Single-Branch Hybrid Resistance Compression Technique for Enhanced Rectifier Performance

Furong Yang[1], Apostolos Georgiadis[2], Spyros Daskalakis[3], Kyriaki Niotaki[4] Yichao Hu[5], Jichao Yang[6] and Chaoyun Song[1]

[1] Department of Engineering, King's College London, London, UK, furong.yang@kcl.ac.uk; chaoyun.song@kcl.ac.uk

[2] 2582 The Hague, The Netherlands, apostolos.georgiadis@ieee.org

[3]Green IoT Solutions Ltd, Edinburgh, Scotland, UK, daskalakispiros@gmail.com

[4]Télécom Paris, Paris, France, kyriaki.niotaki@telecom-paris.fr

[5] Department of Electrical and Electronic Engineering, Imperial College London, London, UK, yichao.hu23@imperial.ac.uk

[6]School of Electrical and Computer Engineering, Cornell University, Ithaca, United States, jy874@cornell.edu

***Abstract*—In this paper, we introduce a novel resistance compression technique which is termed as the Single-branch Hybrid Resistance Compression Technique (SHRCT) aimed at enhancing the performance of rectifiers. While the conventional Resistance Compression Network (RCN) mitigates non-linear impedance variation effects in rectifier circuits, ensuring stable operation under varying input power and load resistance conditions, it typically necessitates at least two branches and consequently multiple surface-mount devices (SMD), resulting in substantial power losses. The introduction of SHRCT revolutionizes resistance compression by eliminating the need for multiple branches, thus reducing the requirement for SMDs, and improving overall efficiency. The proposed rectifier exhibits a notably high RF-DC conversion efficiency, reaching up to a maximum of 74.2%. The SHRCT empowers the rectifier with robust performance capabilities even when faced with huge variations in load resistance and input power. Specifically, the rectifier maintains a consistent 50% RF-DC conversion efficiency across load resistance values ranging from 1k to 10k ohms and input power levels spanning from -10 to 0 dBm.**

***Index Terms*—Resistance compression network (RCN), rectifier, energy harvesting, wireless power transfer.**

I. INTRODUCTION

Ambient wireless energy harvesting (WEH) at radio frequency (RF) using rectennas has garnered significant attention, driven by the growing popularity of autonomous devices and the concept of the Internet of Things (IoT) [1][2]. This technology's capacity to power devices without the need for batteries has facilitated the development of numerous self-sustaining devices, such as low-power sensors and wearable healthcare devices [3][4].

The rectifier, a critical component of rectenna, plays a pivotal role in converting AC power into DC power. It has been the focus of extensive research aimed at improving its performance [5]-[7]. For example, researchers have introduced an ultra-wideband rectifier with a bandwidth spanning from 0.6 GHz to 3 GHz, representing a 133% fractional bandwidth (FBW), and achieving efficiency of 40% within this range [5]. Another noteworthy advancement is the development of multi-band ambient RF energy harvesting rectifiers. These rectifiers have the ability to convert AC power to DC power across multiple frequency bands, making them suitable for a wide range of WEH applications. One such multi-band rectifier has been specifically designed for autonomous sensor networks, operating across three frequency bands, and boasting a maximum efficiency of 60% even at very low power inputs (below 0 dBm) [6].

Nevertheless, the majority of research in this field primarily examines the frequency response of rectifiers, as mentioned earlier. Only a limited number of studies delve into the design of rectifiers that exhibit resilience in the face of realistically environmental factors, such as variations in load resistance and input power. This is primarily due to the complex challenge posed by the nonlinearity inherent in rectifier circuits. The dynamic nature of ambient electromagnetic power, subject to temporal and geographical fluctuations, can lead to changes in input power levels, causing variations in input impedance. These deviations from the ideal conditions can result in a mismatch between the antenna and rectifier, consequently degrading the rectifier's efficiency, reliability and stability [8].

In real world applications, the load of rectifiers is typically connected to diverse devices such as DC-DC converters or power management circuits, which exhibit time-varying input impedances depending on their specific applications. Therefore, in different scenarios, the fluctuating nature of the rectifier's load resistance prevents it from operating under optimal conditions, resulting in suboptimal performance and degradation of efficiency [8].

The incorporation of Resistance Compression Networks (RCNs) serves to reduce the sensitivity of rectifiers and can function as a matching circuit between antennas and rectifiers. Consequently, RCNs are introduced to enhance the resilience of rectifiers in response to varying operating conditions. The term 'RCNs' and its theory were initially coined and employed to reduce the sensitivity of RF resonant inverters [9]. In the context of RF rectifiers, a few lumped-element-based and transmission-line-based RCNs have been constructed, demonstrating robustness in variable conditions. For instance, a lumped-element-based dual-band rectifier employing a 2-branch RCN configuration has been developed to operate across two Industrial, Scientific, and Medical (ISM) bands [8]. The theory and operational principles of the 2-branch RCNs have been explored and applied to optimize a rectifier, resulting in robust efficiency performance across a broad

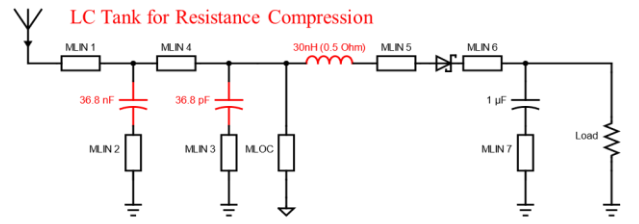

Fig. 1. Detailed schematic of the proposed single-branch resistance compression circuit topology together with the rectifier.

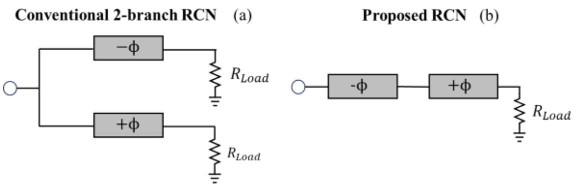

Fig. 2. (a) Conventional two-branch rectifier vs. (b) proposed SHRCT.

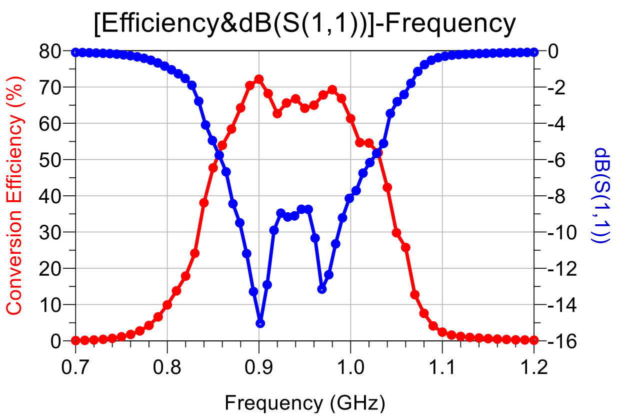

Fig. 3. Simulated conversion efficiency and S_{11} versus operating frequency at input power of 0 dBm and load resistance of 2 kΩ.

range of load resistances and input power levels. In addition, a lumped-element-based Hybrid Resistance Compression Technique (HRCT) has been introduced for the design of a broadband rectifier [10]. The proposed HRCT can maintain a relatively high efficiency over an extremely wide range of load resistance values, spanning from 5 to 80k ohms. These lumped-element-based rectifiers utilize Surface-Mounted Devices (SMDs) in practical implementations, offering benefits such as compact size and the potential for integration into integrated circuits. However, these lumped-element-based RCNs consist of two branches and numerous SMDs, which result in significant power losses and consequently reduced efficiency.

Transmission-line-based RCNs, on the other hand, utilize low-loss microstrip lines instead of lossy SMDs for rectifier optimization. Barton et al., [11] introduced a multi-way transmission-line resistance compression network (TLRCNs) for RF rectifiers. This technique enhances the rectifier's resilience to varying input power and load resistance while reducing power losses. However, transmission-line RCNs tend to have larger dimensions and are not well-suited for integration into integrated circuits, especially at lower microwave frequencies, such as Ultra High Frequency (UHF) band.

In this paper, we introduce a novel Single-branch Hybrid Resistance Compression Technique (SHRCT) aimed to enhance the rectifier's resilience to varying input power levels and load resistance. Additionally, we propose the Single-branch Hybrid Resistance Compression Network (SHRCN), which harnesses the benefits of both lumped-element-based and transmission-line-based RCNs, resulting in a compact design with minimal power loss. To the best of our knowledge, this marks the inaugural application of a single-branch RCN in rectifier design.

II. Single-branch Hybrid Resistance Compression Technique

A. Single-branch Hybrid Resistance Compression Networks

Fig. 1 provides a comprehensive illustration of the SHRCN's structure, consisting of lumped elements and microstrip lines. These lumped elements include an inductor and two capacitors. The microstrip lines have intentionally been configured with short lengths to maintain a compact circuit design. The proposed SHRCN serves as a matching network that can effectively mitigates the non-linearity inherent in electronic devices that employ non-linear components like diodes. Through the incorporation of SHRCN, rectifier performance can exhibit greater resilience to variations in input power and load resistance. In comparison to conventional two-branch RCN (see Fig. 2(a)), the proposed method (see Fig. 2(b)) significantly reduces the number of SMD components used in the circuit. This reduction results in lower power losses and mitigates uncertainties in optimizing multiple chip components. In our proposed topology, the phase difference between the two branches, typically produced by capacitive and inductive networks, is no longer required. The RCN is primarily achieved through an LC tank positioned between the matching components.

B. Optimization Technique & Simulation Results for SHRCN-based Rctifiers

The evaluation and optimization of the proposed SHRCN-based rectifier's performance are conducted through the utilization of a commercial simulator (Agilent ADS). This process employs the harmonic balance (HB) analysis and the large signal scattering parameter (LSSP) analysis. Furthermore, to guide the optimization, specific optimization goals are established, which include constraints placed on achieving minimum RF-DC conversion efficiency under two distinct load conditions: 500 Ohms and 10,000 Ohms. Both constraints are imposed while maintaining a fixed frequency of 900 MHz and a fixed input power level of 0 dBm. These choices ensure that the rectifier's conversion efficiency remains robust across a broad range of load resistance scenarios.

After optimization, we obtain frequency response, resistance compression performance and efficiency versus

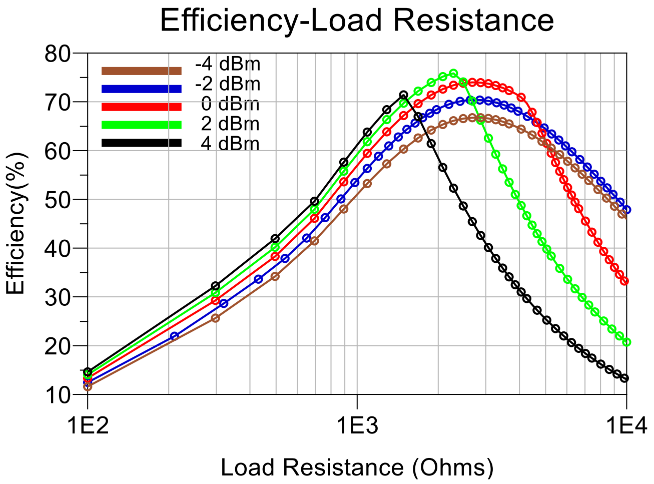

Fig. 4. Resistance compression performance of the SHRCN-based rectifier for various input power levels (P_{in}=-4, -2, 0, 2, and 4 dBm) at 900 MHz.

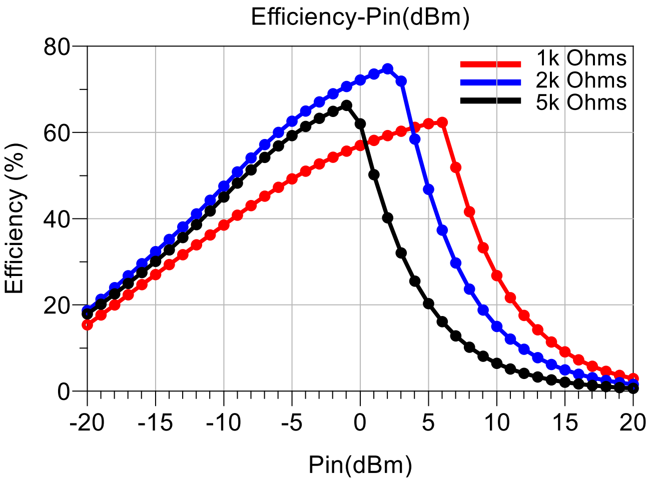

Fig. 5. Conversion efficiency versus input power levels for load resistance R_L=1000, 2000, and 5000 Ω at 900 MHz.

input power plots which are illustrated in Fig. 3, Fig. 4, and Fig. 5, respectively. It is observed that the optimized rectifier exhibits outstanding performance at the frequency of interest. Additionally, its resistance compression performance is exceptionally good, with the efficiency remaining above 50% over a wide range of load resistances (from 1000 to approximately 10000 ohms) and input power levels (ranging from around -10 to 0 dBm). As per Fig.4, an intriguing observation is that the optimal resistance compression performance occurs at approximately -2 dBm, which is slightly below the initial selection point of 0 dBm for the optimization. Furthermore, it is worth noting that the input power level corresponding to the highest efficiency point is around 2 dBm, which is contrary to my initial attempt to optimize the circuit at 0 dBm. This discrepancy may be attributed to the two optimization goal constraints set to broaden the efficiency-load curve.

This suggests that when striving to improve resistance compression performance in SHRCNs, it leads to optimizing for a higher input power level in terms of achieving the highest efficiency. Therefore, for SHRCN-based rectifier circuits, it is

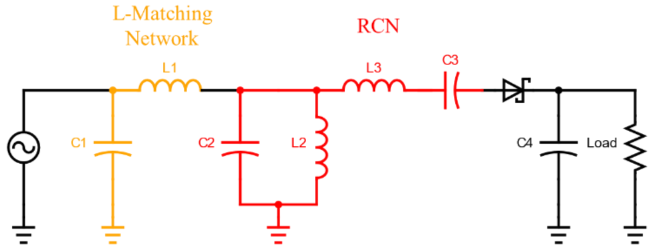

Fig. 6. A lumped-element-based rectifier optimized using conventional RCN and L-matching network.

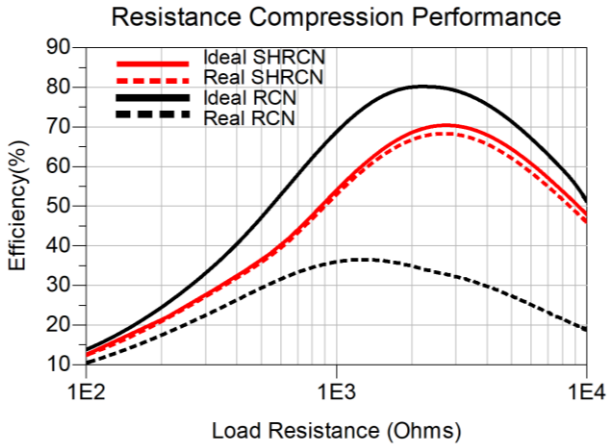

Fig. 7. Comparison of resistance compression performance between SHRCN-based rectifier and conventional RCN-based rectifier at input power of -2dBm.

advisable to optimize them at an input power level slightly higher than our target, as this approach can help enhance resistance compression performance and offset the mentioned effect. To the best of our knowledge, it is the first time such optimization technique has been reported.

III. Comparative Analysis and Discussions

In this section, we perform a comparative analysis between the proposed SHRCN-based rectifier and a conventional lumped-element-based rectifier. To achieve impedance matching and resistance compression in the lumped-element-based rectifier, we employ an L-matching network along with a single-branch RCN, as illustrated in Fig. 6 [10]. Both rectifiers have been optimized to achieve their best resistance compression performance at an input power level of -2 dBm.

The performance comparison between the proposed SHRCN-based rectifier and the conventional (lumped-element) RCN-based rectifier is presented in Fig. 7. It is noteworthy that the conventional RCN-based rectifier demonstrates exceptional efficiency and resistance compression performance when the lumped elements are ideal (no ohmic loss). However, when we consider the real situation (presence of ohmic loss), the performance of the RCN-based rectifier drops significantly and becomes suboptimal. In contrast, the presence of ohmic loss in the lumped elements does not lead to a substantial efficiency drop in the SHRCN-based rectifier. The efficiency and resistance compression performance of the SHRCN-based rectifier remains exceptionally good even in the presence of ohmic loss. This stark difference underscores the robustness and superior performance of the SHRCN-based rectifier when compared to its conventional lumped-element counterpart.

IV. CONCLUSIONS

We have introduced the Single-branch Hybrid Resistance Compression Technique (SHRCTs), comprising Single-branch Hybrid Resistance Compression Networks, along with an optimization technique designed to achieve exceptional resistance compression networks. Furthermore, we conducted an exhaustive analysis of a SHRCN-based rectifier. Its remarkable performance positions it as a prime candidate for constructing exceptional rectennas tailored to various wireless energy harvesting (WEH) and Wireless Power Transfer (WPT) applications. More experimental and simulation results will be presented at the conference.

REFERENCES

[1] S. Kim, C. Mariotti, F. Alimenti, P. Mezzanotte, A. Georgiadis, A.Collado, L. Roselli, and M. M. Tentzeris, “No battery required: Perpetual RFID-enabled wireless sensors for cognitive intelligence applications,” IEEE Microw. Mag., vol. 14, no. 5, pp. 66–77, Aug. 2013.

[2] L.-G. Tran, H.-K. Cha, and W.-T. Park, “RF power harvesting: A review on designing methodologies and applications,” Micro Nano Syst. Lett., vol. 5, no. 1, p. 14, 2017.

[3] T. Beng Lim, N. M. Lee and B. K. Poh, “Feasibility study on ambient RF energy harvesting for wireless sensor network,” 2013 IEEE MTT-S (IMWS-BIO), Singapore, 2013, pp. 1-3.

[4] R. Kanan and R. Bensalem, “Energy harvesting for wearable wireless health care systems” 2016 IEEE Wireless Commun. Netw. Conf., Doha, Qatar, 2016, pp. 1-6.

[5] S. Zheng, W. Liu and Y. Pan, “Design of an Ultra-Wideband High-Efficiency Rectifier for Wireless Power Transmission and Harvesting Applications,” IEEE Trans. Ind. Informat., vol. 15, no. 6, pp. 3334-3342, June 2019.

[6] N. Tung, “Multi-band ambient RF energy harvesting rectifier for autonomous Wireless Sensor networks,” IEEE Region 10 Conf. (TENCON), Nov. 2016, pp. 3736-3739.

[7] Z. Chen et al., “Wearable Rectenna With Integrated Miniaturized Feeding Slot and Rectifier Structure,” IEEE Trans. Antennas Propag., vol. 71, no. 5, pp. 3868-3881, May 2023.

[8] K. Niotaki, A. Georgiadis, A. Collado and J. S. Vardakas, “Dual-Band Resistance Compression Networks for Improved Rectifier Performance,” IEEE Trans. Microw. Theory Tech., vol. 62, no. 12, pp. 3512-3521, Dec. 2014.

[9] Y. Han, O. Leitermann, D. A. Jackson, J. M. Rivas and D. J. Perreault, “Resistance Compression Networks for Radio-Frequency Power Conversion,” IEEE Trans. Power Electron., vol. 22, no. 1, pp. 41-53, Jan. 2007.

[10] C. Song, Y. Huang, J. Zhou and P. Carter, “Improved Ultrawideband Rectennas Using Hybrid Resistance Compression Technique,” IEEE Trans. Antennas Propag., vol. 65, no. 4, pp. 2057-2062, April 2017.

[11] T. W. Barton, J. M. Gordonson, and D. J. Perreault, “Transmission line resistance compression networks and applications to wireless power transfer,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 3, no. 1, pp. 252–260, Mar. 2015.