SWIPT with Biased ASK Modulation and Dual-Purpose Hardware

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***Abstract*—With the emergence of IoT it becomes important to make extremely small batteryless devices that contain both circuitry for data and power reception. While simultaneous transmission of data and power, making optimal use of the scarce wireless spectrum, has been proposed before, it is also possible to consider dual-purpose hardware to decode data and harvest power from the simultaneous wireless information and power transfer (SWIPT) waveform. In this paper we study the trade-off between power and data reception for an integrated receiver. It is shown that the hardware can behave as a rectifier or envelope detector, depending on the excitation's symbol rate and the rectifier's low pass filter's cut-off frequency.**

***Index Terms*—Modulation, Receiver architecture, SWIPT, WPT.**

I. Introduction

Simultaneous wireless information and power transfer (SWIPT) is very useful in IoT applications for avoiding a lot of large batteries. In SWIPT literature, wireless power transfer (WPT) researchers focus on rectifier power conversion efficiency [1],[2]. Wireless information transfer (WIT) focusses on system model designs and energy budget constraints [3]. Neither consider the mutual impact of both subsystems.

Interestingly, when relying on amplitude modulation, it is possible to use the rectifier as information receiver, de facto taking care of the conversion from RF to baseband without the need of a power consuming local oscillator. When considering an integrated power and information receiver (or rectifier), it can not be jointly optimized for power and information, as there is a trade-off between both.

The main contribution of this paper is the joint modelling of information and power reception performance of an integrated receiver circuit with dual-purpose hardware (HW), and the exploration of the trade-off between both for a typical class of SWIPT signals. We derive a design guideline of the waveform and rectifier hardware for a correct information transfer rate.

This scheme can be used in systems where either the transmitter controls its waveform and decides to charge or transfer information to the receiver, or the receiver node can vary its lowpass filter's resistor or capacitor gradually, depending on whether its battery has to be charged or it is ready to decode information.

The rest of the paper is organized as follows. Section II introduces the considered theoretical model to analyse the dual-purpose HW's behaviour for different excitations. The theoretical model and assumptions will be introduced, followed by an introduction to signal's parameters and system trade-offs. Then, experimental results are used to validate the theoretical trade-offs in Section III. Finally, conclusions will be drawn in Section IV.

II. System model

A. Rectifier Model

A typical rectifier consists of a diode, a low pass filter and some matching networks. The theoretical analysis in this paper starts from a simple system model, shown in Fig. 1. In this theoretical model, matching is considered perfect. In most WPT rectifiers the diode is of Schockley type because of its low forward turn-on voltage. In this paper's model, the diode is approximated by a zero-threshold or switch. The rectifier's

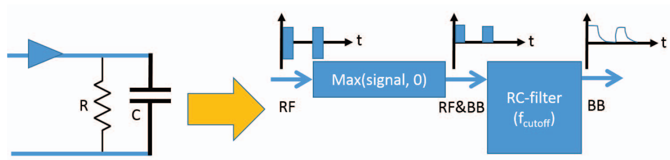

Fig. 1: Model of the system.

low-pass filter consists of a capacitor and resistor, for which the cutoff frequency is given by:

$$f_{\text{cutoff}} = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}. \tag{1}$$

The individual impacts of the rectifier and capacitor are not considered since the diode's behaviour is considered independent of the low pass filter, neglecting the effect of loading.

B. Signals

Since an envelope detector can only detect amplitudes, amplitude shift keying (ASK) of various orders M is used. In typical M-ASK modulation, the lowest amplitude is zero. However, such symbols would not transfer any energy. Hence, a biased version of ASK is considered where the ratio between minimum and maximum amplitude A_{ratio} is also varied, starting at zero, while average symbol power is kept fixed. Biased 4-ASK is illustrated in Fig. 2 for different A_{ratio} where the blue dots represent the amplitudes in the scheme and the red lines represent the minimum power that each symbol has, which increases with increasing A_{ratio}. Fig. 3 shows the minimum amplitude A_{min}, maximum amplitude A_{max} and noise margin for (biased) M-ASK modulation. Different modulations are compared for fixed average symbol power. A_{min} increases, A_{max} decreases and noise margin decreases for increasing A_{ratio}.

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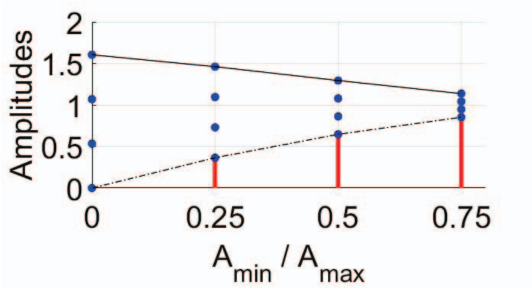


Fig. 2: Biased 4-ASK for different A_{ratio} for fixed average symbol power with symbol amplitudes (blue), minimum symbol power (red), $A_{\max}$ (full black) and $A_{\min}$ (dotted black).

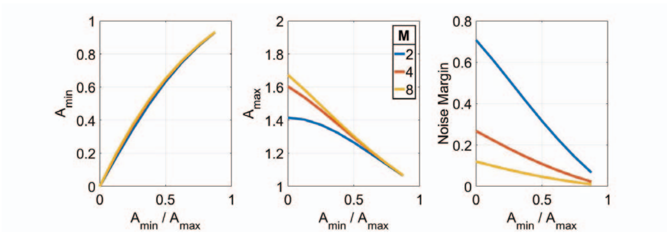


Fig. 3: $A_{\min}$, $A_{\max}$ and noise margin for different A_{ratio} and M, for fixed average symbol power.

C. System analysis

A simple rectifier has a first order low-pass filter at its output, characterised by (1). The filter's time constant τ represents the speed by which the filter charges or discharges. When for example a constant excitation with amplitude $A_{\max}$ is turned off at t_0, the rectifier's output will behave as follows:

$$A(t) = A_{\max} \times \exp \frac{-(t-t_0)}{\tau}, \quad t \geq t_0. \tag{2}$$

When the filter is slow relative to its excitation, output voltage will be reasonably stable, which is desired for WPT. For information transfer however, the output will be sampled at periodic moments in time. Hence, the filter should be able to follow the excitation's envelope in a way that the correct amplitude modulated symbols are obtained when sampled. Worst case, a symbol with maximum amplitude is followed by a symbol with minimum amplitude. To be able to detect the small symbol, the filter has to discharge fast enough so the small symbol's decision boundary is crossed after T seconds. We define T as the information symbol duration, or the inverse of the symbol rate f_{symbol}. This is shown in Fig. 4. The green line shows the filter's output and the blue lines determine the ASK amplitude levels (filled) and decision boundaries (dotted). The equally spaced orange lines indicate where the amplitudes of the output symbols are determined and the purple dots represent symbol amplitudes.

This WIT requirement can be formulated mathematically for an ASK modulated CW by considering the filter's discharging behaviour expressed by (2) and the equation for the decision boundary for the smallest symbol. The expression for the

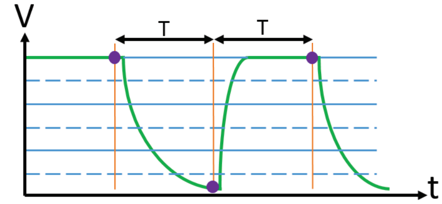


Fig. 4: Output of low-pass filter for pulse train excitation (green) with amplitude sampling moments (orange), symbol amplitudes (blue filled) and decision boundaries (blue dotted).

timing constraint is found by comparing the worst case output level at sampling time and the smallest decision boundary:

$$\begin{aligned} A_{\max} \times \exp \frac{-T}{\tau} &\leq A_{\min} + \frac{A_{\max} - A_{\min}}{2(M-1)}, \\ \frac{T}{\tau} &\geq -ln\left(\frac{A_{\min}}{A_{\max}} + \frac{A_{\max}-A_{\min}}{A_{\max}} \times \frac{1}{2(M-1)}\right), \\ F_{\text{ratio}} = \frac{f_{\text{symbol}}}{f_{\text{cutoff}}} &\leq \frac{-2\pi}{ln\left(\frac{A_{\min}}{A_{\max}} + \frac{A_{\max}-A_{\min}}{A_{\max}} \times \frac{1}{2(M-1)}\right)}, \end{aligned} \tag{3}$$

using (1). This theoretical upper limit is shown in Fig. 5 for different A_{ratio} and M. Fig. 5 and (3) lead to two conclusions.

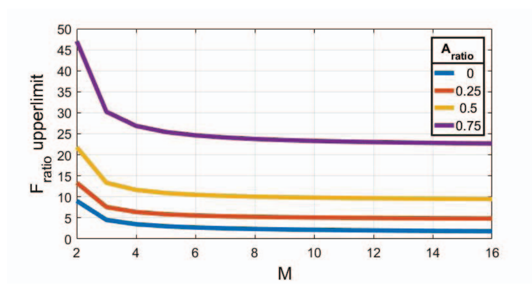


Fig. 5: Theoretical upper limit for F_{ratio}, for (biased) M-ASK modulated SWIPT.

The upper limit decreases for increasing M. This is due to the decreasing noise margin and hence stricter requirement for discharge speed. The second conclusion is the increase of the upper limit for increasing A_{ratio}. This is because $A_{\min}$ and $A_{\max}$ are closer together and the capacitor is allowed to discharge less.

In practice, the hardware will behave differently from our simple model as we neglected many non-idealities and parasitic effects. The RC filter will cause a loading effect on the diode, causing attenuation of the amplitude levels. A pure attenuation will have no effect on the described upper limit since (3) only contains amplitude ratios. Also, the originally uniformly spread amplitude levels of the ASK modulation will deform as the diode's model is exponentially shaped.

III. Experimental analysis

A. Setup

In the measurement setup, depicted in Fig. 6, the Vector Signal Transceiver (VST) (NI PXIe-5645R) is used to generate the M-ASK modulated signals. Its output is connected to the rectifier. The rectifier is based on a single-diode circuit topology with an RC-lowpass filter at its output as described in [4] with f_{cutoff} equal to 192.92 kHz. The rectifier's baseband output is connected back to the VST where the signal is sampled to analyse transient behaviour of the output voltage. Since the VST's input port is 50 Ω terminated, it is connected in series with the load resistor to limit the impact on the rectifier behaviour. This creates a voltage divider which is compensated for in software.

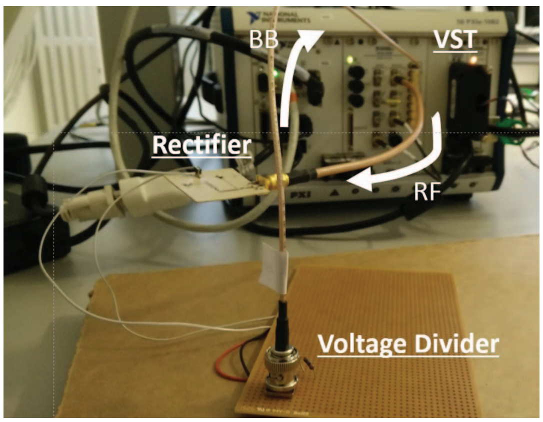


Fig. 6: System setup with dual-purpose rectifier, the VST as RF signal generator and BB interpreter and the voltage divider to connect the VST to the rectifier's output.

B. Measurement results

Fig. 7 shows the measurement results for an unbiased ASK modulated CW with varying M. WIT performance starts to decrease at smaller F_{ratio} for increasing M, which is in line with the theoretical limit, described by (3). Deviations are mainly causes by noise in the system from which higher order modulations suffer more as shown by the calculated noise margin in Fig. 3. Fig. 8a shows the measurement results for a 2-ASK modulated CW with varying A_{ratio} from 0 up until 0.5. WIT performance starts to decrease rapidly for F_{ratio} of 9, 14 and 20 for A_{ratio} of 0, 0.25 and 0.5 respectively, which corresponds to the theoretical limit, described by (3). Fig. 8b shows that a higher A_{ratio} improves WPT efficiency, and that a higher F_{ratio} improves the rectifier power harvesting efficiency. By comparing Fig. 8a and 8b, we see that there is a trade-off between power and information transfer efficiency, depending on F_{ratio}. The downside of increasing A_{ratio} is the decreasing noise margin as shown in Fig. 3 and thus drop in WIT performance for noisy environments.

The measurement results show a realisable throughout close to 10×192.92 kbps at BER = 10^3 for an unbiased 2-ASK modulated CW excitation on the used rectifier. Hence, rectifier designs with large f_{cutoff} enable larger WIT throughputs but require larger bandwidths for WPT.

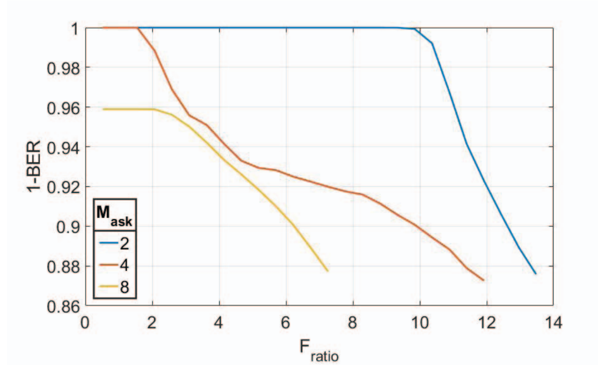
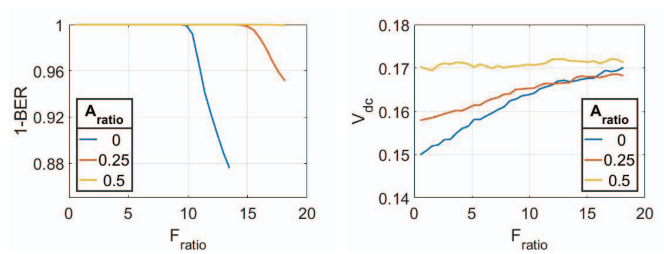


Fig. 7: 1-BER measurement results for 2-, 4- and 8-ASK modulated CW with A_{ratio} of zero.



(a) (b)

Fig. 8: Measurement results of 1-BER (a) and V_{dc} (b) for 2-ASK modulated CW with variable A_{ratio}.

IV. Conclusion

Our simulations and experimental results have shown that rectifier hardware can be considered dual-purpose for specific excitations and used both for energy harvesting and information decoding. The HW's behaviour is determined by the ratio $f_{\text{symbol}}/f_{\text{cutoff}}$. A low symbol rate enables the HW to be used as information decoder. For such a signal, output power ripple will be high but it is shown to enable a throughput of 1.92Mbps. Increasing the symbol rate will results in a more stable output power at the cost of less throughput. Combined WIT and WPT is enabled by varying the amplitude ratio.
Hence, the proposed (biased) M-ASK scheme poses a trade-off between WIT and WPT, determined by the modulation order, amplitude ratio and symbol rate.

Acknowledgement

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