

Strategies for Highly-Integrated Long-Range Silicon Transceivers for Sensor Data Communication

Jacques C. Rudell
University of Washington,
Department of Electrical Engineering
Seattle, WA

Venumadhav Bhagavatula
University of Washington
Department of Electrical Engineering
Seattle, WA

Abstract—The evolving application space for sensor data communication demands wireless transceivers characterized by long-range, small form-factor devices. This paper explores strategies towards the goal of single-hop, long-distance wireless communication for sensor applications using monolithic CMOS transceivers. A regulator-less PA system for sensor communication is highlighted in the context of long-range communication.

I. INTRODUCTION

Sensors are finding an infinite number of applications ranging from intelligence gathering for the military to homeland security, baby and pet monitoring, increasing efficiency of power delivery in smart grid applications, and environmental monitoring, to name a few. Often the usefulness of the information reported by these sensor devices is dependent on the ability to transmit data from the sensor, to an access point. With the evolution of single-chip radios, wireless communication of sensor data has become one of the more popular methods of collecting sensed information. Many of these sensors must remain in remote locations with very limited (or no) access to a battery source. Thus, both the sensor and the wireless device must either utilize a single battery for the life of the device or utilize a form of energy scavenging to run autonomously. Given the lack of a stable energy source in these systems, every joule counts, thus to ensure longevity as well as reliability, research on wireless sensors to date has predominantly focused on maximizing the energy efficiency using joules per bit as the key metric. The sensor transmitter system can be broadly characterized into energy harvesting (EHS) and data-transmission subsystems (DTS) each of which provides plethora of opportunities for energy optimization. Recent reports [1] introduce novel EHS techniques to maximize the energy extraction from solar panels which is critical in conditions where solar energy itself is scarce. Towards the goal of achieving a low power DTS, collaborative mesh networks utilizing very short range transmissions (less than several meters) have evolved as a popular approach. Theoretically, mesh networks provide an optimal solution from the perspective of node energy/bit transmission over a distance “d” [2]. Ideally, this is achieved by concentrating radiated electromagnetic energy along a

well-defined path through multiple short range links, rather than radiating isotropically with a single transmission. While mesh networks are well suited for applications which require a high sensor density, other sensor usage models may require a lower density of sensors as may be the case with environmental monitoring, homeland security and a variety of mobile devices. An alternative approach to sensor data communication is to extend the transmission range of a single sensor node. Such a paradigm shift, the subject of this paper, will require new design techniques for a high efficiency DTS capable of operating over several kilometers while powered by an autonomous energy scavenging device and still retaining the properties of a low-cost, single-chip transceiver.

Section II begins with a description of the challenges associated with long-range transmission. This is followed in Section III with some suggested system strategies which could be applied to enable long-range sensor communication. Section IV will then explore ways to rethink how both system and chip-level circuits are realized to optimize the efficiency under the unique condition of devices running off of an energy storage element. As a demonstration of some of the concepts introduced in this paper, highlights of a Regulator-less Power Amplifier intended for use in a long-range sensor transmitter are given. Finally, Sections V and VI provide some measurements and concluding comments.

II. LONG-RANGE SENSOR DATA COMMUNICATION

As alluded to earlier, there are theoretical energy efficiency advantages to transmitting sensor data using a series of short-range wireless hops when shuttling sensor data to an access point. In short, because the radiated power of an isotropic transmission is dependent on $\sim 1/d^2$, where, d, is the distance from an isotropic transmitter to the intended receiver, a net savings in power of n can be obtain by breaking up a single isotropic transmission into n intermediate nodes; this assumes the same received power in both cases. This savings in power is attractive for many applications with a high density of sensors nodes as is found in mesh networks. Beyond improving the energy/bit efficiency, further advantage is afforded by the pico-cellular nature of collaborative networks which allows frequency reuse. However, there are challenges

associated with a mesh network which limits practical use in many applications, these include issues surrounding network self-assembly and receive wakeup synchronization. Moreover, these challenges become exacerbated when one of the sensor nodes becomes mobile within the network. Lastly, there are remote applications which may not require such a high density between the sensor nodes. Environmental monitoring, homeland security, livestock monitoring and even some envisioned smart grid applications would require sensor nodes that transmit several kilometers.

Assuming an extended transmission range of a single-chip sensor radio could be enabled, future transceivers could communicate with base-stations several kilometers away. Increasing transmission range would allow future integrated sensor radios to leverage existing WiFi, and cellular infrastructure to deliver data in urban areas. Moreover, integration of these radios in CMOS technologies would allow highly programmable radio architectures which could “network scavenge” to find the most energy efficient available communication path to deliver data. Although the vision of enabling sensor radios to communicate directly with existing wireless infrastructure could be years away, the key enabling performance feature is the ability of a small form-factor transceiver to communicate over long-distances (on the order of kilometers) while harvesting enough energy from the surrounding environment.

III. CHALLENGES AND POSSIBLE DIRECTIONS

Many technical challenges must be addressed to fulfill the vision of long-range single-chip sensor transceivers. Central to this challenge is whether or not sufficient energy can be harvested and used for short transmit burst over distances of several kilometers. The issue has been explored in [3] for the specific case of a GSM transmitter delivering one watt of output power while running off of a solar cell. Charge times of less than an hour with moderate outdoor light conditions are necessary to transmit 1 Watt for 577 μ s (Single timeslot in GSM). However, to achieve practical commercial solutions further multi-disciplinary research is required, involving areas of communications, antenna design, power harvesting/electronics, and lastly rethinking both front-end RF circuits and chip-level architectures which are optimized for the specific case of an energy storage element, rather than a fixed voltage battery.

A certain level of feasibility exists for small-form factor, wireless sensor nodes which communicate over long-distances. An analogy can be drawn from the space community where probes sent to remote locations, such as Mars, are expected to communicate back to Earth. If for example, the recent Spirit and Opportunity Mars Explorer Rover (MER) are used as comparison, one notes the solar panel area relative to the MER communication distance is very small. However, very high rate convolution codes using a low-energy transmission are used with very low-data rates [4]. Similarly, the small-form factor associated with the probe limits the antenna size and gain. However, on earth, giant deep space antennas are used in conjunction with massive computing power to search and decode long sequences of data. Thus, both the burden of antenna gain and virtually

limitless computing power reside on the stationary side of the wireless link between the MER and the earth base-station. Similarly, small-form factor sensor nodes which communicate with cell base-stations have similar limitations with respect to energy scavenging, antenna gain, and computing power. However, in the case of cellular sensor communication, again the burden with respect to the modulation, antenna gain/size, could be placed on the base-station side, helping to significantly reduce the required energy of the mobile sensor transceiver; this analogy is highlighted in Fig.1, with a comparison of a MER Direct-To-Earth (DTE) and sensor mote to cell tower communication. As a relative comparison, a ratio of the solar cell area [5][6] to the link distance is provided. The solar cell area for the MER is 6 orders of magnitude less, normalized to the transmission distance, than an envisioned sensor mote which would communicate directly with existing infrastructure.

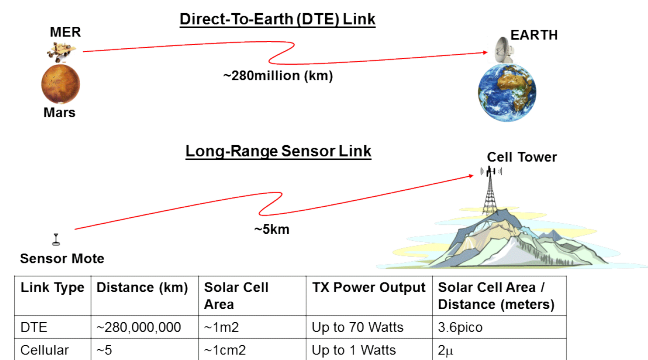


Figure 1: Analogy between Direct-To-Earth (DTE) MER communication and the concept of using small-form factor sensor transceivers to communicate directly with a cell tower.

Analogies can again be drawn from the space community in how to attack the challenges of a small-form factor long-range sensor radio. Both Turbo and LDPC [7] coding techniques are applied to reduce the energy per bit, in low-data rate applications. Likewise, the use of beam-forming architectures to radiate energy in the direction of a base-station effectively reduces the overall required transmission energy compared to an isotropic radiator. A reduction in power can be achieved by a factor equivalent to the number of elements in the phased-array system¹. Lastly, opportunities exist to reduce the required transceiver energy by rethinking and re-optimizing the design of circuits which are more tailored for sensor applications. Specifically, the objective in building these circuits should ultimately be the preservation of energy rather than lowering the power consumption.

A sensor transmitter powered by a super capacitor serves as a good backdrop for a discussion of designing circuits which are specific to sensor applications. During a transmit burst, the ultimate objective is to convert as much charge on the capacitor to radiated power at the antenna. Conventional thinking would suggest regulation of the voltage supplied to the transmitter and PA as a necessary step. Thus, recent

¹The energy/bit efficiency to transmit a given distance is equivalent for the case of both a mesh network with N hops, and a single transmission from a phased-array transmitter with N elements.

research has focused on the design of high-efficiency switching regulators. However, the regulator would still have a loss which degrades the overall TX energy efficiency. This is particularly true in sensor applications where the voltage across the super capacitor starts at a high value during a burst, implying a large voltage drop across the regulator. Assuming a linear rather than a switching regulator, a loss would be associated with this component [8]. A more efficient approach would be to realize circuits, in this case a PA, which could extract energy in the form of charge directly from the capacitor and negate the use of a regulator as is done in applications with a fixed battery supply. As an example of this concept, a regulator-less PA intended for use in long-range sensor applications was realized in a 90nm process with the highlights discussed in the next section.

IV. A REGULATORLESS POWER AMPLIFIER

During a TX burst, the super capacitor discharges and the supplied voltage will drop. The approach described in this paper attempts to eliminate the PA regulator. However, to maintain a constant output power during a TX burst, the output impedance must be dynamically varied as the super capacitor voltage begins to drop; the concept is illustrated in Fig. 2.

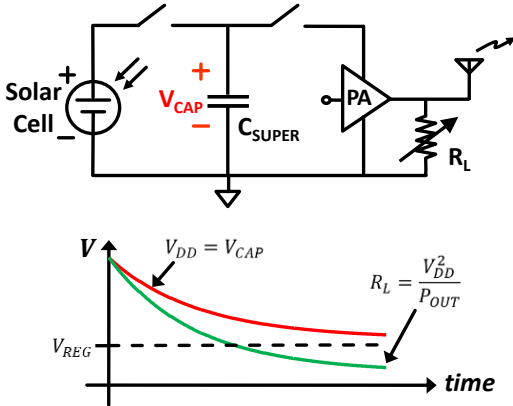


Figure 2: Sensor PA concept illustrating the relationship between PA V_{DD} , PA output power, P_{OUT} , and the PA load impedance R_L .

A block diagram of the regulator-less, variable load impedance power amplifier is shown in Fig. 3. The system is comprised of three major sections: a forward signal path consisting of an injection-locked LC-oscillator PA driver and a Class-E Power Amplifier, a tunable Impedance Transformation Network (ITN), and a feedback path operating as a Power Control Loop (PCL).

An external RF-signal is applied to the input of an injection-locked LC-oscillator (ILO) PA pre-driver stage, shown in Fig. 4(a). A pseudo-differential class-E switching PA with finite slab inductance drives the power combiner, as shown in Fig. 4(b).

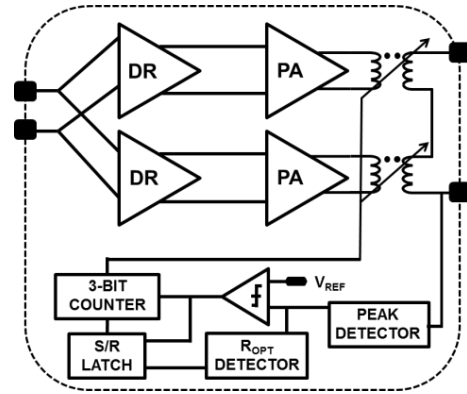


Figure 3: Fully integrated PA block-level diagram.

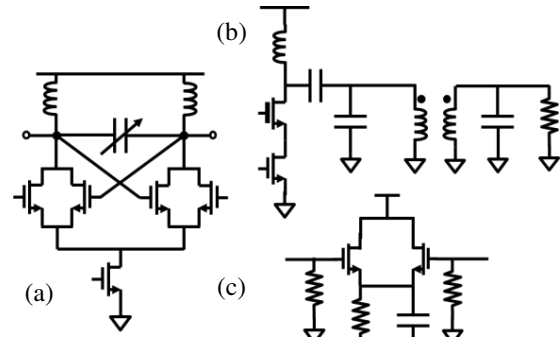


Figure 4: Schematic diagrams of the a) ILO pre-driver, b) Class-E output stage and c) Class-C peak detector.

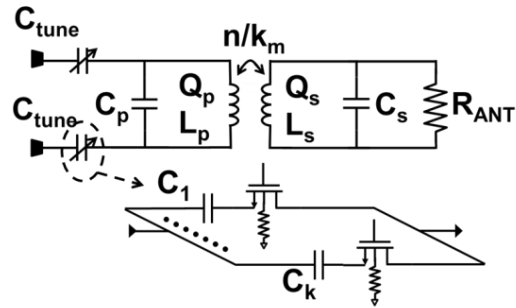


Figure 5: ITN fixed and variable impedance structures.

A two stage tunable impedance matching network is implemented to convert the antenna impedance into an optimal load for the PA. A fixed impedance transformation of 1:8 has been achieved with a 2-to-1 series power combiner architecture, where each integrated transformer has a turns-ratio of 1:2. To maintain constant P_{OUT} at higher supply voltages, the load resistance is tuned using a variable series capacitance, C_{TUNE} , as shown in Fig. 5. For the sake of clarity, a single transformer has been shown instead of the complete power combiner. Using a series-to-parallel conversion at the operating frequency ω_0 , an effective variable shunt resistance (R_P) is realized with a variable series capacitance, as seen in the following equations, where $Q = (\omega_0 R C_{TUNE})^{-1}$

$$R_P = (1 + Q^2)R_{TXF}; \quad C_P = \frac{Q^2}{1 + Q^2}C_{TUNE} \quad (1)$$

From (1), one observes that the effective shunt resistance and capacitance (R_P and C_P) loading the PA change by varying C_{TUNE} . Since the Class-E PA topology, by design, requires a large C_P for a high P_{OUT} , the variation in effective shunt capacitance due to variations in C_{TUNE} (~5% variation in C_P) results in negligible change of the ITN resonant frequency.

The series capacitor C_{TUNE} is realized with a 3-bit binary-weighted array. The associated switches require minimal loss and must handle the high voltages present at the PA output. Therefore, series resistors were placed on the gate and bulk terminals. The switch bulk resistors were created using a high-resistivity native substrate region in the area of the switch.

The PCL using a peak detector shown in fig. 4(c), provides feedback to automatically tune the ITN to a desired PA output power level, thus allowing a large V_{DD} variation during a TX burst. An external reference voltage sets the desired P_{OUT} and a trigger signal is used to initiate the control loop.

V. MEASUREMENT RESULTS

The fully-integrated PA was fabricated in a 90nm 9-metal TSMC CMOS process and occupies 1.92mm x 1.92mm including bond pads. On-wafer probing is performed on a die assembled with test board using chip-on-board packaging. A die-photo is shown in Fig. 6.

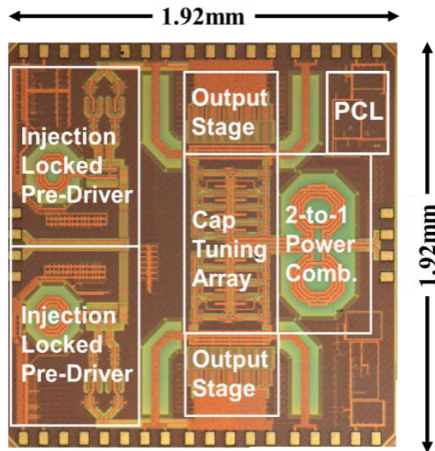


Figure 6: Chip Microphotograph.

The output power (P_{OUT}) as a function of the ITN switch settings is shown in Fig. 7. For a fixed 1.5V supply (V_{DD}), P_{OUT} varies from 19.8 to 21.3dBm as the switches sweep through all possible settings, whereas for a 2.5V supply, the range is from 22.4 to 24dBm. From Fig. 7, one observes that P_{OUT} monotonically increases as the switch settings of the tuning network increase from 000 to 111.

A constant PA output power of +21.6dBm within ± 0.2 dB across a supply-range of 0.35V (1.55V to 1.9V) and within

± 0.8 dB across a range of 1.1V (1.4 to 2.5V) was measured. The peak efficiency of the PA is 10.2% and varies by less than 2% over the full V_{DD} range. The PA resulted in a measured efficiency substantially lower than originally designed and simulated. The need for high-voltage CMOS switches requires a large spacing between elements in the capacitor array, thus requiring long interconnects in the PA ITN. The additional power/efficiency loss is attributed to inaccurate modeling of these long traces. At present, we are investigating methods to eliminate the need for high-voltage CMOS switches while still achieving a high output power solution.

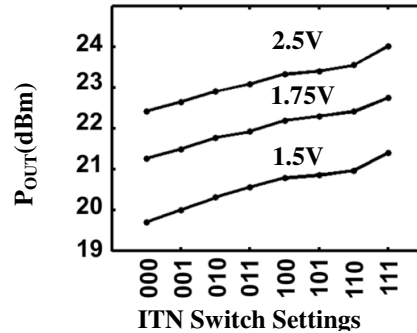


Figure 7: P_{OUT} as a function of ITN Settings at different V_{DD}

Extending range in sensor transceivers has the potential to enable a wide range of new applications. To achieve this goal using integrated radios, future research must focus on exploring signal modulation/coding techniques, novel radio architecture and circuit designs, and new methods of energy harvesting. As a small example of what might be achieved by rethinking radio circuits for long-range sensor applications, a 90nm regulator-less PA was discussed.

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