The Evolution of Wireless Sensor Networks

Recent advances in semiconductor, networking and material science technologies are driving the ubiquitous deployment of large-scale wireless sensor networks (WSNs). Together, these technologies have combined to enable a new generation of WSNs that differ greatly from wireless networks developed and deployed as recently as 5 to 10 years ago. Today's state-of-the-art WSNs have lower deployment and maintenance costs, last longer and are more rugged. They are finding their way into numerous applications in our homes, work places and beyond, bringing new sources of information, control and convenience to our personal and professional lives. Table 1 summarizes several examples of how WSNs can enhance productivity, reduce cost and even save lives.

Table 1. WSNs Bring a Multitude of Benefits to Our Daily Lives

Application	Benefit
Measure micro-climates on farms	Increase crop yield per square km
Monitor traffic on road systems	Steer traffic away from jams, accidents and construction zones; alert emergency services
Detect human presence in homes and offices	Reduce wasted power in HVAC and lighting
Electrical/gas/water metering	Optimize utility distribution systems and reduce inefficiencies

In the future, each WSN application will incorporate a well-established, standardized mix of hardware/software solutions. But for now, wireless system and network designers are faced with making sense of and understanding the complex tradeoffs among many application variables including deployment costs, hardware and software, system reliability, security and performance. Wireless embedded designers must assess these tradeoffs and make multiple decisions, such as transducer and battery technology choices, frequency of wireless operation, output power and networking protocols.

Breaking down the tradeoffs in WSN deployment requires a broad range of specialties within an organization, including energy storage, wireless networking protocols, semiconductor design and sensor/actuator technology. The complexity of WSN design represents one of the most significant barriers to the widespread adoption of WSNs but also provides an opportunity for hardware and software technology suppliers to add value.

Origin and History of Wireless Sensor Networks

To understand the tradeoffs in today's WSNs, it is helpful to briefly examine their history. Like many advanced technologies, the origin of WSNs can be seen in military and heavy industrial applications, far removed from the light industrial and consumer WSN applications that are prevalent today. The first wireless network that bore any real resemblance to a modern WSN is the Sound Surveillance System (SOSUS), developed by the United States Military in the 1950s to detect and track Soviet submarines. This network used submerged acoustic sensors – hydrophones – distributed in the Atlantic and Pacific oceans. This sensing technology is still in service today, albeit serving more peaceful functions of monitoring undersea wildlife and volcanic activity.

Echoing the investments made in the 1960s and 1970s to develop the hardware for today's Internet, the United States Defense Advanced Research Projects Agency (DARPA) started the Distributed Sensor

Network (DSN) program in 1980 to formally explore the challenges in implementing distributed/wireless sensor networks. With the birth of DSN and its progression into academia through partnering universities such as Carnegie Mellon University and the Massachusetts Institute of Technology Lincoln Labs, WSN technology soon found a home in academia and civilian scientific research.

Governments and universities eventually began using WSNs in applications such as air quality monitoring, forest fire detection, natural disaster prevention, weather stations and structural monitoring. Then as engineering students made their way into the corporate world of technology giants of the day, such as IBM and Bell Labs, they began promoting the use of WSNs in heavy industrial applications such as power distribution, waste-water treatment and specialized factory automation.

While the market demand for WSNs was strong, moving beyond these limited applications proved to be a challenge. The military, science/technology and heavy industrial applications of previous decades were all based on bulky, expensive sensors and proprietary networking protocols. These WSNs placed a premium on functionality and performance, while other factors such as hardware and deployment costs, networking standards, power consumption and scalability fell to the wayside. The combination of high cost and low volume prevented the widespread adoption and deployment of WSNs into a broader range of applications.

WSN Technology Transitions

Although the technology for large-volume industrial and consumer applications did not exist in the 20th century, both academia and industry recognized the potential for such networks and formed joint efforts to solve the engineering challenges. Examples of these academic/industrial initiatives include:
- UCLA Wireless Integrated Network Sensors (1993)
- University of California at Berkeley PicoRadio program (1999)
- µ Adaptive Multi-domain Power Aware Sensors program at MIT (2000)
- NASA Sensor Webs (2001)
- ZigBee Alliance (2002)
- Center for Embedded Network Sensing (2002).

The goal of many of these initiatives and standards organizations is to enable high-volume deployment of WSNs in light industrial and consumer applications by reducing the cost and energy per sensor, while simplifying development and maintenance tasks.
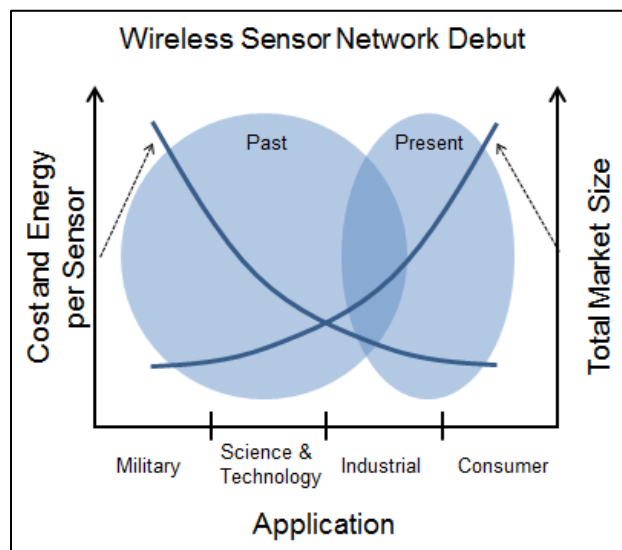

Figure 1. WSNs Gain Market Traction with Decrease in Sensor Costs

Reducing WSN deployment costs while increasing functionality involves major advances in four key technology areas: sensors, CMOS-based semiconductor devices, networking protocols and energy storage/generation technology. The culmination of this effort is the deployment of wireless sensor networks for the emerging Internet of Things (IoT).

Sensor Types

The heart of any WSN lies in the sensors. The past decade has seen rapid advancement in multiple sensing technologies:

- Microelectromechanical systems (MEMS) – gyroscopes, accelerometers, magnetometers, pressure sensors, pyroelectric effect sensors, acoustic sensors
- CMOS-based sensors – temperature, humidity, capacitive proximity, chemical composition
- LED sensors – ambient light sensing, proximity sensing, chemical composition

When combined into a network, these cost-effective sensors enable new applications such as optimizing HVAC control and lighting inside of homes and buildings. According to the US Department of Energy "Annual Energy Outlook 2012" report, HVAC and lighting accounted for 48.1 percent of all commercial energy used in the US in 2010, a significant amount of which was wasted due to the absence of smart systems. Most HVAC and lighting systems are programmed on timers at best and do not take into account the physical presence of humans. Using MEMS, CMOS, and LED sensors to track environmental conditions (humidity, temperature, ambient light) and the presence of people (pyroelectric, proximity, and acoustic), smart systems can be designed to drastically reduce the overall power used by shutting off power to environmental control when no human presence is detected and dimming light fixtures if the ambient lighting is adequate.

Furthermore, once a sensor network is in place, additional functions can be implemented. For example, acoustic sensors can be reused to monitor human physical presence during the day and to detect broken glass from a potential break-in during the evening hours. Another example is using human presence information to eliminate "vampire power" drawn from powered devices (e.g., computer monitors, televisions, etc.) when humans are not present by removing power from wall outlets. Experts estimate vampire power alone is responsible for 7-15 percent of commercial power usage.

Semiconductor Technology Advances

As the semiconductor industry began standardizing on CMOS processing technologies for most semiconductor components by the late 1990s, the hardware required to implement large-scale WSN applications finally reached attractive cost points. Network designers no longer rely on bulky and power-hungry discrete circuit or multi-chip solutions. Instead, new products are coming to market that simplify WSN hardware, such as wireless MCUs – system-on-chip (SoC) devices that contain a general-purpose MCU and an RF transceiver in a single chip. These SoCs include enough high-performance peripherals (amplifiers, ADCs, DACs) and non-volatile memory to handle both the application processing and network protocol stack while simultaneously providing the RF link to the network.

Leading semiconductor suppliers now offer wireless SoCs for WSN applications. For example, Silicon Labs' EM35x Ember® ZigBee® series includes a 32-bit ARM® Cortex™-M3 processor, fully compliant IEEE 802.15.4-2003 transceiver, AES encryption accelerator, an ADC and sub-µA sleep mode currents– all in a single 7 mm x 7 mm QFN package. Developing a sensor node in a WSN with this type of highly integrated solution requires little more than adding a battery and a sensor to the EM35x SoC mounted on an inexpensive circuit board.

Networking Topologies and Protocols

Wireless sensor networking topologies generally fall into four categories: one-way, bi-directional, star and mesh networks.
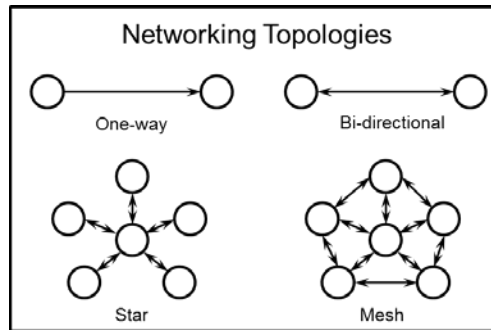
Figure 2. Four Types of Network Topologies

The first networking protocols were simple one-way communication links, still common in applications such as tire pressure monitoring systems, garage door openers and television remote controls. As the need for more advanced topologies became apparent, networking engineers developed low-memory protocols for bi-directional, star and finally mesh technologies. In addition, the industry is making the transition from proprietary to standardized protocols, similar to the transition in MCUs from proprietary instruction sets and toward 8051-based cores for 8-bit processing and ARM-based solutions for 32-bit applications. Having a set of standardized networking protocols such as ZigBee and its variants removes the burden of continuous development costs and frees vendors to focus on their specific applications.

The emergence of cost-effective mesh topologies enables new applications where traditional star topologies come up short. For example, a home lighting application can quickly exceed 30 lights and sensors. A Wi-Fi router is frequently unable to provide whole-house coverage due to multipath propagation or shadowing, but a mesh topology ensures a robust connection to all locations in the house with lowest cost-per-node. Furthermore, mesh topologies enabled by ZigBee software such as Silicon Labs' EmberZNet PRO allow hundreds and potentially thousands of nodes on a single network, much more than the number of devices permitted by Bluetooth (seven) or Wi-Fi (32).

Energy Storage and Harvesting Technologies

The plethora of battery technologies available today for WSNs enables system designers to tailor their energy storage devices to the needs of their applications. For example, the latest lithium battery technologies allow optimization for any operating lifetime or environment. For applications with small temperature variation and short lifetime, lithium manganese dioxide (LiMnO2) batteries provide solid performance at cost-effective prices, while applications demanding large temperature ranges and multi-decade lifetime are satisfied with batteries based on lithium thionyl choride (LiSOCL2) chemistry.

While batteries represent the preferred low-cost energy storage technology, energy harvesting/scavenging devices are beginning to emerge as viable battery replacements in some applications. For example, power can be generated from temperature differences through thermoelectric and pyroelectric effects, kinetic motion of piezoelectric materials, photovoltaic cells that capture sunlight, or even the direct conversion of RF energy through specialized antennas and rectification. Examples of energy scavenging/harvesting devices coming to market today include piezoelectric light and doorbell switches. Research is ongoing in the energy scavenging domain, and deployment costs are expected to continue to fall in the coming years.

Convergence of Technologies

To understand the impact of technology convergence in today's WSN applications, let's examine the power needed to send information from one sensor to an aggregator located about 3 km away in the WSN using wireless MCUs. For the purposes of this example, we will assume a receiver power consumption of 10 mW and sensitivity of -60 dBm for an effective link budget of 80 dB. Furthermore, the transmitter power will be simplified as only the power amplifier. If we examine the number of transmitter

and receiver pairs needed to transmit this data from one end of the network to the next, the following trend emerges as shown in Figure 3.
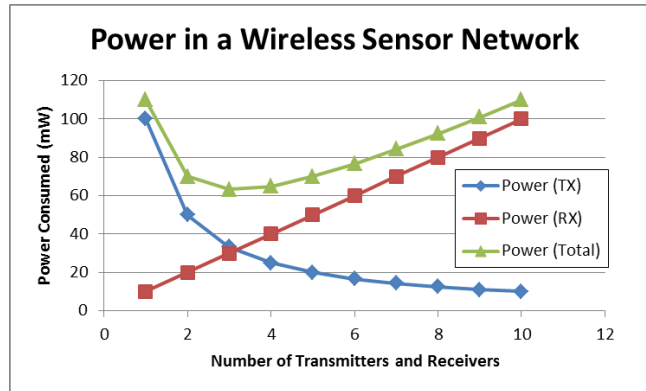

Figure 3. WSN Power Requirements

For a single transmitter/receiver pair, the total power consumed by the network during transmission is 110 mW, but that power drops to 70 mW when a repeater is installed halfway between, representing a 36 percent power savings. Including this repeater means that the network protocol needs to increase complexity beyond a simple one-way link and into a star or mesh network. With the additional repeater in place, the WSN designer is free to place another sensor at only an incremental cost, transitioning the simple repeater into a fully functional sensor node. Having more sensors in the network increases the WSN's utility in accordance with Metcalfe's Law, which states that the network value is proportional to the square of the number of nodes.

While the utility of the network has increased and power consumption has decreased, there was an additional hardware expense of a sensor and transceiver pair. This additional hardware cost is offset because the deployment and replacement cost for a WSN can be 10x the hardware costs involved. In other words, the extended lifetime of the network for a given energy storage technology more than makes up for the additional hardware costs. Likewise, if extended network lifetime is not desired, the network designers are now free to choose a less expensive battery technology.

Looking Ahead

Through advances in sensor, networking, semiconductor and energy storage technologies, future WSNs will combine to form the nervous system of the IoT. When combined with cloud computing and big data processing, the number of applications for and market size of the Internet of Things are almost limitless and will allow humans and machines to interact in unprecedented and unanticipated ways. End users will be able to control their entire home through a single easy-to-use interface. Energy content and distribution systems will increase their efficiency. Farms will produce more crops. Lives will be saved with continuous in-home medical monitoring systems. In short, the coming years are an exciting time in the world of wireless sensor networks. Find out more about Silicon Labs' wireless and RF IC solutions at www.silabs.com/wireless.

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