An Optimum Design of Micro-watt RF Energy Harvesters with RF-DC and DC-DC Conversions

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1． Introduction RF-energy harvesting (RF-EH) attracts researchers as one of the power sources of IoT devices [1]. Rectenna is used for RF-DC conversion [2]. DC-DC charge pump (CP) may also be necessary when the input power of microwaves to the antenna is as low as micro-watt. In [3], design methodology of extremely low voltage CP is proposed when the output voltage and current are given. However, how the system with rectenna and CP can be optimally designed has not been investigated when the power converter needs those two circuits. In this research, an optimum design method to minimize input power at an antenna is proposed when the output condition of CP is given. Based on the design method, rectennas with and without CP as shown in Fig. 1 are compared in terms of the total power-conversion efficiency and the total size of the capacitors required for the system to determine which circuit topology should be selected.

2. Proposed design Available power P_{av} and power conversion efficiency η are defined by (1) and (2), respectively [4].

$$P_{av} = V_{in}^2/8R_{ant} \quad (1) \qquad \eta = P_{out}/P_{av} = V_{pp}I_{pp}/P_{av}, \quad (2)$$

where V_{in} is the input voltage amplitude, R_{ant} is the real part of the antenna impedance, V_{pp} is the output voltage of CP, I_{pp} is the output current of CP. Matching network is optimized so that the P_{av} is minimal per given output condition V_{dd} and I_{outRec} of the rectenna using ADS. CP is designed at two different priorities. One is CP conversion efficiency η_{CP} and the other is CP area A_{CP}. At a certain input voltage V_{dd} of CP, CP is designed to have the highest η_{CP} based on the optimization procedure proposed in [3]. This procedure has been done for various V_{dd} to figure out V_{dd}-I_{inCP} characteristics. Various I_{outRec}-V_{dd} curves are also drawn by changing V_{in}. The system of rectenna and CP is in steady state at an operating point where I_{outRec}=I_{inCP}. Thus, one can find P_{av} at every V_{dd} to convert harvested power to a required output power from CP. Optimum V_{dd} can be determined to make P_{av} minimum. CP is also designed to have the minimum CP area based on the optimization procedure [3] at every V_{dd}. By following the same procedure as described above, one can also find the optimum V_{dd} and the minimal P_{av} under the condition that CP area is minimized.

3． Demonstration As a demonstration of the proposed optimization method, the following parameters are used: V_{pp}=1V, I_{pp}=10μA, R_{ant}=70Ω, RF frequency f_{in}=2.45GHz, V_{dd}=0.2V, 0.4V and 0.6V. The device parameters of rectenna in [2] and the circuit parameters of DC-DC CP in [3] were used. Fig. 2 shows I_{outRec}, I_{inCP}, P_{av} and CP area across V_{dd} when CP conversion efficiency η_{CP} is prioritized. Fig. 2 (a) shows that the I_{outRec}-V_{dd} curve for P_{av}=58μW has an intersection point with the I_{inCP}-V_{dd} curve at V_{dd} of 0.4V. Fig. 2 (a) also shows that the I_{outRec}-V_{dd} curve for P_{av}=230μW passes a point at I_{outRec}=10μA and V_{dd}=1V. Fig. 2 (b) shows P_{av} vs. V_{dd} and CP area vs. V_{dd} for I_{pp}=10μA at V_{pp}=1V. V_{dd} of 0.4V is optimal in terms of both P_{av} and CP area. As a result, rectenna with CP needs P_{av} of 58μW whereas rectenna without CP does P_{av} of 230μW for P_{out} with I_{out}=10μA and V_{out}=1V. Therefore, the former has 4x less input power than the latter does. A similar design procedure was also done to design CP under the condition of minimal CP area. The results are summarized in Table I. The total cap size includes a decoupling capacitor for IC of 100μF, that for CP of 10μF and capacitors of CP.

4． Conclusion We proposed a methodology to design power converters for μW range RF-energy harvesting. One can determine the optimum operating point V_{dd} of the rectenna and CP to minimize the available power P_{av} at an antenna when the output condition of CP is given. The demonstration shows that rectenna with CP can reduce P_{av} by a factor of four compared with rectenna-only RF-DC converter when an operating current of IC is 10μA is required at 1V.

5. References

[1] S. Bi et al., IEEE Comm. Mag., pp.118-125, Apr. 2015.
[2] K. Fujimori et al., Euro. Microwave Con., pp.57-60, Oct. 2011.
[3] S. Tokuda, IEICE general conference, C-12-18, Mar. 2018.
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6. Acknowledge

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Table I Comparison table

Topology	η [%]	V_{dd}^{opt}	total cap size
Rectenna only	4	(1V)	0+100μF
Rectenna with CP (priority: η_{CP})	17	0.4V	0.13μF+110μF
Rectenna without CP (priority: A_{CP})	11	0.6V	25pF+110μF

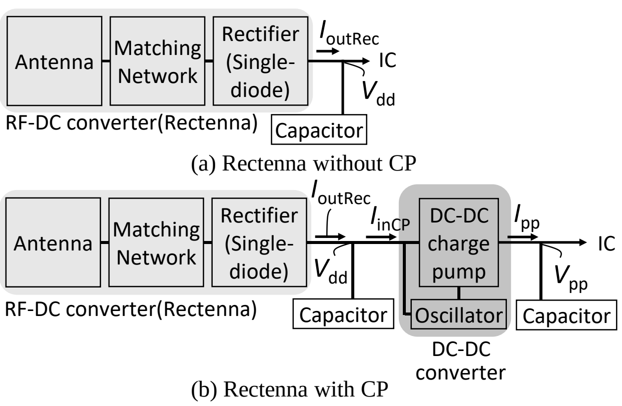

Fig. 1 Circuit block diagram

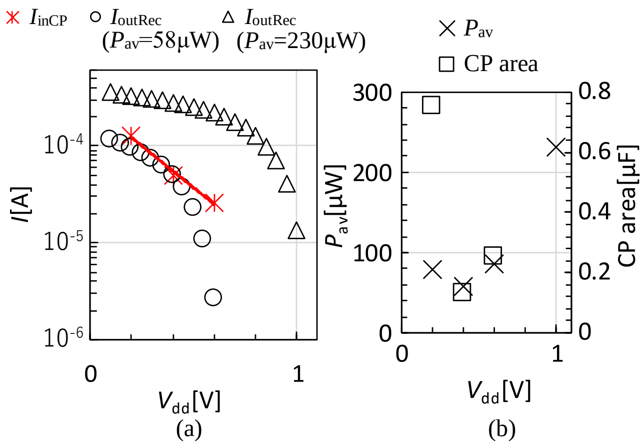

Fig. 2 Demonstration results