A Wireless Sensing Platform Utilizing Ambient RF Energy

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Abstract— **An ambient RF energy harvesting sensor node with onboard sensing and communication functionality was developed and tested. The minimal RF input power required for sensor node operation was -18 dBm (15.8 μW). Using a 6 dBi receive antenna, the most sensitive RF harvester was shown to operate at a distance of 10.4 km from a 1 MW UHF television broadcast transmitter, and over 200 m from a cellular base transceiver station. A complete ambient RF-powered prototype was constructed which measured temperature and light level and wirelessly transmitted these measurements.**

I. INTRODUCTION

In practical wireless sensor usage, the need for a battery limits the application space and increases initial and recurring costs, making traditional wired sensors more appealing in some cases. Ambient RF (Radio Frequency) energy harvesting offers a unique solution to this practical problem and facilitates the implementation of a battery- and supercapacitor-free wireless sensing node with 24-hour operation.

A. Why RF harvesting?

Ambient RF energy as a power source for outdoor sensor nodes has an advantage in that it is typically available at all hours of the day and night. A solar harvesting node which needs to operate during the night must include a large charge storage device, such as a battery or supercapacitor, to deal with the blackout period in which its energy source is not available. An RF harvesting node typically need not deal with such a blackout period, and therefore does not need to store as much energy. When the requirement for on-board energy storage decreases, a smaller (longer-lived, more efficient, and less expensive) storage device may be used. Previous work shows that ambient RF energy levels can be sufficient to operate such a sensing node [1][2].

The charge storage device in an energy harvesting node is often the limiting factor in the node lifespan. Use of rechargeable batteries and/or high density supercapacitors in a solar energy harvesting node, along with techniques to prolong the life of each of these charge storage devices, can lead to operating lifetimes on the order of 10-20 years[3], but the complexity of such a system and the cost of the charge storage device may still limit wide-scale adoption. In this work, a conventional ceramic chip capacitor is used to provide the minimal energy storage needed for the RF harvesting sensor node to operate.

A modern RFID tag, which consists of an RF-powered communication IC and a low-cost printed antenna, has
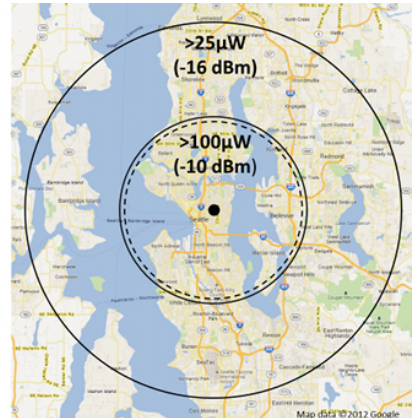

Fig. 1. Available power around one of four 1 MW transmitters in Seattle, WA (2 dBi TX gain, 6 dBi RX gain at 539 MHz). The dotted line indicates the 10.4 km radius tested in this work.

been demonstrated as a good potential form factor for an RF energy harvesting sensor node which doesn't require significant charge storage[4][5].

B. Ambient RF Sources

WiFi transceivers, cellular base stations, AM/FM radio transmitters, and TV broadcast transmitters are all ambient RF energy sources, with varying ubiquity and power output. This work targets TV broadcast and cellular base transceiver station (BTS) signals as ambient power sources, as these signals represent two of the most promising ambient RF sources due to their high transmit power (TV) and ubiquity in urban environments (cellular BTS).
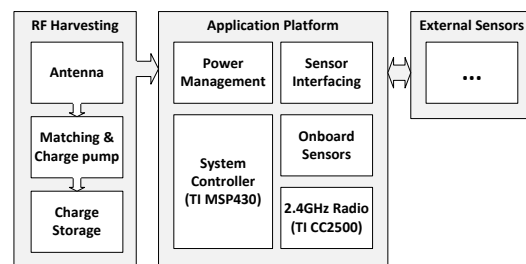

Fig. 2. Ambient RF-powered sensor node architecture

II. System overview

Figure 2 details the sensor node architecture. The first section includes an antenna, harvesting circuit, and charge storage. The second is an application platform which does the useful work of sensing and transmitting data, and also includes power management functionality and simple physical sensors. External sensors may also be interfaced with the system.

The system is duty-cycled to reduce the average power requirements. The majority of the time is spent in a charging state, waiting for a specified charge to accumulate on a storage capacitor. When that charge has been collected, the system switches to an active state and performs one $Sense \rightarrow Process \rightarrow Transmit$ operation. The cycling period is therefore determined by the amount of power available.

A. RF harvesting topologies

Two RF harvesting topologies were characterized and compared. The first harvester (Type 1) is a five-stage discrete Dickson RF charge pump implemented with Schottky barrier diodes. The second (Type 2) uses a discrete full wave rectifier (also with Schottky barrier diodes) in conjunction with a low-voltage DC-DC integrated charge pump.
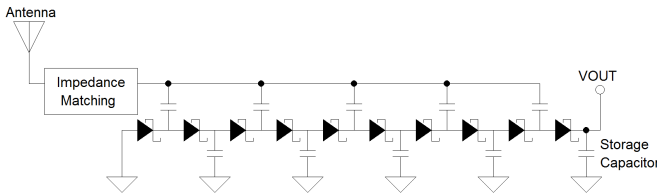

Fig. 3. **Type 1** - Five-stage RF Dickson charge pump harvester
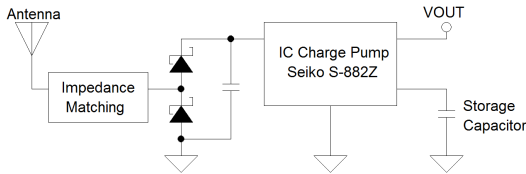

Fig. 4. **Type 2** IC charge pump based RF harvester using S-882Z

The **Type 1** harvester is a five-stage Dickson charge pump implementation made up of Schottky barrier diodes. In this system it requires an external supervisory circuit to monitor the status of the storage capacitor and enable sensor node operation when adequate charge has been collected. This supervisory circuit enables node operation when the storage capacitor voltage reaches 2.4V, and disables operation at 1.8V, allowing the charge to recover.

The **Type 2** harvester makes use of the Seiko S-882Z IC charge pump. A single stage full wave rectifier is used for RF-DC conversion and this low DC voltage provided to the charge pump IC, which has a voltage sensitivity of 300 mV. This IC has an internal voltage supervisor which disables the output while it is collecting charge, behaving nearly identically to the Type 1 supervisory circuit including the use of 2.4V (enable) and 1.8V (disable) thresholds.

B. Power-optimized firmware

A firmware set was developed for the sensor node which provides sensor polling and a minimal radio communication stack. Common sense low-power firmware practices were employed, such as avoiding CPU-intensive math operations, eliminating unnecessary array copies or initialization, and keeping call stacks short. Additionally, the low-power sleep modes of the microcontroller and radio were employed whenever possible

III. Design strategies

Two critical factors which have an impact on the practical usefulness of the RF harvesting sensor node are the operating sensitivity and per-operation energy. These were the two main optimization targets used during the design process.

A. Goal: Improve operating sensitivity

The minimum input power required for operation depends on many factors, with one major factor being the magnitude of the quiescent current draw of the storage capacitor and power management circuit during the charging state. In improving sensitivity, it's critical to minimize the leakage current of these devices.

B. Goal: Minimize operation energy

Reducing the amount of energy required to perform one $Sense \rightarrow Process \rightarrow Transmit$ operation translates to more frequent operation and better temporal resolution in the collected data. Reducing the operation energy also allows for a smaller storage capacitor value to be used, lowering system cost and improving sensitivity and efficiency due to the lower parasitic leakage of smaller capacitors.
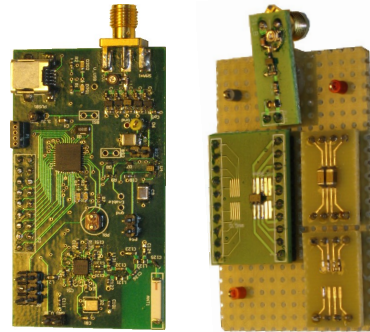

Fig. 5. The ambient RF-powered wireless sensing platform, with Type 1 harvester (left) and early prototype of Type 2 harvester (right).
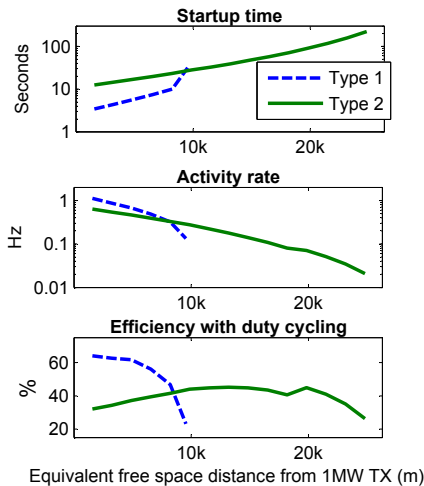
Fig. 6. Cold startup time, activity rate, and efficiency for both harvester topologies vs. emulated distance. The Type 1 and Type 2 harvester sensitivities were -8.8 dBm and -18 dBm, respectively. Efficiency was from 23% to 64% for Type 1, and from 26% to 45% for Type 2. (Uses free-space model, 2 dBi TX gain and 6 dBi RX gain at 539 MHz, C = 160 μF ceramic chip capacitor for both harvesters).

IV. Experimental Results

Prototype implementations of the two RF energy harvesting circuits were constructed (Figure 5) and characterized in both controlled bench testing and real-world scenarios. In the first set of tests, a bench RF power source was used to characterize the performance of each harvester in a controlled situation. The results of this test are shown in Figure 6.

The second set of tests involved connecting the RF harvesting prototypes to an antenna and verifying their ability to operate in an outdoor environment rich in UHF RF energy. Seattle's KZJO-TV broadcast transmitter (Figure 1), as well as a local cellular tower, were targeted as ambient RF energy sources. The TV station operates at 539 MHz and emits up to 1 MW of RF power. In one test, the Type 2 harvester placed at a location 10.4 km away from the KZJO-TV transmitter was able to cold-start and operate with a cycling period of 3 seconds. The cellular BTS (cell tower) targeted transmits with a center frequency of 738 MHz and an unknown power output. Figure 8 depicts the tested locations around the cell tower.

Another experiment demonstrates the feasibility of actual sensing and communication using this platform. A Type 1 harvester and application platform is placed at a location 4.2 km distant from KZJO-TV and is able to measure and transmit ambient light level and temperature at a rate of nearly 1 Hz over a 5.5 hour interval.

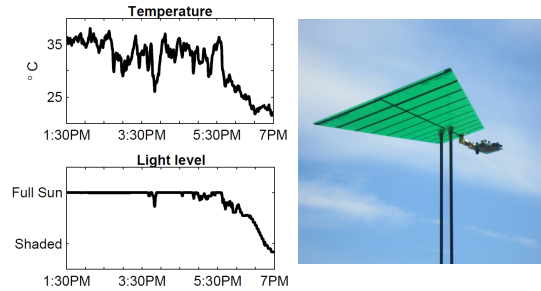The per-operation energy use of the optimized system

Fig. 7. Sensor measurements from the ambient RF harvesting sensor node, reported over a 5.5 hour interval. The sensor node is cast in shadow and cools off later in the day.

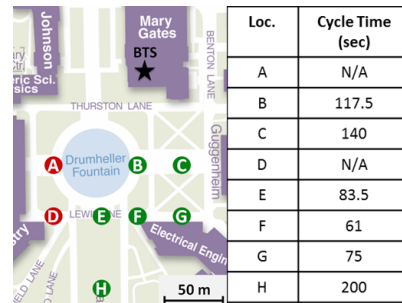| Loc.	Cycle Time (sec)
A	N/A
B	117.5
C	140
D	N/A
E	83.5
F	61
G	75
H	200

Fig. 8. Tested harvesting locations around a 738 MHz cellular base transceiver station (BTS). Type 2 harvester was able to operate at all locations except A and D (6 dBi RX gain, C = 160 μF)

was 218 μJ when measuring and transmitting temperature and light level with a transmit power of +1 dBm.

V. Conclusion

Two ambient RF energy harvesting topologies and a fully functional sensor node were developed and tested in a real-world RF harvesting scenario. The most sensitive harvester allowed sensor node operation at a distance of 10.4 km from a 1MW TV transmitter using a 6 dBi antenna, and over 200 m from a cellular base transceiver station.

VI. Acknowledgements

References

[1] A. Sample and J. Smith, "Experimental results with two wireless power transfer systems," in *Radio and Wireless Symposium, 2009. RWS '09. IEEE*, jan. 2009, pp. 16 –18.

[2] H. Nishimoto, Y. Kawahara, and T. Asami, "Prototype implementation of ambient rf energy harvesting wireless sensor networks," in *Sensors, 2010 IEEE*, nov. 2010, pp. 1282 –1287.

[3] F. Simjee and P. Chou, "Efficient charging of supercapacitors for extended lifetime of wireless sensor nodes," *Power Electronics, IEEE Transactions on*, vol. 23, no. 3, pp. 1526 –1536, may 2008.

[4] A. Sample, D. Yeager, P. Powledge, A. Mamishev, and J. Smith, "Design of an rfid-based battery-free programmable sensing platform," *Instrumentation and Measurement, IEEE Transactions on*, vol. 57, no. 11, pp. 2608 –2615, nov. 2008.

[5] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *Solid-State Circuits, IEEE Journal of*, vol. 43, no. 5, pp. 1287 –1302, may 2008.