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Consumers Embrace the IoT

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November 2016 VOLUME 64, ISSUE 11

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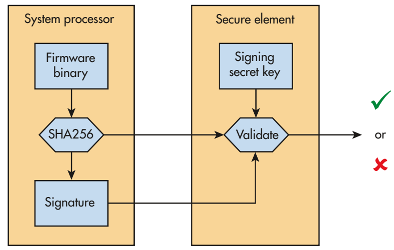

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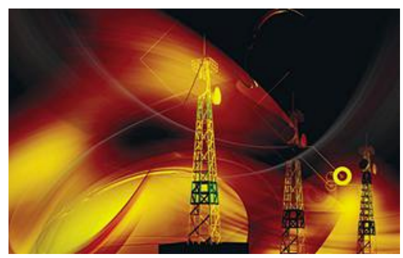

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EDITORIAL MISSION:
To provide the most current, accurate, and in-depth technical coverage of the key emerging technologies that engineers need to design tomorrow's products today.

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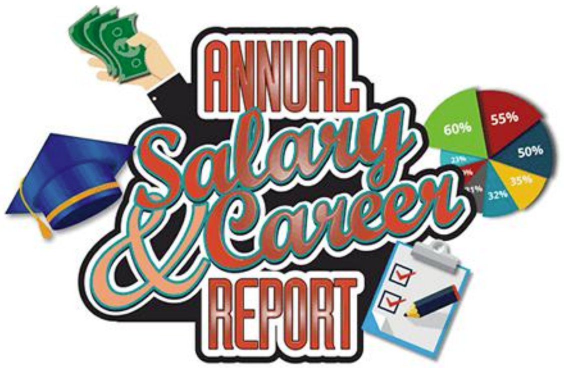
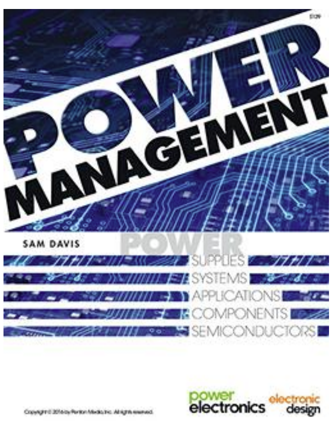


DON'T MISS THE ANNUAL SALARY & CAREER REPORT

http://electronicdesign.com/salarysurvey

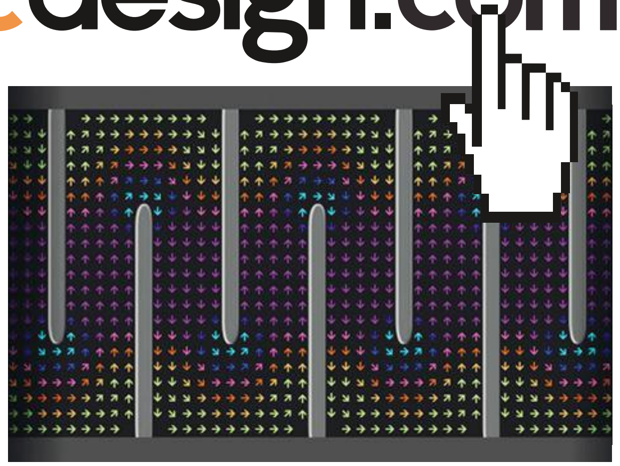
Did you miss last issue's coverage of the 2016 *Electronic Design* Salary & Career Report? Never fear: Get up to speed on this year's findings, which present electrical engineers with a mixed outlook on the industry.



Q&A: POWER ELECTRONICS' SAM DAVIS

http://electronicdesign.com/power/qa-powerelectronicscom-s-sam-davis

In addition to serving as editor-in-chief of PowerElectronics.com, Sam Davis is the author of *Computer Data Displays*, has received the Jesse Neal Award for trade press editorial excellence, and holds a patent for naval ship construction that simplifies electronic system integration. He also has a brand-new e-book out called *Power Management.*



CARBON-FILM MELF: PULSE-LOAD CHAMPION

http://electronicdesign.com/power/carbon-film-melf-pulse-load-champion

Many electronic circuits are exposed to high pulse loads. In some applications, these occur regularly. In others, pulses are incidental, but also inevitable—resulting from electromagnetic-interference (EMI) signals. Unfortunately, due to the increasing miniaturization or intrinsic limitations of electronic components, their pulse-load capability is often insufficient to withstand these pulse loads and they require protection.

GETTING A SENSE FOR REALSENSE AND MERGED REALITY

http://electronicdesign.com/iot/getting-sense-realsense-and-merged-reality

We already had augmented reality (AR) and virtual reality (VR), and now Intel brings us merged reality (MR). The company's CEO, Brian Krzanich, recently revealed the wireless, head-mounted display (HMD) that is part of Intel's Project Alloy.

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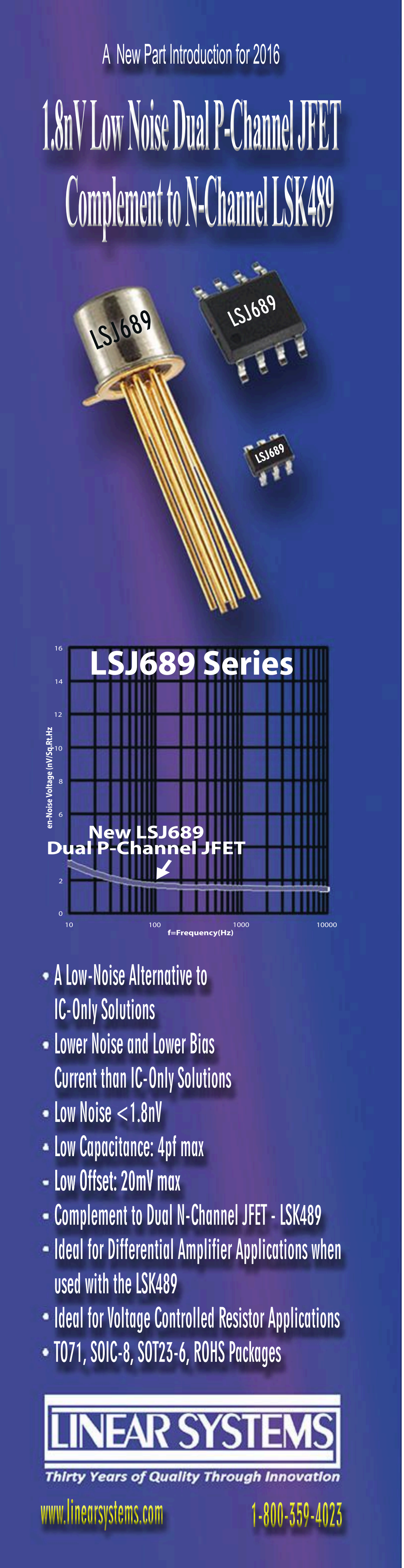

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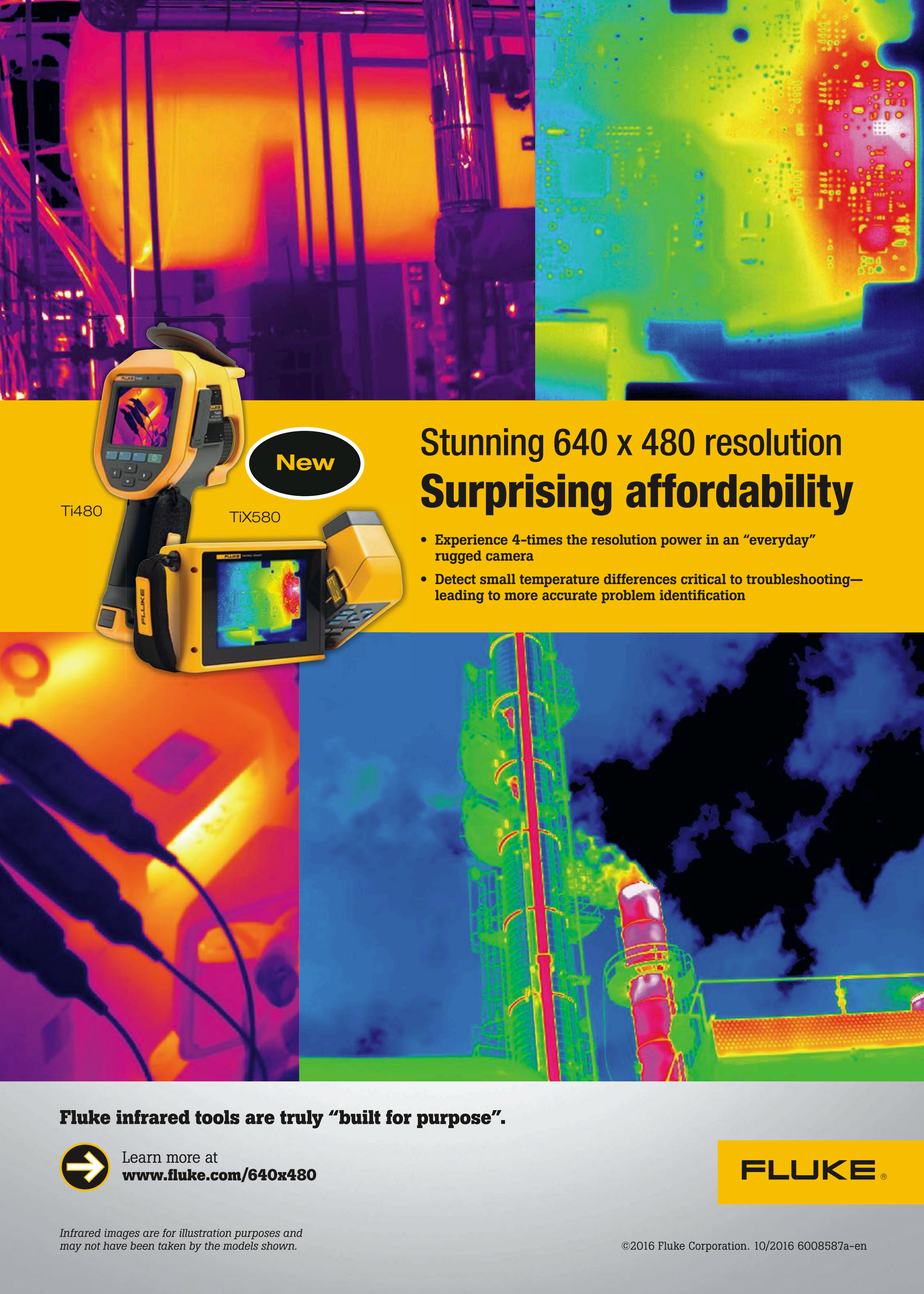
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MARIA GUERRA | Technology Editor
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Wireless Charging Inches Closer to Commercial Reality

More semiconductor companies are adopting wireless power transfer technology to offer chipsets for wireless charging solutions.

The production of wireless charging transmitter and receiver chip-sets based on WPC and A4WP/PMA standards is picking up. Several mobile chipmakers are providing integrated circuits that support at least one of the standards. The wireless charging market is expanding from the smartphone market into other markets with great potential (e.g., the automotive, wearable, industrial, Internet of things (IoT), and medical markets).

Nowadays, most semiconductor companies are members of both the major wireless standards organizations. Chipmakers not only offer certified product solutions for low-power standard (5W), some of them had even started to offer certified higher-power solutions (such as 15W). For example, Rohm received certification from WPC (Wireless Power Consortium) for its reference design using the BD57020MWV wireless power transmitter IC and BD57015GWL wireless power receiver IC. Both receiver and transmitter are certified to be compliant with the new Qi v1.2 standard for medium power. The Qi standard by WPC for medium power enables wireless charging of tablet PCs while allowing smartphones and other mobile devices to be charged up to three times faster than the existing low-power standard (5W). In addition, a Foreign Object Detection (FOD) function is included to provide greater safety by detecting foreign metallic objects before power transfer to protect against possible damage due to overheating.

Another example of wireless chargers becoming a new source of revenue is the announcement made by STMicroelectronics and WiTricity to develop integrated circuits (ICs). WiTricity (an active member of A4WP) and STMicroelectronics are developing semiconductor solutions that combine WiTricity's foundational intellectual property and wireless power-transfer mixed-signal IC-design expertise with ST's leadership in power-semiconductor design, fabrication, and packaging capabilities and resources.

The BD57020MWV works as a controller in the wireless power transmitter based on the Qi compliant by using it with a general-purpose microcomputer. *(Courtesy of Wireless Power Consortium)*

Apple has removed the headphone jack in its new iPhone 7, signaling that the company may finally be shifting toward wireless charging. But the potential adoption of wireless charging by Apple could also introduce yet a new standard, making the standards battle even more complicated. There is no unified wireless power standard and there is no interoperability between the two major standards (Qi and A4WP/PMA), but that has not stopped consumers from seeking out the new technology. Wireless power technology will continue to improve and grow into other markets; the battery-powered electric vehicle and the plug-in hybrid-vehicle are two markets that can benefit greatly from this technology.
I can't wait to see what comes next.

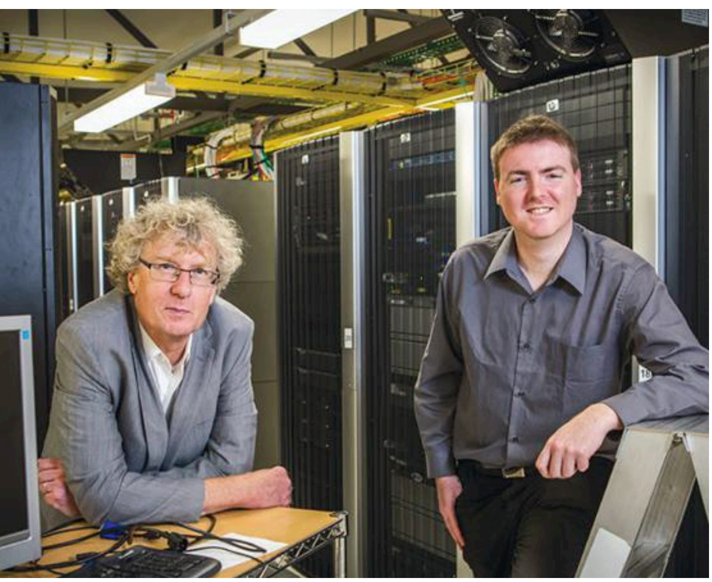
News

FIRST COMPUTER-GENERATED Music Recording Remastered

In 1951, a group of BBC broadcasters arrived at the Computing Machine Laboratory in Manchester, England, for a music recital. There, they made the first recording of computer-generated music, produced by the Mark II computer invented by Alan Turing, widely considered the father of computing.

The recording, stored on a 12-inch acetate disc, holds snippets of the British national anthem, the nursery rhyme "Baa Baa Black Sheep," and a performance of the Glenn Miller's "In the Mood." The recital is famous for being the earliest instance of computer-generated music, but it was not until recently that researchers from the University of Canterbury in New Zealand noticed that the tunes were distorted.

Now these researchers have remastered the recording, which had been preserved in digital form in the British Library's Sound Archive. Using specialized software and traditional editing, they restored the computer's original sound, which resembles a primitive synthesizer.



Jack Copeland and Jason Long have remastered the first recording of computer-generated music after finding that it was severely distorted. *(Image courtesy of the British Library's Sound Archive).*

"The computer itself was scrapped long ago, so the archived recording is our only window on that historic soundscape," wrote the researchers—computer scientist Jack Copeland and composer Jason Long—in a blog post about the restoration.

Playing musical notes is one of the lesser known features of Turing's computer, which filled most of the laboratory's ground floor. The gigantic contraption was connected to a loudspeaker—Turing called it the "hooter"—which emitted a short burst of sound when it received a special instruction. When these bursts were repeated fast enough, the computer created what sounded like a note. By adjusting the pattern of the bursts, engineers could play different notes.

Turing used the notes to troubleshoot the computer, playing different sounds when a program finished or an error occurred. It was not until 1951, when a budding computer scientist named Christopher Strachey wrote the first music programs, that the Mark II became an instrument.

The computer-generated music was imperfect: the computer could only produce an approximate version of a note. But when Copeland and Long analyzed the recording nearly 65 years later, they found there was a significant amount of distortion.

"The frequencies in the recording were not accurate," the researchers said. "The recording gave at best only a rough impression of how the computer sounded." By figuring out how badly the recording deviated from the computer's capabilities, they concluded that the recording was playing too slowly.

"This was most likely the result of the mobile recorder's turntable running too fast while the acetate disc was being cut," Copeland and Long said.

The researchers repaired the recording by playing it faster and filtering out extraneous noise. They also used pitch-correction software to remove a "wobble" in the speed of the recording.

The music's restoration was an interesting experiment, but the researchers said that it also helped to highlight an overlooked part of Turing's legacy. Turing is known for breaking the Nazis' Enigma code during World War II, but he also played a big role in transforming the computer into a musical instrument. ■

Here captures billions of data points to generate three-dimensional maps. *(Image courtesy of Here.)*

DIGITAL MAPPING SERVICE USES Crowd-Sourcing to Plot Roads

HOW DO YOU compete with Google's Waze?

Here, a digital mapping company based in Berlin, believes that it has answered that question. The company recently revealed a new service that warns drivers about accidents and locates open parking spaces by extracting data from cameras and sensors inside hundreds of thousands of cars.

It gives the company increased firepower to rival other digital mapmakers. Waze is a navigation app that pools information from millions of smartphones to plot traffic patterns and alert drivers about accidents and constructions. Google is also using it to help commuters join carpools in San Francisco.

Here has focused on mapping roads using laser-based radars and other sensors, providing data about traffic patterns to cars with dashboard navigation systems. Here's new service, which will debut at the Paris Motor Show this week, expands the number of sources it collects data from. It uses crowd-sourcing to share data between cars manufactured by different brands.

In addition to sharing data from cameras and radars, automakers will also combine data from unlikely sources. For example, the service will extract data from windshield wipers and brakes to warn drivers about wet road conditions or construction work that has slowed traffic. The data is transmitted to the cloud, where it is analyzed, and then distributed in real-time to other cars on the road.

The data can be used to enhance autonomous cars, which need a detailed view of other cars on the road to drive without human intervention. Many experts said that the fatal crash of a Tesla Model S driving in "autopilot" mode might have been prevented if all the vehicles on the road had been sharing location data.

Here, which was previously owned by Nokia, was acquired by German automakers Audi, BMW, and Daimler for $3.1 billion in 2015. Cars built by these brands will have early access to the new service.

Here is not the only digital mapmaker vying for subscribers. Mobileye, an automotive vision chipmaker, has also released a crowd-sourcing service, which extracts information about road conditions and traffic from cameras embedded in cars. It transfers that data to the cloud and sends it out to automakers that subscribe to the service.

It is unclear whether the new service will infringe upon a deal that BMW signed earlier this year to develop autonomous cars with Mobileye and Intel.

Google purchased Waze for $1.1 billion in 2013, but the search engine has advanced its mapmaking agenda in other ways. It recently acquired Urban Engines, which gathers data from pedestrians and other sources to suggest the quickest routes for commuters.

Many automotive companies are piling into digital cartography. Ford recently invested in Civil Maps, a California start-up that uses artificial intelligence to organize data from cameras and other sensors embedded in cars. The company's software renders down the most important data, making it easier to transmit over cellular networks.

Here plans to expand its service to other automakers, so that it can collect more data and create richer views of the road. If more cars are braking, the service can inform drivers further down the road that traffic is slowing. Here could then use cameras embedded in the vehicle to read the construction signs advising drivers to slow down. Analyzing location data and camera images in cities could help drivers find open parking spaces.

But the service also raises questions about organizing and protecting the data. Here said that it is working on a standard for combining automotive data from multiple sources, so that it can be easily pooled from millions of vehicles, brewed in the cloud, and distributed anonymously.

Matthias Mohlig, Here's product manager for automotive services, explained that the automakers subscribing to its service were initially hesitant at sharing sensitive data with each other. Controlling vehicle data is one of the main reasons that they are investing in technology and not using software from companies like Google and Apple.

Mohlig acknowledged that privacy would remain a challenge in the early stages of the new service. "We have to be extremely diligent over privacy, making sure we are completely compliant with privacy laws," he wrote in a blog post.

Another question is whether the cellular networks that shuttle data between vehicles and the cloud are fast enough to send real-time updates. And automakers appear to be acutely aware of the potential challenges: Audi, BMW, and Daimler recently created an organization to build and test fifth-generation, or 5G, wireless technology for connected cars.

Here's service will be available to Audi, BMW, and Daimler vehicles in 2017. But the company believes that the benefits of crowd-sourcing will outweigh privacy concerns and lure other brands to the service.

"What we are seeing today is the technology and automotive industries coming together to create services that will elevate the driving experience," Edzard Overbeek, HERE's chief executive, said in a statement. "These new services are just the beginning." ■

WILLIAM WONG | Embedded/Systems/Software Editor

IoT for the Consumer

The Internet of Things has inundated almost every area of consumer electronics. Check out some of the latest innovations.

The Internet of Things (IoT) covers a lot of ground, and much of it is in the consumer space. There has been a flood of products and the numbers continue to rise. Many have a limited market, but the number has risen into the billions: Gartner estimates 6.4 billion in 2016.

Though IoT devices vary greatly, most have a number of common attributes. These include wired or wireless connectivity, movement of data to the cloud, and an application to configure and monitor the IoT device. The app typically runs on an Android or Apple platform, with Windows and macOS running second. At this point, many consumer IoT devices only interact with the app and the cloud. Still, more are starting to integrate with other devices, often using frameworks like those associated with Google Nest and Apple HomeKit.

COMMUNICATION: IoT'S TOWER OF BABEL

Interaction with other devices can be complicated by the plethora of communication mechanisms, as well as by an overcrowded wireless space. Ethernet dominates wired connectivity, although other wired connections exist, such as power-line networking. Bluetooth and Wi-Fi are most common, but even these have compatibility issues. Bluetooth 4.0 supports Bluetooth Low Energy (BLE), also known as Bluetooth Smart, and classic Bluetooth.

Other low-rate wireless personal area networks (LR-WPAN) include 802.15.4, ZigBee, and Z-Wave. There are proprietary wireless protocols, but these aren't the only alternatives for developers and consumers. Wireless standards like LoRa and ULE, which uses the cordless phone DECT protocol, are in play as well.

Near-field communication (NFC) is often used for synchronization or authentication. It has a short range, and is often utilized for financial transactions (though it isn't limited to that application).

Most devices use a single interface, but some may provide support for two. Typically, gateways will be the only devices that have more than a couple interfaces. Many consumer IoT devices are designed for mobile use, so minimizing power requirements often means limiting wireless support.

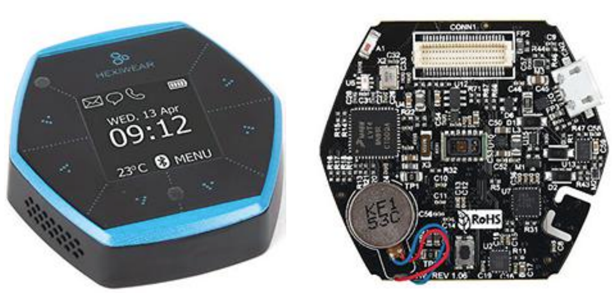
WEARABLE AND MEDICAL IoT

Wearable consumer IoT devices like smartwatches, pulse oximeters, and heart-rate monitors (HRMs) are readily available. Hundreds of smartwatches are now on the market, along with even more fitness bands, including the Samsung Gear 3 *(Fig. 1)*. The Gear 3 hosts a dual-core, 1-GHz Exynos processor with 768 MB of RAM and 4 GB of flash memory that runs the Linux-based Tizen operating system.

1. The Samsung Gear 3 runs Tizen Linux. An LTE version is available.

The watch supports Bluetooth 4.2, 802.11b/g/n, and Magnetic Secure Transmission (MST), as well as NFC. Sensors include a 3D accelerometer, 3D gyro, barometer, HRM, and ambient light. The system has GPS, too. There's even an LTE version that can make calls using the built-in speaker and microphone.

Building a smartphone is no easy task and, given the competition, it's not something that most developers will want to tackle. There are other mobile IoT device applications, however. This is where platforms like Hexiwear *(see "Module Targets Rapid IoT Development" on electronicdesign.com)* come into play. It's based on an NXP Kinetis K64x Cortex-M4 chip. Hexiwear supports Bluetooth LE and 802.15.4. It has a 3D accelerometer, 3D gyro,



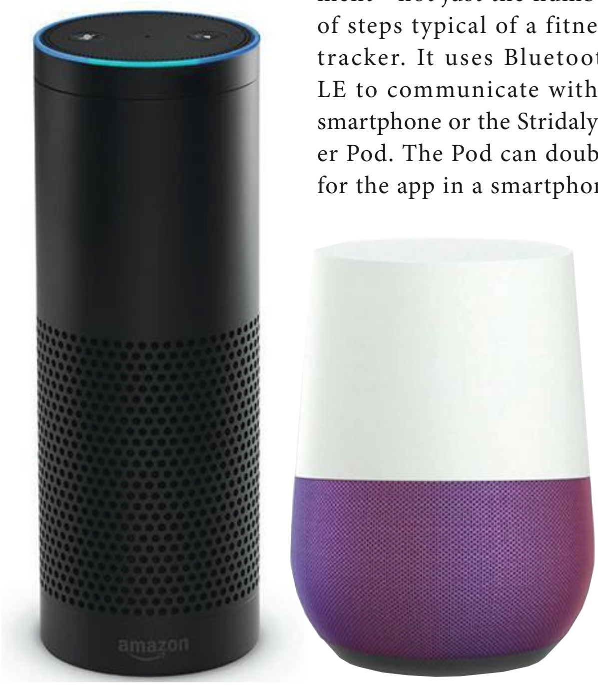
2. The Hexiwear module (left) runs a NXP Kinetis K64x Cortex-M4. It can be customized using a built-in header (right).

3. ReTiSense's Stridalyzer intelligent insole tracks more than a user's number of steps, using a pair of sensors in each insole to track movement and stress.

pressure sensor, light sensor, humidity sensor, and HRM. The platform has a capacitive-touch interface and an OLED display *(Fig. 2)*.

Unlike the Gear 3, Hexiwear is designed to come apart. It can also be inserted in a wristband and has an expansion port. The Micro USB socket is for charging and development.

But watches aren't the only wearable technology being developed; smart clothes and shoes are also becoming available. For example, ReTiSense's Stridalyzer *(Fig. 3)* is an intelligent insole. It tracks foot pressure using a pair of sensors, allowing the system to calculate stress and movement—not just the number of steps typical of a fitness tracker. It uses Bluetooth LE to communicate with a smartphone or the Stridalyzer Pod. The Pod can double for the app in a smartphone and record information, which is useful in the event that you don't want to run around with a smartphone.



4. Home voice-activated control systems like Amazon's Echo (left) and Google's Home (right) can control other IoT devices.

Sleep tracking is often supported by smartwatches and fitness bands, but they need to be worn overnight to be effective. An alternative is a smart bed or, in the case of the Luna Indiegogo project, a mattress cover. The cover includes a range of sensors to track information like the bed temperature and ambient humidity. It also has a light sensor and microphones.

The mattress cover is designed to track people's breathing and heart rate, and is linked to the cloud via Wi-Fi. It even functions as a collaborative IoT device that works with Nest-compatible products. This would let the system adjust the house temperature once you're comfortably asleep. The cover is machine-washable and can be tumble-dried.

HOME AUTOMATION

Home automation is ripe for IoT, but it hasn't been cheap. Most of these devices still come at a premium price, but they are more common. Command-and-control systems like Amazon's Echo, with its Alexa-enabled voice-control system, compete with platforms like Google Home *(Fig. 4)*. These systems provide voice control of other IoT devices like smart lighting, security systems, smart thermostats, and smart HDTVs that are part of the smart home. Wireless connectivity is big change compared to the wired smart homes of the past.

These control systems can double as wireless speakers, but they're also always listening to users. They do not have cameras, yet. Of course, smart cameras are already available for security applications. Still, it's possible to order items to be delivered using Alexa.

Smart lighting has seen everything from multicolored mood lighting to a wireless, DLP projector in a light-bulb form factor. Speaker-based light bulbs include Sengled's Bluetooth speaker bulb and AwoX's StriimLIGHT WiFi smart bulb *(Fig. 5)*. Smartphones can stream audio to the bulbs that can be used in almost any receptacle that's already occupied by a lightbulb.


5. AwoX's StriimLIGHT WiFi bulb surrounds a speaker with controllable LEDs.

6. Smart locks like Kwikset's Kevo can be controlled through a variety of means.

Smart locks like Kwikset's Kevo *(Fig. 6)* can be controlled using a key fob, a real key, a smartphone with Bluetooth 4, or via the internet. Other systems employ communication alternatives like NFC. These devices can provide selective control such as one time access, as well as tracking status and usage.

Tracking status and usage of all sorts of things are part of the IoT mix. For example, plant-tracking devices measure ground water and ambient humidity. And systems like Fishbit monitor pH, salinity, and temperature in an aquarium.

Cats, dogs, and other pets can now have wearable GPS tracking systems, but so can children and adults. For dementia patients, they can be very helpful to caregivers by warning them if a patient leaves a known area.

AUTOMOTIVE IoT

The car is another space where IoT is cropping up. Smart cars have the ability to link devices into their telematics system. The minimum these days is Bluetooth connectivity for tying a smartphone into the audio system, allowing hands-free calling. More advanced systems provide two-way linkages between applications. Streaming audio is a common application.

Some cars now have options to act as a mobile Wi-Fi hotspot. For example, most new GM cars (like the Chevy Bolt) have an option to support OnStar 4G LTE, providing Wi-Fi hotspot capabilities to passengers *(Fig. 7)*. This capability is just the start of more advanced communication and cooperation with other devices. For example, the Bolt can be recharged at home or at charging stations where communication with the vehicle can provide additional services.

There will likely be a never-ending flow of new consumer IoT devices. New application areas are opening up as more sensors are brought into the mix. Smart-metering systems for electricity, oil, and gas cross over from industrial IoT to the consumer space, potentially providing users with more information about their consumption.

There remain a host of issues to resolve, ranging from security and personal privacy to ever-more-crowded communication environments. This will be a challenge given the exploding number of devices. ed

7. Chevrolet's electric Bolt can act as an LTE/Wi-Fi hot spot.

EUSTACE ASANGHANWA | Strategic Marketing Manager, Microchip Technology Inc.
www.microchip.com

Give System Attackers THE BOOT

Incorporating crypto elements into the secure-boot process is quickly becoming a key ingredient in IoT device development.

Secure boot is a critical component of any embedded system. It assures that firmware, the brains of all embedded systems, is as intended by the maker of the system. Moreover, secure boot assures the safe and predictable operation of embedded systems. Its value is easily seen in systems whose failure can lead to potentially catastrophic consequences. Examples of such vital systems include heat controllers of home furnaces and range ovens, engine-control modules in vehicles, traffic-light controllers, therapy delivery systems in implanted medical devices, and controllers of unmanned trains.

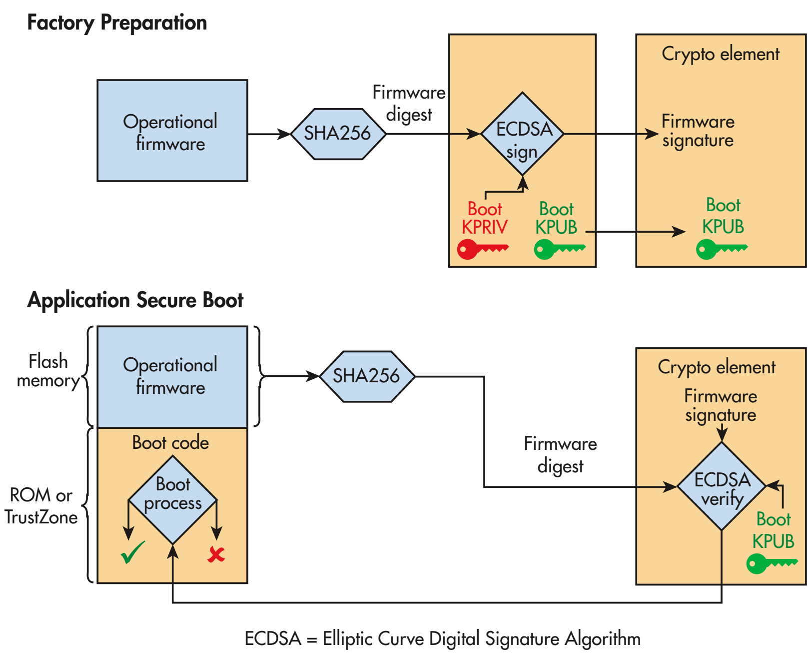
The need for secure boot has always been imposed where required. While secure boot as a subject might traditionally lurk in the background, its use has been enforced by regulations and standards governing the safe operation of critical systems. As such, systems deemed less critical, like a computer mouse or a handheld calculator, might have largely escaped the rigors of secure boot because their failure bore little consequence. However, the Internet of Things (IoT) is changing the definition of what constitutes a critical embedded system.

IoT BRINGS SECURE BOOT TO THE FOREFRONT

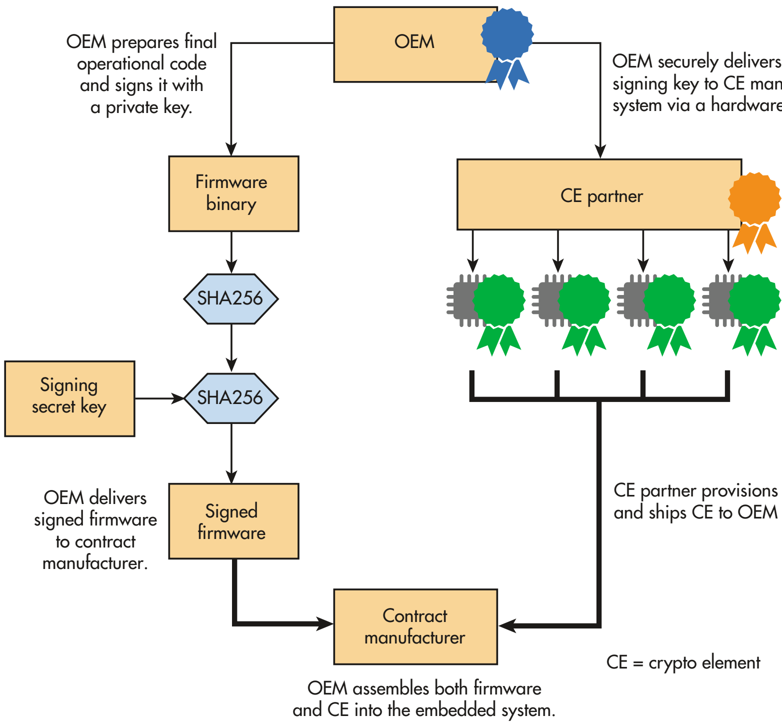
The dichotomy between critical and non-critical systems is evolving. With the emergence of the IoT, all embedded systems are now critical systems—they no longer exist as islands with all features and faults contained within. While, the IoT provides great benefits in connecting embedded systems together, a direct consequence of this networking is the erasure of containment boundaries. Any connected embedded system is now a potential risk, and anyone in the world is a potential victim.

The possibility of damage incurred from injecting faults into the firmware of embedded systems has never been higher. The occurrence of natural system faults, like power surges and communications errors, has largely remained the same, so traditional secure boot methods continue to be effective in that regard. However, the occurrence of human-injected faults, especially of the malicious type, is growing rapidly in breadth and sophistication.

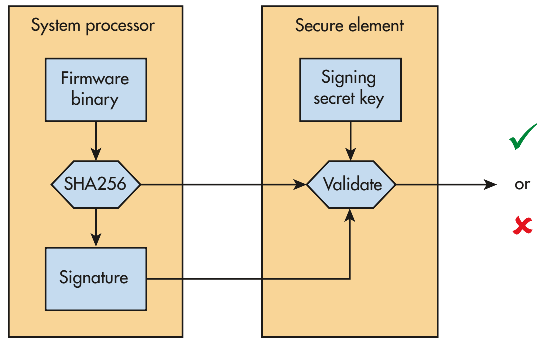
In the past, attackers needed to gain physical access to each individual system to insert malicious faults. Now, with the networking of systems, attackers can leverage an attack on one system to gain access to many other remote systems. This could lead



1. The optimal generalized boot process has both factory preparation and field validation of the signed operational firmware.



2. Shown is a factory setup for the symmetric-key approach to secure boot.



3. Due to difficulties with boot-key secrecy management, the symmetric-key flow verification process is most often found in closed ecosystems.

to the malicious control of a large number of devices, access to critical systems, access to data stored in the cloud, or just notoriety through publicity stunts in data breaches. It underscores why secure-boot solutions must be resistant to attacks and fault injections.

SECURING THE BOOT PROCESS

Secure boot has two fundamental ingredients: the ability to measure the integrity of the firmware, and assurance of the integrity of the measurement process. These long-standing ingredients use cryptography to accomplish respective goals, evolving only in terms of the sophistication of the cryptographic algorithms and the secure hardware methods used to protect the measurement process integrity.

Measuring the firmware's integrity involves use of cryptography to create fingerprints—a small piece of digital encoding that's condensed and representative of the firmware, and thatcan be easily checked for changes. This cryptography is in a class of cryptographic algorithms called hash functions, which generate digests for the fingerprints. The commonly used 256-bit Secure Hash Algorithm, or SHA256, generates 256 digital bits for a digest. SHA256 is the latest in hash algorithms, and while neither the most compact nor elaborate, it strikes a good balance between security and efficient use of embedded-system resources like power, code space, and computing resources.

To set up and achieve secure boot, the embedded-system maker hashes the final operational firmware at the factory and installs both the firmware and digest in the embedded system. During operation in the field, a measuring piece of code in the embedded system hashes the operational firmware and compares the resulting digest to the factory-installed digest. A matching digest indicates that the integrity of the operational code is intact.

To assure the integrity of the process, it's ideal to have the measuring piece of code in a non-mutable memory, such as read-only memory (ROM). Therefore, it won't be susceptible to environmental fault vectors like power surges and other memory corruptors like inadvertent memory modifications. To respond to rapidly changing market needs, it's common to use locked versions of non-volatile memory technologies like flash and EEPROM or dedicated execution environments (e.g., TrustZone technology) in lieu of ROM.

PROTECTING THE BOOT PROCESS AGAINST ATTACKERS

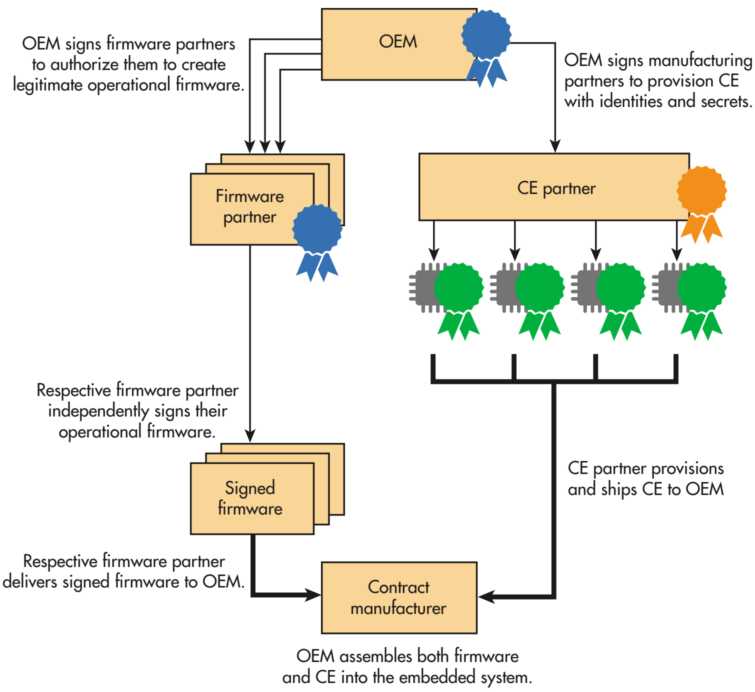
The just-described secure-boot process would be sufficient in the absence of malicious fault injections, but alas, that's not representative of the world we live in. To overcome this process, an attacker simply needs to create his or her own firmware with the corresponding hash digest and install both into the system. This undermines the integrity of the measuring; hence, the need arises for an authenticated measurement process.

Such a process entails the use of secret information, like a key, in conjunction with the generation of the firmware's certification digest or simply a certificate *(Fig. 1)*. The idea is that the adversary would require knowledge of the same secret information in order to generate a consistent firmware-signature pair to thwart the measuring system.

Given that the validation process of the operational code also needs access to the same secret information, the embedded system may fall victim to physical exploitation by the attacker to discover the secret information. Tremendous growth in sophistication of analysis tools and techniques for building advanced embedded systems also works in favor of the attacker, who can gain access to these tools directly, or else through services, to exploit the system.

Without loss of generality, it's easy to envision the progression of this cat-and-mouse game between the embedded-system developer and the attacker. This game would continue if it weren't for special types of integrated circuits called crypto elements (CEs).

CEs are specifically designed to resist attacks such as attempts to retrieve confidential content or tampering. Enforcing secure boot with CEs delivers the integrity needed in the authenticated firmware measurement and validation processes. They can be integrated into the controller or stand alone, providing system architects with flexibility to fit their implementation needs.



4. In an open ecosystem of partners, it's common for an original equipment manufacturer (OEM) to involve several partners to provide subsystems or alternate sources of a system that comprise the embedded system.

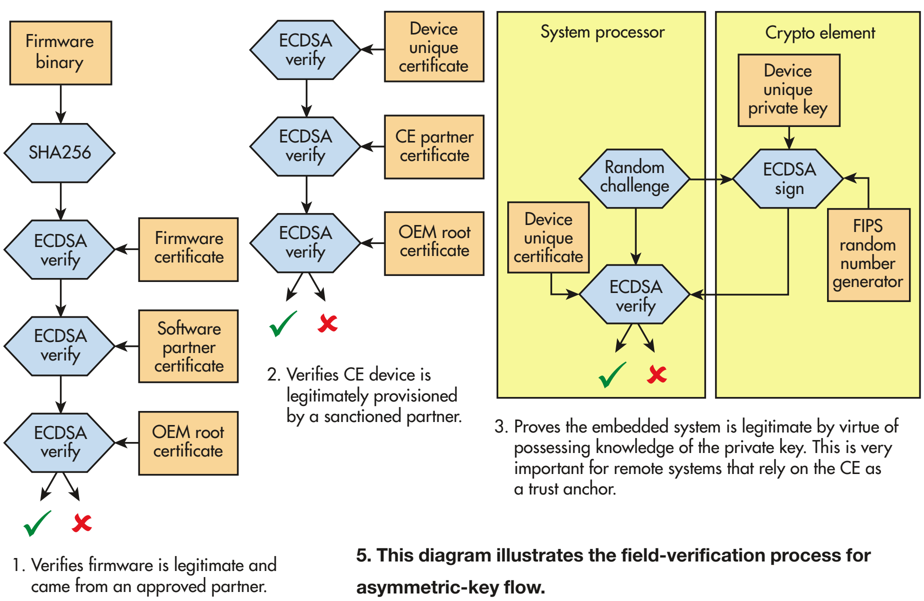
SYMMETRIC- VS. ASYMMETRIC-KEY CRYPTOGRAPHY

While the fundamental ingredients of secure boot, namely measurement and process, remain constant, their realization offers a choice of symmetric- or asymmetric-key cryptographic techniques to govern the overall boot validation process.

Symmetric-key cryptographic techniques use the same or derivatives of the same key in both the factory setup and field-validation stages of the secure-boot process. The SHA256-based authenticated boot process shown in *Figs. 2 and 3* is an example of a symmetric-key boot process. This type of boot process has the advantage of speed, but can potentially suffer from difficulties in managing the secrecy of the boot key in a supply chain. As such, it's most popular with closed ecosystems, where knowledge of keys must reside with a single entity.

Asymmetric-key cryptographic techniques *(Fig. 4)* use separate keys in the factory-setup and field-verification stages of the secure-boot process. The two keys have a relationship governed by a cryptographic algorithm approach such as elliptic curve cryptography (ECC). A special protocol for firmware signing and verification, known as the Elliptic Curve Digital Signature Algorithm (ECDSA), uses ECC.

An asymmetric-key process like ECDSA also works with SHA. In practice, SHA256 measures the operational firmware to create a digest that's subsequently signed using the ECDSA protocol to complete the authenticated firmware process. The resulting signature is a certificate that's attached with the operational firmware for installation into the embedded system *(Fig. 5)*.



5. This diagram illustrates the field-verification process for asymmetric-key flow.

The asymmetry in the key structure allows for a private key, which must remain secret, to be used at the factory for setup; it also allows its mathematically correlated counterpart, called the public key, to be used in the field for the field-validation stage. The public key can be viewed by anyone without impact to the security of the boot process. For this reason, the asymmetric-key-based secure-boot process lends itself better to open ecosystems of several entities.

SECURE BOOT MADE FOR MANUFACTURING

A secure-boot process that requires heavy costs in manufacturing logistics quickly leads to abandonment. An effective secure-boot process is therefore one that determines the integrity of the operational code and measurement process without adding significant time or cost to the manufacturing process.

While asymmetric- and symmetric-key boot processes are optimal in open and closed ecosystems, respectively, employing CEs makes it possible to use any process with either ecosystem while maintaining the confidentiality of the keys. However, the asymmetric-key method offers additional latitude to easily build in a mathematically rigorous process of upholding chain of trust in an open ecosystem of partners.

ENFORCING SECURITY THROUGH ACCOUNTABILITY

The secure-boot process for embedded systems has traditionally been driven through regulations and standards governing product safety. This model was very effective when embedded systems existed as islands of physically contained systems. But networking of systems through the emergence of the IoT eliminates fault containment, thereby creating motivation for attackers and greatly increasing the attention paid to secure boot. Remote accessibility of things means easier access to embedded systems—making anyone, anywhere in the world, a potential victim of system attacks.

While post-mortem analysis may reveal a culprit device that would hold the manufacturer accountable, the damage will have already been done. Motivated to limit their liabilities, manufacturers are taking proactive measures to incorporate tamper-resistant secure-boot processes into their products, with crypto elements their ticket to security success. ed

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LOU FRENZEL | Contributing Technical Editor

The Wireless Spectrum CONUNDRUM

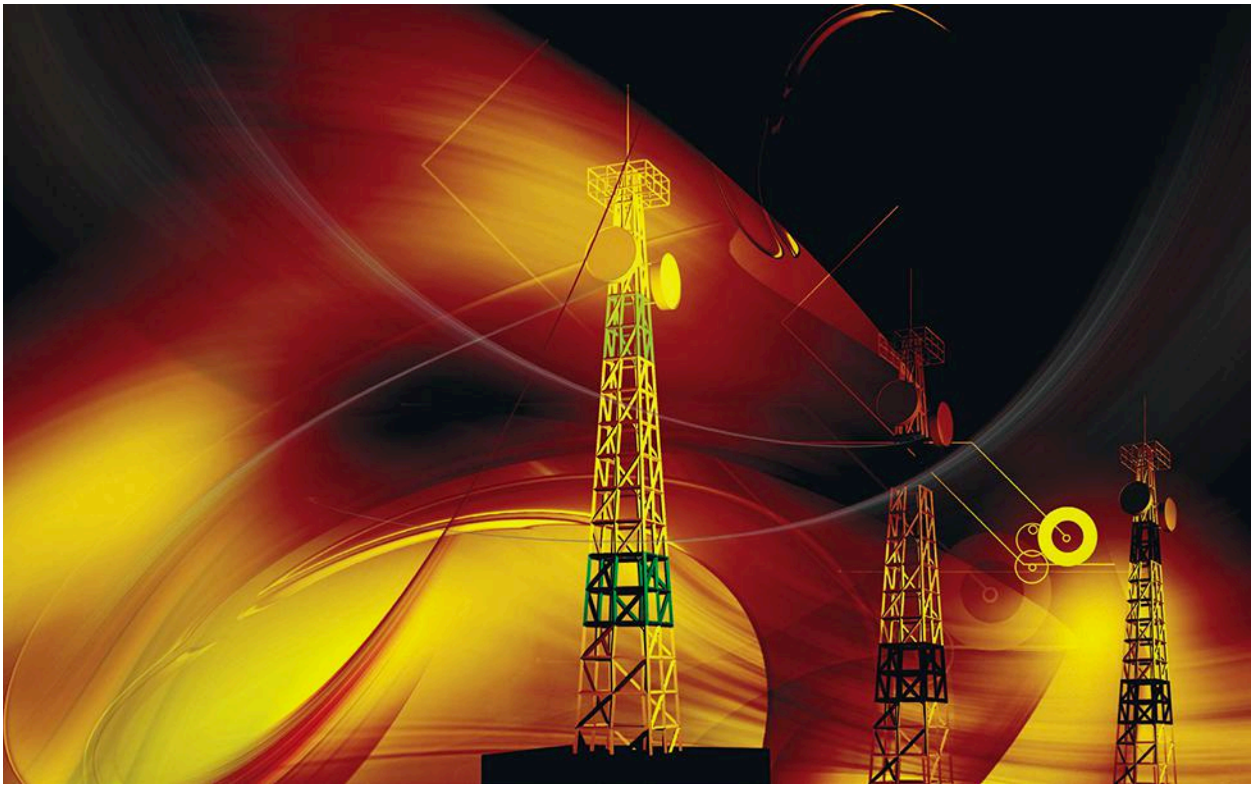
The spectrum shortage has service providers, government agencies, and even wireless designers scrambling to come up with workable solutions.

Spectrum is everything when it comes to choosing or designing wireless equipment. Knowledge of the electromagnetic (EM) spectrum is essential for all engineers working with wireless equipment and systems. It affects what you can transmit as well as how and where, determining everything from rates and range to capabilities and cost. Sometimes you can choose from several options, and other times you're limited to one. If you're not a spectrum wonk, then it's time to become one. This primer on spectrum will help get you started.

WHAT IS SPECTRUM?

Radio signals travel in the free space known as spectrum. Some have called it the ether. More precisely, it's that distribution of electromagnetic signals over a wide frequency range where all radio emissions occur. *Figure 1* shows the complete range of EM signals expressed in frequency and wavelength.

Remember that all radio signals consist of both electric and magnetic fields. The fields travel together at right angles to one another. Wavelength (λ) is the physical length of one cycle of an EM signal, and is expressed as:



$\lambda = C/f$

C is the speed of light at 300 million meters per second and f is the frequency in Hz; λ is expressed in meters. A useful version is:

$\lambda = 300/f_{MHz}$

For example, the wavelength of a 400-MHz signal is 0.75 meters or 75 cm.

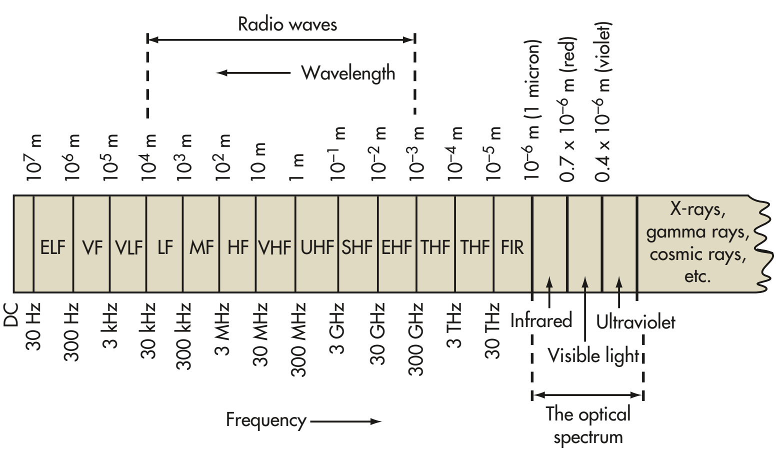
Wavelength is critical to the antenna size. The length of a basic dipole antenna is λ/2, which is inversely proportional to frequency. As frequency increases, it in turn leads to a shortened wavelength and smaller antenna.

Figure 1 shows that the spectrum is normally divided into segments and named; *Table 1* lists these names and ranges. Note also the optical spectrum—light signals are another type of EM radiation, and infrared (IR) in particular is used for communications. Beyond the visible optical spectrum is the never-never-land of ultraviolet, X-rays, cosmic rays, and gamma rays that aren't used for communications.

Any frequency above 1 GHz is generally called microwave. Signals between 30 and 300 GHz are called millimeter waves. Frequencies above 300 GHz but below infrared are mostly unused because there are few practical ways to implement communications devices. This band is called the Terahertz (THz) region.

Table 2 shows the different designations applied to microwave and millimeter waves. It also lists the typical communications services that occur in each of the major frequency bands.

The most useful and desired "sweet spot" of the spectrum is roughly 500 MHz to 3 GHz. This range offers a mix of benefits, such as short practical antennas, reasonable transmission range, sufficient bandwidth to support high data rates, and readily available cost-efficient semiconductor products.



1. This simplified illustration of the electromagnetic frequency spectrum presents the major segments that make up this space.

Up till now, all of the cellular bands are in this range, and the major carriers continue to fight for more spectrum in this space. Most unlicensed short-range wireless standards (Bluetooth, Wi-Fi, ZigBee, etc.) also fall into this range. The bulk of this ideal spectrum is fully allocated, with minimal opportunity for adding new services.

SPECTRUM REGULATION

Due to the scarcity and critical importance of spectrum, it's under government regulation worldwide. All countries have spectrum regulatory agencies. The U.S. agencies are the Federal Communications Commission (FCC) and National Telecommunications and Information Administration (NTIA). The FCC *(www.fcc.gov)* handles all consumer and commercial spectrum, while the NTIA *(www.ntia.gov)* manages the military and government spectrum.

Be sure to check out the websites to get a feel for the enormity of the spectrum challenges. While visiting these sites, sign up for the daily email reports on the latest issues, status, and actions.

Countries also meet every three years at a World Radiocommunications Conference (WRC) to resolve spectrum conflicts, assignments, and related issues. The next WRC meeting is in 2019.

The NTIA maintains a master spectrum chart *(Fig. 2)* that you can download from its site. The chart provides a "big picture" view and confirms the massive complexity involved in allocating and managing spectrum.

You should also get a copy of the Code of Federal Regulations (CFR) Title 47 Parts 0 through 100 *(https://www.fcc.gov/general/rules-regulations-title-47)*, which contain all of the FCC's rules and regulations. The CFR Title 47 is a must-have document for every wireless engineer. Part 2 includes the frequency allocations for the various services, while parts 15 and 18 run down the short-range wireless and electromagnetic-interference (EMI) regulations.

There are two types of spectrum, licensed and unlicensed. Licensed spectrum is allocated by the FCC for specific services (broadcasting, land mobile, cellular, satellite, etc.). This tightly controlled spectrum has strict regulations, and does incur fees. Unlicensed spectrum may be used without direct FCC allocation as long as there's compliance with all related rules and regulations.

CRISIS MODE

The overwhelmingly critical issue right now is that we're running out of spectrum. This is especially true of the aforementioned prime "sweet spot" spectrum. In addition, most of the defined spectrum bands are already allocated; few if any real vacant chunks of spectrum are available. Although some chunks of spectrum currently sit unused, they're assigned for future use. Like real estate, only a finite amount of spectrum exists, and once it's occupied, there's no more to be had. It's a terrible dilemma to face, especially during this massive wireless growth period.

The demand for more wireless services, and thus spectrum, is driven by several factors. The first involves increased cell-phone services—more spectrum is needed to sustain customer growth. On top of that, new technologies (5G) will require more bandwidth to support higher data rates demanded by significantly increased video usage.

Second, the burgeoning Internet of Things (IoT) field is putting a strain on the available unlicensed spectrum. With the predicted billions of connected wireless devices, current spectrum will eventually become overloaded and create considerable interference problems.

While interference is always a problem, noise is another. The radio noise floor is growing due to the increased wireless activity, as well as the increased volume of other products that emit radio signals. These include the ac power lines, light dimmers, CFLs, switch-mode power supplies, motors, welders, and medical equipment. The FCC's Technological Advisory Council (TAC) has launched a survey and study into the noise-floor problem.

Finally, the limited spectrum must contend with general growth in most other wireless services, such as satellite, radar, industrial, automotive, and wireless broadband connections, as well as new yet to be discovered applications. Will there be space for everyone?

TABLE 1: STANDARD DEFINITIONS OF RADIO SPECTRUM SEGMENTS

Name	Frequency range	Applications
Low frequency (LF)	30 to 300 kHz	Navigation, time standards
Medium frequency (MF)	300 kHz to 3 MHz	Marine/aircraft navigation, AM broadcast
High frequency (HF)	3 to 30 MHz	AM broadcasting, mobile radio, amateur radio, shortwave broadcasting.
Very high frequency (VHF)	30 to 300 MHz	Land mobile, FM/TV broadcast, amateur radio
Ultra high frequency (UHF)	300 MHz to 3 GHz	Cellular phones, mobile radio, wireless LAN, PAN
Super high frequency (SHF), millimeter-wave range	3 to 30 GHz	Satellite, radar, backhaul, TV, WLAN, 5G cellular
Extremely high frequency (EHF)	30 to 300 GHz	Satellite, radar, backhaul, experimental, 5G cellular
Terahertz , tremendously high fequency (THF) or far infrared (FIR)	300 GHz to IR	R & D, experimental

TABLE 2: MICROWAVE LETTER BAND DESIGNATIONS

Band	Frequency range	Applications
L	1 to 2 GHz	Satellite, navigation (GPS, etc.), cellular phones
S	2 to 4 GHz	Satellite, SiriusXM radio, unlicensed (Wi-Fi, Bluetooth, etc.), cellular phones
C	4 to 8 GHz	Satellite, microwave relay, Wi-Fi, DSRC
X	8 to 12 GHz	Radar
K_u	12 to 18 GHz	Satellite TV, police radar
K	18 to 26.5 GHz	Microwave backhaul
K_a	26.5 to 40 GHz	Microwave backhaul, 5G cellular
Q	30 to 50 GHz	Microwave backhaul, 5G cellular
U	40 to 60 GHz	Experimental, radar
V	50 to 75 GHz	New WLAN, 802.11ad/WiGig
E	60 to 90 GHz	Microwave backhaul
W	75 to 110 GHz	Automotive radar
F	90 to 140 GHz	Experimental, radar
D	110 to 170 GHz	Experimental, radar

SOLUTIONS

Fortunately, there are multiple potential solutions to the spectrum problem. The primary goal is more bandwidth to support higher data rates. While not all applications need higher rates, the mainstream needs, such as cellular and wireless broadband access, demand them. Most solutions, a few of which are listed here, address that need.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Higher Frequencies

Since higher data rates require more bandwidth, the obvious solution is to go where the bandwidth is: namely, the higher frequencies. The wireless industry has been on this path for decades.

High-frequency (3-30 MHz) applications like land mobile moved on to the VHF spectrum, then on to UHF. Applications such as satellite and radar moved from VHF and UHF to microwaves and now millimeter waves. Today, the primary upward mobility is into the millimeter-wave range. New 5G cellular standards use 27 to 40 GHz bands.

These movements have been based on having the supporting technology; for example, semiconductors that operate reliably at these elevated frequencies. Semiconductors like GaAs, SiGe, SiC, and GaN have made microwave and millimeter-wave applications practical. We're still on the upward frequency path, and it will only end when someone figures out the definitive terahertz-frequency devices.

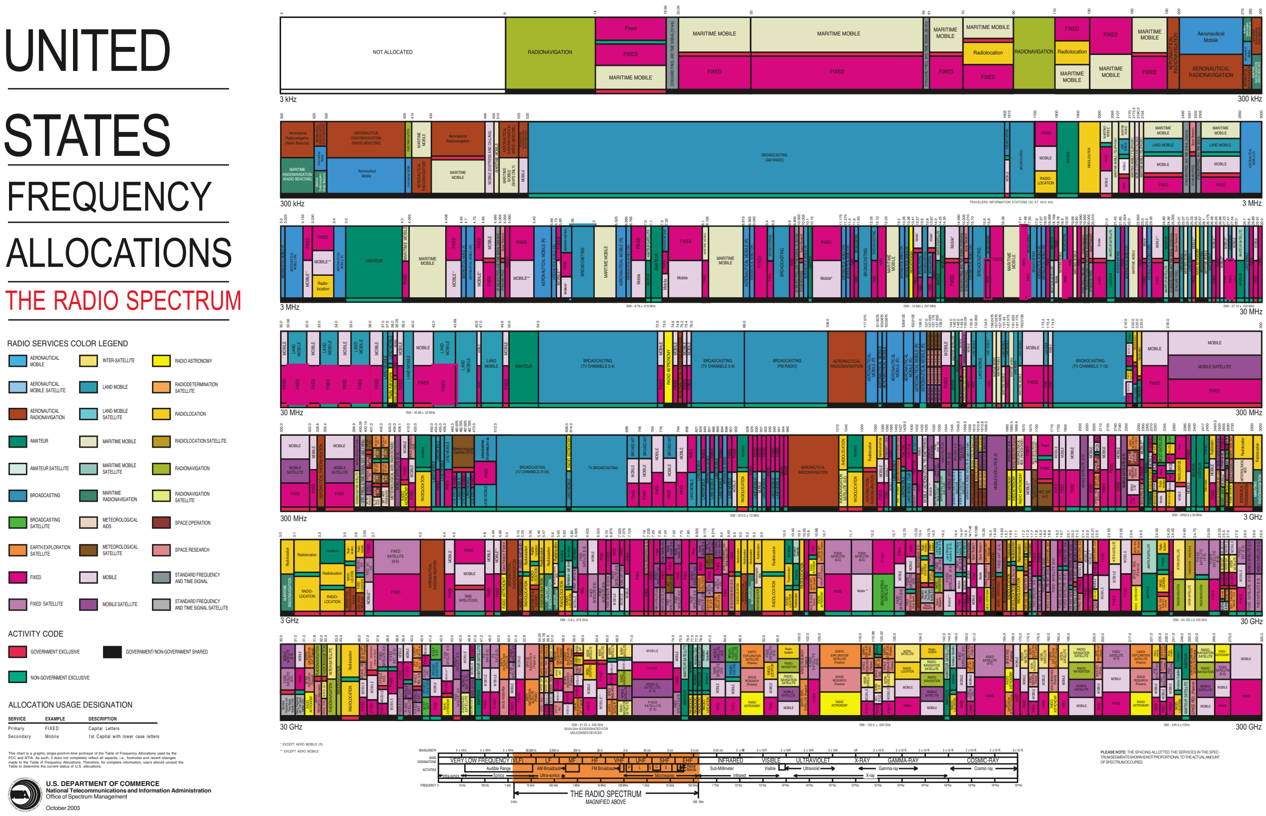
Spatial Diversity

Spatial diversity means that multiple users can use the same band of frequencies without interfering with one another. Also known as frequency reuse, this approach depends on the physics of radio waves. For a given transmit power, as the frequency increases (shorter wavelength), the distance traveled becomes smaller. This is summed up in what's called Friis' formula:

$$P_r = P_t G_t G_r \lambda^2/16\pi^2 d^2$$

Both distance d and wavelength are given in meters. The other units are transmitted power (P_t), received power (P_r), transmitter antenna gain (G_t), and receiver antenna gain (G_r). Receiver sensitivity (R) in dBm is not considered in this expression.

The message of this formula is that the power at the receiver gets smaller as distance increases and as the wavelength gets shorter. In other words, for a given transmit power and fixed antenna gains, the signal at the receiver becomes smaller at the higher frequencies. The higher the frequency, the greater the free space path loss (FSPL). Higher frequencies are essential because they offer lots more bandwidth and shorter antennas; however, range is more limited.



2. This shrunken view of the NTIA's spectrum chart illustrates the vast number of services and overall complexity when it comes to spectrum management.

Semiconductors like GaAs, SiGe, SiC, and GaN have made microwave and millimeter-wave applications practical. We're still on the upward frequency path, and it will only end when someone figures out the definitive terahertz-frequency devices.

Since signals don't travel far, the same frequencies can be used by many without interference. That's why Wi-Fi, Bluetooth, ZigBee, and others can successfully share the unlicensed 2.4 GHz. Signals rarely travel more than 100 meters or so.

The cellular industry also practices frequency reuse by controlling cell-site spacing and using highly directional antennas and power-level control. The 5G standard calls for adaptive beamforming antennas not only to boost radiated power, but to control more precisely who gets the signal so that it doesn't interfere with another.

Spectral Efficiency

Spectral efficiency refers to boosting data rate in narrower channels. This measure is expressed in bits per hertz (bits/Hz). Here are just a few of the tricks being used to cram more data into smaller bandwidths:

- Higher-level modulation techniques like m-QAM, m-PSK, and OFDM have greatly increased data rates in cellular, Wi-Fi, and other wireless systems.
- Use of time-division-multiplex (TDM) methods enables some services to reduce spectrum usage. For example, cellular systems use frequency division multiplexing (FDM), whereby one block of spectrum is for downlink and another for uplink. TDM can be used to eliminate one of those blocks.
- Data compression can boost data in narrow spectrum. Some data (e.g., voice and video) can be compressed and transmitted at lower rates in narrow bandwidths. Digital TV works this way.
- Multiple-input, multiple-output (MIMO) methods are now being used to increase data rates in a channel. The data signal is divided between multiple radios at lower rates and transmitted simultaneously in the same band.

Shared Spectrum

Spectral diversity allows for some spectrum to be shared successfully. However, certain applications require different methods to ensure that interference doesn't disrupt the services.

One example is the use of TV white spaces. White spaces are the unused 6-MHz-wide channels for TV broadcast. TV signals rarely travel more than 100 miles, so TV stations across the country can use the same frequencies. Yet, if new data services utilize the abandoned channels, some means is needed to prevent interference to other data users as well as nearby TV stations. Wireless microphones also use some of these frequencies and are often victims of interference.

Cognitive radio offers one way to mitigate this problem. It's a set of hardware and software procedures that can be incorporated into data radios to prevent interference. For example, cognitive radios "listen" on or monitor a channel before transmitting. If a signal is present, the radio doesn't transmit; instead it waits or goes to find another open channel.

Cognitive radios may also use a database to locate channels that are available in the local area. The radio queries the database on the fly via an internet connection to find an available channel. Sharing spectrum should become more widespread through the development of better cognitive-radio techniques.

Recent spectrum-sharing cases include the sharing of the Unlicensed National Information Infrastructure (UNII) 5-GHz spectrum with 802.11ac Wi-Fi and the Department of Transportation's vehicle-to-vehicle (V2V) communications system called Dedicated Short Range Communications (DSRC). Another sharing negotiation involves the 3.5-GHz band. The Citizens Broadband Radio Service Alliance wants to use parts of this spectrum for LTE cellular service that employs interference-mitigating techniques. Various incumbent federal agencies are reluctant to give up the space or risk interference to a mix of satellite and radar services, though.

Spectrum Reallocation

One way to free up spectrum is to repurpose existing spectrum that's not being used or only used infrequently. For example, underutilized military or government spectrum could be reassigned to commercial applications, where it would be more widely exploited. Such spectrum exchanges are difficult to implement, however, because military/government services don't want to compromise their capability or security. But sufficient pressure from the U.S. Senate on the FCC and NTIA could make it happen.

One forthcoming reallocation activity involves the reassignment of the higher broadcast TV channels (400- to 800-MHz range) that broadcasters have given up over the years. The FCC is currently implementing auctions that sell available spectrum, mainly to cellular carriers. They will then share the revenue with the broadcasters that voluntarily give up their licensed spectrum. Collectively, auctions are one tool employed by the FCC to deliver billions in revenue to the U.S. Treasury.

Innovation

Fresh creativity and innovation can surely aid the spectrum problem. Developments in Terahertz region components could soon push applications into this unchartered territory. Perhaps we will rediscover infrared (IR), which has already shown promise for data transmission. Remember IRdA? Or maybe we can find a way to repurpose the lower-frequency spectrum in the HF range (3 to 30 MHz). HF is mainly used by hams and international broadcasting. How can high-speed data be transmitted in this region that's ripe for reassignment? Ideas, anyone?

Is there really a spectrum crisis? Some say no. But as long as spectrum is finite, a shortage will be forthcoming if wireless applications like cellular, broadband, and the Internet of Things keep growing at a fast clip. If the FCC and NTIA improve their spectrum management practices and support growth, it's possible to minimize or even avoid these spectrum problems. Let's hope that they can be solved rapidly, responsibly, and non-politically, starting now. ed

As long as spectrum is finite, a shortage will be forthcoming if wireless applications like cellular, broadband, and the Internet of Things keep growing at a fast clip.

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5. The Defense Advanced Research Project Agency (DARPA) (www.darpa.mil) is implementing its Spectrum Collaboration Challenge to ensure that the military has sufficient spectrum for future needs.

MARIA GUERRA | Technical Editor

Can Class-D Amplifier Audio Performance Get Any Better?

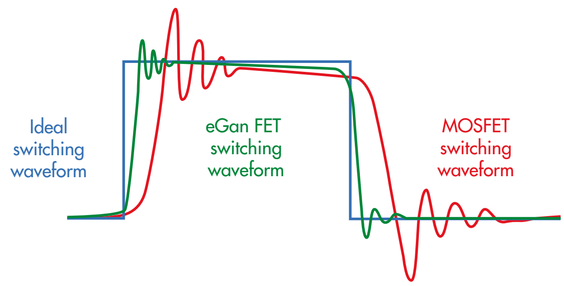
The audio amplifier market is progressively growing while advances in semiconductor technology enable more applications to use class D amplifiers. But are metal-oxide-semiconductor field-effect transistors the only solution?

Class D audio amplifiers can fulfill the requirements for audio applications such as mobile handsets, Bluetooth/wireless speakers, and vehicles, to name a few. These amplifiers dissipate less heat, extend battery life in portable devices, and are much more efficient than linear audio amplifier classes, such as Class A, B, and AB. They are small in weight and size, which makes them suitable for applications like the ones mentioned earlier.

Class D amplifiers also are extremely efficient (often up to 90% or higher) because the output transistors are fully turned ON or OFF during operation. Therefore, there are no power losses in the output device. Class D amplifiers use metal-oxide-semiconductor field-effect transistors (MOSFETs) as switching devices. Typically, they use a pulse-width-modulation (PWM) topology with a fixed-frequency to produce a PWM equivalent of the analog input signal. But they use lowpass LC filters to extract the amplified audio signal, thereby increasing cost and board space.

New filterless modulation techniques eliminate or minimize the use of external filters. Removing LC filters, however, invites the possibility of electromagnetic (EM) radiation caused by the amplifier switching at a frequency much higher than the highest audio frequency to be amplified. To deal with this problem, solutions from semiconductor vendors like Texas Instruments and Maxim Integrated offer filterless spread-spectrum modulation and feedback technique schemes with different output configurations (e.g., one-channel, two-channel, etc.). They mitigate EMI and improve poor Total Harmonic Distortion Plus Noise (THD+N) performance.

Developments in power semiconductor technology had created a new approach for handling higher efficiency with minimal audio distortion. For example, Class D amplifiers can also be developed using enhancement-mode GaN (eGaN) FETs. Efficient Power Conversion's eGaN FET-based Class D amplifiers claim to switch many times faster than power MOSFETs and do not have any reverse recovery charge. As a result, the dead-time—typically



1. Shown is a comparison of MOSFET and eGaN FET switching waveforms. *(Courtesy of EPC)*

25 ns for silicon power MOSFETs—can reportedly be reduced by 80%, to 5 ns or less *(Fig. 1)*. This means that the turn-on and turn-off delay, as well as the rise and fall times for eGaN FETs, will be much faster and contribute less to signal distortion. Very low THD+N also can be achieved, while minimizing Transient Intermodulation Distortion (T-IMD) and the EMI emissions from the amplifier. The EPC9106 reference design has demonstrated 96% efficiency at 150 W / 8 Ω, and 92% efficiency at 250 W / 4 Ω.

With advancements in class D amplifiers, they are now being used in more applications than linear amplifiers used to dominate such as home theaters and televisions. The new solution from Efficient Power Conversion (EPC) for Class D amplifiers, for instance, looks very promising and it might be widely adopted by audio manufacturers in the future. According to Research and Markets, the Class D audio amplifier market is expected to be worth $2.76 billion by 2022, growing at a CAGR of 17.4% between 2016 and 2022. The two-channel Class D audio amplifier currently holds the largest market share and is expected to grow at the highest rate during the forecast period, as it is commonly used in in-car audio and television sets.

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11 MYTHS
About Analog Noise Analysis

Noise is a central topic in analog circuit design, directly affecting how much information can be extracted from a measurement as well as the economy in obtaining the required information. Unfortunately, there's a large amount of confusion and misinformation regarding noise, which has the potential to cause underperformance, costly overdesign, and/or inefficiency of resources. This article addresses 11 of the most persistent myths about noise analysis in analog designs.

1. Decreasing the resistor values in the circuit always improves noise performance.

It's a well-known relationship that noise voltage increases with higher resistor values according to the Johnson noise equation:

$$e_{rms} = \sqrt{4kTRB}$$

where e_{rms} is the rms voltage noise, k is Boltzmann's constant, T is temperature in Kelvin, R is the resistance, and B is the bandwidth.

This leads many engineers to the conclusion that resistor values should be shrunk in order to reduce the noise. Although this is often true, it can't be assumed because specific examples show that larger resistors improve the noise performance.

For instance, in most cases, current is measured by passing it through a resistor and measuring the resulting voltage. The voltage developed is proportional to the resistor value according to Ohm's law, V=I·R. However, as shown above, the Johnson noise of the resistor is proportional to the square root of the resistor value. Because of this relationship, a 3-dB improvement in the signal-to-noise ratio can be achieved each time the resistor value is doubled. This trend continues right up to the point where the voltage developed is too large or the power dissipated is too high.

2. The noise spectral density of all noise sources can be added up and the bandwidth taken into account at the end of the calculation.

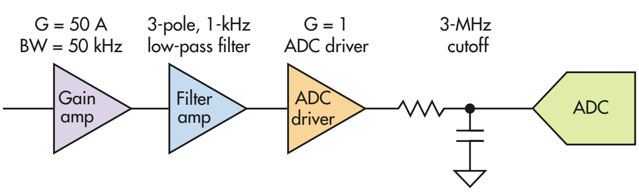
It can save time to combine the noise spectral density (nV/√Hz) of multiple noise sources (voltage noise sources are combined as the root sum of squares) rather than computing the rms noise of each noise source separately. But this simplification is only applicable if the bandwidth seen by each noise source is the same.

It becomes a dangerous trap if the bandwidths seen by each of the noise sources are different. The *figure* shows the implications in an oversampled system. It would appear from the noise spectral density that the gain amplifier will dominate the total noise of the system. However, once the bandwidth is considered, the rms noise contributed by each stage is very similar.

3. It's important to include every noise source in hand calculations.

It may be tempting to consider every noise source in a design, but a designer's time is valuable and such scrutiny can be very time-consuming in large designs. Comprehensive noise calculations are best left to simulation software.

Still, how does a designer simplify the hand noise calculations needed during the design process? Ignore minor noise sources below a certain threshold. If a noise source is 1/5th the rms value of the dominant noise source (or any other noise source referred to the same point), it contributes less than 2% to the total noise and can reasonably be ignored. Designers argue, to some degree, where to draw the threshold line, below which it's not necessary to consider a noise source. At some level, though, whether it's 1/3rd, 1/5th, or 1/10th (which add 5%, 2% and 0.5% to the total noise, respectively), it's not worth worrying about smaller noise sources than that until the design is fixed enough to simulate or calculate fully.



Gain to ADC input	50 V/V	1 V/V	1 V/V		
NSD (RTO)	300 nV/√Hz	39 nV/√Hz	4 nV/√Hz		Not meaningful
rms noise (RTO)	9.7 µV rms	8.7 µV rms	8.7 µV rms		22.3 µV rms

Combined amplifier noise: 15.7 µV rms

This illustrates the justification for using RMS noise rather than spectral density for noise calculations.

4. Pick an ADC driver with 1/10th the noise of the ADC.

Analog-to-digital converter (ADC) datasheets may suggest driving the analog input with a low-noise ADC driver amplifier that has something like 1/10th the noise of the ADC. However, this isn't always the best choice. In a system, it's often worth examining the tradeoff of the ADC driver noise from a system level.

First, if the noise sources in the system preceding the ADC driver are much larger than the ADC driver noise, then choosing a very-low-noise ADC driver will not provide any system benefit. In other words, the ADC driver noise should be commensurate with the rest of the system.

Second, even in the simple case where there's just an ADC and an amplifier to drive it, it may still be advantageous to examine the noise tradeoff and determine its effects on the system. Consider a system that uses a 16-bit ADC with an SNR value that equates to 100-µV rms noise, and an amplifier with 10-µV rms noise as the ADC driver. The total noise when these sources are combined as the root-sum-of-squares is 100.5 µV rms; very close to the noise of the ADC alone.

The following two options that bring the amplifier and ADC into closer balance can be taken into account, as well as the effects on system performance. If the 16-bit ADC is replaced with a similar 18-bit ADC that specifies SNR equivalent to 40-µV rms noise, the total noise would change to 41 µV rms. Alternatively, if the 16 bit ADC is retained, but the driver is replaced with a lower-power amplifier that contributes 30-µV rms noise, the total noise would be 104 µV rms. One of these tradeoffs may be a better choice for system performance than the original combination. It's just a matter of evaluating the tradeoffs and their effects on the overall system.

5. 1/f noise must always be considered in dc-coupled circuits.

Because 1/f noise defies many noise-rejection techniques like low-pass filtering, averaging, and long integrations, it's a menace to very low-frequency circuits. However, many dc circuits are dominated by white noise sources. In fact, they're dominated to the point where it's not useful to calculate the 1/f noise, because it doesn't add to the total noise.

To see this effect, consider an amplifier with a 1/f noise corner (f_{nc}) at 10 Hz and a wideband noise of 10 nV/√Hz. The noise in a 10-second acquisition is computed for various bandwidths with and without the 1/f noise to determine the effect of leaving it out. In this case, wideband noise begins to dominate when the bandwidth is 100 times f_{nc}, and 1/f noise isn't significant when the bandwidth is more than 1000 times fnc. Good, modern bipolar amplifiers can have noise corners well below 10 Hz, and zero-drift amplifiers virtually eliminate 1/f noise altogether.

6. Since the 1/f noise increases at lower frequencies, dc circuits have infinite noise.

Although dc is a useful concept for circuit analysis, the truth is that if dc is considered to be operational at 0 Hz, then there really is no such thing. As the frequency gets lower and lower, approaching 0 Hz, the period gets longer and longer, approaching infinity. The implication is that a minimum frequency can be seen, even in a circuit that theoretically responds to dc.

This minimum frequency depends on the length of the acquisition, or the aperture time, which is the length of time the device's output is being watched. If an engineer turns on a device and watches the output for 100 seconds, the lowest-frequency artifact they could observe would be 0.01 Hz. This also means the lowest-frequency noise that can be observed is 0.01 Hz, too.

To extend this with a numerical example, consider a dc-to-1-kHz circuit in which the output is continuously monitored. If a certain amount of 1/f noise is observed in the circuit in the first 100 seconds, from 0.01 Hz to 1 kHz (5 decades of frequency), then the amount of noise observed in 30 years, which is about 1 nHz (12 decades), can be calculated as $\sqrt{12/5} = 1.55$, or 55% more noise than was observed in the first 100 seconds.

This somewhat banal increase even assumes the worst case—1/f noise continues to increase down to 1 nHz, for which there is, so far, no measured evidence. In theory, when the aperture time isn't well-defined, the 1/f noise could be calculated down to a frequency equal to one over the lifetime of the circuit. In practice, these very long timeline variations are dominated by aging effects and long-term drift rather than 1/f noise. Many engineers set a minimum frequency, such as 0.01 Hz or 1 mHz, for noise calculations in dc circuits to keep the calculations practical.

7. The Noise Equivalent Bandwidth is a multiplier for the noise.

The noise equivalent bandwidth (NEB) is a useful simplification for noise calculations. Some noise from beyond the bandwidth of the circuit can get into the circuit because the gain above the cutoff frequency is not zero. The NEB is the cutoff frequency of a calculated, ideal brick-wall filter that would let in the same amount of noise as would the actual circuit. The NEB is larger than the –3-dB bandwidth and has been calculated for common filter types and orders. For example, it's 1.57 times larger than the –3-dB bandwidth for a 1-pole low-pass filter, or, in equation form, $NEB_{1pole} = 1.57 \cdot BW_{3dB}$.

However, there seems to be consistent confusion about where to put that multiplication factor in the noise equation. Remember that the NEB is an adjustment for the bandwidth, not the noise; therefore, it goes under the square root as follows:

$$e_{RMS} = NSD \cdot \sqrt{NEB_{1pole}} = NSD^* \sqrt{1.57 \cdot BW_{3dB}}$$

8. The amplifier with the lowest voltage noise is the best choice.

When choosing an op amp, the voltage noise is often the only noise specification considered by the designer. But it's important not to overlook the current noise as well. Except in special cases such as input-bias-current compensation, the current noise is typically the shot noise of the input bias current:

$$i_n = \sqrt{2 \cdot q \cdot I_B}$$

The current noise is converted to a voltage via the source resistance. As a result, when a large resistance is in front of the amplifier input, the current noise can be a larger noise contributor than the voltage noise. Current noise typically becomes a problem when using a low-noise op amp with a large resistance in series with the input.

For example, consider Analog Devices' ADA4898-1 low-noise op amp with a 10-kΩ resistor in series with the input. The voltage noise of the ADA4898-1 is 0.9 nV/√Hz, the 10-kΩ resistor has 12.8 nV/√Hz, and the 2.4-pA/√Hz cur-

DESIGN NOTES

3A, 1MHz Buck Mode LED Driver with Integrated Voltage Limiting

Design Note 556

Matthew Grant

Introduction

The LT®3952 monolithic LED driver includes a 4A, 60V DMOS power switch, excellent for driving high current LEDs in buck mode. Among its many features is an input current sense amplifier, which can be leveraged to provide built-in LED voltage limiting in buck mode.

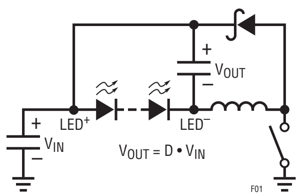


Figure 1. Buck Mode Topology

In buck mode, the anode of the LED string (LED+) is tied to the input voltage and the converter draws current from the cathode of the string (LED–). In the case of an open-circuit, a buck mode converter drives the LED– nearly to GND. The total output voltage should be limited during this open-circuit fault condition.

One method of limiting voltage is to use an external PNP transistor as a level shifter. While this technique is adequate, a more elegant solution can be achieved by leveraging the internal resources of the LT3952.

The trick is to repurpose the input current sense amplifier on the IVINP/IVINN pins to act as a high side voltage regulator as shown in Figure 2.

A resistor divider across the LED string allows the IVINP/IVINN pins to sense the output voltage. When the IVINP/IVINN voltage reaches 60mV, the IVINCOMP output reaches 1.2V and the output is limited. Tying IVINCOMP to FB, as shown in Figure 2, adds the benefits of output overvoltage protection and open LED protection.

For applications that utilize the PWM dimming function, a large value resistor from FB to GND prevents the FB pin from floating during PWM off-time.

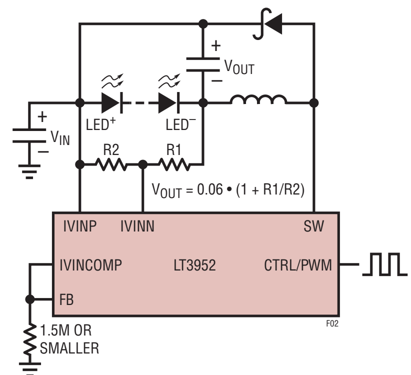


Figure 2. I_{VINP}, I_{VINN} as Output Voltage Limit

Application Circuit

To test the design, an application circuit was built for a 40W, 1MHz buck mode LED driver. With the R1, R2 and R4 values shown, the voltage limit is roughly 22V across the LED string.

Figure 3 shows measurement of the LED– voltage and the LED– open-circuit limit as V_{IN} is swept from 0V

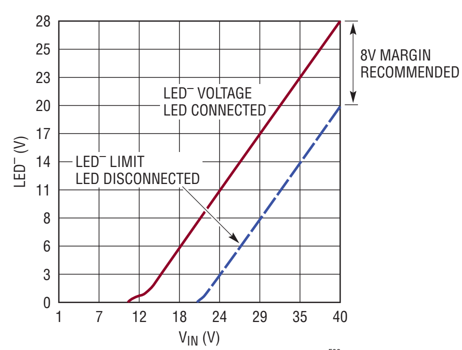


Figure 3. DC Measurement of LED– and LED– Limit

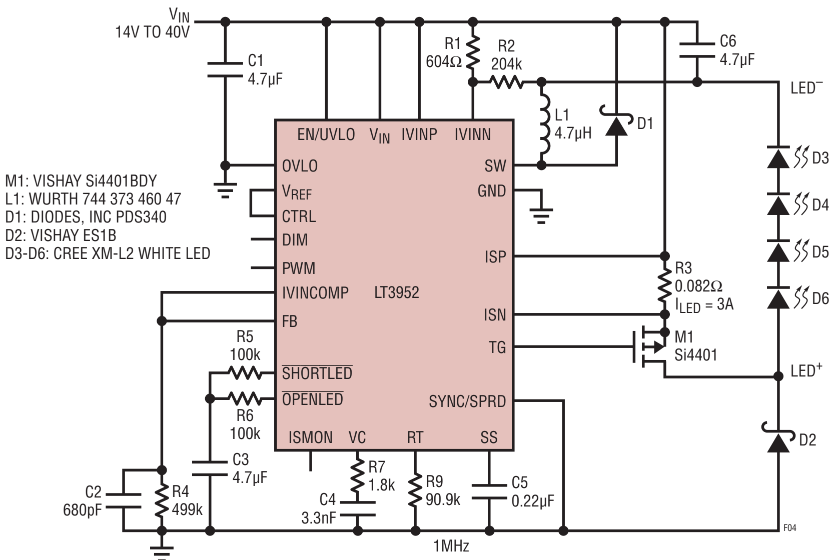


Figure 4. 3A, 40W, 1MHz Buck Mode LED Driver with 22V Output Limit

to 40V using the circuit of Figure 4. The voltage limit tracks the input well over the full operating range.

Figure 5 compares the transient response for an open-circuit condition with and without the use of the output limit circuit: V_{IN} = 36V, I_{LED} = 3A, four series LEDs.

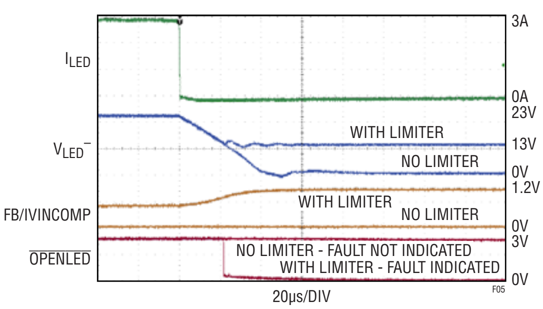


Figure 5. Open-Circuit Fault with and without Limiter

As you can see, an open-circuit fault without the limiter causes LED⁻ to be pulled from its 23V nominal value all the way to ground, resulting in nearly the full 36V input potential from LED⁺ to LED⁻.

With the limiter, however, the output voltage is quickly limited to a more reasonable value. The connection of FB to IVINCOMP allows the fault to be indicated on the OPENLED pin.

The overall efficiency for this 40W solution is greater than 92% at 24V input voltage, and greater than 90% over the entire input voltage range of 14V to 40V.

When using any output limiting technique, remember to leave some margin between the limit voltage and the normal operating voltage.

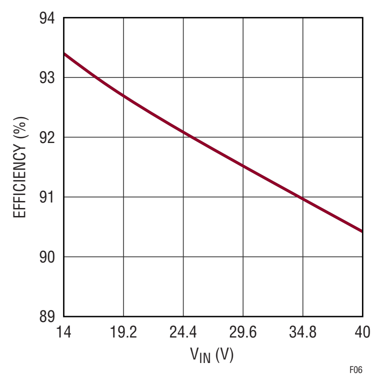


Figure 6. Efficiency vs Input Voltage

Conclusion

The LT3952 is a versatile, high performance platform for driving LEDs in multiple topologies. In addition to input and output current regulation, a host of features such as spread spectrum modulation, all internal PWM generator, and exceptional fault protection simplifies the design of advanced lighting solutions.

Data Sheet Download

www.linear.com/LT3952

For applications help,
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rent noise times the 10-kΩ resistor is 24 nV/√Hz—the largest noise source in the system. In such cases where the current noise dominates, it's often possible to find a part with lower current noise and thereby reduce system noise. This is especially true for precision amplifiers, but high-speed FET-input op amps can help in high-speed circuits as well.

9. The best noise performance is achieved by taking lots of gain in the first stage.

It's often suggested that the gain should be taken in the first stage for better noise performance, which is true because the signal will then be larger than the noise of subsequent stages. However, the drawback of taking gain is that it reduces the maximum signal that can be accommodated by the system.

In some cases, rather than taking a large amount of gain in the first stage—which improves the sensitivity of the measurement but limits the dynamic range—it may be better to limit the amount of gain taken in the first stage. Then digitize it with high resolution to maximize both sensitivity and dynamic range.

10. All resistor types have the same noise for a given resistance.

The Johnson noise of resistors is fundamental, giving rise to a simple equation for the noise of a certain resistor at a certain temperature. However, Johnson noise is the least amount of noise that can be observed in a resistor, and it doesn't mean that all resistor types are created equal with respect to noise.

There's also excess noise, which is a source of 1/f noise in resistors that's highly dependent on the resistor type. Excess noise, somewhat confusingly also called current noise, is associated with the way current flows in a discontinuous medium. It's specified as a noise index (NI) in dB, referred to as 1 µV rms/V_{DC} per decade. This means that if there's 1 V dc across a resistor with a 0 dB NI, the excess noise in a given frequency decade is 1 µV rms.

Carbon- and thick-film resistors have some of the highest NI, ranging up to roughly +10 dB; thus, it's best to avoid them in noise-sensitive parts of the signal path. Thin films are generally much better at around –20 dB, and metal foil and wirewound resistors can drop below -40 dB.

11. Given enough acquisitions, averaging reduces the noise indefinitely.

Averaging is recognized as a way to reduce the noise by the square root of the number of averages. This is conditionally true when NSD is flat. However, this relationship breaks in the 1/f range as well as in a few other cases.

Consider the case of averaging in a system sampling at a constant frequency (f_s), whereby n samples are averaged and decimated by n, and some number m decimated samples are returned. Taking n averages moves the effective sampling rate after decimation to f_s/n, reducing the effective maximum frequency seen by the system by a factor of n and reducing the white noise by √n. However, it also took n times longer to obtain m samples, so the lowest frequency that can be seen by the system is also reduced by a factor of n (remember, there's no such thing as 0 Hz).

The more averages are taken, the lower these maximum and minimum frequencies move on the frequency band. Once the maximum and minimum frequencies are both within the 1/f range, the total noise depends only on the ratio of these frequencies. Therefore, increasing the number of averages provides no further benefit to the noise. The same logic holds for long integration times for an integrating ADC such as multi-slope.

Other practical limits are in play as well. For example, if quantization noise is the dominant noise source, whereby the output of the ADC with a dc input voltage is a constant code with no flicker, then any number of averages will return the same code. ed

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Why You Should Care About Oscilloscope Trigger System Basics

This article pulls back the curtain a bit on the trigger system, one of the most commonly used but least understood subsystems in real-time oscilloscopes.

1. Using *Auto Scale* on the oscilloscope produces this view of a 10-MHz square wave.

2. *Auto Scale* automatically configures the oscilloscope to trigger on the rising edge of Channel 1.

You sit down at your lab bench to debug some funny behavior in a 10-MHz clock. You fire up your oscilloscope, get your probing in place, and hit the almighty *Auto Scale* button, after which you're presented with something like what you see in *Fig. 1*.

Then it strikes you—there are ten million clock cycles occurring every second! How is the oscilloscope able to accurately display such a clean representation of your signal? How is it that the middle of the rising edge of your clock is perfectly aligned at center screen? The answer is the trigger system.

The trigger system is both one of the most commonly used and least-understood subsystems in real-time oscilloscopes. In this article I'm going to pull back the curtain just a bit, and explain what the trigger system does, how it works, and why you should care.

WHAT IT DOES

The sole responsibility of the trigger system is to tell the rest of the oscilloscope what data to care about. It decides when the acquisition system begins acquiring, which means that by default it decides what's displayed on screen and what data is available to make measurements on. It can make these decisions with a very simple set of conditions or very complex conditions, based on user input. Let's consider the example in *Fig. 1*, a 10-MHz square wave. The reason the signal in the image looks so clear and well-positioned on-screen is that the trigger is set up, appropriately, to look for a rising edge on Channel 1, as seen in the trigger configuration dialog in *Fig. 2*.

Remember that to start, we used *Auto Scale*, which chose an appropriate trigger source and threshold based on our input signal. But what would our signal look like without an appropriate trigger configuration?

3. An inappropriate trigger configuration will cause triggers to occur on a predetermined time interval, regardless of signal behavior if auto-trigger is enabled, as seen here. Infinite-persistence has been enabled on Channel 1 to better illustrate what is occurring.

4. Disabling the auto-trigger feature without an appropriate trigger configuration means the oscilloscope won't acquire at all.

In *Fig. 3*, I changed the trigger condition to look for an edge on Channel 2 (which has no signal connected at the moment). The auto-trigger feature, which we can see is enabled in the "Sweep" section of the trigger configuration dialog, is automagically kicking off acquisitions on a regular time interval, giving us a smear of yellow signal trace across the screen.

The signal itself appears to be clearly visible in this image, superimposed over the "smeared" signal trace. Unfortunately, this is just an artifact of the screenshot; that's where the signal happened to line up at the instant I took the screen capture. In practice, auto-triggered acquisitions are only useful in determining the relevant dc parameters to use in setting up your trigger condition. Note that if the auto-trigger feature is disabled, without an appropriate trigger configuration, the scope simply won't acquire *(Fig. 4)*.

The trigger system will always place the trigger point (the instant at which all conditions present in the trigger configuration are met) at t = 0.0 s on-screen. Later on, we'll see how using advanced trigger configurations can help capture infrequent and hard-to-find events, in addition to the simple rising-edge trigger we've seen so far.

HOW IT WORKS

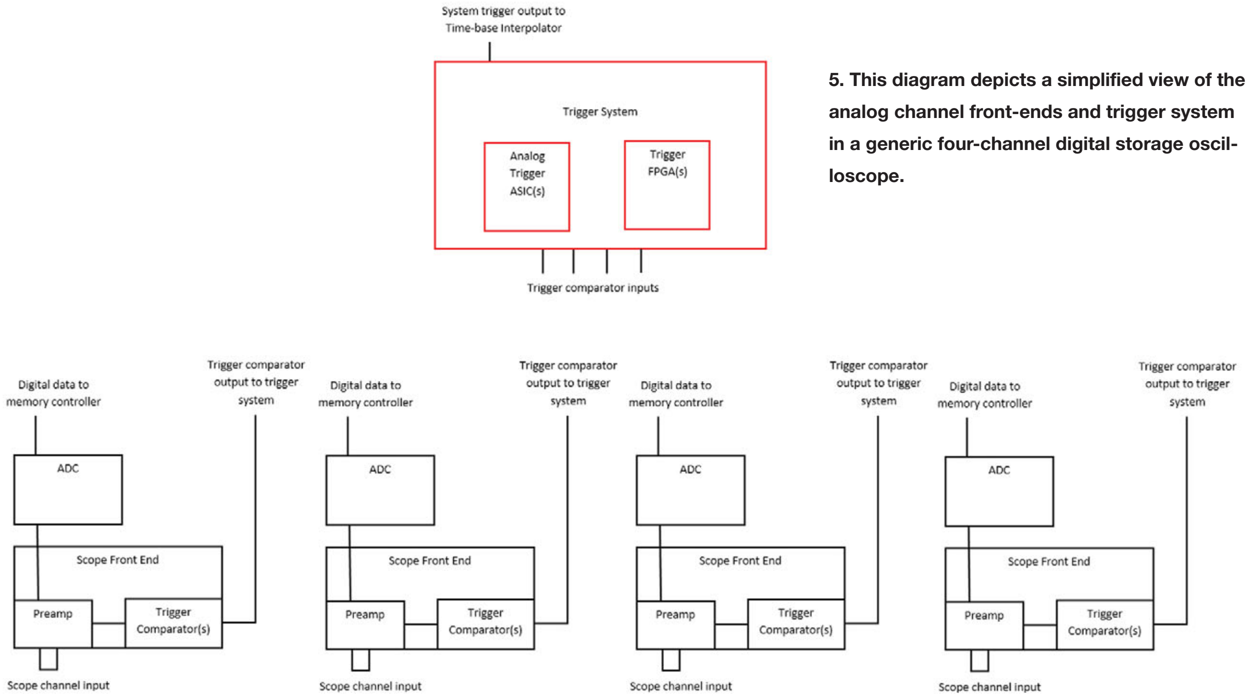
Most real-time oscilloscopes have an "analog" trigger system. This system is actually a mishmash of analog circuitry and digital counters, but it relies on input from analog comparators fed from the scope preamplifier. Some oscilloscopes now feature a "digital" trigger, meaning that the trigger system is entirely digital and is fed with integer data from the analog-to-digital converter (ADC) output.

Both types of systems perform the same function; evaluating whether or not all of the configured trigger conditions are met at a given moment in time. Because fully digital trigger systems are fairly rare, we'll focus on analog trigger systems.

Figure 5 shows a generic representation of the parts of a four-channel DSO (digital storage oscilloscope) that we're concerned with—the analog channel front-ends and the trigger system. The trigger system takes inputs from comparators on all of the analog channels and provides a single output. For convenience, let's focus on a simplified diagram with only one analog channel.

Figure 6 is a simplified, one-channel view of the same systems depicted in Fig. 5. When a signal is connected to the channel input it goes through a series of transformations before it ends up on-screen:

- First, the signal is scaled appropriately and offset if necessary by the preamp. The preamp output is sent to the ADC to be digitized.
- Trigger comparators observe the output of the preamp and fire if it exceeds their set threshold. This threshold is set based on user input, or by helper routines like the almighty *Auto Scale*.
- The trigger system observes all of the trigger comparator outputs in the system and combines them in such a way as to monitor for a given set of conditions. These conditions can be very straightforward (i.e., rising edge on Channel 1) or quite complex (i.e., pulse-width greater than 2.4 ns on Channel 3, followed by a pattern of Channel 1 high, Channel 2 low, and Channel 4 low, held for a duration of greater than 30.0 ns and less than 50.0 ns).
- When the trigger system sees that all of the conditions are met for the specified trigger, it sends a pulse on its output. We call this signal "System Trigger" or "SysTrig" for short. SysTrig is monitored by the acquisition system as well as a special subsystem known as the "time-base interpolator."
- When the acquisition system sees a pulse on SysTrig, it begins to digitize, process, store, measure, and finally display data. We refer to this entire process in general as "acquisition."



5. This diagram depicts a simplified view of the analog channel front-ends and trigger system in a generic four-channel digital storage oscilloscope.

• Before the acquisition data (the waveform), which is now stored in memory, can be displayed on-screen, we need to know how to orient it horizontally. This is where the time-base interpolator comes in. The interpolator monitors SysTrig, just like the acquisition system. When it goes high, it's the interpolator's job to figure out what address in waveform memory matches up with the instant the trigger occurs. It communicates this information to the acquisition system and voila, the result is the desired waveform on-screen, with the trigger point placed perfectly at t = 0.0 s!

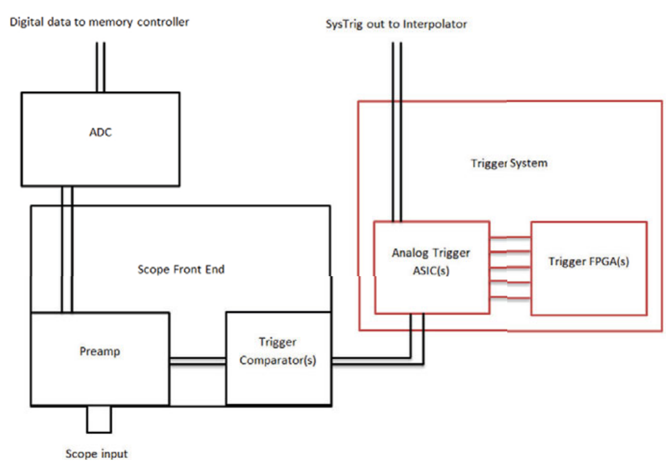
WHY YOU SHOULD CARE

Although some may find the inner workings of oscilloscope subsystems interesting, it's fair to say that most folks couldn't care less. If you're one of those people and you just skipped the entire "How It Works" section above, no sweat, there will not be a quiz at the end! The bottom line is that you should care about the trigger system and take the time to understand it, because it can help you debug difficult issues and save you quite a bit of time and frustration.

Using an oscilloscope in a basic way—that is to say, pushing the *Default Setup* and *Auto Scale* buttons—can tell you a little bit about your signal and is a quick and convenient way to get started. However, if you're interested in capturing an infrequent event, as is often the case when debugging common issues like runts, glitches, and setup-and-hold violations, the trigger system is a powerful tool.

ADVANCED TRIGGER MODES

In addition to edge-trigger mode discussed at the beginning of this article, most real-time oscilloscopes have a number of advanced trigger modes designed to detect common problems. When used in conjunction with "Triggered" sweep (aka, auto-trigger disabled), these modes will ensure that only the behavior you're looking for is acquired and displayed. As an example, let's look for a runt in a square wave. We connect our signal and use our trusty *Auto Scale* button, and all we see is a square wave. No runt in sight!

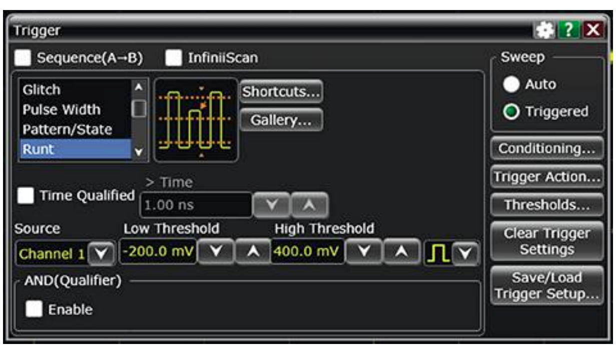


6. This diagram depicts a simplified view of a one-channel digital storage oscilloscope's analog channel front-end and trigger system.

7. Edge-trigger mode isn't a good tool to use when searching for runt events in your signal.

10. Runt-trigger mode quickly identifies and displays the runt event in the signal.

8. Zooming out horizontally with edge-trigger mode shows that something odd is going on with our signal, but it doesn't give us enough information to find the runt event.



9. Runt-trigger mode setup on a Keysight Infiniium S-Series oscilloscope.

Figure 7 shows us that although we suspect a runt is present in our signal, finding it with edge trigger will prove difficult. We can try zooming out a bit.

As shown in *Figure 8*, by zooming out horizontally, we can tell that there's something fishy going on, but it's not entirely clear what. Now, let's use runt trigger mode on a Keysight Infiniium S-Series oscilloscope and see what we can find *(Figs. 9 and 10)*.

There's our runt! The waveform in *Figure 10* is clear and steady, and the event we're interested in, our elusive runt, is right at t = 0.0 s! This is the value of learning the trigger system on your scope. It will allow you to find the events you're interested in, and *only* the events you're interested in, very quickly. Although this example focused on finding a runt, the same sort of example can be demonstrated with glitches, setup-and-hold violations, specific data across multiple channels, data patterns relative to clock edges, edge transition times, etc., using the appropriate trigger mode.

ADVANCED TRIGGER FEATURES

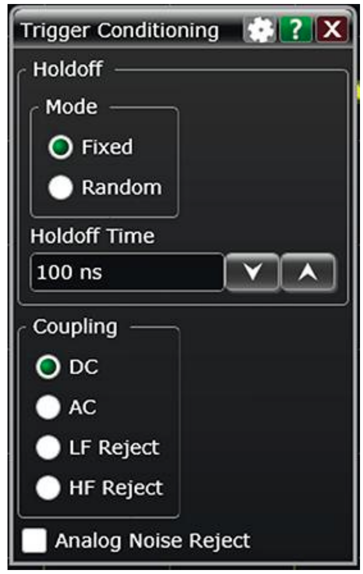
In addition to advanced trigger modes like runt mode discussed above, many oscilloscopes have features that can be used in conjunction with trigger modes to further refine what we want the scope to show. They can also instruct the scope to automatically take actions when a trigger occurs.

Figure 11 shows some common options for trigger conditioning, while *Figure 12* shows some of the things we can configure the oscilloscope to do for us automagically when a trigger occurs. My personal favorite is the "Email on Trigger" feature. If you have a *really* infrequent event, that's no problem—set up your trigger and leave for the weekend. Come back, open up your email, and find all of the data you need!

YOUR EVENINGS AND WEEKENDS WILL THANK YOU

The trigger system is a mystery to many engineers, but it doesn't have to be a mystery to you. Make a point to learn the trigger system on your scope today and you may find yourself with quite a bit more free time in the near future! ed

COLIN F. Mattson is an engineer in Research & Development at Keysight Technologies in Colorado. Focusing on real-time oscilloscope trigger systems, Colin has been with Agilent/Keysight since early 2013. He received his BSEE/CE from Oakland University in 2012.



11. Refine what the oscilloscope displays in a trigger by using the Trigger Conditioning dialog, shown on a Keysight Infiniium S-Series oscilloscope.

12. A wide variety of trigger actions are available on a Keysight Infiniium S-Series oscilloscope.

VICTORIA FRAZA KICKHAM | Distribution Editor

CONNECTED CARS
Spell Opportunity for Manufacturing, Distribution

The auto market continues to drive business for supply chain companies, as rapid growth in connected-car production continues through 2020.

The connected-car market continues to be a boon to supply chain companies, as a recent survey by Gartner points to rapid growth in the market over the next five years. Production of new automobiles equipped with data connectivity—either through a built-in communications module or by a tether to a mobile device—is expected to increase 150%, reaching 12.4 million this year and rising to 61 million in 2020, according to Gartner.

CONNECTED CAR PRODUCTION BY CONNECTIVITY MODE, WORLDWIDE (THOUSANDS)

	2015	2016	2017	2018	2019	2020
Embedded	2,174	4,914	11,097	21,394	33,928	42,949
Tethered	4,681	7,519	9,971	12,374	14,995	17,994
Total	6,855	12,433	21,068	33,768	48,923	60,943

Source: Gartner (September 2016)

This is good news to electronic components manufacturers and distributors, many of which point to the automotive marketplace as a bright spot in an otherwise murky economy. In a mid-year business outlook report this summer, electronic components distributors listed automotive and Internet of Things applications as two of the greatest business opportunities now and into 2017.

A "connected car," as defined by Gartner, is capable of bidirectional wireless communication with an external network to deliver digital content and services, transmit telemetry data from the vehicle, enable remote monitoring and control, or manage in-vehicle systems.

"The connected vehicle is the foundation for fundamental opportunities and disruptions in the automotive industry and many other vertical industries," said James Hines, research director at Gartner. "Connected vehicles will continue to generate new product and service innovations, create new companies, enable new value propositions and business models, and introduce the new era of smart mobility, in which the focus of the automotive industry shifts from individual car ownership to a more service-centric view of personal mobility."

He went on to explain that connected-car technology is an opportunity for automakers to generate post-sale profits through sales of additional services and feature upgrades, as well as enhance brand loyalty through a more personalized customer experience.

"As cars become more automated, they are being equipped with an increasing array of sensing technologies, including cameras and radar systems," Hines explained. "Many automobiles will use image detection as the primary means to identify and classify objects in the vicinity of the vehicle so they can provide more sophisticated responses and even have autonomous control." Gartner also points out that in order to become more automated—and cleaner—automobiles will need 5% more embedded processing functions, year over year, from 2016 through 2020.

"Automated driving functions, such as adaptive cruise control, collision avoidance and lane departure warning systems, necessitate real-time camera and sensor data processing and pattern recognition," the firm said in its September 2016 report. "Improving fuel efficiency and reducing emissions necessitate sophisticated engine and transmission control systems." ed

Op Amps Make Precision Clipper, Protect ADC

By THOMAS MOSTELLER and AARON SCHULTZ, Linear Technology Corp.

IT CAN BE A CHALLENGE to match the voltage range of an analog signal to the input range of an analog-to-digital converter (ADC). Exceeding the ADC's input range will give an incorrect reading. And if the input goes far enough beyond the power-supply rails, substrate currents may flow into the ADC, which can then cause latch up or even damage to the part. However, restricting the input-voltage range to lower, more-conservative levels wastes the ADC's dynamic range and resolution.

A simple op-amp clipper *(Fig. 1)* prevents these problems. The maximum allowable input voltage is applied to the non-inverting input of U1, and the output is fed back to the inverting input via small-signal diode D1. The ADC's reference voltage can be used for the clipping reference if available. When the input voltage is below the reference, U1's output is driven to the positive rail and D1 is reverse-biased, so the input signal passes through without being altered.

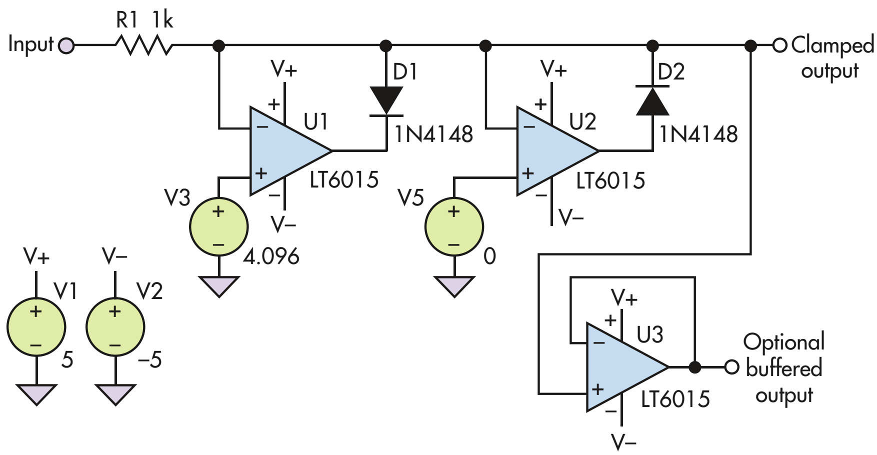
When the input goes above the clamp voltage, the op-amp output reverses and closes the loop through D1. As a result, it effectively becomes a unity-gain follower to the clamp voltage. Input resistor R1 limits the amount of current the op-amp output has to sink. A second op amp (U2) performs the complementary negative clipping function, preventing the signal from going below ground. Thus, in this example, the output signal is restricted to 4.096 V to 0 V out.

While simple in concept, this circuit poses unique challenges for the op amp. First, most modern op amps have back-to-back diodes across their input to prevent the application of large differential voltages to the inputs. This can cause damage to the part or shifts in the input offset voltage. In this circuit, these diodes would prevent the output signal from going more than one diode drop below the positive clamp voltage or one diode drop above the negative clamp voltage.

Deciding whether a given op amp has these diodes can require some detective work. Some parts' datasheets show the presence of the input diodes, but others don't. Another indication of the diodes' presence is a limitation in the Absolute Maximum Ratings section of input current to a few milliamps.

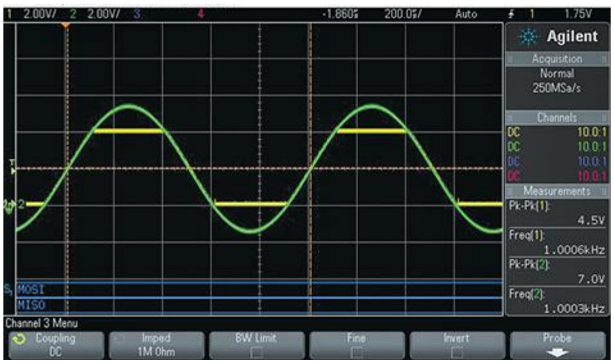
In addition, the output of the op amp has to slew from the "unclamped" to the "clamped" state as quickly as possible in order to clamp a fast-rising signal without a potentially dangerous overshoot. Furthermore, rail-to-rail input and output operation of the op amp is desired so it can function with voltages close to the limits of the power supplies.

The LT6015 family of op amps, which includes the LT6016 dual and LT6017 quad versions, addresses these issues. Because there are no diodes on the inputs, they can have a very large differential voltage, which should not impose a limitation on any practical ADC application. Use of large differential voltages at the input allows the introduction of clamping and other nonlinear circuits. Furthermore, the input voltage can go as high as 80 V above or 25 V below the V– rail, which enables the part to survive inputs that would damage other parts.

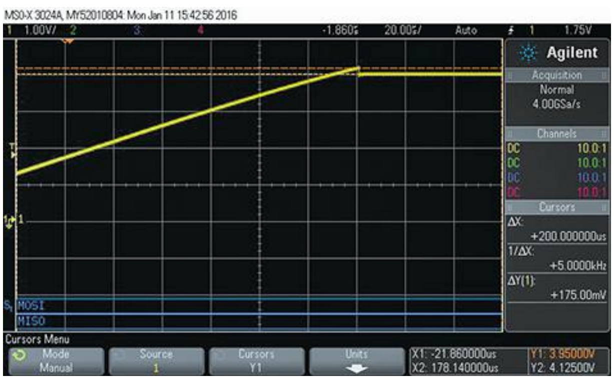


1. This clipping circuit uses a complementary pair of op amps to prevent excessive positive (U1) and negative signal excursions (U2) of the input signal, to maximize available signal dynamic range without damaging overload.

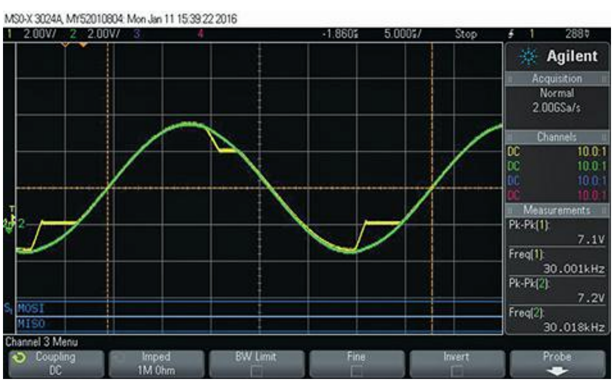
The LT6015 is further unique in that it allows a power-supply range from V+ to V– of up to 60 V, which would make it possible to use the circuit to clamp higher voltages than the great majority of op amps. It also has a slew rate of 0.75 V/µs, which enables it to clamp reasonably fast-rising signals. The sub-100-µV typical offset voltage ensures that the clamping level is very accurate.



2. With the LT6015 and bipolar 10-V supplies, the circuit clamps a 7-V p-p sine wave at 0 and +4 V.



3. The clamping action is small but effective, as shown by this "zoom in" view of the output.



4. Clamping speed also determines the bandwidth; here, the 10-µs clamping-action response is apparent.

Figure 2 shows the LT6015 driven from ±10-V supplies clamping a 7-V p-p, 1-kHz sine wave at 0 V and 4 V. It's hard to see the clamping action, but if you zoom in on the output, you can see a small overshoot *(Fig. 3)*.

Increasing the input frequency to 30 kHz *(Fig. 4)* clearly shows the clamping action taking place in less than 10 µs, limiting the operating bandwidth of the circuit to a few kilohertz. The clamping speed can also be increased by limiting the voltage-supply rails close to the clamping-limit voltages, which lowers the voltage range that the output must slew to go into clamping mode. Since the LT6105 output swings very close to the supply rails, little extra voltage range is needed.

Another limitation on this circuit is that the output resistance is defined by R1, which needs to be at least a few hundred ohms to limit the output of current in the op-amp output. Since some ADCs need to be driven by a low resistance, buffer amp U3 might be required. Using the LT6017 quad-version package would permit a single part to perform all of these functions.

THOMAS MOSTELLER has been a field applications engineer for Linear Technology's Middle Atlantic region since 1990. He has assisted a wide range of military, commercial, and industrial customers with designs in many fields, such as power distribution and supplies, analog signal conditioning, data conversion, and RF and communications applications. Prior to joining Linear Technology, Thomas designed medical equipment for 10 years, and holds a patent in the design of infusion pumps. He earned a BSEE from Drexel University in 1977.

AARON SCHULTZ is an applications engineering manager at Linear Technology. Aaron has worked for 20 years at the chip and system level in design and applications, in fields including solid-state lighting, photovoltaics, multiphase dc-dc and other power-conversion topics, high-speed data communications, fiber optics, and high-speed memory. His schooling includes Carnegie Mellon University ('93) and MIT ('95). By night he plays jazz piano.

New Products

MEMS Accelerometers Enable Early Detection of Defects

ANALOG DEVICES' new ADXL354 and ADXL355 three-axis MEMS accelerometers perform high-resolution vibration measurement with low noise for the early detection of structural defects via wireless sensor networks. Low noise performance along with low power consumption makes it possible to enable low-level vibration measurement applications such as structural health monitoring. The tilt stability of the accelerometers strengthens repeatability over temperature and time, suiting the devices for orientation and navigation systems in unmanned aerial vehicles using IMUs and inclinometers. Repeatable tilt measurement under all conditions enables minimal tilt error without extensive calibration in harsh environments.

The accelerometers, offering guaranteed temperature stability with null offset coefficients of 0.15 mg/C (max), are packaged in hermetic 6 x 6 mm 14-lead LCCs, ensuring that the end product continually conforms to its repeatability and stability specifications. Other technical specifications include ±2 g to ±8 g FSR output with selectable digital filtering from 1 Hz to 1 kHz, and a 25 μ/√Hz low noise density at less than 200 μA current consumption.

The ADXL354 three-axis MEMS accelerometer, with analog output, is priced at \$25.42 each/1,000. The ADXL355, with SPI output, costs \$28.25 each/1,000.

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Low Rss MOSFET Utilizes Advanced CSP Technology

ALPHA AND Omega Semiconductor is now offering the AOC3860, a common-drain 12 V dual n-channel MOSFET with the lowest on-resistance in the product family of 2.15 mΩ typical at 4.5 V gate drive.
The new device improves source-to-source resistance, a critical factor for achieving faster battery charges with a higher charging current in smart phone design.

Rugged Digital Receiver Supports GNU, GSM & Real-Time Spectral Analysis

THE K707 Digital Receiver from Innovative Integration supports two FMC-310 plug-in modules providing up to 6 antenna inputs, 128 independent channels of DDC, and one spectrum analyzer embedded in a Xilinx Kintex-7 FPGA. It offers monitoring and/or recording of wide or narrow-band spectra or channelized IF band data. Supporting GNU radio, GSM digital beamforming and real-time spectral analysis, the receiver provides contiguous recording at 1,300 MByte/s to four SSDs until running out of disk space.

Eight DDC banks, each supplying 16 channels, support monitoring of 128 DDC channels per single module. Each DDC bank can select its ADC source and decimation rate; each DDC channel has its own programmable tuner and programmable low-pass filtering supporting output bandwidth up-to 800 KHz. The spectrum analyzer calculates the wide-band spectrum of raw ADC data or the narrowband spectrum of the cooked DDC output data at a programmable update rate.

A development kit is available for creating custom instrumentation. Custom-made VHDL cores can be inserted into the supplied Framework to create advanced applications.

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ESD protection helps to further improve battery performance and safety.

Charging power increase from 5 W to larger wattages of 15 W or 25 W is achieved by raising either output voltage or output current. For battery packs, this translates to a higher charging current. Typical Rss is 2.15 mΩ with 4.5 V gate voltage, and 2.25 mΩ with 3.8 V gate voltage. The chip, packaged in a 3.05 x 1.77 mm AlphaDFN, has reduced size by 14% and Rss by 10% compared to previous models in the family. The AOC3860 dual n-channel MOSFET, priced at $0.60 each/1,000, is available immediately in production quantities of 8,000 or more with a lead-time of 12-14 weeks..

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National Geographic TAKES ON MARS

Technology Editor Bill Wong takes a look behind the scenes of National Geographic Channel's new "Mars" series.

To date the only Earth-based entities on Mars have been robots *(see "Curiosity Landing Shows NASA At Its Best" on electronicdesign.com)*. NASA is still planning on sending people to Mars sometime around 2030 and is actively developing technologies to make that possible.

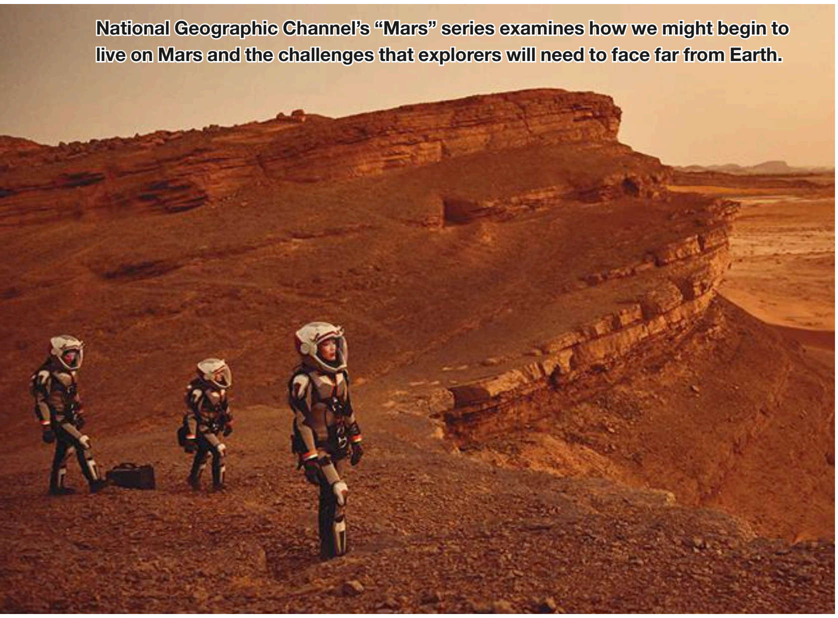
SpaceX CEO Elon Musk has his own plans for Mars. SpaceX has been on the forefront of reusable rockets working with NASA, and SpaceX's Dragon capsule has already delivered material to the International Space Station.

The popularity of movies like *The Martian* have peaked interest in putting earthlings on Mars. The National Geographic Channel's new "Mars" television series debuts this month brought to you by producers Ron Howard *(Apollo 13)* and Brian Grazer *(A Beautiful Mind)*. Like *The Martian*, the "Mars" series will be fiction based in real-world technology, but with more of a twist on technology other than just being technically correct when it is used by the actors. Viewers will get to see the actors as well as vignettes of NASA researchers as they watch the series. This will show both the practicality of going to Mars as well as the challenges and potential solutions that are in the mix. Also, *The Martian* was more of a survival story while the series looks at how Mars might be settled for long-term habitation.

I talked with Dr. Robert D. Braun, Professor of Space Technology, Georgia Institute of Technology, about the series on which he consulted with its writers. Dr. Braun has been intimately involved with NASA and Mars-related projects for many years.

The characteristics of Mars are somewhat different than Earth. For example, wind speeds are higher on Mars, but the dynamic pressure of the wind is lower because the air density is lower. Tornado-like sand storms can cause problems, but they are not necessarily as robust as in the movie.

One of the most challenging areas for this type of exploration will be shielding and redundancy. The electronics used in space are more advanced than in the past, but not on par with what we are used to with computers and smartphones. Single-event upsets (SEUs) are more common with particle shielding like Earth's atmosphere and magnetosphere. One area of research is in active shielding using superconducting magnets.



National Geographic Channel's "Mars" series examines how we might begin to live on Mars and the challenges that explorers will need to face far from Earth.

I recently hosted a webinar, *Challenges for Electronic Circuits in Space Applications*, with Analog Devices and EBV Elektronik in which we talked about the challenges of electronics in space applications. Rugged terrestrial electronics are improving, but those designed specifically for space are needed for Mars. The webinar archive is available on the *Electronic Design* website.

Even the dirt on Mars will be an issue. It is a fine regolith found with properties significantly different compared to terrestrial soil—growing potatoes, as in *The Martian*, notwithstanding.

Dealing with catastrophes, shortages, and people will be just a few of the issues actors will have to deal with. In the meantime, NASA will be working to develop the technology and logistics to make it actually happen. ed

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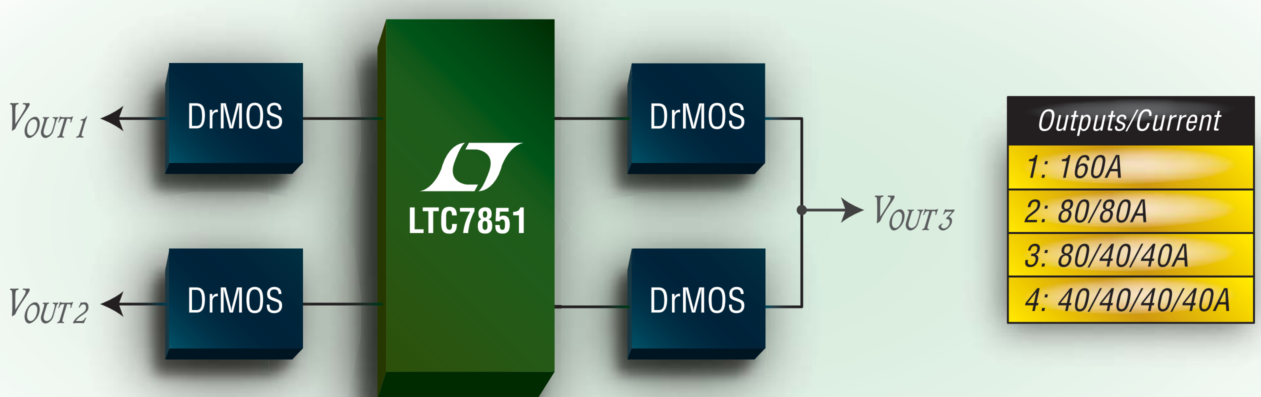

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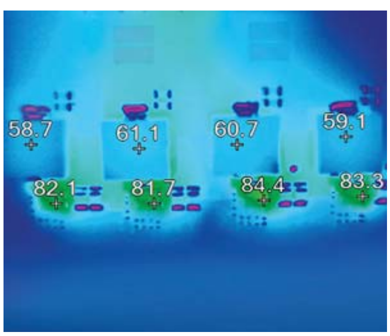

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