$ resistors as R_{L}. The receiver efficiency is evaluated for frequency band 3 of the Powercast multiband energy harvester [5] at 915 MHz center frequency, by varying $P_{\text{in}}^{\text{RF}}$ from -30 dBm to 20 dBm in one decibel steps. The M-PSK signal, henceforth, represents 4-PSK and 8-PSK modulations in the results.

A. *Receiver Efficiency of Phase-Modulated Pulsed RF Signal for Varying Duty Cycle*

We begin by measuring η for an M-PSK modulated RF wave ($\delta = 1$) for different $P_{\text{in}}^{\text{RF}}$. Then using piecewise interpolation, we obtain a continuous estimate for η in terms of $P_{\text{in}}^{\text{RF}}$ and use this as a benchmark to access the efficacy of our proposition. The results are shown in Fig. 3. It is apparent that the estimate accurately matches with the measurements for all δ values. It is evident in Fig. 3 that the plots for $\delta = 0.5, 0.25$ and 0.1 are similar (minor variations due to measurement inaccuracies) to the plot for $\delta = 1$, but shifted to left by $10 \cdot \log_{10}\delta$. This corroborates our proposition in Section II-B2. The proposition also allows us to estimate η for lower values of δ such as 0.01, for which the measurements are not reliable due to PA limitations.[1]

Moreover, it is evident in Fig. 3 that reducing δ also reduces the $P_{\text{in}}^{\text{RF}}$ at which the peak η occurs. The peak η corresponds to the $P_{\text{in}}^{\text{RF}}$ that yields receiver saturation (diode breakdown). As δ is reduced, the peak instantaneous input voltage for a given $P_{\text{in}}^{\text{RF}}$ increases. It implies that the peak voltage corresponding to receiver saturation is achieved at a lower $P_{\text{in}}^{\text{RF}}$ by reducing δ which explains the observation. The results presented in Fig. 3 are valid for any given load resistor ($R_{\text{L}} = 10\ \text{k}\Omega$ in this case). It is possible to attain the peak η at a different $P_{\text{in}}^{\text{RF}}$ with the same M-PSK signal by varying R_{L}. For example, a low duty cycle M-PSK signal can attain the peak η at a higher $P_{\text{in}}^{\text{RF}}$ if a low value R_{L} is connected as the load.

B. *Comparison with Multisines and Other Information Signals*

We compare the η performance of an M-PSK modulated pulsed RF signal with multisine signals ($2, 4, 8, 16$-multisine) since these are considered to be optimal, specifically for RF WPT [2], and with information carrying ($\delta = 1$) single-carrier

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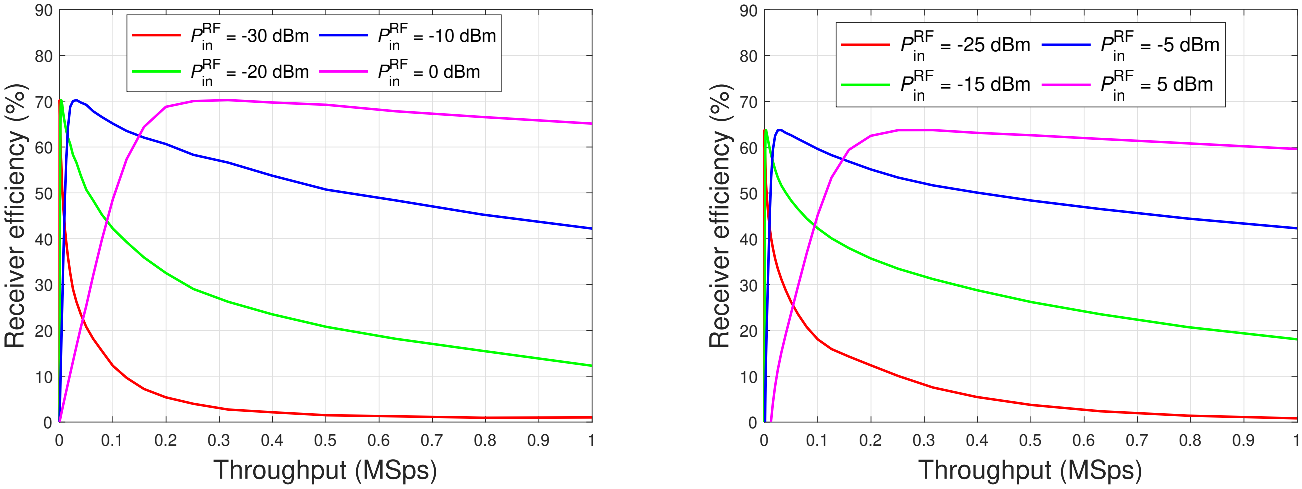
[1] The proposition is also valid for other rectifier circuits (i.e., matching networks and diodes), other load resistors and other frequency bands [8].



(a) for a 10 kΩ load resistor

(b) for a 3.3 kΩ load resistor

Fig. 5: Efficiency–throughput trade-off for M-PSK modulated pulsed RF waveforms in a SWIPT system. Along with the throughput, the horizontal axis also represents the corresponding duty cycle of the pulsed RF waveform.

(SC) 64 quadrature amplitude modulation (QAM), and OFDM M-PSK and OFDM 64-QAM signals. The results are depicted in Fig. 4. We showcase the measurements for an 8-multisine signal and compare it with $\delta = 1/8$ M-PSK pulsed RF, since these two signals have the same peak-to-average-power-ratio of 16. It is clear that the M-PSK pulsed RF signal clearly outperforms the multisine signal. For $P_{\text{in}}^{\text{RF}} > 0$ dBm, where the 8-multisine has higher η than the $1/8\,M$-PSK pulsed RF, we can opt for a higher δ value to obtain greater efficiency than the 8-multisine. This holds true for all the multisine signals.

Next, it is evident in Fig. 4 that the M-PSK signal also yields higher η than SC 64-QAM and OFDM signals (the receiver efficiency of OFDM signal is found to be independent of the underlying baseband modulation). In fact, so long as the M-PSK modulated RF signal has the highest η ($\approx 71\%$ for frequency band 3) amongst all signals at some $P_{\text{in}}^{\text{RF}} = \hat{P}_{\text{in}}^{\text{RF}}$, the M-PSK pulsed RF signal can yield the same maximum η at any $P_{\text{in}}^{\text{RF}} < \hat{P}_{\text{in}}^{\text{RF}}$ by varying just the duty cycle δ. The M-PSK pulsed RF signal, thus, outperforms multisine signal as well as other information signals at all $P_{\text{in}}^{\text{RF}}$ levels.

C. *Receiver Efficiency–Throughput Trade-off*

In a realistic SWIPT system employing phase-modulated pulsed RF waveforms, the transmitter would initially transmit a CW signal to the receiver, in order to receive a feedback about the $P_{\text{in}}^{\text{RF}}$ level at the receiver input. The transmitter then varies δ accordingly (but not necessarily chooses δ that maximizes η) and transmits a phase-modulated pulsed RF signal towards the receiver for SWIPT. Let us now discuss the trade-off that needs to be dealt with while employing phase modulated pulsed RF waveforms with the aid of Fig. 5.

In Fig. 5, we showcase the receiver efficiency–throughput trade-off for different $P_{\text{in}}^{\text{RF}}$. When the duty cycle of a phase modulated pulsed RF signal reduces by a factor δ, the throughput also reduces by the same factor since there is no transmission for $1 - \delta$ portion of the time period of the signal. We observe in Fig. 5 that an increase in the throughput (due to an increase in δ) results in a decrease in η. This implies that the transmitter needs to prioritize either η gain or throughput. For example, in the case of IoT SWIPT sensors that require extremely low throughput, the transmitter could reduce δ as much as possible to attain higher η or even the maximum. Furthermore, we observe that for $P_{\text{in}}^{\text{RF}} \geq -10$ dBm, the efficiency initially increases with throughput, reaches a maximum value and then starts reducing. In such scenarios, the transmitter would reduce the duty cycle only until the peak efficiency is achieved, since any further reduction in δ would reduce both efficiency and throughput. The efficiency–throughput trade-off provides a scope for developing scheduling protocols depending on the SWIPT network type or configuration.

IV. CONCLUSION

This paper experimentally studies the receiver efficiency of phase-modulated pulsed RF waveforms for RF SWIPT. We show that a phase-modulated pulsed RF signal can achieve the same receiver efficiency as a phase-modulated continuous wave, albeit at a lower input RF power level that is determined by the duty cycle of the pulsed waveform. The experimental results showcase that a phase-modulated pulsed RF signal attains higher receiver efficiency than multisines as well as other information signals, while effectively maintaining a zero bit error rate. The analysis of the efficiency–throughput reveals that while reducing the duty cycle of a phase-modulated pulsed RF signal enhances the receiver efficiency, it is detrimental to the throughput of the RF SWIPT system. This trade-off could be utilized to develop application-specific scheduling algorithms for an RF SWIPT system.

REFERENCES

[1] T. D. Ponnimbaduge Perera *et al.*, “Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 264–302, Firstquarter 2018.

[2] B. Clerckx, J. Kim, K. W. Choi, and D. I. Kim, “Foundations of wireless information and power transfer: Theory, prototypes, and experiments,” *Proc. IEEE*, vol. 110, no. 1, pp. 8–30, 2022.

[3] J. Kim, B. Clerckx, and P. D. Mitcheson, “Experimental analysis of harvested energy and throughput trade-off in a realistic SWIPT system,” in *Proc. IEEE Wireless Power Transfer Conf. (WPTC)*, Jun. 2019.

[4] S. Claessens, N. Pan, D. Schreurs, and S. Pollin, “Multitone FSK modulation for SWIPT,” *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 5, pp. 1665–1674, May 2019.

[5] Powercast. P211XXCSR-EVB Datasheet. [Online]. Available: “https://www.powercastco.com/documentation/p21xxcsr-evb-datasheet/”, Accessed on 21 Apr. 2023.

[6] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, 2013.

[7] N. Ayir, T. Riihonen, M. Allén, and M. F. Trujillo Fierro, “Waveforms and end-to-end efficiency in RF wireless power transfer using digital radio transmitter,” *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 3, pp. 1917–1931, Mar. 2021.

[8] N. Ayir and T. Riihonen, “Practical waveform-to-energy harvesting model and transmit waveform optimization for RF wireless power transfer systems,” *IEEE Trans. Microw. Theory Techn.*, 2023, under review.