coverstory *By David Marsh, Contributing Technical Editor*

SAFETY CHECK

Wireless sensors eye tire pressure

TIRE-PRESSURE MONITORING IS ONE OF THE BIGGEST SAFETY IMPROVEMENTS THAT ELECTRONICS TECHNOLOGY CAN GIVE DRIVERS. DIRECT-PRESSURE-MEASUREMENT SYSTEMS HAVE NOW SET THE STAGE TO DISPLACE ALTERNATIVE APPROACHES.

IN ANY CIVILIZED NATION TODAY, public safety is the highest profile activity on virtually every government's agenda. But away from the surveillance satellites, bugged phone lines, and intercepted e-mails, less shadowy government agencies continue to strive to save us from the wider threats that compromise everyday life. High on the list of such dangers are road accidents, which cost countless lives every year. From a technologist's viewpoint, efforts to reduce this carnage take diverse forms. As the bureaucrats freely recognize, car makers have in recent years made huge improvements to vehicle safety, many of which rely heavily on electronics content. Familiar examples include the ABS (antilock-braking systems) and ESP (electronic-stability programs) that appear in so many of today's production vehicles. Keen to stimulate the deployment of advanced technologies, agencies within the United States and the European Union sponsor a variety of safety-related projects, such as collision-avoidance radars (**Reference 1**).

But several, arguably more fundamental, steps can contribute to highway-accident reduction, such as ensuring that the vehicle is in fit condition for use. Within this context, tire health is one of the greatest contributors to safety. As cars come to resemble white goods (household appliances) and their need for frequent servicing diminishes, drivers are becoming ever less aware of the basics that underpin safe motoring. Paradoxically, studies in the United States—currently the world leader in legislating for tire-safety issues—reveal that although some 85% of the population recognizes the importance of maintaining properly inflated tires, most drivers wait until the vehicle's service interval to have a garage technician check the tires. A February 2001 study from the US DOT (Department of Transportation) that surveyed 11,530 vehicles nationwide shows that 27% of passenger cars and 33% of light trucks operate with one or more substantially underinflated tires. The result is that, in the United States alone, an estimated total of 23,000 crashes and 535 fatalities every year involve flat tires or blowouts.

Illustration by Mike O'Leary

With vehicle-service intervals that now approach 50,000 km for some models, lack of attention to routine maintenance clearly creates unnecessary hazards. Underinflated tires are not necessarily obvious, because the circumference changes relatively little from 1 to 3 bar of internal pressure, and 30% underinflation is next-to-undetectable to a casual observer (**Figure 1**). Underinflated tires also consume excess energy, with fuel consumption increasing by approximately 1% for every 0.2 bar of underinflation. Unsurprisingly then, vehicle manufacturers and regulatory authorities are keenly interested in techniques for TPMS (tire-pressure-monitoring systems). These groups recognized this requirement as long ago as 1970, but a cost-effective enabling technology simply wasn't available at that time. But today's technologies allow the US DOT to mandate that most vehicles built from now on will carry a TPMS. Key legislation appears in the TREAD (Transportation Recall Enhancement, Accountability, and Documentation) Act of November 2001, with much support work coming from the US NHTSA (National Highway Traffic Safety Administration). The critical motivation for this legislation started in 2000 with a seemingly systematic series of blowouts on one brand of sport-utility vehicle, a mode of transport that's prone to catastrophic rollovers due to the vehicle's relatively high center of gravity.

Meanwhile—and although no impending legislation exists within Europe—the region's technology-driven vehicle makers embraced TPMS at an early stage, with the result that there's a host of European expertise available to fabricate systems (see **sidebar** "For more information" on the Web version of this story at www.edn.com). Pioneers with systems in mass production include the United Kingdom's Schrader Electronics, which developed the systems that appear in, for example, many contemporary French-manufactured cars. In Germany, a consortium of the country's leading motor manufacturers tasked Alligator Ventilfabrik and Beru with designing a cost-effective TPMS for mass production, with Alligator responsible for the valve assembly and Beru tackling the electronics content. In a more recent, separate effort funded by the EU's information-society-technology program, the Technical Research Centre of Finland (VTT) acted as project coordinator for the Apollo consortium. Published in May 2003, the group's report into intelligent-tire systems aims to help save an estimated total of 4000 lives in Europe every year (**Reference 2**). Given the political impetus within the EU for traffic-accident reduction, it's reasonable to expect TPMS to become mandatory within the foreseeable future.

AT A GLANCE

- ▷ Tire-pressure-monitoring systems may soon be legal requirements.
- ▷ Direct-measurement systems offer dramatically better repeatability.
- ▷ Battery power limits current-generation systems to a life of seven to 10 years.
- ▷ Future systems will employ SAW (surface-acoustic-wave) sensors to eliminate batteries.
- ▷ Direct-digital downconversion enables operation at region-independent 2.45 GHz.

DIRECT MEASUREMENT OUSTS ABS

But for now—and crucially, from the semiconductor vendors' viewpoint—a US Court of Appeals decision of Aug 6, 2003, effectively mandates that all TPMS for North American use shall employ a direct-pressure-measurement technique. It's also reasonable to expect that the economics of mass-production will make it inevitable that vehicles for other regions follow suit. This scenario effectively means that every wheel will carry semiconductor content, creating a demand that's poised to involve a large slice of the approximately 25 million vehicles that car makers in North America and Europe build every year. Japan and Korea, too, have large potential as users of the technology, leading to global-demand figures of some 120 to 150 million units per year by 2008.

Before this court ruling, the NHTSA proposed to allow manufacturers to deploy TPMS that rely on the vehicle's ABS to detect underinflation. Normally deployed to prevent wheel locking due to unequal braking forces, the ABS requires a sensor on each hub to monitor the rotational speed of each road wheel. The so-called indirect-TPMS method minimizes implementation cost by taking advantage of the fact that ABS appears in virtually every production vehicle. (In the United States, car makers use this indirect method on an estimated total of 1.6 million vehicles.) The technique works by comparing the rotational speed of each wheel in normal driving mode and relies on a tire that's substantially underinflated having a rolling diameter that's smaller than its counterparts. As a result, the errant tire rotates faster than correctly inflated members of its group (typically, the partner wheel on the same axle). But some problems exist, such as the system's inability to detect tire deflation of typically less than 30%. Also, tire changes require resetting the system to relearn the dynamic relationship between each wheel, creating lifetime maintenance and calibration issues. And, because the system makes differential measurements, it can't independently treat each wheel. For example, no way exists to detect a case in which all four tires are underinflated to a similar degree, which can easily occur with similar tires over an extended period of neglect. Potential system improvements include analyzing the resonant frequency of each wheel, but this approach isn't cost-effective, because it requires significant computational capacity. Ongoing research suggests that other indirect methods may offer promise. For example, researchers at Stanford University propose a combination of standard automotive-fitment sensors and a GPS to resolve tire-pressure differences to approximately 5% (**Reference 3**).

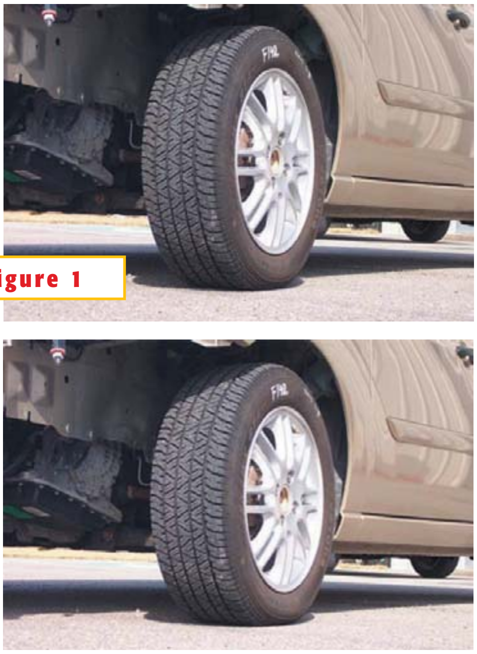
But in NHTSA's tests of four OEM fitment indirect systems, warning thresholds for low-pressure conditions ranged from −8 to −46%, with one system providing no warning at all for pressures as low as 0.98 bar (**Reference 4**). The agency also found huge discrepancies in response times of as much as 10 minutes for similar test conditions, together with a surprising sensitivity to road-surface quality between tarmac and loose surfaces. By comparison, the agency's tests on commercially available pressure-based TPMS (direct systems) yielded an advisory message at an average of a 20% underinflation level and a safety warning at 36% below recommended pressure. Again, significant differences existed in response times that varied from 8 to 136 sec, reflecting differences in the various systems' updating sequences. Compared with the indirect approach, the direct technique has downsides that include greater installation cost, a limited battery life of five to 10 years, and the potential for sensor damage when installing replacement tires or through driver error by curbing the tire. But in general, the direct technique demonstrated its superiority in virtually every respect, most noticeably with the ability to reliably report individual-tire status.

SYSTEMS FACE TOUGH SPECIFICATIONS

Although last year's court decision has created some indecision regarding TPMS-implementation schedules, most observers believe that the NHTSA's direct measurement, "four-tire, 20%" model will enjoy universal adoption. The fundamental requirement demands that the system generates a driver warning when the pressure in any one tire, or in any combination of as many as four tires, falls to 20% or more below the manufacturer's recommended cold-inflation pressure. The EU believes that temperature measurement is also essential to ensure the long-term accuracy and reliability of a TPMS. Temperature monitoring allows the system to compensate for cold-to-warm-running tire-pressure changes and for temperature dependencies within the pressure-sensor device. It also facilitates system shutdown in the case of gross overtemperatures. Although all TPMS aim to withstand the −40 to +125°C automotive range, overtemperature conditions can arise due to factors such as brake-disc heat soak under aggressive driving conditions, when disc-surface temperatures can reach 900°C. For this reason, some systems include thermal-shutdown systems; others specify a 170°C operational capability for a 3- to 5-minute time frame.

Other environmental challenges that TPMS designers must meet are severe. Popular wireless-mounting systems for OEM fitments have a small sensor module that fits inside the tire and carries the valve stem, with the valve-stem nut securing the assembly (**Figure 2**). Aftermarket fitments for applications such as motorcycles typically attach the sensor module to the wheel using a steel strap. This module typically weighs 28 to 35g and requires a small balance correction elsewhere on the wheel assembly. The application has to withstand not only automotive-temperature extremes, but also extreme levels of acceleration and vibration. For example, at a vehicle speed of 250 km/hour, the module in a system such as Pi Research's TPMS for Formula One motor sport is exposed to as much as 1000g, as well as the constant vibration that road-surface irregularities cause. Also, the module must resist compounds that commonly appear in the application, which range from petrochemical ingress to the lubricants that ease tire fitment.

Figure 1



The difference between a correctly inflated tire (top) and one with only 70% pressure (bottom) is difficult for a typical driver to see.

Conventional methods of preserving electronics within harsh automotive environments include conformal coatings and encapsulation within some type of epoxy- or polyurethane-based potting compound. The TPMS application complicates matters by needing an open port to measure pressure, which has led to some design approaches. These include using vibration-dampening potting compounds with special conformal coatings, such as Cookson Electronics' Parylene, an inert, hydrophobic, polymer coating that's applied by vapor deposition. Because it's possible to apply this material in extremely thin layers, it's well-suited to preserving MEMS (microelectromechanical-systems) sensors. Other methods for securing the pressure-port opening include gel coatings and Teflon microfilters.

At the system level, choices for a direct-measurement, radio-based TPMS architecture depend on competing factors that principally comprise the system's technical capabilities versus the vehicle manufacturer's cost constraints and sophistication requirements. A representative system consists of four functional blocks: a sensor and transmitter assembly for each tire, the chassis receiver, the display subsystem, and an optional command channel (**Figure 3**). Basic systems employ transmit-only channels that take advantage of the unlicensed ISM (industrial, scientific, and medical) bands that center on 315 MHz (United States) or 434 MHz (Europe), with Korean customers typically requesting 448 MHz. In this case, wheel-sensor activities are autonomous of any central intelligence and typically require an accelerometer to control wake-up and sleep-mode switching to conserve battery life.

Although it adds to system cost, including a command back channel simplifies the challenge that autonomous sensor/transmitter assemblies face, as well as allows the more sophisticated interrogation and display capabilities that vehicle manufacturers desire. This command channel is often a 125-kHz link

SAW SENSORS ENABLE BATTERYLESS TPMS

Because batteries limit operational lifetime and create maintenance and disposal issues, dispensing with this need is a highly attractive proposition for TPMS (tire-pressure-monitoring-system) designers. Possibly more familiar from their use in high-frequency-communications filters, SAW (surface-acoustic-wave) devices are also useful in strain-based sensor applications, such as pressure and torque, as well as temperature. Given appropriate SAW technology, an RF-backscatter-interrogation technology enables direct-measurement, batteryless TPMS and promises sensors that are many times smaller and lighter than today's battery-powered counterparts.

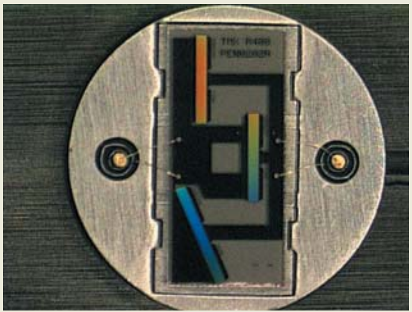


Figure B The spacing between fingers of interdigital transducers determines the wave period in a SAW device.

Such SAW devices exploit the Rayleigh-wave effect, which is named after English physicist Lord Rayleigh (John William Strut), who in the mid-1880s worked on SAW propagation.

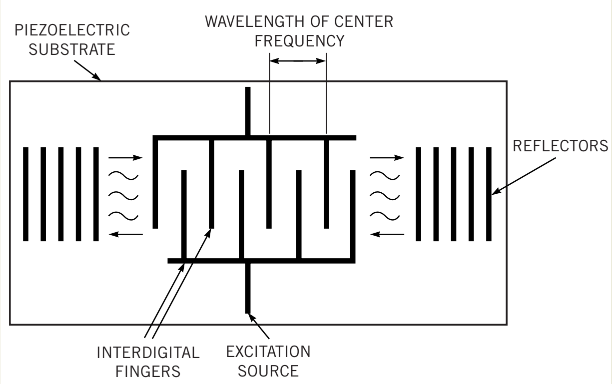


Figure A Transense's three-SAW device provides temperature and pressure information from a package that weighs just 2g.

Surface acoustic waves travel some 100,000 times slower than their electromagnetic counterparts, with typical wavelengths of 1 to 100 microns and amplitudes of around 1 nm. Crucially, the Rayleigh-wave velocity depends on the substrate material and the propagation direction with respect to the crystal lattice but is independent of excitation frequency. SAW-sensor operating frequencies typically range from 50 to 950 MHz.

In a resonant-SAW device, applying an RF waveform to the surface of a piezoelectric substrate via a central IDT (interdigital transducer) that comprises a number of interleaved metal fingers causes particle displacement, principally on the surface of the elastic material. Additional sets of metal fingers on either side of the IDT progressively reflect the expanding surface acoustic wave to set up a standing surface wave with a natural frequency that relates to both mechanical strain and temperature (**Figure A**). Pausing the RF excitation allows the device to ring for a short period, regenerating an RF signal that you can transmit and interrogate over a wireless link. In effect, the SAW device is a passive transponder.

Ray Lohr, technical director of specialist SAW-sensor design-house Transense Technologies, explains that the properties of quartz piezoelectric crystal are anisotropic. By placing just three SAW devices at appropriate angles on one substrate, you can extract independent temperature and pressure information (**Figure B**). A commodity process fabricates the quartz substrate, which rests on two ledges that are integral to the base of the sensor. A central dimple on the device's metal lid presses on the center of the die, so an increase in external pressure causes the die to deform in a simple three-point bend. All three SAW sensors respond to temperature, but only the central one responds to pressure. It's straightforward to derive independent pressure and temperature from the two frequency-difference signals. The hermetically sealed steel enclosure measures 12 mm in diameter by 2 mm thick and weighs just 2g.

Lohr describes the device as a single-port resonant SAW sensor, in which the resonant frequency is compatible with ISM (industrial, scientific, and medical) bands. Sending a short RF burst of less than 1-mW excitation power stimulates the device, which continues to ring for about 20 μsec after the RF transmission. Lohr notes that the low-power return signal of approximately 1 nW has a range of only about 0.2 to 0.5m, so no potential exists for intertransducer interference. A typical whip aerial for in-tire use measures about 170 mm long (less if helically wound), and you can make one from nylon-coated steel wire. External dipoles within each wheel arch are about twice this size and, for lowest cost implementation, link to a central module via coaxial or twisted-pair wiring. An RF ASIC and DSP complete the interrogation system. Overall, Lohr believes that this system promises the lowest installed cost per wheel of any direct-measurement technology.

that relies on inductive coupling. It typically integrates with remote-keyless-entry systems or with another body function via the now-popular LIN (local-interconnect-network) bus (see www.lin-subbus.org). In addition to a test-head range of approximately 2m, other advantages include the ability to set up, test, and debug a TPMS on an automotive-production line. But, regardless of implementation details, the TPMS community generically terms this command-channel capability "POD" (pressure on demand). Current estimates suggest that the systems' greater cost will restrict market penetration to only approximately 10% of all vehicles, and these will comprise high-end luxury cars.

SENSORS VIE FOR LOWEST POWER

At the heart of the system, sensors are key to dependable TPMS operation. Today's biggest TPMS-sensor suppliers are Infineon Technologies' recent acquisition SensoNor and GE NovaSensor, a division of US giant General Electric that also has European roots. (Some other European-based organizations that can offer appropriate sensor products include Technical University of Berlin spin-off First Sensor Technology; IMST; the United Kingdom's Ministry of Defense research-agency spin-off QinetiQ and its manufacturing partner, First Technologies; Transense Technologies; semiconductor-fabrication licensees, such as Melexis; and VTI Technologies.) Traditional semiconductor-pressure-sensor elements employ a piezoresistive technology, in which strain on elements within a Wheatstone bridge generates a pressure-dependent difference voltage. With tension, a piezoresistor's value decreases as the number of charge carriers increases in the direction of the compressive force, so rearranging the circuit such that opposite piezoresistor pairs simultaneously increase and decrease in value maximizes circuit sensitivity.

Devices developed exclusively for TPMS applications, such as SensoNor's SP12, employ MEMS fabrication and integrate temperature, acceleration, and battery-voltage sensors. These last two functions furnish motion detection for system-wake-up control and ensure that the system can warn drivers of impending sensor-battery failure. An integral signal-conditioning ASIC measures pressure with ±0.085-bar accuracy and outputs results over a three-wire SPI-compatible interface. The battery-voltage monitor works as low as 1.8V with ±100-mV accuracy, and the temperature sensor operates over the device's −40 to +125°C operational range with 4°C accuracy. Radial-acceleration resolution is 0.5g from −12 to +115g with ±18% sensitivity. Worst-case current consumption is 3.8 mA at 120°C with all analog modules active during a measurement cycle; typical consumption is about 1 mA less, falling to less than 1 μA at room temperature in standby mode.

Figure 2

Beru's sensor module mounts inside the tire on the valve stem.

SensoNor applications engineer Ronny Weum observes that the sensor bridge consists of a Wheatstone bridge of four piezoresistive resistors. Only the low-power oscillator and interval counters run in standby mode. "In any application," he says, "the SP12 will spend most of the time in this mode. In active mode, the SP12's pressure-measurement time takes a maximum of 6 msec." SensoNor offers the similar SP12T device with an extended pressure-measurement range to suit heavy vehicles, but this device lacks the accelerometer capability. Both devices come in a custom 14-pin SOIC that has a sealed pressure cavity to ease installation issues, with a choice of a top- or bottom-side vent. Development kits are available for both versions.

Marc Osajda, TPMS program manager at Motorola's Toulouse, France, facility, notes that because Wheatstone-bridge circuits require a bias supply, they're relatively power-hungry. He advises that meeting car makers' seven- to 10-year battery-life target demands counting microcoulombs of charge drain for comparison with a cell's typical 550-mA/hour lifetime (**Table 1**). This capacity varies in response to temperature changes, with the cell's internal resistance increasing as ambient temperature falls. For this reason, designers endeavor to ensure TPMS operation to 1.8V and less, although typical specification limits state 2.1V. One method of decreasing power consumption in a Wheatstone bridge involves raising the bridge impedance from a value of, conventionally, a few kilohms. But Motorola chose another approach and employs a capacitive technique for its first-generation MPXY8020A pressure and temperature sensor. This eight-pin, surface-micromachined MEMS device exploits the capacitance change under deflection between two sets of parallel elements to report pressure; a separate, diffused positive-temperature-coefficient resistor enables temperature measurement. Osajda observes that the capacitive technique permits a smaller die than does its piezoresistive Wheatstone-bridge equivalent and can be easily integrated with other CMOS circuitry.

The MPXY8020A's capacitance-to-voltage-conversion amplifier is factory-trimmed for gain, offset, and temperature, with the calibration constants stored in on-chip EEPROM. Communications with external logic are via SPI, with a programmable 8-bit threshold register setting warning parameters. Although the company's $375 demonstration board uses the MC68HC908RF2 microcontroller with its integral RF interface, Osajda says that simple logic offers the best efficiency. "Microcontrollers offer system designers flexibility until very late in design but are power-hungry compared with a CMOS state machine," he says. In standby mode, the MPXY8020A typically consumes less than 1 μA, rising to approximately 400 μA for a temperature measurement and 1300 μA for pressure; a read-mode operation costs 600 μA in the worst case. Accordingly, power-reduction techniques potentially include transmitting only when a problem exists. But system designers demand regular transmissions to ensure healthy operational status, as well as to regularly update the driver's information system. As a result, typical systems measure pressure every 3 to 6 sec to ensure rapid response to problem conditions with an immediate transmission but routinely transmit only every 10 measurements or so. The MPXY8020A includes a micropower, 5.4-kHz oscillator and divider chain that generates a

370-µsec pulse every 3 sec to initiate a conversion, plus a reset pulse about every 52 minutes, which the system can use to emulate watchdog functions.

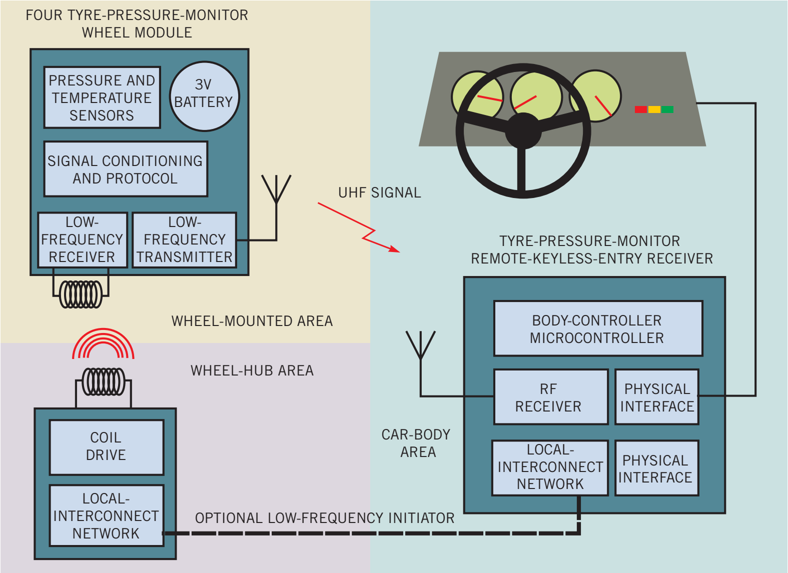


Figure 3 **A typical direct-measurement system links wheel modules to a central receiver that interfaces with the vehicle's information bus, with an optional command channel providing duplex capability (courtesy Motorola).**

RF STIMULATES BATTERYLESS SENSORS

Although significant, sensor-power consumption is secondary to the power level that's necessary to ensure reliable RF transmission between the sensors and the chassis receiver, which can take tens of milliamps. It's therefore salutary to consider what you can save by implementing a motion-detection or POD facility, without which the system will have to run continuously between sleep-mode states.

Martin Motz, TPMS marketing manager for Atmel, estimates that average users drive a car for only approximately 5% of its chronological life, and of this time, the TPMS is active for only a short period. Measurement frequency apart, other factors that help shorten the TPMS active period include the radio system's settling time. According to Motz, his company's new ATA5756 and 5757 chips, respectively suiting 315- and 434-MHz operation, are the first transmitters to benefit from TPMS optimization. Transmission time is typically less than 0.85 msec, 600 µsec of which allows the crystal oscillator to stabilize after power-up; 250 µsec more allows the PLL to settle, whereupon the power amplifier can begin transmission. It delivers about 6 dBm of output power for some 8 mA of active current. Transmission formats are amplitude- or frequency-shift-keying to 20 kbaud using Manchester encoding, or twice that rate using NRZ (non-return-to-zero) coding. Motz notes that these circuits also aim to allow wide crystal tolerances, with the crucial maximum negative resistance set at −650Ω. (The typical value is −1100Ω.)

TABLE 1—TYPICAL TPMS CURRENT CONSUMPTION

Function	Battery use per event
Pressure sensing	225 nA/sec
Temperature sensing	60 nA/sec
Voltage sensing	60 nA/sec
A/D conversion	48 nA/sec
Data processing	8 nA/instruction
Wake-up	53 mA/hour in 10 years
RF transmitting	60 to 100 µA/sec
Nonvolatile memory	0.2 nA/sec/bit
Low-frequency receiving	100 nA/sec per event to 440 mA/hour in 10 years
Overtemperature switching	10 nA/sec
Power management	100 nA/sec per event to 90 mA/hour in 10 years
Silicon leakage	9 mA/hour in 10 years

Other transmitter issues include identification and contention. Inserting a unique identity code into each data gram allows the receiver to identify individual modules and to possibly relearn their positions after vehicle-maintenance procedures, such as wheel rotation. To avoid radio collisions, transmitting-only systems include heavy randomization that minimizes a possibility that POD systems circumvent. Erwin Bartz, vice president of business development at TPMS-maker SmarTire, says that key communications issues include ensuring that the radio spectrum meets regional emission regulations for unlicensed-band operation. The responsible bodies are the FCC (Federal Communications Commission) in the United States and ETSI (European Telecommunications Standards Institute) in Europe. Such regulations define maximum acceptable power levels and spectral leakage within an appropriate power-density mask from measurements that you make in free space.

Bartz notes that, depending on tire construction, installation within the body of a wheel incurs as much as a 25-dB loss, so regulative demands challenge TPMS-application profiles. Also, because the wheel is spinning, it's important to avoid nulls, making antenna design a critical factor; one option uses the valve-stem body as the transmission link. Unlike some implementations that employ a receiver antenna per wheel well, SmarTire's system uses a central receiver module that cuts cost by minimizing wiring-harness requirements. For the future, Bartz foresees batteryless implementations becoming common within five years. (See **sidebar**, "SAW sensors enable batteryless TPMS.")

In a TPMS-applications study of the company's Diversity radio-receiver chip set, Uwe Kopp, marketing manager for data-conversion systems at National Semiconductor Europe, similarly proposes a batteryless system based on 2.45-

GHz operation that circumvents regional dependencies on available unlicensed-band frequencies. It's also easy to limit the range of this high frequency to approximately 80 cm, making wheel-and-tire coding unnecessary. Kopp proposes a system that employs about 10 mW of 2.45-GHz carrier with 5- to 10-MHz amplitude modulation to stimulate quartz-based SAW temperature and pressure sensors. Following an RF burst, these devices continue to oscillate for a short time at their central frequency, plus or minus frequency shifts that represent measurement data. Sensing this return signal reports tire status.

In Kopp's example, the return signal multiplexes into a central radio receiver, which extracts the data by examining the signal's phase information after a conventional bandpass-filter and in-phase, quadrature-demodulator stage. Key system elements include the CLC5903 dual-channel digital downconverter with automatic gain control, the CLC5526 digital variable-gain amplifier, and appropriate ADCs. Kopp calculates that, if 1 bar of absolute pressure represents a 700-Hz frequency shift and 15 Hz provides 1% pressure resolution, the entire signal-processing chain needs about 120 dB of dynamic range. Most of the processing gain comes from the variable-gain amplifiers and the downconverter-control loop, together with some postprocessing in the host DSP. The control loop compresses the dynamic range of the input IF signal before sampling, extending the ADC's dynamic range by as much as 42 dB for 12-bit resolution; meeting the necessary approximately 60-dB signal-to-noise-and-distortion ratio demands at least 10 bits of converter resolution. Converter-sampling frequency must be at least twice the Nyquist limit and preferably more to allow reasonable margin, which a converter such as National Semiconductor's dual 10-bit, 40-MHz ADC10D040 provides.

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Kopp explains that, if the pressure sensor has a nominal frequency of 9.6 MHz, the temperature sensor should be offset to 9.2 MHz to prevent sideband overlap. Because the return signal emanates from a spinning wheel, the digital downconverter separately processes sidebands to remove Doppler shifts. Kopp also notes that the design of the filter between the variable-gain amplifiers and the ADC is crucial. The amplifiers are necessary to increase dynamic range but introduce broadband noise at the converter's input. It's essential to filter out this noise to prevent the converter from generating sampling-image frequency noise that will degrade system performance. National Semiconductor offers a range of evaluation boards and reference designs that you can examine at the company's Web site, www.national.com.□

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