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► **To cite this version:**

Achille Fumtchum, Florin Hutu, Pierre Tsafack, Guillaume Villemaud, Emmanuel Tanyi. High Efficiency Rectifier for a Quasi-Passive Wake-up Radio. ISSCS 2019 - 14-th International Symposium on Signals, Circuits and Systems, Jul 2019, Iasi, Romania. pp.1-4, 10.1109/ISSCS.2019.8801754 . hal-02138667

HAL Id: hal-02138667

<https://hal.science/hal-02138667v1>

Submitted on 24 May 2019

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High Efficiency Rectifier for a Quasi-Passive Wake-up Radio

Achille Fumtchum², Florin Hutu¹, Pierre Tsafack², Guillaume Villemaud¹ and Emmanuel Tanyi²

¹Univ Lyon, INSA Lyon, Inria, CITI, F-69621, Villeurbanne, France

²University of Buea, Buea, Cameroon

Email: florin-doru.hutu@insa-lyon.fr

Abstract—The ubiquity of wireless sensor networks (WSN), as well as the rapid development of the Internet of Things (IoT), impel new approaches to reduce the energy consumption of the connected devices. The wake-up radio receivers (WuRx) were born in this context to reduce as much as possible the energy consumption of the radio communication part. This article aims at proposing a low-cost, high-efficiency rectifier to improve a quasi-passive WuRx performance in terms of communication range. By optimizing the wideband matching circuit and the proposed rectifier's load impedance, the sensitivity was increased by 5 dB, corresponding to an increase of the communication range (13 meters in free space).

I. INTRODUCTION

IoT market is constantly evolving. According to market studies [1], this growth is estimated at 10.8% per year and will be able to reach a park of 35 billion connected objects in 2030. In addition to the size requirements, the connected objects are facing the issue of energy consumption. In this context, energy saving mechanisms have been developed, and specifically the wake-up radio concept appeared. WuRx is a very low power secondary radio that is attached to the main radio receiver. The main radio is powered off when there is no information to be transferred. As soon as some information should be transmitted, the WuRx receives a wake-up signal from the device initiating the communication and then decides to switch on the main radio receiver.

As a comparison, another strategy to save energy at the radio interface level is to operate the radio front-end by duty cycling. According to this principle, the radio front-end runs for one cycle and stops the next one. This technique is less efficient because, for some active cycles, the main radio does not receive any information. It also happens that the transmission begins during the standby cycle and consequently, the device initiating the communication should retransmit its communication demand thereby increasing the network's latency. Consequently, duty-cycled strategies are inefficient in terms of energy consumption and latency for sporadic communications and they cannot be used for critical applications that require high reliability.

One of the WuRx schemes is to transmit the identifier as a frequency spectrum pattern [8]. In this way, the identification may be performed by simple analog circuitry and consequently, the WuRx energy consumption is reduced. The work done so far on the rectifier's design was essentially based on the use of L matching circuits, which limits them to operate on a narrow frequency band. The solution proposed in this paper is to use a wideband, high efficiency rectifier in order to increase the

communication range of such quasi-passive WuRx compared to the initial architecture [8]. Theoretically, the use of matching network with three degrees of freedom (in Pi or in T), allows obtaining a wider bandwidth. Moreover, the butterfly stub in microstrip technology allows obtaining a robust rectifier, having low variation of the electrical characteristics (central frequency and bandwidth) with respect to the technology dispersion.

The rest of this paper is organized as follows: in section II, a non-exhaustive literature review is presented by pointing out the different WuRx architectures. Section III describes the concerned quasi-passive wake-up radio identified by the means of a frequency fingerprint and section IV gives the high-efficiency rectifier characteristics. The performance improvement is demonstrated by the means of circuit-system co-simulations performed by using Keysight's ADS Software. The conclusion and envisaged future work are presented in section V.

II. STATE OF THE ART

As far as energy consumption is concerned, the literature is presenting passive and active WuRx. Passive wake-up radios are those which are exempted from a classical energy source (battery), similar to the ones presented in [2, 3] and which are using the wake-up signal itself as the energy source. Otherwise, active wake-up radios [4, 5, and 6] are based on the use of a classical energy source bringing them a better performance (sensitivity, robustness, etc.) compared to the passive WuRx.

Depending on the operating principle, there are several wake-up radio architectures. The remarkable ones are the super-heterodyne, injection-locking oscillator (ILO) based, super-regenerative, and envelope detector based ones. The super heterodyne receiver has a classical architecture with frequency translation stages that allows good performance in terms of selectivity and sensitivity to the detriment of an energy consumption increase.

In the ILO based wake-up radio receiver, the local oscillator locks on the injection signal which is the received wake-up message transmitted by FSK (Frequency Shift Keying) modulation. The oscillator locks on the received signal and demodulates the FSK signal which is transformed into an OOK (On-Off Keying) one [4].

The super-regenerative wake-up radio operation is based on the start-up transient characteristic of a local oscillator (LO). The LO's output depends on the wake-up signal and on a low-frequency periodic signal provided by a quench generator which modulates the LO's bias current. Like any super-regenerative

receiver, the proposed architecture in [5] has a good sensitivity. Moreover, the entire architecture can be integrated.

The envelope detector is intensively employed for the passive WuRx. This kind of WuRx is using a diode based envelope detector to demodulate a radio frequency input signal (OOK) and to provide its envelope by the means of a parallel RC circuit.

Another classification that can be found in the literature [21] takes into account the recipient of the wake-up signal. Accordingly, there are ID-based WuRx characterized by specific address for the communicating object's (node) identification [22], and broadcast wake-up signal based, in which all nodes in neighborhood receive the same wake-up signal.

The classification related to the communication channel of the main radio and of the WuRx is mentioning in-band radio for which the main radio and WuRx radio used the same frequency, and out-of-band radio that recognizes two different bands of frequencies [23]. The types of WuRx are also related to their implementation technologies such as CMOS and discrete components.

Wake-up radios are employed in a large number of applications such as Industrial, Scientific, and Medical (ISM), aviation, wireless body area network (WBAN), smart metering, etc. In Table I some wake-up radios are presented with their main characteristics.

TABLE I. SOME WAKE-UP RADIOS AND THEIR MAIN CHARACTERISTICS

Ref.	Freq.	Modulation	Power supply	Sensitivity	Year
[4]	868 MHz	OOK	13 nW	-54 dBm	2018
[11]	5.8 GHz	OOK/FSK	470 μ W	-92.5 dBm	2018
[12]	550 MHz	OOK	222 nW	-56.4 dBm	2017
[13]	868 MHz	FSK	70.2 μ W	-61 dBm	2017
[14]	433 MHz	OOK FSK PSK	54 μ W	-80 dBm -78 dBm -77 dBm	2016
[5]	900 MHz	OOK	320 μ W	-87 dBm	2016
[6]	2.4 GHz	OOK	7 μ W	-80 dBm	2015
[2]	915 MHz	OOK	0 μ W	-43 dBm	2015
[18]	868 MHz	OOK	1.276 μ W	-55 dBm	2014
[19]	433 MHz	PWM	278 nW	-51 dBm	2011
[20]	915 MHz	OOK	20 μ W	-69 dBm	2007

From Table I, it can be remarked that the most employed modulation is OOK as the corresponding demodulator is simple i.e. generally an envelope detector (rectifier). In general, when designing the WuRx, there is a trade-off between sensitivity and energy consumption that must be respected.

III. QUASI PASSIVE WAKE-UP RADIO

Another type of wake-up radio strategy was proposed in [8] and experimentally validated in [9]. It is based on the use of a wideband multi-carrier signal to form the identifiers. The architecture of this receiver is presented in Figure 1.

The received signal is divided into two equal parts by the means of a power divider. Two banks of band pass filters, one on each branch (direct and complementary), followed by envelope detectors are transforming the received signal into a proportional DC voltage.

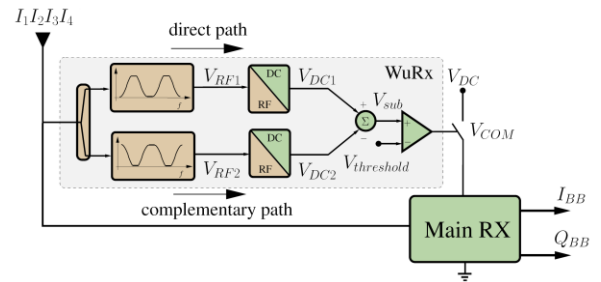


Figure 1. Quasi-passive WuRx architecture.

The filter bank on the direct path has the same frequency shape as the identifier and the filter bank on the complementary path, a complementary shape (a pass-band filter on the complementary path where there is a stop band filter on the direct path and vice versa). This kind of filtering allows that the power level of the signal at the output of the direct path is higher than the power level of the signal at the output of the complementary path when the identifier is received. Consequently, the envelope detectors at the output of the two filter banks are transforming the RF signals (V_{RF1} and V_{RF2}) into corresponding voltages (V_{DC1} and V_{DC2}).

The two DC voltages are applied at the input of an operational amplifier based subtractor, which also plays the role of a voltage amplifier. The subtractor's output voltage is compared to a threshold voltage by using a Schmitt trigger. The reference level $V_{threshold}$ is tuned in such a way that, if the identifier is received, the voltage V_{sub} at the output of the subtractor become superior to $V_{threshold}$ and V_{COM} drives the main receiver's power supply to ON.

The identifier to address this wake-up receiver is formed based on an OFDM signal. The total number of subcarriers in the OFDM signal is divided into N groups. The number N is chosen by respecting technological constraints, notably taking into account the feasibility of filters' quality factors. If random data is sent on a subgroup of subcarriers, the power level on the sub-band is increasing which corresponds to a logical "1". When no data is sent, on a subgroup of subcarrier, the power level at the noise floor and this codes a logical "0". Consequently, $2^N - 2$ possible combinations can be used as identifier.

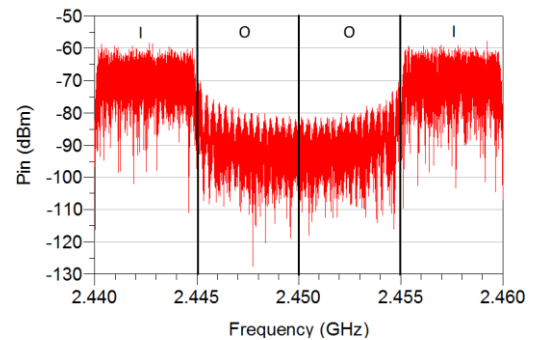


Figure 2. An example of identifier (1001).

Identifiers should accomplish several conditions. Firstly, an identifier should provide an energy level on the direct path higher than the one provided at the complementary path. The second condition is that the eventual surrounding signals should not be able to provide enough energy to activate the WuRx. The last

condition is that only the assigned identifier is able to activate the WuRx. These three conditions help to avoid false wake-ups. By combining these conditions, it comes that, out of 14 possible identifiers, only six of them are fulfilling the requirements of the robust receiver: **1010, 1100, 1001, 1001, 0110, 0011** and **0101**.

Figure 2 shows an example of an identifier: **IOOI**. It can be seen that the bandwidth of 20 MHz is divided into 4 sub-bands each having 5 MHz and corresponding to a digit **O** or **I**.

IV. PROPOSED WIDEBAND, HIGH-EFFICIENCY RECTIFIER

The rectifier is the key part of the quasi-passive WuRx since the receiver's sensitivity is depending on it. The proposed rectifier is based on the SMS7630 diode from Skyworks. This diode is characterized by higher efficiency notably for low power signal conversion. The efficiency of the power converter is given by:

$$\eta = \frac{P_{DC}}{P_{RF}} \quad (1)$$

where η is the conversion efficiency, P_{DC} is the direct voltage power at the output of the converter and P_{RF} is the RF input power.

The microstrip technology is used in order to design the impedance matching circuit. This technology is preferred instead of using lumped components, because it is less dispersive at high frequency.

Figure 3 presents the proposed high efficiency rectifier optimized on a Rogers Duroid (RO4350B) substrate. This hydrocarbon ceramic laminate has superior high frequency performance. The dielectric constant is 3.66, it has a dissipation factor of 0.0031, the substrate thickness is 0.51 mm, and the conductor thickness is 17.5 μm .

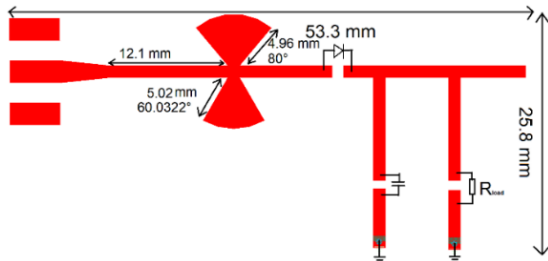


Figure 3. Proposed high efficiency rectifier with a butterfly stub matching circuit and SMS7630 diode.

The other parameters of the rectifier (a 0.1 nF capacitor in parallel with a 5 K Ω resistor) have been chosen because they are maximizing the rectifier's efficiency and consequently maximizing the output DC voltage.

Indeed, as can be seen from Figure 4, the conversion efficiency of the SMS7630 based rectifiers at -30 dBm input power is maximum for a 5 k Ω resistor.

Moreover, one can remark that for various load resistance values, the rectifier based on the SMS7630 diode has better conversion efficiency compared to the rectifier based on HSMS2850, initially presented in [8]. Indeed, this conversion efficiency is 12.7 % at maximum compared to 2 % of the rectifier based on the HSMS2850.

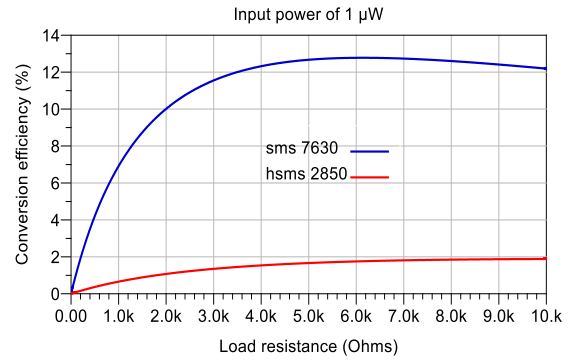


Figure 4. Conversion efficiency results of the HSMS2850 and of the SMS7630 diode based rectifiers.

The target matching bandwidth is 20 MHz, corresponding to the bandwidth of the wake-up signal presented in Figure 2. As it can be seen in Figure 5, the rectifier is well matched from 2435 MHz to 2465 MHz, on required bandwidth (20 MHz around 2.45 GHz). Furthermore, one can remark that the in band ripple of the reflection coefficient is higher in the case of the SMS7630 based rectifier. However, this ripple does not affect the wake-up radio's sensitivity.

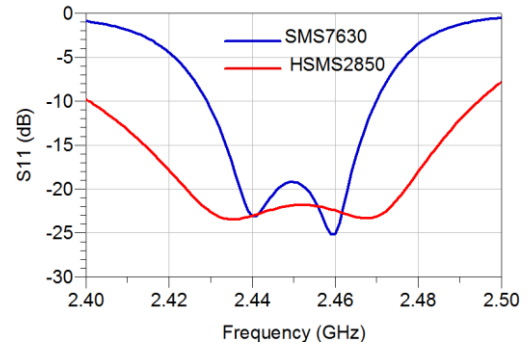


Figure 5. Reflection coefficient S_{11} (dB) at the rectifier's input.

In order to study the efficiency of the proposed rectifier, circuit-system co-simulations on the entire quasi-passive wake-up radio architecture have been performed. The performance criteria was the sensitivity increase for the six viable identifiers.

Moreover, the gain in terms of communication range compared to the HSMS2850 based rectifier was studied. The increase of the communication range was calculated in a free space scenario where the EIRP (Equivalent Isotropic Radiated Power) was of 20 dBm and the receiver's antenna has been considered isotropic. The results are gathered in Table II.

In order to highlight the sensitivity increase, the V_{sub} voltages for the two kind of rectifiers (HSMS 2850 and SMS7630 based) are given in Figure 6. In this case, the identifier IOOI is received with a power level is varying between -50 dBm and -10 dBm.

In that case, the sensitivity is increased by approximately 5 dB. Indeed, if the threshold voltage $V_{threshold}$ is chosen empirically at 1 mV with the SMS7630 based WuRx, the V_{sub} reaches this value for an input power level 4.71 dB lower than in the case of the HSMS2850 based WuRx. This allows increasing the wake-up distance of approximately 13 meters in a free space environment.

TABLE II. Sensitivity and communication range increase for the six viable identifiers

Identifier	Gain	Range increase
IOOI	4.71 dB	12.47 m
IOIO	4.63 dB	12.20 m
OIOO	4.53 dB	11.86 m
OIOI	4.86 dB	12.99 m
IIOO	4.45 dB	11.59 m
OIOI	4.51 dB	11.79 m

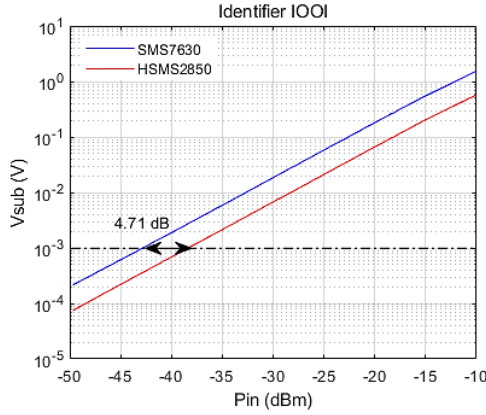


Figure 6. Subtractor's output voltage for HSMS2850 and the SMS7630 diodes based rectifiers.

V. CONCLUSION

This paper presents a wideband high-efficiency rectifier to improve the communication range of a quasi-passive wake-up radio receiver. The rectifier is based on a double butterfly stub architecture that provides a wideband matching, exempted from the lumped components variation. Moreover, the RF to DC conversion efficiency is maximized for low input power levels. The circuit-system co-simulations performed by using the Keysight's ADS Software demonstrated the utility of the proposed rectifier. Future efforts will be undertaken to fabricate the proposed high-efficiency converter for experimental validation of the results obtained in this work.

ACKNOWLEDGMENT

The authors thank the cooperation service of the French Embassy in Cameroon (SCAC) for financial support.

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