Software Tools Lay Foundation For Creating Complete Radar-System Models p29

Smartphone Manufacturers Looking To Latest RF Front-End Solutions To Satisfy Challenges p66

EW Threat Emulation System Brings Realism to Benchtop EW System Design Verification p72

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Switching Speed: Measured 0.25 µs

Model: DTA-22G28G-50-CD-1

Package Size: 1.8" x 1.15" 0.4"
DC Voltage: +15 VDC @ 25 mA
Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
Control: 11-Bit TTL
Switching Speed: Measured 450 ns

http://www.pmi-rf.com/Products/attenuators/DTA-100M40G-30-CD-1.htm
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Model: DTA-18G40G-50-CD-1:

Package Size: 2.0" x 1.8" x 0.5"
DC Voltage: +15 VDC @ 38 mA
Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
Control: 10-Bit TTL
Switching Speed: Measured 120 ns

Model: DTA-26R5G40G-30-CD-1:

Package Size: 2.0" x 1.8" x 0.5"
DC Voltage: +15 VDC @ 38 mA
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Control: 10-Bit TTL
Switching Speed: Measured 0.30 µs

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Model Number	Frequency Range (GHz)	Insertion Loss (dB Max)	Atten Range (dB)	LSB (dB)	Atten Accuracy	Operating Input Power
DTA-100M40G-30-CD-1	0.1 to 40.0	8.0	0 to 30	1.0	±2.5 dB Typ	+20 dBm
DTA-22G28G-50-CD-1	22.5 to 27.5	2.2	1 to 51.175	0.04	±1.0 dB Max	+10 mW CW
DTA-18G40G-50-CD-1	18.0 to 40.0	8.5	0 to 50	1.0	±2.0 dB Typ	+24 dBm CW
DTA-26R5G40G-30-CD-1	26.5 to 40.0	6.0	0 to 30	0.03	±2.0 dB Typ	+24 dBm CW

Phase Shifters:

http://www.pmi-rf.com/Products/MWC/standardmodels.htm#PhaseShifters

Model: PS-360-3237-8-292FF:

Digital

Package Size: 1.8" x 1.15" 0.4"
DC Voltage: +15 VDC @ 20 mA
-15 VDC @ 10 mA
Connectors: 2.92mm (F) & 15 Pin Micro-D-Female
Control: 8-Bit TTL
Switching Speed: Measured 450 ns

Model: PS-30G40G-180-A-292FF:

Analog

Package Size: PE2 Housing 1.08" x 0.71" x 0.29"
DC Voltage: 0 V = Reference
+5 V = 180º
Connectors: 2.92mm (F)

http://www.pmi-rf.com/Products/phaseshift-biphasemod/phaseshifters/PS-360-3237-8-292FF.htm
http://www.pmi-rf.com/Products/phaseshift-biphasemod/phaseshifters/PS-30G40G-180-A-292FF.htm

Model Number	Frequency Range (GHz)	Insertion Loss (dB)	Phase Shift (°)	LSB (°)	Amplitude Error	Phase Shift Error
PS-360-3237-8-292FF	32.0 to 37.0	13.0	358.59375°	1.40625°	±1.5 dB Typ	± 5.0° Typ
PS-30G40G-180-A-292FF	30.0 to 40.0	4.0	180º Typ	Analog	1.5 dB Typ	15º Typ

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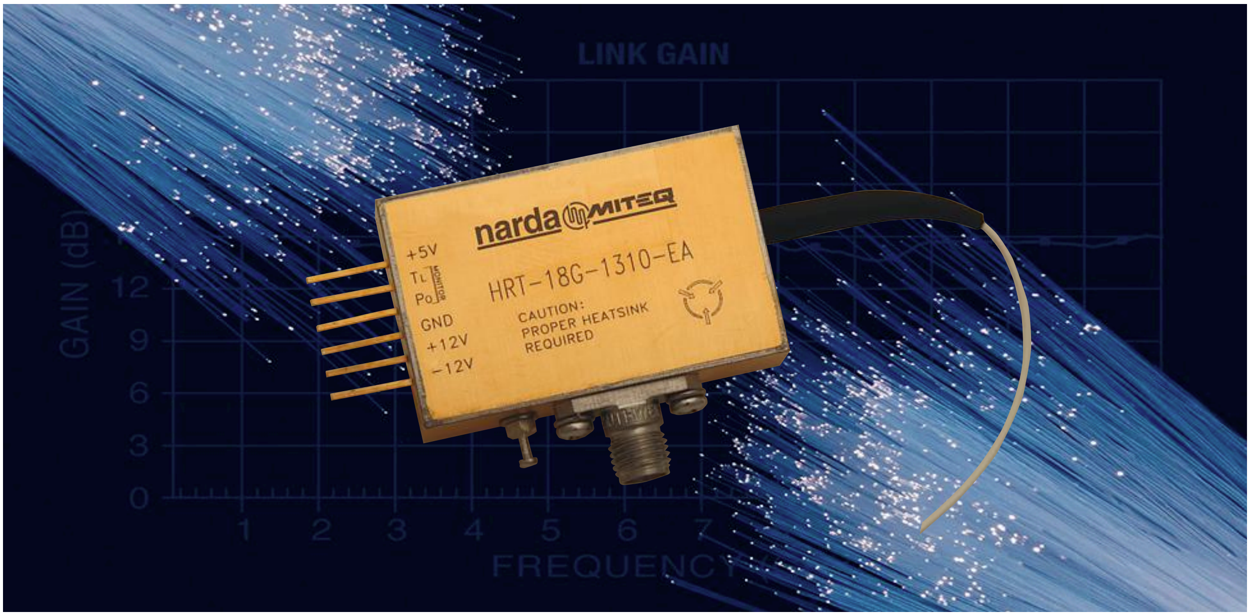

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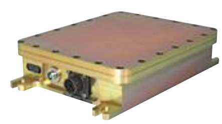

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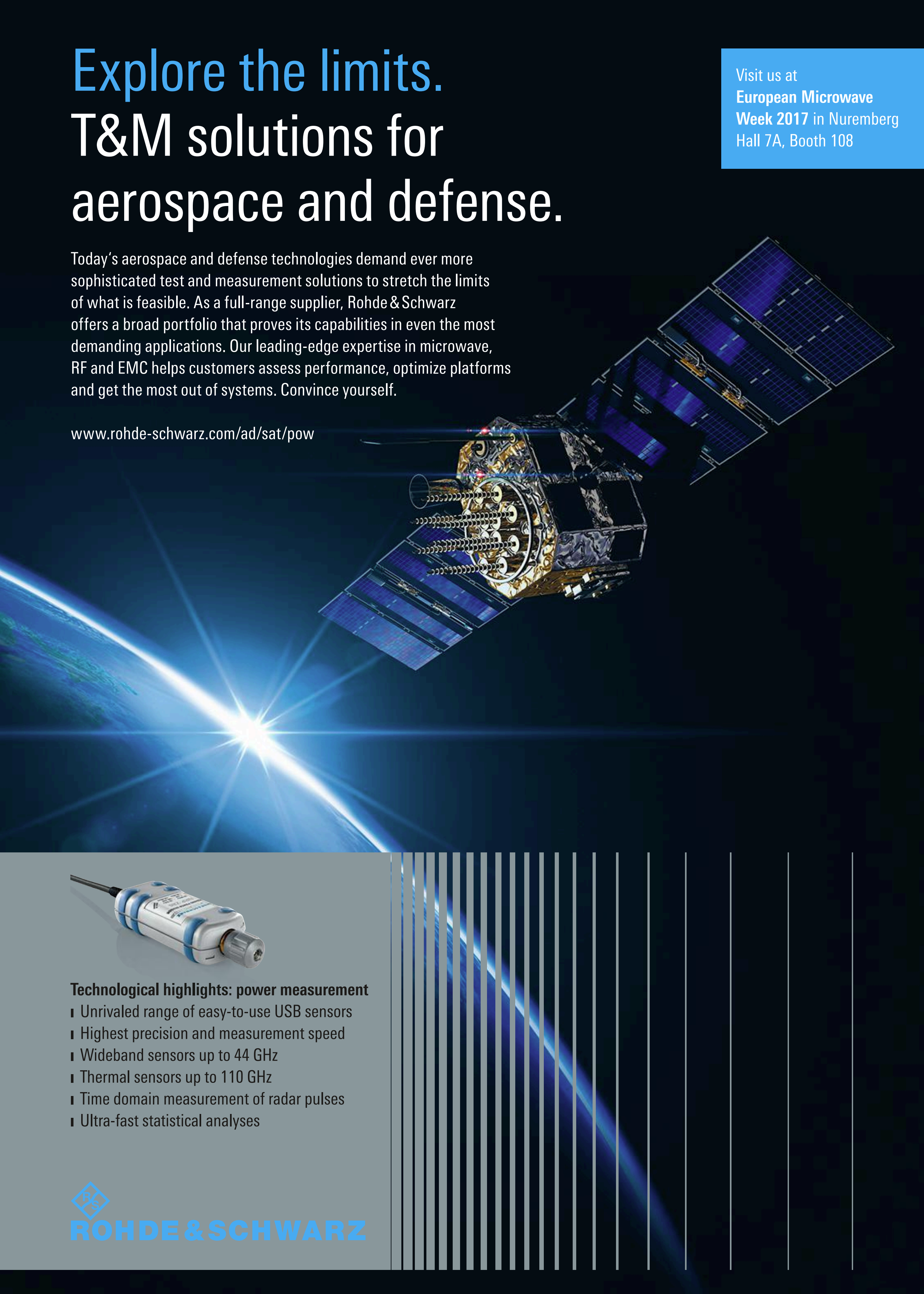
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August 2017 VOLUME 56, ISSUE 8 Microwaves&RF

IN THIS ISSUE

FEATURES

39

45

63

PRODUCT TECHNOLOGY

NEWS & COLUMNS

72

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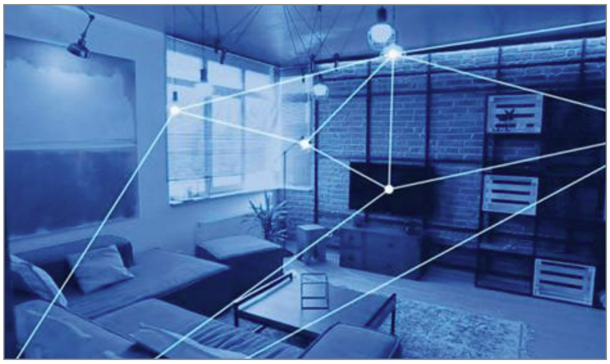


How Bluetooth Mesh Impacts IoT Design

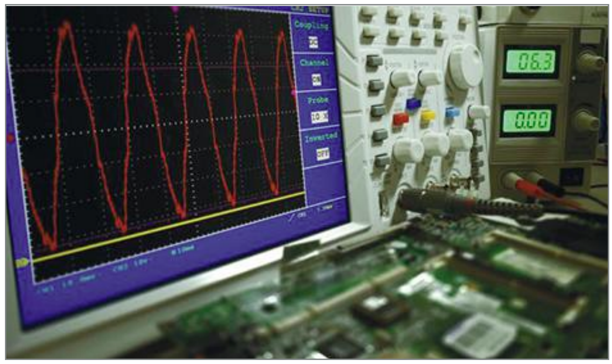
Bluetooth is the oldest and most widely used short-range wireless technology today. With billions of chips sold during its 20-plus years of existence, Bluetooth is found in an impressive array of other products. Now with the addition of its new mesh option, Bluetooth is ready to continue its dominance of the short-range space.

http://www.mwrf.com/systems/how-bluetooth-mesh-impacts-iot-design

Millimeter-Wave Radars in Autonomous Vehicles

Autonomous vehicles: one of today's most fascinating new technological developments. It's crazy to think that newer cars are currently becoming "smart" and are helping us humans avoid potentially fatal accidents. What's even more fascinating is that these smart cars are being developed to completely drive on their own without the help of a driver. So what's the main ingredient behind this autonomous vehicle technology? A millimeter-wave radar.

http://www.mwrf.com/systems/top-advantages-and-challenges-millimeter-wave-radars-autonomous-vehicles



Comparing VNA Performance and Price

Vector network analyzers (VNAs) have long been symbolic of the RF/microwave industry—the one instrument that is only used in the high-frequency industry, and only by those with exceptionally high test-and-measurement budgets. But that has changed in recent years, with more and more engineers finding value in VNA measurements, and more users finding VNAs that are affordable while also providing the performance they need.

http://www.mwrf.com/test-measurement/comparing-vna-performance-and-price

Radar Systems Make History

Radar is an essential electronic system for any military force, whether at land, sea, or in the air. This technology began prior to World War II, helping to turn the tide in favor of the Allied Forces. More than 70 years later, radar systems are becoming more invaluable as part of global EW and ECM efforts.

http://www.mwrf.com/systems/radar-systems-make-history

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Editorial

CHRIS DeMARTINO | Technical Editor
chris.demartino@penton.com

Do Engineers Need Engineering Publications?

Do today's engineers actually need engineering publications? Perhaps a better question is this: How much of the information being published today is helping engineers be more effective in terms of doing their jobs? Between online and printed material, there is no question that a ton of information is being created all the time. But how much of that information is actually useful to engineers? That question is likely to produce a wide range of answers.

Of course, delivering quality information to its audience should be the goal of any media outlet. In the engineering realm, the massive amount of information for engineers to sift through seems to have no end. But does high quantity also translate to high quality? While the internet and social media can produce more content today, just how valuable is that content? How much of today's information is "good" information and how much of it is "not-so-good"?

Another issue concerns the amount of time that engineers have to go through all of the information being made available. With new information to choose from every day, do engineers even have the time to examine it all? Obviously, the answer is "probably not."

With busy schedules, many engineers will simply not be able to do too much with all of the information at their disposal. And if some information is good and some is not, just sorting out one from the other will take time. And even if all of the information is valuable (hold your sarcasm), time constraints would prevent engineers from taking advantage of it all anyway.

At Microwaves & RF, we certainly hope that engineers are benefitting from the information we provide. But how much do engineers depend on us to do their jobs? In other words, is this publication something that engineers read closely? Or does it just get tossed aside without ever being read at all? I'm sure that our subscriber list includes those who do both—with everything in between.

With all of that being said, I hope that the "good" outweighs the "not-so-good" and that our content helps those who choose to read it.

Let me know your thoughts at chris.demartino@penton.com. mw

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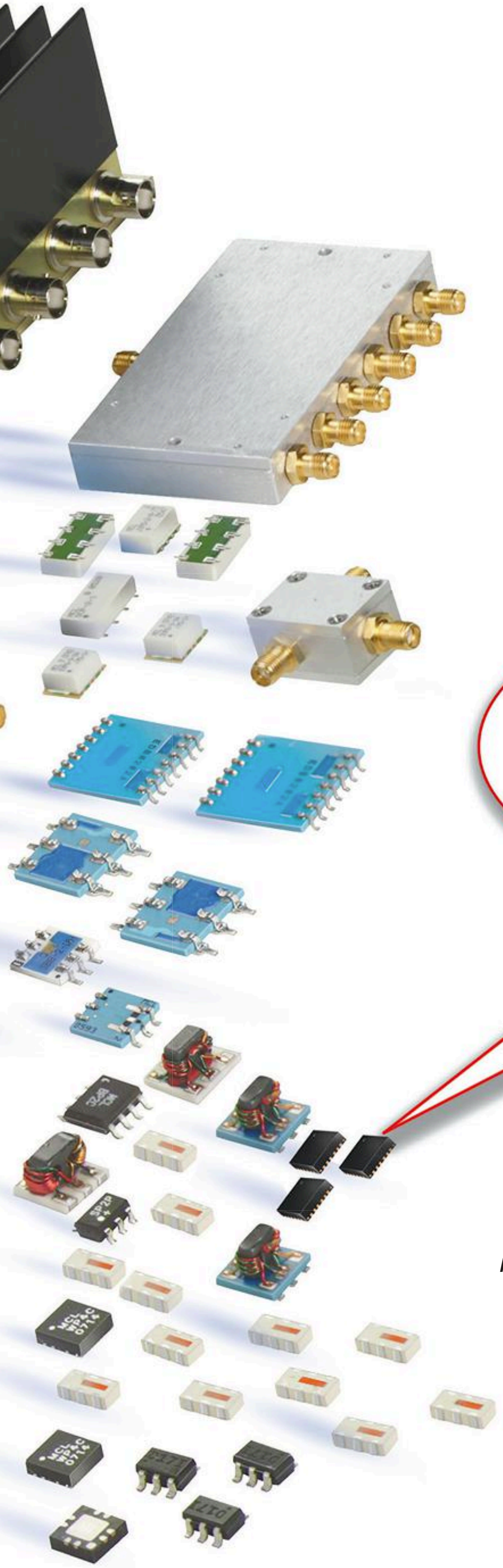


Book Review

JACK BROWNE | Technical Contributor

Defense & Aerospace Electronics 101: The 7 Key Technology Areas of Defense Electronics

MODERN ELECTRONIC DEFENSE TECHNOLOGY will be receiving hearty funding from the current administration, as President Trump seeks to maintain this nation's technological superiority and leadership position on the global military stage. The RF/microwave industry plays a small but vital role in the "upkeep" of military electronics systems, providing electronic solutions— typically at the component, test, and software levels—based on electromagnetic (EM) energy.

These technology contributions fit into the bigger plans of major defense contractors, which develop the complex systems needed by our military troops and allies to stay at least one step ahead of the enemy. Keeping track of the technologies involved is not easy, but a new e-book from *Microwaves & RF, Defense & Aerospace Electronics 101: The 7 Key Technology Areas of Defense Electronics*, provides a quick and easy way to cover a lot of ground in the latest defense technologies.

Sponsored by Anritsu Co., this fast-paced e-book breaks military electronics into seven broad areas: electronic warfare (EW); radar; GNSS, GPS, and navigation; UAVs and drones; IR technology and applications; tactical radio communications; and antennas and phased arrays. For old-timers wondering why systems providing electronic countermeasures (ECM) and surveillance are not on the list, they can be found in the chapter on EW. The e-book is organized with a great deal of overlaps because of the nature of inter-system dependence among military electronic systems.

The e-book is by no means all-inclusive of the massive amount of electronic technology comprising military electronic systems. Rather, it is a starting point for anyone curious about how different defense systems work, with explanations provided in a way that is accessible on many different educational levels. Those involved with testing military electronic systems and their various analog and digital components will find the e-book of particular interest, since each chapter concludes with a look at the various measurement techniques to characterize equipment in that particular technology area. The e-book is available for download as a PDF at *www.mwrf.com*. mw

News

Startup Makes Case for Software-Defined Antennas USING METAMATERIALS

Pivotal Commware, a startup based in Bellevue, Wash., claims to have cracked the code to affordable phased-array antennas that beam communications signals directly into devices, instead of blanketing radio waves over broad areas..

The company's antennas rely on metamaterials instead of costly components that have confined the technology to the defense and aerospace sectors for decades. The antennas act like a platform for what Pivotal calls holographic beamforming, which acts like a traffic signaling system for radio waves to increase the throughput of 4G and 5G networks.

"In that sense, it is a software-defined antenna," said Eric Black, Pivotal's chief technical officer and a former Boeing scientist, in a phone interview. "Because you can shape the radio pattern of the antenna using software, you don't need to physically go out and reconfigure the antenna."

Pivotal, which was founded in 2016 and raised $17 million in June from investors including Bill Gates, is the fourth metamaterials spinoff from investment firm Intellectual Ventures. Founded by former Microsoft chief technology officer Nathan Myhrvold, the firm has stockpiled over 200 patents for metamaterials, which bend light, sound, and radio waves in unnatural ways.

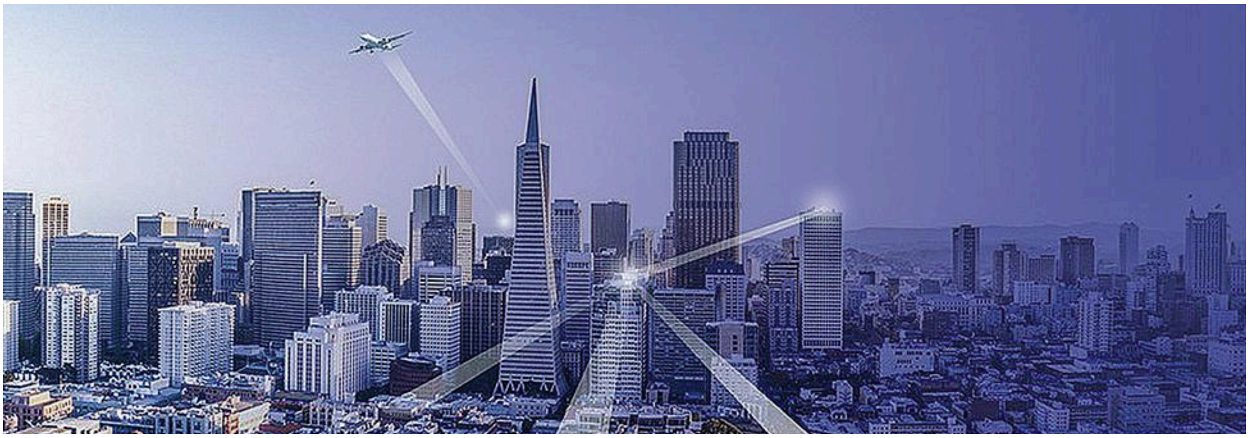
The concept of phased-array beamforming is a century old. But traditional phased arrays need bulky and expensive phase shifters to dynamically control antenna beams. MIMO systems, in which two or more transmitter and receivers coordinate to beam signals into multiple devices, require digital signal processors (DSPs) that consume lots of power.

Pivotal's antennas are more streamlined. "Instead of phase shifters or DSP radios, we use this very simple switched control antenna element, which could be as simple as a varactor or field-effect transistors," Black said. "Our cost is lower, size is thinner, weight is lower, and power consumption is lower."

Pivotal's metamaterial antennas consist of a printed circuit board covered in metal cells smaller than the wavelength of the radio waves being manipulated. The control software activates antenna elements to scatter radio waves into beams with all the normal characteristics of a radiating aperture, which allows the same spectrum band to be reused by multiple beams simultaneously.

The software changes the properties of the antenna by pointing out where to apply dc biases, which can switch control elements within a microsecond. The antennas suppress side-lobes that could cause interference, improving spectral efficiency or how much data can be transmitted to a certain number of smartphones or other devices.

With holographic beamforming, signals can travel further with higher gain. That would be particularly useful to prevent



millimeter waves to be used in 5G networks from being blocked by buildings and from fading over just a few kilometers. Black said that the company had prototype antennas that span 500 megahertz to 60 gigahertz.

Pivotal's value proposition is that its beamforming antennas boost throughput for cellular networks and provide a cheaper way to haul information between base stations instead of using fiber optic cable. The antennas could also reduce base stations along shores for connecting ships, along tracks for trains, and across the country for airplanes and drones.

"We think that travel—whether by plane, train, or ship—shouldn't be a broadband dead zone," said Brian Deutsch, Pivotal's chief executive, after the company announced its funding round in June. "In this market, broadband connectivity worthy of the name means continuous tracking by high gain beams with electronic-speed beam switching."

Pivotal has already turned heads. For the last year, it has been reaping revenue from a contract with an in-flight wireless provider for airplanes. "End of last year, I'm sitting down with accountants trying to figure out whether this pre-Series A start-up is going to have to pay taxes or not," Deutsch said in an interview. He declined to identify the customer.

Pivotal is not alone is trying to spruce up electronically scanning arrays. Torrance, Calif.-based Thinkom supplies the phased array antennas used for Gogo's in-flight communications system, but its platform mechanically rotates a series of internal resonating plates to assist in directing radio beams. Pivotal's are completely electronic and can conform to curved surfaces.

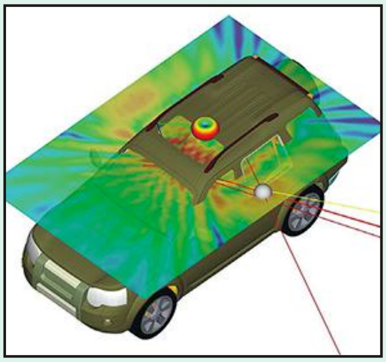
With the $17 million in funding, Pivotal plans to aggressively grow its 20-person workforce and expand the facilities where it does development work. The company is also looking to hire software programmers to help make it easier for wireless companies to add holographic beamforming to current cellular networks, Black said.

Other Intellectual Ventures spinoffs include Kymeta, which has raised $217 million in funding over the last five years to develop metamaterial antennas for satellite communications. The other two are Echodyne and Evolv Technology, which sell radar vision systems and airport security scanners, respectively. Together, they have raised $73 million. ■

ANSYS ACQUIRES SOFTWARE FIRM That Brings Simulations to Life

ANSYS, WHICH SELLS popular tools for simulating and analyzing antennas, announced that it had acquired Computational Engineering International, whose software creates realistic views of simulation data destined to be logged in databases or plotted on graphs.

The company's flagship software, called Ensight, is used for computational fluid dynamics, which can replicate wind curling over car bodies and visualize chemicals swirling through an oil refinery. But ANSYS views that software as a platform that could extend to its entire product portfolio, including tools that predict how electromagnetic fields sprout from antennas.



ANSYS' flagship software, called Ensight, is used for computational fluid dynamics, which can replicate wind curling over car bodies and visualize chemicals swirling through an oil refinery.

In an interview, Mark Hindsbo, vice president of ANSYS' design and platform business unit, did not promise specific product changes. But he offered examples of what could be done with Ensight integrated into electromagnetic tools like HFSS, which uses mathematical programs called solvers to flag emissions and coupling issues.

For example, engineers could clearly see how antennas inside drones react to pockets of interference and wireless dead zones. The visualization tools could make it easier to assess how antennas installed on cars cope with interference in cities. Hindsbo said that some partners had already used Ensight and ANSYS electromagnetic solvers together.

"But that is not a product plan, not something we are going to ship tomorrow," Hindsbo said, adding that both companies were meeting this week to discuss what simulation tools—other than those for computational fluid dynamics—could benefit from Ensight's visual prowess.

ANSYS already runs post-processing on its simulation data, but it is not on the same level as CEI's software. Going forward, the two businesses will plan products together closely, Hindsbo said.

Still, microwave and radio frequency engineering seems ripe for the Ensight treatment. As cars and factory equipment start chatting wirelessly, engineers are increasingly using simulation software for antenna prototyping and placement. But these simulations can generate terabytes of data, which CEI's software could make easier to understand.

CEI, which split from supercomputing firm Cray in 1994, has only 28 employees but more than 750 customers in markets like aerospace and automotive. The company, based in Apex, N.C., sells software that turns complex data generated by simulations into animations that run in simulated real-world environments.

"The next generation of products will not be built without simulation up and down the product development cycle, from early concepts to digital twins that run until production," Hindsbo said. CEI's tools will help

(Continued on page 24)

PEREGRINE SEMICONDUCTOR FURTHER Fills Out Executive Ranks

PEREGRINE SEMICONDUCTOR SHUFFLED its executive deck for the second time this year, creating two roles to guide its silicon strategy for front-ends inside smartphones and other wireless gadgets.

Early this month, the company announced its new vice president of engineering, Keith Bargoff, who oversaw Peregrine's technology platforms the last two years. It has also hired Sumit Tomar, a former general manager of Qorvo's wireless infrastructure business, as vice president of product marketing.

The new hires follow another series of executive edits. In March, Peregrine hired Stefan Wolff, former head of Intel's mobile communications business, to be chief executive. Chris Cable, the former chief, slid into the chief technology officer role and also became global director of research and development at Peregrine's parent Murata.

At the same time, Dylan Kelly assumed the chief operating officer role after six years as general manager of Peregrine's mobile wireless solutions business. He said in a statement on Tuesday that Peregrine's growing roster of engineers and products required a new leadership structure.

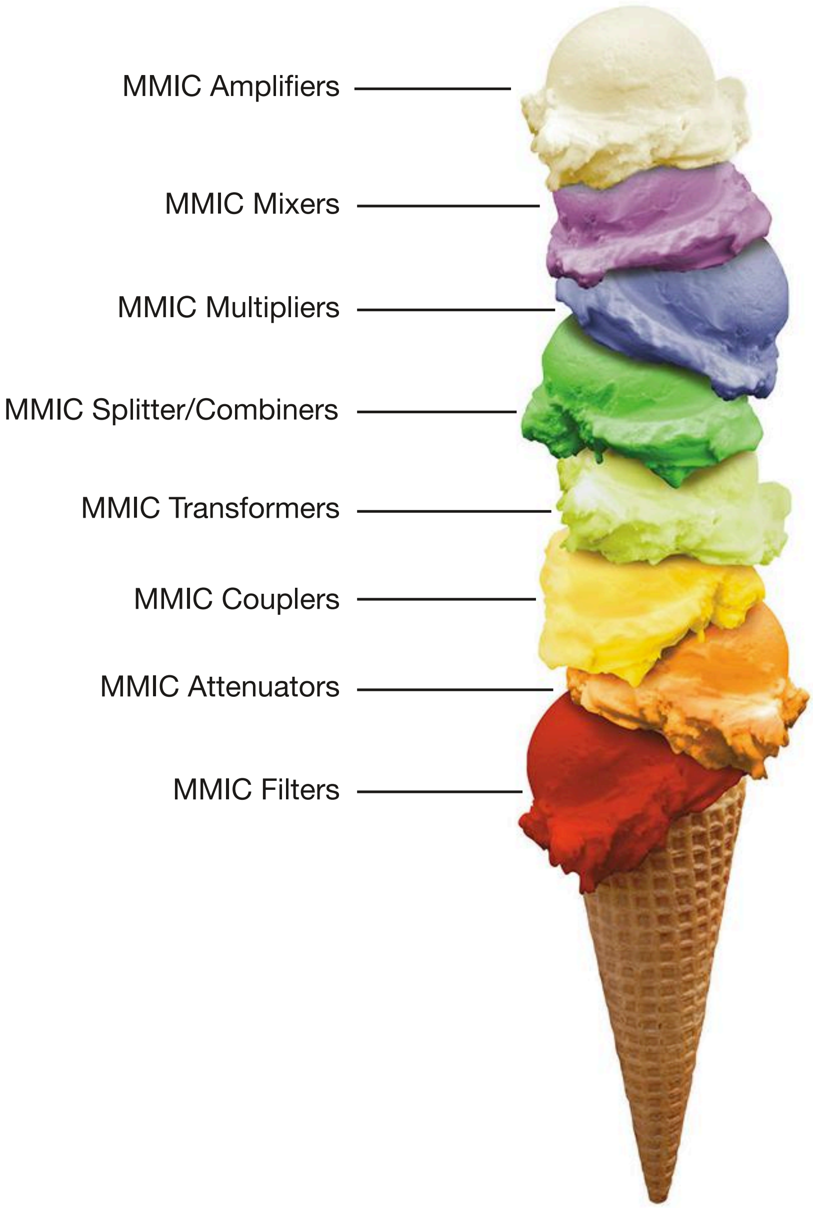
Taken together, the recent executive changes are among the biggest since Murata paid $471 million for Peregrine's business in 2014. It was a sizable bet on the company's silicon-on-insulator products—more commonly called RF SOI—which can compress the growing complexity of wireless parts that handle a wider range of frequency bands.

These chips involve bonding silicon to both sides of an insulator to reduce parasitic capacitance, allowing power amplifiers and wireless filters to be etched on the same front-end device. That results in cheaper and smaller chips, which have slowly chipped away at the hegemony of gallium arsenide (GaAs) at higher frequencies in smartphone and aerospace applications.

Others are also betting on the technology. GlobalFoundries, one of the biggest contractors for manufacturing chips, said in February that it would start accepting orders for its latest RF SOI manufacturing process. Last year, Soitec began baking RF SOI wafers measuring 300 millimeters, up from the 200mm wafers that it had previously sold to foundries like TowerJazz and TSMC.

Soitec says that more than 20 billion chips struck from its RF SOI wafers have been sold worldwide.

Kelly, Peregrine's chief operating officer, said that the company has "aggressive" plans for growth and is now looking to fill 35 new engineering jobs. In February, it opened a 13-person development center in Austin, Texas. ■



Mini-Circuits

The other guy

(Continued from page 21)

apply that data more intelligently and present it visually, so that both engineers and executives can grasp it, he added.

ANSYS has already been moving toward simulating antennas in the virtual world. Two years ago, the company acquired Delcross Technologies, whose software lets users not only analyze individual antennas and other parts but also simulate how those parts can affect the ability of a smartphone or car to transmit and receive data.

CEI's software could shed light on a further question: "How do the electromagnetics change if you alter the layout of a fighter jet or car now that you are bouncing between geometry and electromagnetics and the environment?" Hindsbo said. "Those are places where you can speculate on the effects of visualization."

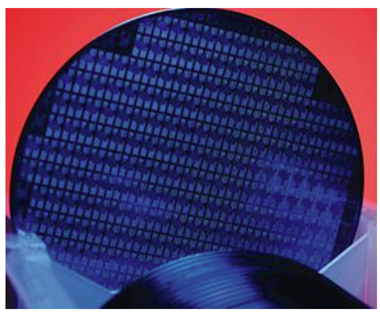
ANSYS—which last year generated $988.5 million from selling software used to design everything from rockets and bridges to wearables and airplanes—did not reveal the terms of the deal.

"Joining ANSYS will give our customers access to the best engineering simulation technology on the planet, and EnSight will help ANSYS users make faster, smarter decisions," said Anders Grimsrud, CEI's president, in a statement. "It's a win-win." ■

WIN SEMICONDUCTORS SIGNALS
Staying Power of Gallium Arsenide

THE STAYING POWER of gallium arsenide is paying off for Win Semiconductors, one of the largest contract manufacturers for the chips, which are used widely in smartphones and wireless infrastructure.

That came through clearly in the foundry's quarterly earnings, which reflected the fact that suppliers had been slow to replace gallium arsenide—more commonly known as GaAs—with silicon and other compound semiconductors like gallium nitride.



Though expensive, power amplifiers based on GaAs still pump out more powerful signals at higher frequencies than silicon. Though the chips are less efficient than gallium nitride in high-power applications like radar, GaAs excels in small-signal devices, especially where low noise is required.

Win has also reaped returns from companies packing more wireless chips into smartphone front-ends to communicate over a wider range of frequency bands. The company's net income in this year's second quarter rose to around $24.05 million, up 47% from the previous quarter and 3% from the same quarter last year.

Win's results come after the company updated its newest factory in May, Fab C, to increase the output of GaAs by around 5,500 wafers per month. The foundry has installed equipment for growing other compound semiconductor wafers, etching massive microwave integrated circuits, and fabricating optical devices.

Kyle Chen, Win's chief operating officer, said that the new fab would more than double the company's wafer capacity when it is finished. Located in Guishan, Taiwan, the factory started filling orders last year for smartphone and wireless infrastructure customers, spitting out wafers that measure 150 millimeters in diameter.

Eric Higham, an industry analyst for Strategy Analytics, wrote in a February report that around 70% of the wireless chip industry's revenues would be from gallium arsenide in 2021, down from 80% of the industry's business in 2016. Other compound semiconductors like GaN and indium gallium phosphide would grow the fastest, he said.

Win's revenue for the quarter increased to $126.4 million, up 16% from last quarter, and up 7% over last year's second quarter results. The company predicted that its revenue in the third quarter of the year would be between 10 and 15% higher than this quarter's. ■

LIGHTWEIGHT FOLDED ANTENNA FITS UAV Telemetry Systems

UNMANNED AERIAL VEHICLES (UAVS) are gaining ground for civil and military applications, with their growing numbers emphasizing the importance of reliable communications links between operators and UAVs. For that purpose, researchers from several educational institutions in Spain developed a lightweight, embedded folded printed quadrifilar helix antenna (FPQHA) with wide-angle coverage for telemetry and remote-control systems in UAVs. The compact antenna and its feed network were designed for integration into the inner part of the UAV's tail fuselage to reduce aerodynamic drag.

The antenna was designed for use at UHF, from 865 to 871 MHz with left-handed circular polarization (LHCP) and an omnidirectional radiation pattern. Target design specifications included an axial ratio (AR) of less than 3, a 3-dB beamwidth of 180 deg. (−90 to +90 deg.), more than 2.5 dB gain, and more than 15.3 dB cross-polarization discrimination. The antenna was constructed with low-loss, lightweight materials to reduce weight without compromising performance. It consists of a folded, printed, four-helix, radiating section and a compact feed network. It was designed with the aid of commercial 3D electromagnetic (EM) simulation software—CST Microwave Studio from Computer Simulation Technology (*www.cst.com*)—with a prototype fabricated according to the dimensions detailed in Microwave Studio.

The antenna was built and integrated inside the UAV's fiberglass tail fuselage and measured in a spherical anechoic chamber. The antenna structure was fabricated on 0.127-mm-thick, low-loss commercial circuit substrate material with permittivity (ε_r) of 2.17. The feed network was formed of commercial 90-deg. hybrid circuits from Mini-Circuits (*www.minicircuits.com*) on 0.4-mm-thick FR-4 PCB material. A number of measurements were performed on the prototype antenna, including radiation pattern, AR versus theta and versus frequency, gain, and S-parameters. The UAV's fiberglass fuselage was found to have minimal effect on the antenna's performance, which includes high gain across the frequency range and consistent axial ratio with frequency.

The embedded FPQHA provides wide-angle coverage from within the tail fuselage of a UAV, operating at UHF to provide telemetry and remote-control functions while adding little weight and volume to the UAV. The 50-Ω antenna and feed network feature less than 13.5-mm radius, length of less than 230 mm, and weight of less than 15 g. The compact antenna can be produced by means of low-cost manufacturing processes, making it a viable solution for UAV telemetry applications in civil and military areas.

See "Optimizing Phase-Noise Performance," *IEEE Microwave Magazine*, Vol. 18, No. 4, June 2017, p. 108.

ANTENNAS FOCUS on Near-Field Applications

NOT ALL ANTENNAS are required to generate radiation patterns reaching "to the moon." For some applications, it is an antenna's near-field (NF) radiation characteristics that are of most interest. To better understand the design considerations in creating near-field-focused (NFF) microwave antennas, a pair of researchers from Italy's University of Pisa explored the different types of antennas and arrays that could be used for NF applications.

NFF antennas are attractive for a number of short-range wireless applications. Focusing the electromagnetic (EM) field at a point in the antenna's NF region results in an increase in the EM power density in a size-limited region close to the antenna's aperture. This type of focus can be achieved by controlling the phases of the antenna aperture's radiation sources in such a way that their EM field contributions add in phase at the target focal point. Antenna arrays provide the flexibility for achieving such in-phase focus.

NFF antenna parameters depend mainly on the antenna's electrical size, L/λ, and the focal distance normalized to the antenna size, R_F/L. For a given NFF antenna focused along the boresight direction, both the depth of focus (DoF) and the focus width increase when the focal point moves far from the array plane. An NFF array can increase the EM field amplitude in the antenna NF region while also reducing the antenna FF radiation.

A number of technologies are available for building NFF microwave antennas, including Fresnel zone plate lens antennas, transmitarrays, and reflectarrays. In transmitarrays and reflectarrays, the required phase shift is obtained by properly modifying one or more geometric parameters of the unit cell of the quasiperiodic transmitting or reflecting surface, respectively.

Designing a NFF microwave antenna with specific features, such as dual focus areas, requires advanced synthesis techniques. One proposed technique involves representing an antenna's amplitude and phase NF patterns in terms of the coefficients of spherical vector wave functions, and then solving a set of linear equations for them. Another synthesis technique is to reconstruct the NF amplitude and phase patterns with a least-squares method, using a set of field samples selected over a spherical surface. The researchers point out that because of the strong dependence of a NFF antenna on surrounding material, such as body tissue, each NFF antenna must be optimized for its intended application.

See "Near-Field-Focused Microwave Antennas," *IEEE Antennas & Propagation Magazine*, Vol. 59, No. 3, June 2017, p. 42.

HONGLEI CHEN and RICK GENTILE | MathWorks
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Model Multi-Domain Simulation Frameworks for COMPLEX RADAR-SYSTEM DESIGNS

Current software tools lay the foundation for creating complete radar-system models.

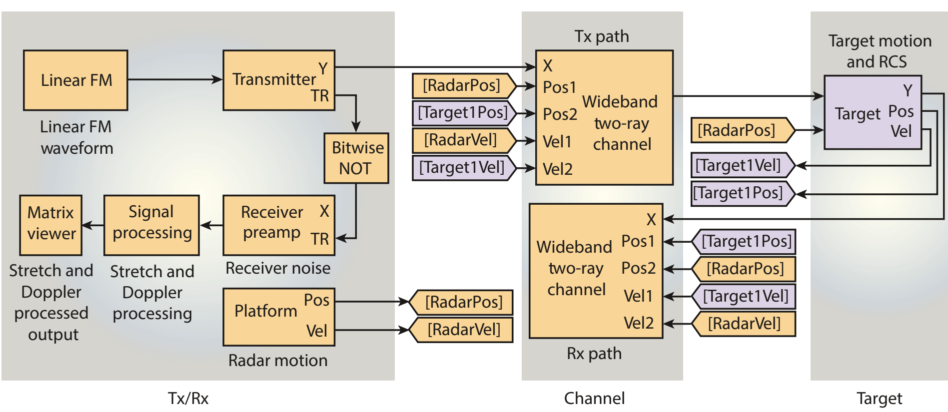
As radar-system designs become more intricate, the ability to properly model a multi-domain simulation framework is more crucial than ever in terms of influencing decision-making and detecting issues early on in a project. Phased-array antennas are now being used in new designs, ushering in an extended set of capabilities that includes electronic beamsteering and spatial signal-processing techniques.

However, these added capabilities increase system-level complexity. This complexity, coupled with growing levels of interference sources and smaller cross-section targets, is making it extremely difficult for engineers to achieve desired radar performance levels.

Thankfully, radar-system models help to limit the challenges associated with the complexities of today's design workflow. These models can be used to help justify upgrades to mature, fielded systems before any hardware is procured or developed, and can even assess the lifecycle of a system by understanding how it performs as failures occur—ultimately leading to lower design costs and faster time-to-market.

EXPLAINING THE MODEL

Simulink was used to create a multi-domain, system-level model *(Fig. 1)*. This model covers radar blocks from waveform generation to the transmit/receive chain to the spatial signal-processing components. Environmental and target modeling are also included to complete the system scenario.



1. Shown is a multi-domain radar-system model.

The model shown in Fig. 1 illustrates a low-power X-band radar that can detect targets with small radar cross-section (RCS) values ($< 0.5\ m^2$). The required radar coverage for the system in this example is 35 km with a range resolution of 5 meters. This type of radar is typical of a system used to fill gaps within a network of larger surveillance systems.

Each of the building blocks shown in Fig. 1 can also be easily implemented in MATLAB. It's possible to set up each building block to match the desired system configuration. For example, the waveform description, required transmit power, and antenna gain are parameterized and can be directly configured in each of the blocks. *Figure 2* shows sample MATLAB code for radar pulse-level processing.

WAVEFORM DESIGN

Once the requirements are set for the range and Doppler resolution, as well as the minimum and maximum range of the desired coverage, one can interactively design the appropriate baseband waveform parameters needed to achieve these system requirements. *Figure 3* shows a combination of waveform parameters that will achieve the requirements described. The resulting waveform characteristics from these baseband parameters are denoted in the figure to show that the requirements have been met. *Figure 4* shows the corresponding matched filter response, which aligns with the performance goals for this system.

For this type of radar system, the objective is to design a system that requires a low transmit peak power with the intent to translate directly into a lower-cost solution. With lower cost and less system complexity, it should be easier to deploy more systems. The low-power requirement must also be balanced with the need to detect low cross-section targets. Thus, it is required to design an array for the X-band system with a large gain.

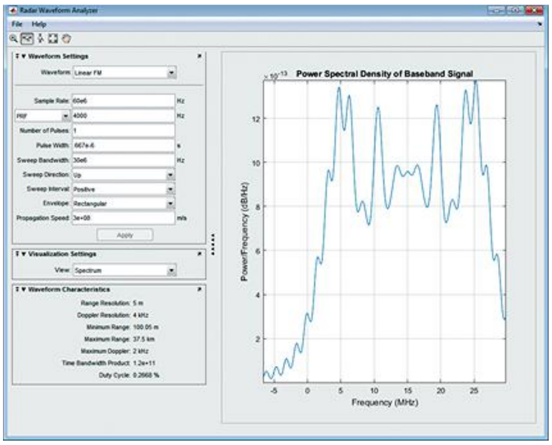
BUILDING AN ARRAY

The array parameters, including the geometry, element spacing, lattice structure, and element tapering, can be interactively designed and analyzed. The intended array for the X-band system is a 36-×-36 element array with uniform spacing between each element. *Figure 5* shows the resulting array geometry. The radar beam that can be generated with this type of array is able to be steered in azimuth and elevation. An antenna array of this size for X-band is small enough to be easily mounted on a variety of support structures, making deployment of this type of system much easier.

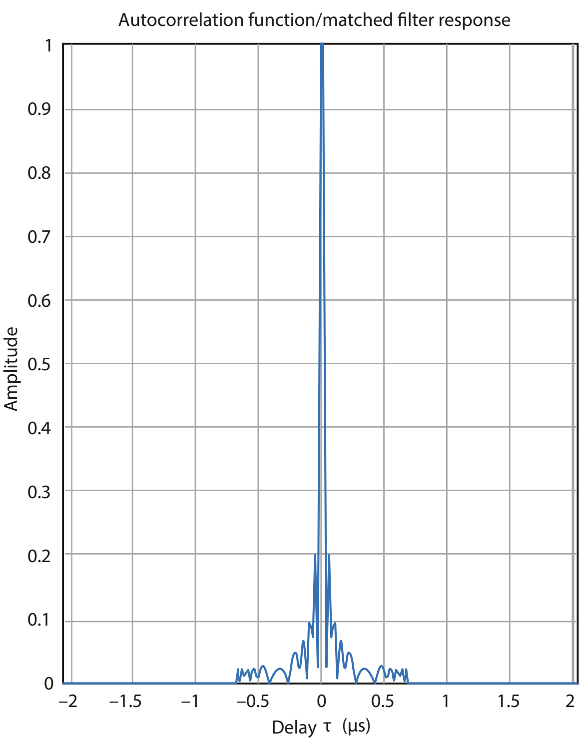
The array design can be directly used in the system model. Due to the large number of elements in the array, the resulting antenna directivity allows the peak power to be less than 20 W. This performance is based on an array directivity of 34.73 dBi. Taylor weighting has been applied to reduce the side-lobe levels.

```
%% Generate radar pulses
For ii=1:numPulses
     wf=step (waveform);                                  % Generate waveform
     [tgtPos, tgtVel] = step (PlatformModel, 1/prf);      % Update target position
     [~, tgtAng] = rangeangle (tgtPos, radarPos);         % Calc range/angle to target
     s0 = step (txGain, wf);                              % Amplify signal
     s1 = step (txArray, s0, tgtAng);                     % Radiate signal from array
     s2 = step (ChannelModel, s1, radarPos, tgtPos,...    % Propagate to target & return
         radarVel, tgtVel);
     s3 = step (TgtModel, s2);                            % Reflect signal from target
     s4 = step (rxArray, s3, tgtAng);                     % Receiver signal at array
     s5 = step (rxPreamp, s4);                            % Add rx noise
end
```

2. This code was written for radar pulse processing.



3. Users can enter a number of waveform settings.



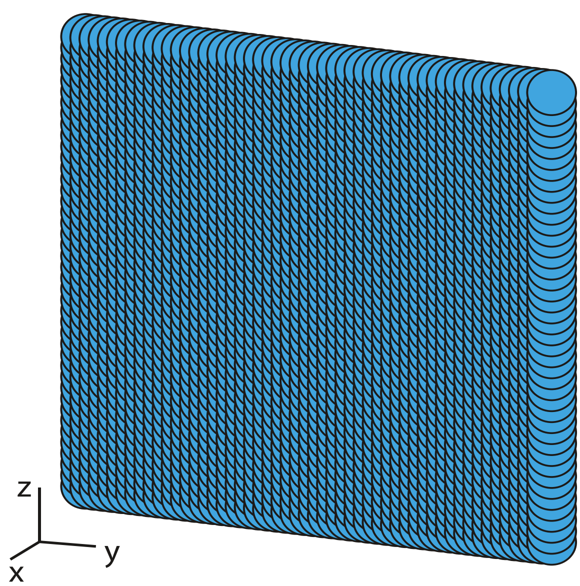
4. Here is the matched filter response of the radar-system design.

If a higher level of fidelity in the model is needed, a specific antenna element can be designed using a full-wave solver in Antenna Toolbox. One can also model the effects of mutual coupling between antenna elements, which typically impacts the beam pattern as it is steered off boresight in both azimuth and elevation. As a result, one can easily see how the array design affects the performance, making it possible at an earlier stage to either change the design or adjust the requirements for downstream processing.

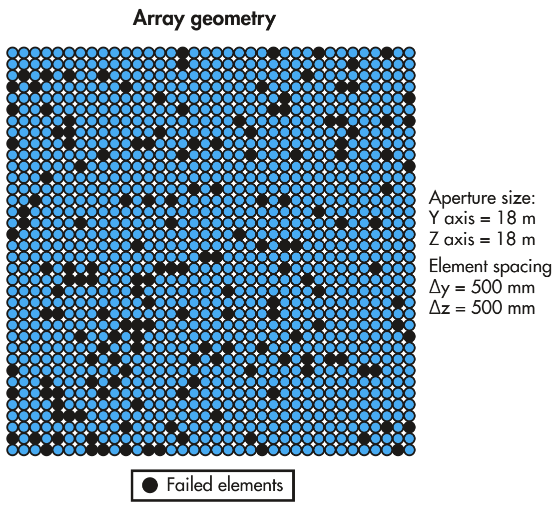
"WHAT IF" ANALYSIS

Before moving on to some of the other radar blocks, it is interesting to note that the model can also be used to support a variety of specific "what-if" analysis exercises that relate to more detailed design tradeoffs and lifecycle planning. For example, the framework in place can be referenced for the best implementation of array-thinning techniques.

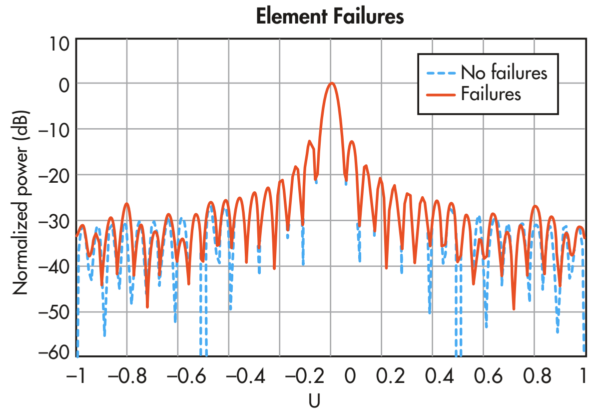
Alternately, *Figures 6 and 7* show one way to evaluate the impact of failed elements in the array. This evaluation can be important for determining maintenance cycles. For a radar site that is not staffed 24/7, multiple failures can be tolerated before a site is visited and the failures are repaired. Fig. 7 shows the degradations in the beam pattern with 15% of the elements failed.



5. This figure illustrates a 36-×-36 uniform rectangular array (URA).

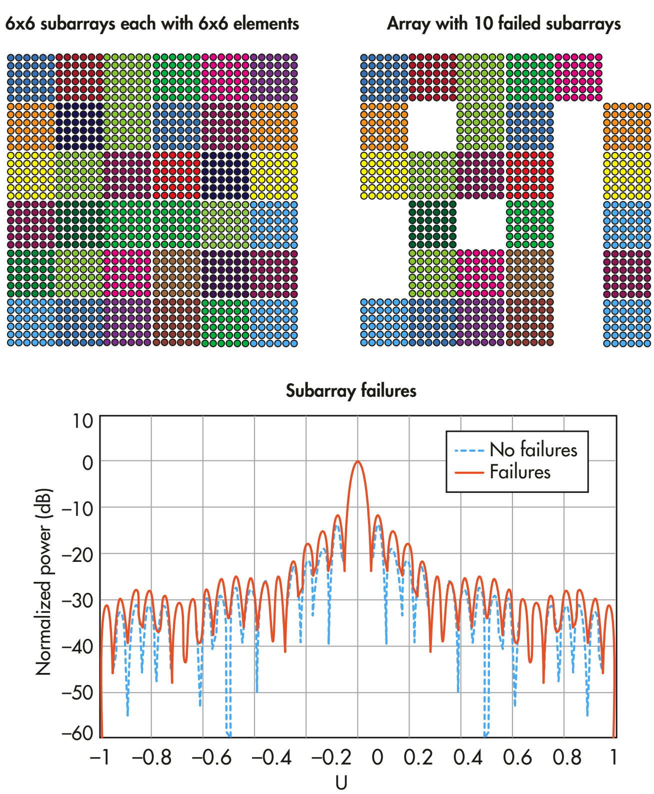


6. Shown is a 36-×-36 array with failed elements.



7. These plots show how element failures affect the beam pattern.

Similar analysis can be performed at the subarray level as well. *Figure 8* illustrates the array built up from 6-×-6 subarrays. The resulting beam pattern is also shown, with 10 of the 36 subarrays in a failed state. Again, this type of data can be used to determine how many subarrays should be implemented. Moreover, it can be utilized in a way similar to the maintenance concept described earlier.



8. This figure illustrates a 36-×-36 element array that is built with 6-×-6 subarrays. The beam pattern is shown with no failures, as well as with 10 failed subarrays.

MODELING A COMPLETE SCENARIO

Tools are available for each component to help quickly complete a system model. In this example, targets of varying complexity (including RCS fluctuations and angle- and frequency-dependent RCS behavior) are created. These targets can also be set in motion in the model. This capability provides insights into whether the design meets all performance goals. Various factors, such as line-of-sight propagation effects due to rain, fog, and gas, as well as channel fading, can be included to improve the model's fidelity.

To emulate the complex RF environment, it's possible to integrate signal-source models to test interference mitigation techniques and assess complexity levels prior to implementation. In this model, targets are added with an RCS value of 0.05 m^2. This type of scenario has taken on new importance with the increased use of drones and unmanned aerial vehicles (UAVs).

In addition, fidelity in the RF domain can be extended by building up subarrays with models of RF components, such as phase shifters, amplifiers, etc. Simulink can serve as a platform to perform multi-domain simulation because it provides customizable block libraries and solvers for modeling and simulating dynamic systems. Since it is integrated with MATLAB, one can incorporate algorithms into models and export simulation results to MATLAB for further analysis.

FORMING MULTIPLE BEAMS

In this signal-processing subsystem, multiple beams are formed that cover various azimuth and elevation angles in front of the array. These same channels also estimate the directions that the returned signals are arriving from. The matched filter shown in Fig. 4 provides the system with a processing gain that improves the detection threshold. A time-varying gain is added to the model so that a constant threshold can be used for detection across the entire detectable range.

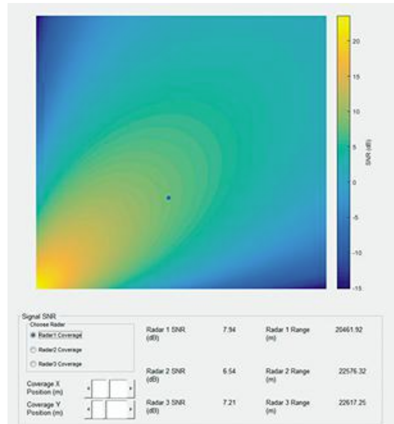
The resulting pulses are non-coherently integrated. The combination of these techniques allows processed returns for a single integration interval to support target detections at a desired signal-to-noise ratio (SNR). Results can be visualized in a vari-

ety of ways, including power vs. time and intensity vs. time.

In this example, the simulated targets have a non-fluctuating RCS of 0.5 m^2 and are located throughout the area of radar coverage. It should be noted that the blocks used in the simulation are scalable. Each input and output is clearly defined such that custom blocks can be swapped into the model or extended to an existing block. Among the resulting data sets from the model is I/Q data generation for each processing interval.

ASSESSING RADAR NETWORK COVERAGE

By using this model as a starting point, one can also investigate ways to perform analysis on potential networks of radars. For example, consider a simple configuration of three systems that are placed with overlapping coverage to avoid any gaps. *Figure 9* illustrates the SNR in one of the three coverage areas. A SNR of at least 5 dB is the goal given the combination of signal processing and integration that was implemented.



9. This is the SNR view for one of three radar systems.

TIME AND COST SAVINGS

While off-the-shelf radar model components provide all of the basic building blocks for a full system model, the simulation framework also has the flexibility to be extended with custom additions for each portion of the radar design. As demonstrated in the examples, the radar-system design workflow, from requirements analysis to design tradeoffs to system development, can benefit from this work.

Modeling such an elaborate radar system early in the design process is able to save countless hours and reduce program costs by exposing design issues in the early stages of the project. Furthermore, a full system model can simulate a radar system for signal-processing development or generate the radar echo(s), resulting in I/Q data that can be tuned to algorithms. After tuning the algorithm, it is easy to replace the synthesized data with measured data at any location in the model, speeding up development processes and saving cost on future designs as well. mw

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JACK BROWNE | Technical Contributor

Trying to Keep the Noise Down

In electronic components and systems, noise is inevitable. While it can't be stopped, it can be measured and understood to the point where its effects can be overcome.

NOISE IS A limiting factor is many receivers and other systems. Essentially, it is unwanted energy that sets the sensitivity of a receiver. Noise masks signals of interest at lower levels, preventing the receiver from detecting them. It is almost unavoidable and exists in all electronic systems, from audio and baseband electronic devices through the highest terahertz frequencies and optical electronic systems. While it cannot be eliminated, it can be controlled and managed, enabling receivers to operate effectively with low-level signals.

All components at normal operating temperatures generate some amount of noise when power is applied, due to the random motion of the electrons that account for the flow of current. This is one form of noise, known as thermal noise, associated with the heat that is a byproduct of the applied power. This heat is generated at all temperatures above absolute zero (−273°C) since, in theory, charge carriers do not move at a temperature of absolute zero.

Thermal noise has a Gaussian distribution, with noise levels spread evenly with frequency. As a result, the amount of noise in a component or circuit increases with bandwidth. For this reason, filters that narrow the bandwidth will also lower the noise. In a 50-Ω system at room temperature (typically +25°C), the thermal noise power density is −174 dBm/Hz.

The thermal noise power from a noise source, N, can be found from the simple relationship,

$N = kTB$, where

where

k = Boltzmann's constant ($=1.38 \times 10^{-23}$ J/K);

T = the temperature (in degrees Kelvin); and

B = the bandwidth in Hz in which the noise is measured.

From this equality, the relationship of noise power to bandwidth is obvious and clear proof of the need for filtering or some other form of bandwidth reduction in order to limit noise in communications systems. Similarly, noise increases

1. Noise sources can be simple diode-based components with coaxial connectors capable of generating a given ENR across a frequency range of interest. *(Photo courtesy of Noisecom)*

2. Precision noise sources are available in many forms, with connectors to match those on a DUT. *(Photo courtesy of Noisecom)*

3. Programmable noise sources such as this additive white Gaussian noise (AWGN) generator are microprocessor-controlled to speed and simplify automated noise measurements. *(Photo courtesy of Noisecom)*

with increasing temperature (which is why cryogenic cooling is often used in applications where low noise is essential). (*Note*: A conversion from °C to °K follows from 0°K = −273°C, so that +273°K = 0°C and so on.)

One of the most essential of electronic components, the resistor, also produces a root mean square (RMS) noise voltage (V_n) as a function of bandwidth and temperature:

$$V_n = (4kTBR)^{0.5}$$

where R = the resistance (in Ω) of the resistor.

From this relationship, it is apparent that noise increases with increasing resistance, and resistance should be as low as possible to minimize noise.

Receiver designers and other users of low-noise amplifiers are familiar with a noise parameter known as noise figure (NF) and a related parameter, noise factor. Noise factor is essentially the ratio of the SNR at the output of a device under test (DUT), such as an amplifier, to the SNR at its input, or before it added its own thermal noise to the signal path. The NF is a way of expressing NF in dB, with lower values indicative of less noise.

MEASURING NOISE

Noise in RF/microwave systems is characterized in various ways, including by excess noise ratio (ENR), carrier-to-noise (C/N) ratio, SNR (in dB), NF (in dB), and noise power density (in dBm/Hz). It can also be measured in a number of ways, using specialized instruments, such as a noise-figure meter, or general-purpose instruments, such as a power meter or a spectrum analyzer.

In all cases, a known source of noise that has been precisely calibrated is an important part of measuring the noise of a DUT since it provides a reference or starting point from which to base the subsequent noise measurements. Noise sources can be simple diode-based components (*Fig. 1*) with coaxial or waveguide connectors (*Fig. 2*) or more sophisticated programmable instruments for automated noise measurements (*Fig. 3*).

Noise sources are typically characterized by their usable frequency ranges and their excess noise ratio (ENR). For a noise diode, the ENR is the difference between the diode's noise level when it is switched on versus when it is switched off. A switchable noise source can be placed at the input of a DUT and measurements made for the on and off states at the output to determine noise figure.

In addition to measuring the noise characteristics of a DUT, a precision noise source is a form of low-noise test signal generator, since it provides signal energy at all frequencies simultaneously and can be used with a spectrum analyzer to measure such parameters as filter response and amplifier gain for its calibrated bandwidth.

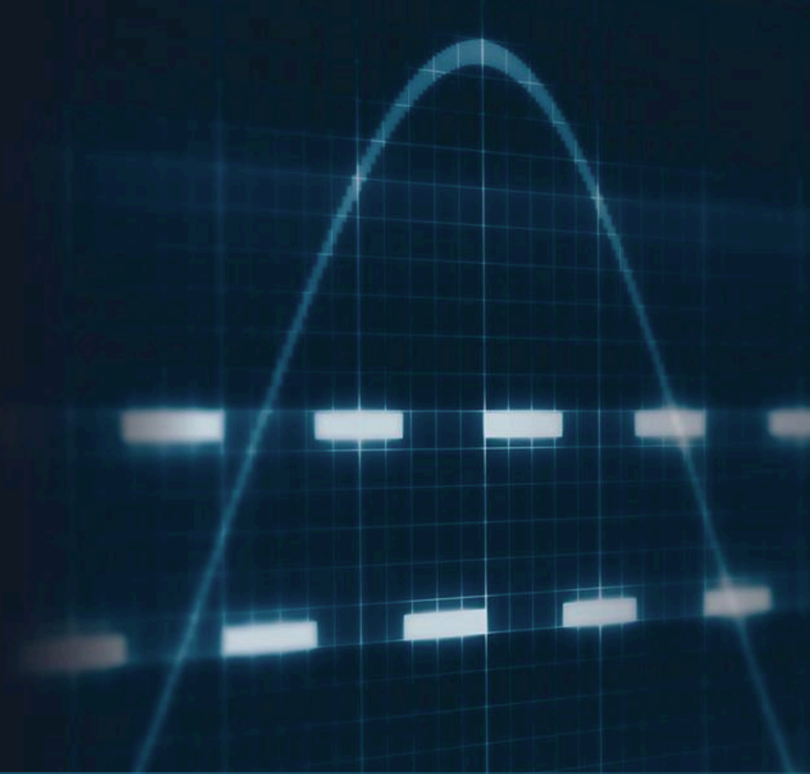
In terms of calculating NF, its relationship to ENR is as follows:

$$NF \text{ (in dB)} = ENR - 10\log(Y - 1)$$

where $Y = P_{on}/P_{off}$ and where P_{on} and P_{off} are the output power levels of the DUT when the noise source at the input of the DUT is biased on and off, respectively.

Calibrated noise sources are used with a spectrum analyzer, an RF power meter, or a noise-figure meter to determine different noise parameters, such as NF. A noise-figure meter essentially subtracts the noise level at the input of the DUT, such as a mixer or amplifier, from the noise level at the output of the DUT to determine the noise added by the DUT.

Thermal noise is one form of noise that haunts RF/microwave components and systems, with other forms of noise, such as shot noise and Johnson noise, often present. One of these other types of noise, for example, is phase noise, which is commonly generated in amplifier and oscillator circuits. As with the instruments for measuring noise figure, specialized phase-noise analyzers have been developed and are available from several manufacturers for precise measurement of phase noise over different frequency ranges. mw



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Strong Defense Depends On a Technological Edge

Maintaining a tactical advantage requires defense electronic systems that are one generation beyond anything an adversary can field.

ELECTRONIC SYSTEMS HAVE long been something of a "front end" for most military activities. While battles are fought by people, electronic systems provide warnings of trouble and communications between troops. There are many different electronic systems used as part of military activities, including communications, electronic warfare (EW), and radar systems. In all cases, these systems must leverage the latest electronic technologies to provide the greatest benefits to the warfighter.

Military communications systems face many challenges to successful operation, including interception of signals and jammers that prevent radios from receiving signals. For years, terrestrial military radios have been following a trend of "borrowing" technology from commercial cellular telephones to make military radios smaller, lighter, and more secure.

As a result, military radios employ many of the digital modulation formats used in commercial wireless communications devices, along with the programmability of software-define-radio technology to switch frequency bands and communication formats when one band is being jammed or is unavailable due to interference or weather conditions.

In the interest of security, different branches of the military have formulated different waveforms for ground mobile radios (GMRs) including the Soldier Radio Waveform (SRW) and the wideband networking waveform (WNW). With terrorism rampant, communications security is critical not just on the battlefield but for homeland security, law enforcement, and government users. In addition to more advanced communications waveforms, modern military radio solutions must be capable of working with legacy waveforms still in use, such as the Link 16 waveform.

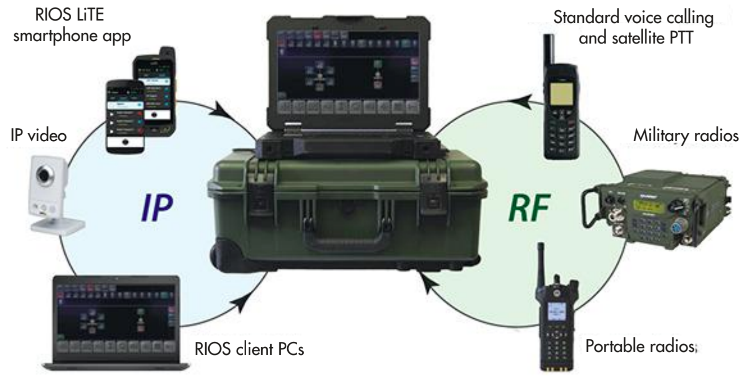
Tactical terrestrial military radios are meeting these challenges by means of hardware with extremely broadband frequency coverage, including satellite-communications (satcom) frequencies, and through the flexibility of software-defined-radio (SDR) technology, which can change the radio's operating characteristics to match the requirements of a particular network. As an example, the RF-7800M-HH tactical radio (*Fig. 1*) from Harris Corp. (*www.harris.com*) is built to withstand the rigors of the battlefield, but it looks very much like an early-generation cell phone.

In spite of appearances, however, it is quite advanced, with a Software Communications Architecture (SCA) based on software programmability to adapt to changing environments. It provides simultaneous voice and high-speed-data communications using narrowband and wideband radio waveforms. The software-upgradeable radio uses both ANW2C and M-TNW waveforms and has the capability to network with a variety of other types of radios, including military satcom radios. It is capable of frequency hopping for security and available with optional satcom TDMA capability.

1. Modern military portable radios rely on SDR technology to minimize the impact of interference and jamming signals. *(Photo courtesy of Harris Corp.)*

With the many different design approaches used in terrestrial and airborne tactical radios—and a desire by military users to have access to commercial radios and even Internet of Things (IoT) sensors for surveillance data—military communications interoperability is one of the prime concerns for modern military communications technology. Military ad hoc networks consist of radios and users not just on the ground and in ground vehicles, but in aircraft-mounted radios as well (and in some cases, in UAV-mounted radios). All must be capable of communicating in a secure manner.

Interoperability depends on fixed and mobile ad hoc network (MANET) nodes, such as the RIOS TAC2 Tactical Radio Interoperability Gateway from Systech Corp. (*www.systechcorp.com*). It allows many different users, such as public safety, federal agencies, and military users, to inter-



2. Advanced radio networking gateways allow many different wireless users at many different frequencies to interconnect with high security. *(Photo courtesy of Systech Corp.)*

connect with many different radios and frequency bands, including HF, VHF, UHF, and 700/800-MHz bands (*Fig. 2*). It includes interfaces for RIOS Client Computers, RIOS LiTE for Android and iPhone commercial cell phones, and options for satellite phones and Voice-over-Internet-Protocol (VoIP) devices.

The mobile gateway is compatible with a variety of tactical radios, including those from Motorola, Harris, and Kenwood. It has an on-board router with full wireless capabilities for cellular, Wi-Fi, and WLAN connectivity to support communications among many different devices (*Fig. 2*). Signals from one radio format can be converted to another radio format and retransmitted to a desired network not matter the format or frequency, allowing communications between initially incompatible devices.

The mobile gateway has on-board power management for continuous power from AC or DC source or its integrated lithium-ion rechargeable battery pack. The 40-lb. gateway is designed to run for 6 to 8 hours on its built-in battery pack. It is an example of the type of gateway equipment needed for rapid formation of wireless mesh networks and MANETs to enable communications interoperability, especially with the growing number of networked wireless IoT devices used for data gathering and signal detection, as well as autonomous UAVs under network control.

Cognitive radio technology is also helping to meet military challenges of communications interoperability. This technology, which essentially uses computer intelligence to automatically select the radio characteristics needed for successful communications, not only adapts to different network requirements, but can instantly switch to unoccupied frequency bands in the event of interference and/or jamming.

3. An inflatable satcom antenna was developed to improve portability when establishing satcom ground stations. The antenna can be set up in less than three hours. (Photo courtesy of the U.S. Army. *(Photo courtesy of the U.S. Army)*

Technology advances for military communications are affecting more than just radios—even components considered mature sometimes get a new look. The U.S. Army recently unveiled an inflatable ground-terminal antenna for satcom systems (*Fig. 3*). The ground antenna transmit and receive (GATR) ball is the Army's latest satcom component. It is much lighter and more portable than traditional satellite dish antennas. The GATR ball is designed to be carried anywhere in the world in a few cases, and can be inflated and assembled in less than two hours to perform a variety of communications services.

40 YEARS LATER, GPS STILL GOING STRONG

EARLIER THIS YEAR, Rockwell Collins *(www.rockwellcollins.com)* celebrated the 40th anniversary of receiving the world's first Global Positioning System (GPS) satellite signal, establishing a new standard in navigation and location accuracy. The first GPS satellite was known as NYS-2, and the signal was received by a Rockwell Collins engineer, David Van Dusseldorp, sitting on the roof of a company building in Cedar Rapids, Ia. and adjusting an antenna every five minutes.

Retirees involved in the project, including Van Dusseldorp, were invited back to commemorate the event. "We had leaders and team members working together, and I knew we could meet the challenge put before us," he recalled. "The future of GPS was uncertain at the time, but I really felt like we had just accomplished something important."

Soon after receiving the signal, Rockwell Collins was awarded the Navstar GPS user equipment contract by the U.S. Air Force, and the company would build upon that to become a leader in GPS technology and products for aerospace and defense. Since that historic day 40 years ago, Rockwell Collins has introduced more than 50 GPS products, including GPS anti-jam and precision landing systems. It has delivered more than one million GPS receivers for commercial avionics and government applications, helping shape how the world navigates both on the ground and in the air.

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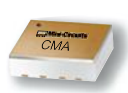

3 x 3 x 1.14 mm

Model	Freq. (GHz)	Gain (dB)	P_{OUT} (dBm)	IP3 (dBm)	NF (dB)	DC (V)	Price $ ea. (qty 20)
CMA-81+	DC-6	10	19.5	38	7.5	5	8.95
CMA-82+	DC-7	15	20	42	6.8	5	8.95
CMA-84+	DC-7	24	21	38	5.5	5	8.95
CMA-62+	0.01-6	15	19	33	5	5	7.45
CMA-63+	0.01-6	20	18	32	4	5	7.45
CMA-545+	0.05-6	15	20	37	1	3	7.45
CMA-5043+	0.05-4	18	20	33	0.8	5	7.45
CMA-545G1+	0.4-2.2	32	23	36	0.9	5	7.95
CMA-162LN+	0.7-1.6	23	19	30	0.5	4	7.45
CMA-252LN+	1.5-2.5	17	18	30	1	4	7.45

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Sergeant First Class Brian Horne, information assurance supervisor for the 369th Signal Battalion (SB) that has developed the portable antenna, explained that “it can be set up and operated by a crew of three just about anywhere.” But the antenna doesn’t sacrifice performance for portability. It provides larger bandwidth capacity than the legacy antenna system it replaces, allowing operators to send more data.

Sargent Moises Orta, a multichannel transmission systems operator/maintainer for the 369th SB, concurred with this assessment: “The GATR Ball is capable of more data transfer in a smaller package compared to the traditional satellite systems.”

Airborne nodes are of growing importance for military communications networks, and the technology for such communications has been in development for several years. Boeing (*www.boeing.com*) and the U.S. Air Force recently demonstrated networking between multiple ground stations and several aircraft, using Boeing’s Talon HATE airborne networking system. Flight tests were conducted at Nellis Air Force Base, N.V. with two Talon HATE pods on two F-15C aircraft.

Communications were performed with the military’s Link 16 waveform, Common Data Link (CDL) protocol, and Wideband Global Satcom (WGS) satellites. Additional flight testing also validated intraflight data-link communications between F-22 aircraft. Such never-before-possible intra-aircraft networking will provide fighter pilots with invaluable additional data, including intelligence gathered from pilots in other aircraft.

Of course, communications is just one technology area within defense electronics, with innovation and development taking place in many other key areas, including in EW and radar systems. EW systems are following a technology path that parallels that of tactical radios, relying on embedded system computers for analysis and decision making regarding acquired signal information when reacting to different threats.

Known as cognitive EW, the technology has been in development for several years, motivated by DARPA’s Adaptive Radar Countermeasures (ARC) program and the fear that traditional EW systems would not be agile enough to respond to the rapidly changing waveforms generated by enemy adaptive radar systems. Major contractors involved in development of cognitive EW systems include BAE Systems (*www.baesystems.com*), Boeing, Lockheed Martin (*www.lockheedmartin.com*), and Raytheon Co. (*www.raytheon.com*).

DARPA is pursuing an open-architecture approach with the ARC program to enable U.S. airborne EW systems to automatically generate electronic countermeasures (ECM) responses against new, unknown, and adaptive radars in real time. Having an open architecture will allow for development of EW systems in a modular hardware and software configuration so that updating a system by changing modules will have minimal impact on other elements of the EW system. The modules developed for the ARC program will be suitable for new systems and for retrofitting existing EW systems.

The ARC modules should be capable of isolating unknown radar signals in the presence of other signals, both friendly and hostile, and perform analysis on the signals to determine the nature of the potential threat. An ARC solution must be capable of synthesizing and transmitting ECM signals to the threat radar for a desired response, and assess the effectiveness of the countermeasures based on the over-the-air observable behavior of the threat transmitter.

About three years ago, the U.S. Navy established a need for what is described as electromagnetic maneuver warfare (EMW), to measure environmental variables at multiple heights from a fixed location, such as the deck or mast of a ship. The data would be part of predicting the EM and electro-optical (EO) propagation from surface ships to support data from and the performance of radar, EW, laser, and communications systems.

The EMW efforts were begun because of a dissatisfaction with existing in situ sensors, which were deemed expensive and unreliable, and the quest was to replace such sensors with a more accurate and practical solution. Any system solution should also be maintainable in a naval environment. Technologies being considered include acoustic sounders, Doppler LIDAR and LIDAR spectroscopy, and passive radiometry.

This is a brief survey of recent trends in defense electronics, with similar pursuits of technology improvements in all areas. While some of these programs are aimed at combatting the growing use of enemy UAVs to perform surveillance and carry weapons, contractors such as Raytheon are also working with the Air Force Research Laboratory (AFRL) Directed Energy Directorate at Kirtland Air Force Base, N.M. on the integration of high-power electromagnetic (HPEM) weapons into suites of aircraft weapons. Such weapons are meant to disable enemy electronic systems without harming soldiers.

Continuing efforts at technology improvements, such as the practice of "persistent surveillance,"—the use of software-defined sensors to gather intelligence, even as environmental conditions are changing—are helping to maintain a tactical edge for U.S. troops and their allies. Strong funding from the current administration should help to continue to support this trend of technological advances and improvements. mw

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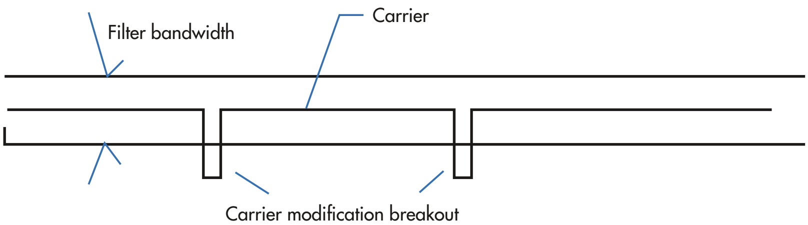
Carrier Modifications Make Ultranarrowband Modulation

Ultranarrowband modulation can be generated by making small modifications to a carrier signal, thus improving C/N ratio and BER performance in digital communications systems.

Wireless systems and services occupy bandwidth, which is limited. But not all wireless applications require wide-bandwidth channels. Emerging applications such as sensors for Internet of Things (IoT) functions need just enough bandwidth to move the amount of data generated by the sensor to a communications gateway that is connected to the internet.



1. Changes in amplitude or phase can result in barrier "breakout" which appears as missing carrier cycles or parts of cycles.

For industrial and commercial applications such as these, ultranarrowband (UNB) wireless technology is very attractive as a means of providing a wireless link without occupying a great deal of frequency spectrum. One of the challenges in adopting UNB technology, however, lies in generating the necessary signals—essentially carriers without sidebands.

In modern communications systems, modulated carrier signals occupy fairly wide-bandwidth channels to transfer voice, video, and data. Because of the wide-bandwidth channels, including sidebands, channels must be sufficiently separated in frequency to avoid overlapping sidebands and causes of interference between channels. But UNB-modulated channels, which theoretically have no sidebands and can compress large amounts of data into communications channels as narrow as 1 Hz or less, can be closely spaced while still occupying very little total frequency spectrum.

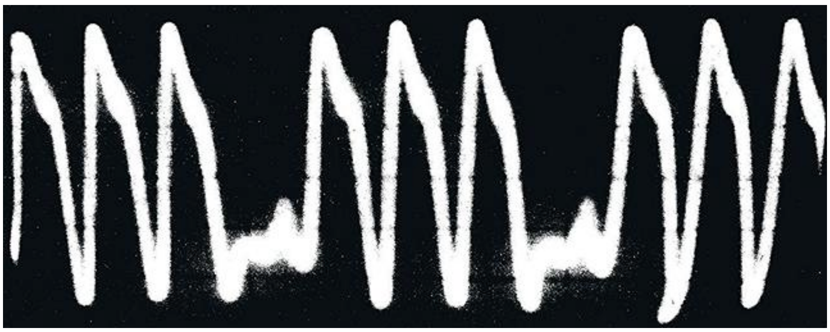
Of course, UNB-modulated signals must be generated before they can be used in practical applications. For the past 20 years, perhaps a dozen different methods have been proposed for generating UNB signals. In comparing the methods, it becomes apparent that all have a common trait of modifying the carrier signal in some way. As Lee pointed out,[1] one goal in the use of any modulation format was to achieve as little distortion as possible on the carrier waveform, since an undistorted continuous-wave (CW) carrier requires 1 Hz or less filter bandwidth to deliver the modulation information.

As an example, assume a carrier signal that is modified by changing frequency and a narrowband filter (with passband of 1 to 2 kHz wide). The modifications to the carrier causes a "breakout" that leaves a hole or space in the signal (missing cycles or portions of cycles) that appears at the output of the filter *(Fig. 1)*. All UNB modulation methods experience such breakouts.[2] A carrier signal can be modified by changes in amplitude or phase. In either case, the signal that is being transmitted consists of the fixed-frequency carrier along with some very low-level sin(x)/x sidebands.

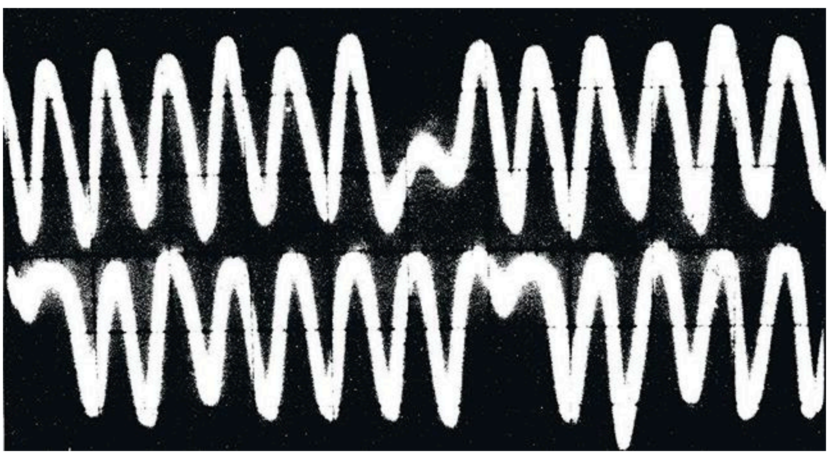
The addition of some form of modulation, whether based on changes in amplitude or frequency/phase, is obvious for a waveform where the carrier is being stretched, causing the carrier to be at a lower frequency during the bit change. For a modulation method that uses 90-deg. changes in phase, the carrier cycles will be stretched by 90 and 270 deg., lowering the carrier frequency at those points and causing a breakout at the data-transition edges *(Fig. 2)*. In a case of missing cycles with amplitude modulation (AM), the change in carrier cycles is 360 deg.

For other UNB modulation methods, the carrier signal must have the DC component of the breakout event restored *(Fig. 3)*. A limiter cannot be used for this purpose, and the modulation circuitry must exhibit a nonlinear response in order to achieve the UNB modulation. Restoring the DC component in such as case is difficult for a system that must provide a large dynamic range.

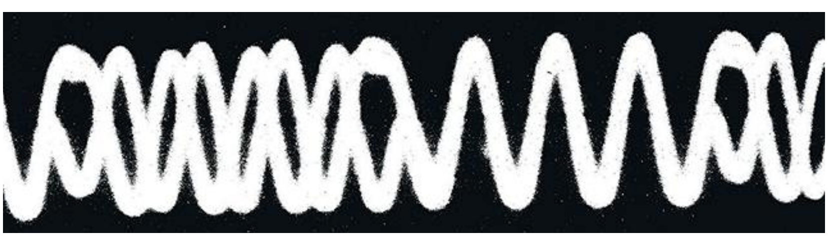
The sin(x)/x level of the system must be proportional to the phase angle of the carrier modification or width of the carrier breakout. Thus, 90 to 270 deg. for the 90-deg. phase method has lower sin(x)/x sidebands than the sidebands resulting from the 360-deg. breakout for a missing carrier cycle.



2. A breakout or missing cycle in a CW waveform causes both frequency and amplitude modulation.



3. A missing cycle must be evident for a detection method to determine if it represents a digital 0 or 1.



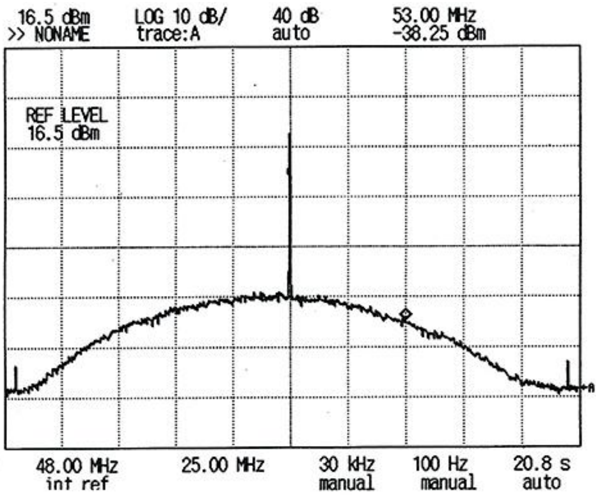
4. For 90-deg. phase modulation of the carrier, the data is between modified carrier points, and a limiter can be used. This trace shows a 12 Mb/s data rate and 48-MHz IF.

Carrier breakouts can be used in various ways as part of an approach to producing UNB modulation. Breakouts can be used to mark the presence of a digital one, digital zero, or both, according to the carrier modification method that is chosen. The sin(x-)/x sidebands which are the AM that results from the carrier modifications can be removed further by filtering, which has no effect on the phase angles or how the breakouts are used to convey digital information.

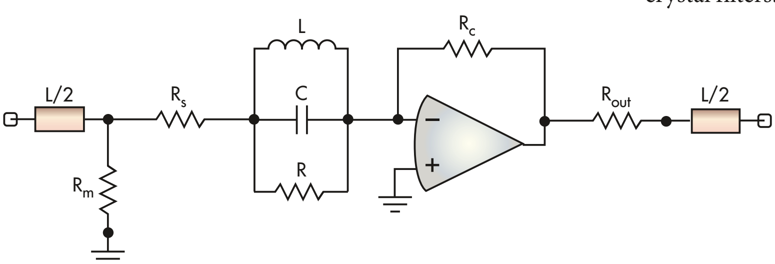
For 90-deg. phase modulation of the carrier, data is between carrier modification points *(Fig. 4)*, so a limiter can be used to achieve the modulation since it ignores the amplitude of the carrier modification points.[3,4] A 90-deg. phase modulation angle is optimum; for smaller angles, the sin(x)/x sideband shoulders are reduced by as much as 3 dB, but the bit error rate (BER) is worse.

For angles greater than 90 deg., the BER remains the same but the sin(x)/x shoulder reduction is not as great. *Figure 5* shows the UNB spectrum for a data rate of 12 Mb/s with a 48-MHz intermediate frequency (IF) and applies to all methods used to create UNB modulation.

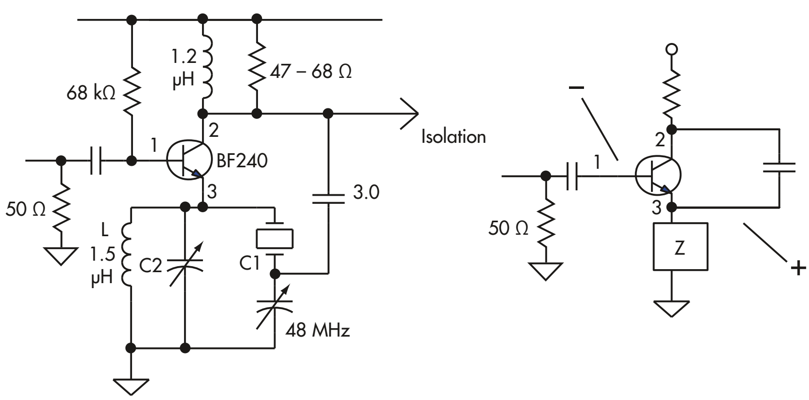
Communications channels that employ this carrier breakout approach to transfer data can be located very close in frequency to one another. Testing on UNB channels spaced only 10 kHz apart has shown successful reception of transmitted data, regardless of data rate.[5] In these tests, performed with specialized filters, the modulated signal sidebands were not required as part of the transmissions. Such closely spaced UNB-modulated carriers meet most FCC requirements for radiated signals.



5. A UNB spectrum features a carrier with negligible sin(x)/x wideband levels.



6. This is an example of an LC filter that can be used as a zero-group-delay filter for UNB modulation.



7. This schematic diagram shows a crystal filter designed for use as a zero-group-delay filter in UNB-modulated systems.

The filters used in this testing are known as negative-group-delay filter or zero-group-delay filters.[6] If such filters are not used, the modified carrier cycle will be smoothed over (by filters with positive group delay) and lost (along with any data represented). Conventional bandpass filters (BPFs) exhibit positive group delay, which means they integrate and smooth over input signals.

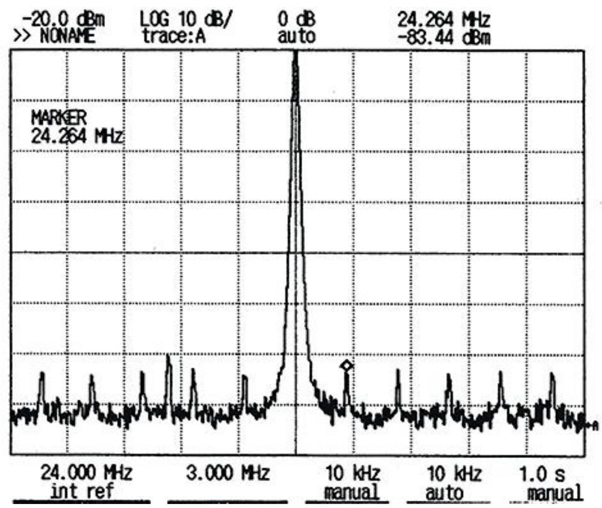
Unfortunately, negative-group-delay filters are not covered in any engineering textbooks, although information on such filters is available on the internet. Some of the types of negative-group-delay filters that have been used to achieve UNB modulation include the Walker shunt filter, the transformer reflected shunt filter, the series emitter filter with feedback,[6] and the wavelet filter. A series emitter filter with positive feedback is a quality factor (Q) multiplier circuit where gain is controlled by a discrete resistor.

Negative-group-delay filters should more accurately be referred to as zero-group-delay filters. True negative-group-delay operation is not possible, since it implies negative time. Filters with zero group delay are possible, and they can be realized using L and C components or with crystal resonators *(Figs. 6 and 7)*. LC filters are generally not recommended for UNB applications, since they tend to have poor shoulder reduction and broader bandpass characteristics than crystal filters.

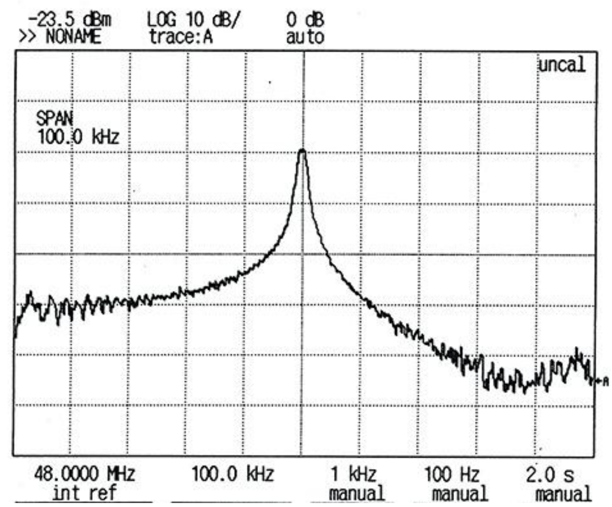
Figure 8 shows the spectrum of a phase-modulated signal following one stage of a zero-group-delay BPF. There are no sidebands and the sin(x)/x pattern is removed, thus there are no contributions to the carrier phase shift or amplitude molestation. *Figure 9* is the bandpass response of a crystal filter with zero group delay. The 3-dB bandwidth is about 500 Hz for a 48-MHz intermediate frequency (IF). Any sidebands, such as the sin(x)/x AM pattern, are reduced by approximately 30 to 40 dB.

ERROR PROBABILITY

In *Fig. 10*, the curve on the right shows binary-phase-shift-keying (BPSK) modulation, which is being used here as a reference for comparison. By using UNB modulation, the carrier-to-noise ratio (C/N) is improved by about 3 dB. This dramatic improvement has been measured by a number of researchers, including those at xG Technology *(www.xgtechnology.com)* and UNBTech. The improvement is shown in the minimum-sideband (MSB) curve, for which the filter bandwidth is assumed to be



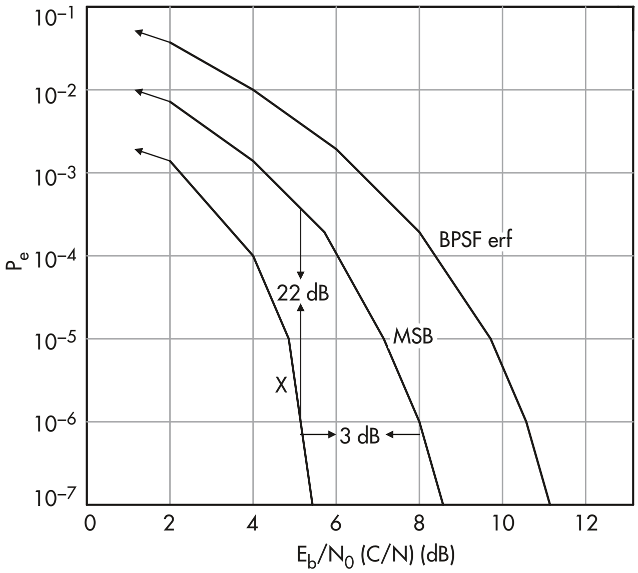
8. This spectrum shows a phase modulated signal after one stage of a zero-group-delay BPF.



9. This is the bandpass response of a crystal zero-group-delay filter with 3-dB bandwidth of approximately 500 Hz for a 48-MHz IF.

equal to the data rate (no additional filter bandwidth is needed for removal of sidebands).[7]

A reduction in noise power is generally beneficial to the performance of any communications system. The noise power, P_n, is given by $P_n = kTB$, where k is Boltzmann's constant (1.38 × 10^{-23} J/K); T is temperature (in °K); and B is bandwidth (in Hz). Such a reduction is possible if the bandwidth of the negative-group-delay filter is equal to or less than the bit rate.



10. The plot shows the BER for a UNB or minimum-wideband (MSB) signal. The results can be achieved with all UNB modulation methods.

UNB methods offer a distinct performance advantage compared to BPSK modulation, which is often used as a reference for digital data communications. UNB provides a 6-dB improvement over the BER performance possible at the theoretical limits of BPSK and 8 dB better than differentially encoded BPSK.

For example, a communications system transmitting data at 12 Mb/s using binary-phase-shift-keying (BPSK) modulation uses a filter bandwidth of 12 MHz. However, by using MSB or one of the UNB phase-modulation methods described earlier, and the crystal filter of Fig. 7, the resulting noise bandwidth is only about 500 MHz, following the probability of error (P_e) calculations detailed in Eq. 1:

$$Pe = 0.5\text{erf}(X) = 0.5\text{erf}(E_b/N_0)^{0.5}$$

$$= 0.5\text{erf}\{[(\text{signal power})(\text{noise power})]/[(\text{bit rate})(\text{bandwidth})]\} \quad (1)$$

As Eq. 2 shows, this is a noise-bandwidth reduction of 12,000,000/500 or 24,000:

$$X = [(\text{signal energy/bit rate})/(\text{noise energy}/12{,}000{,}000)]^{0.5} \rightarrow [(\text{signal energy/bit rate})/(\text{noise energy}/500)]^{0.5} = (24{,}000)^{0.5} = 154.91933 \quad (2)$$

The error probability decreases as the noise power decreases with decreasing filter bandwidth. The carrier-to-noise (C/N) ratio becomes smaller, moving the curve for X in Fig. 10 toward the left.

In applying Eq. 2, it can be seen that changing from a 12-MHz filter bandwidth to a 500-Hz filter bandwidth results in a dramatic improvement in C/N ratio and an increase in X of almost 155 or 22 dB. This can be seen plotted as the line marked by "X" at the left of the MSB curve in Fig. 10. The P_e has been improved by 22 dB. Also, the C/N ratio required to produce a given bit error rate (BER) is lowered by approximately an additional 3 dB, which represents a significant improvement in the C/N ratio. Alternately, signal power can be reduced by 3 dB (Eq. 1), keeping the C/N ratio and the MSB curve the same, as X varies with the C/N ratio.

UNB methods offer a distinct performance advantage compared to BPSK modulation, which is often used as a reference for digital data communications. UNB provides a 6-dB improvement over the BER performance possible at the theoretical limits of BPSK and 8 dB better than differentially encoded BPSK. In fact, since the data rate, filter frequency, and bandwidth are independent, the data rate can be varied with UNB or frequency modulated (FM) to modulate a UNB signal with audio. mw

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Design Feature

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Can MEMS Deliver for 5G Mobile Networks?

So much promise has been laid on MEMS technology as a solution for countless problems, but with the coming of 5G wireless networks, MEMS components may finally have a chance to perform.

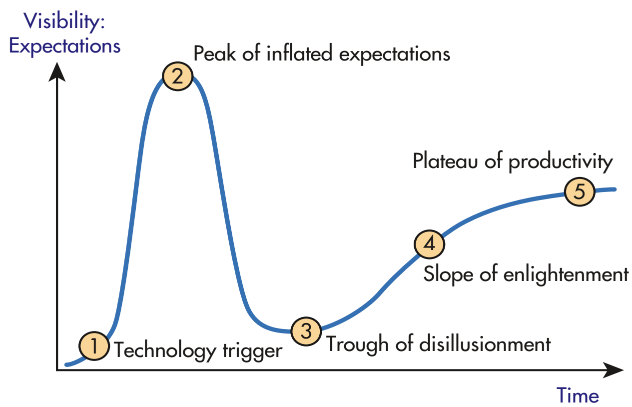
RF microelectromechanical-systems (MEMS) technology has been in use for about two decades, although from a market perspective, the disappointments seem to outweigh the successes. Full deployment of the technology is yet to come, however, and 5G mobile communications standards may be fertile ground to exploit the full potential of MEMS technology.

For more than 20 years, research articles have touted the capabilities of RF-MEMS passive components, such as micro relays and variable capacitors (varactors). These components have been lauded for their low loss, high isolation, and wideband performance. In addition, their use in higher-level assemblies, such as multiple-state impedance tuners and programmable phase shifters, pointed to broad mass-market adoption of MEMS devices and components.

Early predictions forecast widespread MEMS adoption.[1] Bearing in mind the classic transceiver (transmitter/receiver) architecture of mobile telephone handsets, the deployment of RF-MEMS was seen to follow two phases. In the first phase, MEMS passive components, such as antenna switches and RF/IF filters, would replace their counterparts based on conventional (discrete component or MIC) technologies.

The development of more integrated MEMS devices—such as multiple-channel selectors with embedded filtering functions, as well as hybrid mixer/filters—would lead to the second phase, and to a rethinking of the transceiver architecture in terms of MEMS technology. The RF transceiver block diagram would be simplified, with fewer LNAs and increased coverage of services and frequency bands.

The actual evolution of MEMS technology was much different. From 2002 to 2003 and for about one full decade through about 2013, market forecasts predicted a massive penetration of RF-MEMS technology into consumer markets for mobile phones.[2] But market estimates of hundreds of millions of U.S. dollars were systematically downsized with each market analysis, and the integration of the cellular transceiver and expected market consolidation never occurred.



1. The plot shows the typical hype curve cycle followed by new technologies, from their introduction to maturity and market absorption.

Such fluctuating market behavior can be explained by an empirical graphic tool, known as a hype curve.3 When a novel technology emerges, expectations of its market impact grow quickly (*Fig. 1*). As soon as possible exploitations are analyzed into details, the initial enthusiasm drops quite steeply to a minimum. This takes place for various reasons, including lack of maturity of the technology, integration/qualification issues, and costs.

This drop in expectations is also a trigger that focuses attention towards any weaknesses in the technology and its applications. This leads to the final part of the hype curve cycle, which is the consolidation of a certain technology in one or more market applications and segments.

Fitting the evolution of RF-MEMS technology into the boundaries of a classical hype curve cycle does not seem a simple task. Staring at one decade of market studies, forecasts, and rumors, it's as if the hype curve of MEMS-based RF passive components underwent two subsequent peaks of inflated expectations—and, consequently, two harsh drops.[2]

The first deflation, which occurred around 2003 to 2004, was mainly driven by technology *intrinsic factors*. In particular, reliability (including medium- and long-term mechanical and electrical reliability), packaging, and integration with standard technologies, were the main factors impairing the employment of MEMS devices into commercial market. Moving forward from that time, research efforts targeted those problem areas, leading to significant improvements. From then on, the evolution of RF-MEMS technology has followed the standard pattern of hype curve cycles.

Improvements in reliability, packaging, and integration level triggered a second peak of inflated expectations around 2009 to 2010, followed by another steep fall afterwards. The motivation of such a singular behavior can be attributed to *extrinsic factors* linked to the surrounding market environment, rather than to RF-MEMS technology itself. In fact, mobile communications through 3G and 3.5G were not really in need of components with the enhanced characteristics of MEMS-based RF passives components. The exploitation of RF-MEMS technology has always been more oriented to a *technology push* rather than a *market pull* philosophy.[2]

With 4G-LTE mobile communications mobile devices—and their use of touchscreens, integration of antennas inside the handset, and increased difficulty of including ad hoc performance-boosting circuitry—a trend of degradation in the quality of communications began.[4] It was estimated that the ratio of theoretical versus actual RF signal quality was decreasing with a pace of about 1 dB/year for over a decade.

Because of the aforementioned factors, smartphone antennas were not working under optimal conditions, leading to slower download speeds, reduced quality of voice service, lower energy efficiency, and more dropped calls. Therefore, fixed impedance matching between the transmitting/receiving antenna and the RF front end (RFFE) adopted in previous mobile handsets generations was no longer the best option.

This change in mobile communications scenario boosted demand for reconfigurability and tunability of passive components, which RF-MEMS technology has always been capable of addressing. In 2012, information emerged about RF-MEMS-based adaptable impedance tuners (from WiSpry) in Samsung Focus Flash Windows smartphones.[5] In Fall 2014, Cavendish Kinetics (CK) announced commercial adoption of its RF-MEMS-based antenna tuning solution in the Nubia Z7 smartphone, manufactured by the Chinese ZTE Corp.[6]

In early 2017, CK went public with the adoption of its RF-MEMS solutions by more than 40 LTE smartphones, including the Samsung Galaxy A8.6 Other important players, such as Qorvo, extended the functionality of commercial RFFEs by adopting RF-MEMS switching units.[7]

It seems that RF-MEMS technology, after a nearly 20-year period of inflated expectations and harsh disappointments, is making its way along the hype curve toward the so-called plateau of productivity (*Fig. 1*). However, this is not a time of final accomplishments for RF-MEMS technology but the beginning of something new.

Opportunities lie ahead for RF-MEMS in the devices and infrastructure of 5G mobile communications systems. Although the transition from 4G-LTE to 5G should be smooth, 5G will represent a total different paradigm, not just with its use of millimeter-wave frequencies but with machine-to-machine (M2M) functionality[8] and the enormous amount of IoT data it will handle.

Predictions call for 5G data capacity as much as 1,000 times that of 4G-LTE, delivering 10 Gb/s to each user. In support of M2M and vehicle-to-vehicle (V2V) applications, 5G latency must be low (on the order of milliseconds). In addition, more symmetry between downlink and uplink data transmission capacity will be needed for a 5G standard that can handle M2M applications.

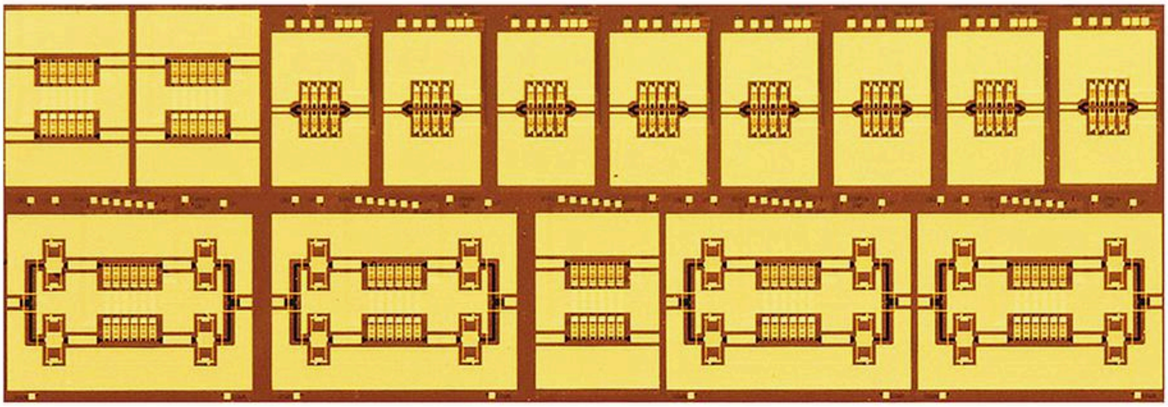
Radio access technologies (RATs) for 5G must address three areas to increase the amount of transmitted data[9]:

- Modulation order
- Aggregated bandwidth
- Order of multiple-input, multiple-output (MIMO) antennas

If enhancing the first degree of freedom (DoF) is a challenge to be met mainly at algorithm and electronic design levels, then addressing the second and third items will require flexibility in hardware reconfigurability. In particular, improving the aggregated bandwidth means increasing the number of carrier aggregation (CA) components. In terms of hardware specifications, RF transceivers will need to quickly change frequencies as different bands are available in a 5G wireless system.

Increasing MIMO is a matter of having arrays/matrices of integrated antennas (e.g., 4×4) small enough to be employed in smartphones, and driven by high-performance RFFEs with improved switching and filtering characteristics to minimize interferences and crosstalk.

In terms of mobile communications infrastructure, another trend on its way of consolidation is the frequency diversity across the backhaul portion of the network hierarchy. To this regard, a clear frequency divide will characterize 5G networks. The classical macro-cells, covering extended areas, will mainly work in the sub-6 GHz range. On the other hand, the large data throughput required will be enabled via significant network densification.



2. These RF-MEMS reconfigurable attenuators were fabricated at Fondazione Bruno Kessler (FBK).

Small cells will be deployed, covering limited spaces such as a single office building or shopping mall. The use of small cells will enable the use of data transfer via licensed and unlicensed millimeter-wave frequencies, but they will require arrays of reconfigurable antennas and RF drivers capable of advanced beamforming for effective directivity and efficient area coverage.

A wish list for RF passive components based on the expectations of 5G systems and handsets could look like the following:

1. Very wideband switches and switching units with high "off" isolation and low through loss, and low adjacent-channel crosstalk from 2 to 3 GHz to 60 to 70 GHz or higher.
2. Reconfigurable filters with high stopband rejection and low passband loss.
3. Wideband multiple-state impedance tuners.
4. Programmable step attenuators with multiple configurations and flat amplitude and phase characteristics from a few GHz to 60 to 70 GHz.
5. Wideband analog phase shifters.
6. Hybrid devices with a combination of phase shifting and programmable attenuation (the functions of points 4 and 5 combined into a single device).
7. Miniature antennas and arrays, possibly integrated monolithically with one or more devices from points 1 through 6.

These passive-component needs can be addressed by MEMS technology. Since this technology is capable of integrating different functionalities, it provides opportunities for hardware reductions. In fact, reconfigurable phase shifters and programmable attenuators could be monolithically integrated with an array of millimeter-wave antennas using MEMS technology.

If RF-MEMS-based products are in the process of being consolidated in 4G-LTE applications, larger market volumes are possible for emerging 5G applications, both for handsets and for infrastructure. At present, few reports address RF-MEMS devices being tested for use in possible 5G requirements[10,11] (*Fig. 2*). However, more information on this topic is forthcoming, in the form of an e-book written by the author and produced by IOP Publishing (ISBN: 978-0-7503-1545-6).

The book will analyze the challenges of RF-MEMS technology for 5G applications, with practical modeling and design examples. Given the struggle of RF MEMS for its first 20 years, the future of the hype curve cycle may look much different with the onset of 5G mobile communications networks. mw

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Vector Rotator Solves Satcom Antenna Skew

This solid-state vector rotator provides electronic adjustments to the skew that commonly occurs when aligning antennas in satellite communications systems.

Successful operation of in-flight internet and entertainment services requires accurate polarization alignment of the satellite and receive antennas for linearly polarized signals. Typically, the polarization alignment of the satellite and transceiver is accomplished by an electromechanical device that either rotates the antenna feed or other spatially operated devices that rotate the received signal vector. As will be seen, it is possible to provide the same rotational adjustment by means of a solid-state approach, rotating a received signal vector such that the result provides the original signals transmitted with cross-contamination from the other polarization removed.

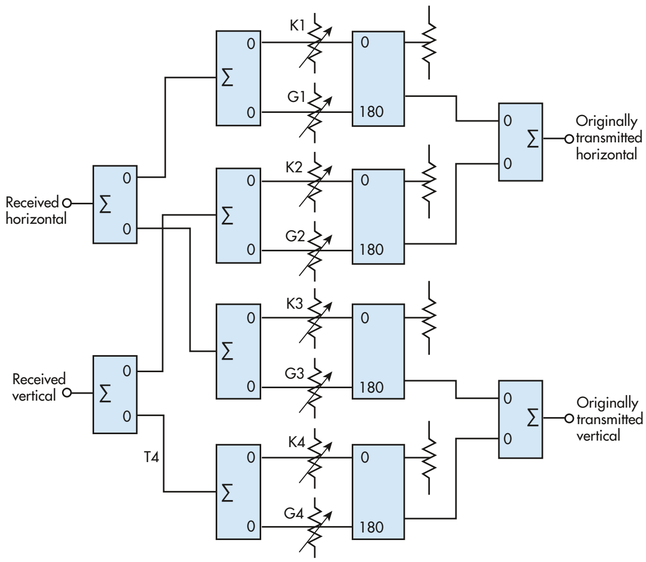
Figure 1 shows a block diagram of the vector rotator circuit, based on a low-frequency operational-amplifier (op-amp) circuit described in an earlier article.[1] Whereas the low-frequency op-amp version had the advantage of being frequency-invariant over the usable range of op amps, it was limited in frequency by those same devices. That basic low-frequency version is shown in *Figure 2*.

The proposed hybrid circuit performs the same vector rotation, but is better suited for microwave and millimeter-wave frequencies. The op amps in the original circuit perform the function of summing and subtraction of the scaled in-phase (I) and quadrature (Q) input signals. In the hybrid circuit, the inverting and adding functions are provided by 180-deg. hybrids, and the purely summation function is provided by 0-deg. power combiners. The op-amp circuit used resistors to set the scale factor of the input I and Q vectors, whereas in the hybrid circuit, attenuators set the scale factors.

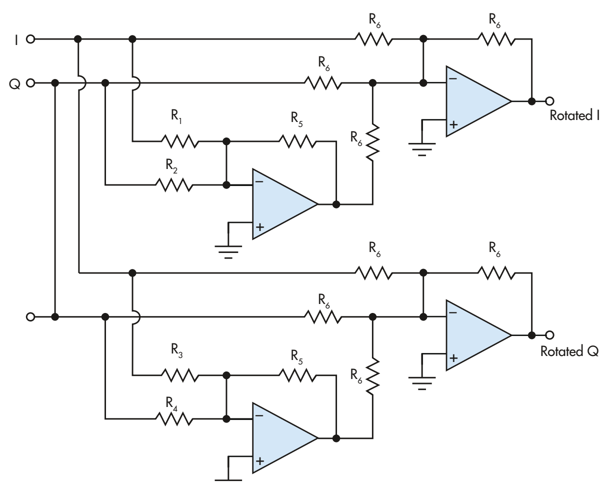
The theoretical operation of the circuit is based on the vector representation of the received signals represented in eq. 1:

$$S_R = [H_T\cos(\phi) - V_T\sin(\phi)]\hat{x}_H + [H_T\sin(\phi) + V_T\cos(\phi)]\hat{y}_V \quad (1)$$

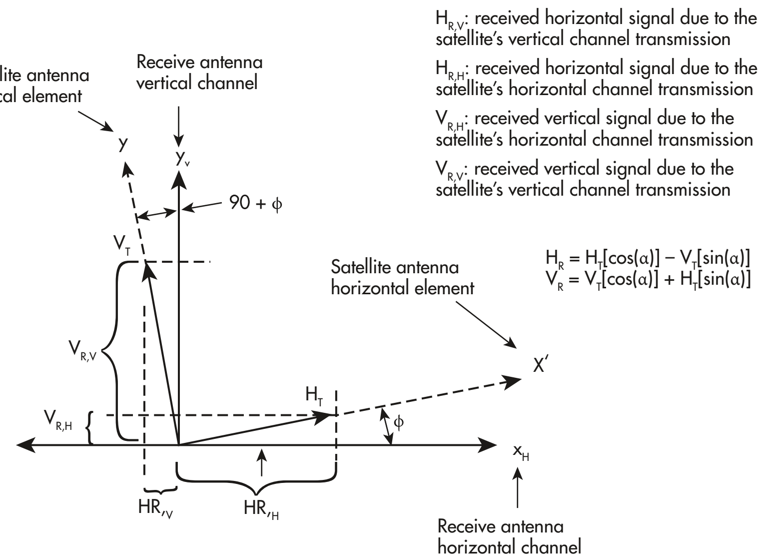
where S_R is the received signal; H_T is the transmitted horizontal signal; V_T is the transmitted vertical signal; $\hat{x}_H$ is the



1. This block diagram shows the hybrid construction of an RF vector rotator.



2. This is a low-frequency version of the vector rotation circuit.



3. Satellite antenna misalignment results in cross-channel coupling.

Typically, the polarization alignment of the satellite and transceiver is accomplished by an electromechanical device that either rotates the antenna feed or other spatially operated devices that rotate the received signal vector.

received horizontal signal reference axis; $\hat{y}_V$ is the received vertical signal reference axis (where x_H is the horizontal channel and y_V is the vertical channel); and ϕ is the angle of misalignment between the transmit and receive antennas.

Figure 3 illustrates the relationship between the satellite's antenna reference system and the earth, or in-flight transceiver's antenna reference system. If you assume that all hybrids have the same insertion loss (–3 dB) for each input to output, and normalize the output amplitude by the overall loss factor, then the output can be written as:

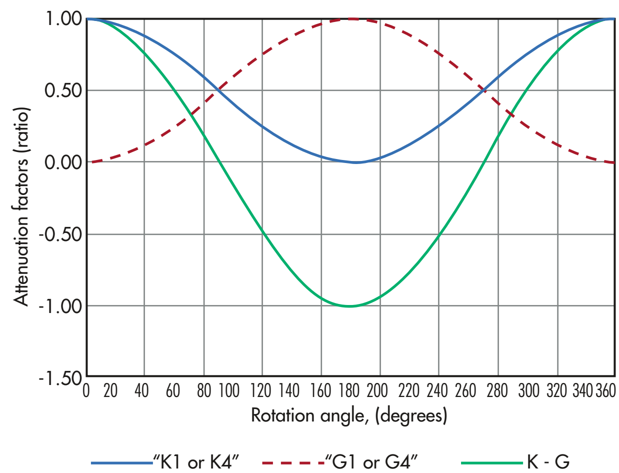
$V_0 = H_T[m_1\cos(\phi) + m_2\sin(\phi)]$
$+V_T[m_2\cos(\phi) - m_1\sin(\phi)]$
where $m_1 = k_1 - G_1$ and $m_2 = k_2 - G_2$.
If $m_1 = \cos(\phi)$ and $m_2 = \sin(\phi)$, then:
$V_0 = H_T[\cos^2(\phi) + \sin^2(\phi)] + V_T[\cos(\phi)\sin(\phi) - \cos(\phi)\sin(\phi)] \rightarrow V_0 = H_T$

In a similar derivation for the output of the vertical channel:

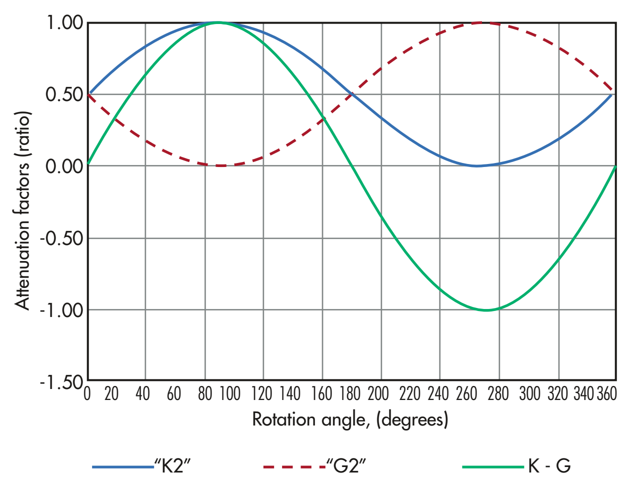
$V_0 = H_T[m_3\cos(\phi) + m_4\sin(\phi)] + V_T[m_4\cos(\phi) - m_3\sin(\phi)]$
where $m_3 = k_3 - G_3$ and $m_4 = k_4 - G_4$.
If $m_4 = \cos(\phi)$ and $m_3 = -\sin(\phi)$, then $V_0 = H_T[-\sin(\phi)\cos(\phi) + \sin(\phi)\cos(\phi)] + V_T[\cos^2(\phi) + \sin^2(\phi)] \rightarrow V_0 = V_T$

Using the preceding determination for m_1, m_2, m_3, and m_4 dictates the following relationships:

$k_1 - G_1 = \cos(\phi)$;
$k_2 - G_2 = \sin(\phi)$;
$k_3 - G_3 = -\sin(\phi)$;
$k_4 - G_4 = -\cos(\phi)$;



4. Attenuation factors K_1 and K_4 and G_1 and G_4 are plotted here.



5. Attenuation factors K_2 and G_2 are plotted as a function of rotation angle.

These relationships can be realized with the following equations:

$k_1 = \cos^2(\phi); G_1 = k_1 - \cos(\phi);$
$k_2 = 0.5 + 0.5\sin(\phi); G_2 = k_2 - \sin(\phi);$
$G_3 = 0.5 + 0.5\sin(\phi); k_3 = G_3 - \sin(\phi);$
$k_4 = \cos^2(\phi); G_1 = k_1 - \cos(\phi);$

Plots of the k and G values are shown in *Figures 4, 5, and 6.*

Detailed derivation along with a spreadsheet model *(Fig. 7)* that allows for variation of all hybrid losses, phase differences, and interconnecting parameters is available upon request. The spreadsheet model does not lend itself to complicated variations of the components and interconnecting lines, but does allow investigations of real circuit tolerances to the extent of manual effort tolerated by the investigator. An Octave-based program is being developed to make it easy to manipulate the myriad of variables in an actual circuit fabrication. mw

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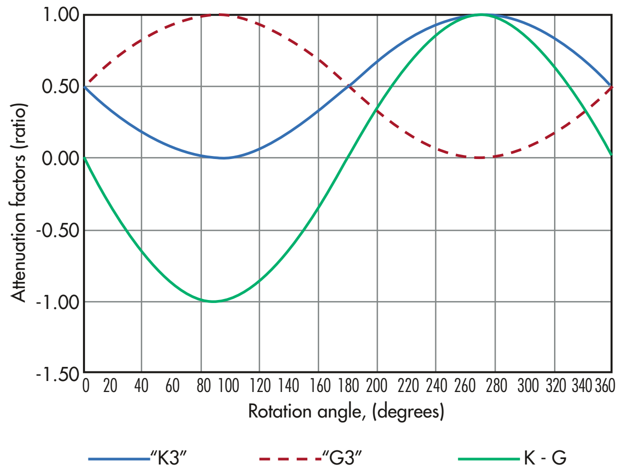
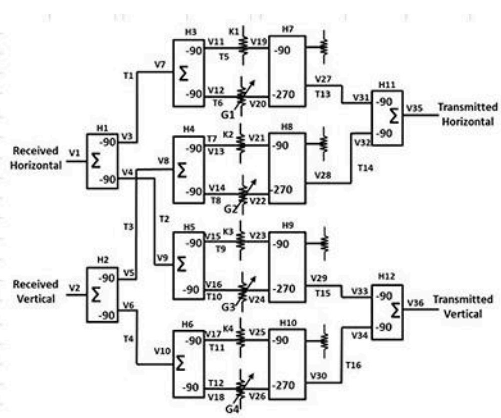
An Octave-based program is being developed to make it easy to manipulate the myriad of variables in an actual circuit fabrication.



6. Attenuation factors K_3 and G_3 are plotted as a function of rotation angle.

Vector Angle (Hor=x-axis; Vert=y-axis)=	(Degrees) 45.00		

			Starting
Gain Factor, dB =	-12.04		Values:
	Horiz Comp	Vert Comp	
	Mag	Mag	Mag
Horizontal Channel Output =	1.000	0.000	1.000
Vertical Channel Output =	0.000	1.000	1.000



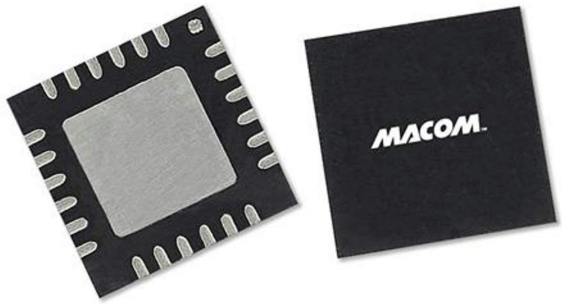
	From Port 1				From Port 2				Sum of Both Ports				Vector Component Signs of Output		
V35:	Horiz Comp		Vert Comp		Horiz Comp		Vert Comp		Horiz Comp		Vert Comp		Horizontal	Vertical	Horizontal Output
	Mag	Angle	Mag	Angle	Mag	Angle	Mag	Angle	Real	Imag	Real	Imag			
	0.250	0.00	0.004	-180.00	0.000	0.00	0.004	0.00	0.250	0.000	0.000	0.000			
	Real	Imag	Real	Imag	Real	Imag	Real	Imag	Mag	Angle	Mag	Angle			
	0.250	0.000	-0.004	0.000	0.000	0.000	0.004	0.000	0.250	0.000	0.000	90.000	1.000	1.000	
V36:	Horiz Comp		Vert Comp		Horiz Comp		Vert Comp		Horiz Comp		Vert Comp				Vertical Output
	Mag	Angle	Mag	Angle	Mag	Angle	Mag	Angle	Real	Imag	Real	Imag			
	0.004	-180.00	0.000	0.00	0.004	0.00	0.250	0.00	0.000	0.000	0.250	0.000			
	Real	Imag	Real	Imag	Real	Imag	Real	Imag	Mag	Angle	Mag	Angle			
	-0.004	0.000	0.000	0.000	0.004	0.000	0.250	0.000	0.000	90.000	0.250	0.000	1.000	1.000	

7. This spreadsheet model of the solid-state vector rotator includes the effects of variations due to hybrid losses, phase differences, and interconnecting parameters.

JACK BROWNE | Technical Contributor

When Time Delays Make More Sense Than Phase Shifts

The differences between RF/microwave phase shifters and delay lines are actually quite slight.



1. RF/microwave phase shifters come in many packages, including 4-b digital models in 4 × 4 mm PQFN plastic SMT packages. *(Photo courtesy of MACOM)*

2. Larger coaxial RF/microwave phase shifters can be designed with added features to simplify an application, such as a digital readout of phase. *(Photo courtesy of ARRA)*

PHASE SHIFTERS AND DELAY LINES are commonly used components in many high-frequency systems, included for their signal-altering capabilities. Although a delay in the phase or the timing of a signal are essentially the same thing, phase shifters and delay lines are designed with different goals in mind: to provide signal adjustments in the frequency and time domains, respectively, over a design frequency range.

Phase shifters are usually designed for changes in insertion phase of as much as 360 deg., or one wavelength, at a maximum frequency of interest. When a greater amount of phase shift or delay is required at a particular frequency, the solution lies in an RF/microwave delay line, which is specified in terms of the delay time, rather than the phase shift, at a frequency of interest.

In a phased-array antenna, for example, the different phases of multiple antenna elements must be adjusted so that the signals radiated by the different elements add in phase, providing the functionality of a physically much larger conventional antenna. Phase shifters provide the means of making phase adjustments to the antenna elements and their individual amplifiers or transmit/receiver (T/R) modules, so that signal contributions of each antenna element add in phase. Similarly, phase shifters can be used for antenna beam steering in a wide range of systems.

Phase shifters are passive components and, in fact, some passive components such as baluns and hybrid power combiners/dividers will also add a phase shift to a circuit. A quadrature hybrid divider, in theory, divides an input signal into two output signals that are 90 deg. apart in phase and 3 dB lower (typically more) in amplitude than the starting signal. Unlike a phase shifter, this 90-deg. shift in phase is independent of frequency. Ideally, a phase shifter changes the phase of an input signal without changing its amplitude (typically less).

Phase shifters can be implemented in a number of different ways, with the most straightforward being to extend the transmission path length. In doing so, the phase of the nominal or reference phase of a circuit or system is increased. The amount of phase shift achieved by the additional length of transmission line will be a function of the velocity of propagation (V_p) of the transmission medium.

In stripline, for example, in which a metal conductor is surrounded by dielectric material, EM propagation occurs entirely within the dielectric material, and V_p is the same for all signal traces—no matter how wide or where they are located. In microstrip, however, in which the metal conductor is exposed to the air, part of the EM propagation occurs in the air. The dielectric constant of a circuit is a combination of the dielectric circuit-board material and the air. For microstrip, V_p depends on the width of the trace and the height of the trace above the ground plane, and a phase shifter must be designed with attention to these details.

A simple phase shifter can be designed with a number of switchable transmission-line paths of different lengths, with a reference signal path representing a 0-deg. phase shift. Additional, longer signal paths are typically fabricated in quarter-wavelength ($\lambda/4$) increments of a design frequency, such as 90, 180, and 270, and 360 deg. By switching to the different paths, a phase shift proportional to the additional transmission-line length will be achieved.

Low-frequency (below UHF) phase shifters are typically realized with lumped-element circuit approaches to reduce the size of the transmission paths that would otherwise be required at those lower frequencies. In general, switched line, loaded line, and reflection approaches are commonly used to create phase shifters, although a number of novel approaches have also been applied—for example, separating input signals into in-phase (I) and quadrature (Q) signal components, and recombining the I and Q signals in different ways to achieve broadband phase shifts.

Most recently, microelectromechanical-systems (MEMS) technology has been used to create RF/microwave phase shifter in semiconductor-sized circuits in which the different propagation paths are selected by mechanical switches. MEMS-based phase shifters, due to their mechanical nature, are particularly resistant to interference from surrounding EM fields and have been candidates for phase-shifting applications in hostile operating environments. Standard semiconductor processes, such as GaAs pHEMT technology, have also been used to implement RF/microwave phase shifters that can be housed in miniature surface-mount packages.

An RF/microwave phase shifter is an analog circuit, no matter which design method is used to achieve the phase shift, although both analog and digital control methods have been used to control the phase of a phase shifter. Analog phase shifters are usually operated by means of a control voltage and the changes in phase are usually continuous across the total phase-control range and frequency range. In contrast, digital phase shifters use different numbers of bits to select one of a number of discrete phase states.

In terms of physical size, RF/microwave phase shifters can be as small as the MEMS or semiconductor-based chips that are housed in miniature plastic surface-mount-technology (SMT) packages *(Fig. 1)*, or much larger components with add-on features such as digital readouts of phase *(Fig. 2)*. RF/microwave phase shifters are available from a larger number of suppliers in many forms, including as packaged chips and in coaxial packages with a variety of different connector types.

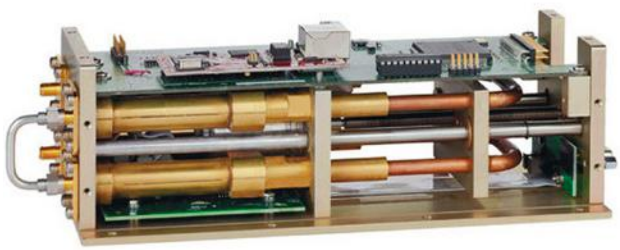
CREATING A DELAY

As noted earlier, when a total delay of more than one wavelength (360 deg.) is needed at a target frequency, as might be the case with many radars, EW systems, and test-and-measurement applications, an RF/microwave delay line provides a practical means of achieving those longer delays. In a radar system, for example, a delay line makes it possible to perform signal analysis on a large number of acquired pulses by delaying some of the pulses in time. In a communications system with multiple clock sources, delay lines make it possible to introduce delays to a faster clock to synchronize its timing with a slower clock.

As with phase shifters, delay lines employ a number of different technologies in an attempt to create long transmission paths in small spaces. One of the simplest delay lines is a coaxial cable. Delay lines have also been based on creating long transmission-line paths on microstrip circuits. Multiple microstrip circuits can be cascaded to increase the length of the delays.

The time delays possible with a given delay-line technology depend on the propagation velocity of the delay line circuit medium, such as the crystal or glass substrates used to fabricate surface-acoustic-wave (SAW) or bulk-acoustic-wave (BAW) delay lines. In these components, RF/microwave signals are converted to acoustic signals which experience significant delays across the substrate materials, enabling the components to achieve long delay times in smaller packages.

Delay lines have been implemented as analog and digital circuits and as mechanically tuned structures, such as mechanical trombone structures that are capable of long delays over extremely broad frequency spans *(Fig. 3)*. Trombone delay-line structures have been combined with stepper motors to form programmable delay lines with delays available in high-resolution steps, with as much as 100 ns total delay possible over bandwidths as wide as DC to 18 GHz.



3. Delay lines based on trombone delay structures can achieve extremely long delay times with low loss over wide frequency ranges. *(Photo courtesy of Colby Instruments)*

Although the trombone delay-line approach exhibits low loss, even lower loss is possible through a delay-line technology known as RF over fiber. In this method, an RF input signal is converted to an optical signal and transmitted over a fiber-optic link to a receiver which provides the signal delays. The optical signals are then reconverted to RF/microwave signals.

While RF-over-fiber delay lines are more of a subsystems nature, typically packaged in rack-mount enclosures, they are well suited for applications requiring extremely long delay lines but with losses that are considerably lower than with other coaxial or waveguide delay-line design methods. They can be customized to meet specific requirements, such as inclusion of amplifiers to produce signal gain along with the delay. mw

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What are the Top Challenges Facing Smartphone Manufacturers?

Handset manufacturers are looking to the latest RF front-end (RFFE) solutions to satisfy increasingly complex requirements.

Rising mobile data demand continues to create complex RF challenges for smartphone manufacturers. Globally, mobile data consumption grew 63% in 2016, and is projected to increase sevenfold by 2021, according to the Cisco Visual Networking Index.

Growth is largely being driven by video traffic, which already accounts for more than half of mobile data use, and is projected to account for more than 75% by 2021. Video consumption is also driving demand for faster networks, as well as greater network capacity. This need will become more acute as the smartphone increasingly becomes users' primary device for streaming TV and movies, including higher-resolution 4K video. The growth of real-time video uploading, as well as new usages such as augmented and virtual reality, will drive demand for faster uplink and downlink connections.

In the long term, 5G is expected to deliver multi-gigabit data rates to the handset, but widespread 5G deployments are several years away. To support the demand in the near term, mobile network operators and handset makers are applying a combination of techniques to increase the performance of 4G networks, with a target of delivering 1 Gbps to advanced handsets.

Four approaches are key to achieving this goal: advanced carrier aggregation (CA), LTE over unlicensed spectrum, higher-order modulation, and 4×4 multiple-input, multiple-output (MIMO). Each of these approaches adds RF complexity to handsets, and smartphone manufacturers will need to support all four to deliver 1-Gbps data rates. Adding to the challenges, manufacturers need to squeeze this added complexity into the relatively fixed space allocated to the RF front-end (RFFE). Power management in the RFFE is also becoming even more of a priority as manufacturers seek to maximize battery life and support a new higher-power LTE standard.

CARRIER AGGREGATION COMPLEXITY

Today, CA is the primary method that operators are using to drive higher data rates. CA combines multiple LTE carriers (called component carriers) to increase bandwidth beyond the 20-MHz single-carrier maximum and deliver data rates greater than 150 Mbps. It also enables network operators to use their fragmented spectrum holdings more efficiently. Most operators initially implemented CA only in the downlink path, to support user demand for streaming video and other applications that primarily involve data downloads rather than uploads.

Many early implementations aggregated only two component carriers. Now, however, operators are combining three, four, or even five to further increase data rates. In general, three or more component carriers are required to provide more than 40-MHz bandwidth and deliver speeds greater than around 300 Mbps. Because of this trend, and because spectrum allocations differ in each country, there has been an extraordinary increase in the number of different band combinations that handsets must support. This drives incredible complexity in the RF pathways within the handset, particularly in premium smartphones designed for global use. *Figure 1* shows how the number and complexity of CA band combinations have increased over time.

As the number of combined bands increases, so does the likelihood that some of the combined bands will share the same phone antenna. This situation creates new filtering challenges. To support simultaneous communication on multiple component carriers, the device's RFFE must support multiple open, parallel transmit and receive paths between the transceiver and the antenna. At the same time, it must provide sufficient isolation between those paths to avoid problems (e.g., desensitizing the receiver).

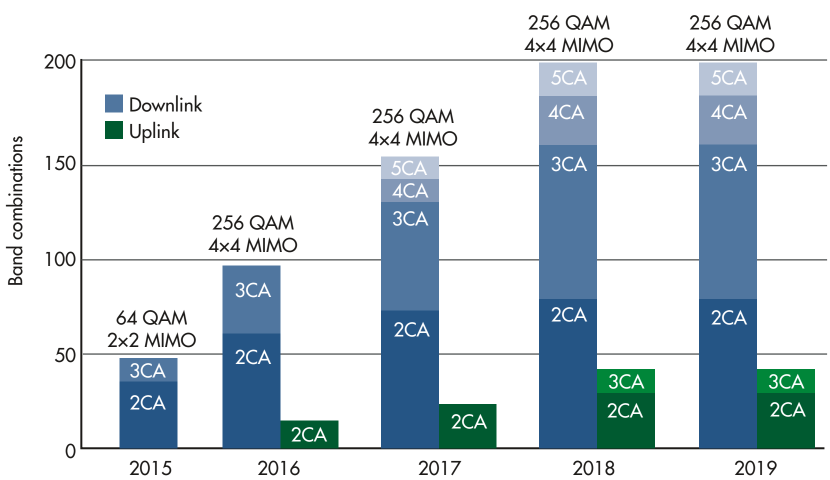
Multiplexers provide a solution to this quandary. They combine all of the transmit and receive filters for multiple aggregated bands into a single component, allowing them to connect to the antenna at the same time while providing the required isolation between them. Without using a multiplexer, it may be impossible to meet system requirements for isolation between bands—and between the transmit and receive frequencies of FDD-LTE bands—together with low insertion loss and low current consumption.

However, designing multiplexers presents difficulties that increase exponentially with the number of aggregated bands, due to the growing number of potential interactions between all the filters within the multiplexer. The filters must be carefully co-designed to maintain low insertion loss and high linearity, while achieving adequate rejection of harmonics.

Considering all the possible interactions, there are eight isolations required in a quadplexer (four filters, used for aggregating two FDD-LTE bands) and 18 in a hexaplexer (six filters for three bands). For mid-band and higher frequencies, high-Q bulk acoustic wave (BAW) filters are essential to provide the steep skirts required to avoid interference between closely spaced bands, combined with low insertion loss. *Figure 2* shows performance data for a Qorvo hexaplexer, illustrating the low insertion loss and rejection of adjacent bands.

For smartphone manufacturers, the choice of antenna architecture—including the number of frequency bands allocated to each antenna and the way the bands are partitioned among the antennas—will drive the decisions about the multiplexing required to support the desired CA combinations.

CA BAND COMBINATIONS AND ADVANCED MODULATION DRIVE RF COMPLEXITY



1. This figure illustrates the growth in the number of CA band combinations.

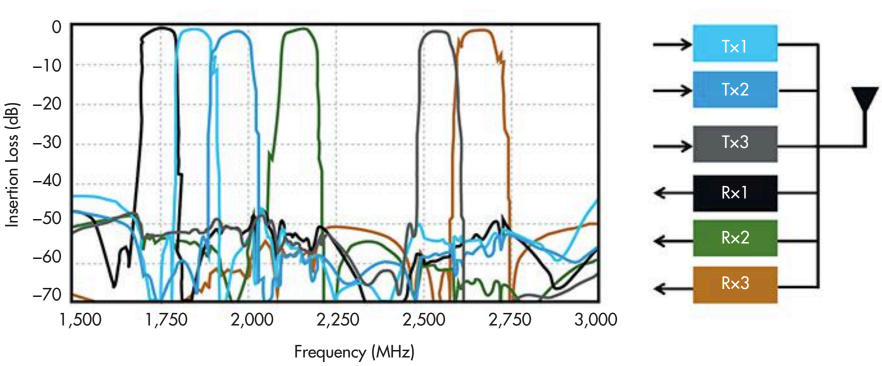
While early CA deployments focused on downlink, uplink CA is also being adopted as trends such as uploading real-time video gather strength. Though fewer band combinations have been defined, and are generally limited to two or three carriers, they present new and unique RF challenges. In China, intra-band uplink CA (combining carriers within the same band) is being used to overcome the uplink bandwidth limitations of TDD-LTE. The higher peak-to-average power ratios (PAPRs) and wider bandwidth of these signals requires highly linear power amplifiers (PAs). Envelope tracking (ET) is needed to maximize PA efficiency at high power output. Filters must also be capable of handling the higher power output. With inter-band uplink CA (combining carriers in different bands), high linearity in front-end components, such as switches, are required to avoid problematic intermodulation frequencies that can be created by interactions between signals.

HIGHER FREQUENCIES AND HIGHER-ORDER MODULATION

Adding frequency bands, including higher-frequency LTE bands and unlicensed frequencies, is an important element of operators' plans to increase network capacity and performance. Key technologies include Licensed Assisted Access (LAA), which uses CA to combine unlicensed 5-GHz spectrum (shared with Wi-Fi) with licensed LTE bands. Use of these higher-frequency bands for LTE will require highly linear front-end components and new filtering and multiplexing solutions.

Higher-order modulation is also being employed to squeeze higher data rates out of existing networks. For example, the increase from 64 QAM to 256 QAM in the download link provides up to 33% greater throughput. However, the higher signal-to-noise ratio needed for 256 QAM also requires higher linearity and lower insertion losses in the RFFE.

ENABLING ADVANCED CA WITH HIGHER ORDER MULTIPLEXERS

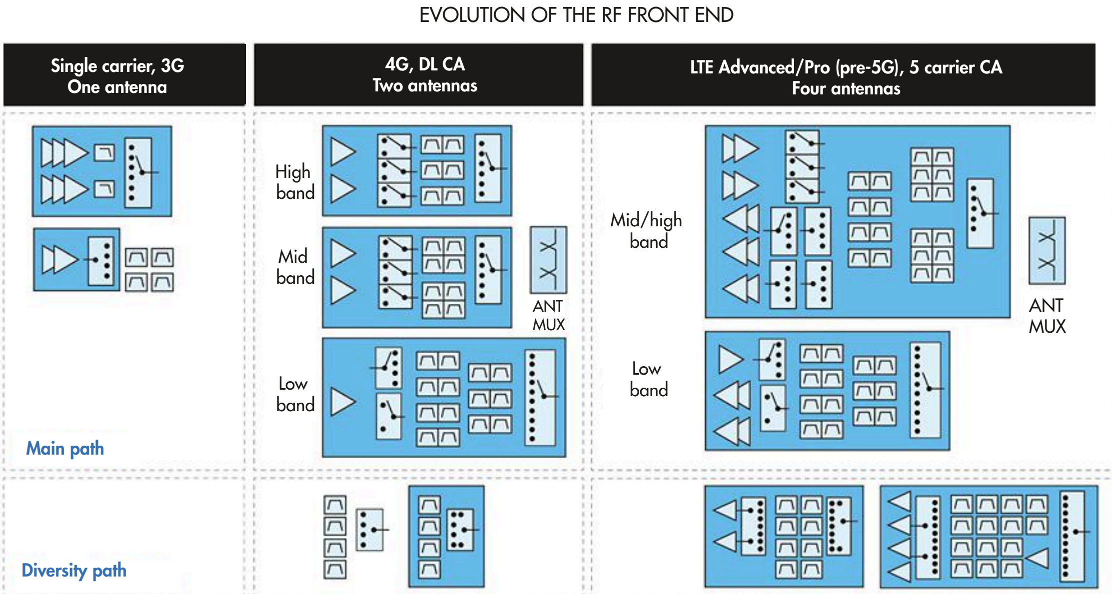


2. Higher-order multiplexers, such as this hexaplexer, are required for advanced CA.

INCREASING RF FRONT-END INTEGRATION

To achieve gigabit performance, handsets will need to support four simultaneous downlink data streams. This transition from 2×2 to 4×4 MIMO means smartphones must accommodate entire additional RF chains as well as more antennas. This will drive increasing levels of integration in the RFFE.

Today's premium handsets already use highly integrated RFFEs. Qorvo's RF Fusion, for instance, employs



3. This figure shows the transformation of the RFFE.

advanced packaging techniques to integrate all primary PA, filtering, and switching functionality into compact modules respectively covering low-, mid-, and high-band frequencies. The RFFE architecture is evolving to still higher levels of integration, such as the consolidation of medium and high bands into a single module *(Fig. 3)*. This requires new higher-order multiplexers to enable aggregation of mid- and high-bands sharing the same antenna. Besides saving space, this approach eliminates the need for on-board matching between components, which may reduce losses for both the transmit and receive paths by 1.0 dB or more.

Antenna tuners will be required for each antenna. This requirement is not just to support the growing number of frequency bands, but also to optimize performance, since the continuous changes in the handset's RF environment may affect each antenna differently.

POWER MANAGEMENT CHALLENGES

The growing complexity of RF pathways within the smartphone increases potential losses. Thus, it is even more difficult to achieve targets for output power at the antenna and receive sensitivity while minimizing power consumption to conserve battery life. Envelope tracking (ET) is an important technology for increasing power efficiency. To date, it has been used primarily in flagship phones, but is now spreading to mid-tier phones. ET continuously adjusts the PA supply voltage to track the RF envelope and maximize PA efficiency, thus reducing power consumption.

A different power management challenge has been created by the new LTE Power Class 2 standard, which doubles antenna output power to +26 dBm on the high-frequency Band 41. The added power compensates for the greater propagation losses at higher frequencies, allowing operators to maximize coverage with existing LTE infrastructure. Supporting Power Class 2 in handsets requires low-loss, high-linearity filters to effectively dissipate the additional heat generated at higher output power, such as BAW solidly mounted resonator (SMR) filters, along with increasingly efficient PAs meeting stringent error vector magnitude (EVM) requirements.

SUPPORTING THE EXPANDING CAPABILITIES OF MID-TIER SMARTPHONES

Fast-expanding Chinese manufacturers have been largely responsible for driving rapid growth in mid-tier smartphones within that country—the world's largest smartphone market. Now, those manufacturers are looking to expand from China's domestic market to selling overseas. This requires them to balance several factors. Adding RF content enables each handset model to support more bands for broader geographic use, thus minimizing the number of different models manufacturers need to produce.

On the other hand, manufacturers need to limit the component costs of each handset, since the mid-tier category is highly price-sensitive. The net result is likely to be that RFFEs designed for mid-tier smartphones, such as the Qorvo RF Flex, will become progressively more integrated while still leaving room for design flexibility.

CONCLUSION

The quest for gigabit speeds is creating extraordinary RF complexity in handsets. RFFEs must integrate more functions while providing very high linearity, minimizing insertion loss, and reducing power consumption. As RF complexity increases, handset manufacturers will increasingly rely on RFFE suppliers that can help solve these challenges, providing integrated solutions that meet stringent requirements. mw

SHED LIGHT ON IoT MATTERS

WHILE THE INTERNET OF THINGS (IoT) is expected to have a profound impact on society in general, many questions are also associated with it. For instance, one grey area surrounding the IoT has to do with its actual definition. Additional questions concern how it will be used, along with the extent of its impact. These topics and more are discussed in a new white paper from Qorvo titled *"The Impact of the IoT Demystified."*

The white paper begins by describing the IoT as an application or service that collects information from sensors, analyzes the data, and then does something with that data. One example mentioned is an electronic lifestyle coach, which collects data via a wristband, analyzes the data, and instructs the person wearing the wristband to live a healthier lifestyle. Another example is an electronic security guard that analyzes data from motion sensors or cameras and then creates alerts.

Qorvo Inc., 7628 Thorndike Rd., Greensboro, NC 27409; (336) 664-1233; www.qorvo.com

Making better decisions in a faster time is the fundamental objective behind the IoT, according to the white paper. The author states that the IoT can offer various benefits, such as reducing wasted energy, improving the quality of products, and upgrading environmental monitoring. The white paper also mentions some of the downsides associated with the IoT, explaining that it will redefine jobs and skills and possibly even create social unrest. Essentially, there will be winners and losers, as some jobs could be lost while others are created.

IoT security and privacy are discussed as well. While the IoT is not entirely secure, the white paper makes the claim that security risks are generally acceptable when compared to the benefits of IoT applications. An IoT application also has the tradeoff between its benefits and a sacrifice of some level of privacy. Lastly, to demonstrate the importance of the integrity of the IoT, an alarm system example is presented.

ADVANCED DACs BRING RF SIGNAL GENERATION TO LIGHT

GENERATING COMPLEX RF SIGNALS traditionally involves vector signal generators (VSGs) with in-phase quadrature (I/Q) modulators and analog synthesizers. However, an alternative approach takes advantage of high-speed digital-to-analog converters (DACs), enabling complex signals to be directly generated at microwave frequencies. In the white paper *"Overcoming RF Signal Generation Challenges with New DAC Technologies,"* Tektronix discusses the technology behind direct RF complex signal generation.Furthermore, a technique is presented that can be utilized to expand the frequency range of generated signals.

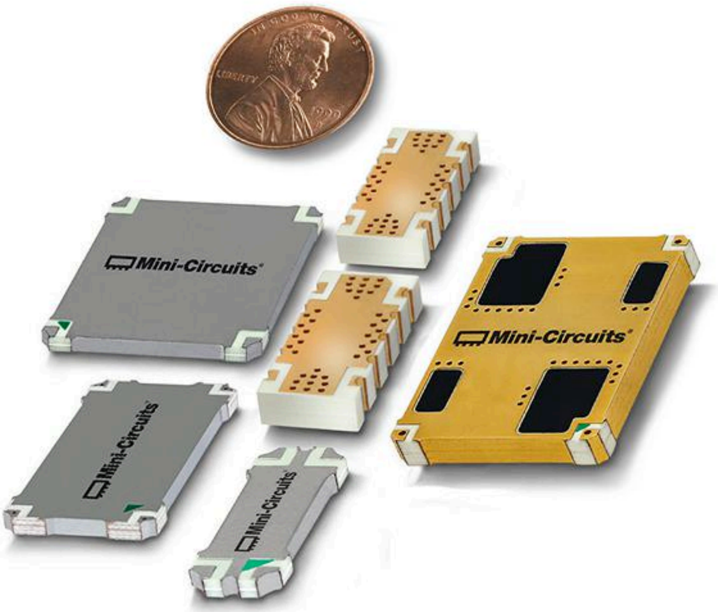
Tektronix Inc., 14150 SW Karl Braun Dr., Beaverton, OR, 97077; (800) 833-9200; www.tek.com

The white paper first explains that the common method of generating complex RF signals basically involves modulating a carrier signal. Essentially, a local-oscillator (LO) generates this carrier signal, which is modulated by a vector modulator. To illustrate this signal generation process, a simple block diagram is presented that shows an arbitrary waveform generator (AWG) supplying I/Q signals to a VSG.

The white paper points out that the traditional method of complex RF signal generation has the disadvantage of degraded signal modulation quality due to I/Q amplitude and phase imbalance and LO leakage. These pitfalls, which can be compensated for to some extent, are due to hardware non-idealities of the vector modulator. Another disadvantage is the increased cost and complexity for large-scale, multi-channel RF systems.

Modern DACs can integrate more functionality into a single chip, with some advanced versions incorporating features like finite-impulse-response (FIR) filters, digital interpolation, complex modulation, and numerically controlled oscillators (NCOs). As a result, complex RF signals can be directly generated in an efficient and compact manner. A simplified block diagram of the high-speed, 16-bit DAC used in Tektronix's AWG5200 Series of AWGs is shown. The functionality of this DAC is explained in detail.

The white paper analyzes the frequency response of a DAC in mathematical terms. The magnitude of the complex output spectrum of a DAC generating an arbitrary waveform is illustrated. Examples of direct RF signal generation using the AWG5200 Series are described. The document also explains how the frequency range can be extended by implementing a superheterodyne upconversion method.



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EW Threat Emulator Delivers from the Bench

This EW threat emulation system brings tremendous realism to benchtop EW system design verification.

FEW TECHNOLOGIES IN the defense electronics inventory face greater challenges or play a greater role in ensuring warfighter survivability than electronic warfare (EW) systems. They must not only detect an adversary's radar, typically in a dense electromagnetic (EM) signal environment, but also determine how to defeat it and then attempt to provide a solution that cancels or minimizes the threat. Failure can be a matter of life or death.

Test regimes for readying an EW system for the field are exhaustive, ranging from simulation and emulation on the benchtop to higher and higher (and increasingly costly) levels of stress testing to ensure effective operation under a wide range of operating conditions, ultimately resulting in exposure to an enormous array of threats on an open-air test range.

This "final exam" last step is the potential deal breaker because there are few such test ranges and many programs to test, so there is typically a long waiting list. Fail this test and the next chance will be months (and perhaps a year) away. Nevertheless, these systems are required for final sign-off before the asset can be deployed.

Taking this "do-or-die" final test scenario into consideration, it's essential that testing against threat waveforms begins as early as possible in the design process, when it's easiest to perform and EW system changes can be made quickly and inexpensively. The greater the realism in this testing, the better the chances of success are during the candidate EW system's Initial Operational Capability (IOC) evaluation. Achieving this requires that emulated signal environments be highly representative of those the system will experience in service.

An effective EW emulator must create the signal environment for all moments in time, all RF emitter positions and ranges, and for all emitters as they dynamically move through a battlespace with changing amplitudes, phases, and frequencies. Fortunately, modern field-programmable-gate-array (FPGA) architectures and real-time frequency synthesizers allow for such realism to be generated for bench-top and open-range applications.

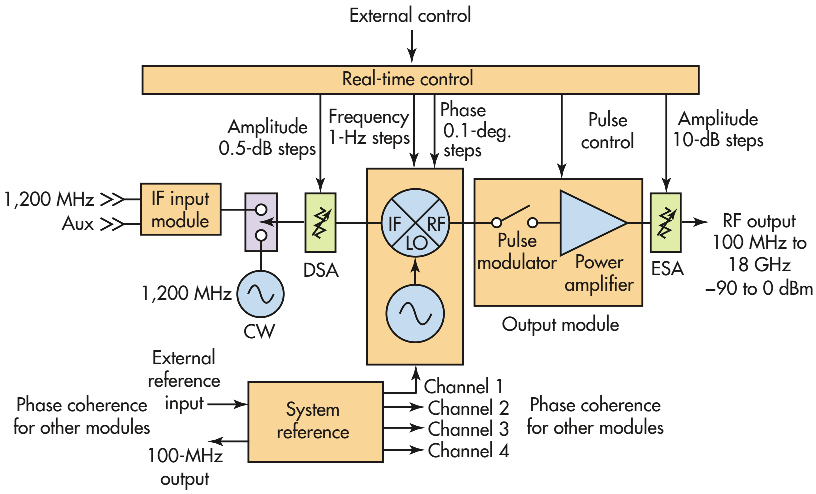
The Giga-tronics Real-Time Threat Emulation System (TEmS) was created to make this achievable as a modular and scalable commercial-off-the-shelf (COTS) benchtop EW threat emulation solution *(Fig. 1)*. The company combined its 35 years of experience in high-performance frequency synthesizers with the capabilities of partners with long experience in creating closed-loop, high-fidelity signal environment emulations.

1. The TEmS system combines signal generation and analysis hardware with kinematic-based real-time emulation software to form a benchtop system that expands the realism of EW system testing.

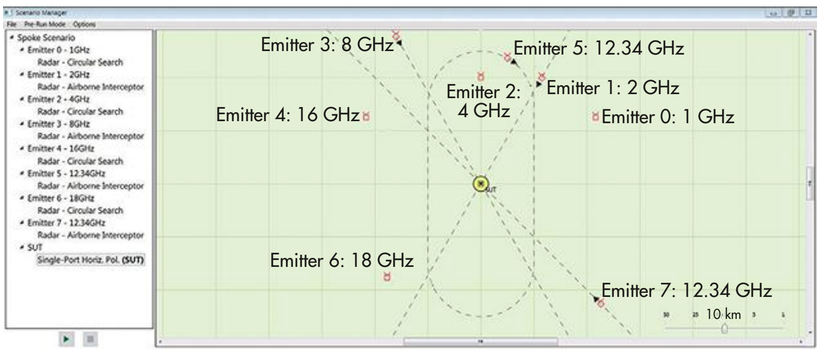
The TEmS system is compact enough to fit on a test bench. It is equally suited for use in early design verification, and is modular so it can be reconfigured for more complex testing during final system verification. This modular approach allows the hardware to scale at the module level rather than through the addition of expensive standalone instruments.

Its open-loop software lets designers improve their system design at any stage of development. In short, the ability to test all or part of a system at the board, module, and system level makes it possible for engineers to identify and fix design issues well before testing on the range.

TEmS is the only test system that performs phase-coherent upconversion and provides a deterministic real-time interface to control frequency, phase, and amplitude at the RF carrier. While these parameters could have been controlled at baseband



2. The Advanced Signal Generator (ASG) provides high-resolution control of amplitude, frequency, and phase for signals to 18 GHz.



3. TEmS simulated battlespace showing platform/emitter designations and locations.

frequencies, that approach is limited in dense signal emulation environments because the emulation system's digital-to-analog converter (DAC) must share its available signal output power across all simulated threats and have sufficient sample bandwidth to create agile emitters.

These capabilities enable users to create high-performance scripted open-loop emulations and are the building blocks for real-time closed-loop emulation systems. In addition, the TEmS open-loop software incorporates the comprehensive kinetic effects (the movement of all types of emitters in relation to each other in space) that are essential for creating a signal environment that realistically represents what the EW system will encounter in service.

The system's agile wideband upconverters are used for signal synthesis and real-time control of RF parameters. Signal generation with high-resolution control is performed by the Giga-tronics Advanced Signal Generator (ASG) *(Fig. 2)*, part of the firm's Real-Time Synthesizer (RTS) family of modules for multi-channel, phase-coherent, upconverters and downconverters.

The ASG is based on a 100-MHz reference, which also provides additional outputs for synchronization of other modules in the emulation system. The ASG is capable of high-resolution tuning of generated signals, with 0.5-dB amplitude resolution, 1-Hz frequency resolution, and 0.1-deg. phase resolution.

Real-time control of the ASG's frequency, phase, and amplitude is accomplished through a parallel binary-coded-decimal (BCD) interface allowing frequency, phase, and amplitude to be changed in less than 1 microsecond over a frequency range of 100 MHz to 18 GHz. This supports synthesis of multiple emitters on a single RF channel that operate at different RF center frequencies. Each ASG module can translate an IF waveform signal centered at 1200 MHz to anywhere in the spectrum between 100 MHz and 18 GHz. The IF can have an intrapulse Instantaneous Bandwidth (IBW) up to 1 GHz for output frequencies above 4 GHz.

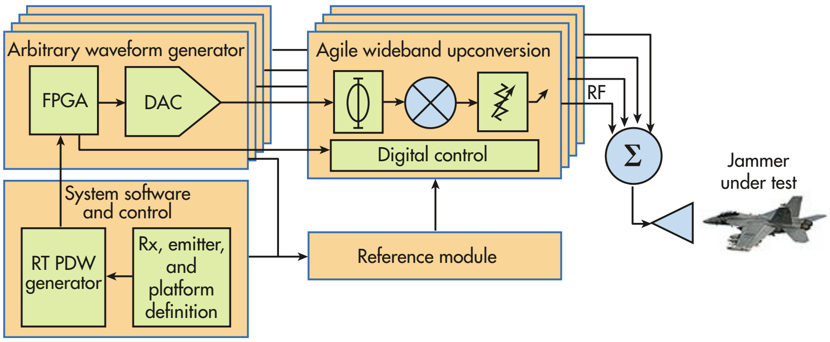
Multiple, phase-coherent channels are realized using the system reference module that distributes the required analog timing signals plus Local Oscillator (LO) signals across Zone 3 of the AXIe chassis. The reference module also provides a 100 MHz reference output for maintaining phase-coherent operation across multiple AXIe chassis. AXIe Zone 3 implements a coherent analog synchronization bus for sharing frequency reference signals and critical timing clocks from the reference module.

The approach eliminates a significant amount of front-panel cabling and uses AXIe's active backplane for external PCIe and Ethernet interfaces. The chassis reports its status over PCIe or Ethernet and will signal a fault condition via a front-panel light-emitting diode (LED).

The TEmS open-loop emulator accommodates up to 31 platforms (30 emitters and 1 system under test) for emulation of dense threat environments. It supports Direction Finding/ Angle of Arrival (AoA) testing via automatic multi-channel software control of amplitude and phase.

The TEmS software offers a "pre-run" mode so users can see how the emitters and receiver interact in the battlefield scenario without exercising the complete emulation system. For example, *Fig. 3* shows an 8 Red Force emitter scenario interacting with the Blue Force receiver under test at the center of the simulated battlespace. Four ground emitters are represented by the red squares and four airborne emitters by the red diamonds. The track of each airborne emitter is shown by the dotted lines in the display. This scenario was scripted to run for 5 min. (300 s).

The hardware configuration for this scenario is shown in *Fig. 4*. The outputs from each generator are summed to form a composite signal for cabled or open-air radiation into the



4. This four-channel configuration is suitable for emulation of dense emitter environments.

jammer. Users can configure the system to use one, two, or all four RF channels. The TEmS simulation software automatically determines the most efficient use of the parallel RF channels based on pulse parameter timing, alleviating the need for the threat analyst to assign specific emitters to specific output channels.

Two simulations were run in the scenario of Fig. 3—first with two RF channels, then with four. Statistics were enabled for each simulation to determine the PDW pulse dropout rate. With just two RF channels, more than 60,000 pulses were dropped (the sum of the 2-channel dropped PDWs), with Emitter 3 experiencing the highest dropout rate. Enabling all four RF channels significantly improved the dropout rate to just 122 pulses over the 5-min. simulation. None of the pulses from Emitter 3 experienced dropouts *(Fig. 5)*. By using four rather than two channels, the pulse dropout rate was dramatically reduced.

In summary, integration and verification of the functionality and performance of modern EW systems require emulation of realistic signal environments that accurately represent the quantity and quality of threats, while accurately applying the resulting effects of the emitter platform's kinematics, which affect what the candidate receiver will experience in operation. The Giga-tronics TEmS' upconverting real-time digital control interface and phase-coherent architecture provides these capabilities in a benchtop, modular, and scalable form-factor that provides an extremely high degree of realism. mw

Run Time Stats — 2-Channel Statistics

Emitter	Generated	PDWs Dropped	Threshold
0	488805	5517	3543516
1	400004	0	673320
2	490642	3778	3543336
3	555306	44690	273336
4	486643	6612	3545666
5	448767	857	574064
6	486198	7057	3545666
7	599996	0	273336

Channel	PDWs Total Generated
0	3261274
1	695087
2	0
3	0

Run Time Stats — 4-Channel Statistics

Emitter	Generated	PDWs Dropped	Threshold
0	493194	61	3482808
1	400004	0	659976
2	482665	0	3503988
3	599996	0	259992
4	472020	61	3525156
5	442952	0	574064
6	489300	0	3490558
7	599996	0	259992

Channel	PDWs Total Generated
0	3221139
1	690736
2	67474
3	778

5. Shown are pulse dropout rate statistics.

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Consider LPNAs for Your Next Design

Low-phase-noise amplifiers can help tackle the impact of phase noise for a range of applications, enabling designers to meet system-level requirements.

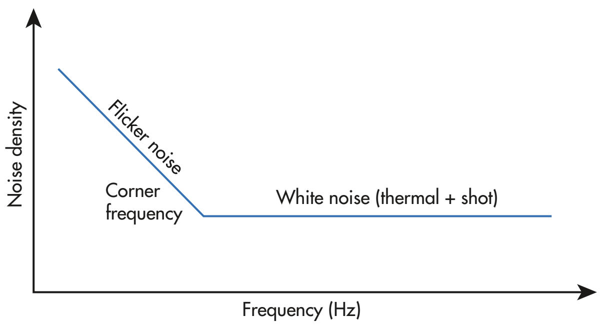
NOISE IS A phenomena that is fundamental to electronics. Its random and non-deterministic behavior can cause obstacles in the design and characterization of circuitry. There are a variety of noise sources that are dependent upon the medium (e.g., vacuum tubes, solid-state devices, and crystal oscillators). Some of the major noise contributors are thermal, shot, and flicker noise. Essentially, the products of all the noise sources actualize as time-dependent, random fluctuations in amplitude and phase—also known as amplitude modulation (AM) and phase modulation (PM) noise. These form the lower limit of a signal that can be detected and amplified.

Phase noise has become a critical parameter in communications systems and radar due to technological advances that demand higher spectral purity over wider bandwidths, along with better sensitivities. In these cases, design engineers choose oscillating sources with low phase noise. However, they may overlook the effects of residual, or additive, phase noise. Low-phase-noise amplifiers (LPNAs) offer the capability of reducing any additive phase noise effects, thereby saving efforts and increasing cost-effectiveness.

WHITE NOISE (SHOT AND THERMAL)

Noise on the particle level can be expressed by the fluctuations in the numbers or velocities of groups of mobile electrons. It can manifest itself in a number of ways, depending on the medium leveraged.[1] Thermal noise, also known as Johnson-Nyquist noise, describes the intrinsic noise of an electrical conductor in terms of its temperature and resistance. It is a kinetics phenomenon that involves collisions between the free electrons of a substance and its lattice at any temperature above absolute zero (K= 273°C).[1]

At the small signal level in solid-state electronics, noise figure (NF) can be expressed in terms of the thermal noise of the semiconductor. NF is the decibel conversion of the noise factor. For an amplifier, the noise factor is the ratio of the noise power to the available thermal noise power of the source resistance. Thermal noise, which is fundamental to the material, is often white noise at equal intensities across frequencies.



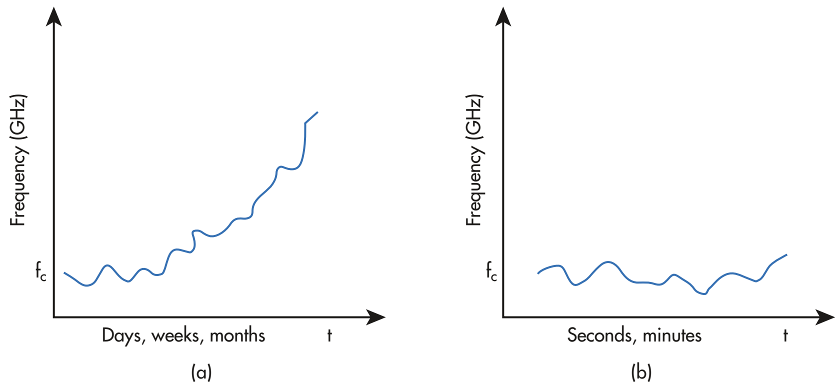
1. In a noise spectrum, flicker noise dominates at frequencies up to the corner frequency. White noise dominates at frequencies above the corner frequency.

Shot noise is also spectrally white. It is a result of the fluctuations in electrical currents, due to the random passage of discrete electrical charges through the potential barriers in p-n junctions.[2] Both fundamental and frequency-independent noise sources are often considered in the NF of an amplifier, and therefore weigh into the sensitivity of a receiver.

FLICKER (1/f) NOISE

Flicker noise, which occurs at low frequencies, is believed to be an extrinsic source of noise caused from surface imperfections, contaminants, and defects in thin film and polycrystalline devices. These "flickers" were originally discovered by Johnson at Bell Labs during his study of vacuum tubes. The fluctuations observed at low frequencies were notably larger than what is expected from shot and thermal noise.

The frequency at which this phenomena occurs is dependent on the type of device and varies from a few Hz for some bipolar devices to 100 MHz for gallium-arsenide (GaAs) field-effect transistors (FETs).[2] *Figure 1* shows a general noise frequency spectrum of an amplifier in which flicker noise dominates the low-frequency band, while frequency-independent white noise (shot and thermal) may reside at intermediate and high frequencies.



2. Shown is both long-term (left) and short-term (right) oscillator stability.

Phase noise, which is random, is generally a lower energy emission. Its variance around the mean can decrease with averaging. In essence; spurious signals are systematic and deterministic in origin, while phase noise is not.

PHASE NOISE

Phase noise, which is produced by oscillators, is essentially a blanket term that accounts for short-term, random-frequency instabilities. It can be a product of flicker noise and white noise. This parameter is expressed in units of dBc/Hz, or noise per unit bandwidth at a given offset from the carrier frequency.

SHORT-TERM VS. LONG-TERM FREQUENCY STABILITY

Ideally, an oscillator would produce a perfect sine wave with no phase or amplitude fluctuations. Stability can be defined as the statistical estimate of the frequency or time fluctuations of a signal over a given time interval. It can be broken down into long-term stability and short-term stability.[4] Long-term stability is measured over intervals ranging from minutes to years, while short-term stability is often associated with fluctuations that occur within 100 seconds (*Fig. 2*).

RANDOM VS. SPURIOUS

Both phase noise and spurious signals are short-term and emit at non-integer multiples of the generated output frequency. On a spectrum analyzer, spurious signals can be seen with relatively high power. They are generally continuous and unaffected by averaging.

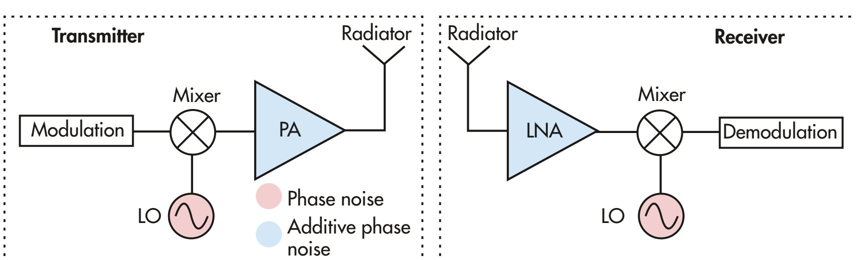
ADDITIVE (RESIDUAL) PHASE NOISE

While leveraging NF in the analysis of a transmitter/receiver system has a great deal of merit, it does not account for phase noise and additive phase noise. Typically, NF is measured by applying a white noise source to the input of the device-under-test (DUT). This approach does offer some insight into the added noise of a low-noise amplifier (LNA) in a receive chain. However, it does not take into account the injected carrier signal in a real application (and thus any noise near the carrier frequency), nor any potential large-signal conditions.

Figure 3 shows a basic communications system. Here, the local oscillator (LO) is the source of the phase noise. The LO signal then passes through other components, which have the potential to add to the noise. Typically, amplifiers are subject to tests for additive phase noise, as they can have a higher flicker-noise-corner frequency than the LO—depending on the transistor topology and the substrate (JFET, BJT, GaAs FET, CMOS, etc.). This effectively increases the noise floor of the system and decreases the sensitivity of a receiver.

A designer tasked with meeting particular phase noise requirements in a system may need to obtain information concerning the phase noise and additive phase noise in a circuit to identify the dominant noise source in a system. LPNAs can remedy situations in which an original signal can become hidden in both the phase noise and additive phase noise of a receiver or transmitter.

BIT-ERROR-RATE EFFECTS OF PHASE NOISE AND ADDITIVE PHASE NOISE



3. Shown here are basic transmit (left) and receive (right) signal chains. The LOs are the phase noise sources, while the amplifiers add residual, or additive, phase noise.

Bit-error-rate (BER) is a parameter leveraged in wireless communications to measure the amount of data that gets lost from a transmission due to noise and interference. For instance, a BER of 10^{-9} can be expressed as one bit error for every 10^9 bits received. Poor BERs can lead to poor audio/video quality, lost data, or retransmissions.[9] Designers attempt to minimize the BER in order to optimize the spectral effi-

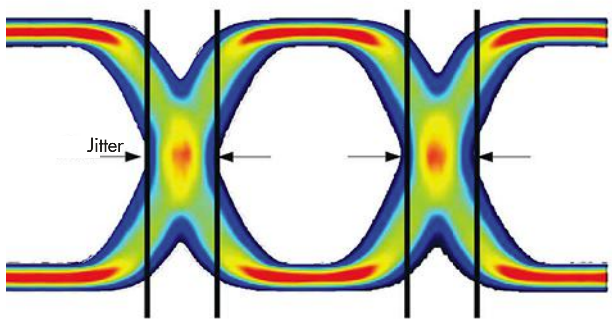
Phase noise has become a critical parameter in communications systems and radar due to technological advances that demand higher spectral purity over wider bandwidths, along with better sensitivities.

ciency, or information rate transmitted over a bandwidth, of a system using the least amount of energy per bit to induce a better Quality of Service (QoS).[7]

The global market for BER testers is approaching $1 billion USD this year due to faster data throughputs, higher transmission capacity, and an increased focus on quantifying the reliability of a communication system. All of these factors call for the minimization of any noise at both the transmitter and receiver.[12]

One method to improve BER is to reduce the data rate to improve the overall transmission time. However, this approach decreases the data throughput. Another method involves choosing a strong signal through slow and robust modulation or line coding schemes and applying channel coding schemes, such as redundant forward error correction codes.[11] These are both external adjustments that can be performed (and sometimes need to be performed) due to the distortions and interference in the system often caused by phase noise and additive phase noise. Limiting white noise and pink noise within the communications system may simplify the design process.

Phase noise directly causes jitter and reciprocal mixing, which in turn increases the BER. Reciprocal mixing occurs when the noise sidebands of the LO mix with strong signals that are close in frequency to the wanted signal. This scenario produces unwanted noise products at the intermediate frequency and degrades the receiver sensitivity.[8] The short-term random frequency variations cause random time-domain jitters (packet delay variation), or deviations from the period of a signal, limiting the selectivity of the receiver (*Fig. 4*).



4. This eye diagram illustrates jitter in a signal transmission. Phase noise contributes to random, non-deterministic jitters.

CLUTTER IN RADAR

Radar applications leverage the Doppler shift, or frequency shift of moving objects, in order to detect aircraft or vehicles in the vicinity.

The Doppler frequency shift is directly proportional to the velocity of the object and the transmitter's carrier frequency, defined by the following equation:

$$|f_D| = 2 \cdot v_r/\lambda = 2 \cdot v_r \cdot f_{tx}/c_0$$

Where f_D is the Doppler shift;

f_{tx} is the transmit frequency;

c_0 is the speed of light; and

v_r is the speed of the aircraft.

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Accounting for white noise can be an effective model in applications that can both operate under small-signal conditions and can filter out the noise near the carrier frequency without losing a transmission.

A few simple calculations from the equation can illuminate the approximate minimum velocity of an object necessary to be detected by certain radar by ensuring that the Doppler shift is beyond the common 10-kHz flicker noise corner where flicker noise (and potentially phase noise and additive phase noise) dominates.

For instance, military X-band radar has a transmit frequency of approximately 10 GHz. Object speeds below 300 mph expect a Doppler shift below 10 kHz. L- and S-bands (~2 GHz) are commonly used for commercial/military air traffic control (ATC) and air route surveillance radars (ARSRs). Object speeds at the same 300 mph expect a Doppler shift of approximately 1800 Hz. The target return can easily get lost in the phase noise and additive phase noise of the LO and amplifier.

Additionally, motion from the landscape, such as wind, rain, birds, and trees, could cause clutter that can make it more difficult to demodulate a transmission. A common solution to this is to employ narrowband receive filters to reduce clutter. But this approach limits the data throughput and can be an obstacle in terms of obtaining information on slow moving objects. For instance, an unmanned aerial vehicle (UAV) equipped with sophisticated apparatus on an Intelligence, Surveillance, and Reconnaissance (ISR) mission may require both high data throughputs over a larger bandwidth while detecting slow moving objects.

CONCLUSION

With the increase in bit rates in technologies across a wide array of industries, low-phase-noise oscillators and LPNAs can mitigate the effects of both phase noise and additive phase noise. They can at best solve major issues in data transmissions without the need to increase transmitter power or antenna diameter (of a ground station), or simply be another helpful tool to increase the sensitivity of the receiver. In both cases, time and money can be saved.

Accounting for white noise can be an effective model in applications that can both operate under small-signal conditions and can filter out the noise near the carrier frequency without losing a transmission. However, many applications require more. Amplifiers often add significant residual phase noise that can go overlooked, since many systems are optimized according to the phase noise from the source (LO). It is important to assess the overall system noise floor in real scenarios. Oftentimes, that can call for limiting both phase noise and additive phase noise. mw

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Capitalize on EDA When Developing MIMO, Phased-Array Antenna Systems, Part 1

Advances in software are leading to more effective design flow for phased-array systems by leveraging measured radiation patterns and gain-tapering data, among other factors.

PHASED-ARRAY ANTENNAS ARE becoming a popular solution in a variety of applications, with new active electronically scanned arrays (AESAs) finding their way into automotive driver assist systems, satellite communications, advanced radar, and more. The complexity and cost issues associated with developing communications systems based on phased-array antennas are being addressed through new functionalities in electronic-design-automation (EDA) software.

EDA tools support designers by providing them with the means to develop new system architectures and component specifications, as well as implement the physical design of individual components and verify performance prior to prototyping. This first part of a two-part series discusses these trends and presents recent advances in EDA tools for phased-array-based systems.

1. The design environment encompasses circuit, system, and EM analysis in addition to interoperability with third-party design flows.

PHASED-ARRAY PRIMER

Electronically steered antennas are an array of individual radiating elements with phase and amplitude controlled either digitally through analog/RF components, or by using hybrid techniques to control beam direction without the need to physically move the antenna. By controlling phase and amplitude of the input signal to the individual elements, one can achieve steerable directivity of the antenna beam over both azimuth and elevation. Design considerations for an AESA radar system include the individual radiating elements (antenna design), the RF link budget of the feed network that is directly tied to component performance (e.g., insertion losses and impedance mismatch), and the array itself.

Given the complexity of the task, design groups need a system-aware approach that enables team members to explore phased-array behavior at different levels of abstraction. These development stages range from early conceptual models with little detail to highly defined array models that account for true component interactions and possible impairments. Designing the complex packaging schemes for high-frequency signaling must be addressed with circuit simulation and electromagnetic (EM) analysis tools specialized for RF and microwave electronics.

DESIGN MANAGEMENT AND EDA TOOLS

While actively steered phased-array antennas have many advantages, they are also extremely complex. Moreover, cost of production is significantly higher than conventional antenna design, especially non-recurring development costs.

As the industry shifts toward highly integrated phased-array systems, it is critical for in-house systems expertise to work closely with hardware developers to fully explore the capabilities and tradeoffs among possible architectures and integration technologies. In addition, a start-to-finish design flow made possible with EDA software has become critical in moving beyond the initial system simulation, which focuses on early architecture definition, to the development of link budgets and component specifications.

A preferred phased-array system design flow manages the start-to-finish front-end development, embedding RF/microwave circuit simulation and/or measured data of radio/signal-processing (behavioral) models within a phased-array system hierarchy. With such software, the system designer can select the optimum solution, ranging from hybrid modules through fully integrated silicon core RF integrated-circuit (RFIC) devices, to address the specific requirements of the targeted application.

Perhaps more importantly, a system-aware approach, carried throughout the entire phased-array development cycle, enables the team to continually incorporate more detail into their predictive models and observe the interactions between array components. Then they can make system adjustments as the overall performance inadvertently drifts from early idealized simulations.

Design failure and the resulting high costs of development are often due in part to the inability of high-level system tools to accurately model the interactions between the large number of interconnected channels, which are typically specified and characterized individually. Overall phased-array performance is neither driven purely by the antenna nor by the microwave electronics in the feed network. Simulations must therefore capture the combined interaction to accurately predict true system behavior. Circuit, system, and EM co-simulation enable verification throughout the design process.

PHASED-ARRAY DESIGN FLOW

Visual System Simulator (VSS) is the system-level simulator offered within the NI AWR Design Environment. The simulator provides full system performance as a function of steered-beam direction, inclusive of the antenna design, and the active and passive circuit elements used to implement the electronic beamsteering.

System components can be modeled in greater detail using Microwave Office circuit simulation, inclusive of EM analysis for antenna design and passive device modeling using AXIEM 3D planar and Analyst 3D finite-element method EM simulators. These tools are fully integrated into NI AWR Design Environment, supporting seamless data sharing within the phased-array hierarchy.

Furthermore, the AntSyn antenna synthesis and optimization module is able to generate individual antenna designs from performance specifications. The resulting geometries can be imported into AXIEM or Analyst for further EM analysis and optimization. Capabilities within this suite of tools *(Fig. 1)* include design-assist add-on products. Another capability is interoperability with third-party tools, such as printed-circuit-board (PCB) tools for layout, RFIC tools for design/layout, and EM tools for analysis.

Highlights of phased-array analysis in VSS include:

- Automate/manage the implementation of beamforming algorithms and determine phased-array antenna configuration from a single input/output block.
- Accomplish array performance over a range of user-specified parameters, such as power level and/or frequency.
- Perform various link-budget analyses of the RF feed network. Measurements include cascaded gain, noise figure (NF), output power (P1dB), gain-to-noise temperature (G/T), and more.
- Evaluate sensitivity to imperfections and hardware impairments via yield analysis.
- Perform end-to-end system simulations using a complete model of the phased array.
- Simulate changing array impedance as a function of beam angle to study the impact of impedance mismatch and gain compression on front-end amplifier performance.

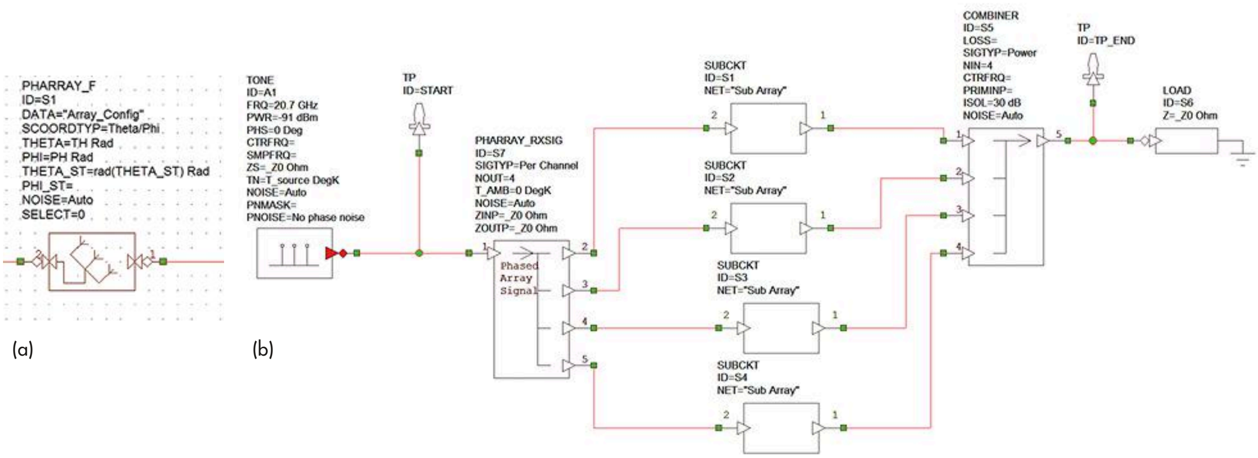
DEFINING PHASED-ARRAY CONFIGURATIONS

Specifications for any phased-array radar are driven by the platform requirements and intended application. For example, weather observation, which has relied on radar since the earliest days of this technology, most commonly uses airborne surveillance radar to detect and provide timely warnings of severe storms with hazardous winds and damaging hail. The weather surveillance radars are allocated to the S, C, and X frequency bands. These bands have wavelengths on the order of 10, 5, and 3 cm, respectively. While the shorter wavelength radars provide the benefit of smaller antenna size, their radiated signals are significantly affected by atmospheric attenuation.

Requirements for 10-cm wavelength (S-band) weather surveillance radars, based on years of experience with the national network of non-Doppler radars (WSR-57), are shown in the *table*.[1] These requirements showcase some of the application-specific metrics that drive range, frequency, antenna size, and gain. They represent the starting point for the system designer,

S-BAND WEATHER SURVEILLANCE RADAR REQUIREMENTS.

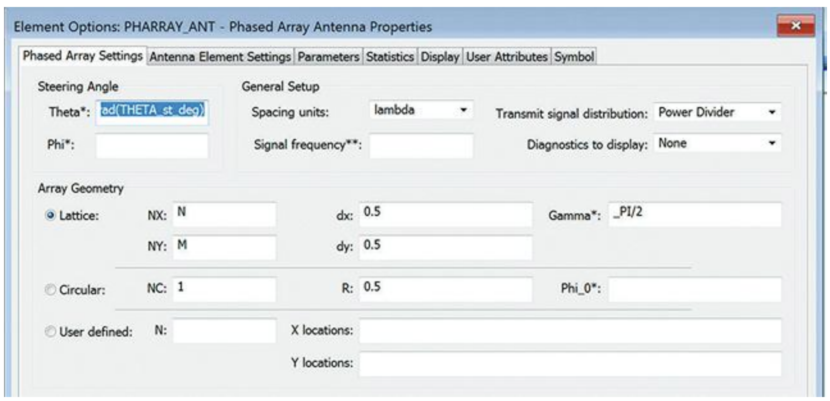
1.1. Surveillance	
1.1.1 Range:	460 km
1.1.2 Time:	< 5 minutes
1.1.3 Volumetric coverage:	hemispherical
1.2. SNR:	> 10 dB, for Z . 15 dBZ at r = 230 km
1.3. Angular resolution:	≤1°
1.4. Range sample interval Δr	
1.4.1 for reflectivity estimates:	Δr < 1 km; 0 < r < 230 km Δr < 2 km; r < 460 km
1.4.2 for velocity and spectrum width estimates (r < 230 km):	Δr=250 m
1.5. Estimate accuracy:	
1.5.1 reflectivity:	≤1 dB
1.5.2 velocity:	≤1 m s^{-1}; SNR> 8 dB; σ_v = 4 m s^{-1}
1.5.3 spectrum width:	≤1 m s^{-1}; SNR>10 dB; σ_v = 4 m s^{-1}



2. A single model can delineate thousands of antenna elements (a), replacing system designs based on individually defined elements (b).

who will also weigh cost and delivery concerns as well as available semiconductor and integration technologies, when considering possible architectures and defining individual component performance targets.

VSS equips system designers with the capabilities needed to convert these requirements into hardware specifications and work out the initial design details. Starting with the phased-array configuration, VSS is able to represent thousands of antenna elements with a single model. This enables the antenna design team to quickly produce radiation patterns with basic array properties, such as number of elements, element spacing, individual element gain or radiation pattern (imported measured or simulated antenna data), array configuration, and gain taper. The model *(Fig. 2a)* allows designers to specify the array's physical configuration based on various standard lattice and circular geometries, as well as custom geometries.



3. Shown is the portion of the phased-array parameter dialog box that contains geometry configuration options, including lattice, circular, and user-defined configurations.

The array behavior is easily defined through a parameter dialog box or data file that contains configuration parameters, such as gain and phase offset, theta/phi angles of incidence, number of elements in both X/Y locations (length units or lambda-based), spacing, and signal frequency. This model greatly simplifies early exploration of large-scale phased-array configurations and individual antenna performance requirements in comparison with the old method of implementing such a model using basic individual blocks. With the older approach, array sizes were generally limited to several hundred elements, each modeled as a single-input/single-output block *(Fig. 2b)*.

Figure 3 shows a portion of the VSS parameter dialog box used to quickly define an antenna-array architecture utilizing standard or custom geometries. The lattice option allows configuration of the phased array in a lattice pattern, which is configured using the number of elements along the X and Y axes (NX and NY), element spacing along these axes (dx and dy), and gamma (the angle between these axes).

Setting gamma to 90° results in a rectangular lattice, while setting it to 60° creates a triangular lattice. Any positive value for gamma may be used to configure the lattice, while the circular option enables configuration of circular phased arrays with one or more concentric circles. The number of elements in each concentric circle and the radius of each circle can be defined as vectors by variables NC and R. Examples of lattice and circular array configurations are shown in *Figures 4a and 4b.*

To demonstrate some of the capabilities of the phased-array model, an example project was constructed showing two 15-×-5 element arrays operating at 2.99 GHz *(Fig. 5)*. One model represents an array of lossless isotropic antennas defined simply by setting the antenna gain to 0 dBi, while the elements of the other array utilize a data set containing the

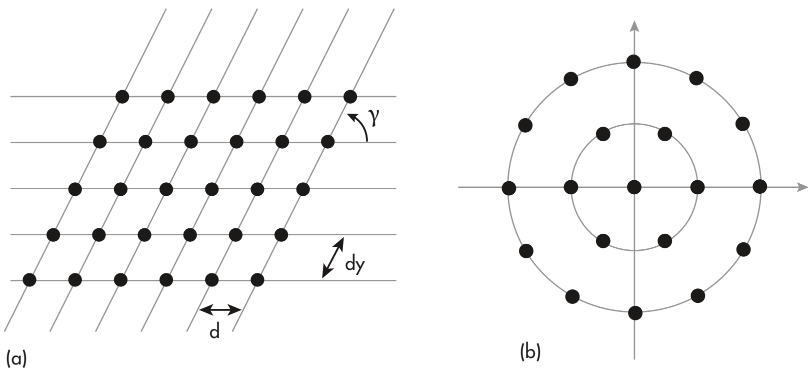
radiation pattern of a single simulated patch antenna. Both arrays use a lattice configuration with half-wavelength spacing between elements and uniform gain tapering.

For the simulation shown, the steering angle (theta) was set to 15°. Note that the antenna and phased-array blocks support specifying the signal direction using U/V coordinates as well as theta/phi angles.

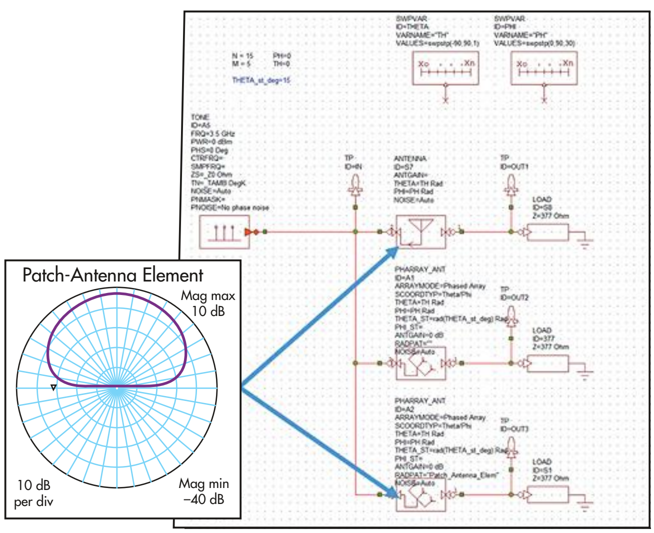
The VSS array model provides antenna designers with a rapid and straightforward tool to observe key antenna metrics. One can examine the main beam and side-lobe behavior as a function of any number of variables, including array size *(Fig. 6a)* and configuration, gain versus steering angle, and the occurrence of grading lobes as a function of element spacing and/or frequency *(Fig. 6b)*. The element spacing was increased from 0.5λ to 0.95λ to demonstrate how array spacing affects side-lobe growth.

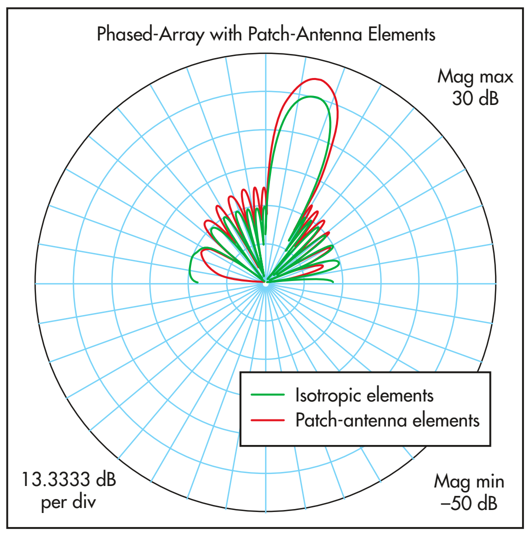
From these results, the array design team can develop an optimum configuration for the given requirements, such as range and overall array physical size. In addition, the team can provide design targets for the individual antennas and incorporate subsequent antenna simulation results back into the array analysis.

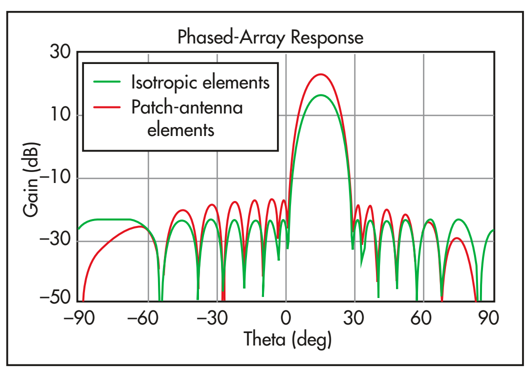
Control of the amplitude excitation through gain tapering is often used to control beam shape and reduce the side-lobe levels. A number of commonly used gain tapers are implemented in the phased-array block. Gain-taper coefficient handling defines whether the gain taper is normalized or not. If it is, the taper is normalized to unit gain. Standard



4. These illustrations depict lattice (a) and circular (b) array geometries for phased arrays.

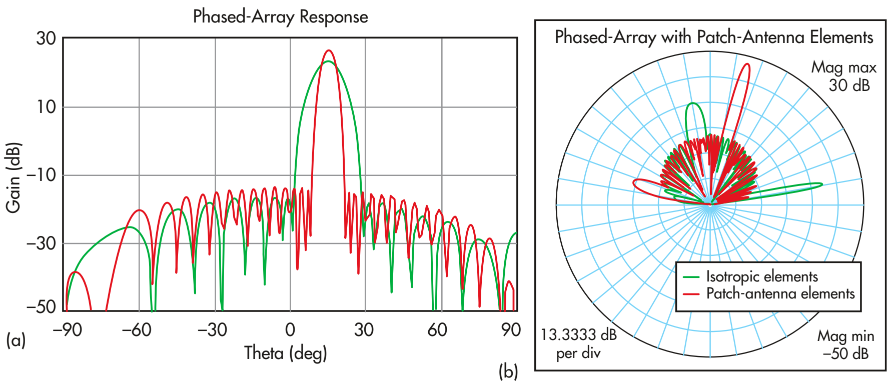




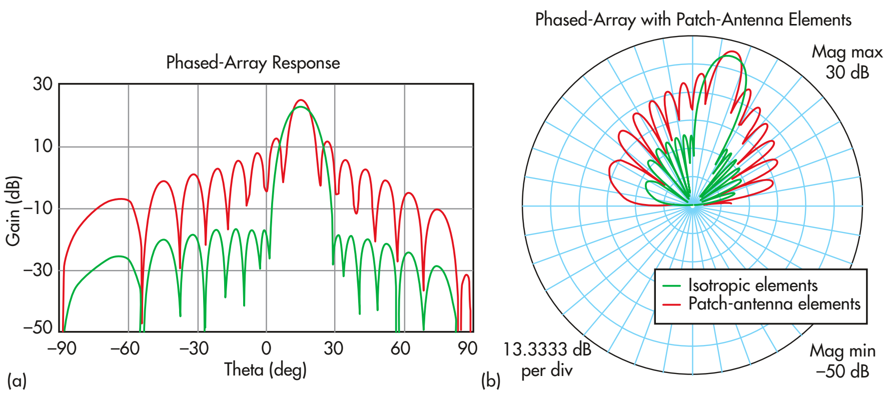


5. These two 15-×-5 element phased arrays are based on isotropic and patch-antenna radiation patterns, respectively. Theta angle is set to 15°.

gain tapers implemented in the phased-array model include Dolph-Chebyshev, Taylor Hansen, and uniform. The earlier example (15-×-5 element patch array) was re-simulated with Dolph-Chebyshev gain tapering in place of uniform gain tapering, showing the impact on the main beam and side-lobes (Fig. 7). In addition, the user can define custom gain tapers by specifying the gains (dB) and phases for each array element.



6. Shown are radiation patterns for 15-×-5 and 30-×-5 arrays (a), and side-lobe behavior for a 15-×-5 array with an element spacing of 0.95λ at steering angles of 15° and 80° (b).



7. This figure compares simulation results of the 15-×-5 patch array with uniform and Dolph-Chebyshev gain tapering.

CONCLUSION

The first part of this series has introduced new capabilities in EDA software to configure the physical attributes (number of elements and element spacing) of a large-scale phased-array antenna, incorporating measured or simulated antenna radiation patterns and defining any gain tapering to manage the antenna gain, directivity, side-lobes, and more. Part 2 of this series will investigate the individual antenna element design, addressing mutual coupling, the impact of element location, and array impairments due to element failure. mw

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JACK BROWNE | Technical Contributor

Manual Probe System Positioned for THz Testing

This probe system makes measurements at the limits of commercial VNAs, and well into the THz frequency range.

PRACTICAL SEMICONDUCTOR DEVICES at millimeter-wave frequencies will be needed to enable the realization of the many small cells with high-data-rate capacities for Fifth Generation (5G) wireless communications networks. Part of developing those high-frequency, high-speed devices will be testing them during design and development and then in production. The TS150-THZ manual probe system from MPI Corp. *(www.mpi-corporation.com)* has been designed for on-wafer measurements not just through the entire millimeter-wave frequency range, but at terahertz (THz) frequencies as well.

The TS150-THz manual probe system *(see figure)* is designed for benchtop use, with easy access to a device under test, such as a semiconductor wafer. It is well suited for four-port S-parameter measurements with a high-frequency vector network analyzer (VNA). It has a low-profile configuration with a large, rigid platen, providing enough room for large-area micro positioners for maneuvering test probes for measurements from RF through terahertz frequencies.

The system is also well suited for optical and impedance-related load-pull measurements. In addition, it accommodates mounting of several of the high-frequency extenders used with VNAs for testing at millimeter-wave and terahertz frequencies.

The TS150-THz probe station features a vibration-absorbing base and a four-port bridge designed to simplify access to DC biasing and four-port RF measurements. The unique platen is made of nickel-plated steel and has three discrete lift positions for probe contact, separation, and safety loading of a DUT. The probe station is designed not only to perform repeatability measurements, but to ensure the long operating lifetimes of test probe tips.

For example, an "auto contact" position function moves the probe tip to the contact pads on a DUT with ±1 μm repeatability. In addition, the separation (from the contact point) repeatability is also within ±1 μm, ensuring that all mechanical positioning conditions during wafer probing remain consistent.

The x-y-z positioning of the chuck is performed with great position, and with respect for the mechanical and electrical requirements of making probe contacts to microscopic DUTs at such high frequencies. Positioning is achieved with the aid of a puck-controlled air bearing stage which is capable of rotational (theta) positioning of 360 deg. with a fine theta travel range of ±5 deg. The theta settability resolution within this fine travel range is 7.5 × 10-3 gradient with less than 10 μm planarity.

The TS150-THz manual probe station can be configured for measurements to 330 GHz and beyond.

The chuck x-y stage has a total travel range of 180 × 300 mm with a fine travel range (for precise positioning) of 25 × 25 mm. The x-y positioning resolution in this fine-travel range is better than 1 μm. The chuck z-dimension stage has a travel distance of 10 mm with better than 1-μm adjustment resolution.

The precision and accuracy provided by the probe station provides numerous benefits not often considered for on-wafer measurements, especially at these frequencies. The automatic positioning capabilities, such as the "auto contact" functionality, help to remove the variability of a single operator's actions and the variability from one operator to another.

The TS150-THz manual probe station is available with various chuck options, a PCB holder, and a wide range of accessories. The latter include DC/RF/THz micro positioners, optics, and microscopes for a wide range of measurement applications. The company, which has worked for several decades with test-equipment supplier Rohde & Schwarz *(www.rohde-schwarz.com)* on high-frequency measurement solutions, has also developed a line of wafer probes based on microelectromechanical-systems (MEMS) technology.

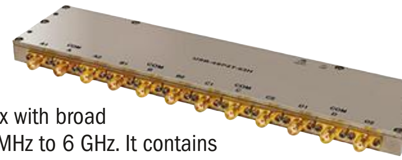
MPI CORP., Advanced Semiconductor Test (AST) Div., 2F-2 No. 30, Taiyuen St., Chupei City, Hsinchu County 30267, Taiwan, Republic of China; +886-3-5551771, www.mpi-corporation.com

Product SPOTLIGHT

Amplifier Module Has Wide Dynamic Range to 2.4 GHz

Mini-Circuits' model HXG-242-4+ is a compact amplifier module that combines low noise figure with high IP3 from 0.7 to 2.4 GHz. It provides consistent noise figure and gain, with low noise figure of typically 2.2 dB at 0.7 GHz, rising to only 2.5 dB at 2.4 GHz. The gain is typically 16.0 dB at 0.7 GHz and 13.6 dB at 2.4 GHz. The output power at 1-dB compression is also consistent with frequency: +22.2 dBm at 0.7 GHz, rising gradually to +23.3 dBm at 2.4 GHz. The amplifier tops off its dynamic range with high IP3, typically +45.7 dBm at 1.5 GHz. The RoHS-compliant amplifier module features integrated matching and optimization circuits and is supplied in a ceramic package measuring 6.4 × 7.0 × 2.4 mm and designed for use from -40 to +85°C. It runs on +4.8 to +5.2 V DC and consumes 140 mA at +5.0 V DC.

USB Solid-State Switch Matrix Controls 10 MHz to 6 GHz



Mini-Circuits' model USB-4SP2T-63H is a USB-controlled solid-state switch matrix with broad frequency range of 10 MHz to 6 GHz. It contains four independent SPDT switches with fast switching speed of 250 ns (typ.). The switch matrix features high linearity, with typical IP3 of +50 dBm across the full frequency range. Insertion loss is 1.6 dB from 10 to 700 MHz, 2.0 dB from 700 to 2500 MHz, 2.8 dB from 2500 to 500 MHz, and 3.0 dB from 5000 to 6000 MHz. Isolation between ports ranges from 100 dB at the lowest frequencies (10 to 700 MHz) to 61 dB at 6000 MHz. The switch matrix measures 8.4 × 2.00 × 0.475 in. with 12 female SMA connectors and a USB Mini-B port for power and control. Software is available at any time from the Mini-Circuits website.

High-Power Bidirectional Coupler Spans 2000 to 6000 MHz

Mini-Circuits' model BDCH-10-63 is a bidirectional coupler that provides 10-dB coupling from 2000 to 6000 MHz. It maintains coupling to a tolerance of ±1 dB and with typical accuracy of ±1.5 dB, with typical directivity of 22 dB across the full frequency range. Designed using stripline technology, the coupler handles as much as 100 W RF power with low insertion loss of typically 0.1 dB and can pass as much as 2 A current from input to output ports. It achieves excellent return-loss performance, with 22-dB typical return loss at all ports. Suitable for applications in S- and C-band radar systems as well as in some cellular infrastructure equipment, the coupler is supplied as an open PCB measuring 0.2 x 0.56 x 0.08 in. with wraparound terminations. It is designed for operating temperatures from -55 to +105°C.

Two-Section Reflectionless Filter Passes DC to 300 MHz

Mini-Circuits' model XLF-42M+ is a reflectionless lowpass filter with passband of DC to 300 MHz, frequency cutoff of 350 MHz, and wide stopband to 10 GHz. The filter maintains a 50-Ω match across its wide stopband to eliminate reflections. It has low insertion loss of 2.3 dB from DC to 300 MHz and 3.0 dB at 350 MHz. The passband VSWR is typically 1.30:1 or better from DC to 300 MHz. This two-section design achieves high stopband rejection of typically 34 dB from 660 to 6800 MHz and 49 dB from 6800 to 10,000 MHz. The stopband VSWR is typically 1.30:1 from 660 to 6800 MHz and 2.20:1 from 6800 to 10,000 MHz. Amplitude variations are held to ±0.3 dB across the operating temperature range of -55 to +105°C. The RoHS-compliant filter is well suited for military communications and satellite and terrestrial radio application. It is supplied in a QFN package measuring 0.197 × 0.197 × 0.039 in.

DC-to-18-GHz Cables Flex Into Tight Spaces

Mini-Circuits' 141-SMSM+ series Hand-Flex™ flexible coaxial cables are 4-in.-long coaxial assemblies with SMA female bulkhead connector at one end an SMA male connector at the other end. The configuration eliminates the need for bulkhead adapters and the minimum bend radius of 8 mm simplifies interconnection of even closely spaced components. The rugged RoHS-compliant cables handle maximum power levels of 546 W at 0.5 GHz, 387 W at 1 GHz, 121 W at 10 GHz, and 90 W at 18 GHz. The insertion loss is typically 0.05 dB from DC to 2 GHz and no more than 0.21 dB from 2 to 18 GHz. The return loss for each connector is typically better than 30 dB across the full frequency range.

Voltage-Variable Equalizer Flattens Gain/Loss to 1220 MHz

Mini-Circuits' model VAEQ-1220+ is a 50-Ω voltage-variable equalizer designed to correct for gain or loss variations across a wide frequency range of 50 to 1220 MHz. Using control voltages of 0 to 7 V, the equalizer achieves an attenuation range of 15.2 to 1.7 dB at 50 MHz and 3.3 to 2.5 dB at 1220 MHz. The deviation from linear attenuation is only ±0.2 dB for the full frequency range. The equalizer draws 15 mA from a +5-V supply voltage and 20 mA from a control voltage of 0 to +7 V. It can handle input signal levels to +23 dBm and delivers a typical 1-dB compression point of +30 dBm and typical IP3 of +55 dBm. The voltage-variable equalizer is supplied in a surface-mount package measuring 0.394 × 0.394 × 0.150 in. (10 × 10 × 3.8 mm) and can handle operating temperatures from 0 to +85°C.

CHRIS DeMARTINO | Technical Editor

Jump-Start Filter Design with Sophisticated Simulation Techniques

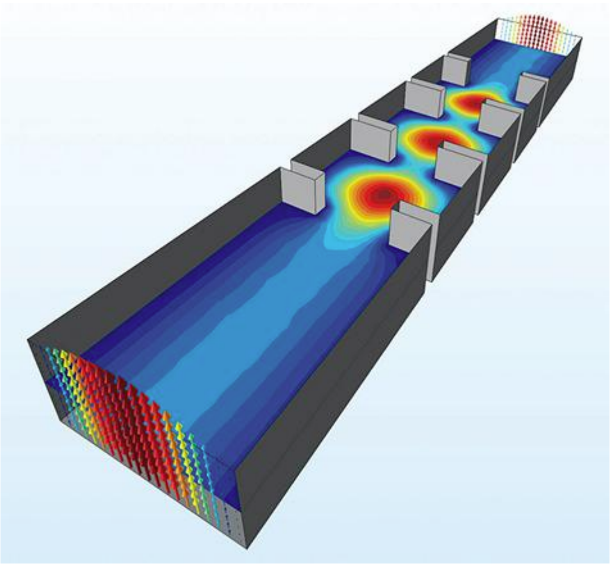
One software tool can accelerate the time needed to model filters while still maintaining the capability to acquire very precise data.

Designing RF/microwave filters generally involves utilizing software tools to create simulation models. One factor that designers must be mindful of when modeling a filter is the amount of time needed for a simulation to execute. This length of time can be quite substantial in some cases.

Of course, when simulating a filter design, simulation data is acquired over a user-specified frequency range. Data is obtained across this frequency range at an interval that is also specified by the user. By decreasing the frequency interval, or step size, designers can essentially model filters more precisely. However, decreasing the step size generally comes at the expense of increasing the time needed for the simulation to execute.

One software company, COMSOL (*www.comsol.com*), has developed methods that can significantly reduce filter simulation time without sacrificing precision. With the RF Module, which is an add-on product to COMSOL Multiphysics software, designers can quickly simulate filters even when specifying a small step size.

This article explains how the Frequency-Domain Modal method within the RF Module software can accelerate filter simulation time. Two design examples are presented to illustrate how this method can benefit filter designers. The first design presented is a waveguide bandpass filter. A microstrip edge-coupled bandpass filter design is then analyzed. All simulations were performed with an Acer Aspire R14 R5-471T laptop, which has a 2.3-GHz Intel Core i5-6200U processor.



1. This figure shows the simulation model of the iris-coupled waveguide bandpass filter.

WAVEGUIDE BANDPASS FILTER EXAMPLE

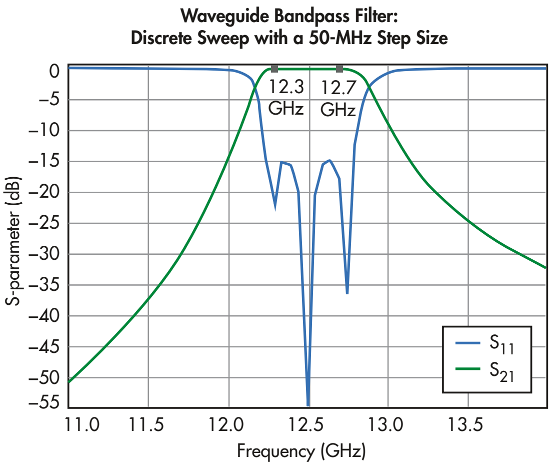
The first example presented is an iris-coupled waveguide bandpass filter with a center frequency of approximately 12.5 GHz. This filter has a WR-75 interface. *Figure 1* shows the simulation model.

This waveguide filter was first simulated with the standard discrete sweep method. The frequency range of the simulation was 11 to 14 GHz. The step size was set to 50 MHz. *Figure 2* shows the simulation results. Furthermore, the simulation time was approximately one minute, 20 seconds.

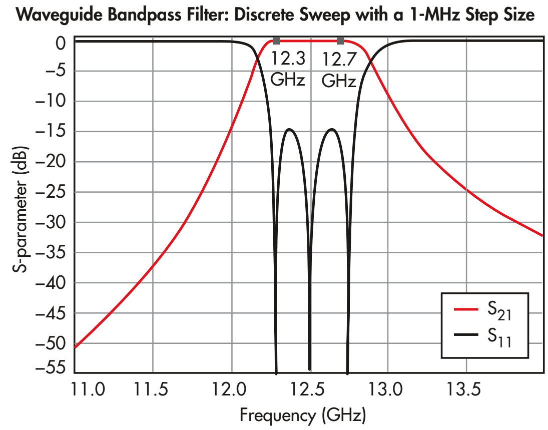
Figure 2 shows rough S-parameter plots—especially for S_{11}. These results are due to the 50-MHz step size. Clearly, designers are likely to need smoother plots, which correlate to more precise modeling. Thus, a smaller step size is needed.

To acquire more precise data, the step size was then reduced to 1 MHz. The frequency range of 11 to 14 GHz remained the same. Simulating the filter with a 1-MHz step size produced the S-parameter plots shown in *Fig. 3*. Clearly, the 1-MHz step size produced much smoother plots in comparison to using a 50-MHz step size. However, the 1-MHz step size also increased the simulation time to almost one hour, demonstrating the tradeoff between precision and time.

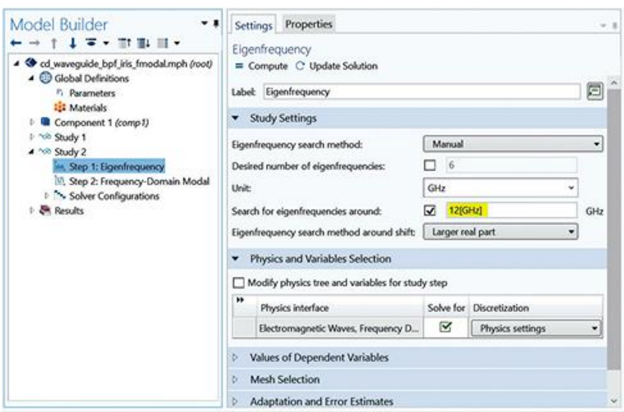
To overcome the precision and time tradeoff, the Frequency-Domain Modal method can be utilized. With this method, filters can be simulated in a fraction of the time needed for a discrete sweep simulation to execute.



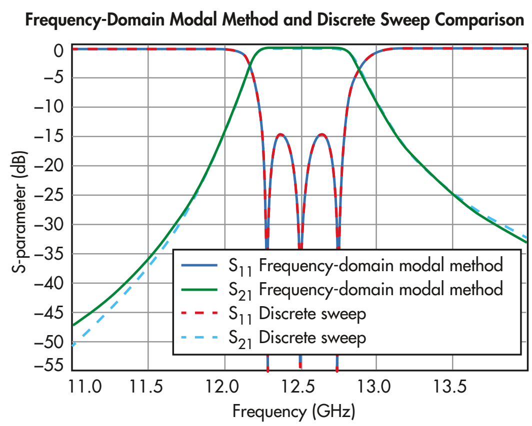
2. Shown are the simulated S-parameters of the waveguide filter when using a 50-MHz step size.



3. This graph depicts the simulated S-parameters of the waveguide filter when setting the step size to 1 MHz.



4. The "Search for eigenfrequencies around" parameter should be set to somewhere around the lowest passband frequency.



5. This graph illustrates the results from the Frequency-Domain Modal simulation along with the results from the discrete sweep simulation. The step size is set to 1 MHz for both simulations.

The Frequency-Domain Modal method involves an eigenfrequency analysis, which enables a structure's resonance frequencies to be captured. The information from the analysis is used in the Frequency-Domain Modal study. The benefit of the Frequency-Domain Modal method is that it enables quick simulations of filters even when a small step size is specified.

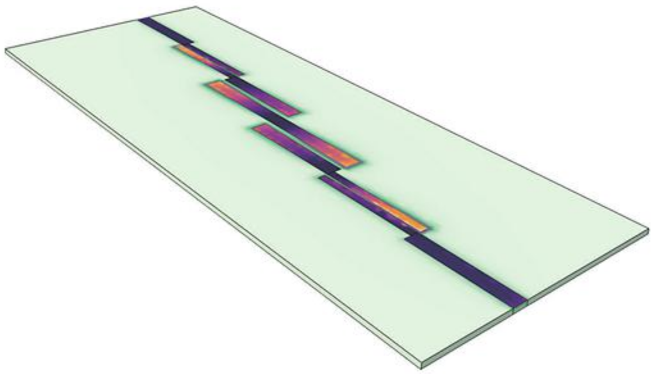
To demonstrate the Frequency-Domain Modal method, the waveguide bandpass filter was then simulated using this method. *Figure 4* shows the software's user interface when selecting the Frequency-Domain Modal study. One of the important parameters shown in *Fig. 4* is "Search for eigenfrequencies around." To obtain good results, this parameter should be set to a frequency value that is in the vicinity of the lowest passband frequency. Thus, 12 GHz was specified for this simulation.

For the Frequency-Domain Modal simulation, the same 1-MHz step size was used. The frequency range of 11 to 14 GHz also remained the same. *Figure 5* shows the results of this simulation along with the results of the previous discrete sweep simulation with a 1-MHz step size. The graph shows that the results from both simulations are very close. However, only a little more than one minute was needed for the Frequency-Domain Modal simulation to execute. These results therefore demonstrate the effectiveness of the Frequency-Domain Modal method.

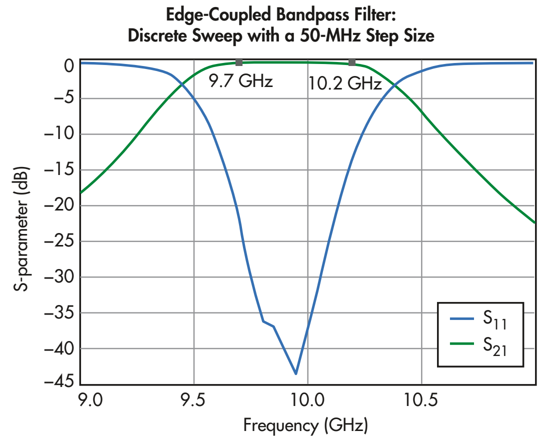
In essence, one approach to design a filter such as this could be to first utilize the standard discrete sweep method with a larger step size in order to obtain preliminary results. The Frequency-Domain Modal method could then be used with a smaller step size to acquire more precise data. This approach could save valuable time in comparison to simply performing a discrete sweep simulation with a smaller step size.

MICROSTRIP EDGE-COUPLED BANDPASS FILTER

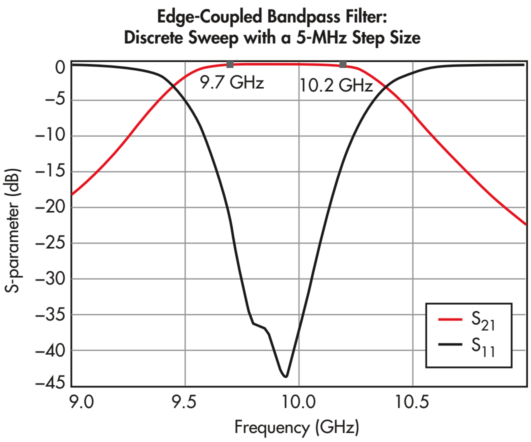
The second design example is a microstrip edge-coupled bandpass filter. This filter has a passband from 9.7 to 10.2 GHz. It is designed on a 10-mil-thick Rogers RT/duroid 5880 laminate. *Figure 6* shows the simulation model.



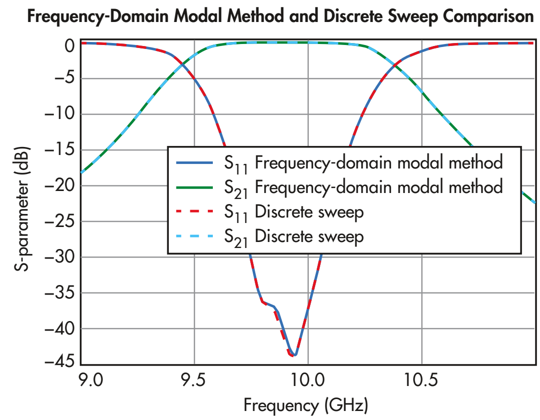
6. This image illustrates the microstrip edge-coupled bandpass filter model.



7. These plots show the simulated S-parameters of the microstrip edge-coupled bandpass filter when using a 50-MHz step size.



8. This graph illustrates the simulated S-parameters of the microstrip filter when using a 5-MHz step size.



9. This graph shows the simulation results of the microstrip filter when using the Frequency-Domain Modal method along with the simulation results when using the discrete sweep method. The step size is set to 5 MHz for both simulations.

This filter was also first simulated with the standard discrete sweep method. The simulation was performed across a frequency range of 9 to 11 GHz. The step size was set to 50 MHz. Figure 7 shows the results of the simulation, which needed approximately 13 minutes to execute. Once again, the plots reveal a rough shape due to the 50-MHz step size.

The step size was then decreased to 5 MHz. The frequency range of 9 to 11 GHz remained the same. The simulation results are shown in *Figure 8* . As expected, this simulation produced smoother plots. However, the simulation needed approximately two hours to complete.

The microstrip filter was then simulated using the Frequency-Domain Modal method. The step size remained at 5 MHz. The frequency range of 9 to 11 GHz also remained the same. Moreover, the "Search for eigenfrequencies around" parameter was specified at 9.5 GHz.

Figure 9 shows the results of the Frequency-Domain Modal simulation along with the previously shown results from the discrete sweep simulation with the same 5-MHz step size. As can be seen, the simulation results are practically identical. However, while the discrete sweep simulation needed approximately two hours to execute, the Frequency-Domain Modal simulation only needed approximately three minutes, 30 seconds. This analysis therefore further validates the Frequency-Domain Modal method.

In conclusion, this article demonstrated that the Frequency-Domain Modal method within the COMSOL Multiphysics software can benefit anyone involved with designing RF/microwave filters. The analysis validated that filter simulation time can be drastically reduced without having to sacrifice the precision that designers need. Those who are interested can also visit COMSOL's Application Gallery, which contains various filter models. Step-by-step instructions are provided to explain the process of building a model.

L-Band Transistor Delivers 500 W Power

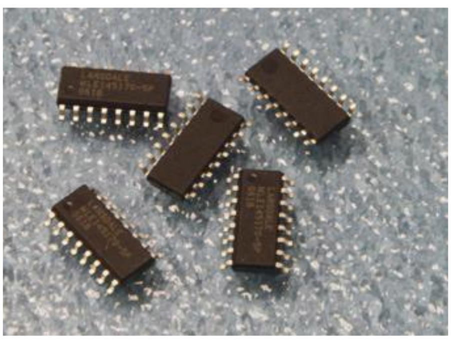
THE QPD1003 is an L-band internally matched field-effect transistor (IMFET) from Qorvo is now available from stocking distributor RFMW, Ltd. It provides 500 W output power at 3-dB compression (P3dB) for L-band communications or radar systems from 1200 to 1400 MHz. The GaN power transistor achieves 65% power-added efficiency (PAE) with 20-dB small-signal gain across the bandwidth. It operates on a +50-V dc supply and is supplied in a flange-mount package with input and output ports matched to 50 Ω.

RFMW, LTD. (QORVO STOCKING DISTRIBUTOR), 188 Martinvale Ave., San Jose, CA 95119, (408) 414-1450, email: info@rfmw.com, *www. rfmw.com*

Transceiver Tackles 300 MHz to 6 GHz

THE AMC597 is a transceiver module for use from 300 MHz to 6 GHz. It consists of four of the company's AD9371 transceivers and an XCKU115 FPGA with 20-GB of DRAM from Xilinx (www.xilinx.com). The transceivers are tunable over 300 MHz to 6 GHz, covering most licensed and unlicensed cellular bands, with a 250-MHz transmit/synthesis bandwidth and 100-MHz receive bandwidth. The module supports FDD and TDD operation and is suitable for use in 3G and 4G base transceiver system (BTS) applications.

VADATECH, INC., 198 N. Gibson, Henderson, NV 89014, *www.vadatech.com*



PLL Synthesizer is Resurrected

THE ML145170 single-chip phase/frequency detector with serial interface is now available with full support from Lansdale Semiconductor. The frequency synthesizer integrated circuit (IC) can be used with input signals from 5 to 80 MHz or from 25 to 185 MHz, depending on input signal levels, to generate stabilized outputs. Originally designed and built by Motorola/Freescale Semiconductor, it features an easy-to-program architecture. Due to the patented BitGrabber registers, no address/steering bits are required for random access of the three registers. As a result, tuning can be accomplished via a 2-Byte serial transfer to the 16-b N register. The synthesizer IC is available in a choice of dual-in-line-package (DIP) and surface-mount-technology (SMT) packages, including DIP-16, SO16, and TSSOP-16 packages.

LANSDALE SEMICONDUCTOR, INC., 5245 South 39th St., Phoenix, AZ 85040-0123, (602) 438-0123, *www.lansdale.com*

Tuning Control Switch Adjusts 4G Antenna

THE ULTRACMOS PE613010 single-pole, single-throw (SPST) tuning control switch was recently selected in bare-die form by Monarch Antenna for a tunable (700-to-800-MHz) 4G smart antenna design. The open-reflective switch operates with low-voltage CMOS control from 100 to 3,000 MHz and exhibits low insertion loss of 0.2 dB at 900 MHz and 0.4 dB at 1,900 MHz. It handles power levels to +38 dBm and features low on resistance of 1.2 Ω. The switch, which has high ESD tolerance, runs on supplies of +2.3 to +4.8 V dc.

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CBL	All-purpose workhorse cables for highly-reliable, precision 50Ω measurement through 18 GHz	DC-18	SMA, N
APC	Crush resistant armored cable construction for production floors where heavy machinery is used	DC-18	N
ULC	Ultra-flexible construction, highly popular for lab and production test where tight bends are needed	DC-18	SMA
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* All models except VNAC-2R1-K+

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