

An Ultra-low Power Voltage Regulator System for Wireless Sensor Networks Powered by Energy Harvesting

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A sensor network is composed of individual sensor nodes that can monitor environmental and physical conditions by communicating with other nodes. Sensor nodes may be powered by harvesting ambient energy. A typical radio frequency (RF) energy harvesting system is shown in Fig. 1 [1]. The rectenna is a hybrid antenna/rectifying diode assembly which captures RF energy. The charge pump boosts the voltage level to charge the battery, and then the voltage is regulated by a DC-DC converter before providing it to the sensor. Because the RF power density is very low (e.g. only a few tens to hundreds of $\mu\text{W}/\text{cm}^3$), one needs to minimize power consumptions within individual subsystem blocks.

A sensor node usually has at least two working modes (active mode and standby mode). In active mode, a node consumes high current to collect data or communicate with other nodes. In standby mode, it consumes little current. When sensor node changes between the two modes, the DC-DC converter senses the load change and through feedback a constant voltage is provided to the load. The commonly used DC-DC converter is a low-dropout linear regulator, which is composed of an error amplifier, a pass element and the feedback network [2]. Because of the low input power level, one needs to minimize the quiescent current of the regulator to reduce its power consumption. However, the quiescent current cannot be reduced without bound, otherwise it takes a long time to charge the gate capacitance of the pass element, so the system is slow and may fail to respond to rapid change in load current.

Sensor nodes in different operating modes demand different currents. We propose an ultra-low power hybrid regulator system which utilizes sensor mode information. The hybrid regulator system is composed of two switches and two regulators with different amounts of quiescent current consumption. The system block diagram is shown in Fig. 2. The key idea is to switch between the two regulators depending on the operating state of the sensor. When sensor is in active mode, it needs moderate current. In this case, switch SW is closed and regulator I delivers to the sensor the active mode current. At the same time, regulator I consumes a few μA of quiescent current itself. When sensor changes into standby mode, only a small current is needed, so SW is open and SW/ is closed, and regulator II is used to deliver the standby mode current to the sensor. Regulator II only consumes a nA-range quiescent current itself.

The average quiescent current ($I_{q,avg}$) of the hybrid regulator system can be expressed as

$$I_{q,avg} = \frac{I_{q1}t_{active} + I_{q2}t_{standby}}{t_{active} + t_{standby}} \quad (1)$$

Where I_{q1} and I_{q2} denote the quiescent currents of regulator I and II, respectively. t_{active} and $t_{standby}$ denote the active mode time and standby mode time, respectively. For most of the time the sensor stays in standby mode, i.e., $t_{active} \gg t_{standby}$, so the average quiescent current is much smaller than I_{q1} . The

smaller the duty cycle ($D = \frac{t_{active}}{t_{active} + t_{standby}}$) is, the smaller average quiescent current.

The two switches in the regulator system can be implemented using PMOS transistors instead of NMOS because NMOS is poor at passing high voltages. The two regulators can be implemented using two current sources with little supply voltage dependence. Fig. 3 shows structure of the current source [3] used when the sensor is in active mode, and Fig. 4 shows the current source when sensor is in standby mode. Both structures employ a self-biasing scheme to generate reference currents. The reference currents are mirrored by transistor M_{out} to generate the load currents needed. The sensor standby mode current could be only nA range, and the nA reference current generated by the commonly used structure has a relatively high supply dependence. In our design, M11-M17 generate current I_1 , which is then mirrored by M18 to $m \cdot I_1$; M21-M27 generate current I_2 , which is then mirrored by M28 to $n \cdot I_2$. $m \cdot I_1$ and $n \cdot I_2$ have equal supply dependences. By doing subtraction, the supply dependence would cancel out and the final reference current $I_{ref} = m \cdot I_1 - n \cdot I_2$ is supply independent.

The chip has been fabricated using AMI 0.5 μm process. The sensor node we considered requires 1.8V supply voltage, and 0.1 μA standby mode current and 6mA active mode current. When the sensor is

in standby mode, its equivalent load resistance is $18M\Omega$. Because the input resistance of the oscilloscope is also mega-ohms range, the output voltage measured by the oscilloscope would not indicate the actual voltage drop across the load. So we assumed that the standby mode current was $60\mu A$, which means the load resistance is $30K\Omega$. The loading effect of the measurement instrument can then be neglected. This assumption would not make our previous analysis of the hybrid regulator system invalid, because the standby mode current is still much smaller than the active mode current. Fig. 5 shows the measurement result obtained from the chip. The duty cycle is 10% (i.e., the sensor spends 10% time in active mode). When the sensor is in standby mode, the output voltage to the load is $1.9V$. When the sensor is in active mode, the output voltage is $1.75V$. The output voltages are different from the modeled $1.8V$ because the output currents deviate from the required value due to process variations.

References

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- [3] P. Gray, P. Hurst, S. Lewis and R. Meyer, "Analysis and design of analog integrated circuits", Fifth edition, New York: Wiley, 2009, pp. 307-311.

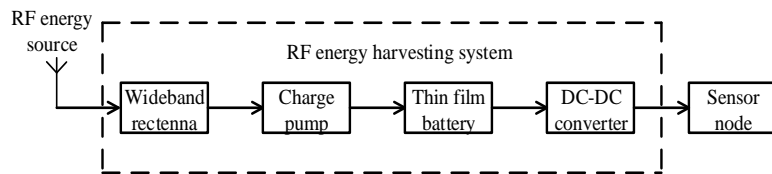


Fig. 1 RF energy harvesting system block diagram

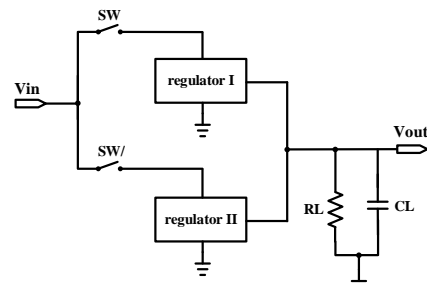


Fig. 2 Hybrid regulator system

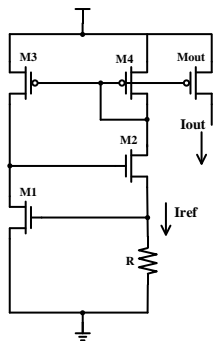


Fig. 3 Active mode current source

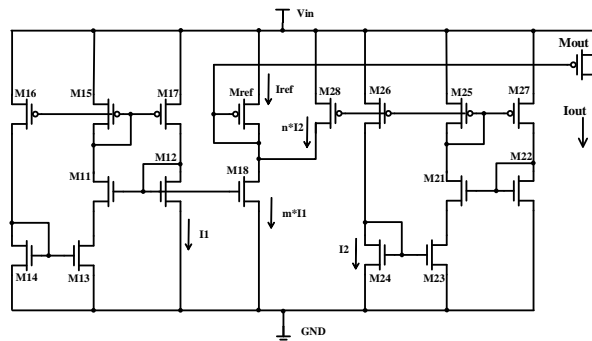


Fig. 4 Standby mode current source

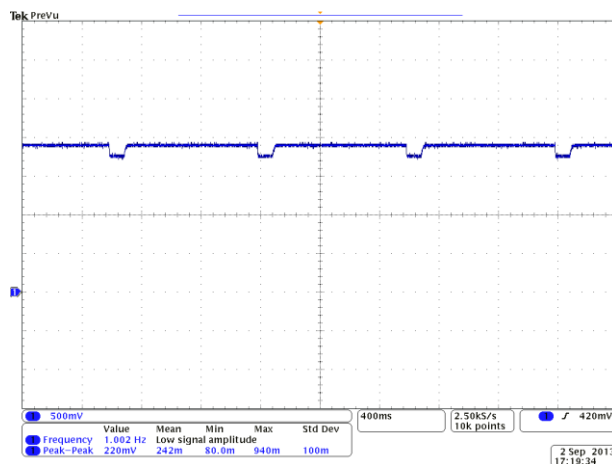


Fig. 5 Measured output voltage