Green Monitoring Using A Wide Area Radio Network for Sensor (WARNS) Communication

Venumadhav Bhagavatula, William Wesson and Jacques C. Rudell
Electrical Engineering Department
University of Washington
Seattle, WA
e-mail: jcrudell@u.washington.edu

***Abstract*—Enabling long-range, small form-factor transceivers can address a number of green and environmental monitoring applications. This paper explores an alternative method for sensor data communication using long-range wireless transceivers to communicate sensor data. A Wide Area Radio Network for Sensor (WARNS) communication which allows direct communication of a sensor mote to a base-station several kilometers away is proposed along with a discussion on the associated hardware challenges. A study is also provided for one of the most challenging hardware blocks in a WARNS radio, the Power Amplifier (PA).**

Keywords-sensor motes; mesh networks; smart grid; power amplifier; solar cells ; energy harvesting

I. INTRODUCTION

The evolution of small form-factor, single-chip wireless transceivers has enabled many new previously unimaginable forms of connectivity. One such area which has benefited from low-cost miniature radios is the ability to not only acquire information from micro-sensors but also transmit this data in real time over a wireless link. For the past decade researchers have been exploring new circuit topologies, radio architectures, networking methods and approaches to energy scavenging which allow autonomous operation of mobile wireless transceivers for sensor data communication [1]. The very nature of sensor applications typically demands that a single device reside remotely, for potentially several years, thus much research effort has been placed on minimizing the transmit energy on a per bit basis.

The need to minimize energy usage for wireless sensor applications has led to the popularity of mesh (or collaborative) networks, Fig.1. In such systems, data is transmitted through a series of short-range wireless links to minimize the distance between sensor nodes in the network and thus reduce the required transmit power.

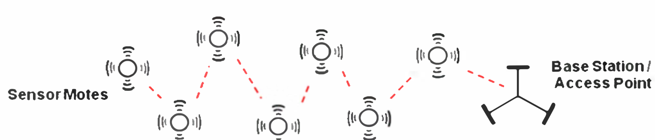

Figure 1. MESH network data flow from a sensor node to an access point.

Previous analysis based on the well-known path loss characteristics of isotropic radiation using (1),

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{1}{4\pi d f}\right)^2 \quad (1)$$

has shown that an optimal distance between individual nodes in a collaborative mesh system theoretically yields the lowest energy consumption per bit, when transmitting a given distance (d) [1].

Although collaborative networks realize an optimal power consumption solution under ideal conditions, several practical drawbacks erode the energy advantages in networks comprised of very short range wireless links. Periodically, each node must “wake up” to assess whether data from adjacent nodes must be routed through said node. This requires additional “receive wakeup” energy to allow network synchronization and routing. Moreover, the optimal energy usage in mesh networks assumes each node is ideally positioned relative to adjacent sensor motes. This may not be practical, particularly for applications where the individual sensors nodes are deployed from an airplane or mobile vehicle with the resulting final position of each sensor mote, relative to other nodes, being random [2]. The power advantages associated with mesh networks are further challenged upon initial deployment by the complexity associated with “network self-assembly”. Additionally, there are sensor applications which may have low-spatial density requirements. In such cases, deployment of a large mesh network to acquire information in remote locations would require numerous nodes collecting redundant data. Lastly, there are a plethora of envisioned applications which would require sensor mobility, further complicating the routing of data in a mesh network.

In this paper, an approach to sensor network communication which more closely resembles characteristics of Wide Area Networks (WAN) is proposed as an alternative to mesh systems. Specifically, this work seeks to explore communication of a sensor node to a base-station several kilometers away. The concept, which shall be named a Wide Area Radio Network for Sensor (WARNS) communication, is described in Section II. This is followed in Section III with a feasibility study of the transceiver hardware necessary for practical long-range communication using conventional energy scavenging devices[1], off-the-shelf super-capacitors,

[1]Note: This feasibility study limits the energy scavenging device to a solar cell and the energy storage element to a super-capacitor.

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and a custom power amplifier. Finally, summary comments are given in the conclusion.

II. WARNS SYSTEM

In an effort to vastly increase a sensor node's communication range, a Wide Area Radio Network for Sensor (WARNS) communication is suggested, Fig. 2. A key aspect of this network is the realization of small form-factor wireless transceivers which utilize conventional energy scavenging devices, such as solar cells, and have the ability to transmit several kilometers with modulation methods compatible for communication with standards-based wireless networks. If future sensor motes could transmit data over distances commensurate with cellular communication, the potential exists to leverage available infrastructure and thus provide coverage for virtually all urban and suburban locations worldwide. Moreover, potential multimode solutions would further expand network access through standards based systems such as WiFi and Bluetooth. Other access points could include predator type drones for military or surveillance applications.

WARNS is ideally suited for remote sensor applications or those requiring low spatial density. Examples could include environmental monitoring [3] for global warming research or homeland security applications – such as "tripwires" – to sense chemical, biological, or nuclear material.

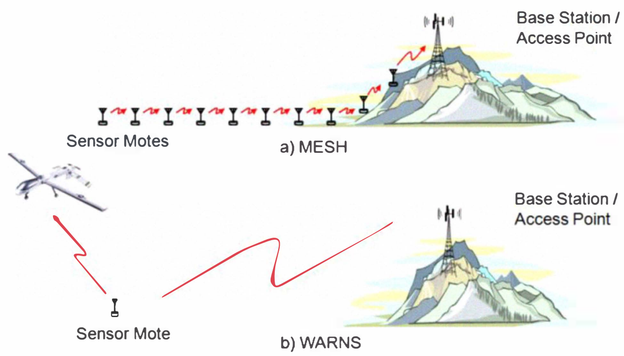

Figure 2. WARNS versus mesh Sensor Networks

In these examples, mesh based systems or hybrid wired and wireless solutions as proposed by the NIMS network [6] would involve significant infrastructure investment to support sensor motes in remote locations. The environmental impact associated with deployment of complex mesh and NIMS networks further inhibit use for many applications. In addition, WARNS would easily facilitate sensor communication for remote mobile applications. Examples might include reporting livestock vital signs and, if reliability concerns could be adequately addressed, human health monitoring applications.

Lastly, numerous "Smart Grid" scenarios are evolving which utilize wireless transceivers to intelligently gather and distribute renewable forms of energy. One such example, "Smart Wires" [4], uses a method of "dynamic rating" [5] to optimally balance transmission power line capacity to match real-time environmental conditions including air temperature, wind speed and direction. Smart Wires could substantially increase the power transfer capacity of low-cost renewable energy found in remote locations, including Northern Canada and parts of the Southwestern United States, to population centers several hundred miles away. Many of these power lines are routed through remote locations and acquiring sensed information about Smart Wire dynamics require communicating data over an equivalent distance. Long-range wireless transmission could address this need in remote locations.

III. GSM: A CASE STUDY

A. Energy Harvesting & Simplified Transmitter Model

A key aspect for the feasibility of WARNS is the ability to acquire enough energy in the sensor mote to allow a transmit (TX) burst at high output powers. This study focuses on the upbanded version of GSM-PCS 1900, at 1.9GHz, with a maximum output power of 1Watt. The question becomes, is it possible to transmit a sustained burst of +30dBm (1Watt) for a duration of one GSM timeslot (577μs) using small form-factor solar cells and super-capacitors? Table I shows a power density comparison of small form-factor energy sources. Button batteries are insufficient to allow output power levels for sustained durations in the field and among conventional renewable sources of energy solar cells provide the best power density [7]. Therefore, this work focuses on the use of solar cells used in conjunction with a super-capacitor.

TABLE I. POWER DENSITIES FOR VARIOUS ENERGY SOURCES

Power Source	Power Density ($\mu W/cm^3$)	Lifetime
Lithium Battery	100	1yr
Solar Cell	10-15000	∞
Air Flow	380	∞
Temperature Gradient	50	∞

A simplified circuit model used to benchmark the form factor for a WARNS transmitter is shown in Fig.3. The solar cell charges a super capacitor which is then connected to the PA during the TX burst. An estimate of energy stored on the capacitor can be obtained and compared to the total energy required to transmit a single GSM packet at maximum output power,

$$\frac{1}{2}C \cdot \Delta V^2 = P_{out} \cdot N \cdot T_{frame} \quad (2)$$

where T_{frame} is the duration of a single GSM timeslot, P_{out} is 1Watt for maximum power and N is the number of transmitted GSM timeslots. Our research targets building a CMOS PA which can operate on a lower supply voltage of 1V and utilizes solar cells which charge a super capacitor to 2.5V. In addition, the PA should maintain a constant output power as the super capacitor voltage varies from 2.5V to 1V. Assuming that an energy source could charge the voltage on the capacitor to 2.5V, a quick calculation using (2) reveals that a 0.5mF capacitance is sufficient to transmit one GSM timeslot.

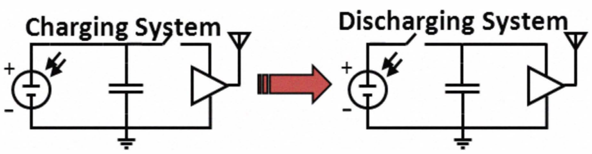

Figure 3. Simplified diagram of the solar cell, storage element and PA.

B. *Super-Capacitor Sizing*

Additional insight on feasibility is gained by re-writing (2) as a function of the change in voltage across the capacitor,

$$\Delta V = \sqrt{\frac{2 \cdot T_{frame} \cdot P_{out}}{C}} \qquad (3)$$

During a TX burst, there is a drop in the amplifier supply voltage. By increasing the capacitor size, ΔV is reduced for a given TX burst, however, both charge time and capacitor area are increased. Thus, the transmit duty cycle will be reduced to account for longer charge times between TX bursts. Using component areas for commercially available capacitors this trade-off is shown in Fig. 4.

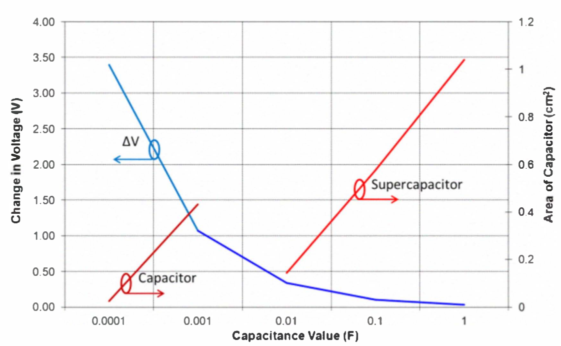

Figure 4. ΔV and capacitor area vs. capacitance value

IV. 'REGULATOR-LESS' POWER MANAGEMENT

As shown in (3), when a frame is transmitted, energy is drawn from the super capacitor resulting in a corresponding voltage drop. In order to maintain a constant PA output power, there are two possible design strategies. One is to use a supply regulator to supply a constant V_{DD} to the PA. The second alternative approach is realized by designing a PA that could allow a wide variation in the supply voltage (V_{DD}) while maintaining a constant output power, without explicit use of a supply regulator.

A. *Switching Regulators*

Two possible approaches exist for regulating the V_{DD} of a PA. The first and preferred method from an efficiency perspective is the class of switching regulators such as a buck or boost-buck regulator. Switching regulators have the advantage of attaining efficiency well above 90% in CMOS. However, for high-power output applications as found in cellular like PAs, there are stringent requirements on both the spectral mask and the wideband TX spectrum. This makes the use of switching regulators coupled with long-range cellular PAs problematic. The switching noise found in these types of regulators often create both close-in and far-from-carrier spurious components, thus negating their use in cellular PA applications. In addition, switching regulators require an inductance where both the value and the Q are incompatible for integration in silicon. For our research, we neglected the use of switching regulators for the aforementioned reasons.

B. *Liner Low Drop Out (LDO) Regulator*

An alternate approach to supply regulation is through the use of an LDO. The generic topology of an LDO consists of a p-channel MOSFET switch designed to source the large supply current and a feedback loop to control the regulated output voltage, $V_{reg\text{-}pa}$. If we define supply voltage to the LDO as the on-board super capacitor to be $V_{super\text{-}cap}$, then the efficiency of the LDO is

$$\varphi_{ldo} = V_{reg-pa} / V_{super-cap} \qquad (4)$$

The efficiency of the regulator is inversely proportional to the super capacitor voltage. Thus, the power efficiency of the system is degraded by the regulator efficiency. Assume, as in the previous section, a PA with a 1V supply that utilizes a super capacitor which charges to 2.5V. For this example, the minimum efficiency occurs when the super-capacitor is fully charged (2.5V) and the overall transmitter efficiency may be expressed as,

$$\varphi_{sys} = \varphi_{ldo} * \varphi_{pa} = \frac{1.0}{2.5} * \varphi_{pa} = 0.4 * \varphi_{pa} \qquad (5)$$

Thus, at the beginning of a TX burst, the capacitor voltage is largest while the LDO efficiency is at a minimum. This is particularly problematic when the PA is transmitting at maximum output power.

To address the inefficiencies associated with using an LDO we have designed a CMOS PA that eliminates the need for a constant V_{DD}.

C. *Simulation Model for WARNS PA*

While the implicit goal of our research is to design circuits with the lowest power consumption[2], the explicit goal is the development of circuits and architectures which allow practical long-range transmission using small form-factor conventional energy scavenging sensor motes. In this feasibility study we constrained our PA design to fit within a volume of 1cm^3. The actual PA will be integrated as a single-chip CMOS device, occupying negligible area: therefore, the

[2] Maximum output power for a PCS 1900 PA is +30dBm. Therefore, it's difficult to argue that one is building an "ultra-low power" circuit when the PA is delivering 1 Watt of output power.

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residual space is intended for both the energy scavenging solar cells and super capacitors.

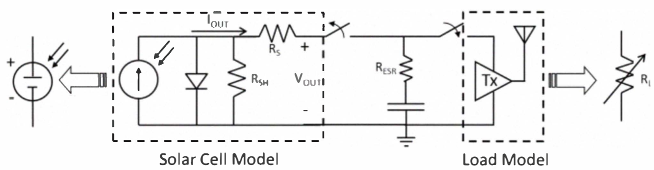

Figure 5. Solar cell symbol and equivalent circuit model

A circuit model was built to mimic the the charging and discharging states of the transmitter described in Fig.3. A unique property of this transmitter is the lack of a voltage regulator. The PA and transmitter draw constant energy from the discharging super-capacitor during a TX burst. As shown in Fig.5, a solar cell can be modeled as a light-controlled current source in parallel with a diode. R_{SH} and R_S constitute the parasitic shunt and series resistances respectively and I_{OUT} represents the output – or charging – current of the solar cell [8]. In the case where the solar cell load is a capacitor, V_{OUT} will increase until the shunt diode forward biases, at which point the capacitor will cease to store extra energy and fix the supply voltage. The validity of this model was confirmed by matching simulation results with the performance of commercially available solar cells measured in the lab.

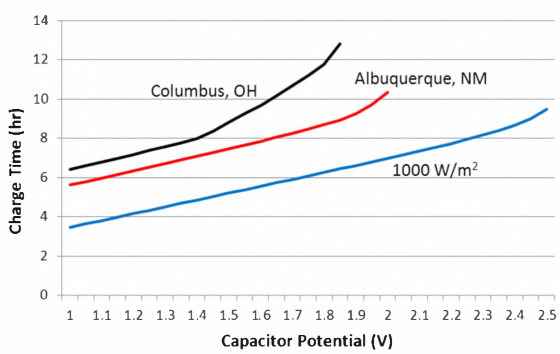

Figure 6. Charge times vs. capacitor voltage for a 1F capacitor with the solar cell model

To mimic realistic charging scenarios charge times were simulated for different lighting conditions [9]. Fig.6 depicts the charging time required for a given supply voltage for a 1F super-capacitor with 70mΩ series resistance under different lighting conditions. The solar cell charging currents are closely modelled to commercial solar cells [10]

In order to maintain constant output power, we have developed a PA which delivers constant power to a variable load impedance, adjusted as the supply voltage drops. When using a *constant power-output load*, simulations were run to determine the total available transmit time that can be extracted from a charged capacitor, as well as the minimum capacitance value needed to send one GSM packet. Using the circuit shown in Fig.5 a 1F super capacitor was first charged to varying voltage levels, then discharged through a switch with 10mΩ series resistance into a constant power load. Fig.7 shows the potential transmit length at several PA output power levels as a function of charge time. It should be noted that the charge times shown in Fig.7 are for a capacitor charging from 0V. In typical operation, the capacitor will not discharge completely to 0V, resulting in significantly less recharge time for the next burst.

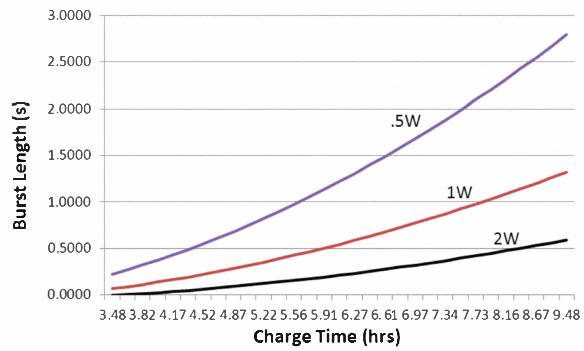

Figure 7. Circuit Simulation results of burst length vs. charge time

Currently, we are realizing a 90nm TSMC 9-metal CMOS regulator-less transmitter which allows a constant draw of energy from a super-capacitor. This PA will more efficiently convert charge to output power and is estimated to achieve maximum output power for a GSM burst (1Watt). In addition, the voltage on the super-capacitor will be allowed to discharge to a lower voltage than what otherwise could be allowed with an integrated voltage regulator.

V. Conclusion

A new concept for long-range sensor communication was presented. Although many questions and challenges remain for the realization of WARNS communication, some aspects appear feasible. In particular, this paper presented a simulation model of a custom integrated CMOS PA assembled with off-the-shelf components for the solar cell and super capacitor. It was found that in a $1cm^3$ area sufficient energy could be stored, to sustain burst of numerous PCS 1900 (GSM) timeslots.

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