Analysis of Rectifiers Under Various Multitone Excitations and Using Different Diodes in Low-Power Conditions

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***Abstract*— This paper presents the results of an extensive theoretical and numerical analysis of different diodes behaviors for energy harvesting (EH) applications, with respect to multitone excitation, in low-power conditions. First, a suitable implementation of the Harmonic Balance technique is adopted to provide a fast and reliable estimation of rectifiers performance under different multi-sine excitations, for increasing number of tones and for different frequency shifts. The chosen operating frequency is 5.8 GHz. A study on the effects of different rectifiers on the RF-to-dc conversion efficiency in the band under multitone excitation, is proposed. The simulations have shown how the circuit parameters of the nonlinear device affect the performance of the rectifier as the number of tones varies. In particular, the focus has been put on a comparative study between circuit simulations and numerical analysis of the performance of rectifiers and their effect on the RF-to-dc conversion efficiency, as a function of their junction capacitance.**

Keywords—energy harvesting, Harmonic Balance, multitone, nonlinear, rectifiers.

I. INTRODUCTION

With the emerging development of new technologies for Internet of Things (IoT) applications and the exponentially increasing number of connected devices, one of the most remarkable challenges is to keep power consumption as low as possible, enhancing the devices lifetime. As a result of the growth of wireless communication systems, electromagnetic energy can be extracted from the environment, providing sufficient power for low-consumption devices [1].

Overcoming the limit of battery replacement, RF Energy Harvesting (EH), provides several benefits to RFID such as a longer lifetime, enhanced reliability, and less expensive costs. While efficient diodes and rectifier topology can improve the RF-to-dc conversion efficiency on the receiver side [2], multitone excitation input was recently proposed to improve the performance of a rectifier at the transmitting side [3].

In [4],[5] the reading range of Radio Frequency Identification (RFID) tags is extended by means of RF input signals with a high peak-to-average power ratio (PAPR).

In [6], a theoretical and experimental analysis of a rectifier under multitone excitation is presented. The results demonstrated that using multisine signals as the excitation in an EH system can be advantageous if the goal is to increase the generated DC Power and RF-DC conversion efficiency. The work demonstrates that, for the same average power, the output of a single tone excitation and a multisine excitation may be dramatically different, with a considerable DC power increase in the multisine scenario.

On the other hand, in [7], a theoretical analysis of the effects of multitone excitation on the RF-to-dc conversion efficiency is proposed. Harmonic Balance simulations and a numerical approach have been evaluated for low-power conditions (from -50 to -10 dBm), where results reported lower dc output power levels with respect to single-tone RF input signals, with the same average power level.

This work attempts to bridge the gap present in the various solutions and methods in the literature, focusing on the study of rectifiers under different multitone excitations. By means of Harmonic Balance simulations, different RF input conditions are considered. Firstly, three multitone spectra are exploited with up to 8 tones: linear, logarithmic, and gaussian-distributed. Subsequently, a comparative study on the conversion efficiencies obtained from three different commercial diodes under multitone excitation is proposed. Finally, a numerical approach is presented, accompanied by a verification carried out through Harmonic Balance simulations, of the effects of the diodes circuit parameters on the dc output power, with particular attention to their junction capacitances.

II. EFFECTS OF DIFFERENT MULTITONE SPACINGS ON THE RF-TO-DC CONVERSION EFFICIENCY

A simple rectifier topology in series configuration is analyzed under multitone excitations for low average input power levels from -30 dBm to -10 dBm. The set of simulations is performed for f_0 = 5.8 GHz and for varying number of tones N and frequency spacing around f_0. For comparison purposes, the simulations are set up in such a way that the average input power is kept constant. The circuit schematic is reported in Fig. 1, where the microstrip lines TL1, TL2, TL3 and TL4, realized on a 0.813-mm-thick ROGERS 4003C substrate, constitute the linear embedding network of a one-diode rectifier. To focus on the diode nonlinear behavior under multitone excitations, the linear subnetwork is first considered lossless.

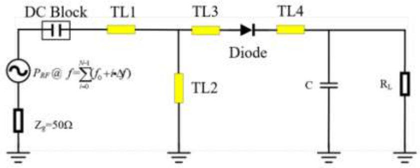
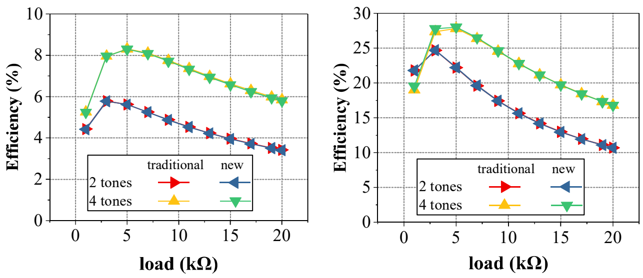


Fig. 1. Circuit schematic of the exploited series-configuration rectifier.

For the proposed multitone analysis, fast and accurate Harmonic Balance simulations are performed by means of the circuit simulator Keysight ADS, using the method introduced in [8], where the multitone inputs are represented as the higher harmonic commensurable excitations of the common frequency spacing. In this way, although the resulting spectrum is denser, the analysis is faster and more accurate. Furthermore, any no. of input tones is allowed with no additional burden. In the first analysis, the Schottky diode HSMS2850 from Avago is chosen for the rectifier design. Fig.2 shows a comparison between RF-to-dc conversion efficiency, computed as in [9] as a function of the dc-load, for two references RF input power levels: -10 dBm and -20 dBm. It can be confirmed that differences between the two regimes are negligible, while the computational time is reduced by two orders of magnitude when the number of intermodulation tones is 4. Moreover, the traditional simulation method cannot handle a multitone signal with N > 4 tones, while no limitations are experienced in the formulation adopted in [8].



(a) (b)

Fig. 2. Comparison of simulated RF-to-dc conversion efficiencies for the HSMS2850 diode at (a) -20 dBm and (b) -10dBm as function of the load, using the standard multi-tone Harmonic Balance simulation and the method in [8].

In the following analysis, three different frequency spacing techniques are exploited: linear, logarithmic, and gaussian. Table I contains the corresponding fundamental tones for an 8-tone excitation. To quantify the RF-to-dc conversion efficiency variation under multitone excitation with respect to single-tone excitation, the Multitone Efficiency Increase (MEI) figure of merit is defined:

$$MEI = \frac{Eff_{N\,tones}}{Eff_{single-tone}} \quad (1)$$

where:

$$Eff_{single-tone} = \frac{P_{dc}}{P_{RF}} \quad (2)$$

$$Eff_{N\,tones} = \frac{P_{dc}}{P_{RF1}+P_{RF2}+\cdots+P_{RFN}} \quad (3)$$

$$\sum_{i=1}^{N} P_{RFi} = P_{RF} \quad (4)$$

and P_{dc} is the output dc power, P_{RF} the single-tone RF input power and the P_{RFi} the power associated to each tone, provided that the average power superposition equals P_{RF}.

TABLE I

FREQUENCIES OF THREE DISTRIBUTION

Distribution	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
linear	5.800	5.805	5.810	5.815	5.820	5.825	5.830	5.835
logarithmic	5.800	5.811	5.818	5.823	5.827	5.830	5.833	5.835
gaussian	5.800	5.802	5.807	5.814	5.822	5.829	5.834	5.836

unit: GHz

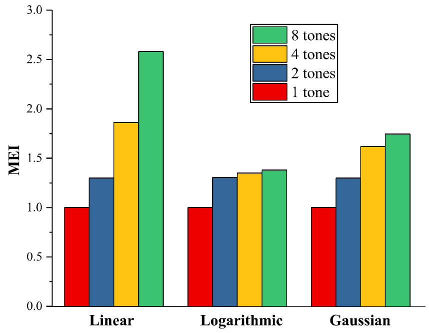


Fig. 3. Simulated MEI values, for -20 dBm at the input port of the HSMS2850 rectifier, for thre multitone excitation with up to 8 tones.

The MEI behavior for different multitone excitations, with respect to the single-tone one, is reported in Fig. 3, for an average P_{RF} of -20 dBm: it can be observed that for N ≤ 2, the tone spacing law does not significantly affect the MEI which is of about 1.3 for all the excitation formats. An evident advantage for the linear spacing is observed when N exceeds 4, while the logarithmic spacing results to be less sensitive to the increase of N. Adopting linear frequency spacing, with N=8 and Δf=5 MHz, the MEI is equal to 2.6, while the logarithmic and gaussian-distributed multitone spectrum result in a MEI of 1.35 and 1.65, respectively. Similar results have been obtained for an average P_{RF} of -10 dBm.

III. JUNCTION CAPACITANCE IMPACT ON MULTITONE PERFOMANCE

In this section, a study based on nonlinear simulations is dedicated to investigate the effects of the diode parameters, and in particular of the junction capacitance C_j, on the RF-to-dc conversion efficiency and on the MEI defined in (1) when the rectifier is excited by multitone at low input P_{RF}. The results are then theoretically justified, using simplified models, as in [10]. Three different commercial diodes are considered: i) VDI-ZBD from Virginia Diodes, ii) SMS7630 from Skyworks Inc. and iii) HSMS2850 from Avago, whose main parameters are reported in Table II.

TABLE II

SPICE PARAMETERS OF THREE DIODES

Diode	B_V (V)	C_{j0} (pF)	I_S (μA)	R_S (Ω)	V_{bi} (V)
HSMS2850	3.8	**0.18**	3	25	0.35
SMS7630	2	**0.14**	5	20	0.34
VDI-ZBD	2	**0.009**	5.9	21.4	0.26

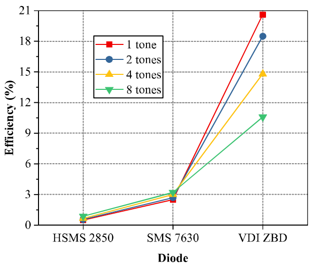
In EH applications, C_j plays a key role in rectifier design. Usually, low junction capacitance diodes are preferred to minimize the inverse current. Figs. 4 shows the RF-to-dc conversion efficiency evaluated using three different rectifiers optimized for the three diodes, for a different number of tones linearly spaced in the 5.8-GHz band and for an average input power level of - 30, -20 and -10 dBm. For the proposed simulations, three different sets of circuit parameters are optimized, one for each diode. In particular, each rectifier is optimized for maximizing the RF-to-dc conversion efficiency over the[-25:-15] dBm power range. The corresponding optimized circuit parameters are reported in Table III. From inspection of the Figs. 4, it can be confirmed that for all the considered power levels, the rectifier adopting the diode with the lowest C_j outperforms the others.

TABLE III

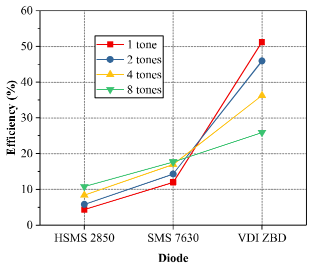
PARAMETERS OF RECTIFIERS

Diode	TL1*		TL2*		TL3*		TL4*		Load
	W	L	W	L	W	L	W	L	(Ω)
HSMS2850	2.9	5.9	0.3	9.7	2.2	4.6	2.4	6.4	4000
SMS7630	1.8	13.7	1	5.5	3.5	4.6	3.2	5.5	6000
VDI-ZBD	2.6	4.4	4.6	11.9	0.6	9.1	0.6	8	4000

*unit: mm



(a)



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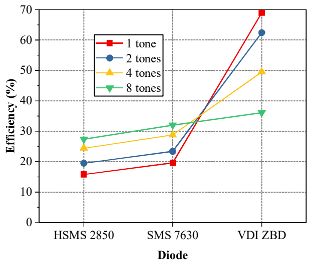

(c)

Fig. 4. Simulated RF-to-dc conversion efficiency for three different diodes and different number of tones at (a) -30dBm, (b) -20dBm and (c) -10dBm.

Furthermore, increasing the number of tones does not always improve the efficiency, but it is dependent on the combination of the diode parameters and the power levels involved. Indeed, for the lowest C_j (realized by the VDI-ZBD diode) a multi-tone excitation at such power levels does not improve the performance. On the contrary, for the SMS7630 and the HSMS 2850 diodes, an efficiency increase with an increasing number of tones can be observed for average input powers of -20dBm and -10 dBm only. However, as expected, the highest efficiency is always achieved by the VDI-ZDB, the one the lowest junction capacitance.

To validate the results obtained through Harmonic Balance simulations, a theoretical calculation procedure is presented, carried out through a numerical analysis implemented on MATLAB. In Fig. 5, the adopted circuit model of the diode is shown: R_s is the series resistance, R_j and C_j describe the nonlinear junction resistance and capacitance, (as a function of the junction potential V_j) R_L is the dc-load.

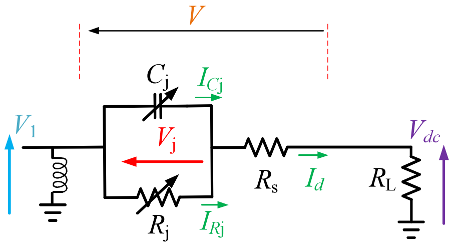

Fig. 5. Nonlinear diode circuital model exploited in the numerical analysis.

In the analytic calculation, two currents are considered: I_{Rj} and I_{Cj}, which describe the current flowing into the nonlinear resistance and the nonlinear junction capacitance current I_{Cj}, respectively. The following calculations are simplified using the fundamental frequencies only of the multi-tone excitations. When the input voltage is lower than turn-on voltage of the diode, the junction resistance is considered infinite. The voltage across the diodes and the junction (V_j) can be written as [10]:

$$V = -V_{dc} + V_1 \tag{5}$$

$$V_j = -V_{jdc} + V_{j1} \tag{6}$$

where V_1 is given by:

$$V_1 = \sum_{i=1}^{N} V_i \cos(\omega_i t) \tag{7}$$

and V_{dc}, V_1, V_{jdc} and V_{j1} are the dc-output voltage, the multitone RF input voltage, the dc, and the RF component across the junction, respectively. When the junction resistance is infinite, $V_{dc}=V_{jdc}$, $V_1=V_{j1}$. From circuit simulation, the dc-characteristic of the diode current I_{Rj} can be extracted and modeled with polynomial interpolation as a function of the applied voltage:

$$I_{Rj} = \sum_i a_i V_d^j \tag{8}$$

$$P_{LOSSRs} = \frac{1}{2\pi}\int_0^{2\pi} (I_{Rj} + I_{Cj})^2 R_s \, d\theta \tag{9}$$

$$P_{LOSSJunc} = \frac{1}{2\pi}\int_0^{2\pi} I_{Rj} V_d \, d\theta \tag{10}$$

where P_{LossRs} and $P_{LossJunc}$ describe respectively the losses from the series and junction resistance. The RF-to-dc conversion efficiency can be computed as:

$$\eta = \frac{P_{dc}}{P_{dc}+P_{LOSSJunc}+P_{LOSSRs}} \tag{11}$$

where the rectified dc-output power P_{dc} is:

$$P_{dc} = \frac{V_{dc}^2}{R_L} \tag{12}$$

To compute the theoretical analysis through numerical simulations, initially, two starting values are assumed for the dc-voltage V_{dc} and the tones amplitudes V_1, given a fixed value of R_L. Subsequently, from the extracted I_{Rj} from Eq.8 it is possible to calculate the average value of the current, as follows:

$$I_{d,dc} = \frac{1}{2\pi}\int_0^{2\pi} I_{Rj} \, d\theta \tag{13}$$

According to Kirchhoff's law in the load-path, the algorithm compares the current flowing through R_L, and it compares it with the value found from Eq.13. If the two results do not coincide, the algorithm automatically adjusts the value of V_1, to have the desired equality. When the latter is verified, the algorithm proceeds by calculating the losses described in Eq. 9 and 10. Furthermore, the rectified dc power by the diode is calculated through Eq.12. Once the RF-to-dc conversion efficiency is calculated, the latter is used to calculate the input power to the rectifier:

$$P_{RF} = \frac{P_{dc}}{\eta} \tag{14}$$

Fig. 6 shows the comparison between the simulated and calculated losses produced by the three diodes, which exhibits different junction capacitances, and for a different number of tones.

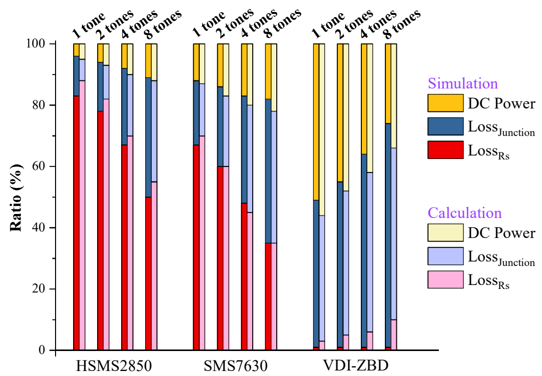

Fig. 6. Simulated and calculated results, including the losses produced by the diodes and the dc-output, at -20 dBm, for different number of tones and diodes.

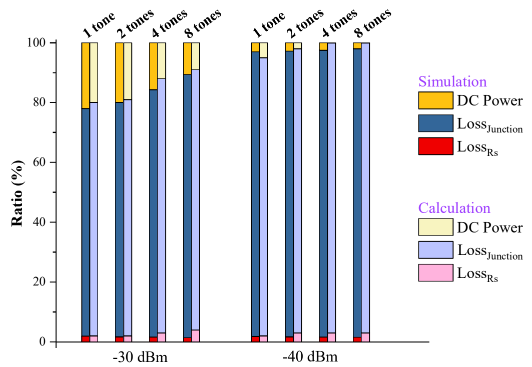

Fig.7 Simulated and calculated losses and performance for the VDI-ZBD diode for -30 dBm and -40 dBm, exploiting up to 8 tones.

The results reported a good agreement between simulations and the proposed algorithm for both the RF-to-dc conversion efficiency and the losses produced by the diode. Numerical calculations confirm that the impact of the variation of the diode parameters, and of the junction capacitance in diodes under multitone excitation degrades the performance of the rectifier as the C_j decreases. For a low C_j value (VDI-ZBD), an increase of P_{LossRs} and P_{LossCj} can be observed; from 3% to 10% and from 41% to 56% respectively, which leads to an overall decrease of the rectifier efficiency. Furthermore, to verify that the proposed study is extendable to any low-level power value, an analysis at -30 dBm and -40 dBm is proposed, exploiting the VDI-ZBD diode. A comparison between simulated and the numerical solution provided by the algorithm is shown in Fig.7.

Simulations and calculation reported that also for different low-power levels, exploiting a low C_j diode in multitone excitation is disadvantageous. In fact, as the number of tones increases, also the losses increase, leading to a lower efficiency. A 10% and 3% losses increase can be observed for the -30 and -40 dBm respectively, with respect to the single-tone excitation.

IV. Conclusions

In this work a detailed analysis of rectifiers under different multitone excitations in low-power conditions, is presented. Firstly, by means of a fast and accurate Harmonic Balance simulation method, different frequency spacing laws are studied, to identify to the optimal multitone optimal frequency distribution. Next, a study on how the use of different diodes affects the performance of the rectifiers for EH applications, is presented. Simulations reported how low-C_j diodes degrade the performance of the rectifiers under multitone excitations. To verify the simulation results, a simplified analysis of the effects of the diode parameter, and of the junction capacitance, on the losses produced by the diode and consequently the effects on the RF-to-dc conversion efficiency is presented. The results produced by the numerical analysis have therefore validated those of the simulations, thus verifying that only some diodes, those with a higher Cj, are advantageous in case of multitone excitation. Diodes with a low Cj are therefore preferable in single-tone excitation conditions, where they can offer their maximum performance.

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