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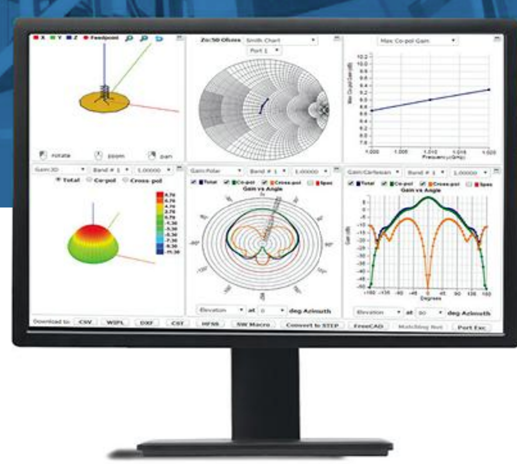

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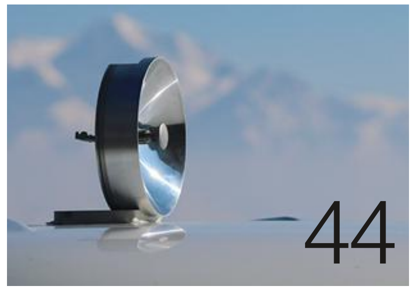

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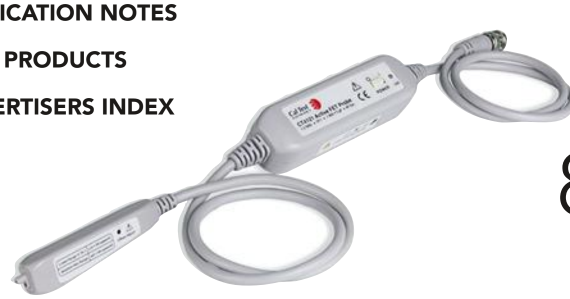

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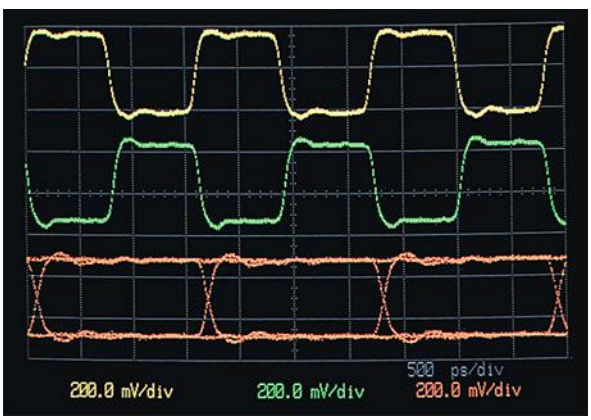

Plot shows complementary clocks and PRBS (opt. 01) outputs at 622.08 Mb/s with LVDS levels. Traces have transition times of 80 ps and jitter less than 1 ps (rms).

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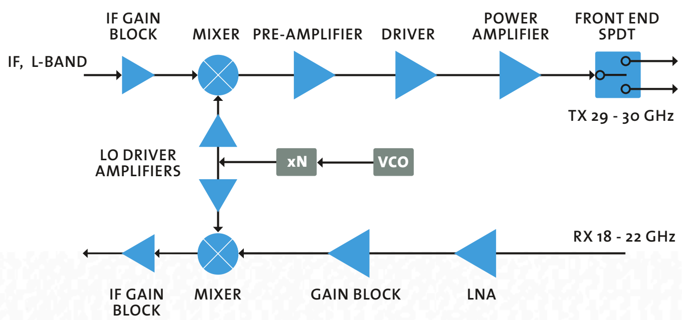

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2017 Microwaves & RF Salary & Career Report

The results of this year's Microwaves & RF Salary & Career Report show an industry that appears to be stable—but also one that needs more youth. Read on and download the full report.

http://www.mwrf.com/community/2017-microwaves-rf-salary-career-report

5 Key Elements of a TCXO—How Temperature Affects It

So far in our oscillator series, we've touched on the most important aspects of oven-controlled crystal oscillators (OCXOs) and temperature-compensated crystal oscillators (TCXOs). This time we'll discuss five key elements of a TCXO and the impacts of temperature.

http://www.mwrf.com/components/5-key-elements-tcxo-and-how-temperature-affects-it

Will Gesture Sensing Drive Home Automation?

Developments in smart-home electronics and home automation are driving new generations of human-machine interfaces. Gestures, which do not rely on cloud-based intelligence to understand and act on spoken word commands, are an exceptionally promising approach to home-automation control. They are evolving on several fronts.

http://www.mwrf.com/systems/will-gesture-sensing-drive-home-automation

The Speed of Light is Not Fast Enough

If the speed of light is 186,363 miles per second, and it takes a radio signal 19.5 hours to go from transmitter to receiver, what is the distance between the transmitter and receiver? The answer is 13,082,682,600 miles. Yes, about 13 billion miles, give or take a few million miles rounding error. That's about how far away the Voyager 1 spacecraft is from Earth.

http://www.mwrf.com/community/speed-light-not-fast-enough

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Editorial

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COMSOL Previews New Multiphysics Software Features

Held last month in Boston, the COMSOL Conference 2017 featured keynote sessions, a large number of mini-courses, and many user presentations. Those in attendance represented a wide range of disciplines, demonstrating the large scope of COMSOL's software.

At the conference, the company announced the upcoming release of the latest version of its multiphysics software, COMSOL Multiphysics 5.3a. The new release will include a number of features that are sure to benefit those in the RF/microwave industry who are currently—or perhaps considering—using COMSOL Multiphysics. Version 5.3a is scheduled to be released before the end of 2017.

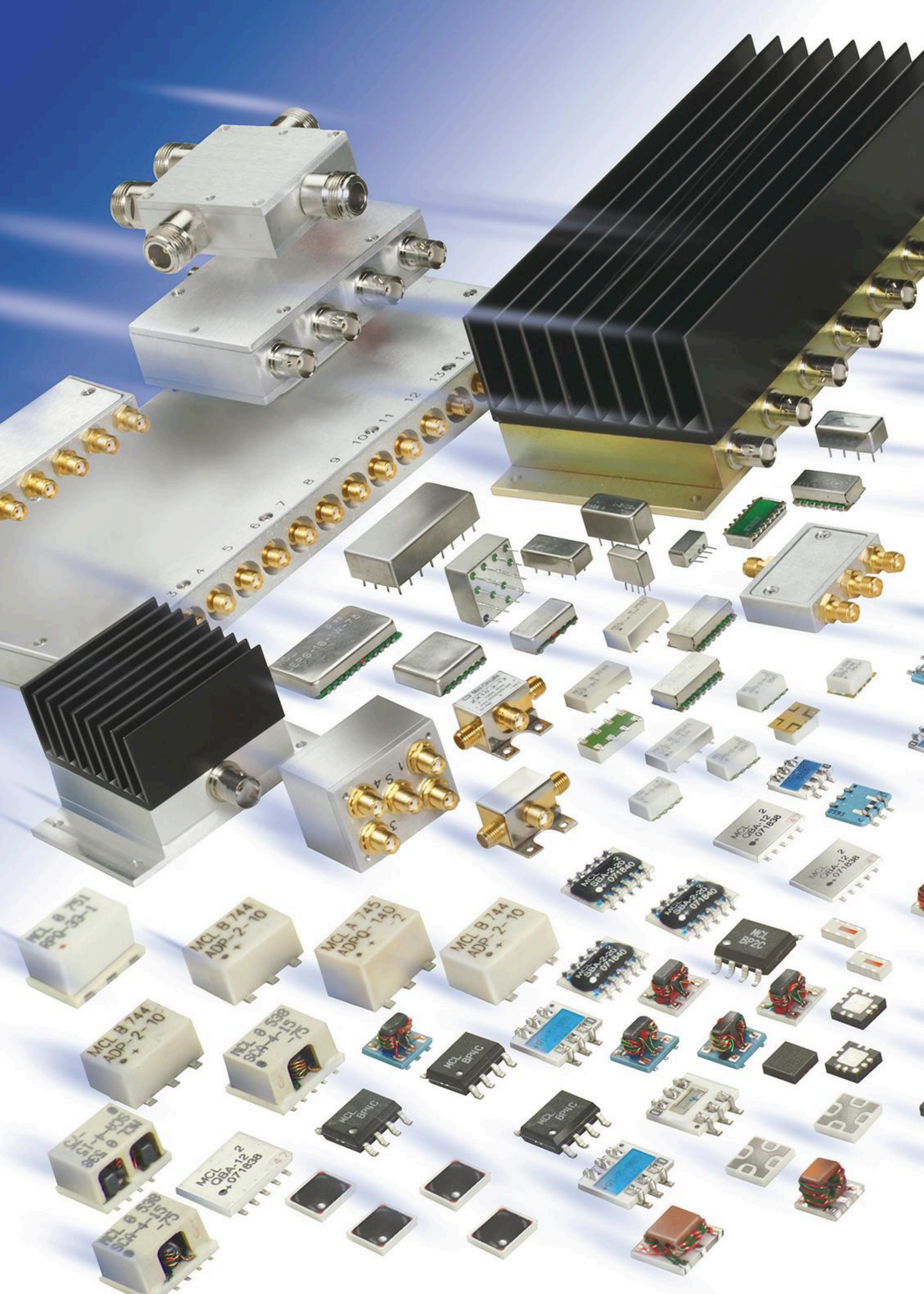
One notable update of this latest version is the addition of more than 60 substrate materials to the material library. Users will be able to choose from a large number of Rogers substrates that are now included in the software. Previously, a designer would need to select a blank material and then manually enter the material properties. The addition of these substrates eliminates the need to manually enter the properties for these particular ones. In addition, more substrates are expected to be added to the library in the future.

The addition of the new substrate materials isn't the only update. RF/microwave engineers can also look forward to a new Adaptive Frequency Sweep. This capability will allow users to compute the frequency response of a linear model more efficiently while using a very fine frequency resolution with the asymptotic waveform evaluation (AWE)—a reduced-order modeling technique.

In addition, the release of COMSOL 5.3 earlier this year introduced a new RF parts library (not to be confused with the material library). Version 5.3a will update the RF parts library by including edge-launch connectors from Signal Microwave *(www.signalmicrowave.com)*. These connectors assist in modeling RF components that support high-speed connections and high data rates.

As mentioned earlier, the conference featured a number of mini-courses. One of particular interest to RF/microwave engineers was titled "Electromagnetics: Wave Electromagnetics, from RF to Optical." The mini-course discussed some of the latest updates to the RF Module add-on, as well as various tips and tricks. One specific topic focused on how the RF Module can allow bandpass-filter-type devices to be modeled faster. Another mini-course pertinent to RF/microwave engineering was a hands-on electromagnetics session.

Anyone interested in learning how to model these applications can contact COMSOL for a live demo. In addition, the COMSOL blog *(https://www.comsol.com/blogs/)* contains a number of useful posts. mw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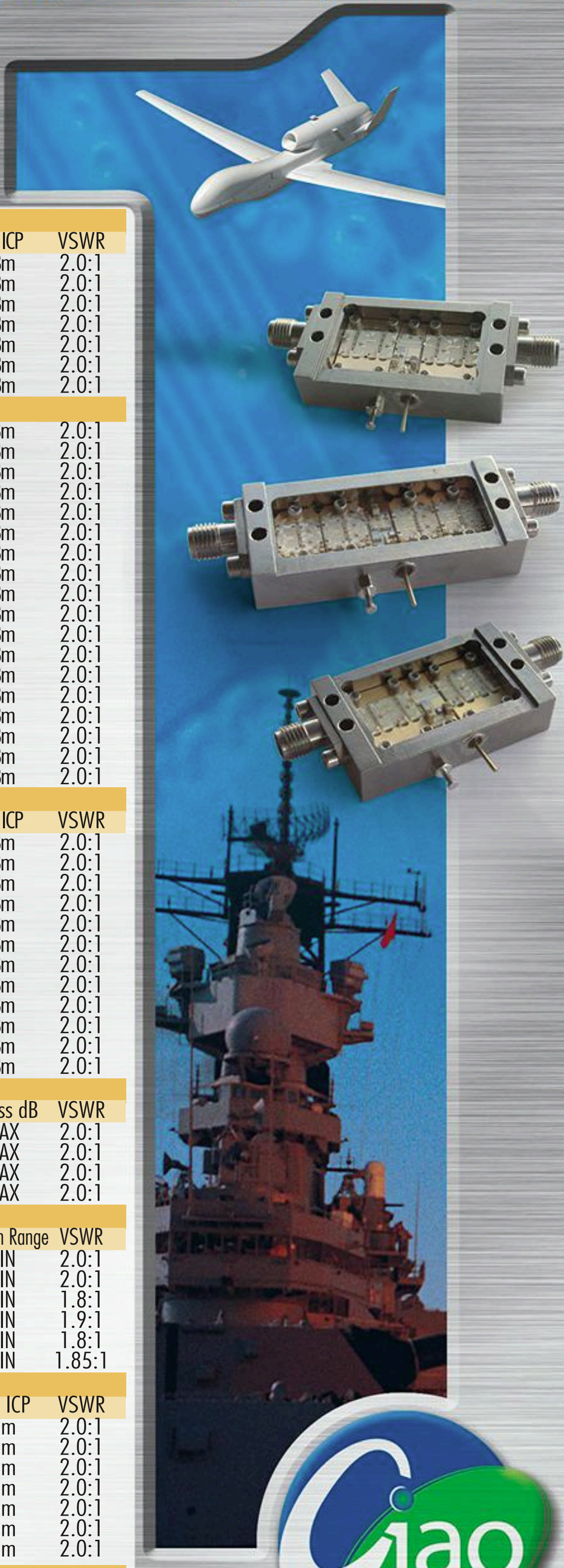

OCTAVE BAND LOW NOISE AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2110	0.5-1.0	28	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	12.0-18.0	25	1.9 MAX, 1.7 TYP	+10 MIN	+20 dBm	2.0:1
CA1826-2110	18.0-26.5	32	3.0 MAX, 2.5 TYP	+10 MIN	+20 dBm	2.0:1

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2111	0.4 - 0.5	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA01-2113	0.8 - 1.0	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3117	1.2 - 1.6	25	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3111	2.2 - 2.4	30	0.6 MAX, 0.45 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3116	2.7 - 2.9	29	0.7 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA34-2110	3.7 - 4.2	28	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA56-3110	5.4 - 5.9	40	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA78-4110	7.25 - 7.75	32	1.2 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA910-3110	9.0 - 10.6	25	1.4 MAX, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA1315-3110	13.75 - 15.4	25	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3114	1.35 - 1.85	30	4.0 MAX, 3.0 TYP	+33 MIN	+41 dBm	2.0:1
CA34-6116	3.1 - 3.5	40	4.5 MAX, 3.5 TYP	+35 MIN	+43 dBm	2.0:1
CA56-5114	5.9 - 6.4	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6115	8.0 - 12.0	30	4.5 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6116	8.0 - 12.0	30	5.0 MAX, 4.0 TYP	+33 MIN	+41 dBm	2.0:1
CA1213-7110	12.2 - 13.25	28	6.0 MAX, 5.5 TYP	+33 MIN	+42 dBm	2.0:1
CA1415-7110	14.0 - 15.0	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA1722-4110	17.0 - 22.0	25	3.5 MAX, 2.8 TYP	+21 MIN	+31 dBm	2.0:1

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA0102-3111	0.1-2.0	28	1.6 Max, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA0106-3111	0.1-6.0	28	1.9 Max, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-3110	0.1-8.0	26	2.2 Max, 1.8 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-4112	0.1-8.0	32	3.0 MAX, 1.8 TYP	+22 MIN	+32 dBm	2.0:1
CA02-3112	0.5-2.0	36	4.5 MAX, 2.5 TYP	+30 MIN	+40 dBm	2.0:1
CA26-3110	2.0-6.0	26	2.0 MAX, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA26-4114	2.0-6.0	22	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA618-4112	6.0-18.0	25	5.0 MAX, 3.5 TYP	+23 MIN	+33 dBm	2.0:1
CA618-6114	6.0-18.0	35	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA218-4116	2.0-18.0	30	3.5 MAX, 2.8 TYP	+10 MIN	+20 dBm	2.0:1
CA218-4110	2.0-18.0	30	5.0 MAX, 3.5 TYP	+20 MIN	+30 dBm	2.0:1
CA218-4112	2.0-18.0	29	5.0 MAX, 3.5 TYP	+24 MIN	+34 dBm	2.0:1

LIMITING AMPLIFIERS

Model No.	Freq (GHz)	Input Dynamic Range	Output Power Range Psat	Power Flatness dB	VSWR
CLA24-4001	2.0 - 4.0	-28 to +10 dBm	+7 to +11 dBm	+/- 1.5 MAX	2.0:1
CLA26-8001	2.0 - 6.0	-50 to +20 dBm	+14 to +18 dBm	+/- 1.5 MAX	2.0:1
CLA712-5001	7.0 - 12.4	-21 to +10 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1
CLA618-1201	6.0 - 18.0	-50 to +20 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	Gain Attenuation Range	VSWR
CA001-2511A	0.025-0.150	21	5.0 MAX, 3.5 TYP	+12 MIN	30 dB MIN	2.0:1
CA05-3110A	0.5-5.5	23	2.5 MAX, 1.5 TYP	+18 MIN	20 dB MIN	2.0:1
CA56-3110A	5.85-6.425	28	2.5 MAX, 1.5 TYP	+16 MIN	22 dB MIN	1.8:1
CA612-4110A	6.0-12.0	24	2.5 MAX, 1.5 TYP	+12 MIN	15 dB MIN	1.9:1
CA1315-4110A	13.75-15.4	25	2.2 MAX, 1.6 TYP	+16 MIN	20 dB MIN	1.8:1
CA1518-4110A	15.0-18.0	30	3.0 MAX, 2.0 TYP	+18 MIN	20 dB MIN	1.85:1

LOW FREQUENCY AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure dB	Power-out @ P1-dB	3rd Order ICP	VSWR
CA001-2110	0.01-0.10	18	4.0 MAX, 2.2 TYP	+10 MIN	+20 dBm	2.0:1
CA001-2211	0.04-0.15	24	3.5 MAX, 2.2 TYP	+13 MIN	+23 dBm	2.0:1
CA001-2215	0.04-0.15	23	4.0 MAX, 2.2 TYP	+23 MIN	+33 dBm	2.0:1
CA001-3113	0.01-1.0	28	4.0 MAX, 2.8 TYP	+17 MIN	+27 dBm	2.0:1
CA002-3114	0.01-2.0	27	4.0 MAX, 2.8 TYP	+20 MIN	+30 dBm	2.0:1
CA003-3116	0.01-3.0	18	4.0 MAX, 2.8 TYP	+25 MIN	+35 dBm	2.0:1
CA004-3112	0.01-4.0	32	4.0 MAX, 2.8 TYP	+15 MIN	+25 dBm	2.0:1

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Book Review

JACK BROWNE | Technical Contributor

Amplifiers Give Defense Systems a Boost

AMPLIFIERS ARE ESSENTIAL components in defense systems, whether to send radio signals or to energize the pulses needed for radar and electronic-warfare (EW) systems. Amplifier designers chase a somewhat elusive goal of trying to squeeze the highest efficiency possible from their designs, whether using vacuum tubes such as traveling-wave tubes (TWTs) or the latest gallium nitride (GaN) high-power solid-state transistors. For system-level specifiers, making an intelligent choice in a high-power amplifier (HPA) for a defense system benefits from having a solid basic education on the different types of HPAs and amplifier technologies currently available and a great deal of that information can be found in a digital e-book sponsored by MACOM, “Amplifiers Give Defense Systems a Boost” *(http://pages.mwrf.com/focus-on-defense-amplifiers-give-defense-systems-boost-confirm).*

The e-book is highly focused on defense-related applications rather than commercial wireless communications systems. It covers the types of topics expected for military electronic systems, including the differences between amplifiers processing continuous-wave (CW) and pulsed signals, how solid-state and vacuum-tube amplifiers differ, and an essential exploration of the meaning of amplifier linearity and the type of defense-related applications where it is of extreme importance.

Admittedly, there are many different types of amplifiers that are used within defense-based electronic systems and this e-book is focused only on RF/microwave amplifiers, in both solid-state and tube forms. It does not cover audio amplifiers or any of the more exotic amplifiers involved in capturing and detecting short-duration signals, such as successive-detection log-video amplifiers (SDLVAs). But what it does cover regarding RF/microwave amplifiers is an understanding of achieving high gain and efficiency over the typically broad bandwidths found in EW and electronic-counter-measures (ECM) systems. It reviews the particularly challenging operating conditions in military systems, such as wide temperature ranges, shock, vibration, and humidity, and how both tube and solid-state amplifiers can be designed to maintain consistent performance even when thrust into the most hostile operating conditions.

The e-book serves as an excellent starting point for defense system integrators wanting to know more about the current state of RF/microwave power amplifiers. mw

News

METAWAVE AIMS TO MAKE
Automotive Radar More Perceptive

Metawave was founded this past summer to create digital eyes that can discriminate objects and map the surroundings of autonomous cars. The company, which recently raised $7 million in its first funding round, plans to do that with a new type of radar.

The company says that its synthetic aperture radar will be capable of electronically steering signals in narrow beams, using control software embedded in a circuit board. This is possible because the radar's antenna is fabricated out of metamaterials, which exploit tiny repeating structures to bend radio waves in unnatural ways.

Metawave is also trying to improve the intelligence of radar, which normally only identifies location and speed. The radar will apply deep learning algorithms to infer the size and shape of objects, enabling it to discriminate a pedestrian, for example, from another car on the road. This way, the radar sends cleaner data to central processors, which can make quicker decisions about avoiding obstacles.

Metawave was started in August by chief executive Maha Achour, an electrical engineer who previously formed Rayspan, which went out of business trying to sell metamaterial antennas for smartphones. The other founder is chief technology officer Bernard Casse, a former manager at the Palo Alto Research Center (PARC), which Metawave spun out of.

In the future, autonomous cars will employ a wide array of sensors—including cameras, radar, and lidar—to provide redundancy. Cameras struggle at night and in rainy weather, while lidar has limited range and can interfere with other lidar on the road. Radar can compensate for these shortcomings, while other sensors compensate for the gaps in radar, which normally have low resolution.

"The auto industry has gone through cycles to find the best camera and the best lidar, and now it's the radar era—time to find the best and smartest radar platform," Casse said in a statement about Metawave's funding. The company is now looking to hire engineers. It has not said when it could release a final product.

Metawave is not alone in trying to give radar both tracking and mapping capabilities. Echodyne, which has raised $44 million from investors including Microsoft founder Bill Gates, is applying its metamaterials expertise to create short-range automotive radar. The company has not said when it will be released.

Oculii has built radar sensors that position other cars on the road in three dimensions, while Oryx Vision has raised $67 million for its coherent optical radar, which uses lasers to illuminate the road and measures the reflected signals to locate objects. The sensor resembles radar almost more than lidar because it treats the reflected light as a wave, not a particle.

Among the investors in Metawave's fundraising were Khosla Ventures, Motus Ventures, and Thyra Global Management. Further out, the firm plans to tune the same metamaterials and algorithms for wireless antennas, which could connect cars to 5G networks. ■

—James Morra, Associate Editor

ANTENNA SUPPLIER TAOGLAS Expands into Wireless Filters

TAOGLAS ANNOUNCED THAT it had created a new business unit selling wireless filters, which tune into specific frequency bands used in cellular communications and global positioning systems and block out interference from others.

The company, which sells embedded antennas for everything from wearables to connected cars, has manufactured these parts internally for years. But now, Taoglas is trying to sell inexpensive filters to others. The parts are typically paired with amplifiers and switches in wireless front ends, which hand off signals between radios and antennas.

"We've seen the frustrations our own engineers have had in quickly sourcing reliable components for active antenna and electronic designs," said Dermot O'Shea, the company's chief executive, in a statement.

Other firms are pouring money into wireless filters, which are growing in importance as more frequency bands are enlisted for wireless communications. Last year, Skyworks paid $225 million for Panasonic's wireless filter business, including patents. For the next year and a half, Qualcomm will continue making payments as part of a $3 billion deal for TDK's filter division.

Taoglas will sell ceramic, surface acoustic wave, and coaxial filters for Internet of Things applications using unlicensed spectrum or satellite navigation systems using GNSS and GPS. "Today's mobile and IoT applications require high-performance RF filters, in a form factor and cost that makes sense for our customers," O'Shea said. ■

—James Morra

INTEGRA BUYS CORWIL to Expand Chip Assembly and Testing

INTEGRA TECHNOLOGY SAID that it had acquired Corwil, moving into die prep and assembly for high-reliability chips used in satellites, medical gadgets, and factories. Integra is already in the business of semiconductor testing and qualification for the same applications.

The company, based out of Wichita, Kansas, said that the recent deal made it a "single point of contact" for preparing dies and assembling circuits, as well as qualifying, characterizing, probing, and testing for potential failures in radio frequency and other types of chips.

Integra also performs tests to cull out counterfeits, which are usually older chips remarked to appear newer than they are. These chips not only pose a threat to sensitive medical and aerospace electronics, but also cut into business. Last year, the Semiconductor Industry Association said that counterfeit chips cost the U.S. chipmakers an estimated $7.5 billion.

Both Integra and Corwil operate as halfway houses on the fringes of the chip industry, readying chips for market after they leave factories. Brett Robinson, Integra's chief executive, said that the deal would give customers a more complete suite of semiconductor amenities.

Robinson said that the acquisition "provides our mutual customers with one of the largest U.S.-based semiconductor die prep, assembly and test offerings in the industry." Integra did say how much it paid for Corwil.

Integra appears to be keeping its hands off the business. Founded in 1990, Corwil will continue to operate out of Milpitas with the same employees, management team, and products. Before the sale, Corwil had been owned by private equity firm Tonka Bay Equity Partners, based in Minnetonka, Minnesota. ■

—James Morra

QUALCOMM TESTS FIRST 5G Silicon Specimen

QUALCOMM ANNOUNCED ITS first 5G cellular modem almost four years before a final standard was scheduled to be published. It could still have to edit the chip to suit the standard, which is targeting everything from cars to smartphones to sensors.

But in October, the company teased test results of the silicon specimen, which it wants inside smartphones within the next two years. The modem shuttled 1.2 gigabits per second in tests at Qualcomm's labs in San Diego. The final product will provide 5 gigabits per second, making it around 20 times faster than the latest 4G silicon.

The X50 modem conveyed data using the 28 gigahertz band, which in the future could handle spillover from lower bands traditionally used in cellular networks. But wireless firms are still probing for ways to compensate for millimeter wave's energy loss over long distances and tendency to bounce off walls, which could hurt Qualcomm's modem in the real world.

Dimitris Mavrakis, research director for ABI Research, said that the results came "three months before the official 3GPP standard is frozen, however it is possible that Qualcomm's announcement will skew the market and the standards discussion in its favor. It certainly has the potential to kick start the next round of discussion that will lead to commercial 5G."

Qualcomm recently lobbied to trim six months from the wireless industry's 2020 timetable. In August, Qualcomm principal engineer Wanshi Chen replaced another Qualcomm employee Dino Flore as chairman of the 3GPP radio access network group, which is scrambling to complete a draft of the standard before the end of the year.

In a separate announcement, Qualcomm also previewed a reference manual so that companies can integrate the X50 modem into smartphones and other gadgets. That could gird Qualcomm against competitors like Intel, which has also built a 5G prototype, and Mediatek, which has assigned more than a hundred engineers exclusively to 5G.

The new modem could also give Qualcomm a facelift after protracted legal battles over patent licensing fees with Apple, which has signaled that it may create a custom modem for its smartphones. In May, Apple poached Esin Terzioglu, who for the last nine years was in charge of Qualcomm's wireless modems at the heart of the recent lawsuits. ■

—James Morra

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LASER DUNE BUGGY Battles Armed UAVs

UNMANNED AERIAL VEHICLES (UAVS) have become commonplace as battlefield "birds of prey," equipped for offensive maneuvers. Because they represent relatively low-cost weapons, suitable defensive measures should also be cost-effective, and the high-energy lasers (HELs) have proven to be quite capable in defending against armed UAVs. Raytheon Co. is working on bringing these defensive laser-based systems where needed, having developed low-cost dune buggies equipped with HELs that can combat rugged desert terrain *(see photo)*.

"Basically, we're putting a laser on a dune buggy to knock drones out of the sky," explains Dr. Ben Allison, director of the company's high energy laser product line, who works on Raytheon's campus in McKinney, Tex. The job requires a bit more than simply bolting down a laser system into a ground vehicle, since the HEL must be combined with a variation of Raytheon's Multi-spectral Targeting System infrared (IR) and electro-optical sensors, and with everything installed on a Polaris MRZR all-terrain vehicle—the aforementioned dune buggy.

Allison's efforts were motivated by a report from Raytheon Chairman and CEO Tom Kennedy about an allied nation's use of a Patriot missile to shoot down a low-cost drone equipped with grenade type munitions, as well as the need for a cheaper means to shoot down armed drones. Allison sought to use Raytheon's existing resources to develop a more cost-effective counter-UAV defense system than a Patriot missile, and without having to perform an extended amount of research to achieve the solution. By combining the HELs with the multiple sensors on an all-terrain vehicle, the defensive system provides the necessary power and the mobility needed to defense against UAVs. It can run on stored charge from 220 VAC or be equipped to run on a generator on board the all-terrain vehicle. ■

—Jack Browne, Contributing Editor

USAF RETURNS TO LOCKHEED MARTIN for Laser-Guided Bombs

THE U.S. AIR FORCE has awarded Lockheed Martin a $131 million contract for follow-on production of Paveway II Plus Laser Guided Bomb (LGB) kits, the ninth consecutive year in which it has selected Lockheed Martin for the majority share of the LGB kits in this annual competition. The award also includes all available funding for the service's foreign military sales and replacement kits.

"The U.S. Air Force and its foreign military sales partners realize significant savings in their defense budgets with our affordable and combat-proven LGBs," says Joe Serra, Precision Guided Systems director at Lockheed Martin Missiles and Fire Control. "This innovative and cost-effective guidance package supports greater precision for warfighters."

Paveway II Plus includes an enhanced guidance package that improves accuracy over legacy LGBs. Qualified for full and unrestricted operational employment in GBU-10, GBU-12, and GBU-16 (1,000-lb) configurations, Paveway II Plus LGBs are cleared for use on U.S. Air Force, U.S. Navy, and international aircraft authorized to carry and release LGBs. Lockheed Martin, which has been a qualified supplier of Paveway II LGB kits since 2001, has delivered more than 100,000 LGB kits to date. The LGB kits are produced in the firm's 350,000 ft.2 production facility in Archbald, Pa. ■

—Jack Browne

TESTING INTEGRATED MM-Wave Antennas

MILLIMETER-WAVE FREQUENCIES represent tremendous available bandwidth for short-range communications, notably in emerging 5G wireless networks. To enable such communications, compact (mainly integrated) antennas will be needed, and they will require testing at those high frequencies. Many of these antennas will be in the form of monolithic microwave integrated circuits (MMICs), posing new sets of challenges for engineers faced with measuring the performance levels of these integrated antennas.

In search of solutions, several researchers from the Institute of Microwave Engineering at Germany's Ulm University reviewed some of the challenges in measuring three-dimensional (3D) electromagnetic (EM) fields of on-chip antennas, including the presence of a wafer probe near the fields. Their proposed test system enables measurements of the radiation patterns of integrated antennas at frequencies as high as 280 GHz.

Challenges facing the researchers in developing their measurement system stemmed from the small wavelengths (about 1 mm) of the signals under test. The slightest changes in antenna under test (AUT) and/or probe position will result in phase and amplitude measurement errors. The presence of wafer probes causes reflections in far-field antenna radiation measurements and results in limited scanning areas for near-field radiation measurements. Even bending and movement of test cables can result in changes in test results at millimeter-wave frequencies.

As a solution for positional stability and resolution, a robotic arm was used to control the receive antenna as well as an on-wafer probe for measurements on integrated antennas. The robotic arm works with a vector network analyzer (VNA) and system computer, with the computer coordinating the required positioning data and VNA tuning for each measurement.

The test system is capable of on-the-fly measurements (while an AUT and receive antenna are moving) as well as point-to-point measurements, where the robotic arm moves an AUT to different points along a programmed test path and the VNA is triggered to make measurements at each stopped position. The VNA is equipped with appropriate frequency-converter modules to cover the millimeter-wave frequency band of interest.

The measurement system was used to perform measurements as high as 280 GHz with a horn antenna as the AUT. The robotic control arm provide six degrees of freedom, featuring 350 μm positioning accuracy and 50-μm repeatability. Alignment of the receive AUT can be performed with the aid of a laser range finder. Measurements of the horn antenna at 280 GHz agreed closely with computer simulations. The researchers performed a thorough uncertainty analysis of the measurement system, with calculated measurement uncertainties of less than 0.3 dB—impressive for the frequencies under test.

See "The Challenges of Measuring Integrated Antennas at Millimeter-Wave Frequencies," *IEEE Antennas & Propagation Magazine,* Vol. 59, No. 4, August 2017, p. 84.

ORTHOGONAL BEAMFORMING Serves Multiple Users

WIRELESS COMMUNICATIONS NETWORKS must handle ever-increasing numbers of users with growing demands for bandwidth in the form of transmitted and received voice, video, and data. Conventionally, base stations can transmit data to a number of users at the same frequency at the same time by using a feedback channel, although this adds to the complexity of the communications channel and system.

However, by using multiple antenna elements to create a number of beams in predefined directions at the same time and the same frequency, and keeping the beams orthogonal to one another—using a process known as orthogonal beamforming (OBFM)—it is possible to communicate large amounts of information to multiple users at the same time, with minimal interference among the users.

Various methods are used to support multiple users on the same frequency, including multiple-input, multiple-output (MIMO) techniques and several forms of beamforming approaches, but often a feedback channel is required to minimize interference among the different beams. However, by making use of beam direction-of-arrival (DOA) information, it is possible to use multiple beams at the same frequency while also minimizing interference and delivering excellent bit-error-rate (BER) performance.

Researchers from the School of Telecommunication Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand propose a system model in which multiple users are operating at the same frequency with a single antenna element. In their design, however, the wireless basestation uses multiple linearly aligned antenna elements to differentiate the different signal vectors of the received beams, including multipath signals from users.

Using simulations of beam patterns at 30, 60, 90, and 120 deg. with an experimental signal-processing algorithm developed with MATLAB mathematical software from MathWorks (www.mathworks.com), high gain was achieved with the main beams with strong suppression of sidelobes, resulting in high signal-to-interference-plus-noise ratio (SINR). The OBFM approach shows great promise for achieving high data throughput with multiple wireless users, provided that DOA estimation errors for the multiple beams can be minimized (through the use of effective DOA algorithms).

See "Orthogonal Beamforming for Multiuser Wireless Communications," *IEEE Antennas & Propagation Magazine,* Vol. 59, No. 4, August 2017, p. 39.

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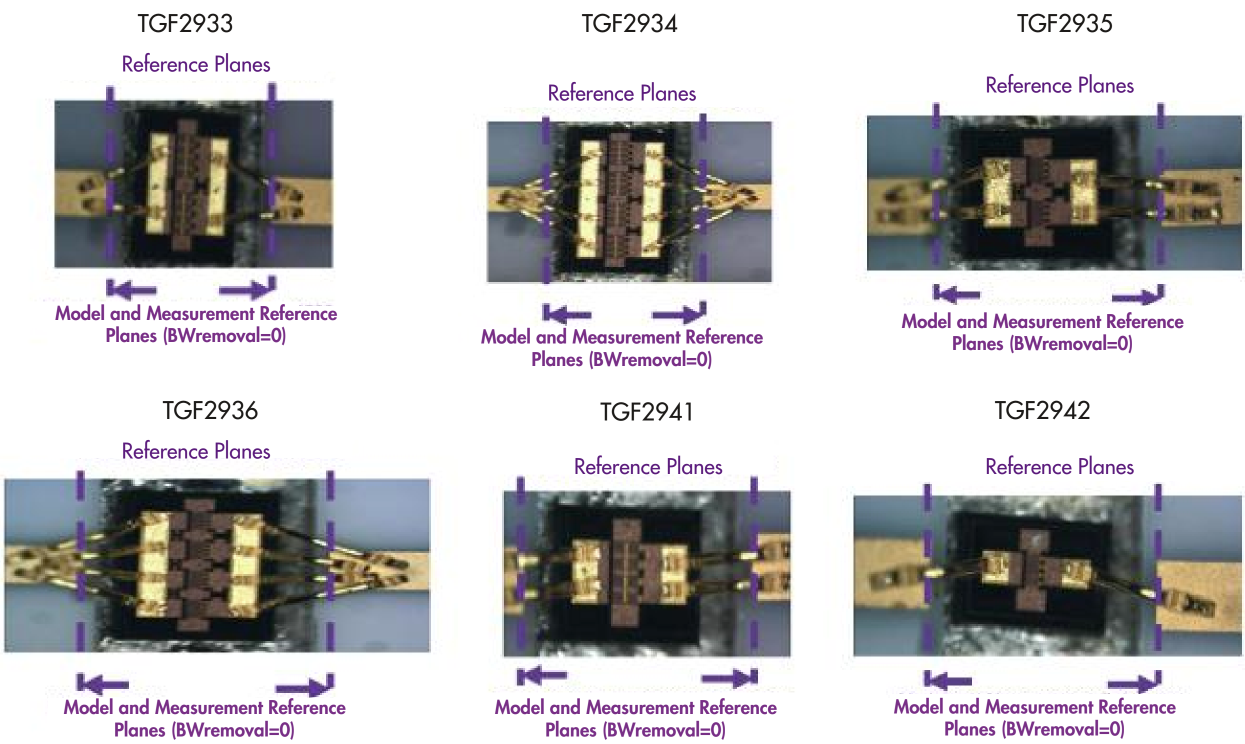
Advanced Nonlinear and Noise Modeling of High-Frequency GaN Devices

A feature-rich set of simulation models enables high-frequency PA and LNA design for a 0.15-µm GaN die family.

Gallium-nitride (GaN) technology has been rapidly growing as the material of choice for HEMT devices in the RF/microwave industry due to its high-efficiency operation and its specific properties being ideal for high-frequency and high-power applications. GaN technology has also proven applicable for high-frequency, low-noise receiver circuitry. More recent processes in GaN transistor development have used shorter gate lengths to address increasing opportunities for use in designs at 10 GHz and above.

This expanding utilization of GaN technology has led to demand for highly accurate, nonlinear advanced models that are effective for electronic design of various modes of high-efficiency power amplifiers (PAs), as well as low-noise applications. This article focuses on the features and capabilities of a set of advanced models for Qorvo's 0.15-µm GaN die devices for both nonlinear and low-noise high-frequency designs.[1]



1. Shown are images of Qorvo GaN15 discrete die transistors. Model and measurement reference planes are indicated (BWremoval feature = 0; bond wire effect included in model)

QORVO GAN15 TECHNOLOGY

The Qorvo GaN 15 (QGaN15) process is shorter gate length technology capable of supporting applications through 40 GHz, as compared to QGaN25 (for applications to 18 GHz) and QGaN50 (for applications to 10 GHz).[2] The process uses AlGaN/GaN epitaxial layers grown on high thermal conductivity silicon-carbide (SiC) substrate. Performance parameters of the QGaN manufacturing technology include maximum currents of 1.15 A/mm and maximum frequency of oscillation (f_{max}) as high as 160 GHz,[3] with nominal operating voltage of 28 V.

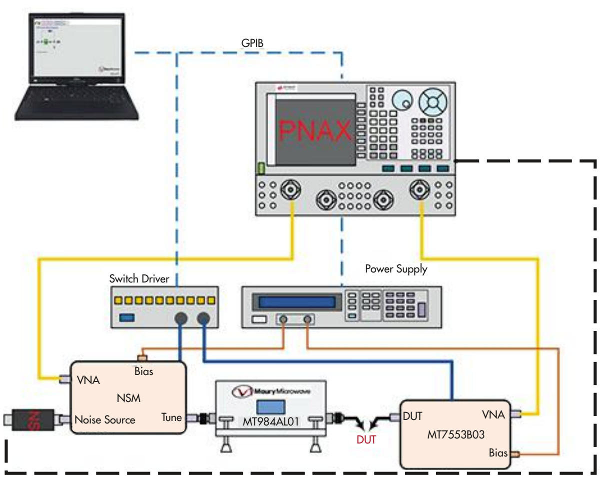
Models for six of the many transistor devices available from Qorvo are now included in the Modelithics Qorvo GaN Library.[4] These are the TGF2933, TGF2934, TGF2935, TGF2936, TGF2941, and TGF2942 *(Fig. 1)*. Two model versions were developed for each of the six discrete die transistors, a small-signal/noise model and a nonlinear model. The small-signal/noise model provides for highest linear and noise simulation accuracy in comparison with the small-signal simulations of the nonlinear models. However, for these die, the nonlinear models also provide good predictions of small-signal S-parameters and noise parameters if designers happen to prefer to use the same model for both linear and nonlinear simulations.

SMALL-SIGNAL/NOISE GAN HEMT MODEL VERSIONS

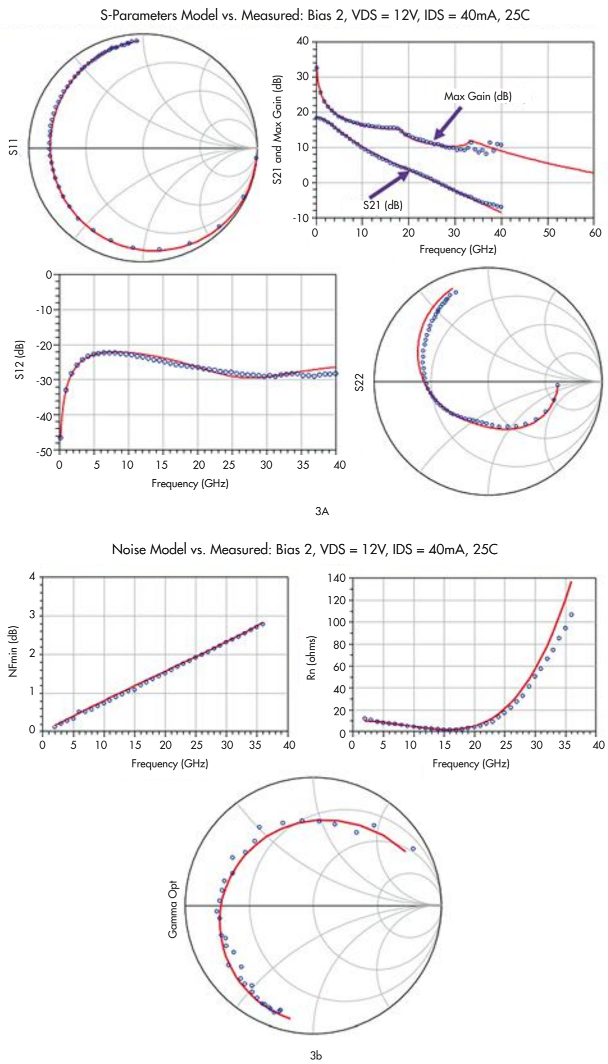
The small-signal transistor models are optimized for broadband S-parameters and noise at specific operating bias conditions. These models offer slightly enhanced model-to-measured accuracy for the small signal simulation, which is of primary importance in low-noise amplifier (LNA)/receiver applications. In such applications, the use of a GaN device may be preferred due to tolerance to large-signal inputs (therefore eliminating the need for limiter circuitry) and/or linearity requirements.

Precision broadband measurements from two test bench configurations were used to validate the small-signal model version. A multi-bias S-parameter test bench was used that consisted of a vector network analyzer (VNA) along with bias tees, bias voltage source, RF wafer probe station, and a PC. Measurement calibration software was used that enabled efficient bias sweeps along with multi-line TRL calibration with custom microstrip standards.

The noise parameter testing bench consisted of a Keysight PNA-X VNA, noise source, biasing equipment, Maury tuner, noise receiver module, switch box, and power distribution hub *(Fig. 2)*. This system, which is capable of noise parameter characterization to 50 GHz, was used for noise modeling of the QGaN15 transistors to 36 GHz. *Figure 3* shows the model-to-measurement accuracy of the TGF2942 small-signal model.



2. Shown is a block diagram of the Maury Microwave-/Keysight Technologies-enabled noise parameter setup.



3. This figure illustrates the 0.2-to-40 GHz S-parameter (a) and 2-to-36 GHz noise model (b) performance for the TGF2942 small-signal model (HMT-QOR-TGF2942-SS-001). The parameters are as follows: Vds = 12 V, Ids = 40 mA, 25°C, 50-Ω Smith charts. The solid red lines represent model data, while the blue circles represent measured data.

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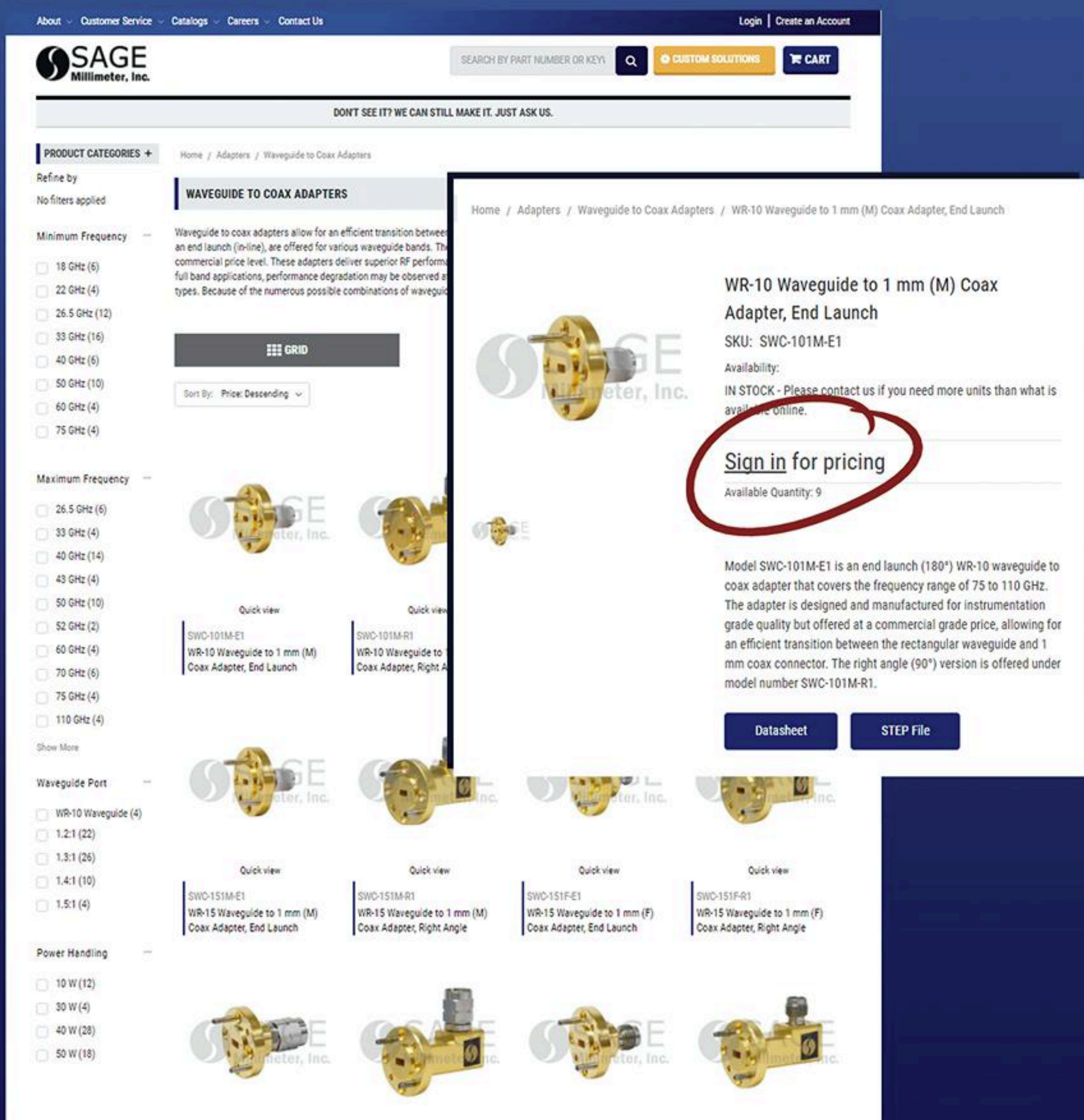

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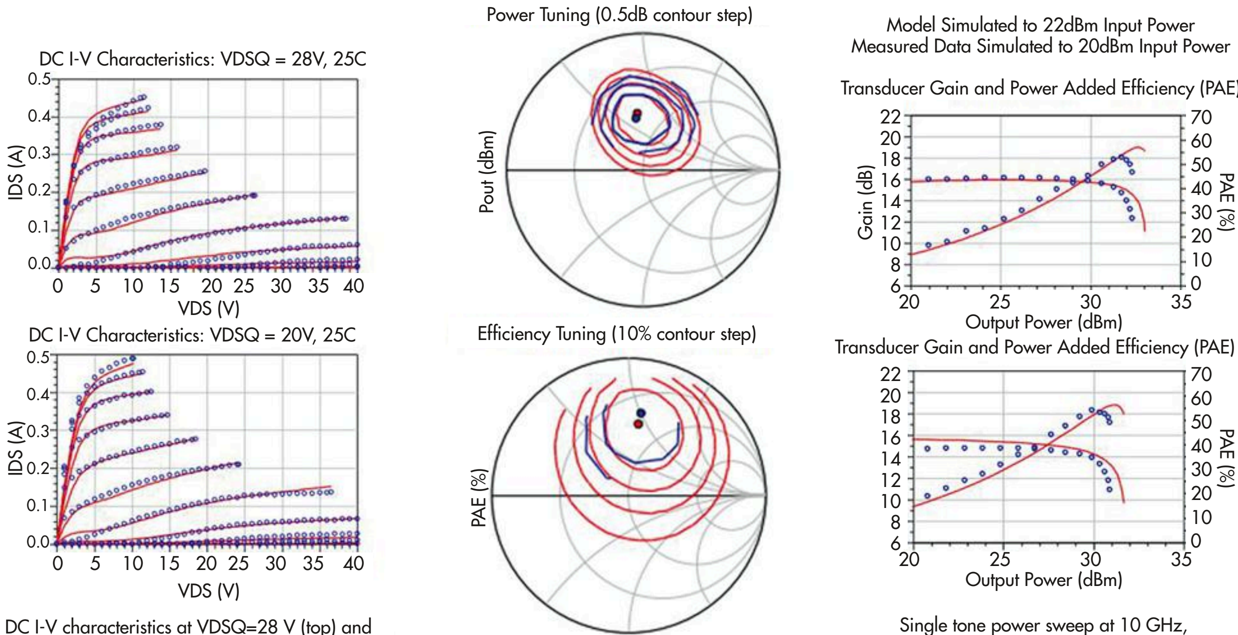

DC I-V characteristics at VDSQ=28 V (top) and VDSQ=20 V (bottom). Vgs varies from -1 to 4 V with 0.25 V steps. Vds varies from 0 to 40 V with 1 V steps.

Load pull validation at 10 GHz, Vds=20 V, Ids=20 mA, Input power=18 dBm, Z0=50Ω center, 25C. Pulsed bias conditions, duty cycle=10%, pulse length=100 μs.

Single tone power sweep at 10 GHz, Vds=20 V, Ids=20 mA, 25C. Power tuned (top) and PAE tuned (bottom)

4. Shown are nonlinear model-to-measurement performance comparisons of the Qorvo TGF2942 GaN transistor model for I-V, load-pull, and power-sweep simulations. The red lines represent model data, while the blue circles represent measured data.

LARGE-SIGNAL GAN HEMT MODEL VERSIONS

The nonlinear model versions are developed using a Modelithics-modified Angelov model implemented with Verilog-A code. They are validated with the same S-parameters and noise measurements used for the small signal model, along with current-voltage (IV) and large-signal load-pull data. The models include additional simulation features, such as scalable V_{DSQ} range, temperature scalability, and self-heating effects. The large-signal model versions offer advanced intrinsic IV sensing for waveform optimization, making the models compatible with the latest design techniques for various classes of power amplifiers, such as Class A, AB, F, and J. *Figure 4* shows example non-linear model performance data.

SUMMARY

The use of GaN manufacturing technology is very effective and efficient for high-frequency transistor devices. The technology is advancing and the use of GaN in the RF/microwave industry is growing quickly. The availability of accurate models with advanced simulation features is very important to designers. Electronic design allows for cost-effective design optimization, but accurate models are a necessity to successful simulation.

ACKNOWLEDGEMENTS AND ADDITIONAL INFORMATION

This article expands upon a presentation delivered at the 2016 EDI CON conference held in September 2016 in Boston. The authors would like to thank Qorvo for collaboration related to this work as part of the Modelithics Vendor Partner (MVP) program, as well as Keysight Technologies and Maury Microwave for measurement solution collaboration.

A trial of the Modelithics Qorvo GaN Library for Keysight ADS and/or NI AWR Design Environment is available to approved designers and can be requested at *https://www.modelithics.com/mvp/qorvo*.

For designer convenience, an extensive collection of documentation and example workspaces related to the Modelithics Qorvo GaN device models is available. mw

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JACK BROWNE | Technical Contributor

Synthesizing Stable Microwave Signals

Signal generation is an essential function for transmitters and receivers, with analog and digital frequency synthesis methods used to create RF/microwave signals with high stability.

FREQUENCY SYNTHESIS HAS long represented a means of generating high-frequency signals that remain stable over time and temperature. At RF and microwave frequencies, many different synthesis techniques exist, based on analog and digital components and presenting many different tradeoffs in terms of size, cost, and performance, but the many different requirements for stable RF/microwave signals have justified the use of many different frequency synthesis methods, using both analog and digital approaches. Frequency synthesizers can range in size from tiny integrated circuits (ICs) to full rack-mountable electronic systems with modulation and other functions. As this first of a two-part article on frequency-synthesizer fundamentals will show, frequency synthesizers may vary widely in their frequency ranges and step sizes, but they share goals of attempting to generate precise, noise-free output signals as repeatedly as possible, even when operating under harsh conditions.

Microwave frequency synthesizers generally attempt to stabilize the phase of a high-frequency oscillator, such as a dielectric resonator oscillator (DRO), voltage-controlled oscillator (VCO), or yttrium-iron-garnet (YIG) oscillator, by locking it within one or two tuning loops to the phase of a lower-frequency reference oscillator, such as a temperature-compensated crystal oscillator (TCXO) or an oven-controlled crystal oscillator (OCXO). Phase noise is often a performance parameter of comparison for many frequency synthesizers, with many designs attempting to approach the stability of the thermal noise floor of -174 dBc/Hz at room temperature.

These analog frequency synthesizers employ some multiple of the reference frequency oscillator to compare the phase of the reference to that of the higher-frequency microwave oscillator. When an integer multiple of the reference oscillator's frequency is used for phase comparison, it is known as an integer-N phase lock loop (PLL) frequency synthesizer. When a fractional multiple of the reference oscillator's frequency is used, it is referred to as a fractional-N PLL frequency synthesizer. Single or dual loops can be used for phase comparison, with multiple loops providing greater overall phase stability but requiring longer settling times or frequency switching speeds.

Frequency synthesizers generate many of the signals used for transmission and reception in RF/microwave systems. Synthesizers can take on many forms and power requirements, as determined by the needs of a system, and can range in size from multiple-function integrated circuits (ICs) to instrument-sized rack-mount assemblies, complete with power-supply circuitry. As this first of a two-part article on frequency synthesizer fundamentals will show, frequency synthesizers may vary widely in their frequency ranges and step sizes, but they share goals of attempting to generate precise, noise-free output signals as repeatedly as possible, even when operating under harsh conditions.

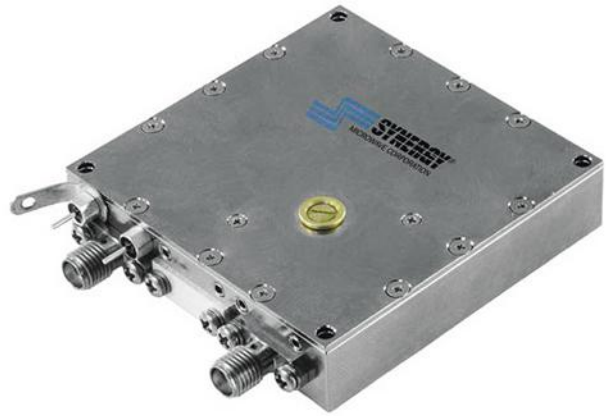
1. Modern analog frequency synthesizers can pack all required circuitry into a surface-mount-technology (SMT) package. *(Photo courtesy of EM Research)*

In one of the most popular realizations of analog frequency synthesizers, a PLL uses the low-noise characteristics of a reference oscillator to stabilize the phase of a higher-frequency tunable oscillator, such as a current-tuned YIG oscillator or a voltage-controlled oscillator (VCO). Phase-locked oscillators can also be produced for wide tuning ranges as well as for single, fixed frequencies, housed in miniature surface-mount-technology (SMT) packages measuring a fraction of an inch square with low power consumption for portable and battery-powered applications *(Fig. 1)*. They can also be as elaborate as rack-mountable instruments, complete with full modulation and programming capabilities. In addition to the use of PLL ICs and discrete components to implement analog frequency synthesizers, RF/microwave frequency synthesizers can be implemented with digital circuit approaches, taking advantage of high-speed digital components such as digital-to-analog-converters (DACs) to produce high-frequency signals with high resolution and low noise levels.

A PLL's phase detector is a critical component in the PLL circuitry, using feedback to synchronize the output frequency of the tunable oscillator to the input frequency of the reference oscillator, in effect locking the output phase of the higher-frequency oscillator to the input phase of the reference oscillator, which is usually a source that has been designed for high stability, such as an OCXO or a TCXO. By using a PLL feedback loop, the phase noise of the higher-frequency oscillator essentially becomes that of the lower-frequency reference oscillator.

The use of IC technology in realizing different portions of analog and digital PLL frequency synthesizers has helped to boost the performance and repeatability of these frequency sources while keeping sizes small. A recent advance by Synergy Microwave Corp. *(see Microwaves & RF, March 2015, p. 87)* in the development of an application-specific IC (ASIC) to enhance the performance of a line of PLL-based frequency synthesizers from 100 MHz to 15 GHz provides generous functionality and control that fits within 2.25 × 2.25 in. modules or 1.00 × 1.25 in. surface-mount-technology (SMT) packages because of the high circuit density of the ASIC *(Fig. 2)*.

In larger, instrument-grade housings *(Fig. 3)*, frequency synthesizers are combined with modulation capabilities to serve as test signal sources. All power supplies and required functionality are included in the instrument enclosure. Not all newer synthesized test sources require 19-in.-wide rack-mount enclosures, with compact frequency synthesizers such as the QuickSyn microwave synthesizers from National Instruments *(www.ni.com)* fitting within PXI instrument modules and combining a number of different frequency synthesis technologies to pack generous performance into small enclosures. The synthesizers can be provided across frequency ranges as wide as 0.5 to 10 GHz and 0.5 to 20 GHz, achieving low noise and fast switching speed at the same time. The VCO-based frequency synthesizers conserve power while achieving relatively fast switching speeds with low noise levels, leveraging DDS techniques for fast switching speeds even with frequency steps as small as 0.001 Hz.



2. The novel use of ASIC control circuitry enabled outstanding broadband PLL frequency performance in miniature surface-mount frequency synthesizers. *(Photo courtesy of Synergy Microwave Corp.)*

3. Instrument-grade frequency synthesizers include power supplies, switching functionality, and modulation sources to mimic system-level signal sources. *(Photo courtesy of Rohde & Schwarz)*

SETTING TARGET LEVELS

In addition to a target phase-noise level at a particular offset frequency from the carrier, an analog PLL frequency synthesizer can be designed with a number of different performance targets, including power consumption, switching speed, spurious and harmonic noise, and output power. The frequency tuning range of the frequency synthesizer will be dictated by the choice of tunable oscillator for the synthesizer, such as a dielectric-resonator oscillator (DRO), VCO or YIG-tuned oscillator.

Due to needs for higher levels of integration in many systems, PLL frequency synthesizers are increasingly implemented by means of digital circuits, such as integer-N or fractional-N PLL frequency synthesizers. In an integer-N PLL synthesizer, for example, the output of the VCO or other tunable oscillator is controlled by integer factor of multiplication of the reference oscillator to achieve the required output frequency. A digital counter structure is used to divide the fre-

(Continued on page 68)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Sensor Expectations Get Flipped Upside Down

The benefits of LoRa technology reach a wide range of applications—even a trampoline park.

WHEN YOU THINK about enterprise Internet of Things (IoT), what comes to mind? Industrial settings like factories, maybe? Mission-critical environments like data centers, perhaps? How about wireless sensors that measure pressure, vibration, and more on massive machinery and expensive equipment? It's unlikely that the first thing that would come to mind is a trampoline park full of kids who are bouncing, bouncing, bouncing, and then asking their parents if they saw that amazing flip they just executed to perfection.

What about LoRa networks? What comes to mind when you think about the way that LoRa technology is being used in IoT implementations? Chances are that you are envisioning remote locations where industrial equipment resides in far-off settings, where only the long-distance capabilities of LoRa would make sensor networks practical. Again, it's unlikely that you would envision LoRa-based networks in an urban fun center with adults and coworkers competing to do the farthest bounces from one trampoline to the next.

And yet, that is exactly what's happening at an expectations-busting IoT implementation at a Freedome trampoline park in the UK (*Fig. 1*). This project has significant implications for enterprise IoT overall because it opens up a new world for how low-power sensor networks with LoRa can be utilized.

THE IoT AND TRAMPOLINES

First, let's bring you up to speed on Freedome, which is a new concept for indoor trampoline parks from the company that invented the concept, Sky Zone. Freedome is an aerial freestyle park that combines trampolines with sports activities, physical challenges, digital technology, and a multimedia environment, creating a unique play experience for kids and adults alike.

Freedome uses technology in ways that have never been part of trampoline parks before, creating fun, digitally-driven challenges for participants while also creating a dynamic audio and visual experience. But the technology isn't just for visitors' entertainment. The use of technology also extends to Freedome's operational management. In particular, IoT sensors play a critical role in the way the company manages its day-to-day operations and supports its growth strategy.

Freedome wanted to use technology to ensure the safety of visitors while also learning as much as possible about which activities are the most fun. The company could then evolve the design and amplify the fun. Discussions then began with a company called Sensorstream that centered on how to use wireless sensors to address these needs. Sensorstream is a UK-based firm that is doing groundbreaking work in the deployment of IoT networks. Some key objectives came to the forefront:

- Ensure the safety of visitors by utilizing sensors to:
  1. Monitor that children do not accidentally go into restricted areas like underneath the trampolines, into employee-only areas, or other locations with safety concerns.
  2. Track that proper safety protocols are followed for maintenance and operations of all trampolines and other equipment.
- Enhance the design of the facility to deliver more of what visitors enjoy by:
  1. Learning which activities visitors utilize the most, monitoring for novel ways that visitors are enjoying the activities, and gathering other useful information about usage patterns.
  2. Then translating that business intelligence into actionable decisions about how to enhance the design of the facility.

Those last two objectives will likely resonate with anyone involved in enterprise and industrial IoT because they mirror two of the primary reasons why every company uses sensor networks: safety and operational efficiency/improvement. With those objectives in mind, the traditional prescription would have been to implement a short-range, low-power sensor network. However, Sensorstream went in a very different direction, and in doing so has opened up a new realm of applications for LoRa technology.

1. Freedome uses technology in ways that have never been part of trampoline parks before, creating fun, digitally driven challenges for participants while also creating a dynamic audio and visual experience.

FUNDAMENTALS OF LoRa

As context for readers who are less familiar with the technology, LoRa provides secure, bi-directional data transfer and communications with IoT networks over long distances, and over the course of years, without a battery change. It can send and receive signals up to 10 miles—and that distance can extend to hundreds of miles with additional gateways, if needed. LoRa is often referred to as a low-power wide-area-network (LPWAN).

LoRa nodes are also inexpensive, allowing companies to create a low-cost backhaul network that bypasses fiber or cell service. Thus, they are able to avoid the high cost of building fiber to a remote site or the cost of a cell contract. These costs can be expensive for the kind of connectivity an IoT deployment necessitates.

LoRa is also highly scalable and interoperable, and is compatible with both public and private networks for the data backhaul and bi-directional communications. One of its best qualities is the ability to perform in harsh RF environments with vibration, interference, extreme temperatures, etc. These conditions are quite common in industrial environments and remote locations where the elements can go to extremes.

The attribute of LoRa that typically gets the most attention is the long-distance capabilities, which make it ideal for remote installations that may be miles or hundreds of miles from traditional telecommunications infrastructure. While that is indeed a valuable attribute for geographically remote projects, LoRa has other attributes that give it a much broader set of applications (like the Freedome implementation in an urban setting). These attributes include:

- Remarkable power usage efficiency that makes them a very low maintenance option, requiring very infrequent battery changes.
- A low overall bill-of-materials (BOM) cost that makes it possible for organizations to implement a large number of sensors while still staying within a modest project budget.
- Simplicity of installation and connectivity, allowing a "stick-and-go" rollout rather than a complex, drawn-out process of installing the sensors and getting them properly networked.
- The ability to operate reliably in complex wireless environments, such as urban settings, where RF "noise," electrical interference, and physical objects create so many problems for other technologies.
- Ease of repeating these installations at other locations as the company expands in Europe and globally.
- And "baked-in" security that differentiates it from other IoT technologies, making it a good match for corporate security policies.

LoRa may not be the first technology that comes to mind for this type of application. However, attributes like its energy efficiency, near-immunity to interference, enterprise-grade security, and ease of implementation made it ideal for the Freedome project. Sensorstream's implementation used its rugged, stick-and-go Sensor Action Monitors and Action Links connected together with a Sensorstream Wide Area Network.

The devices are easily deployed without the need for complex RF expertise *(Fig. 2)*. They can be repositioned without difficulty to monitor new areas as needed. The sensors and WAN utilize Laird's Sentrius RM1xx LoRa + BLE module as a foundational technology. LoRa works well as a complement for BLE in battery-powered networks of IoT devices because it can operate for an extended time on a battery and requires very infrequent maintenance—just like BLE.

HOW SENSORS CAN ENHANCE A TRAMPOLINE PARK

Sensorstream has completed an implementation of a LoRa-based IoT network at one of Freedome's UK locations as a pilot project for a potential large-scale rollout. The sensor environment collects and reports a variety of motion and access data in real time to each facility's staff, alerting them if visitors have ventured into an unauthorized area. The alerts are delivered via smartphone to staff members, who can respond immediately and ensure that children stay where they should be and keep on bouncing.

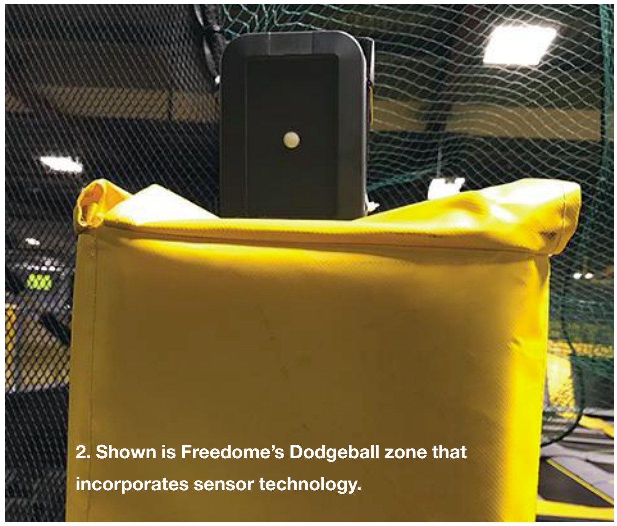
The sensors are also used as an audit trail to ensure that staffers are conducting safety checks and maintenance protocols that must be done on schedule. They also provide alerts concerning other real-time operational issues that may need immediate response. In addition, the sensors deliver information related to environmental conditions in different areas of the trampoline park.

By using LoRa, the sensors are able to operate reliably even in an electrically cluttered indoor environment without the need for expensive infrastructure. This is particularly important given the urban/suburban geographic location of the facilities with an abundance of competing wireless signals nearby.

It is also important given the physical shape of the building, the layout which presents physical obstructions that would ordinarily create difficulty for RF signals, the high number of consumer devices that visitors bring into the facility each day, and a Wi-Fi-intensive environment that so often creates difficulty for IoT networks. While LoRa's long-distance capabilities often get top billing, the technology's capability to successfully operate even in "cluttered" environments make it invaluable for much more than remote locations.

The Sensorstream IoT network also provides business intelligence that is playing an important role in helping Freedome enhance visitors' experience over time and grow the company. The sensors collect data with regard to activity usage and behavioral patterns that are easily interpreted in the form of heat maps and other graphical information. By understanding which activities visitors enjoy the most, the company is able to deliver more of what people want through insights from data analysis rather than traditional, unreliable questionnaires.

This intelligence is captured throughout the day for each facility. It is accessible any time via a web dashboard, giving the company the ability to analyze current data against historical data and make informed decisions about design enhancements and operational changes. Not only would customers at existing trampoline parks be better served, but also future customers at new facilities that are being planned as the company grows.



2. Shown is Freedome's Dodgeball zone that incorporates sensor technology.

Freedome is also using this information to guide its marketing activities, highlighting activities within the park that resonate most with consumers and that encourage past patrons to return.

The ultra-long battery life makes LoRa-based sensors easier to maintain than other types of wireless sensors that require battery replacements more often. That is all the more important in a non-industrial environment like a trampoline park, where the staff does not include engineers whose daily job is to tend to monitoring equipment. In this way, LoRa takes IoT a step closer to the set-it-and-forget-it goal that engineers are striving for, with sensor networks that require attention as infrequently as possible. Energy consumption is one of the key advantages of LoRa that does not receive as much attention as it should, and it is an attribute that makes it very attractive for deployments where minimal battery replacements is a priority.

LoRa-based sensors also give Freedome enterprise-grade security built into its IoT networks that align with their corporate security strategy today and in the future. With many wireless technologies, security is an afterthought, bolted on after the fact to address vulnerabilities that emerge over time. In contrast, LoRa is the first sensor technology that includes enterprise-level security built in with encryption and other attributes. As a result, companies can have peace of mind that IoT networks will not be an open door for security breaches. As IoT security becomes a hot-button issue for more companies, this implementation for Freedome is a compelling example of how LoRa-based networks make security sense for enterprise that want to embrace IoT without fearing the traditional security tradeoff.

In so many ways, this IoT implementation goes against the grain of what you expect from a LoRa-based network and from an implementation in an urban/suburban setting. Not every company is a trampoline park like Freedome, but every company in urban locations faces a similar set of challenges related to the density of RF signals, the need for inexpensive stick-and-go installations rather than complex setup and network initiation processes, the desire for wireless sensors to be worry-free for as long as possible through things like battery life, and enterprise-grade security that is built in from the start rather than bolted on in a series of fixes later on.

Not every company uses its IoT network to keep track of bubbly, giggling kids and kids at heart from ages 2 to 102, but Freedome's implementation is a case study in how IoT networks using LoRa technology can be used for enterprise-class safety, operational efficiency, and business intelligence. mw

Design Feature

CLINTON CATHEY | Chief Executive Officer, Optisys
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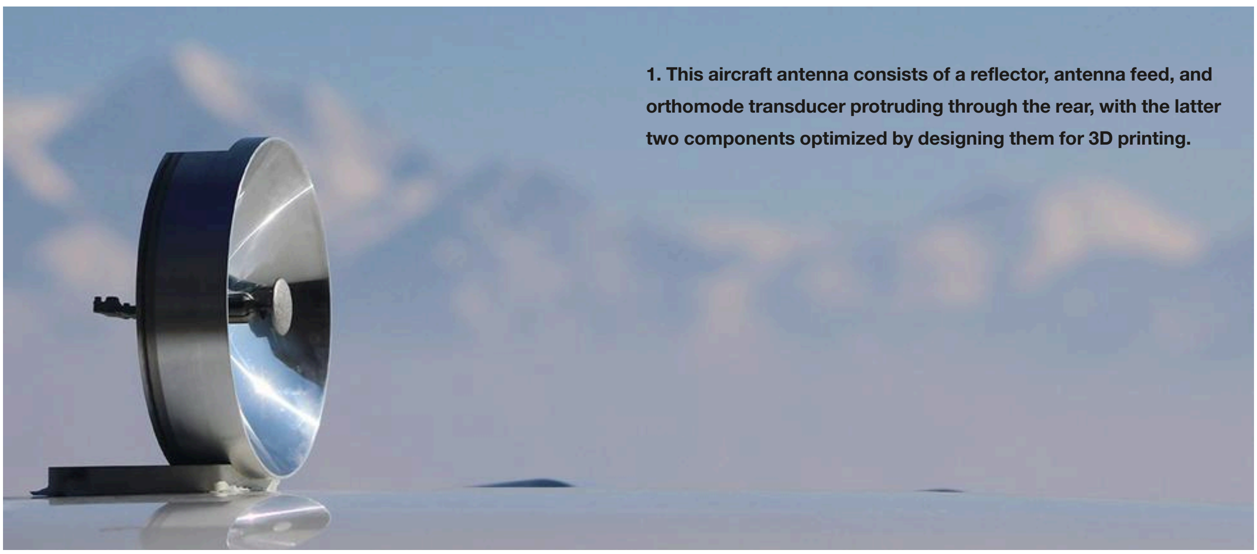
Additive Manufacturing Yields Optimized Antennas

By designing RF/microwave antennas for production using 3D laser printers, size, time, cost, and complexity can be saved while gaining many performance benefits.

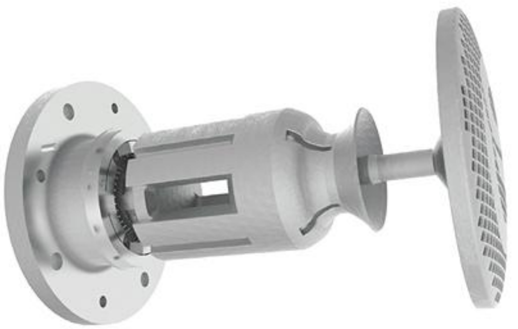


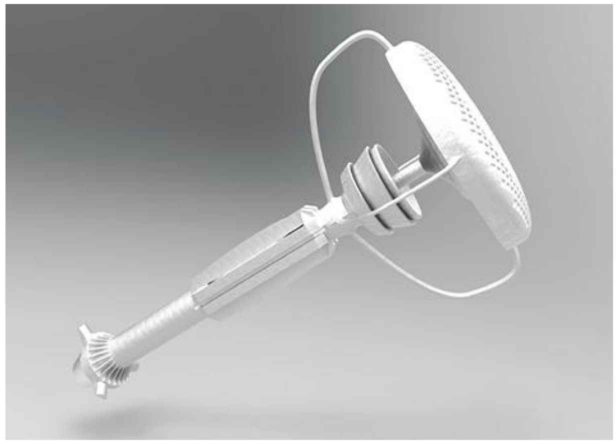
1. This aircraft antenna consists of a reflector, antenna feed, and orthomode transducer protruding through the rear, with the latter two components optimized by designing them for 3D printing.

Antennas are electronic components that rely on precise mechanical engineering for performance. As communications and other electronic systems grow in complexity, so too do the antennas required to transmit and receive their waveforms. But through the use of additive manufacturing (AM) and three-dimensional (3D) metal printing, even advanced antenna arrays can be reduced in size and complexity. By redesigning a Ka-band 4 × 4 monopulse array and producing it with a 3D printer, what had been a complex component with 100 different parts was reduced to a smaller, single-piece antenna with the same performance capabilities.

The reduction of size and number of parts wasn't the only benefit gained by 3D printing the antenna array. Conventional methods of manufacturing antennas such as this monopulse array can take eight months of development time on average, plus three to six more of build time. By using 3D printing for this monopulse array test case, it was possible to reduce the lead time to two months. In addition, production costs were reduced by 20 to 25% and nonrecurring-engineering (NRE) costs reduced by 75%. The savings in the weight of the monopulse array amounted to an almost unbelievable 95%.

In addition to what this test-piece project revealed about its capabilities, 3D printing was also found to offer a number of other advantages. When designing multiple antenna components into a single part, the result is an overall reduction in the insertion loss of the combined parts. Because antennas produced by means of AM and 3D laser printing are so much





2. These are examples of metal antenna feeds designed and produced by means of 3D metal printing.

smaller than antennas produced by conventional subtractive manufacturing methods, this also lowers insertion loss dramatically despite the higher surface roughness of the AM construction, for similar or even better RF performance than conventional assemblies.

The 3D metal printing process can be performed with a number of different metals, including titanium and stainless steel, but aluminum is the preferred building material for antennas. This is due to its high surface conductivity and strength when exposed to shock and vibration. It's also lightweight with strong corrosion resistance.

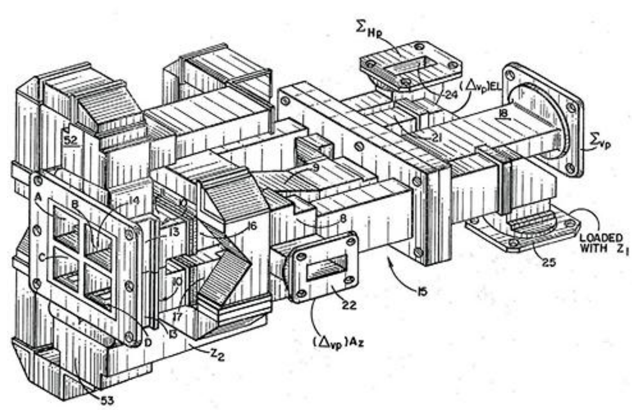
In terms of RF performance, metal produced by means of 3D metal printing exhibit virtually the same properties as a solid piece of the same material. Metal structures produced by 3D laser printers have been tested in rigorous vibration environments and exhibit the same coefficient of thermal expansion (CTE) as wrought metals. This also gives them better stability over temperature than plastic RF components.

AM allows a new way of manufacturing antennas, although the use of AM also requires antennas to be designed for 3D printing. Early adopters of 3D printing applied it to the creation of prototypes, but antennas designed with industrial AM production in mind can be produced quickly and with less complexity than traditional subtractive manufacturing methods, in which unnecessary materials are removed to leave behind the desired structures *(Fig. 1)*. The Ka-band monopulse tracking array is one example of what is possible by applying AM to the design and production manufacturing of RF/microwave antennas *(Figs. 2 and 3)*.

Optimum use of AM for component design depends on a seamless interweaving of design and 3D printing to precisely meet customer specifications. Often parts that were originally intended to be produced by means of traditional subtractive manufacturing methods do not take full advantage of the benefits of 3D printing.

In fact, conventional manufacturing methods can negatively impact RF performance *(Fig. 4)*. Those problems add time and money to traditional antenna manufacturing, as there are often a huge number of parts in a conventional design: typically a daunting array of 100 or more individ-

3. Optisys CBO Janos Opra (left) and COO Rob Smith are reviewing antenna components produced by means of 3D metal printing.



4. This drawing illustrates the complexity of a metal antenna system designed to be constructed by traditional subtractive manufacturing methods.

The use of 3D AM to produce antennas results in components that are routinely smaller than antennas built with conventional manufacturing approaches. The smaller size of their additively manufactured products greatly shortens the overall distance that an RF signal had to travel within the system—a huge benefit to antenna performance.

ual metal components—including the hollow, rectangular waveguides so critical for channeling the electromagnetic energy carrying the data—that are joined together via brazing, plunge electrodeposited metal (EDM), and/or multiple bolted joints.

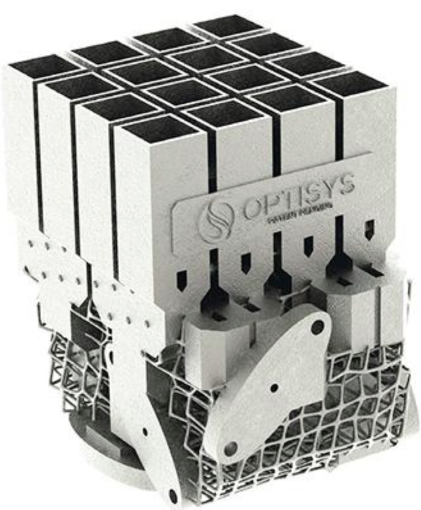
Such assemblies can be large, with unique shapes creating internal geometric hazards that can interfere with the flow of the very data the antenna is supposed to convey. The joining of the different parts has the potential to form a discontinuity that can cause RF losses and reflections. Even the tightness of the screws used to join parts can cause variations in the insertion loss performance. Each of the seams can turn into an unwanted smaller "subantenna" of the main structure.

Tolerances can also be an issue when a hundred or more parts are joined together *(Fig. 5)*. Each of the many separate parts must be inspected independently, then assembled with the hope that their sum will translate into the expected RF performance. The tolerances of each part must be precise; however, when many pieces are integrated together, the tolerance stackup can become significant, resulting in electrical performance degradation.

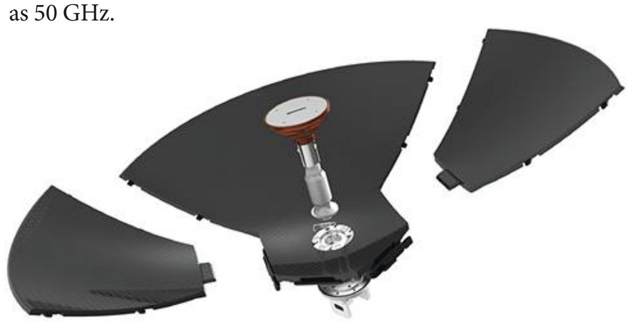
In contrast, AM and 3D printing support a more precise type of systems-engineering approach. By viewing an antenna assembly as an integrated structure in which all the parts are combined into a single functional part, it is possible to reduce lead times on new antenna designs from months to weeks; dramatically reduce the size and weight of the antenna; and offer resulting cost benefits to customers. Of course, refining any 3D printing process for RF design requires extensive testing to validate that performance meets expectations.

The use of 3D AM to produce antennas results in components that are routinely smaller than antennas built with conventional manufacturing approaches. The smaller size of their additively manufactured products greatly shortens the overall distance that an RF signal had to travel within the system—a huge benefit to antenna performance. The accuracy and precision afforded by AM methods supports the mechanical tolerances and dimensions needed for higher-frequency microwave and millimeter-wave antennas—such as those used in satellite communications, line-of-sight (LOS) communications, aircraft systems, and unmanned aerial vehicles (UAVs)—with the small sizes and light weights of the antennas providing added benefits for these applications.

The Ka-band monopulse tracking array produced as a one-piece component *(Fig. 6)* was characterized at frequencies to 30 GHz, both for benchtop and outdoor environments. Similar designs have passed demanding vibration testing for military requirements. Other antennas designed and produced by means of 3D AM have achieved operating frequencies as high as 50 GHz.



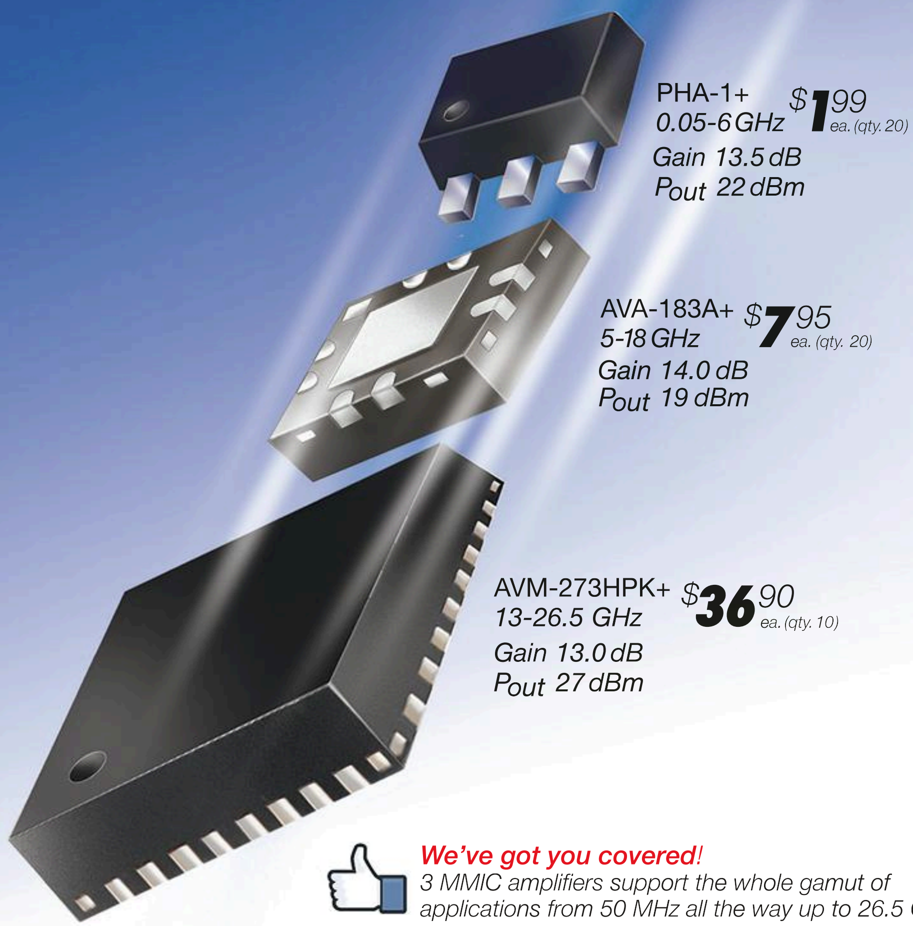
5. This one-piece, functional assembly antenna was designed and manufactured by optimizing a 100-piece design for AM 3D printing.



6. This segmented antenna can be disassembled and fit into a soldier's backpack. The reflector is made from composite material by a partner company, while the feed structure in the center of the antenna structure is produced by 3D laser printing.

MMIC AMPLIFIERS

50 MHz to 26.5 GHz



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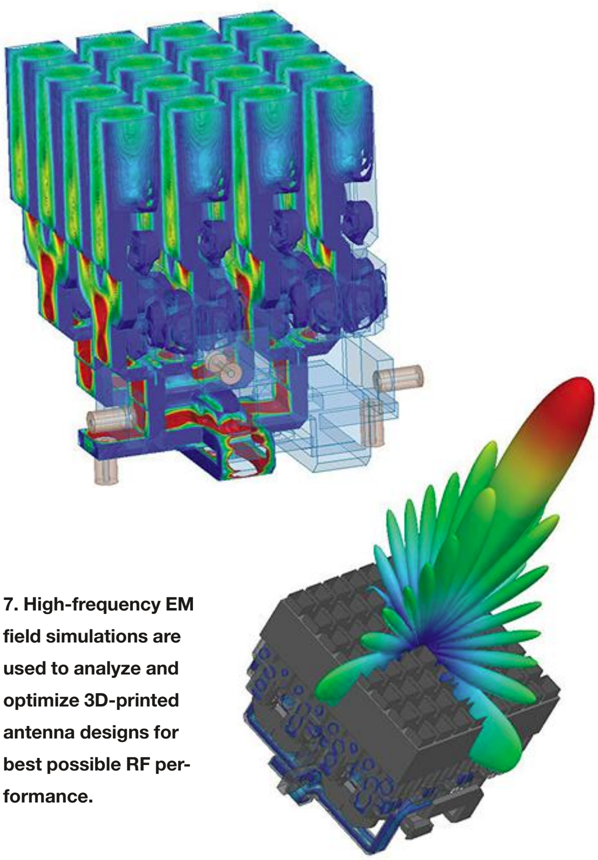
The 3D laser printer from Concept Laser *(see sidebar)* used to manufacture antennas provides fine mechanical resolution with smooth metal surfaces. Aluminum is the material of preference for a build; it stands up better than plastics to environmental stresses (from terrestrial applications to outer space), and has essentially the same properties as a solid piece of the same material.

The antennas are designed specifically for the AM process. A design starts with the RF requirements for the finished product. The use of AM is coupled with RF/microwave design expertise to avoid internal geometry issues, as well as to deliver the lowest insertion loss and the highest RF possible for each design. Passing inspection can be challenging, since many critical geometries are internal and formed by laser melting—rather than achieved by assembling separate parts—and can't be measured directly.

To create an antenna with AM 3D printing, a microwave simulation of the antenna design has been developed using ANSYS HFSS 3D electromagnetic (EM) simulation software from ANSYS (www.ansys.com). The software models the high-frequency EM field inside the air cavity of the proposed antenna array *(Fig. 7)*. Once a satisfactory HFSS simulation has been developed, the file is imported into SolidWorks 3D CAD software from SolidWorks *(www.solidworks.com)* to determine the optimum thickness for the aluminum walls that will surround the array's air cavity and enable 3D printing the design as a single metal assembly.

An optimum topology is developed, adding just enough extra material where needed to create an integrated unit that will print consistently. Support structures are also added where needed, using Autodesk Within 3D printing software from Autodesk *(www.autodesk.com)* and merging the result using SolidWorks and software from Magic Software *(www.magic-software.com)*. In this manner of designing and producing an RF antenna, an antenna can be created and modified according to any number of specialized requirements. These include thermal, stress, structural, and tolerance analysis, along with system-level electrical requirements for the antenna.

AM simplifies the addition of new features to an existing 3D design, as well as the assembly of finished parts—except, of course, in those cases where a design is produced as a single part, where no assembly is required. Over time, the AM 3D printing approach can allow for further reduction in an antenna's parts count, refining the design for smaller size and improved performance. As the number of parts decreases, the amount of rework diminishes and production time declines. As an added benefit, antennas and other components with fewer parts require less maintenance and service over time. mw



7. High-frequency EM field simulations are used to analyze and optimize 3D-printed antenna designs for best possible RF performance.

3D METAL PRINTING TECHNOLOGY AT A GLANCE

ANTENNAS, WAVEGUIDE COMPONENTS, and other metal parts at Optisys are manufactured with a 3D metal printing system from Concept Laser, a GE Additive company (www.conceptlaserin.com/en/home.html). It uses a high-energy laser to melt and fuse standard commercial batch materials in powdered form. A single-component metal powder is first completely fused. Once it has set and solidified, it is a finished component with almost ideal material properties. Precise contours can be formed by using a scanner. A 3D component is constructed layer by layer, applying and melting additional metal powder as needed. Layer thicknesses can be controlled from 15 to 500 µm.

Parts are created without mechanical tools, without the limits of conventional subtractive manufacturing methods on component geometries or internal configurations, drawing upon input data from 3D electromagnetic (EM) simulation and computer-aided-design (CAD) software. The 3D laser printer produces parts without waste, in contrast to the etching and cutting of conventional metal manufacturing processes. The LaserCUSING laser-based metal melting process does not produce emissions, forming 3D structures with high efficiency.

GLENN ROBB | Principal Engineer, Antenna Test Lab Co.; (919) 200-0292
www.antennatestlab.com

Don't Let These Excuses Get in the Way of Antenna Testing

By designing RF/microwave antennas for production using 3D laser printers, size, time, cost, and complexity can be saved while gaining many performance benefits.

With the growing reliance on wireless communications systems, antennas are essential for keeping system users "connected," although antennas are also often one of the more taken-for-granted components in a wireless communications system. Even so, many design engineers ignore the importance of real-world antenna performance for a number of reasons or excuses (*Fig. 1*).

Many engineering system designers report that they buy external antennas for their system designs, assuming that a particular antenna will perform exactly as specified on its data sheet. Unfortunately, in what is an extremely competitive marketplace, antenna suppliers and manufacturers have been known to vie for a customer's attention through the use of optimistic or even exaggerated performance levels on their data sheets at attractively low prices.

1. **Many different types of antennas are used in new product developments, although their data sheets may not be fully representative of their performance levels.**

In particular, some performance parameters (such as gain) are often advertently or inadvertently reported on a data sheet, based on results recorded in overly "friendly" test environments that are not representative of the operating conditions in an actual, installed application.

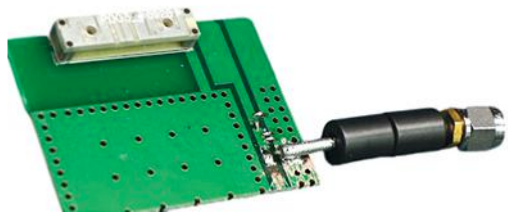
When specifying antennas for cellular or Industrial-Scientific-Medical (ISM) band applications below 900 MHz, the printed-circuit-board (PCB) size will greatly affect the average gain and efficiency of an installed antenna (*Fig. 2*). Flex antennas and their feed lines (often with miniature U.FL RF connectors) typical employ radiation from the feed line as part of the antenna's total radiation pattern.

Because of this, feed line routing will have a huge impact on the performance and antenna patterns produced by a flex antenna on a particular PCB design. Lacking actual antenna pattern data for such an installation, the data sheet gain presented for an omnidirectional antenna is likely to be peak gain (measured in some random direction).

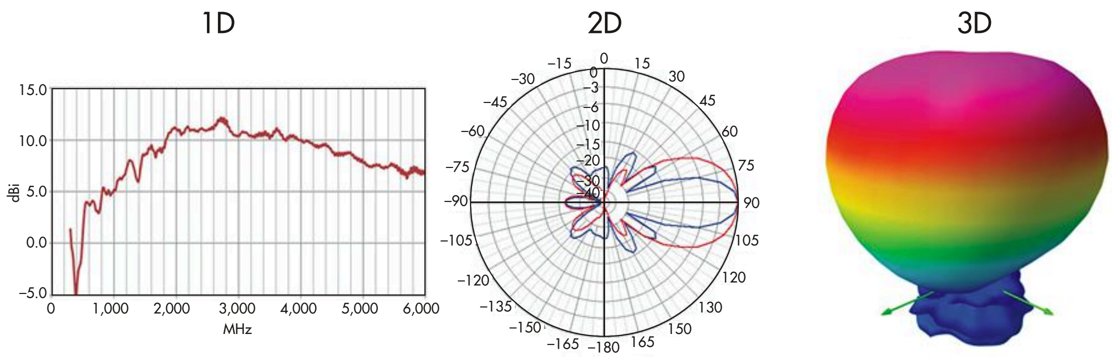
System integrators often explain that they buy "premium" antennas for their system design rather than low-cost antennas with inferior performance. Suppliers of low-cost components such as antennas may take shortcuts in terms of production-line testing to reduce their operating cost, and the impact can often be seen in the poor quality of the final product.

Still, the old adage that "price equals quality" may not always ring true, or always guarantee higher performance simply because on antenna costs more than another. One way to verify whether a higher price has resulted in higher performance is by antenna performance testing in a qualified test laboratory. The investment in testing verifies critical antenna performance parameters and eliminates any questions about the antenna's contributions to system-level performance.

Some system integrators forego antenna testing because their designer or contractor has performed extensive computer simulations on the antenna and these simulations show



2. **This PCB antenna is shown with a coaxial probe attached to the test board for measurement purposes.**



3. A qualified antenna test facility such as Antenna Test Lab Co. can provide measurement results for a wide range of parameters and in many different formats.

the antenna's performance to be a close match to the system's requirements. Simulations are a wonderful tool in hardware development and optimization, but they have never taken the place of hardware or system verification. No circuit designer would skip their hardware testing based on simulations.

Any antenna designer worth their salt will want verification, as well. Antenna testing is inexpensive compared to total product development costs, and antenna testing can reveal any performance nuances that might have been missed by the software in a computer simulation. In addition, the antenna test data from a qualified test laboratory can be incorporated into further computer simulations to improve the efficiency and effectiveness of antenna performance optimization (*Fig. 3*).

Product developers have noted that their chip antenna has been tested by the antenna's manufacturer, and they are now following the antenna supplier's recommendations for installation on a PCB. Unfortunately, every PCB design is different and achieving optimal performance is never simply a matter of using a "cookbook" PCB layout.

Antenna component manufacturers provide a great deal of layout guidance and minimum circuit-board sizes to guide the best use of their products. To produce the performance levels shown on antenna data sheets, antenna suppliers typically perform testing of an antenna as part of an optimized demonstration board, with additional layouts developed as iterations of that demonstration circuit board.

But in an actual application, the clutter presented by surrounding structures—such as batteries, cables, and displays—can adversely affect the performance of a PCB-mounted antenna in ways that testing and even simulations cannot reveal. To save time and anguish as part of the design process, an antenna testing service can characterize an antenna embedded on a blank PCB representing the potential final design, with or without additional components mounted to learn more about how the antenna's performance will appear in the final design.

Product developers have at times assumed their antennas are good enough without testing since prototype designs are providing suitable levels of overall performance during data-link testing under laboratory conditions. But such casual communications link tests with prototypes often do not yield enough information about the antennas or the full product design under all operating conditions.

Full design verification requires more extensive testing, such as waveform analysis on an oscilloscope or signal analyzer. Qualified antenna test laboratories can provide more extensive test data on active or passive antennas to help better understand results from link testing.

Often, a particular antenna may be deemed acceptable for a new design because it has been used successfully in the past. But this assumption may also be part of the perpetuation of mediocre performance in a new product. The thinking that "this is the way it's always been done" will not lead to reaching new performance levels. Verifying the performance of an antenna should be considered as part of adding an improvement to a new product design. A properly verified antenna design can then be reused with confidence.

When the PCB for a new product design passes FCC/EN radio compliance testing, the antenna is often assumed to be acceptable, with no need of further testing. But compliance testing focuses on controlling interference that could be originating from a new radio design. Various spurious emissions and band edge checks are made in detail, along with a few other modulation parameters, but such testing does not attempt to quantify the antenna performance.

Antenna performance is often assumed to be good when an antenna shows good VSWR or return loss during testing with a vector network analyzer (VNA). But antennas with return loss of better than 10 dB have also been found to suffer from poor radiation efficiency (less than 10%). When a chip antenna layout (or an all-copper PCB antenna) has a particularly poor return loss, a great deal of trial-and-error impedance matching can result in the addition of inductive/capacitive (L/C) impedance-matching components that seem to help.

However, with VSWRs above 10:1 or more, there can be a large amplification of current in impedance-matching inductors and boost of voltage in impedance-matching capacitors, multiplying their inherent losses. The high losses of these components masquerade as radiation resistance, even though the antenna may not be practically matchable. This is a case where the matching components yield a "good match" by absorbing RF energy, not by transferring it to a radiating antenna.

One way to learn if this may be happening to a circuit design is to perform the "hand test," by waving a hand over a board and its antenna and monitoring the effects on return loss measurements. If there are no effects from the hand being in close proximity to the circuit board and its antenna, then the design is acting as a dummy load rather than an antenna. In addition, if a compact antenna exhibits unexpectedly wide return-loss bandwidth, it is probably a result of high internal losses and not the radiation resistance.

System designers fail to test an antenna for a new design because it works well in free space. But for the same reasons noted earlier, an embedded antenna will be affected by surrounding hardware, such as cables, shields, displays, and other components mounted on a PCB or within a product enclosure. Any structures that are within a quarter wavelength of the antenna must be considered part of the antenna.

The simple assumption that an antenna manufacturer meets its published specifications has been a long-running excuse not to perform additional antenna measurements. But failure to meet those specifications will impact the performance of a new product design using that antenna, making it worthwhile to perform additional antenna characterization at a qualified test facility. When those measurements reveal differences from the published data sheets, these results should be shared with the supplier of that antenna.

An antenna test laboratory can fortify a design with an independent evaluation of its antenna, performed in an anechoic chamber. As mentioned earlier, testing is relatively low in cost, with complete radiation pattern testing performed over wide swept-frequency ranges from facilities such as Antenna Test Lab Co. for as little as $450. Data can be provided for a large number of parameters, including gain; radiation efficiency; VSWR (return loss); radiation patterns in boresight, polar, or spherical formats (1D, 2D, or 3D formats). The test results can provide insights into antenna performance that leave nothing to chance as part of a larger design. mw

GLENN ROBB is the founder and principal engineer of Antenna Test Lab Co.

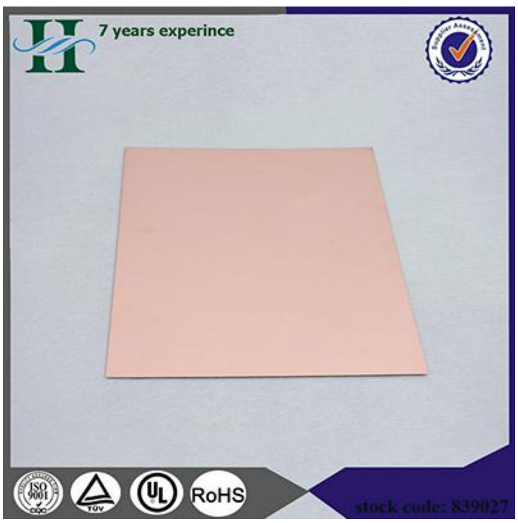
JACK BROWNE | Technical Contributor

Should You Choose Hard or Soft PCB Materials?

These materials differ in their rigidity and various other characteristics, resulting in differences in how readily they can be transformed into high-frequency circuits.

Materials for printed circuit boards (PCBs) can contribute a great deal to the success or failure of a final circuit design, since those materials affect thermal behavior as well as the electrical and mechanical characteristics of the circuit. At one time, the choice in RF/microwave circuit-board materials was simply between a "hard" or rigid circuit material, typically based on some form of ceramic material, and a "soft" or flexible type of circuit material, often based on Teflon or polytetrafluoroethylene (PTFE) with some form of filler.

The number of circuit material choices has grown with time—with circuit materials now available optimized for specific types of designs, such as antennas, or even frequency ranges, such as millimeter-wave frequencies—although most of the materials can still be categorized as being hard/rigid or soft/flexible in nature. Reviewing some of the differences between the two basic types of RF/microwave circuit materials may help clarify when it makes the most sense to use one type or another for a particular high-frequency application.



1. FR-4 is a thermoset plastic laminate, glass-reinforced epoxy circuit material which has represented an industry standard in terms of ease of drilling and metallization. *(Courtesy of Alibaba)*

Hard circuit materials are typically based on some form of ceramic base, such as alumina (Al_2O_3), aluminum nitride (AlN), and beryllium oxide (BeO). Hard or rigid materials also serve as substrates for many integrated circuits (ICs), such as gallium arsenide (GaAs), gallium nitride (GaN), silicon (Si), and silicon carbide (SiC). Soft circuit materials are generally formed from an epoxy or plastic, such as PTFE forming a coating around a glass weave, or with some form of glass or ceramic filler to provide strength and rigidity to the plastic dielectric material.

Dielectric materials used for RF/microwave PCBs must undergo different processes, such as metallization with conductive metals such as copper or aluminum, and drilling of holes for mounting of components on PCBs and mounting of boards in enclosures. It has long been one thermoset plastic laminate in particular, glass-reinforced epoxy material known as FR-4, which has represented a kind of industry standard in terms of ease of drilling and metallization. FR-4 *(Fig. 1)* has made possible low-cost production of PCBs with reasonable performance at RF/microwave frequencies. It is formed of woven-fiberglass cloth with an epoxy resin binder. The FR stands for "flame retardant." It is more flame retardant than G10 materials and so has largely replaced them.

FR-4 is relatively flexible and easy to machine and position as PCBs within larger enclosures, but suffers high dielectric loss (dissipation factor) at microwave frequencies. These high losses make it poorly suited for high-speed digital circuits or high-frequency analog applications above a few GHz.

Materials engineered for low dissipation factor at higher frequencies, including flexible circuit materials based on PTFE such as RO3000 and RO4000 *(Fig. 2)* from Rogers Corp. *(www.rogerscorp.com)*. Less-flexible ceramic circuit materials such as alumina circuit materials from Kyocera *(www.kyocera.com)* commonly used in automotive millimeter-wave-frequency packaging are better suited for use with circuit transmission lines at microwave and millimeter-wave frequencies, although with considerably higher price tags than FR-4 materials.

FR-4 is an example of a thermoset plastic resin material, a heat-cured hydrocarbon resin. It requires a hardener or accelerator system to reach its thermoset stage. In contrast, flexible circuit materials based on PTFE are thermoplastic materials. Compared to thermoset plastic resin materials, PTFE/glass fabric materials can achieve tighter thickness tolerances across a sheet of material for good consistency in Dk and dissipation factor (dielectric loss) across the material.

Flexible circuit materials based on PTFE such as RO3000 and RO4000 have gained in popularity because of their ease of machining (quite similar to FR-4) and their low dielectric losses at microwave frequencies. They provide excellent extended high-frequency performance and are often combined with FR-4 and other circuit materials in multilayer circuit configurations to achieve cost-effective use of the different circuit materials for different (non-RF) functions.

Circuits based on soft-type RO4350B laminates can be manufactured using standard FR-4 multilayer circuit processes. RO4350B has a hydrocarbon/ceramic base, with very low dielectric loss at RF and microwave frequencies. Multilayer constructions can be formed by combining RO4350B materials with Rogers 4450 prepreg, or even by combining the high-frequency circuit materials with standard FR-4 prepreg materials.

Cost-effective design approaches often restrict the caps or end materials of a multilayer circuit stackup to the RO4350B materials where the performance is most needed, implementing less critical RF/microwave functions to FR-4 or other circuit materials in the stackup. In this way, the overall cost of the multilayer circuit stackup is managed without sacrificing electrical performance.

Soft circuit materials based on PTFE thermoplastic materials have low moisture absorption compared to thermoset materials. The moisture absorption can cause variations in the impedance of transmission lines fabricated on that material. PTFE/woven glass materials generally meet the flammability requirements of UL-V0 without the addition of flame retardant. Microwave materials based on thermoset resins generally require addition of flame retardant to meet UL-V0, which in turn can lower the copper peel strength, or materials based on thermoset resins will not meet UL-V0 requirements for the thinnest of materials.

Some basic differences in power-handling capabilities between more rigid PCB materials such as alumina and softer, PTFE-based circuit materials makes the former types of materials better suited for higher-power portions of a system, such as its dc bias or RF power amplification. In creating a multilayer circuit stackup using different circuit materials, a key requirement is for a compatible bondply material that is capable of providing reliable adhesion between two different circuit materials, such as ceramic and PTFE-based circuit materials, in a multilayer circuit stackup.

2. RO3000 and RO4000 materials are PTFE/glass combinations with low moisture absorption and low dielectric loss at RF/microwave frequencies. *(Courtesy of Rogers Corp.)*

The thermal characteristics of the different materials, such as coefficient of thermal expansion (CTE), should also be compatible to avoid irregularities in expansion and contraction with temperature at interfaces between two different circuit materials.

Alumina or aluminum oxide (Al_2O_3) circuit material is among the most popular of hard circuit substrate materials due to its excellent electrical and mechanical properties. However, for a ceramic circuit material with much higher thermal conductivity than the other hard or soft circuit materials, as might be used to manage heat from the active devices of a power amplifier, aluminum nitrate (AlN) has thermal conductivity of 170 W/m-K compared to 26.9 W/m-K for alumina.

Ceramic circuit materials are often used in the fabrication of multilayer thick-film circuits with a few different metallization systems, such as in low-temperature-cofired-ceramic (LTCC) constructions with embedded passive circuit elements.

Tightly controlled material thickness is instrumental in achieving the controlled-impedance transmission lines that are a part of RF/microwave circuitry, and PTFE/glass circuit materials can achieve tight thickness tolerances along with corresponding tight tolerances in material dielectric constant (Dk). PTFE-based circuit materials provide excellent consistency across a board, with many characteristics that make those materials extremely popular for many different high-frequency circuits. mw

TAKE NOTICE OF IEEE 802.11ax

THE NEW IEEE 802.11AX standard promises to significantly improve the performance of Wi-Fi networks. But what are these improvements? And will IEEE 802.11ax really be a significant upgrade over IEEE 802.11ac? These topics are discussed in a new white paper from Qorvo titled "Wi-Fi .11 AX – What's It All About?"

The white paper explains that performance and range are two significant factors associated with Wi-Fi, with performance essentially being data rates. In practical terms, the common scenario one encounters when in search of a Wi-Fi network is presented. This scenario involves turning on a laptop and then seeing a long list of routers or access points. Many of these routers are using the limited number of overlapping channels. In essence, these channels are being shared by users, meaning the end result is interference.

Essentially, throughput in dense environments can suffer as a result of two devices talking through each other in the same channel at the same moment. Furthermore, this form of interference is actually worsened by routers and access points utilizing the highest possible output power to improve range, according to the white paper. Essentially, more output power causes more interference, as well as causing a signal to "bleed" from one channel into other channels.

According to the white paper, the goal of IEEE 802.11ax is not necessarily higher data rates. Rather the objective is to use as many channels as possible in the 2.4- or 5-GHz band—at the same moment in the same area. A scenario is then illustrated in which a home is reaping the benefits of IEEE 802.11ax.

The impact of IEEE 802.11ax for both product suppliers and consumers is discussed. Specifically, "flat power," which means uniform output power across the band, is one important aspect. Also mentioned is the consumer desire for smaller Wi-Fi routers, which is possible with IEEE 802.11ax because it uses all available channels with the highest efficiency. The white paper concludes by discussing the implications of using either the 2.4- or 5-GHz band.

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LEARN THE ABCs of VNAs

THE VECTOR NETWORK analyzer (VNA) is an essential test instrument in the RF/microwave industry. They are used in a wide range of applications for both design validation and manufacturing production testing. In the primer, "Introduction to VNA Basics," Tektronix discusses VNAs in detail, explaining why they are used, how they compare to other RF test instruments, and much more."

According to the primer, the VNA dates back to around 1950. They make many modern technologies possible, as all wireless systems contain components in which performance can be verified by using a VNA. Specifically, an RF front end consists of various components, such as filters and amplifiers, which can be tested with a VNA.

The primer then describes the VNA's basic operation. In simple terms, a VNA contains a source that generates a known stimulus signal, as well as a set of receivers. This stimulus signal is injected into the device-under-test (DUT). The signal that is reflected from the input of the DUT and the signal that passes through the DUT are both measured by the VNA receivers. These signals are then compared to the known stimulus signal. Moreover, the primer describes four important VNA specifications: frequency range, dynamic range, trace noise, and measurement speed. Each one is explained in greater detail.

The differences between a VNA and a spectrum analyzer are explained. The primer also explains S-parameters, which are the fundamental VNA measurement. The next topic described is the functionality of a VNA that allows S-parameter measurements to be achieved. Moreover, the importance of VNA calibration is emphasized. Calibration is required to reduce errors that can affect measurements. According to the primer, the three main types of measurement error are systematic errors, random errors, and drift errors.

Different types of VNA measurements are presented. Swept-frequency measurements are explained, with example measurements of both a passive filter and an antenna. Time-domain measurements are also described, as well as swept-power measurements. The last type of measurement explained is multi-port component testing.

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Tech Viewpoint: What's Behind the 5G Buzz?

This article examines some of the key 5G technologies currently in the works, along with the tools needed to facilitate them.

Fifth-generation (5G) networks are the next major phase of mobile telecommunications beyond the current 4G LTE standards. 5G technology needs to be specified, developed, and deployed by a variety of industry players, including network equipment vendors, network operators, semiconductor vendors, device manufacturers, and electronic test-and-measurement equipment makers.

There has been much discussion of how 5G will transform products ranging from mobile phones to next-generation automobiles. What isn't widely understood are the specific technologies that will make 5G different from 4G LTE. Let's take a look at the technology changes that are underway as the industry shifts from the 4G LTE standard to 5G.

5G DEMAND DRIVERS

Two major trends are behind the rapid investment in 5G development. The first is the exponential growth in demand for wireless broadband networks capable of carrying video and other content-rich services. The second is the Internet of Things (IoT), where a large number of smart devices communicate over the internet. To achieve these objectives, 5G will provide extreme broadband speed, ultra-low latency, and ultra-reliable web connectivity based on Internet Protocol (IP; *Fig. 1*).

By providing higher bandwidth capacity than current 4G-enabled network capabilities, 5G will enable a higher density of mobile broadband users and support ultra-reliable device-to-device and massive machine communications with the following features.

1. Enhanced Mobile Broadband (eMBB) for high-capacity and ultra-fast mobile communications for phones and infrastructure, virtual and augmented reality, 3D and ultra-HD video, and haptic feedback.

KEY 5G PARAMETERS	
Latency in the air link	<1 ms
Latency end-to-end (device to core)	<10 ms
Connection density	100x vs. current 4G LTE
Area capacity density	1 (Tbit/s)/km^2
System spectral efficiency	10 (bit/s)/Hz/cell
Peak throughput (downlink) per connection	10 Gbit/s
Energy efficiency	>90% improvement over LTE

1. Shown are some of the significant 5G parameters.

2. Ultra-reliable and Low Latency (URLLC) for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications and autonomous driving.

3. Massive Machine-Type Communications (mMTC) for consumer and industrial IoT and Industry 4.0 mission-critical machine-to-machine (MC-M2M) communication.

WHEN CAN WE EXPECT 5G?

The 3GPP standardization group defines the wireless 5G standard, with help from many participants and contributors around the globe. Release 15 of the 3GPP standard, expected by March 2018, will introduce the 5G standard *(Fig. 2)*. Modulation schemes, beamforming techniques, millimeter-wave technology, and massive multiple-input, multiple-output (MIMO) architectures are expected to be significantly different from current 4G technologies.

Current 5G research and development focuses on these enabling technologies, including hybrid beamforming, millimeter-wave and massive MIMO systems, 5G channel modeling and waveforms, and rapid field trials of 5G design concepts. This 5G physical layer will depart from 4G LTE in a number of ways, so as to improve spectral efficiency and data rates.

One distinctive feature is a significant jump in the number of active antennas and antenna arrays, and the related issues of beamforming and millimeter-wave RF signal processing. New modulation and coding schemes, power and low-noise amplifier designs, and channel models all need to be developed. Let's take a closer look at the technologies that will play a key role in the arrival of 5G.

PHYSICAL LAYER ALGORITHMS AND CHANNEL MODELS

Researchers and engineers contributing to the 5G standard form working groups to study, propose, and select technologies to achieve the goals of the new standard. These working groups have already defined important aspects of the new 5G physical layer, including:

• Channel models, including tapped delay line (TDL) and clustered delay line (CDL) channel models as specified in 3GPP TR 38.901

• New radio waveforms to improve spectral efficiency by limiting out-of-band emissions, including Filtered OFDM (F-OFDM), Windowed OFDM (W-OFDM), and Cyclic Prefix OFDM (CP-OFDM)

• New coding schemes such as LDPC for data and polar codes for control information, error correction, and improved data rates

• Link-level simulation reference design, enabling one to measure the throughput of a 5G link using the provided waveforms and channel models

MILLIMETER-WAVE: HIGHER-FREQUENCY OPERATION

Higher data rates (multi-Gbps) drive the need for wide-bandwidth systems. However, the available bandwidth in the spectrum up through 6 GHz is not sufficient to satisfy these requirements (current cellular operation is below 3 GHz). This has moved the target operating frequency bands up into the millimeter-wave range for the next generation of wireless communication systems. For example, 5G equipment developers such as Huawei and Nokia have announced 5G New Radio (NR) trials with AT&T, Verizon, China Mobile, NTT DOCOMO, and others. Those trials will operate in the midband spectrum from 3.3 to 5.0 GHz, as well as the millimeter-wave spectrum at 28 GHz and 39 GHz, showcasing the unified 3GPP-based 5G NR design across diverse spectrum bands.

High frequencies will provide larger bandwidth availability and smaller antenna dimensions for a fixed gain, or higher gain for a given antenna size. However, this increases modem complexity in baseband and RF designs. To study the performance, an accurate channel model for the new frequencies in 5G is needed.

MASSIVE MIMO: MORE ANTENNAS

Another key technology for achieving greater spectral efficiency is massive MIMO. Massive MIMO, sometimes referred to as large-scale MIMO, is a form of multi-user MIMO in which the number of antennas at the base station is much larger than the number of devices per signaling resource. The large number of base-station antennas relative to user devices results in a channel response that is quasi-orthogonal and has the potential to yield huge gains in spectral efficiency.

Such conditions would enable many more devices to be served with the same frequency and time resources within a given cell compared to modern-day 4G systems. Designers face a challenge when scaling the number of antennas into the hundreds:

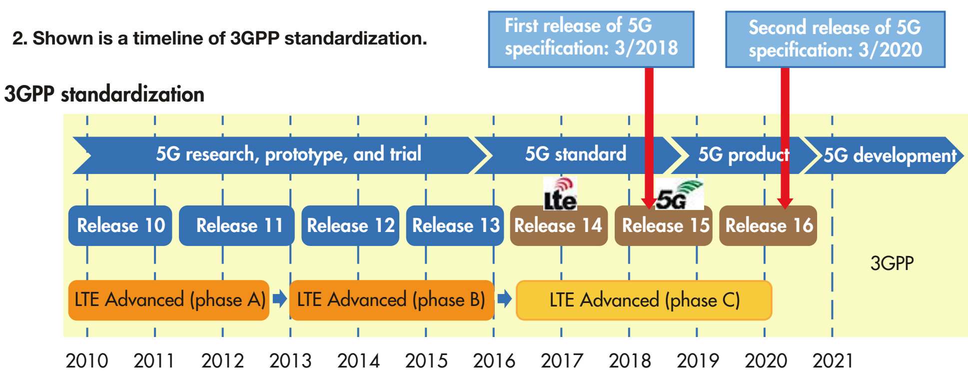
1. The simulation speed of traditional antenna design tools is slow for large antenna arrays.
2. It is difficult to simulate antenna coupling.
3. Hybrid beamforming is needed to optimize the increased number of RF chains.

FAST PROTOTYPING OF 5G SYSTEMS WITH HARDWARE TESTBEDS

Engineers working on 5G designs have realized the value of rapid design iterations and of quickly placing proof-of-concept prototypes in field trials. Hardware testbeds employed as flexible and reconfigurable design platforms have proven to be dependable and efficient for the rapid design and verification of new concepts, as well as for their deployment in pre-commercial field trials. The tools and workflows that interface to testbeds must support rapid design iterations and rapid deployment of new algorithms or design changes. Software tools like MATLAB and Simulink provide engineers with tools to help study and develop the 5G standard, such as channel models, new radio waveforms, new coding schemes, and link-level simulation reference design.

As the wireless industry anticipates the final result of 3GPP standardization process, engineers are already at work exploring, prototyping, and testing the enabling technologies of 5G.

2. Shown is a timeline of 3GPP standardization.



CHRIS DeMARTINO | Technical Editor

Baseband VST Aims to Solve Tomorrow's Test Requirements

This new baseband vector signal transceiver (VST) comes on the heels of last year's RF model, allowing for a complete wireless test solution.

Last year, National Instruments (NI; *www.ni.com*) made headlines by introducing the PXIe-5840, the company's second-generation vector signal transceiver (VST; *see RF Measurement Modularity Redefined)*. Covering a frequency range of 9 kHz to 6 GHz, the PXIe-5840 can achieve 1 GHz of instantaneous bandwidth. Not resting on its laurels, NI again made news earlier this year by unveiling the PXIe-5820 baseband VST *(Fig. 1)*.

The PXIe-5820 baseband VST can achieve 1 GHz of in-phase/quadrature (I/Q) instantaneous bandwidth for generation and analysis. The new VST combines a wideband I/Q digitizer, wideband I/Q arbitrary waveform generator (AWG), and user-programmable field-programmable gate array (FPGA) into a single instrument. Furthermore, this capability is all contained in a single two-slot PXI Express module.

1. This baseband vector signal transceiver (VST) can achieve 1 GHz of I/Q instantaneous bandwidth.

The PXIe-5820 is well suited to meet the needs of next-generation wireless communications, such as 5G and IEEE 802.11ax. Specifically, the PXIe-5820 VST can achieve an error vector magnitude (EVM) of better than -54 dB when utilizing the IEEE 802.11ax 1024-QAM modulation scheme.

A key benefit of the PXIe-5820 is that it can be synchronized with the PXIe-5840 RF VST to sub-nanosecond accuracy. Thus, both VSTs can be used in combination to create a complete test solution for RF and baseband differential I/Q testing of wireless chipsets. Envelope tracking (ET) and digital pre-distortion (DPD) power amplifier (PA) techniques are supported by the VST test solution. Moreover, the PXIe-5820 includes a number of LabVIEW sample projects.

5G MEASUREMENT EXAMPLE

NI's VST test solution allows for the generation and analysis of potential 5G waveforms. *Figure 2* shows a PXI chassis that contains both the PXIe-5840 RF VST and the PXIe-5820 baseband VST. The PXIe-5820 is configured in loopback mode, meaning that its I/Q input and output ports are connected to each other via cables. The PXIe-5840 can also be configured

2. Shown is the test setup that contains both the RF and baseband VSTs.

(Continued on page 76)

CLAIRE MASTERSON | Analog Devices
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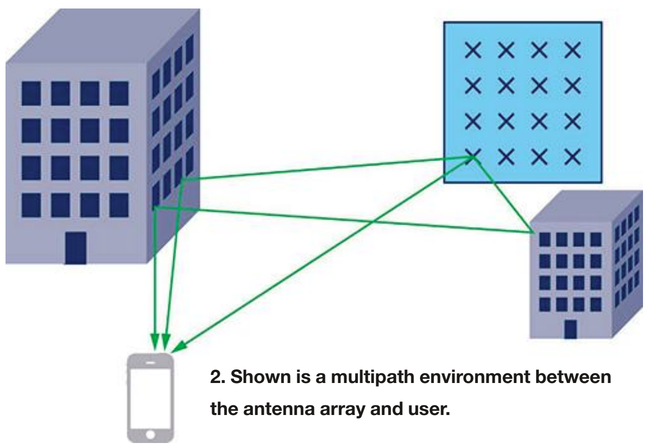
Defining Massive MIMO in a 5G World

Massive MIMO technology and 5G communications are often mentioned in the same sentence. This article takes an in-depth look at the former, and how it applies to the latter.

THE INSATIABLE DEMAND for high-speed mobile data is creating a series of pressing design challenges as today's cellular base stations strain to handle an increasingly saturated RF spectrum. In many dense urban areas, our ability to continuously accelerate transmit and receive data speeds is under threat.

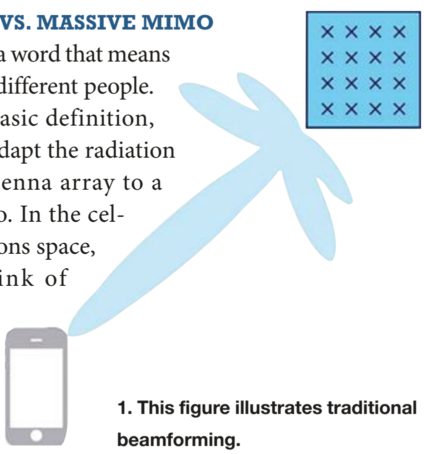
One path forward is to deploy base stations with large numbers of antennas that simultaneously communicate with multiple spatially separated user terminals over the same frequency resource and exploit multipath propagation. Often referred to as massive multiple-input, multiple-output (MIMO), this technology is also described as beamforming with a large number of antennas. But this raises the question: What is beamforming?



2. Shown is a multipath environment between the antenna array and user.

BEAMFORMING VS. MASSIVE MIMO

Beamforming is a word that means different things to different people. According to its basic definition, it is the ability to adapt the radiation pattern of the antenna array to a particular scenario. In the cellular communications space, many people think of beamforming as steering a lobe of power in a particular direction toward a user *(Fig. 1)*. Relative amplitude and phase shifts are applied to each antenna element to allow for the output signals from the antenna array to coherently add together for a particular transmit/receive angle and destructively cancel each other out for other signals. The spatial environment that the array and user are in is not generally considered. This is indeed beamforming, but is just one specific implementation of it.

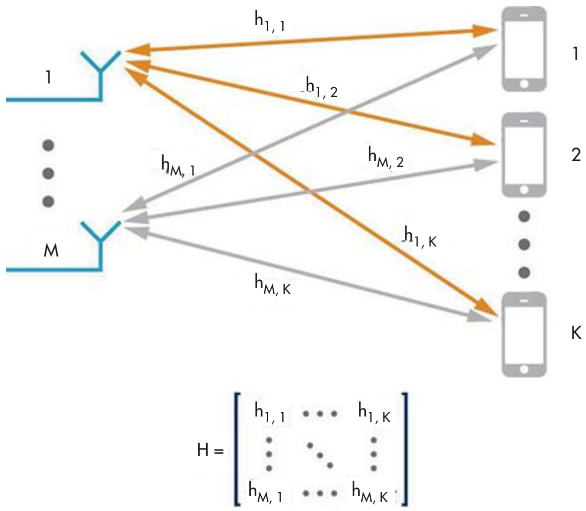


1. This figure illustrates traditional beamforming.

Massive MIMO can be considered as a form of beamforming in the more general sense of the term, but is quite removed from the traditional form. "Massive" simply refers to the large number of antennas in the base-station antenna array. "MIMO" refers to the fact that multiple spatially separated users are catered for by the antenna array in the same time and frequency resource.

Massive MIMO also acknowledges that in real-world systems, data transmitted between an antenna and a user terminal—and vice versa—undergoes filtering from the surrounding environment. The signal may be reflected off buildings and other obstacles, and these reflections will have an associated delay, attenuation, and direction of arrival *(Fig. 2)*. There may not even be a direct line-of-sight between the antenna and the user terminal. It turns out that these non-direct transmission paths can be harnessed as a power for good.

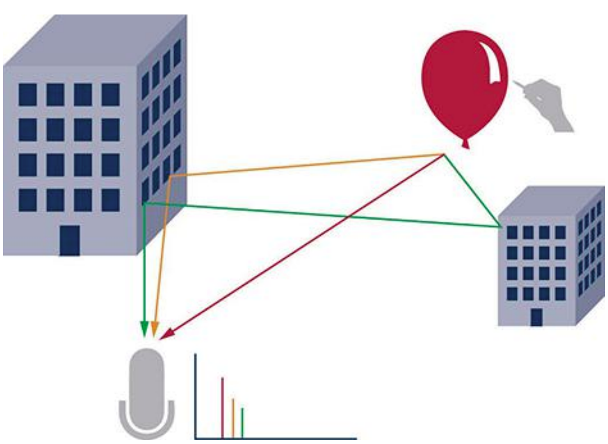
In order to take advantage of the multiple paths, the spatial channel between antenna elements and user terminals needs to be characterized. In the literature, this response is generally referred to as channel state information (CSI). This CSI is effectively a collection of the spatial transfer functions between each antenna and each user terminal. Such spatial information is gathered in a matrix *(Fig. 3)*. The next section looks at the concept of CSI and how it is collected in more detail. The CSI is used to digitally encode and decode the data transmitted from and received by the antenna array.



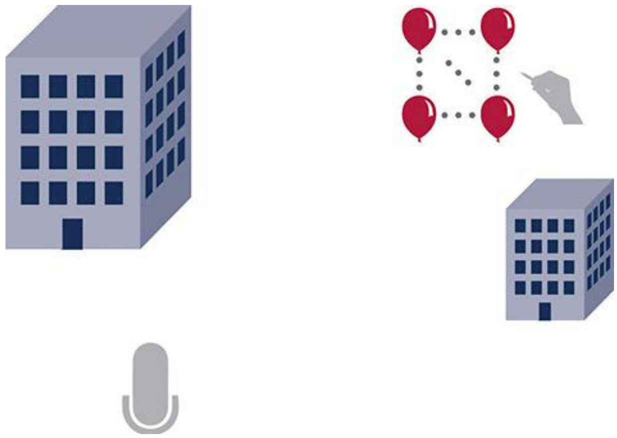
3. Channel state information is needed to characterize a massive MIMO system.

CHARACTERIZING THE SPATIAL CHANNEL BETWEEN BASE STATION AND USER

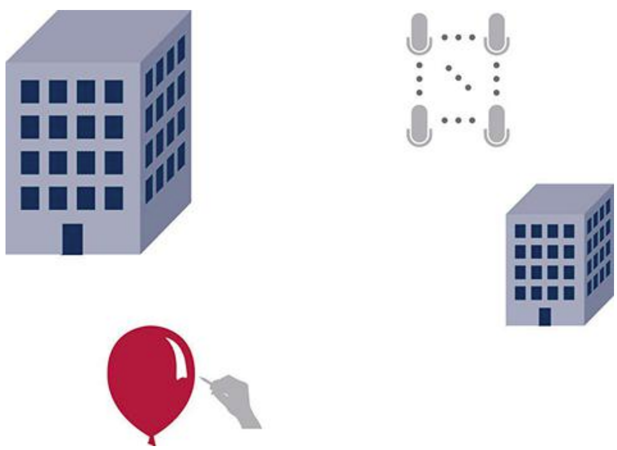
An interesting analogy is to consider a balloon being popped at one location, and the sound of this pop (or impulse) being recorded at another *(Fig. 4)*. The sound recorded at the microphone position is a spatial impulse response that contains information unique to the particular position of both the balloon and the microphone in the surrounding environment. The sound that is reflected off obstacles is attenuated and delayed compared to the direct path.



4. An audio analogy demonstrates the spatial characterization of a channel.



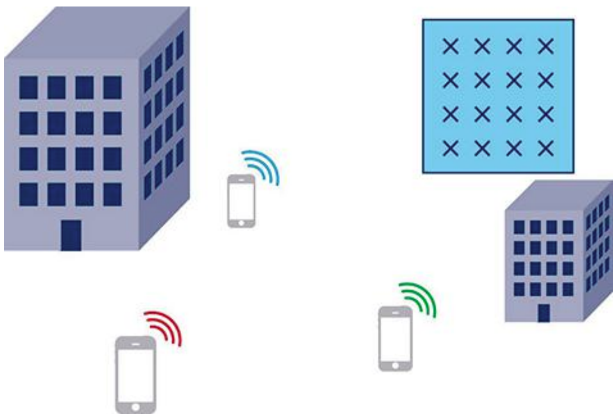
5. This figure is an illustration of an audio analogy for downlink channel characterization.



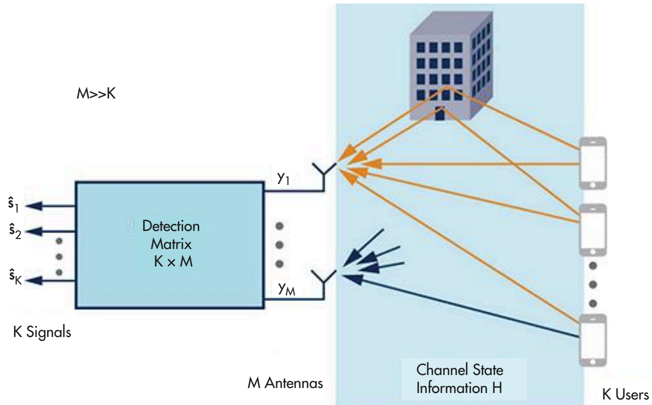
6. Shown is an audio analogy for uplink channel characterization.

If we expand the analogy to compare to the antenna array/user terminal case, we need more balloons *(Fig. 5)*. Note that in order to characterize the channel between each balloon and the microphone, we need to burst each balloon at a separate time so the microphone doesn't record the reflections for different balloons overlapping. The other direction also needs to be characterized *(Fig. 6)*. In this instance, all the recordings can be done simultaneously when the balloon is popped at the user terminal position. This is clearly a lot less time-consuming!

In the RF space, pilot signals are used for characterizing the spatial channels *(Fig. 7)*. The over-the-air transmission channels between antennas and user terminals are reciprocal, meaning the channel is the same in both directions. This is contingent on the system operating in time division duplex (TDD) mode as opposed to frequency division duplex (FDD) mode.

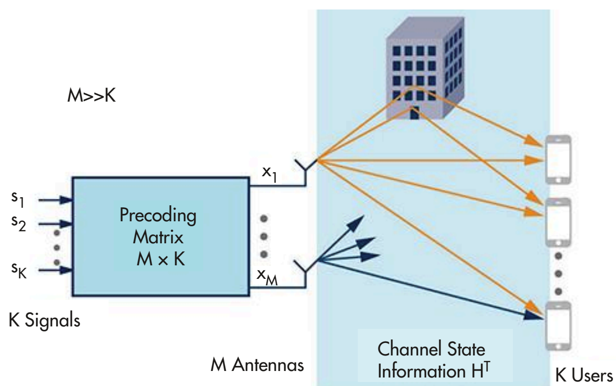


7. **This figure illustrates how each user terminal transmits an orthogonal pilot symbol.**



DETECTION TYPE	
Maximum ratio (MR)	$\hat{s} = H^H y$
Zero forcing (ZR)	$\hat{s} = (H^H H)^{-1} H^H y$
NMSE or RZF	$\hat{s} = (H^H H + \beta \ell)^{-1} H^H y$

8. **Shown is a depiction of uplink signal processing. H denotes the conjugate transpose.**



PRECODING TYPE	
Maximum ratio (MR)	$x = H^* s$
Zero forcing (ZR)	$x = H^*(H^T H^*)^{-1} s$
NMSE or RZF	$x = H^*(H^T H^* + \beta \ell)^{-1} s$

9. **This figure illustrates downlink signal processing. T denotes the transpose, while * denotes the conjugate.**

In TDD mode, uplink and downlink transmissions use the same frequency resource. The reciprocity assumption means the channel only needs to be characterized in one direction. The uplink channel is the obvious choice, as just one pilot signal needs to be sent from the user terminal and is received by all antenna elements.

The complexity of the channel estimation is proportional to the number of user terminals, not the number of antennas in the array. This is of critical importance given the user terminals may be moving, and hence the channel estimation will need to be performed frequently. Another significant advantage of uplink-based characterization is that all the heavy duty channel estimation and signal processing is done at the base station, and not at the user end.

So now that the concept of collecting CSI has been established, how is this information applied to data signals to allow for spatial multiplexing? Filtering is designed based on the CSI to precode the data transmitted from the antenna array so that multipath signals will coherently add at the user terminals position. Such filtering can also be used to linearly combine the data received by the antenna array RF paths so that the data streams from different users can be detected. The following section addresses this in more detail.

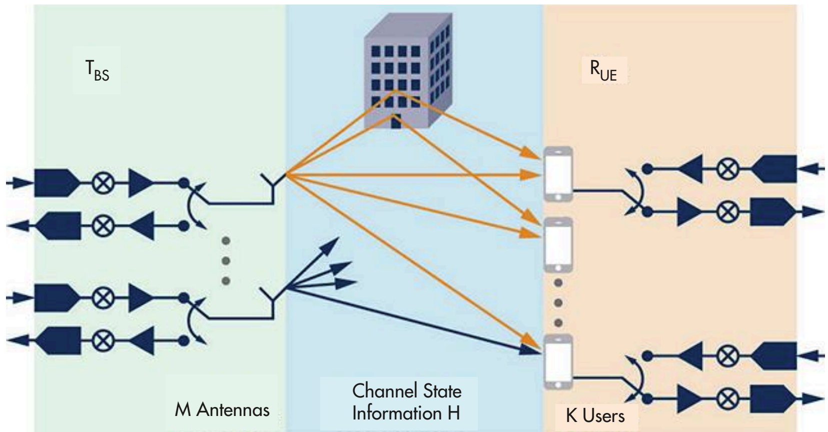
THE SIGNAL PROCESSING THAT ENABLES MASSIVE MIMO

In the previous section we described how the CSI (denoted by the matrix H) is estimated. Detection and precoding matrices are calculated based on H, and there are a number of methods for calculating these matrices. This article focuses on linear schemes. Examples of linear precoding/detection methods are maximum ratio, zero forcing, and minimum mean-square error. Full derivations of the precoding/detection filters from the CSI are not provided in this article, but the criteria they optimize for—as well as the advantages and disadvantages of each method—are discussed. Additional references provide a more detailed treatment of these topics. [1, 2, 3]

Figures 8 and 9 give a description of how the signal processing works in the uplink and downlink, respectively, for the three linear methods previously mentioned. For precoding, there may also be some scaling matrix to normalize the power across the array that has been omitted for simplicity.

Maximum ratio filtering, as the name suggests, aims to maximize the signal-to-noise ratio (SNR). It is the simplest approach from a signal processing viewpoint, as the detection/precoding matrix is just the conjugate transpose or conjugate of the CSI matrix, H. The big downside of this method is that inter-user interference is ignored.

Zero forcing precoding attempts to address the inter-user interference problem by designing the optimization criteria to minimize for it. The detection/precoding matrix is the pseudoinverse of the CSI matrix. Calculating the pseudoinverse is more computationally expensive than the complex conjugate, as in the maximum ratio case. However, by focusing so intently on minimizing the interference, the received power at the user suffers.



10. This figure shows a real-world downlink channel.

Minimum mean-square error tries to strike a balance between getting the most signal amplification and reducing the interference. This holistic view comes with signal processing complexity as a price tag. The minimum mean-square error approach introduces a regularization term to the optimization—denoted as β in Figs. 8 and 9—that allows for a balance to be found between the noise covariance and the transmit power. It is sometimes also referred to in literature as regularized zero forcing (RZF).

This is not an exhaustive list of precoding/detection techniques, but gives an overview of the main linear approaches. Nonlinear signal processing techniques, such as dirty paper coding and successive interference cancellation, can also be applied. Although these techniques offer optimal capacity, they are very complex and difficult to implement.

The linear approaches described are generally sufficient for massive MIMO, where the number of antennas gets large. The choice of a precoding/detection technique will depend on the computational resources, the number of antennas, the number of users, and the diversity of the particular environment the system is in. For large antenna arrays where the number of antennas is significantly greater than the number of users, the maximum ratio approach may well be sufficient.

THE PRACTICAL OBSTACLES REAL-WORLD SYSTEMS PRESENT TO MASSIVE MIMO

When massive MIMO is implemented in a real-world scenario, there are further practical considerations to be taken into account. As an example, consider an antenna array with 32 transmit (Tx) and 32 receive (Rx) channels operating in the 3.5-GHz band. There are 64 RF signal chains to be put in place, and the spacing between the antennas is approximately 4.2 cm given the operating frequency. That's a lot of hardware to pack into a small space. It also means there is a lot of power being dissipated, which brings inevitable temperature concerns. Analog Devices' integrated transceivers offer a highly effective solution to many of these issues. The AD9371 will be discussed in more detail in the next section.

Previously in this article, the application of reciprocity to the system to drastically cut the channel estimation and signal processing overheads were discussed. *Figure 10* shows the downlink channel in a real-world system. It is split into three components: the over-the-air channel (H), the hardware response of the base station transmit RF paths (T_{BS}), and the hardware response of the user receive RF paths (R_{UE}).

The uplink is the opposite, as R_{BS} characterizes the base station receive hardware RF paths. T_{UE} characterizes the user transmit hardware RF paths. While the reciprocity assumption holds for the over-the-air interface, it does not for the hardware paths. The RF signal chains introduce inaccuracies into the system due to mismatched traces, poor synchronization between the RF paths, and temperature-related phase drift.

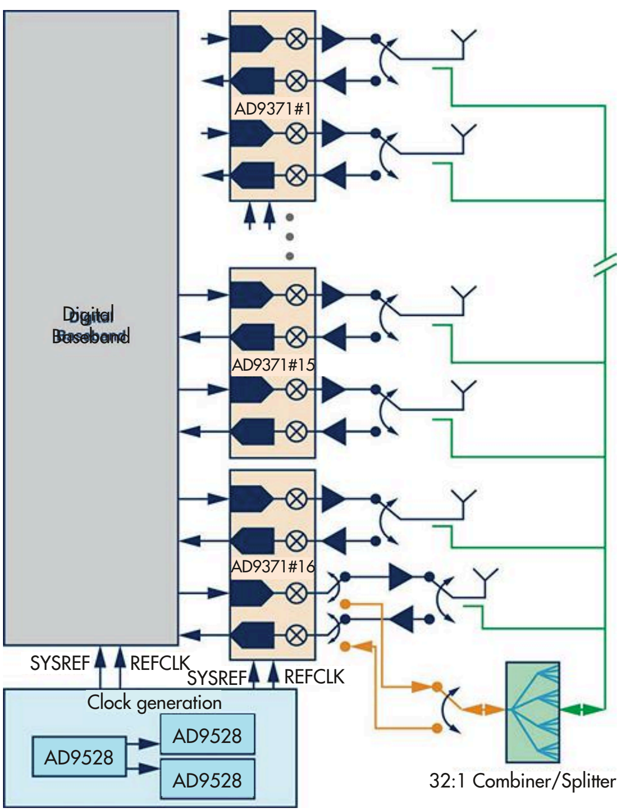
Using a common synchronized reference clock for all local-oscillator (LO) PLLs in the RF paths, and synchronized SYSREFs for the baseband digital JESD204B signals will help address latency concerns between the RF paths. However, there will still be some arbitrary phase mismatch between the RF paths at system startup. Temperature-related phase drift contributes further to this issue, and it is clear that calibration is required in the field when the system is initialized and periodically thereafter. Calibration allows for the advantages of reciprocity such as maintaining the signal processing complexity at the base station and keeping the uplink only channel characterization. It can generally be simplified so that only the base station RF paths (T_{BS} and R_{BS}) need to be considered.

There are a number of approaches one can chose from in calibrating these systems. One is to use a reference antenna positioned carefully in front of the antenna array to calibrate both the receive and transmit RF channels. It's questionable whether having an antenna placed in front of the array in this way is suited to practical base-station calibration in the field.

Massive MIMO spatial multiplexing has the potential to become a game-changing technology in the cellular communications space, allowing for increased cellular capacity and efficiency in high-traffic urban areas.

Another is to use mutual coupling between the existing antennas in the array as the calibration mechanism. This may well be feasible.

The most straightforward approach is probably to add passive coupling paths just before the antennas in the base station. This adds more complexity in the hardware domain, but should provide a robust calibration mechanism. To fully calibrate the system, a signal is sent from one designated calibration transmit channel, which is received by all RF receive paths through the passive coupled connection. Each transmit RF path then sends a signal in sequence that is picked up at the passive coupling point before each antenna, relayed back to a combiner, and then to a designated calibration receive path. Temperature related effects are generally slow to change, so this calibration does not have to be performed very frequently, unlike the channel characterization.



11. Shown is a block diagram of a 32-Tx, 32-Rx massive MIMO radio head that features the AD9371 transceivers.

ANALOG DEVICES' TRANSCEIVERS AND MASSIVE MIMO

Analog Devices' range of integrated transceiver products are particularly suited to applications where there is a high density of RF signal chains required. The AD9371 features two transmit paths, two receive paths, and an observation receiver, as well as three fractional-N PLLs for RF LO generation in a 12-mm × 12-mm package. This level of integration enables manufacturers to create complex systems in a timely and cost-effective manner.

A possible system implementation featuring multiple AD9371 transceivers is shown in *Fig. 11*. This is a 32-transmit, 32-receive system with 16 AD9371 transceivers. Three AD9528 clock generators provide the PLL reference clocks and JESD204B SYSREFs to the system.

The AD9528 is a two-stage PLL with 14 LVDS/HSTL outputs and an integrated JESD204B SYSREF generator for multiple device synchronization. The AD9528s are arranged in a fanout buffer configuration with one acting as a master device, with some of its outputs used to drive the clock inputs and the SYSREF inputs of the slave devices. A possible passive calibration mechanism is included—shown in green and orange—where a dedicated transmit and receive channel are used to calibrate all the receive and transmit signal paths through a splitter/combiner, as discussed in the previous section.

CONCLUSION

Massive MIMO spatial multiplexing has the potential to become a game-changing technology in the cellular communications space, allowing for increased cellular capacity and efficiency in high-traffic urban areas. The diversity that multipath propagation introduces is exploited to allow for data transfer between a base station and multiple users in the same time and frequency resource. Due to reciprocity of the channel between the base station antennas and the users, all the signal processing complexity can be kept at the base station, and the channel characterization can be done in the uplink. Analog Devices' RadioVerse family of integrated transceiver products allow for a high density of RF paths in a small space, making them well suited for massive MIMO applications. mw

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2. Michael Joham, Josef A. Nossek, and Wolfgang Utschick, "Linear Transmit Processing in MIMO Communications Systems," *IEEE Transactions on Signal Processing,* Vol. 53, Issue 8, Aug. 2005.
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(Continued from page 38)

quency of a VCO, YIG, DRO, or other tunable high-frequency oscillator for comparison with the phase of the reference oscillator. By using fractional-N multiplication factors when comparing the phases of the two oscillators in a PLL frequency synthesizer, frequency tuning can be performed with high resolution, in extremely fine tuning steps.

Requirements vary a great deal in terms of bandwidths and tuning ranges, but the goal of most RF/microwave frequency synthesizers is to provide stable, low-noise signals within the frequency band of interest required for tuning a system. Analog frequency synthesizers often use the principles of PLLs to compare the phase of a high-frequency oscillator, such as a VCO or DRO, to that of a lower-frequency reference oscillator such as a TCXO or an OCXO, so that higher-frequency oscillator will take on the frequency stability of the lower-frequency reference oscillator.

APPRECIATING SPECIFICATIONS

Whether using an analog or digital architecture, an RF/microwave frequency synthesizer will achieve some performance levels at the cost of others, such as tuning frequency resolution versus frequency tuning speed. As noted earlier, single-sideband (SSB) phase noise is often a driving performance parameter for many systems since such noise can limit the receive sensitivity and dynamic range of the system. But, depending upon a system's application, other performance parameters may be required.

For example, for a receiver that must be capable of tuning across a wide portion of frequency bandwidth with high speed, such as to detect signal activity in a given bandwidth, frequency tuning speed may be of greater importance ultimately than phase noise, and it may be desirable to fashion a frequency synthesizer with relatively large frequency tuning steps for the sake of achieving high-speed frequency tuning speeds. For portable radio applications, a combination of low phase noise, low spurious noise, and high power efficiency may help a radio to provide the best receive sensitivity for the longest time while operating on rechargeable batteries. The physical size of a frequency synthesizer, especially for a portable system design, is also an important consideration, as well as how well it handles motion and vibration. No one frequency synthesizer type provides an ideal solution for all applications with many tradeoffs to consider depending upon the requirements of an application.

Next month, the second part of this "Engineering Essentials" article on frequency synthesizers will focus on DDS sources and how they differ from analog PLL-based frequency synthesizers, and when and why it might make sense to specify a DDS rather than an analog PLL-based frequency synthesizer for a particular application. mw

JACK BROWNE | Technical Contributor

Spread Spectrum Trims EMI in MEMS Oscillators

These clock sources are available with LVCMOS outputs from 1 to 141 MHz, using several programmable operating parameters to significantly reduce EMI levels.

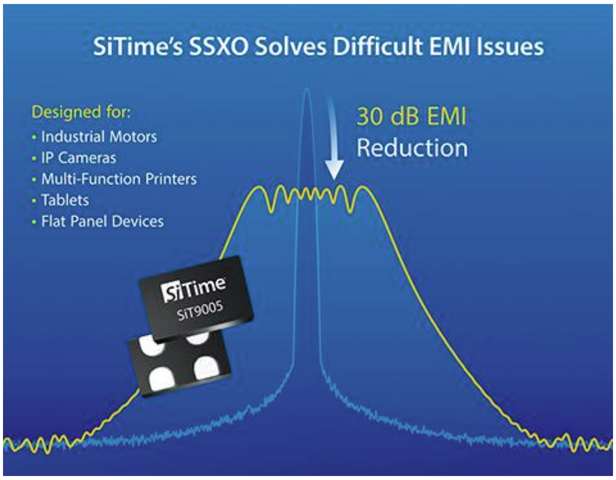
Electronic timing functions are traditionally provided by oscillators based on quartz-crystal resonators, although microelectromechanical-systems (MEMS) oscillators are being applied more often in applications once dominated by quartz-crystal oscillators. MEMS oscillators use mechanical structures, such as miniature tuning forks, to achieve resonant frequencies. MEMS devices are fabricated from silicon semiconductor materials and can be made smaller and operate with less power consumption than quartz crystal oscillators.

In addition, with the application of spread-spectrum techniques, as in the case of the SiT9005 MEMS oscillator from SiTime (www.sitime.com), they can even achieve a significant reduction in electromagnetic interference (EMI) compared to quartz crystal oscillators.

As signal sources, clock oscillators can leak enough EM energy to cause EMI and radio-frequency interference (RFI). In some cases, when clock signal power is high and with fast rise/fall times, sufficient radiation can be generated which can interfere with nearby circuits and/or equipment. Because of this, the FCC sets maximum EMI levels which all electronic equipment must fall below. The SiT9005 helps reduce EMI without additional shielding by using spread-spectrum clock modulation, as well as programmable clock signal rise/fall times.

The MEMS-based SiT9005 provides LVCMOS outputs, available with any frequency from 1 to 141 MHz and with duty cycles ranging from 45 to 55%. The clock oscillator promises as much as 17-dB reduction in EMI for fundamental-frequency outputs and as much as 30-dB reduction in EMI for harmonics. It features outstanding frequency stability of ±20 ppm. The SSXO can be housed in one of three different packages for compatibility with many circuit designs: 2.0 × 1.6 mm, 2.5 × 2.0 mm, and 3.2 × 2.5 mm *(see figure)*.

The SiT9005 is well suited for timing applications in industrial and consumer electronic products—including battery-powered devices, since it operates on low voltages with low current consumption. It is designed for typical supply voltages of +1.8 to +3.3 V dc, with typical current consumption of 5.0 mA for a 40-MHz source running on a +1.8-V dc supply. The typical disable current draw is 4.6 mA for a 40-MHz source running on a +1.8-V dc supply. The typical stand-by current is 0.4 μA for a +1.8-V dc supply, and 2.1 μA for a supply of +2.5 to +3.3 V dc.



The SiT9005 MEMS clock oscillator uses spread spectrum techniques along with programmable rise/fall times for reduced EMI.

For the uninitiated, although MEMS oscillators are essentially mechanical devices, they provide excellent timing stability, with very little jitter or variations between clock cycles. At 40 MHz with spread function on or off and running on a +1.8-V dc supply, the cycle-to-cycle clock jitter is 22 ps or less, and typically only 12.5 ps. For supplies from +2.5 to just under +3.3 V dc, whether the spread spectrum function is on or off, the worst-case cycle-to-cycle jitter is 15 ps and typically 10.5 ps. At +3.3 V dc, with the spread function on or off, the worst-case cycle-to-cycle jitter is 12 ps, and typically 8.5 ps.

The MEMS clock oscillators are RoHS- and REACH-compliant with startup time of 5 ms. They are designed for operating temperatures from –40 to +85ºC for user-selected frequencies from 1 to 141 MHz.

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CHRIS DeMARTINO | Technical Editor

New Embedded Smart Modems Bring Cellular Communication to the IoT

Three new cellular modems were recently unveiled that are intended to allow OEMs to equip their devices with cellular IoT connectivity.

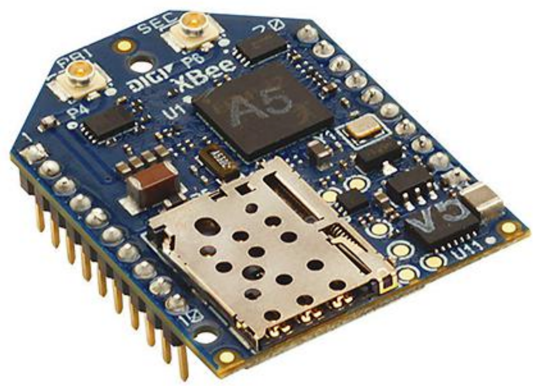
Enabling Internet of Things (IoT) connectivity is a specialty of Digi International (*www.digi.com*), which was formed in 1985 long before the term "IoT" even existed. Among the company's products are Digi XBee RF solutions, which support a number of wireless applications. Digi recently made news by expanding its XBee lineup with the introduction of three new cellular modems (*see photo*).

The new cellular smart modems are the Digi XBee Cellular LTE Cat 1, Digi XBee Cellular LTE-M, and Digi XBee Cellular NB-IoT. According to Digi, the new modems allow original equipment manufacturers (OEMs) to easily integrate cellular connectivity into their devices. Building on the Digi XBee ecosystem, these new products allow the Digi XBee platform to support an even greater number of wireless applications.

Digi XBee Cellular LTE Cat 1 allows OEMs to integrate 4G cellular technology into their devices at a lower price point than previous LTE technologies, according to the company. The Digi XBee Cellular LTE-M and Digi XBee Cellular NB-IoT modems are intended to support the new LTE-M and narrowband-IoT (NB-IoT) technologies, respectively. Both allow for lower costs and extended battery life in IoT applications. Furthermore, Digi XBee Cellular LTE-M is intended for the North American market, while Digi XBee Cellular NB-IoT will find its way into Europe.

Digi XBee Cellular LTE Cat 1 and Digi XBee Cellular LTE-M are both FCC and carrier end-device certified. Thus, OEMs can avoid the cellular certification process. Digi XBee Cellular NB-IoT is CE/RED certified, which makes it ideal for low-power wide-area (LPWA) applications in Europe.

As stated, the new cellular modems allow for easy integration. For example, an OEM may want to design an LPWA device to operate with existing LTE Cat 1 infrastructure. In the future, that OEM could switch to Digi XBee Cellular LTE-M or Digi XBee Cellular NB-IoT with little or no hardware/software redesign.



Shown is one of the recently introduced embedded modems that enable cellular IoT connectivity.

PERFORMANCE FEATURES

The new modems have a number of features, chief among them programmability: Local intelligence can be programmed on the modem itself through the MicroPython interface. The modems are also software-upgradeable to allow for Bluetooth Low Energy (BLE) and Bluetooth Mesh connectivity. In addition, users can take advantage of the advanced manageability features offered by the Digi XCTU configuration tool and the Digi Remote Manager, which enables the management and control of devices from a central and secure platform.

All three modems have the same 20-pin through-hole form factor. Furthermore, each achieves a transmit power level of +23 dBm.

Digi XBee Cellular LTE Cat 1, along with its development kit, will be in available in January 2018. Digi XBee Cellular LTE-M and its development kit will be available in February, while the Digi XBee Cellular NB-IoT modem and development kit will be available in April. mw

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CHRIS DeMARTINO | Technical Editor

New Technology Redefines Channel Emulation for 5G Millimeter-Wave Systems

Researchers at NYU WIRELESS are creating a new channel emulation methodology for 5G systems.

There is no doubt that the New York University (NYU) WIRELESS academic research center is at the very center of 5G research and development *(see "NYU Wireless Drives Next-Generation Technology and Partnership Propels 5G Development" at www.mwrf.com)*. One specific area that is under investigation with regard to 5G millimeter-wave systems is channel emulation. In fact, NYU WIRELESS recently made headlines by revealing that it has developed what is believed to be the first commercial emulator for 5G millimeter-wave systems. While channel emulation has been used for quite some time, this article explains how researchers at NYU WIRELESS are redefining it for 5G.

CHANNEL EMULATION 101

Before discussing channel emulation for 5G systems, it is helpful to first present a brief introduction of channel emulation itself. Aditya Dhananjay, a postdoctoral research fellow at NYU as well as the co-founder and president of MilliLabs *(www.millilabs.com)*, is leading 5G channel emulation efforts at NYU WIRELESS. "Let's says you are building base stations and cell phones and you want to test them," Dhananjay says. "One way of testing them is by doing over-the-air (OTA) field trials.

"You take your base station and cell phone out into the real world and you test them to see how they do in different scenarios," he continues. "Then you can see in the real world if the design is adequate." *Figure 1* shows a basic illustration of OTA testing.

However, OTA field trials have significant drawbacks. "OTA field testing is very time consuming and expensive," Dhananjay explains. "And the amount of data you can get from field trials is extremely limited. Since the design of wireless communication systems is highly iterative, it's not good if the testing stage is extremely long and expensive."

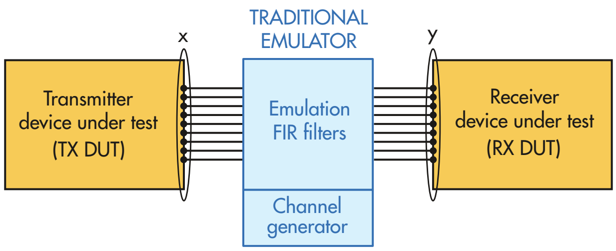
Channel emulation is therefore the common approach for testing wireless systems (*Fig. 2*). "The alternative to field trials is by utilizing what is known as emulation," Dhananjay says. "With emulation, you don't go out into the real world. You keep your transmitter and receiver in the lab and you put an emulator box in the middle.

"Instead of transmitting signals over the air, signals are fed to the emulator using cables," he continues. "The emulator will modify these signals as if they had gone over the real wireless channel. The resulting signals are then fed to the receiver using cables. So you can sit in the lab and program the emulator for different scenarios. The advantages are that you don't have to leave the lab and the results are highly reproducible. You can really test and see where your designs are working and where they are going wrong.

"The bottom line is that emulators are a critical tool," Dhananjay adds. "They have been used for the design of wireless systems for a long

1. This figure is a simple illustration of OTA testing.

time. 2G, 3G, 4G, and Wi-Fi systems have all been developed using channel emulators."



2. Shown is a simple block diagram of a traditional channel emulator.

FOCUSING ON 5G

As mentioned, channel emulators have been used to design wireless systems for a long time. However, the focus now shifts to 5G communications. Are there emulators for 5G systems? The answer is no, says Dhananjay, noting that these systems are going to be fundamentally different from existing wireless technologies.

"The part of the 5G ecosystem we are talking about is millimeter-wave frequencies," he elaborates. "With the millimeter-wave bands, you now have huge amounts of bandwidth. That's the first difference—the bandwidths are extremely large."

He continues: "The second difference is that the number of antennas you are going to have on your transmitter and receiver is extremely large in comparison to 4G systems." Specifically, phased-array antennas are expected to be an important aspect of 5G, as they will be used to overcome the high path losses at millimeter-wave frequencies.

The points mentioned explain why the traditional emulation model is not suitable for 5G systems. "If you were to take the traditional emulation model and just scale it up for 5G systems, there are a number of problems," Dhananjay explains. "You might easily have 256 antennas on the base station side and 64 antennas on the user equipment (UE) side. Surely, you are not going to connect that many cables from the transmitter to the emulator and from the emulator to the receiver—that's not even possible. And even if you had that many cables and wanted to do it, there is no simply no way of connecting cables to a phased-array antenna. So there's no mechanism available to connect the antennas to the emulator."

Furthermore, the challenges actually extend beyond the reasons already stated. "Even if someone comes up with some technology that enables you to connect a phased array to a box using cables, the emulator would still be incredibly hard to build," he adds. "The reason why is the computational complexity of the emulator goes through the roof. If the number of antennas goes up by two orders of magnitude and the bandwidth also goes up by two orders of magnitude, the computational complexity of the emulator goes up by four orders of magnitude."

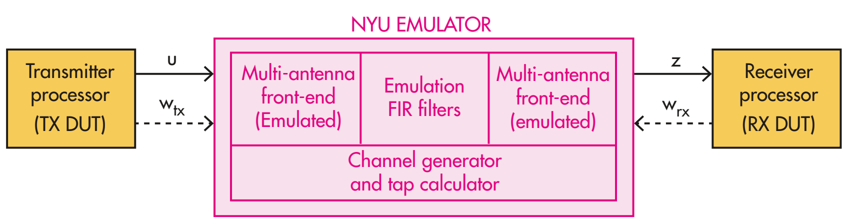
What is the actual meaning of computational complexity with regard to channel emulators? Dhananjay explains: "Computational complexity boils down to multipliers, which are the most basic hardware component that you need to build an emulator. The number of multipliers that you need is actually a function of the number of antennas in the transmitter and receiver. Even if you were to do the emulation in the most efficient manner possible, the number of multipliers you are going to need is huge. So the hardware costs are going to rise and become impossible."

A NEW PARADIGM IN CHANNEL EMULATION

So how exactly can one build a channel emulator for 5G millimeter-wave systems? Dhananjay and his team believe they have the solution. *Figure 3* shows a block diagram of this new 5G emulator, which they say is a "new paradigm" in channel emulation. The most notable difference is that the emulator actually includes the multi-antenna front ends.

"The emulator is going to emulate the antennas in addition to emulating the wireless channel. In this new emulation paradigm, you get rid of the front ends altogether," Dhananjay says. "You take the emulator box and put it in the middle. Instead of the transmitter telling its phased-array which direction to beamform, the transmitter tells the emulator which direction to beamform.

"Similarly," he continues, "instead of the receiver telling its phased-array where to beamform, the receiver tells the emula-



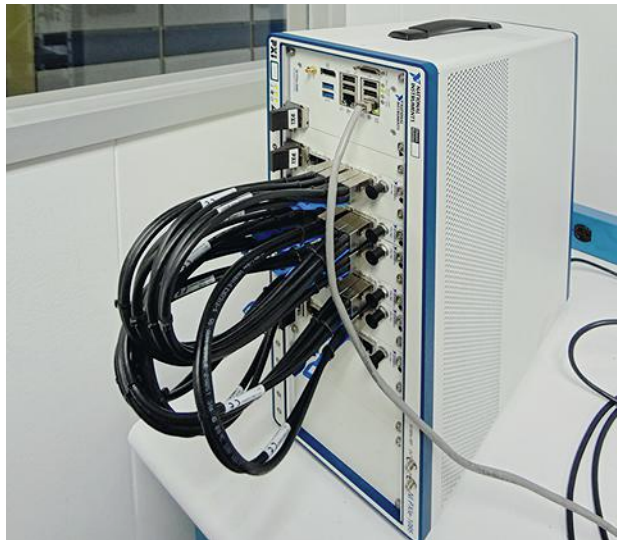
3. This figure illustrates how the multi-antenna front ends are incorporated into the new 5G emulator.

"The emulator is built entirely with commercial-off-the-shelf (COTS) components from National Instruments (NI). In fact, NI gave us this hardware as part of a donation." — Aditya Dhananjay

tor which direction to beamform. Essentially, the emulator not only emulates the wireless channel, but also the phased-array front ends on both sides."

While the team originally built the emulator for internal research, they later realized it has commercial viability. "We built this emulator because we needed a 5G emulator and there were just no solutions out there," Dhananjay recalls. "But then we realized that it actually has commercial promise. The emulator is built entirely with commercial-off-the-shelf (COTS) components from National Instruments (NI). In fact, NI gave us this hardware as part of a donation." *Figure 4* shows the actual 5G emulator hardware.

In summary, Dhananjay and his team are clearly engaged in groundbreaking work in the area of 5G millimeter-wave channel emulation. This article shed some light on the new channel emulation approach for 5G. This area is certainly one to watch as researchers strive to make 5G a reality. mw



4. Shown is the actual emulator hardware that was donated by National Instruments (NI).

Vector Signal Transceiver

(Continued from page 60)

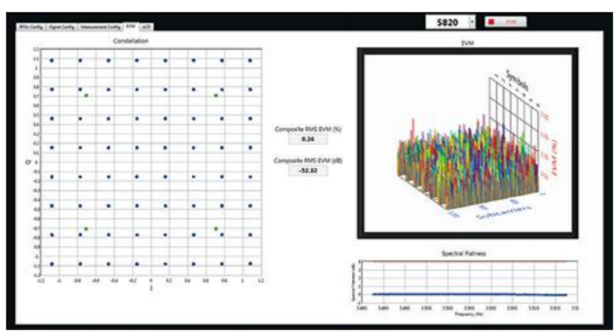
in loopback mode, meaning that its RF input and output ports are similarly connected to each other with a cable.

Figure 3 shows the spectrum of a potential 5G waveform that was created by operating the PXIe-5820 in loopback mode. The figure shows four 100-MHz carriers, resulting in a total bandwidth of 400 MHz. This same functionality can be implemented in the RF VST by selecting the RF model *(top right of Fig. 3)*.

In addition to spectral analysis, the VST test setup allows EVM measurements to be performed by selecting the EVM tab. *Figure 4* shows the PXIe-5820 VST achieving an EVM of less than -52 dB. Again, the same measurements could also be performed using the RF VST.

To sum up, the PXIe-5820 baseband VST is just the latest innovative product from NI. It offers industry-first capabilities and continues to demonstrate NI's position with regard to next-generation wireless technology. mw

3. This potential 5G waveform can be generated by the VST test solution.



4. EVM measurements can also be performed with the VSTs.

Two-Way 90-deg. Power Splitter Handles 200 W from 0.7 to 2.7 GHz

Mini-Circuits' model QCH-272+ is a two-way, 90-deg. power splitter capable of handling power levels as high as 200 W from 700 to 2700 MHz. The 50-Ω power splitter features outstanding amplitude unbalance of ±0.1 dB and phase unbalance of ±0.9 deg. across the full frequency range. The full-band insertion loss is typically 0.3 dB and no worse than 0.5 dB, while isolation between ports is typically 22 dB and no worse than 17 dB. The typical full-band VSWR is 1.15:1. The RoHS-compliant power splitter is well suited for balanced amplifiers and antenna feeds in commercial and military systems. It measures 1.8 × 0.4 × 0.19 in. (45.72 × 10.16 × 2.03 mm) with wrap-around terminations for good solderability. It has an operating temperature range of -55 to +105°C.

LNA Silences Noise from 0.5 to 15.0 GHz

Mini-Circuits' model ZX60-153LN+ is a coaxial low-noise amplifier (LNA) that combines excellent broadband noise figure with high gain from 0.5 to 15.0 GHz. The typical noise figure ranges from 2.1 dB at 2 GHz to 3.7 dB at 15 GHz, while the typical gain is 17 dB with ±2.7 dB gain flatness across the full frequency range. The output power at 1-dB compression (P1dB) is typically +16.4 dBm at 8 GHz while the output third-order intercept point (IP3) is typically +28.3 dBm at 8 GHz. The RoHS-compliant amplifier measures 0.74 × 0.75 × 0.46 in. with SMA connectors and is designed for operating temperatures from -40 to +85°C. It is an excellent candidate for multiband commercial and military receivers, enabling a single amplifier to perform the job of two or three.

2.4-mm Coax Adapter Spans DC to 50 GHz

Mini-Circuits' model 24F-24M+ is a 2.4-mm male-to-female coaxial adapter with low insertion loss and outstanding VSWR from DC to 50 GHz. Capable of mating broadband, opposite-sex connectors and cable assemblies in test equipment and communications systems, the RoHS-compliant coaxial adapters are constructed with passivated stainless-steel body for high long-term reliability. The typical insertion loss is 0.05 dB from DC to 5 GHz, 0.12 dB from 5 to 20 GHz, and 0.20 dB from 20 to 50 GHz. The typical VSWR is 1.10:1 from DC to 5 GHz, 1.03:1 from 5 to 20 GHz, and 1.06:1 from 20 to 50 GHz. The low-cost adapters are designed for operating temperatures from -55 to +100°C and are available from stock.

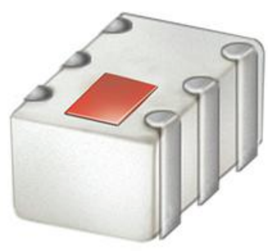
DC Block Connects 10 MHz to 40 GHz

Mini-Circuits' model BLK-K44+ is a wideband coaxial DC block with low insertion loss and excellent return loss from 10 MHz to 40 GHz. The typical insertion loss is 0.06 dB from 10 MHz to 2 GHz and only 0.43 dB from 2 to 40 GHz. The typical return loss is 35 dB from 10 MHz to 2 GHz, 25 dB from 2 to 10 GHz, and 23 dB from 10 to 40 GHz. The RoHS-compliant DC block is equipped with a 2.92-mm male and a 2.92-mm female connector and is a good fit for commercial and military test and communications systems. It handles maximum input power of +33 dBm (2 W) and operating temperatures from -55 to +100°C and is constructed with a stainless-steel body and coupling nut for excellent long-term reliability.

Coaxial SPDT Switch Controls 5 to 6000 MHz

Mini-Circuits' model ZSW2-63DR+ is a reflective, coaxial, single-pole, double-throw (SPDT) RF switch that handles typical input power to +36 dBm (4 W) at 1-dB compression from 5 to 6000 MHz. The typical insertion loss is 0.33 dB from 5 to 1000 MHz, 0.6 dB to 2500 MHz, 0.9 dB to 5000 MHz, and 1.1 dB to 6000 MHz. The typical isolation between the RF common port and either switch port is 39 dB from 5 to 1000 MHz, 30 dB to 2500 MHz, 22 dB to 5000 MHz, and 18 dB to 6000 MHz. Isolation between the two switched ports is typically 40 dB from 5 to 1000 MHz, 32 dB to 2500 MHz, 20 dB to 5000 MHz, and 18 dB to 6000 MHz. The solid-state switch offers typical switching speed of just 6 µs and operates on a single supply of +2.3 to +4.8 V dc. It measures 2.00 × 1.50 × 0.60 in. (50.8 × 38.1 × 15.23 mm) and is designed for operating temperatures from -40 to +85°C. The switch is equipped with three female SMA RF connectors and a 9-pin D-sub connector for DC power and control and is a good fit for ATE applications.

LTCC Balun Transformer Handles 240 to 770 MHz



Mini-Circuits' model NCS2-771+ RF balun transformer provides an impedance ratio of 2:1 (secondary; primary) from 240 to 770 MHz, making is a candidate for a wide range of applications where conversion from a 50-Ω single-ended line to a 100-Ω. balanced line is needed. It handles input power to +33 dBm (2 W) with low insertion loss of typically 0.2 dB across the full frequency range. Fabricated on low-temperature cofired ceramic (LTCC), the RoHS-compliant balun transformer achieves typical full-band amplitude unbalance within 0.5 dB and typical full-band phase unbalance within 5 deg. (relative to 180 deg.) It is supplied in an 0805 package measuring 0.079 × 0.049 × 0.037 in. (2.0 × 1.24 × 0.94 mm) and capable of handling operating temperatures from -40 to +85°C.

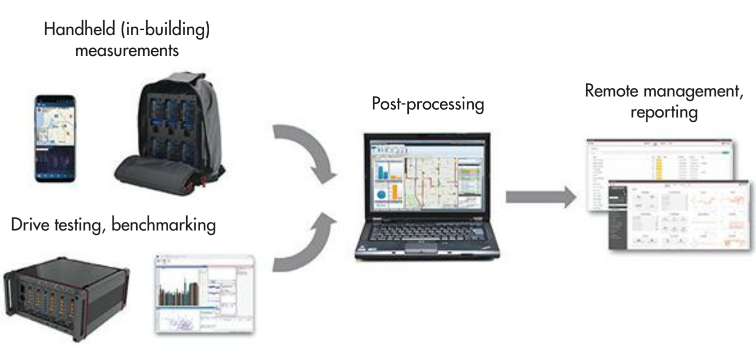
ADITYA KASARANENI | Sales Engineer, Keysight Technologies
www.keysight.com

OPEX/CAPEX Pressure Drives e2e Automation of RF Measurements

Wireless network testing can take advantage of automation to deliver an end-to-end (e2e) solution that improves quality and lowers costs.

From the beginning stages of LTE network deployment to the impending roll-out of 5G, we've observed a rather significant evolution in wireless network testing. Such testing has transformed from being data-collection and post-processing centric to being an automated solution that performs end-to-end (e2e) processes. In other words, data collection, remote management, and post processing are all contained in a single process flow *(Fig. 1)*. An increase in urgency, complexity, capital expenditure (CAPEX)/operating expenditure (OPEX), and competition are a few of the drivers behind this evolution.

For example, distributed-antenna-system (DAS) installations and deployments typically require special permissions and limited time to access venues, making it critical to ensure that the turnaround time for system verification is quick and without glitches. On the macro-cell segment with pre-post launch optimization and site verifications, an engineer was traditionally required to monitor the drive test gear with another "coordinator," controlling when and what types of test measurements needed to be made.



1. Measurements, post-processing, and remote managing and reporting all merge into one automated flow.

MINIMIZING ERRORS AND SAVING OPEX WITH AUTOMATION

Typically, tasks revolve around coordinators sending the different files to the drive test engineers; ensuring version compatibility; communicating start/stop times pertinent to maintenance windows; checking in real-time over phone or text on the progress; and managing measurement data. Typically, at this point, the coordinator transitions to interface with a "post-processing" team. This team provides information concerning measurement data availability for post-processing and tracking progress to ensure the report is received by pertinent personnel.

Overall, significant human intervention is needed that is not only primarily OPEX-heavy, but also introduces the possibility of user errors along the way. This could easily become a big problem when project deliveries are extremely time-critical, which is normally the case.

TAKE THESE FOUR STEPS TO ACHIEVE E2E MEASUREMENT SUCCESS

To successfully utilize an automated RF measurement solution, four basic issues must be resolved to result in quality of end-user experience (QoE) and offer possibilities for direct OPEX savings:

- Automation
- Integrity
- Real-time analytics
- Integration

Automation: Remove and restrict human intervention in all possible areas of the process

The basis is built around a centralized, web-based service to seamlessly enable remote control and management of measurement fleets. Measurement and analytics products are integrated. A single user

can control nationwide measurement campaigns, reducing and eliminating the need for dedicated drive test engineers, coordinators, and manual post-processing.

Integrity: Identify potential failures as and when they happen

In a complex system that involves hardware and software, failures are certain to happen and should be expected. The key is to be able to identify these problems when they happen and issue alerts to quickly fix them. This requires a system that provides automated processes to address such failures. It should have advanced, customizable alerting mechanisms that allow for failures to be addressed before they affect the project.

Real-time analytics: Access network measurement data, make changes, and validate results in real-time

Smooth management is enabled by advanced dashboards for monitoring and real-time reporting. This way, a user can, in real-time, visualize the performance of the network, make changes, and validate them. Customized alerts simplify this process by identifying scenarios automatically.

For example, a user can configure custom alerts to identify areas with good reference signal received power (RSRP) but poor signal-to-noise ratio (SNR), and troubleshoot with real-time parameter changes and validation. Add to it the ability of an enterprise-level analytics system to pipe in core network data, correlate with drive test data, and provide customizable dashboards that have correlated data from both RAN and Core networks.

Integration: Consolidated view of processed information from multiple sources

It's typical to run into situations where RAN optimization is gated by core network issues that don't show up in RAN measurement data. At the same time, the root-cause detection in these cases can be a cumbersome process. Seamless integration of any type of core network data with RAN measurement data, along with customizable analytics, is enabled by analytics solutions.

CUSTOMER CASE 1: NETWORK VENDOR WITH MANAGED SERVICE CONTRACT

Issue: Customer collects data from numerous drive test teams in the country and the data is downloaded for further post-processing. Once downloaded, the report generation takes days, with the possibility for corrupted data and failures in measurements. The current process is error-prone, as manual work brings the possibility of mistakes in the process and requires rework to be done.

Solution: Implementation of a cloud-based solution for remote management of drive-test measurements with fully automated report generation.

Benefit: Less errors in drive test measurements, leading to cost savings due to less re-drives. An improved quality of network is made possible thanks to more exact measures that enable exact troubleshooting. Reporting times have gone from days to hours, giving troubleshooting and optimization teams a more real-time picture of LTE network status, again improving network quality. The time reduction enables direct OPEX savings.

CUSTOMER CASE 2: OPERATOR WITH NEED FOR CONTINUOUS REAL-TIME BENCHMARKING

Issue: Customer faces churn and needs to understand in more detail where network issues reside compared to the competition. Customer must swiftly troubleshoot and improve network quality.

Solution: Implementation of a cloud-based solution for remote management of autonomous unattended measurement solutions located in vehicles across the region, combined with automated reporting.

Benefit: Remote management of autonomous measurement probes, combined with automated reporting, enables the operator to obtain an overarching, real-time view of the network in comparison to the competition. Instant troubleshooting in challenging areas can be initiated and network improvement projects better targeted, ultimately focusing on improved network quality, increased customer satisfaction, and reduced churn. The condensed dashboard view of the network can easily be distributed at various levels of management and operative personnel throughout the company.

SUMMARY

The constant cost pressure and evolving measurement needs have changed the nature of RF measurements. The focus today is an automated, single-process flow that performs e2e processes from data collection, to remote management, to post processing. The nature of such full-scale solutions is complex and requires integration between various measurement and analytics products. Instead of starting integration efforts from scratch, it is more effective to search for a single vendor solution, hence ensuring smoother setup and faster time to benefits.

The error-proneness of the old approach shouldn't be underestimated. A variety of problems can crop up when companies perform drive testing and optimization: Errors in file naming, connecting to projects, selecting files manually, and sending files to incorrect folders.

Keysight's Nemo Cloud, combined with its Nemo-branded RF measurement and analytics products, provide a solid base for automated e2e measurements that include drive testing, benchmarking, in-building measurements, and minimizing errors. The end results are process (time and quality) improvements and OPEX savings. mw

FOR MORE information on Keysight's Nemo-branded RF measurement and analytics solutions, please visit www.keysight.com/find/nemo.

CHRIS DeMARTINO | Technology Editor

Copper Mountain Technologies Takes 1-Port VNAs to the Next Level

Handheld vector network analyzers (VNAs) are a specialty of Copper Mountain Technologies. This article takes a closer look at the R180, the company's latest model.

When thinking of RF/microwave test-and-measurement equipment, bulky benchtop instruments are what often come to mind. However, some manufacturers are now offering smaller, portable test instruments. One company that is known for building test instruments in small sizes is Copper Mountain Technologies *(www.coppermountaintech.com)*, which specializes in vector network analyzers (VNAs). One of the company's product lines currently on the market is the Cobalt series of VNAs. Copper Mountain also offers a product line of 1-port VNAs which, in its own words, delivers "lab-grade performance in a handheld device."

The company was kind enough to loan me an R180 1-port VNA, the newest addition to the 1-port VNA product line *(Fig. 1)*. Introduced earlier this year, the R180 covers a frequency range of 1 MHz to 18 GHz. It is well suited for both cable and antenna measurements, among other use cases. Material testing is another specific usage of note.

While the standard model is equipped with a type-N male connector, customers can also choose to purchase the R180 with a type-N female, 3.5-mm male, or 3.5-mm female connector. Furthermore, the R180 has the significant advantage of being able to connect directly to a device-under-test (DUT). Thus, a test cable is not required to perform measurements.

18-GHZ VNA IN YOUR HAND

The obvious first impression of the R180 VNA is its size, as it can essentially fit in the palm of your hand. One can easily carry the VNA from one location to another. Moreover, the R180 connects to a laptop or desktop computer via a USB cable. Once the VNA is connected to a computer, Copper Mountain's software application enables the measurement values obtained by the VNA to be displayed on the computer screen.

1. The R180 can cover frequencies from 1 MHz to 18 GHz.

The software application is very simple to download. While the company provided a USB drive that contained the software, anyone can also simply download the software from Copper Mountain's website. Once the software is installed and the VNA is connected, operation should be relatively easy for anyone who has prior experience using a VNA.

Figure 2 shows the software application upon starting it with the VNA connected. Typical VNA functions can be seen in the figure, such as *Scale, Trace, Calibration, Marker*, and many others. As an example, clicking on Scale subsequently displays a number of options that users can choose, such as *Scale, Auto Scale, Ref Value,* and *Ref Position*. All of these options are obviously familiar to those who have previously used a VNA.

2. The software application allows users to easily select various VNA functions.

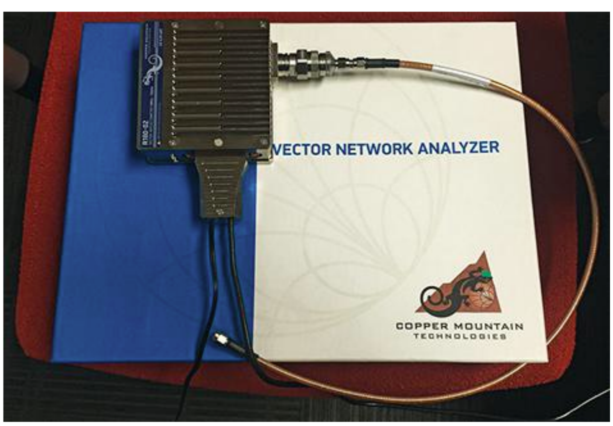
Turning on the Demo Mode displays a virtual VNA measurement without an actual DUT connected to the VNA. This feature essentially allows one to explore the software and its capabilities without even needing an actual unit to test.

In addition, clicking the Trace button allows users to choose a number of data display formats, including *SWR, Return Loss, Cable Loss*, and *Smith Chart*. Distance-to-fault (DTF) measurements are also made possible by selecting either the *DTF SWR* or *DTF Return Loss* formats. In addition, *Phase* and *Expanded Phase* are two additional data display formats. In summary—and reiterating an earlier point—the software application is relatively easy to use.

The software application also allows users to save measurement values as touchstone files. Creating a touchstone file is essentially as simple as a few mouse clicks. Of course, this feature enables one to incorporate the measured values obtained from the R180 in a software simulation tool of choice.

Furthermore, anyone who has used a VNA knows how essential calibration is. Copper Mountain offers a selection of automatic calibration modules, as well as several mechanical calibration kits. For the example shown later, calibration was carried out using a 3.5-mm mechanical calibration kit with female connectors.

One additional point that should be mentioned in regard to the software application is the *Demo Mode* feature. Turning on the *Demo Mode* displays a virtual VNA measurement without an actual DUT connected to the VNA. This feature essentially allows one to explore the software and its capabilities without even needing an actual unit to test. No doubt, this feature could certainly be helpful to some users.

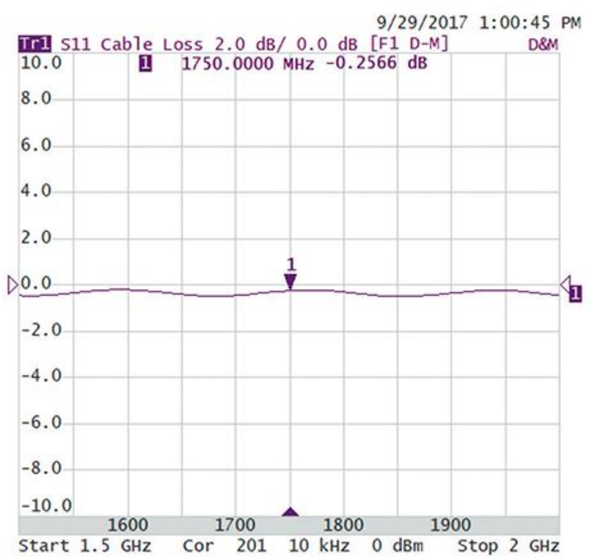


3. Cable loss can be performed with the R180.

SIMPLE CABLE MEASUREMENT

As stated, cable measurements represent one area of use for the R180. *Figure 3* shows the R180 being used to measure the loss of an 18-in. SMA cable. *Figure 4* illustrates a plot of the cable's loss from 1.5 to 2.0 GHz. It should be stated that the operating manual for the R180 contains step-by-step instructions to measure the loss of a cable such as the one shown. The example presented in the manual is a 30-m coaxial cable.

The R180 is certainly a worthy product for anyone in need of a handheld VNA to measure cables, antennas, and more. Not only can the VNA fit in one hand, the software is easy to use and offers the features needed for effective measurements. It is clear that Copper Mountain has a winning product with the R180. mw



4. The software application can display cable loss plots such as the one shown.

Website Offers Windows to Millimeter-Wave World

SAGE MILLIMETER HAS upgraded its web site to provide ease of access to more than 2500 millimeter-wave products covering 18 to 170 GHz. Products range from components to test equipment and visitors to the site can view full data sheets and performance plots. Visitors who register an account also receive pricing information and can take advantage of rapid delivery of in-stock items, receiving those products within three business days. The extensive lines of millimeter-wave components include amplifiers, antennas, attenuators, filters, mixers, and oscillators.

SAGE MILLIMETER INC., 3043 Kashiwa St., Torrance, CA 90505; (424) 757-0168, *www.sagemillimeter.com*

FET Probe Provides 1.2-GHz Bandwidth

THE CT4121 IS a compact FET probe with high input resistance, low input capacitance and 1.2-GHz bandwidth well suited for timing analysis and checking high-speed logic circuits. It handles voltages to ±40 V with ±2% accuracy. It is compatible with oscilloscopes from all major manufacturers and can be powered by an included 9-V battery or by a USB connection from the oscilloscope. The probe provides 10× attenuation and a power indicator LED.

CAL TEST ELECTRONICS, 22820 Savi Ranch Pkwy., Yorba Linda, CA 92887; (888) 256-2246, (714) 221-9330, *www.caltestelectronics.com*

VCO Delivers High Output at 4 GHz

THE DCSR4000-8 VOLTAGE-CONTROLLED oscillator (VCO) provides a 4-GHz output with at least +4.5 dBm output power. It operates from tuning voltages of 0.5 to 8.0 V dc with typical tuning sensitivity of 6 MHz/V. The VCO draws maximum current of 32 mA at +8 V dc. It features -18 dBc typical harmonic suppression with typical phase noise of -109 dBc/Hz offset 10 kHz from the carrier. Designed for operating temperatures of -40 to +85°C, it is supplied in a miniature, surface-mount-technology (SMT) package.

SYNERGY MICROWAVE CORP., 201 McLean Blvd., Paterson, NJ 07504; (973) 881-8800, *www.synergymwave.com*

GaN Amp Powers 0.7 to 6.0 GHz

THE TA1164 BROADBAND solid-state power amplifier provides at least 10 W CW typical output power and 20 W typical saturated output power from 0.7 to 6.0 GHz for test and military jamming applications. Based on GaN technology and equipped with internal DC conversion, it operates from a voltage supply of +12 to +36 V dc. The amplifier provides 35-dB typical gain with 3-dB typical gain flatness. It draws 3.5 A typical current and exhibits 16 dB typical input return loss. Quiescent current draw is typically 2.8 A. The amplifier features typical switching time of 1 us. It measures 4.9 × 4.7 × 2.08 in. with SMA female connectors and weighs 19 oz. without an optional heatsink. It is designed for operating temperatures from -40 to +85°C.

TRIAD RF SYSTEMS INC, 11 Harts Lane, E. Brunswick, NJ 08816; (855) 558-1001, *www.triadrf.com*

Attenuator Has 32-dB Control from 26 to 40 GHz

THE A3P-85N-3AM is a digitally controlled PIN diode attenuator with a 32-dB attenuation range from 26 to 40 GHz. It provides attenuation control in 0.125-dB steps with ±2.5-dB attenuation flatness. The 50-Ω attenuator exhibits 2.0:1 VSWR with 4-dB insertion loss. It is controlled via 8-b TTL-compatible binary logic with switching speed of 1 µs. It is supplied in a package measuring 2.0 × 2.5 × 0.75 in. and handles +15 dBm CW input power and 1 W (+30 dBm) maximum input power.

G.T. MICROWAVE INC., 2 Emery Ave., Randolph, NJ 07869; (973) 361-5700, *www.gtmicrowave.com*

Waveguide-to-Coaxial Adapters Reach 110 GHz

A LINE OF WAVEGUIDE-TO-COAXIAL adapters covers a frequency range of 1.7 to 110.0GHz in 21 waveguide bands from WR-10 to WR-430 consisting of 89 models. The adapters support 13 different types of coaxial connectors for satcom, radar, and telecom applications. They are available in a wide range of waveguide sizes and flanges with VSWR as low as 1.15:1.

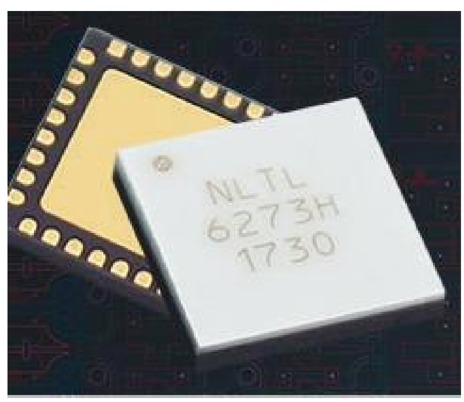
PASTERNACK ENTERPRISES, 17802 Fitch, Irvine, CA 92614; (949) 261-1920, *www.pasternack.com*

GaN PA Boosts 2 to 6 GHz

MODEL SSPA 2.0-6.0-250 is a GaN power amplifier (PA) that delivers 250 W nominal output power and 300 W saturated output power from 2 to 6 GHz. It features 20 to 25% CW power efficiency with 70-dB typical small-signal gain. The worst-case input and output VSWR is 2.0:1. The PA achieves on/off switching times of 10 µs or better and meets MIL-STD-810 requirements for shock and vibration. It is equipped with reverse-polarity, over-temperature, and over/under-voltage protection functions.

AETHERCOMM INC., 3205 Lionsgate Ave., Carlsbad, CA 92010; (760) 208-6002, *www.aethercomm.com*

MMIC Comb Generator Shaves Phase Noise to 5 GHz



THE NLTL-6273SM is a MMIC nonlinear-transmission-line (NLTL) comb generator with low phase noise and harmonics. It generates output signals from 0.7 to 5.0 GHz, with usable overtones to 24 GHz. The comb generator is based on GaAs Schottky varactor diodes and housed in a 5 × 5 mm QFN surface-mount-technology (SMT) package. The residual phase noise measured for fifth-harmonic output signals generated from a 1-GHz, +23-dBm input signal is -120 dBc/Hz offset 1 Hz from the carrier, -150 dBc/Hz offset 1 kHz from the carrier, and–170 dBc/Hz offset 100 kHz from the carrier. Maximum harmonics are -24 dBc for a 1-GHz input and -12 dBc for a 2-GHz input. The comb generator, which is designed for use with input signals at levels from +16 to +26 dBm, has an operating temperature range of -55 to +100°C.

MARKI MICROWAVE INC., 215 Vineyard Ct., Morgan Hill, CA 95037; (408) 778-4200, *www.markimicrowave.com*

Package Holds Pair of GaN-on-SiC Transistors

RFMW, LTD. is now providing design and sales support for the QPD2731 Doherty power device from Qorvo. It combines two GaN-on-SiC transistors in a single package to maximum gain, efficiency, and linearity. Suitable for wireless macro base stations, it provides 50 W average output power from 2.5 to 2.7 GHz when operating from a +48-V dc supply. It delivers 316 W peak Doherty output power with Doherty gain of 16 dB and Doherty drain efficiency of 60% when providing average power of +47.5 dBm. The RoHS-compliant device is supplied in a four-lead earless ceramic flange package.

RFMW LTD. (QORVO STOCKING DISTRIBUTOR), 188 Martinvale Lane, San Jose, CA 95119; (408) 414-1450, *www.rfmw.com*

COTS Amplifier System Withstands MIL-STD Screening

THE SKU 2126 power amplifier system is a commercial-off-the-shelf (COTS) design that is fully tested to MIL-STD-810 for shock, vibration, temperatre, and humidity as well as MIL-STD-461E for EMI/RFI. It operates from 20 to 500 MHz with 1 kW saturated output power and 800 W output power at 1-dB gain compression. The typical gain is 60 dB, with a gain adjustment range of 20 dB. Worst-case second- and third-harmonic levels are -20 and -10 dBc, respectively, with worst-case spurious levels of -60 dBc. The rugged power amplifier system can be supplied in configurations for AC or DC supplies.

EMPOWER RF SYSTEMS INC., 316 W. Florence Ave., Inglewood, CA 90301; (310) 412-8100, *www.EmpowerRF.com*

Rack-Mount Amp Delivers 50 W from 0.7 to 6.0 GHz

THE HPA-50W-63+ is a rack-mount, broadband high-power amplifier that provides as much as 50 W (+47 dBm) saturated output power from 700 to 6000 MHz. It features +43 dBm typical output power at 1-dB compression with output third-order intercept point of typically +50 dBm. It offers 56 dB typical gain with 97 dB typical reverse isolation and is well suited for test applications, including reliability testing and EMI and antenna testing. The RoHS-compliant amplifier, which is supplied in a 3U-high rack-mount enclosure with internal fans and a number of self-protection functions, runs on ac line power of 85 to 264 V. The amplifier is designed for maximum input signal level of +5 dBm and operating temperatures of 0 to +50°C.

MINI-CIRCUITS, P.O. Box 350166, Brooklyn, NY 11235-003; (718) 934-4500, *www.minicircuits.com*

GaN Amplifier Module Powers 6 to 18 GHz

THE BME69189-50 is a solid-state power-amplifier (PA) module based on GaN technology for applications from 6 to 18 GHz. It provides more than 50 W typical output power at 3-dB compression with 47-dB typical gain across the full bandwidth. The gain flatness is within ±4 dB. The Class AB linear PA module exhibits maximum input/output VSWR of 2.0:1. It features typical second- and third-harmonic distortion of better than -15 and -25 dBc, respectively, with better than -60 dBc spurious performance. The DC-to-RF efficiency is typically 14%. The PA module measures 6.56 × 3.50 × 0.84 in., weighs 1.5 lbs. or less, and is supplied with field-replaceable SMA female input and output RF connectors. It is designed for operating temperatures from -40 to +55°C.

COMTECH PST, 105 Baylis Rd., Melville, NY 11747; (631) 777-8900; *www.comtechpst.com.*

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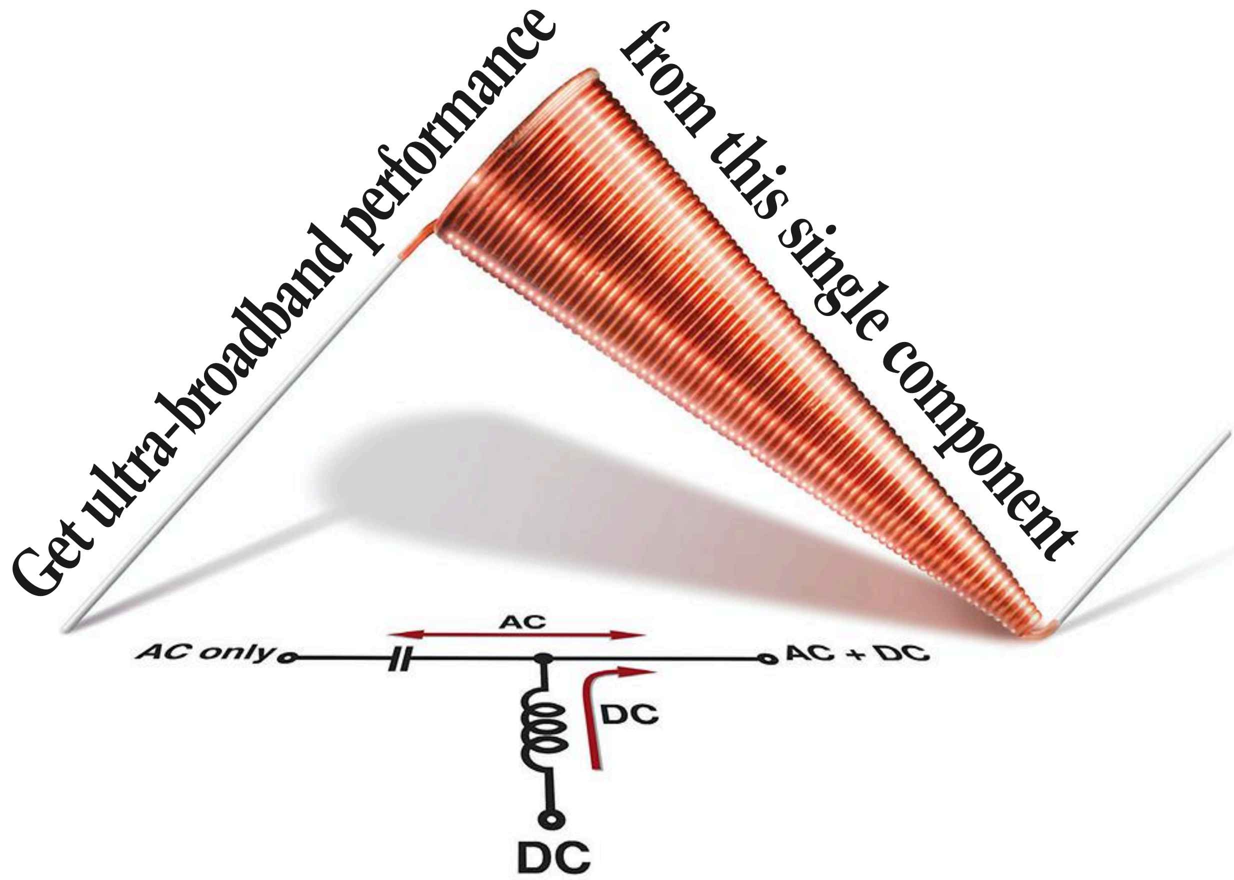

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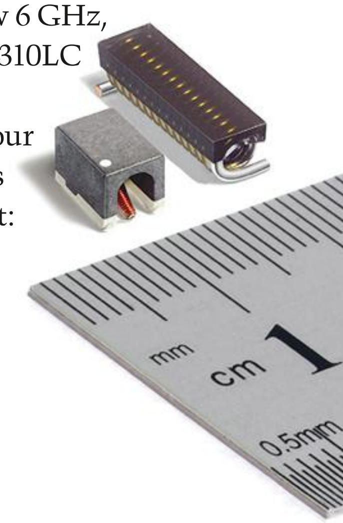

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