Technique Review for Differential Drive Crossing Coupling Rectifier in RF Energy Harvester

Zu-shuai XIE, Zhi-qiang WU and Jian-hui WU*

National ASIC System Engineering Research Center, Southeast University, Nanjing, People’s Republic of China

*Corresponding author

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Abstract. This paper presents a comprehensive technique review for CCDD rectifier. It includes the challenges for the design of RF-to-DC rectifier and techniques for the efficiency improvement by controlling the gates and bodies of MOS in CCDD rectifier. The comparison of different techniques for efficiency improvement is concluded. The idea for novel CCDD is discussed and simple simulation result is shown in this paper.

Introduction

Over the past decades, low power design has attracted massive researches to push integrated system to consume as less as power with proper trade-off between parameters. Many low power and low voltage circuits have been reported [1]. However, it is still challenging to maintain these circuits working more than ten years without battery. Though integration has massively been increased driven by Moore’s law and power consumption has aggressively decreased, battery capability has not kept the pace of industry’s development. This trend has severely constrained the deployment of IoT. As the network of IoT requires massive nodes, about several millions, the battery replacement extremely increases the management cost.

![Figure 1. Main blocks for RF energy harvesting system.](image)

Energy harvesting technology is emerging as an excellent candidate to achieve self-sustainable nodes for IoT applications [2]. It has attracted intensive researches among academics. Although wireless energy among the free space features the minimal energy density due to the transmission loss among the above energy sources, RF energy harvesting attracts the researchers’ interests for its potential feasibility and compatibility with RF transceiver as antenna can both achieve signal receiving/transmitting and energy converting, so no extra energy converter component is required.

As shown in Fig. 1, a simplified system blocks for RF energy harvesting constitutes with antenna, RF-to-DC rectifier and Power management unit (PMU). Antenna is used to receive the ambient RF energy in open air. RF-to-DC rectifier achieves to obtain the required DC energy. PMU is used to dynamically control the received energy. And high efficiency of RF-to-DC rectifier plays the most important role in RF energy harvesting system. As shown in Fig. 2, RF-to-DC rectifier can be categorized into two branches: single rectifier (Fig. 2a) and CCDD rectifier (Fig. 2b). This paper only focuses on the efficiency improvement techniques for CCDD rectifier.
The rest of this paper is organized as follows. In section 2, the challenge for rectifier design will be stated. In section 3, techniques for high efficiency by controlling the gate and body of differential drive crossing coupling rectifier are reviewed. Finally, section 4 concludes this paper.

![Figure 2: RF-to-DC rectifier. (a) sing-end rectifier; (b) CCDD rectifier.](image)

**Challenges for RF-to-DC Rectifier**

**Input Impedance Variation**

As indicated in [3], the input impedance of RF-to-DC rectifier is not only affected by the turn-on/turn-off impedance $Z_{in,ON}/Z_{in,OFF}$, which are decided by both transistors’ sizing and the amplitude of input voltage, but also affected by the output condition $V_{out}$. For this reason, wide variation range of input impedance is triggered, which cause severe challenge for input impedance matching in order to obtain as much as energy from ambient RF signal. Due to the wide variation of input impedance, it is very difficult to realize optimized system efficiency over wide input power range.

**Threshold Voltage $V_{TH}$**

The transistors’ $V_{TH}$ plays an important role in the design of RF-to-DC rectifier. As shown in Fig. 3[4], optimized $V_{TH}$ is existed to obtain maximum efficiency. When $V_{TH}$ is too small, the reverse current dominates the charging process, which causes low efficiency under this condition. While $V_{TH}$ is too large, the charging current is too small and more input amplitude is required to overcome $V_{TH}$. This cause the decrease of efficiency. However, $V_{TH}$ is a parameter affected by process, voltage and temperature (PVT), so this strong relationship with $V_{TH}$ leads to the difficulty to design RF-to-DC rectifier satisfying wide corners and temperature range.

![Figure 3: $V_{TH}$ vs efficiency [4].](image)

**Techniques Review of CCDD Rectifier for High Efficiency**

In order to improve the efficiency of CCDD rectifier, several techniques from the circuit level have been reported. And they are categorized into two branches, as followed.
Techniques by Controlling the Gate of CCDD Rectifier for High Efficiency

Figure 4. Different techniques by controlling the gate of transistor for high efficiency in CCDD rectifier.
(a) [5]; (b) [6]; (c) [7]; (d) [8]; (e) [9].

As shown in Fig. 4, the techniques by controlling the gate of transistor for high efficiency in CCDD rectifier are summarized. As shown in Fig. 4(a), (b) and (c), in order to depress the reverse current when input voltage is large enough, the output voltage is sensed and the dynamical controlling the gate of PMOS is achieved by different components [5-7]. With these methods, the reverse current is reduced, however, the charging current is simultaneously depressed due to the amplitude-aware characteristics. As for Fig. 4(d), the implementation of the static bias is done by connecting the gate of PMOS to the same point as done in dynamic bias technique but using a signal from the previous stage. The AC component of this bias potential is the same as the one used in dynamic bias technique, but the DC level is lowered by $V_{out}/N$, N is the number of stages [8]. In Fig. 4(e), the gate of PMOS is controlled by sensing the input signal, which is used to insert a negative dc level to the input RF signal to obtain more negative RF signal [9], so that more charging current is achieved during its conduction phase. With this configuration, the sensitivity of RF-to-DC rectifier is increased.

Techniques by Controlling the Body of CCDD Rectifier for High Efficiency

Figure 5. Different techniques by controlling the body of transistor for high efficiency in CCDD rectifier.
(a) [10]; (b) [11]; (c) polarity-aware CCDD rectifier.
Except for the gate control for high efficiency, another way is to control the body of transistors to directly adjust $V_{TH}$. As shown in Fig. 5, several techniques have been reported. In Fig. 5(a), the bodies of NMOS are connected together to $\text{DC}_{\text{in}}$ and the bodies of PMOS are connected together to $\text{DC}_{\text{out}}$ [10]. With this configuration, dynamic threshold voltage is obtained, which improves the power conversion efficiency when the input power is small. In order to realize amplitude-aware dynamic control of bodies of transistors, diode-connected MOS transistors ($D_{1-4}$) are added to dynamically reconfiguring the rectifier according to the input power and polarity [11], as shown in Fig. 5b. Although it dynamically controls $V_{TH}$ according to the input power, it does not improve the sensitivity of the RF-to-DC rectifier. In order to realize both dynamic threshold voltage and enhanced sensitivity, a novel CCDD rectifier is shown in Fig. 5c. The bodies are used to dynamically control the threshold voltage, so that both large charging current and small reverse current are obtained without any depression on charging current as this configuration is polarity-aware.

As shown in Fig. 6, output voltage comparison between conventional CCDD rectifier and polarity-aware CCDD rectifier is presented. It indicates that when the input voltage is not enough, the polarity-aware rectifier can obtain higher output voltage compared with the convention one.

![Figure 6. Output voltage comparison between conventional CCDD rectifier (dash line) and polarity-aware CCDD rectifier (solid line).](image)

As indicated in Table 1, comparison between different techniques for high efficiency is summarized. Although body control with amplitude-aware solution realizes highest PCE, about 83.7% at 0.9GHz, higher PCE can be achieved with the introduction of polarity-aware solution in body control scheme.

| Control methods | Ref. | Amplitude-aware /Polarity-aware | Adv. | Disadv. | $PCE_{\text{max}}$(%) | Fre.(GHz) |
|-----------------|------|--------------------------------|------|---------|---------------------|-----------|
| Gate control    | [5]  | Amplitude-aware                | small $I_{\text{reverse}}$ | small $I_{\text{charge}}$ | 65      | 1                     |
|                 | [6]  |                                |      |         | 65.3                | 0.433     |
|                 | [7]  |                                |      |         | 66                  | 0.9       |
|                 | [8]  |                                |      |         | 42.8                | 0.915     |
|                 | [9]  | Polarity-aware                  | smaller $I_{\text{reverse}}$ | normal $I_{\text{charge}}$ | 70      | 0.953                |
| Body control    | [10] | Amplitude-aware                 | small $I_{\text{reverse}}$ | normal $I_{\text{charge}}$ | 69.5    | 0.953                |
|                 | [11] | Amplitude-aware                 | smaller $I_{\text{reverse}}$ | normal $I_{\text{charge}}$ | 83.7    | 0.9                 |
Conclusion
This paper focuses on the review of the efficiency improvement techniques in CCDD RF-to-DC rectifier in RF energy harvesting system. Two branches are categorized based on the control of gates and bodies of transistors. And the amplitude-aware methods not only depress the reverse current, but also the charging current. So the polarity-aware methods based on body control can realize higher power conversion efficiency. This novel CCDD rectifier features huge potential in high sensitivity RF energy harvesting system.

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