Integrated CMOS Transceivers Applied to Defense Applications in a Wide Area Radio Network for Sensor (WARNS) Communication

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***Abstract*—Enabling long-range, small form-factor transceivers can address many remote and/or mobile sensing applications. This paper explores an alternative method for sensor data communication using long-range wireless transceivers to transmit sensor data which is ideally suited for many military applications. A study is also provided for one of the most challenging hardware blocks in a WARNS radio, the Power Amplifier (PA). This paper concludes with some comments on potential future areas of research for long-range highly-integrated transceivers.**

Keywords-sensor motes; mesh networks; barrier coverage; 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.

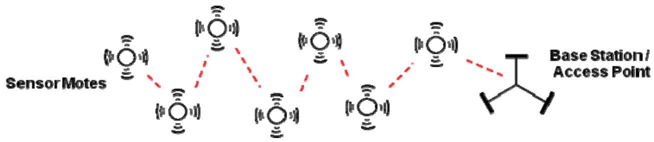

Figure 1. MESH network data flow from a sensor node to an access point.

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]. This is particularly true in many defense applications where the sensors are relatively remote and deployed randomly; an example being barrier coverage applications. 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 Wide Area Radio Networks 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] and a custom power amplifier. Finally, summary comments are given in the conclusion.

[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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II. WARNS SYSTEM

A key aspect of the WARNS 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 with communication on either standards-based wireless networks or custom designed systems. 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.

With sufficient range enabled through new transceiver architectures, these wireless devices could be made to communicate with access points found either on Unmanned Ariel Vehicles (UAVs) or Satellite stations. Such a transceiver will be realized through a combination of new wireless technologies which specifically emphasize small form-factor, high integration, low-cost transceivers which communicate over long distances. New methods of signal modulation, antennas customized for high gain when placed close to a ground plane, customized transceiver architectures which optimize energy efficiency rather than power efficiency and new methods of energy scavenging will all play a roll towards realizing long-distance wireless sensor communication.

WARNS is ideally suited for remote sensor applications or those requiring low spatial density. Examples could include environmental monitoring [3] or homeland security applications – such as "tripwires" – to sense chemical, biological, or nuclear material [4].

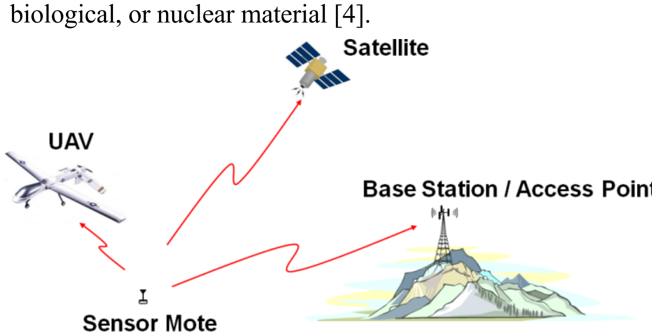

Figure 2. WARNS versus mesh Sensor Networks

In these examples, mesh based systems or hybrid wired and wireless solutions as proposed by the NIMS network [5][5] 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.

One particular remote-sensing application that has garnered research attention is that of reliable barrier coverage[2]. The ability to surreptitiously detect vehicle or troop movement can provide significant advantages in applications on both home and hostile soil. Depending on the area to be covered, the only means of barrier installation may be by airdrop. This coupled with acquisition of sensor data by UAVs is a proposed new scenario for recovering data in the field. If a short range wireless network is utilized, issues with receive wake-up energy, node placement, and self-assembly may limit the practical area of barrier coverage. Since WARNS contains long-range wireless sensors, barrier coverage can be utilized in extremely remote areas.

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[6]. 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.

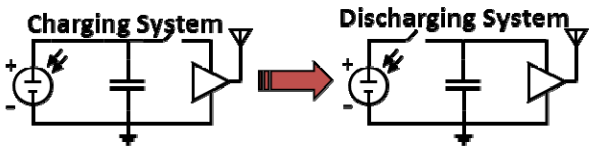

Figure 3. Simplified diagram of the solar cell, storage element and PA.

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,

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

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.

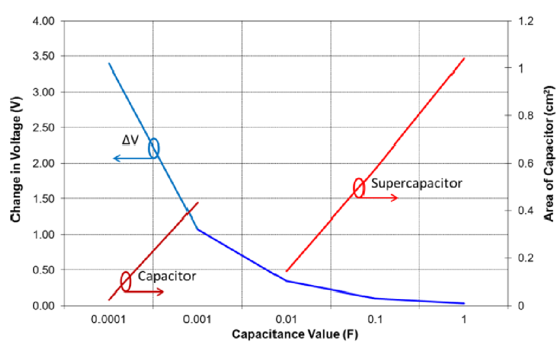

Figure 4. ΔV and capacitor area vs. capacitance value

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 maintain a constant PA V_{DD}. The second 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. 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. Linear 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

$$\varphi_{ldo} = V_{reg-pa} / V_{super-cap} \tag{4}$$

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

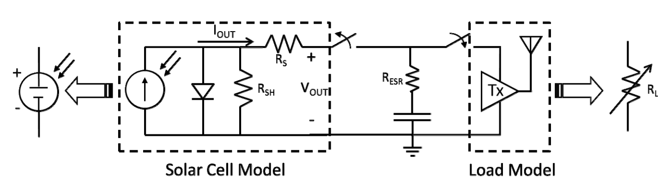

Figure 5. Solar cell symbol and equivalent circuit model

A circuit model was built to mimic the the charging and discharging states of the transmitter described in Fig.3. The PA and transmitter draw constant energy from the discharging super-capacitor during a TX burst.

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.6 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.6 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.

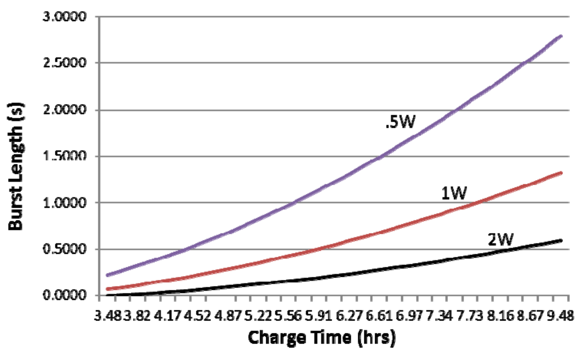

Figure 6. Circuit Simulation results of burst length vs. charge time

V. Additional Challenges For WARNS

Although much of the work described in this paper explores the feasibility of implementing single-chip solutions for the transceiver portion of a WARNS radio, other areas of innovation with respect to antenna design, architecture and signal modulation are yet to be explored.

A. Antennas for Near-Ground Transmission

One intuitive argument which relates the power consumed as a function of transmission distance, can be made from the perspective of path loss and radiation patterns for a single long-range transmission vs. numerous short range hops as found in a MESH system. Fig. 7 illustrates the comparison where it becomes immediately evident that a more efficient radiation of electromagnetic energy is accomplished with the MESH as opposed to a WARNS like system.

Similarly, phased-array transmitters could be applied to single-hop sensor transmission using beamforming techniques. The reduction in required phased-array transmit power as compared to isotropic radiation is proportional to the number of elements in the array. However, to match the theoretical energy per bit of a mesh transmission, the number of elements in the antenna array would need to match the number of nodes in a mesh network. This would be rather impractical and therefore, other techniques combined with a phased-array transmitter should be explored.

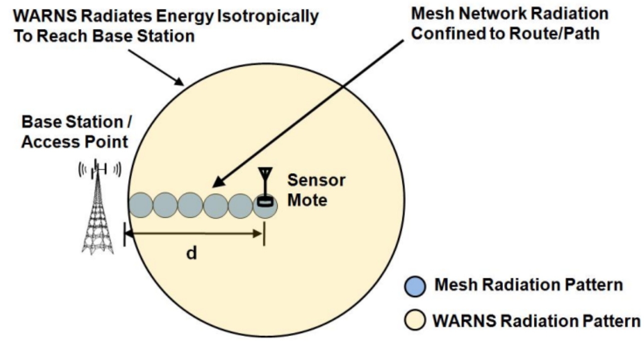

Figure 7. Radiation patterns for both isotropic and mesh transmission.

VI. Signal Modulation and Networking

A yet relatively unexplored area towards the reduction of required power consumption in unattended ground sensors is the use of sophisticated signal processing and coding techniques. This is similar to what is already done with deep space probes. For space applications, the emphasis is on utilizing vastly superior antenna gains and processing power on earth, while the space probe with limited energy scavenging, transmits at a high coding rate to reduce the E_b/N_o. At the University of Washington, we are currently exploring similar techniques applied to unattended ground sensors where the basestation could allow sophisticated processing algorithms to decode transmitted sensor signals.

VII. 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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