Ultra Low Power Microsystems using RF Energy Scavenging (Invited)

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Abstract

RF energy scavenging enable very small, battery-less sensing and processing systems. Power and timing information are extracted from an RF signal from a base station. A single chip RF powered system can include digital processing, two way telemetry and complete sensor interfaces.

Introduction

RF powered microsystems hold the promise of the smallest, lightest and in many cases the cheapest system solution. The elimination of the battery saves significant cost and weight. Furthermore for biomedical applications, the removal of the battery or power leads removes the hazards of infection and contamination. The die of an RF scavenging microsystem can be smaller than $1mm^2$ and weigh as little as 0.02g. Emerging applications range from the tracking of food, to biomedical implants and to the study of small animals, insects and even single cell organisms.

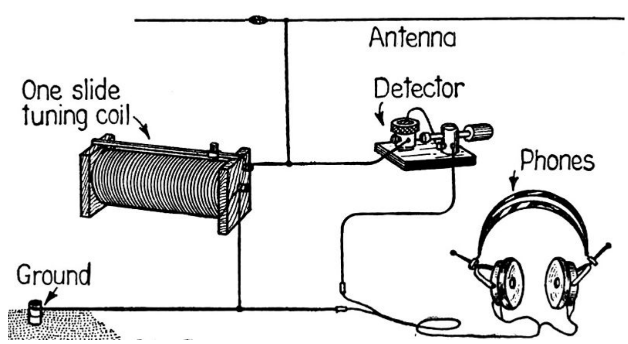

Figure 1 – A crystal radio set from Gernsback's 1922 book "Radio For All". The tuned signal picked up by the antenna is rectified by a metal-semiconductor diode to detect the AM signal. The audio power delivered to the headphone is entirely derived from the RF signal. (This figure is from Wikepedia: http://en.wikipedia.org/wiki/File:CrystalRadio.jpg.)

Low power semiconductor-based systems that employ RF energy scavenging have a long history, dating back a century. The earliest radios were passive systems and relied completely on collected RF energy. These early solid-state receivers (Figure 1) relied on the contact between a metal 'cat's whisker' and a crystal to form a metal-semiconductor rectifying diode. RF energy can be

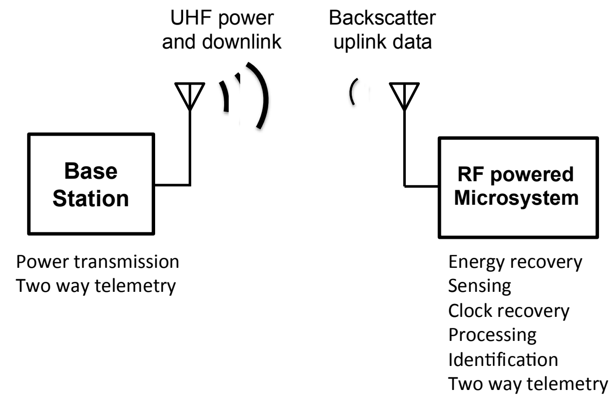

Figure 2 – A base station transmits power, data and a clock to the RF-powered microsystem. Uplink data is efficiently transmitted by backscatter modulation.

scavenged from the ambient or from a dedicated base station. Because ambient RF signals (e.g. WLAN, GSM) are relatively weak [1], in modern systems a base station that transmits power and timing and communicates downlink/uplink data to the wirelessly powered device is preferred (Figure 2).

Overview

In the wirelessly powered device (Figure 3), an antenna collects RF energy and also transmits/receives data. An RF-DC converter rectifies the incident RF signal to power the system.

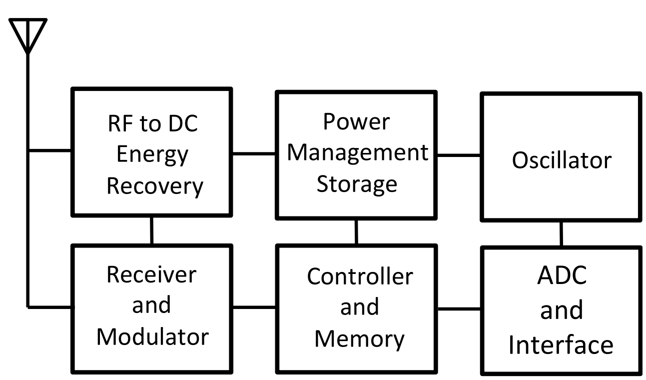

Figure 3 – Block diagram of an RF powered microsystem. A single antenna collects RF energy and also transmits and receives data. The microsystem also incorporates

On-chip power management circuitry ensures a consistent supply voltage. Recovered energy can also stored locally on a capacitor or battery. A simple processor manages sensing, identification and telemetry. RF powered sensing systems can also include an ADC, and an on-chip sensor. Furthermore, some RF powered systems, such as biomedical implants, include actuation or stimulation channels.

Data transmission from the device to the base station can be active or passive. Passive transmission modulates a load connected to the device antenna. This modulation alters the amplitude or phase of the signal reflected back to the base station. Because this approach involves only connecting or disconnecting a passive load, it requires very little energy, typically on the order of 1µW. An active transmission system incorporates a transmitter [2]. Although the use of an active transmitter can increase the telemetry range, the power required to operate an active transmitter is on the order of 1mW, which is often higher than can be scavenged from the base station signal. Data transmission from the base station to the device usually takes the form of amplitude modulation of the RF power signal. This downlink data signal is also encoded to embed a timing signal.

Energy Recovery

One of the biggest challenges in the design of an RF energy scavenging system is the performance of the RF-DC converter. Earlier systems used Schottky diodes, but these are usually not available in CMOS processes. The primary focus for CMOS processes has been the development of circuits that perform efficient rectification and also efficient amplification of the DC supply, to allow reliable circuit operation in the presence of a weak antenna signal.

The threshold voltage and the body effect limit the efficacy of FETs in rectifier circuits. Several circuit schemes have been developed to counter the losses due to these limitations. Beginning with the body effect, Figure 4 shows the drawback of using a fixed connection to set the body voltage. An attractive alternative [3] is the circuit shown in Figure 5, which actively connects the well to the lower of the two S/D voltages.

Figure 4 – A well bias with a fixed connection to either the source or drain can lead to the well being set to too high a voltage leading to reverse leakage.

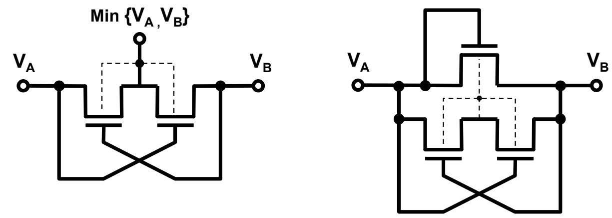

Figure 5 – As proposed in [3], the circuit shown on the left, connects the well to the lower of the two voltages, V_A and V_B. This scheme is used with a diode on the right.

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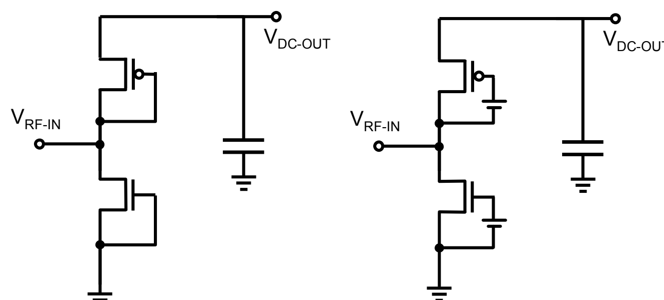

Figure 6 – MOSFETs can function as diodes in a rectifier (left). To overcome the voltage drop due V_T the equivalent of a battery can be added placed in series with the gate (right).

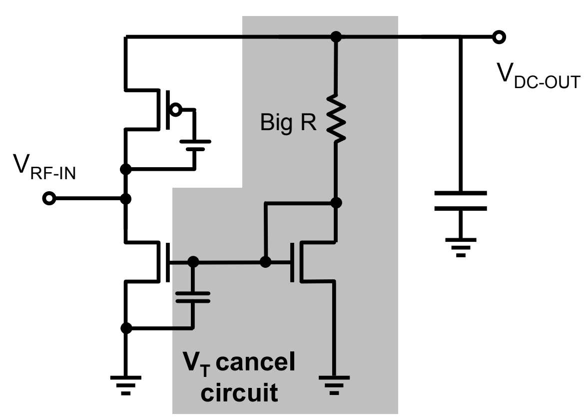

Figure 7 – Internal V_T cancellation circuit proposed by H. Nakamoto, et al. [5]. The large resistor minimizes bias current. This circuit tracks process and temperature variation.

In [4] a capacitor functions as the V_T cancelling battery and this capacitor voltage is periodically refreshed through a switched capacitor scheme. In [5] (Figure 7), an on-chip V_T cancellation circuit generates the appropriate voltage. This continuous-time approach consumes little power, has less parasitic capacitance than other schemes and enables an excellent overall efficiency of 36%. Diode-capacitor chains can be used to generate a DC voltage supply larger than the antenna signal amplitude. The Dickson multiplier (Figure 8) [6], originally proposed by Dickson for memory applications, is widely used.

Clocking and Processing

Most RF powered systems scavenge timing information from the base station signal. Local clock generation with a crystal is expensive in terms of power, weight and size. A clock signal can be embedded through Manchester or FM0 encoding of the downlink signal. Other low power options include injection-locking a local oscillator to the incident RF power signal [2] or digitally calibrating a very-low power (sub 1μW) current-starved oscillator [7]. Near threshold operation enables very efficient digital logic operation at low supply voltage [7].

Power Management

A low drop out regulator can generate a consistent internal voltage supply. Another option, explored in [8], is make circuitry supply insensitive and remove all regulation eliminating the complexity and voltage drop of a regulator. A promising approach for long-range devices is to store energy on a large capacitor until enough energy is available to operate the wireless device for a short burst [2]. The challenge is that operating time is short even with a very large on chip capacitor.

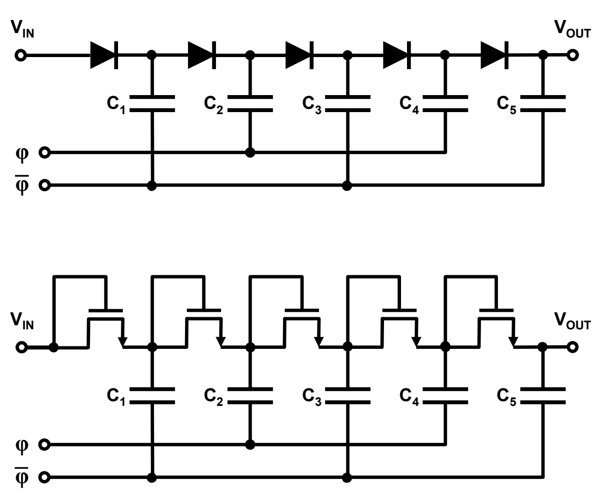

Figure 8 – The Dickson multiplier [6], originally proposed for memory applications, is widely used as an RF-DC converter in RF powered systems.

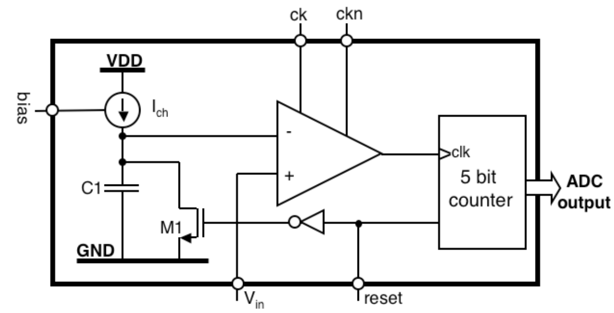

Figure 9 – In [1] a very-compact slope-based ADC is implemented on the RF powered device. The digital value is determined by measuring the time for an on-chip generated ramp waveform to intersect the input signal value.

Sensing Interface

Simple sensors that measure temperature [8], light or magnetic fields can be implemented in standard CMOS. New compact energy-efficient ADC architectures are enabling RF powered digitization of sensor data. Time-based ADCs are especially attractive if an accurate, low-jitter clock can be recovered from the reader. In [2] (Figure 9) a very compact slope-based ADC is implemented on an RF powered device. The digital value is determined by measuring the time for an on-chip generated ramp waveform to intersect the input signal value. A more efficient time-based scheme [9] (Figure 10) incorporates a counter and time-to-digital converter to achieve an overall efficiency of better than 100fJ/conv.step, and a total power consumption of 14μW for a conversion rate of 1MS/s at 9 effective bits. Switched-capacitor successive approximation ADCs are also very energy efficient but occupy more area, have a large input capacitance and place additional burdens on reference generation. Compressive sensing is an emerging approach that exploits signal sparsity to reduce sample rate and power consumption [10].

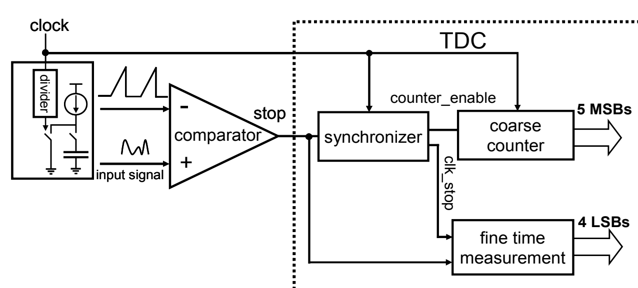

Figure 10 – A more elaborate time-based scheme [9] incorporates a counter and time-to-digital converter (TDC) to achieve an overall efficiency of better than 100fJ/conv.step, and a total power consumption of 14μW for a conversion rate of 1MS/s at 9 effective bits resolution.

Conclusion

RF energy powered systems enable small, light and cheap microsystem solutions. Table 1 presents some typical specifications. Applications range from RFID to emerging applications such as biomedical implants and the monitoring of insects and small animals.

TABLE 1
TYPICAL SPECIFICATIONS

Frequency bands (far field)	900MHz, 2.4GHz
Base station transmit power	4W EIRP
RF-DC efficiency	10-35%
Processor	1-3μW
Non-volatile memory [5]	<15μW
Passive modulator	1μW
AM (downlink) demodulator	1μW
Voltage reference	<1μW
ADC [9]	<10μW
Temperature sensor	1μW
Die area	~1mm^2

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