W H I T E P A P E R

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Wireless sensor networks open new frontiers for a smarter world

TI's available ultra-low-power technology enables autonomous remote monitoring and communications for new sensing applications.

Introduction

Networks of sensors consisting of numerous small nodes that communicate wirelessly are now feasible, thanks in part to IC solutions developed by Texas Instruments (TI) for wireless utility meters. These and related solutions from TI provide sensing, management for energy harvesting and storage, measurement calculations, system control, data conversion, wireless communication and other essential functions. Developers can use these components today to build a variety of types of wireless sensor nodes that can affordably extend traditional automated control applications and open new areas of monitoring and control.

One of the most promising visions in electronics for the near future is the deployment of wireless sensor networks (WSNs)—that is, networks consisting of dozens to thousands of small sensors that measure, calculate and communicate wirelessly among themselves and to central systems. The individual sensors or nodes will function on extremely little power, harvesting the ambient energy around them to operate, so that they can be installed without a costly wired infrastructure and can keep going for years without maintenance. Small and inexpensive, these systems have been dubbed "stick-on" sensors to emphasize how easy they will be to install. Consisting of dozens, hundreds or even thousands of these nodes, WSNs will make affordable multipoint sensing that until now has been prohibitively expensive, enabling dynamic control that reduces costs and extends capabilities.

To take just one example, a large building such as a food warehouse can have scores of wireless thermostats monitoring temperature and humidity, all reporting back to a central system that dynamically adjusts air flow and cooling to keep conditions uniform and minimize spoilage. The sensors could be placed in unusual locations—underneath shelves, at the bottoms of bins, even on the food items themselves—to give a more accurate picture of the variation in conditions. As this example illustrates, WSNs will find wide application in areas such as industrial control and heating, ventilation and air conditioning (HVAC), which have traditionally relied on sensors. But as the variety of sensing nodes increases, they will also enable new types of applications such as body-area networks (BANs) that monitor health, agricultural networks that aid in crop cultivation, and environmental networks that help reduce pollution, warn of earthquakes or prevent widespread forest fires.

Smart Grid: A vanguard application for distributed intelligence

One of the most important applications of distributed sensing is in the power industry, which is increasingly finding new ways to measure and communicate the flow of electricity throughout the grid to enable efficient, reliable service. The movement toward an intelligent power network—frequently referred to as the "Smart Grid"— promises not only to improve delivery but also to help keep costs in line through improved infrastructure maintenance and a better understanding of patterns of consumption.

Virtually every stage of power production and delivery can benefit from such remote sensors, from generators to high-power transmissions and substations, from street-level power lines and transformers to points of access in homes, factories and office buildings (Figure 1). Sensors in these spots can detect usage patterns and report back to central systems, enabling the grid to fine-tune itself to meet demand while preventing overloads that can cause power outages and reduce the life of equipment. Grid intelligence is also essential to the integration of distributed power sources such as solar arrays, wind farms and geothermal plants.

Corresponding movements toward providing communications among previously unintelligent equipments have been dubbed the “Smart Home” and “Smart Factory,” as well as the all-inclusive “Internet of Things.” Whatever the label or principal area of use, these forms of distributed intelligence will bring about new types of applications for greater convenience and productivity.

The Power Grid

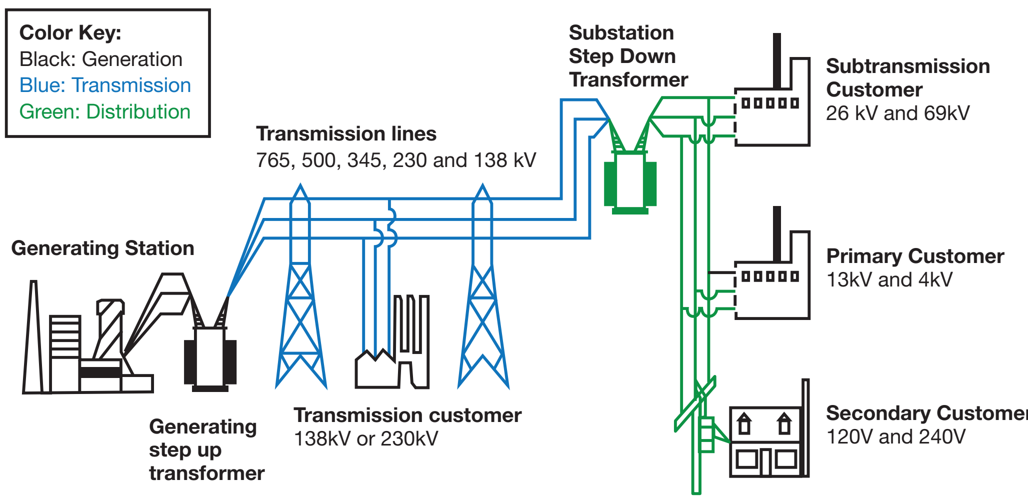

Figure 1. The Smart Grid will extend intelligence and omni-directional communications throughout the power supply system for more reliable, efficient power consumption.

Enabling wireless utility meters

Wireless nodes will be responsible for only some of the distributed intelligence in the Smart Grid, since many sensors will use wired data networks or the power lines themselves for the physical network medium. But in one important respect, power companies are already leading the way in adopting wireless technology to communicate measurements. For a number of years, utilities have been engaged in replacing traditional electromechanical meters with digital meters that can be read wirelessly. At the very least, wireless utility meters save the cost of having someone look at the meter every month; now the meter reader can pass by and obtain a reading in a fraction of the time that was previously required, often without entering the premises. More sophisticated meters often communicate over a wider area as they collect and send data that can help utilities estimate demand patterns and provide services more efficiently.

TI has played a key role in developing the integrated circuit technology that enables wireless meters, and TI customers are important providers of these equipments. An industry leader in low-power analog and mixed-signal technologies, TI has a long history of creating IC products that can be used in power-sensitive applications such as portable products, as well as in industrial and automotive control systems. Today, the same technology that was developed for wireless utility meters is available in later-generation components that consume even less power, making these appropriate for creating sensing nodes for wireless networks. WSNs that use these solutions will help distribute intelligence into the home, office, factory, farm, recreational areas, and natural areas—anywhere that we want to gather data to help us understand and control conditions.

Ultra-low power consumption is the key to WSNs

Designers who are creating remote wireless sensors have to achieve the right balance among a number of system requirements, including the size, cost and reliable supply of components, as well as design support tools and software libraries. Still, the factor that is essential to remote sensor nodes is the availability of ultra-low-power (ULP) components. Without ULP microcontrollers, memories, sensors, transceivers and other system functions, remote wireless sensors are not feasible at an affordable cost. Technology that can gather and store ambient energy from light sources, vibrations or heat is also critical to the success of these devices and the WSNs they comprise (Figure 2).

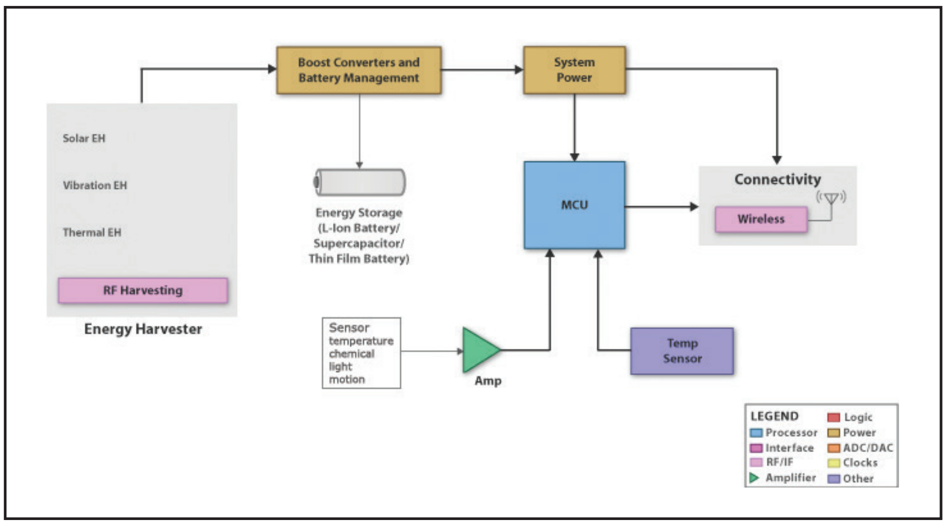

Figure 2. Energy harvesting requires ultra-low-power components for all stages of the signal chain and power management.

At the heart of any measurement system is the microcontroller unit (MCU) that performs calculations and controls the system. Wireless sensor nodes require ULP microcontrollers that sleep for long periods—usually for more than 99 percent of the time—in order to conserve power. Active cycles consist of waking quickly, performing measurement, communication and control functions efficiently, and returning to sleep. Because of the large number of potential applications for sensors, the MCU must include enough peripheral functions to make it flexible, yet be able to turn off the ones that are not in use in order to save power. Similarly, the MCU software must be written to minimize operations and take advantage of whatever power saving features are built into the device.

Like the microcontroller, all the other system components must be designed to consume extremely small amounts of power as they perform their tasks. Memories have to be of sufficient size to hold programs and data, as well as fast enough to support short activity cycles when the MCU is awake. Yet memories also have to be designed for power-efficient reads and writes, and for minimum power dissipation while retaining stored data during sleep cycles. Data converters must be fast enough to support system input and output, but use no more power than is necessary to perform their tasks. ULP transmitters have to become active and shut down quickly, send and receive short bursts of data during waking cycles, transmit over wide enough areas to meet network requirements, and possibly support different transmission formats for flexibility. Depending on the needs of the network, nodes may also need to receive data, bringing in slightly different considerations for conserving power.

The design of the power supply subsystem is extremely important in wireless sensor nodes. The energy source, whether a solar panel, thermal or piezoelectric transducer, or other device, must be supported by circuitry designed to maximize energy harvesting despite the irregularities of ambient conditions. Energy storage in a rechargeable battery or supercapacitor, or both, requires careful management in order to optimize power so that it can be available whenever it is needed. Elements that sense heat, current, chemicals or other environmental conditions must be sufficiently sensitive for accurate readings, yet not power-hungry. When all these components have been selected to meet the right tradeoffs of functionality and low power consumption, the sensor node should be capable of functioning autonomously for years.

TI's ULP products for wireless sensor nodes are available

Based on its expertise in designing IC products for a variety of applications, TI is able to offer solutions that meet the power requirements of wireless sensor nodes. Many of these solutions are extensions of products that were designed for wireless utility meters, so the technology has been extensively tested in the field. Taken together, TI's ULP products provide a complete system solution with in-depth support, allowing designers to create wireless sensor nodes quickly for a wide variety of WSN applications.

Wolverine MSP430 MCUs

At the center of TI's wireless sensing solution is the "Wolverine" MSP430 microcontroller. With an architecture specifically designed for ULP, Wolverine MCUs provide a 50 percent overall reduction in power consumption from previously available devices. The MCUs are based on a 130-nanometer (nm) ultra-low-leakage process technology that reduces both active and quiescent power, and the entire design library for the device was re-engineered to take advantage of these power savings. Power-efficient elements in the library include analog components as well as digital, so that the MCUs integrate peripherals such as a 12-bit high-precision analog-to-digital converter (ADC) that can sample 200,000 times per second while consuming only 75 µA, and a real-time clock (RTC) with calendar and alarm that can run at only 100 nanoamps (nA).

Wolverine's on-chip power management technology includes support for seven operating modes, advanced power gating, and a highly responsive adaptive regulator. The MCU is divided into multiple power domains to enable dynamic management of each part of the device in accordance with the specific demands of the application. This feature, long a part of the MSP430 architecture, is now more fine-grained than ever, extending to individual modules within larger functional blocks. In order to minimize the power loss each time the system switches from standby to active mode, the device uses its power gating controller to keep active the modules that are requesting a clock, while putting idle modules in a retention mode. In addition, intelligent power management eliminates the need for external buffer capacitors by automatically adapting to changes in loading, such as when a high-frequency module is powered on. All of these power-saving features automate power management in a seamless manner that is transparent to developers.

Fast, low-power FRAMs

The Wolverine MSP430 architecture is also significant in its integration of ferroelectric random access memory (FRAM). FRAM is like DRAM in structure except that data is stored in a crystal state, not by charge. Thus, FRAM has read/write access and cycle times similar to DRAM, and it is correspondingly compact. Unlike DRAM, however, FRAM is non-volatile and can continue to hold data when the system is powered off. By comparison with the non-volatile Flash memories that are frequently used for programs, FRAMs are faster, require far less power, and can be written to many more times. Wolverine MCUs with integrated FRAM thus represent an important step forward in power savings for ULP systems such as wireless sensor nodes.

Among the problems that Flash memories present is the fact that relatively high voltage levels of 10 to 15 V are required for writes, necessitating the use of a charge pump and using a lot of power for each operation. In addition, Flash memories must be erased before writes, a factor that complicates write operations, interrupts system operations, and generally wastes time and power while the rest of the system waits. Finally, Flash memories have a limit of about 10,000 write operations, a number that is insufficient for a system that needs to update its data from several times a second to every few seconds, and must continue doing so non-stop, year after year. Although Flash is often used for program storage, these factors prevent its use for data, so blocks of volatile SRAM must be used instead. At system power-down, data must be written from the SRAM to Flash for non-volatile storage, and a corresponding data read from Flash to SRAM takes place on power-up.

FRAM is truly a random access memory where each bit can be read or written individually, and it has a simple, single-step write process with no separate erase required. FRAM requires only 1.5 V for writing, so that no charge pump is required, and no lag results from interrupting the system to erase existing data. As a result, FRAM write accesses are 100× faster than Flash writes, and the active write energy required for FRAMs is up to 250× less

(Figure 3). In addition, writes to FRAM are virtually unlimited—on the order of 1015 write cycles—so that there is no difficulty with using the memories for data storage. Program and data memory can be unified in a single block and partitioned according to the application's needs. Data remains in memory during power-down, allowing designers to eliminate not only the external charge pump, but also the large capacitors that energize it. For energy harvesting systems such as wireless sensor nodes, the power savings from FRAM can make the difference that enables the design to succeed.

	FRAM	Flash
Write speed (13KB)	10 milliseconds	1 second
Average active power	100 µA/MHz	260 µA/MHz
Write endurance	100 trillion+ writes	10,000 writes
Dynamically bit-wise programmable	Yes	No
Supports unified memory with flexible program/data partitioning	Yes	No
Audiology (digital hearing aids)	Ventilation/respiration	Nuclear

Figure 3. Comparing FRAM and Flash in device-embedded memories

Nano-power energy harvesting

Successful designs for wireless sensor nodes will have to gather energy from environmental sources. Power subsystems will have to optimize the available microwatts to milliwatts of power generated from solar, thermoelectric, electromagnetic and vibration sources, then store the extracted energy in elements such as Li-ion batteries and supercapacitors. TI's bq25504 boost charger is designed specifically for power management on this scale, featuring a low quiescent current and high conversion efficiency. Maximum power point tracking (MPPT) optimizes energy extracted from DC harvesters, such as solar panels under varying light and thermoelectric generators (TEG) under varying thermal conditions. The results can be dramatic: in a small-scale solar-powered system, use of the device can increase the usable harvested energy by 30 to 70 percent compared to a linear regulator. Such efficiency allows designers to harvest more energy from smaller solar panels and other transducers, enabling more miniaturized sensing nodes at lower costs.

ULP wireless connectivity

Wireless utility meters today benefit from TI's expertise in low-power RF circuitry, and the same technology is available for use in wireless sensor nodes. TI's CC2500 and CC2520 devices, for example, are low-cost 2.4-GHz transceivers designed for very low-power wireless applications. The circuitry is intended for the 2400- to 2483.5-MHz ISM (Industrial, Scientific and Medical) and SRD (Short Range Device) frequency band. The RF transceiver is integrated with a highly configurable baseband modem that supports various standards-based modulation formats.

ULP sensing

Sensing elements for system input are as varied as the wide range of environments where WSNs operate. For certain applications, TI technology can significantly reduce the size and power consumption of the sensing element. For instance, the company's TMP006 infrared MEMS temperature sensor reduces both power consumption and size by more than 90 percent, giving manufacturers the ability to accurately measure temperature within confined areas such as equipment housings. TI also offers sensor analog front ends (AFE) such as the highly integrated LMP91050 nondispersive infrared gas sensor AFE, which enables ultra-compact sensing solutions used to detect CO_2 and refrigerants such as Freon. Sensing technology that results from TI developments in other fields, such as the company's work with automotive manufacturers, may also be adapted for the requirements of WSNs.

WSNs will make a smart world even smarter

As the Smart Grid deploys piece by piece, it will be joined by intelligent communications among powered equipments everywhere: in homes, offices, factories, even in the outdoors (Figure 4). Such equipments and their networks will themselves be extended by wireless sensor networks that monitor conditions and report back to central systems, thus enabling control over extremely wide areas.

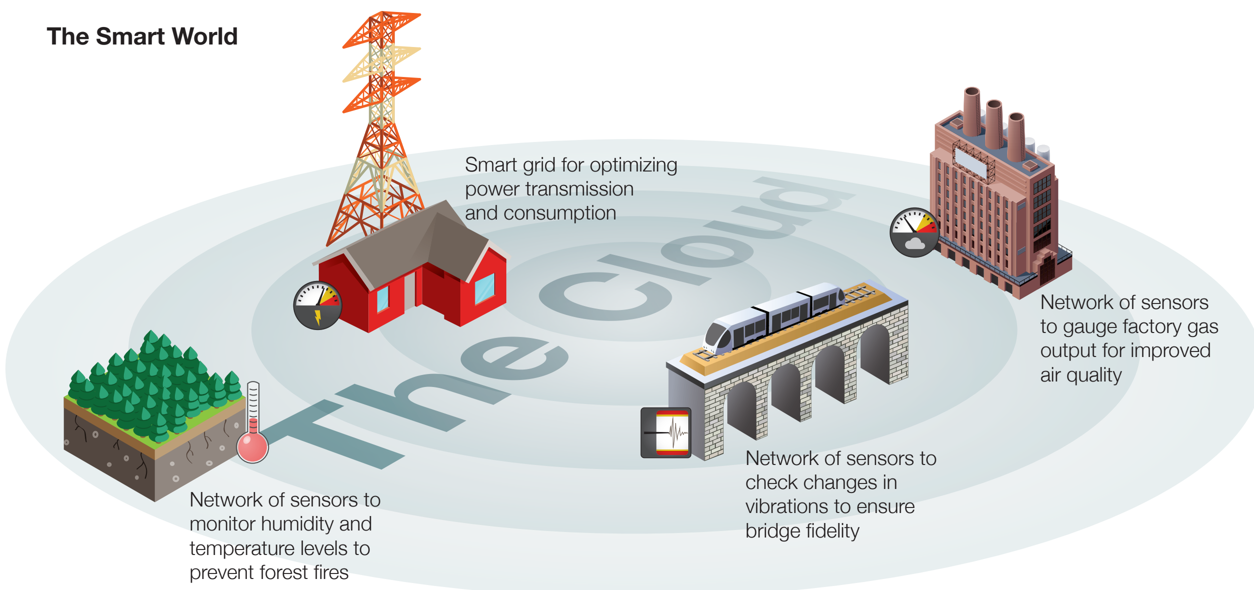

Figure 4. The Smart Grid will be complemented by many power and sensing networks used in a wide variety of environments.

These WSNs depend on the availability of inexpensive, ultra-low-power components that can harvest ambient energy, sense local conditions, perform necessary measurement functions, and periodically communicate information via wireless transmissions. Based on its work with wireless utility meters and other applications, TI has already developed this technology and today offers products that enable the development of "stick-on" sensor nodes for a variety of applications. Thanks in part to TI technology, smart networks are widening the boundaries of today's smarter world.

For more information, visit www.ti.com/innovation-cloud.

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