Future Integrated Sensor Radios for Long-Haul Communication

Jacques C. Rudell, Venumadhav Bhagavatula, and William C. Wesson

ABSTRACT

As CMOS single-chip radios enter the era of *big data*, techniques to acquire, communicate, and store sensor data will evolve to address new demands placed by a rapidly changing application space. Research and development on wireless sensor radio communication over the past decade has been largely focused on energy efficiency for short-range communication. However, going forward, sensor radios will require new modes of communication, which include leveraging existing network infrastructure and increasing the communication range of a single device. This article overviews several existing approaches for wirelessly communicating sensor data, followed by potential future strategies to enhance range and connectivity using single-chip wireless sensor transceivers. As an example of devices for long-range sensor communication, a regulator-less CMOS power amplifier specifically tailored for the demands of longer-range sensor data communication is described. This PA was designed to provide a fixed high-output power using a dynamic voltage supply as commonly found in sensor applications where an energy storage element (super capacitor) supplies the transceiver. The PA system is integrated in a 90 nm CMOS process, has a peak output power of 24 dBm, with an efficiency of 12 percent at 1.8 GHz, making this device suitable for data communication over distances of several hundred meters. As the PA supply varies from 2.5 to 1.5 V, the power control loop maintains a constant output power with an accuracy of ±0.8 dB.

INTRODUCTION

Sensors are finding an almost 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, environmental monitoring, and the ability to sense devices for the Internet of Things. 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 [1, 2]. Many of these sensors must remain in remote locations with very limited (or no) access to a battery source. As such, over the life of the device, power is supplied by a single battery, or some form energy scavenging is used to achieve autonomy. Given the lack of somem form of energy source in these systems, every joule of an energy source becomes precious. 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 challenges of delivering sensor data wirelessly is really a multidisciplinary problem involving networking, signal modulation, electromagnetics/antenna design, power electronics, and, of course, exploration of more efficient, highly integrated wireless transceivers.

This article begins with an overview of the challenges associated with wireless transmission of sensor data, with an emphasis on exploring the extension of range. System strategies to enable long-range sensor communication are described, particularly with respect to transmitting data. As a demonstration of the concepts introduced in this article, highlights are presented of a regulator-less power amplifier based on a tunable matching network. Finally, we provide some measurements and suggestions for future areas of research.

OVERVIEW OF WIRELESS SENSOR SYSTEMS

Early wireless sensors utilized mesh networks to report data; employing numerous ultra-low-power radios with cell sizes of less than a few meters between adjacent nodes. As a result, for long-distance sensor transmission of several kilometers, data must hop through hundreds, if not thousands of individual nodes along the mesh to reach an access point. This is convenient for applications requiring a dense coverage of sensors for data collection. In addition, several advantages are afforded by the short-range transmission found in collaborative mesh networks. First, the small cell size (several meters in diameter) allows frequency reuse, thereby enabling multiple sensor-to-sensor data links within a tight geographical area. The second advantage, from a theoretical perspective, relates to maximizing transmission energy efficiency on a bit/joule basis by optimizing the

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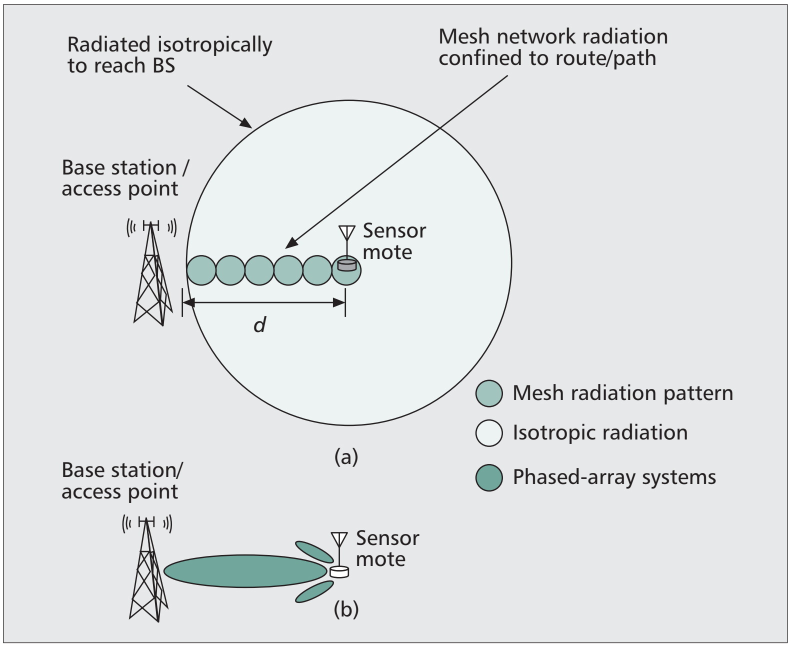

Figure 1. a) Collaborative mesh networks and direct transmission; b) potential beam-forming phased-array systems.

node-to-node transmission distance [2] (depending on the path loss conditions and transceiver characteristics). However, several practical considerations add significant complexity to this class of networks. Issues such as network self-assembly [3], receiver wake-up time synchronization [4], scheduling between various cells, and re-outing around errant nodes have proven to be a challenge for long-distance wireless sensor communication.

The traditional wireless sensing community has long accepted that theoretically, the optimal energy efficiency on a per bit basis (Joules/bit) is achieved when numerous smaller "picocells" are used. The optimal distance, r_{opt}, between sensor motes for maximum energy per bit efficiency, assuming isotropic radiation patterns, has been established in [2]. For a fixed distance, d, transmitting data using several ultra-low-power power amplifiers (PAs) cascaded over a series of nodes is more efficient in terms of Joules per bit than making a single transmission using a higher-power output PA. A more intuitive conclusion to the analysis may be drawn by visualizing the radiation patterns of transmitters for picocells in mesh networks, as compared to a single long-range transmission (Fig. 1a). Assuming isotropic antennas, energy radiates concentrically from the transceiver in both systems. When compared to a single long-range transmitter, the smaller picocells, using lower-power transmitters, radiate energy a relatively short distance to reach adjacent cells. Therefore, to travel long distances, mesh networks ideally contain and direct the electromagnetic energy along well defined paths. This also suggests potential future directions for research on long-distance (kilometers) sensor communication by utilizing phased-array beam steering systems (Fig. 1b).

Any advantage with respect to energy efficiency in short-range mesh networks assumes an optimal and uniform spacing between sensor nodes. This assumption of uniformity between nodes has proven problematic for many applications where deployment is rendered in an uncontrolled and random fashion. Sensor nodes used in barrier coverage applications to detect intruders at the boundary of a battlefield, border, or coastline serve as examples. Situations arise where rapid deployment of barrier coverage mesh networks becomes necessary and are created, for example, by dropping sensor nodes via aircraft or artillery ordinance delivery systems. Accordingly, the position of each node relative to one another is random and influenced by many factors, including wind and terrain [8]. To ensure adequate barrier coverage, spatial redundancy is often used at the expense of utilizing extra sensor nodes. Moreover, complex network self-assembly and node redundancy further erode the energy efficiency advantage of mesh networks.

For shorter-range wireless sensor applications, other communication systems based on radio frequency integrated circuit (RFIC) technology show significant promise. These devices commonly use an approach of backscattered energy to derive power for both transceiver reception and transmission [5]. Similar techniques seeking to harvest energy from ambient TV and cellular signals using wireless power transfer have been explored [6].

Recent efforts have focused on reducing the synchronization problems while extending the range of mesh networks, by utilizing partially hardwired solutions. The Networked Infomechanical Systems (NIMS) project proposed a combination of hardwired and wireless connectivity to communicate information from mobile sensing devices [7]. While these hybrid sensing networks will improve energy efficiency when transmitting information across long distances, such a network requires overhead for deployment. In addition, the mobility of the devices inside the network would be limited to the area of deployment.

An alternative approach, discussed in this article, is the possibility of single-hop long-range sensor communication from the sensor node directly to an access point. Sensors placed in relatively remote locations, or applications where a low density of sensor coverage is sufficient, remove much of the motivation for short-range transceivers coupled through a collaborative network. Examples could range from remote monitoring of temperature, humidity, precipitation, and rainfall levels, to data collection for global warming research, or perhaps homeland security applications. One major advantage of an extended node range is the potential to exploit existing cellular, WiFi, and PAN network infrastructure, thus conceivably leveraging existing coverage in any urban areas, saving the cost of deploying a custom network. In addition, if a sensor radio for long-distance communication is realized in complementary metal oxide semiconductor (CMOS) technology, highly programmable radio front-ends with multi-standard capability could be envisioned [9, 10]. This implies a sensor node that could intelligently find the most available, and energy-efficient, access point, even including collaborative mesh networks. Thus, as shown Fig. 2a, a single sensor node could be randomly placed in virtually any environment and left to "network-scavenge" for the closest and most energy-fficient access point.

Although many issues spanning a broad selection of disciplines (including networking, digital signal processing, power electronics, and communications theory) would need to be addressed to realize the vision of a long-range sensor transceiver, this article focuses on one of the most challenging aspects of front-end transceiver electronics, specifically the transmitter and PA systems. Techniques for cellular (long-range) and sensor (short-range) PAs have developed independently over the past decade due to the significantly different system specifications (power levels) as well as system architectures (energy sources). The long-range sensor PA [11] proposed in this article lies at the intersection of these two fundamentally different radio front-ends.

Any autonomous sensor-transmitter can be separated into two basic subsystems, as shown in Fig. 2b: the energy harvesting subsystem (EHS) and the data transmission system (DTS). A block diagram of the proposed sensor-transmitter, which attempts to improve the DTS efficiency, is shown in Fig. 3a. The system contains a solar cell, super-capacitor, switches (SW1, SW2), and a CMOS PA. During the charging phase, solar energy is harvested by a solar cell and stored on a super-capacitor via switch SW1. As soon as sensor data is available, switch SW2 closes to connect the super-capacitor directly to the PA. To maximize the super-capacitor energy utilization, while concurrently maintaining constant output power, this PA uses a unique tunable matching network (TMN). The sensor PA also includes a fully integrated control loop that monitors the output power and modulates the TMN in response to variations in the super-capacitor voltage.

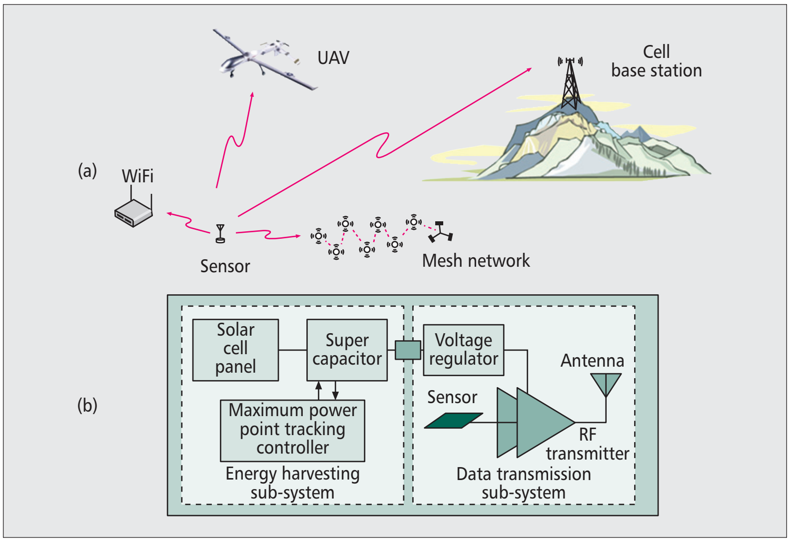

Figure 2. a) Long-range wireless sensor devices, and the potential for networking scavenging; b) data transmission system (DTS).

Strategies for the Unique Demands of Sensor Power-Supply Variation

With respect to the target output power, cellular and mesh-based sensor transmitters represent two opposite ends of the performance spectrum. Mobile cellular handsets communicating with a remote base station must transmit power levels on the order of +30 dBm (1 W) and achieve transmit distances exceeding several kilometers. In contrast, mesh-based sensor transmitters typically deliver output power levels of mere microwatts; more than six orders of magnitude lower. Most sensor transmitters are fully autonomous, and operate by using renewable forms of energy, such as solar, vibrational, wireless power transfer, or thermal energy. An energy storage element (typically a super capacitor) then supplies the radio for normal operation. This fully autonomous operation is a key property for transmitters that are required in remote locations with minimal human presence. The envisioned long-range sensor transmitter must achieve cellular-like transmit distances while retaining the autonomous nature of a sensor mote.

A key challenge with the proposed sensor PA relates to designing power-efficient transceiver circuits that are unique to the method of energy acquisition, storage, and utilization in sensor systems. In cellular transceivers, the PA typically operates directly from a rechargeable lithium-ion battery [12]. Although the voltage may change by 20 percent as the battery discharges, cellular handsets are acutely dependent on recharging the battery. In contrast to the relatively constant battery voltage, the voltage across a super-capacitor in a sensor-transmitter decreases every time a transmit burst occurs. Moreover, renewable sources of energy (e.g., solar) could potentially be unreliable. For example, an arbitrarily scattered sensor-transmitter that lands in an area shaded by a tree might take a much longer time to harvest energy than would sensor transmitters landing in the middle of an open field with better exposure to daylight. The goal of any sensor-transmitter is to implement a strategy to maximize the *active time* (burst time), defined as the duration of time over which the voltage supplied by the super-capacitor is sufficiently large to transmit data at the desired power level. A sensor TX that can transmit data for supply voltages ranging from 2.5 to 1.5 V has a longer active time than one that operates over a smaller range of 2.5 to 2.0 V. For this example implementation, the PA was designed to operate at as low as 1.5 V.

The sensor PA must maintain constant output power while the super-capacitor discharges, and the corresponding supplied voltage decreases. The problem definition appears very similar to the role played by integrated voltage regulators in complex systems-on-chip. Voltage regulators, linear and switch-mode based, are widely used circuit blocks that minimize fluctuations from a battery or supply line for a wide range of

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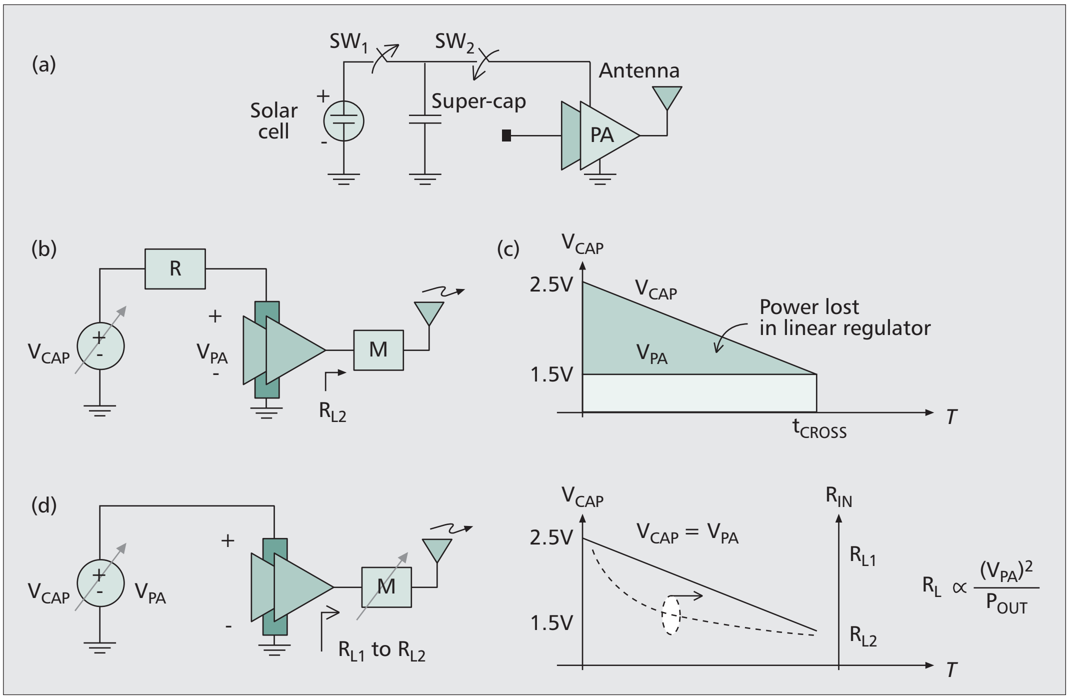

Figure 3. a) Simple energy scavenging device with super-cap, and transmitter; b) regulation of sensor energy source; c) conceptual plot of LDO losses in sensor systems; d) conceptual diagrams of regulator-less PA and tunable matching network.

loading conditions. Thus, understanding the needs of a long-range sensor transmitter involves knowledge with respect to the advantages and disadvantages of the different regulator-based solutions.

Linear Regulator

Linear regulators are also known as low dropout regulators (LDOs). The most basic form of an LDO can be viewed as an analog negative feedback loop that constantly compares the regulated output voltage (supply voltage to the PA) with a fixed reference voltage. If an instantaneous variation in the load current results in a deviation in the regulated output voltage, the feedback system kicks in to correct the error. The input to the LDO consists of an energy source (e.g., a battery or a super capacitor) with a voltage potential higher than the regulated output voltage. The difference between the voltage potential of the energy source and the regulated output voltage is called the *drop-out* voltage. To maximize the regulator efficiency it is important to minimize the drop-out voltage, which is challenging for sensor applications where the supply voltage from the energy storage element has significant variation.

While LDOs are extensively used for analog, digital, and mixed-signal systems, the low power efficiency associated with large drop-out voltages in high-power sensor PAs introduces significant limitations. As described previously, the goal of sensor PA design is to maximize the active time of the transmitter during a burst. This is accomplished by using an LDO, with a PA designed to operate off of the lowest voltage possible. This implies that at the beginning of the burst, a large dropout voltage would exist across the LDO. Thus, high LDO efficiency and large burst time result in two conflicting requirements.

To highlight the inefficiency of an LDO used in a sensor radio, Fig. 3b illustrates a hypothetical current and voltage supplied by the storage element to power the TX. At the beginning of the transmitter operation, a large voltage drop exists across the linear regulator, introducing an additional power loss directly proportional to the average current flowing through the PA, and the difference between the unregulated voltage (V_{CAP}) and the regulated PA supply voltage (V_{DD}), as seen in Fig. 3a. The highlighted section in Fig. 3b indicates the power lost in the linear regulator as the super-capacitor discharges, which ultimately degrades the overall transmitter efficiency. Equation 1 describes the reduction in overall transmitter efficiency (η) as a function of the ratio V_{MAX}/V_{DD}, where V_{MAX} is the fully-charged super-capacitor voltage.

$$\eta = \frac{2}{1 + \frac{V_{MAX}}{V_{DD}}} \tag{1}$$

From Eq. 1, one notes that for a $V_{MAX} = 3V_{DD}$, the maximum transmitter efficiency is 50 percent assuming a PA with zero power loss.

Buck-Boost Regulator

Switch-mode regulators and their applications in polar RF transmitters have been active topics of research over the past decade. There are two advantages associated with switching regulators as opposed to an LDO. First, this class of regulators lack an analog feedback loop and can easily achieve a power efficiency exceeding 80 percent. Second, a switch-mode regulator can regulate an input above (buck-topology) and below (boost-topology) the desired regulated output voltage. As a result, a larger range of supply voltage variation associated with the energy storage element can be tolerated.

The challenge of integrating an LDO on chip typically depends on a design that uses a reasonably small value of capacitance, allowing a fully integrated solution. Likewise, a common barrier toward integrating a switch-mode regulator lies in the large value required for the inductor. The quality factor and value of the inductance used in switching regulators typically demand the use of off-chip discrete inductors, which runs contrary to the goal of integration. While off-chip inductors could possibly be tolerated at the expense of a larger form factor, a secondary concern is the interaction between the switching regulator clock (F_{SR}) and the PA switching frequency (F_{PA}), assuming a switched-based PA is used. Mixing action between these two clock frequencies often results in unwanted spurious emission at multiples of the beat frequencies, $F_{PA} \pm F_{SR}$. For high-power cellular transmission, mixing spurs could ultimately lead to both in-band and out-of-band spectral mask violations. While spurious emission (spurs) is generally not a problem for low-power sensor transmitters, which communicate over several meters, radios that transmit over long distances must produce an output spectrum that meets stringent guidelines for both in-band and out-of-band emission.

Regulator-less PA

Given the aforementioned drawbacks of both linear and switch-mode regulators, there is a strong motivation to eliminate the regulator altogether. However, eliminating the regulator and connecting the sensor PA directly to the super capacitor makes transmitter output matching network design challenging. The dynamic nature of the sensor PA's unregulated supply voltage leads to a unique relationship between the PA matching network and the super capacitor voltage, which is best understood by considering a GSM transmit signal at maximum power output (+30 dBm). For example, consider the two extreme voltages on the super capacitor, the first being when the super capacitor is fully charged to V_{MAX}, and the other when the storage element has discharged to a value V_{MIN}. By applying realistic V_{MAX} and V_{MIN} values of 2.5 and 1.5 V, respectively, the impact of this supply variation on the PA performance can be explored. If a matching network is designed for maximum output power (+30dBm) with a $V_{PA} = V_{MAX}$ (2.5 V), then as the capacitor discharges to V_{MIN} (1.5V), the PA output power would drop to +26dBm; this assumes a switch-based PA where the output power, P_{OUT}, is proportional to V_{PA}^2. Conversely, if a matching network is designed for a P_{MAX} (+30 dBm), at V_{MIN} (1.5 V), the output power would now be too high (+34 dBm) when the capacitor is fully charged (2.5 V).

To maintain constant output power, a tunable matching network (TMN) that dynamically adjusts the PA load resistance to track the large variation in the supplied super capacitor voltage is proposed. As shown in Fig. 3d, to maintain a constant output power when the super-capacitor discharges and the supply voltage (V_{CAP}) decreases, the PA load must scale down at a rate proportional to V_{PA}^2. The TMN (M_X) transforms the fixed antenna impedance into a variable load, R_L, at the PA output over the supply voltage range.

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Tunable Matching Network

The desired function of the TMN is to modulate the real part of the PA load impedance. Moreover, it is critical to maintain the PA output resonant tuning as close to the carrier frequency as possible. The realization of the TMN implemented in this chip is best described by starting with a series RC. The series RC network with $Q = 1/\omega RC_{TUNE}$ can be transformed into an equivalent parallel RC network at frequency ω_c.; this transformation is defined by

$$R' = R(1+Q^2) = R\left(1+\frac{1}{(\omega_c RC_{TUNE})^2}\right) \quad (2)$$

$$C' = C_{TUNE}\frac{Q^2}{1+Q^2} = \frac{C_{TUNE}}{1+(\omega_c RC_{TUNE})^2} \quad (3)$$

The TMN, which relies on series-to-parallel transformations, consists of an integrated transformer along with a tunable series capacitance, C_{TUNE}, implemented with a switch capacitor bank. By varying the value of C_{TUNE}, this modulates the network, Q. R', the effective parallel PA load resistance is a strong function of Q, and ultimately C_{TUNE}. In addition, C', the effective parallel load capacitance, is a weak function of Q and C_{TUNE}. Thus, the real part load impedance seen from the perspective of the PA can be modulated by varying C_{TUNE}, while the capacitance remains relatively constant, helping to maintain a desired resonant frequency.

Voltage excursions greater than 2.5 V_{DD} at the TNM input make the implementation of the switches in the capacitor bank challenging. To address reliability concerns associated with these switches, a bootstrap technique was employed by attaching a resistor, R_{gate} and R_{bulk}, to the gate and bulk device terminals, respectively. The addition of R_{gate} is straightforward, with a physical resistor placed in series with the switch gate. However, the realization of R_{bulk} in standard CMOS relies on increasing the distributed resistance of the substrate in the immediate vicinity of the switch through the use of a high-resistivity native silicon layer (Fig. 4c) [15].

A block diagram of the sensor PA is shown in Fig. 4a. The power-combined PA architecture utilizes two parallel signal paths. The PA consists of an injection locked LC-oscillator-based pre-driver (DR) stage cascaded with a pair of common-source switching devices in the output driver stage, followed by the TMN and an on-chip power combiner. A digital power control feedback loop, which digitally modulates the switches in the TMN, is also integrated with the PA core.

Switch-based PAs operate the active device in an ON-OFF fashion to achieve high efficiency. The PA implemented for this sensor TX most closely matches the traditional Class-E topology with a load matching network designed to meet a zero-voltage switching (ZVS) condition. However, unlike a traditional Class-E PA, which utilizes a series LC filter at the output, this PA implements a parallel resonant network with a transformer and series tuning capacitance to realize the TMN (Fig. 4b).

The PA pre-driver stage exploits the constant-envelope nature of a Gaussian modified shift keying (GMSK) signal provided in the GSM standard by using an injection-locked oscillator (ILO), which drives the gate of the output stage rail to rail.

The on-chip logic requires only two explicit external control signals: CAL and V_{REF}. CAL is a trigger signal to initiate the operation of the PCL, while V_{REF} is an external reference voltage that maps to a desired output power level. The PCL includes a three-bit counter to control the switches in the TMN. A peak detector senses the voltage swing at the antenna and maps it to a voltage V_{FB}, which goes to the feedback loop. The relative values of V_{FB} and V_{REF} determine the operation of the feedback loop and control the state of the three-bit counter. Details of the power control-loop implementation, including the peak and R_{opt} detectors, are given in [16].

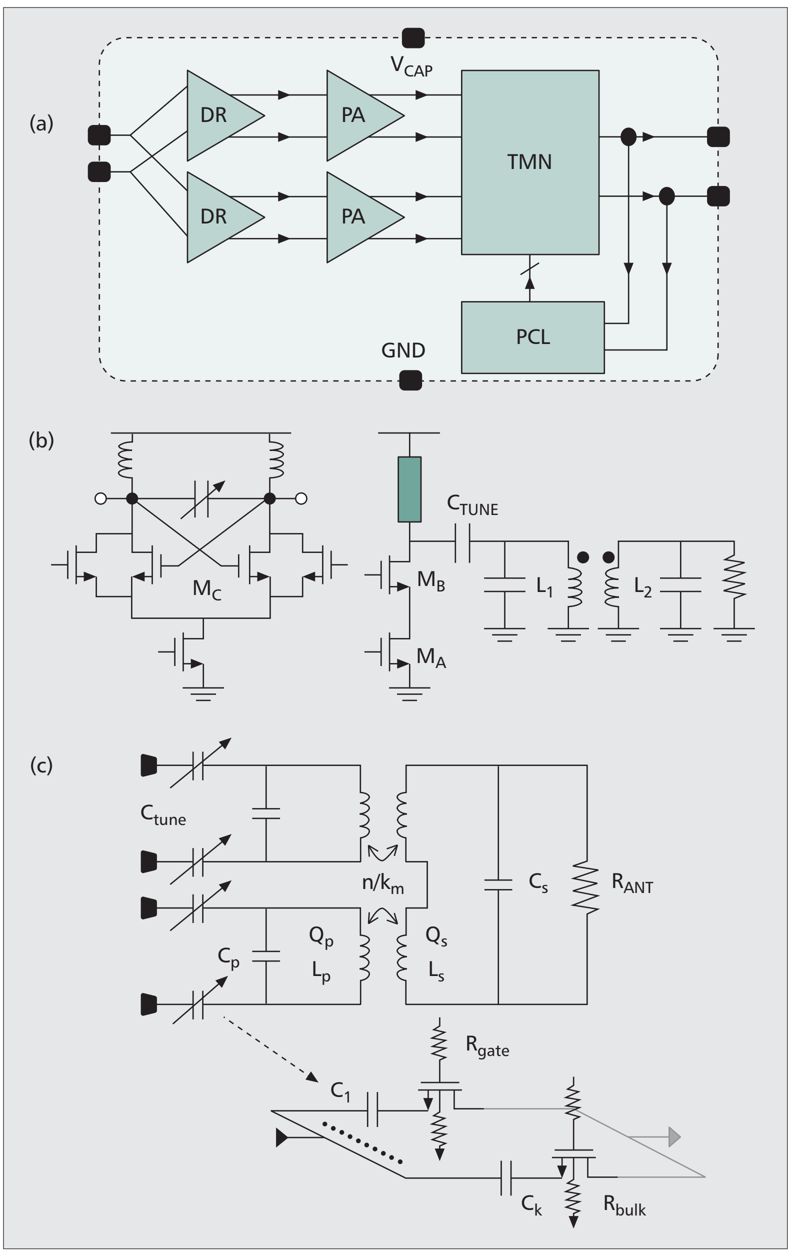

Figure 4. a) PA with tunable matching network (TMN) and power control loop (PCL); b) simplified schematic of PA first and second stages; c) power combining transformer with switch network.

Measurement Results

The PA was implemented in a standard 90 nm CMOS process with a nine-metal stack including one ultra-thick metal (UTM) layer; the die photo is shown in Fig. 5a. All passive components, including the TMN and finite choke inductance, have been integrated on the PA chip. The core measures 1.92 mm × 1.92 mm.

On-chip wafer probing was done to measure the PA's performance. There are two modes of operation to characterize this device: open-loop and closed-loop power control. In the open-loop mode, the switches in the TMN are controlled with off-chip digital codes; for the closed-loop mode, the TMN settings are controlled by the PCL. For the PCL to function, a one-time calibration is required for the on-chip peak detector. Performed in open-loop mode, this calibration consists of measuring V_{FB} while the TMN is cycled through the different power settings to generate an output-power vs. detector-voltage table. The external reference voltage (V_{REF}), indicating the target output power, is then selected based on this table.

The power modulation curves as a function of the TMN switch settings for three different supply voltages are shown in Fig. 5b. The power monotonically increases as the TMN switch control cycles through the settings 000 to 111. These results verify that the shunt-load resistance and the PA output power can be modulated by varying C_{TUNE}. The output power is regulated as a function of the variable supply voltage. As the super-capacitor discharges from 2.5 to 1.5 V, the total variation in output power delivered to the antenna is limited to 21.5 dBm ± 0.8 dB.

While the PCL and TMN have been experimentally verified, the sensor PA's output power is approximately 5 dB lower than the designed value. The source of this loss has been traced back to the high bulk-impedance switches in the TMN. The *N*-type MOS (NMOS) switches in the TMN utilize an area of 0.4 mm × 0.4 mm. This large spacing introduces significant area overhead and parasitics in the signal path. The capacitor bank introduces approximately 600 μm of additional routing between the PA and the power combiner. While extensive simulations were performed to capture the effects of distributed resistance in the substrate and metal routing, inaccurate modeling resulted in lower peak efficiency (12 percent) than designed. After de-embedding the 2.5 dB cable loss, a peak output power of 24 dBm is measured.

Finally, to observe the linearity with modulated data, the sensor PA is tested with a Global

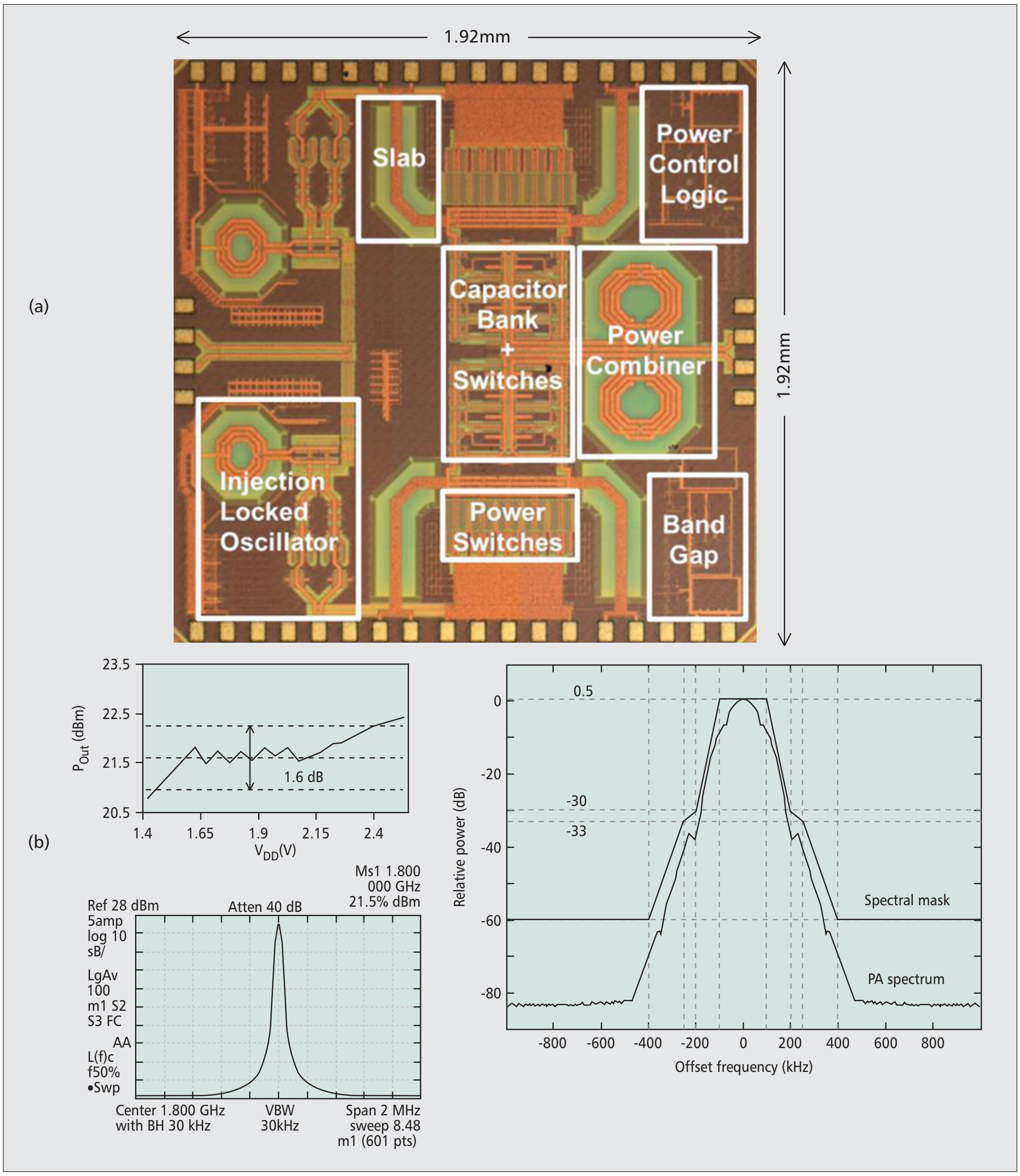

Figure 5. a) PA die photo; b) measurement results.

The realization of small-form factor wireless transceivers for long-haul communications will require innovative ideas from many fields if these devices are ever to become common place in the consumer electronics space.

System for Mobile Communications (GSM) input signal. The PA is set to its peak output power state, with all the switches of the TMN turned on. A 30 kHz spectrum analyzer resolution bandwidth was used while obtaining a power spectral density (PSD) measurement. The spectrum, shown in Fig. 5b, was averaged over 500 samples. The measured PSD at offset frequencies of ±200 kHz, ±250 kHz, and ±400 kHz meets the GSM spectral mask requirements.

To date, tunable elements at the output of the PA have been proposed for efficiency and linearity improvement [17], as well as multimode [18] and multi-band operation [13]. Circuits addressing the issue of high voltage standing wave ratio (VSWR) variation at the antenna-PA interface also exploit methods to tune the PA load. While the work in this article has been presented in the context of a sensor TX for long-range transmission, the PA load impedance tuning techniques are easily extended to the aforementioned applications. A majority of the solutions previously proposed use discrete off-chip components, micro-electromechanical systems (MEMS) [14], or non-standard CMOS processes like silicon on sapphire and silicon on insulator (SOI). In contrast, the PA, TMN, and digital PCL described in this article are fully integrated in a standard CMOS process.

Future Directions and Conclusions

The realization of small-form-factor wireless transceivers for long-haul communications will require innovative ideas from many fields if these devices are ever to become commonplace in the consumer electronics space. Initial proof of feasibility for a device using energy-con-

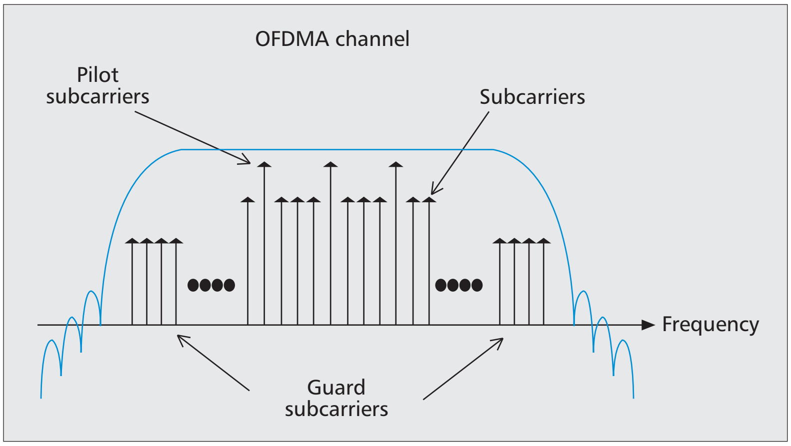

Figure 6. Potential future strategies for data insertion using existing networks.

strained radios can be found, but for an entirely different set of applications. Almost identical challenges are faced by 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 for comparison, one notes that the solar panel area relative to the MER communication distance is very small. However, very high rate convolution codes using low-energy transmission are used with very low data rates [19]. 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 resources to search and decode long code sequences. 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, size-constrained sensor nodes that communicate with cell base stations have analogous 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.

Analogies can be further drawn from the space community in how to attack the challenges of a small-form factor long-range sensor radio. Both turbo and low-density parity check (LDPC) [20] coding techniques are applied to reduce the energy per bit in low-data-rate applications. Likewise, the use of beamforming architectures to radiate energy in the direction of a base station would help to more efficiently use transmitted power (Fig. 1). Phased-array transmitters have similar energy saving arguments compared to mesh networks, when the number of elements in the array is equivalent to the number of nodes required to reach an access point using a collaborative network. Lastly, opportunities exist to reduce the required transceiver energy by rethinking and re-optimizing the design of circuits that are more tailored for sensor applications. Specifically, the objective in building these circuits should ultimately be the preservation of energy rather than lowering power consumption.

Many questions arise surrounding the system and networking level aspects of wide area sensor motes. Adoption of these devices by cellular, third, fourth, and fifth generation carriers will require the development of wireless sensors that non-invasively communicate with cellular base stations to minimize the impact on voice and data traffic capacity.

Wireless systems that seek to enhance transmitter power efficiency often use constant envelope modulation signaling such as frequency shifting (FSK), Gaussian FSK (GFSK), and minimum shift keying (MSK). Therefore, some control of the modulation and signaling between a cell base station and the mobile sensor node is desired. Modulation compatibility with GSM seems clear, as the standard already utilizes constant envelope GFSK modulation, and scenarios exist where data could be inserted into the network using SMS messaging schemes. However, most third and fourth generation wireless standards utilize some form of orthogonal frequency-division multiple access (OFDMA) modulation. In fourth generation standards, not all of the subcarriers are used; many are left available as either a guard band or a pilot tone (Fig. 6). Recent work on cognitive radios suggests using the guard bands associated with OFDMA signals to opportunistically insert data [21, 22], which could potentially be used for sensor communication.

In conclusion, a sensor PA designed to complement existing ultra-low-power short-range multihop mesh-network-based sensors, with the explicit goal of enabling long-range single-hop data transmission, has been presented in this article. To enable efficient utilization of harvested ambient energy, a regulator-less PA has been proposed. An impedance tuning network and feedback loop to autonomously regulate the output power with a variable supply voltage are presented. A prototype circuit fabricated in a 90 nm CMOS process achieves a peak output power of 24 dBm and power regulation within 21.5 ± 0.8 dB. A broader discussion has been presented in this article on potential future areas of research to realize the vision of dropping a sensor node in any urban environment, with instant connectivity, a reality.

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