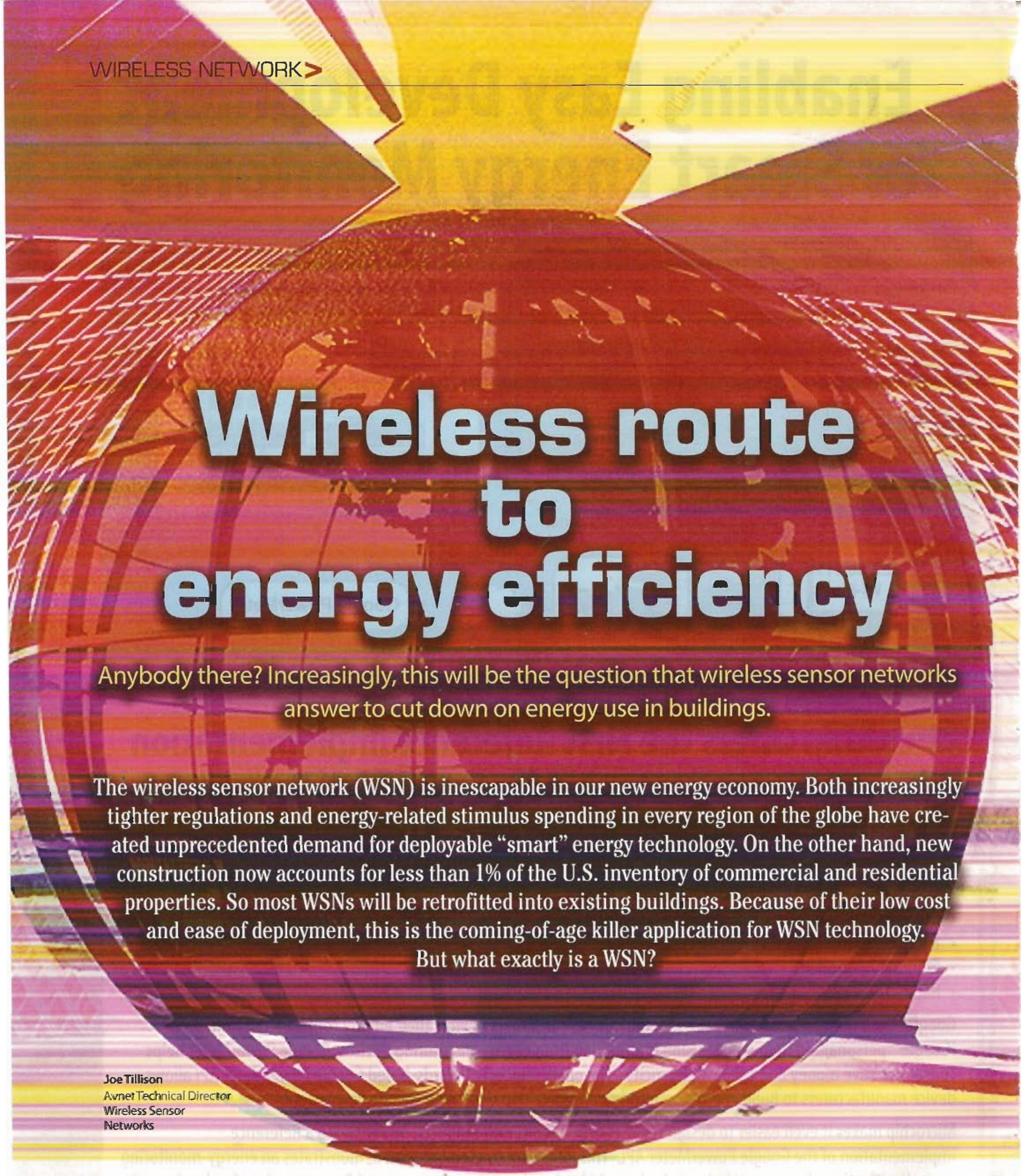

Wireless route to energy efficiency

Anybody there? Increasingly, this will be the question that wireless sensor networks answer to cut down on energy use in buildings.

The wireless sensor network (WSN) is inescapable in our new energy economy. Both increasingly tighter regulations and energy-related stimulus spending in every region of the globe have created unprecedented demand for deployable "smart" energy technology. On the other hand, new construction now accounts for less than 1% of the U.S. inventory of commercial and residential properties. So most WSNs will be retrofitted into existing buildings. Because of their low cost and ease of deployment, this is the coming-of-age killer application for WSN technology. But what exactly is a WSN?

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One of the easiest gains in smart energy management comes from simply managing for occupancy — that is, sensing occupancy and controlling power as necessary to traditional systems like HVAC controls, elevators/walkways, and lighting. More sophisticated systems might integrate sensors for temperature, pressure, humidity, natural light, and even air quality. But before deploying wireless technology in the control loop, there are several issues to consider.

First is the communication protocol. Unfortunately, the market is still fragmented. There is no convenient standard. ZigBee, with nearly $500M in U.S. Smart Grid grants to alliance members, is the odds-on favorite to emerge as the dominant wireless standard for building automation. But other protocols, such as WirelessHART and EnOcean, are already widely deployed.

There are also countless proprietary protocols offered by WSN vendors, each claiming its own unique advantages. While a protocol backed by an adopted standard offers the promise of vendor interoperability, some proprietary protocols can provide solutions tuned to specific performance parameters like simplicity, network resiliency, or security. On the other hand proprietary protocols can lock users to a single vendor for future upgrades and could restrict flexibility.

Next is network configuration. Wireless sensors are designed to use three basic networking topologies: point-to-point, star (point-to-multipoint), or mesh. Topology is integral, of course, to the choice of protocol. It will determine overall system flexibility, scalability, cost, and performance.

Point-to-point simply denotes a dedicated link between two points and isn't really a network at all. Star networks are aggregations of point-to-point links, with central master nodes that manages individual links to a fixed number of slave nodes and handle all upstream communication. Master nodes can also link with other masters to extend networks in various configurations, sometimes called cluster or tree networks.

The inherent weakness of a star network is that the master is a single point of failure; if a master node fails, the entire network (or sub-network) fails. For an example of a 16-node star network of MEMS-based sensors, have a look at Freescale Semiconductor's ZSTAR3 evaluation tool.

Mesh networks offer the most resiliency and flexibility. This includes the ability to create self-organizing ad-hoc networks that reconfigure ("self-heal") when a network is altered, making setup and maintenance easier. The ultimate in mesh networks is a full mesh — where every node can directly link with every other node — but the linking complexity of a full mesh quickly becomes unmanageable as the network grows larger.

Most practical mesh protocols use a type of pseudo-mesh with limited peer-to-peer communication links and a multi-hop routing algorithm optimized for least hops, nearest neighbors, or lowest power. These offer a reasonable compromise between complexity and flexibility. As a point of reference, ZigBee can operate in any of these three network configurations. But ZigBee's flexibility can be one of its biggest challenges and is the reason many vendors develop their own tweaked ZigBee or proprietary protocols. This flexibility requires more complex software overhead and processing resources than simpler protocols. The resulting wireless sensor costs more and uses up battery life more quickly.

Other important considerations are the frequency band and method of RF signaling. Wireless sensors are intended for low-data-rate control and monitoring, so they don't have the same high-throughput requirements as wireless data networks.

For example, the ubiquitous IEEE 802.11a/b/g WiFi standard is designed to support throughput up to 54 Mbps, making it power hungry, thus overkill for wireless sensors. Bluetooth, which has lower throughput at 2 Mbps, is a star network limited to seven slave nodes, with a limited 10-m range (Class 2). Generally Bluetooth networks are too small and too slow for WSN, requiring as much as three seconds just to establish a link (compared with 15 msec for ZigBee). The recently released Bluetooth LE spec for Body Area Networks (formerly Wibree) is a low-energy, non-voice version of Bluetooth much more in line with the needs of low-power sensors.

With rare exception, WSN devices today use the license-free Industrial-Scientific-Medical (ISM) frequency bands of 433/868/915 MHz or 2.4 GHz with open-air range up to 600 m. The sub-gigahertz frequency allocations vary in different regions of the globe, but the 2.4 GHz band is recognized worldwide. This is one of the primary reasons for the wide use of the 2.4 GHz IEEE 802.15.4 radio standard. (The 2.4 GHz ISM band is used by 802.11, Bluetooth, and 802.15.4.)

Being license free, these frequencies can be employed without prior government approval, but users must tolerate any interference generated by other sources. Typically, ISM devices use a combination of RF encoding techniques and protocol handshakes to mitigate interference and to ensure reliable data transfer. The IEEE 802.15.4 radio uses spread-spectrum modulation techniques, collision-avoidance algorithms (similar to Ethernet) and frame validation/verification to ensure successful data transfers.

A note on ZigBee and IEEE 802.15.4: While often used synonymously, IEEE 802.15.4 and ZigBee are two different things. The IEEE 802.15.4 specification only defines the physical signaling and MAC layer implementations (based on the OSI model), while ZigBee completes the upper layers, including the complex rules for the networking protocol. Many other protocols besides ZigBee, both proprietary and standards-based, are built upon the same IEEE 802.15.4 radio.

Deconstructing a wireless sensor

Several critical technologies are key to a good wireless sensor design. The first is the actual sensor itself. In energy-related applications, the purpose of the wireless node is simply to provide the remote capability to monitor (sense) temperature, instantaneous current and voltage levels, wind speed and direction, room occupancy, solar irradiance, or many other physical inputs. They might also control (actuate) external devices like relays, pumps, motors, or cooling systems in a closed-loop control system such as a motor-driven sun-tracking mechanism. There is an enormous variety of precision sensors and actuators today.

Inside the JN5139 is a low-power wireless microcontroller that can handle ZigBee applications. The device integrates a 32-bit RISC processor, transceiver, 192kB of ROM, 96kB of RAM, and several analog and digital peripherals. The device stores system software, including protocol stacks, routing tables, and application code/data. An external flash memory loads in application code at runtime. Among other things, the device integrates power-saving and timed-sleep modes.

At the heart of the sensor node is a small, ultra-low power microcontroller (MCU). The MCU in a battery-powered wireless sensor typically has a low active-duty cycle; that is, it periodically wakes up to perform a task and then returns to sleep mode, working perhaps only tens of milliseconds every minute or so.

Because the MCU could spend over 99.9% of its working life in its lowest power (sleep) mode, the

Protocol	Governing Body	Comment
6LoWPAN	IETF	Ipv6 networking over WPAN.
ANT	Proprietary	Frequency adaptive, isochronous TDMA.
Bluetooth LE	Bluetooth SIG	Body area networks.
DASH7	ISO/IEC	Asynchronous command-response. Substantial DOD investment.
DigiMesh	Proprietary Digi-International	Time synchronized CSMA.
EnOcean	Proprietary EnOcean GmbH (120 Member Alliance)	Self-powered sensors and switches.
ISA100.11a (aka SP100)	ANSI/ISA	Similar but incompatible with wirelesshart. Also transports Fieldbus, Modbus, Profibus.
JenNet	Proprietary Jennic	Small Footprint Staco with WirelessHART. Also Transports Fieldbus, Modbus Profibus.
MiWi	Proprietary Microchip	Simpler MIWI P2P Version has no routing.
ONE-NET	Open Source	Wide support from 8- and 16-Bit MCU suppliers.
SimpliciTI	Proprietary Texas Instruments	Range extenders add up to four hops.
SNAP	Proprietary Synapse Wireless	Supports bridging to TCP/IP or ZigBee with transparent RPC calls.
SynkroRF	Proprietary Freescale	Basis for RF4CE.
WirelessHART	HART Communication Foundation	Channel hopping TDMA. Compatible with WiredHART.
ZigBee	ZigBee Alliance	Multi-vendor interoperability.
ZigBee Pro	ZigBee Alliance	Adds routing, options, and security.
ZigBee RF4CE	ZigBee Alliance	Simplified ZigBee without mesh capability for RF remote control.
Z-wave	Proprietary Zensys (160 Member Alliance)	Popular for wireless home controls.

amount of current used in sleep mode is critical. Many MCUs today have sub-microamp sleep currents. But also important are the low power consumption while in active mode and processing speed. The MCU must be able to wake up quickly, have the processing power to perform the intended task — which includes processing the communications protocol — and return to sleep mode as quickly as possible, minimizing time spent in active mode. The sensor's average power consumption, and ultimately its battery life, is determined by its power specs and the duty cycle ratio of sleep and active modes.

As with the MCU, the transceiver should have low-power features such as an ultra low power sleep mode, low RX power, programmable TX power, and a wake-up timer. Receiver sensitivity (in dBm) is a commonly referenced figure of merit because better sensitivity indicates better range. But look carefully at the datasheet. Most advertised values are measured inconsistently and under the most favorable setup conditions. Transceivers available today offer a range of options for carrier modulation and carrier frequencies covering both the sub-gigahertz and 2.4 GHz ISM bands, and provide a simple serial interface for the MCU.

As an example, Silicon Labs EZRadio family of products includes completely integrated RF transceivers covering the 315, 433, 868 and 915 MHz ISM bands with support for FSK modulation, selectable output power, 1.8 µA sleep mode, and wake-up timer that can be programmed from 1 msec up to several days. While integrated transceivers typically include all the necessary RF circuitry – filters, amplifiers, mixers, modulator/demodulator – external impedance matching baluns and antennas are still necessary. Antennas can be 50-Ω plug-in rubber ducky style, chip, or PCB antennas designed into the circuit board. Lower carrier frequencies generally require larger antennas but also have longer range.

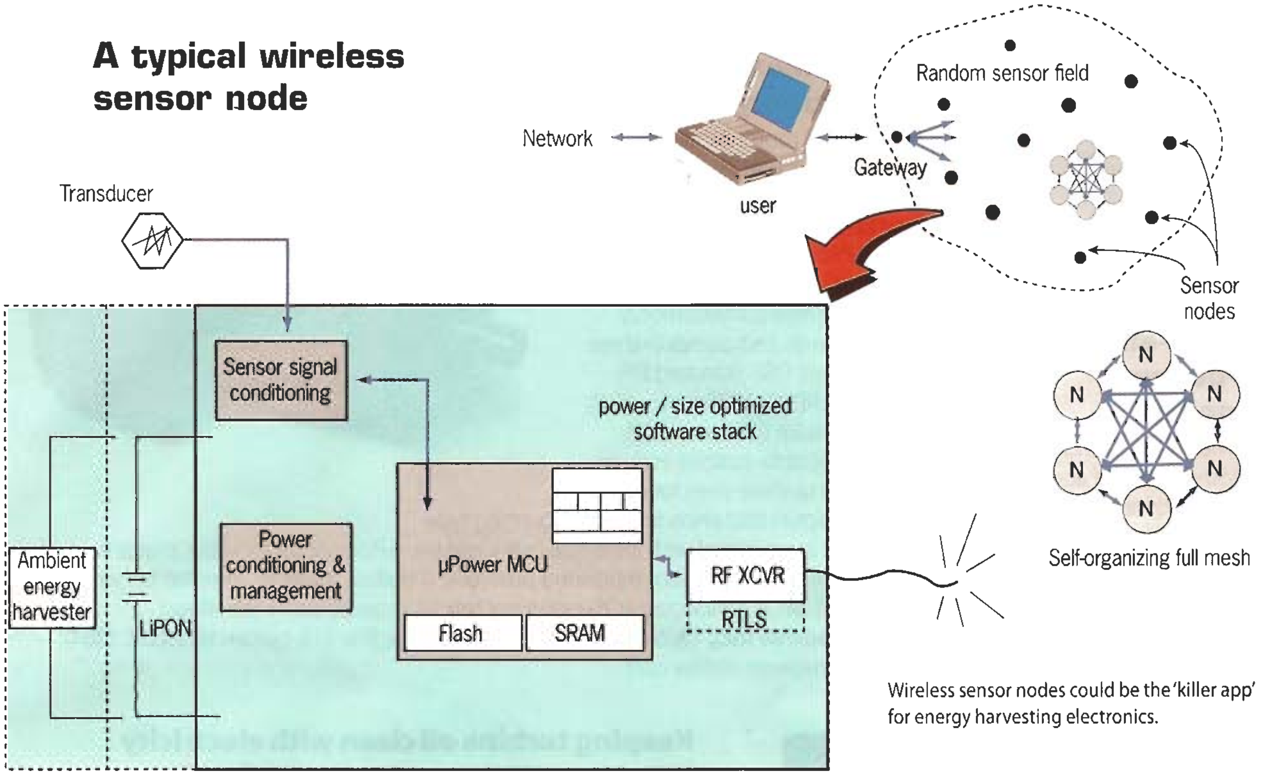
Increasingly, the chip industry is more standards-based radios with low power MCUs to yield devices optimized for WSN applications. The selection of these System-on-Chip devices continues to grow.

There has been one interesting development under the IEEE 802.15.4 standard. An amended specification called IEEE 802.15.4a incorporates Real Time Locating Systems technology into the radio to provide for precision ranging. This new capability could enable applications that use a moveable sensor's distance and position to locate it physically in the network. Potentially, this could be used to actively track important assets such as expensive solar panels or test equipment, or to simplify the commissioning task in the field.

Perhaps the most critical element of the wireless sensor is the "software stack." The stack is the collection of software modules that execute on the MCU to implement a particular protocol. Software stacks are optimized around various performance needs such as standards compliance, power efficiency, speed of execution, and memory footprint. There are seemingly an infinite number of trade-offs, which is one reason there are so many protocol options.

The software stack may also restrict the MCU selection, depending on whether a particular stack is available on a particular MCU architecture, or vice versa. IC suppliers generally offer tested and certified stacks tuned to own their devices that comply with standards such as ZigBee, as well as own their (usually simpler) proprietary stacks with different optimizations. Off-the-shelf module suppliers provide products that include pre-programmed software stacks according to the targeted protocol.

A typical wireless sensor node



Sensor node block diagram

Wireless sensor nodes could be the 'killer app' for energy harvesting electronics.

Harvesting energy

A wireless sensor designed carefully for minimal power consumption can last several years on a single coin-cell-style CR2032 lithium battery. But maintaining the batteries in hundreds of sensors can be a challenge in itself. While technically not a necessity, energy harvesters are quite possibly the most interesting of the key technologies for a wireless sensor, and an essential for self-contained, zero maintenance sensors.

Surprisingly, many ambient energy sources, when converted to electrical energy, can supply the meager power needs of wireless sensors. The most common source is, of course, photovoltaic; not just for collecting solar power, but also to collect small amounts of power from indoor lighting. A commonly available 1-in^2 PV cell can collect several milliwatts of power continuously from a normally lit office.

Both vibration energy harvesting that exploits the piezoelectric effect, and thermoelectric harvesting that exploits the Seebeck effect between two materials with a temperature differential, can provide hundreds of microwatts continuously. Any such sources can provide enough power for a wireless sensor if the energy is appropriately collected and stored.

Enter the thin-film rechargeable lithium battery. These batteries are relatively low capacity – microampere-hours rather than milliampere-hours – but they are small, recharge quickly, and have plenty of discharge capacity to provide short bursts of power a wireless sensor needs.

As an example, the Cymbet CBC3150 is a 50-µAh, surface-mount battery with an integrated power manager. When used in combination with an energy harvesting device, it can collect, store, and provide enough power for a low-duty-cycle wireless sensor.

Resources

Avnet sensor networks page includes information about the Freescale Semiconductor ZSTAR3 evaluation tool, Silicon Labs EZRadio, and the Cymbet3 CBC3150 battery, *http://em.avnet.com/SmartNetworks*

Build or buy?

The research firm IDTechEx estimates there were 141 players in the WSN market last year. With so many suppliers and a wide range of performance options, does it makes more economic sense to design and build or buy off-the-shelf wireless modules. You'll pay more for ready-made modules. But the up-front engineering investments for the build-your-own approach, even assuming you already have RF designers and test equipment, could make this option both costly and schedule-prohibitive.

RF Monolithics, a supplier of both RF components and complete modules, conservatively estimates the economic crossover point for a ZigBee module is well in excess of 25,000 units per year. Off-the-shelf modules also have the advantage of coming pre-certified to FCC and ETSI requirements. In the build-vs.-buy debate, there is no right answer for everyone, but there are certainly plenty of options.

In summary, one can't help but get a sense that we are on the verge of an explosion of WSN deployments for energy applications. There's a need to sense and control more of our environment for the sake of energy efficiency. The emergence of practical, standards-based RF technology and wireless sensor networks offer a convenient way of saving energy that is both economic and easily deployed. **EE&T**