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The Future of RF Filtering in a 5G World **p20**

Integration Tips for FPC Antennas **p28**

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2021 Technology Forecast:

6G AND BEYOND

p10

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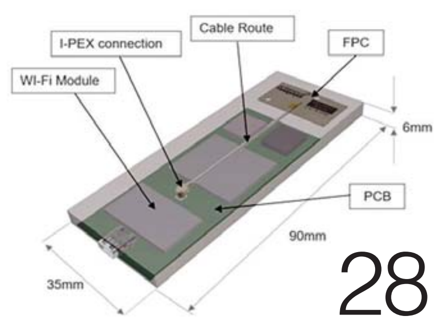

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Editorial

DAVID MALINIAK | Editor
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Polishing the Old Crystal Ball Once Again

Yes, it's *Microwaves & RF's* 2021 Technology Forecast issue, in which we once again attempt to peer into the future to predict things to come (and hope that we're not veering into fantasy).

It's that time of year again, when multitudes of prognosticators elucidate visions of marvelous technological progress and we in the B2B media eagerly snap up their scribblings. Why? Because "that time of year" is "Technology Forecast" issue time, and here is *Microwaves & RF's* offering for 2021.

I've been in this business for quite some time, much of it spent with our sister publication, *Electronic Design*. And as such, I've been in the middle of a bunch of Tech Forecast issues. It's fun to talk to industry luminaries and get their thoughts on where things may be heading in the coming year and the years to follow.

But even experts don't always get everything right. I recall a Tech Forecast article I wrote in the early 90s timeframe when I was *Electronic Design's* Components and Packaging technology editor. In an interview with someone about laptops and how engineers would deal with burgeoning thermal issues, I learned that by the mid-1990s, microprocessor clock speeds would have reached the lofty heights of 400 to 500 MHz. The problem with that, my source said, was heat, lots of heat dissipated by that mighty CPU. So much, in fact, that you wouldn't be able to use it in a laptop unless it also contained an elaborate liquid-cooling system.

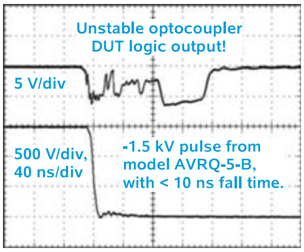
It turned out that he was right on the clock-speed prediction: DEC's Alpha 21164A CPU ran at 400 to 500 MHz in 1996 (CPUs running at that clock speed wouldn't be common until the late 90s). But the liquid-cooling part? Well, it's only recently that ASUS announced its ROG GX700VO, which it claims as the world's first liquid-cooled gaming laptop. I guess fans and heatsinks held up pretty well.

I have higher hopes for *Microwaves and RF's* 2021 Forecast issue. No one's talking about liquid cooling at all. But rather, we have some rather sober and well-grounded thoughts about the direction of things like smart homes. Look at "Can CHIP Make the Seamless Smart Home Real?" *(p. 16)*. Qorvo's Cees Links ponders the fragmented nature of disparate smart-home ecosystems and how they might finally come together through the efforts of the Zigbee Alliance's Project Connected Home over IP (CHIP) Working Group.

But, if it's far-reaching forecasting you seek, the issue's cover story, "6G: Fantastic, Yes. Fantasy? Not So Much" *(p. 10)*, will probably scratch that itch. The article is realistic in its understanding that we won't see 6G in the real world for a good long time. Indeed, 5G has a long way to go before it reaches its own potential. However, it paints a picture of a truly revolutionary technology that will take advantages of future advances in AI and machine learning paired with insane data rates and immense bandwidth. I only hope I'm around to see it!

There's a lot more Technology Forecast than we could fit into this issue, so be sure to visit *mwrf.com* for an augmented Forecast experience. mw

Transient Immunity Testers



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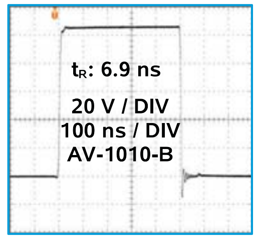

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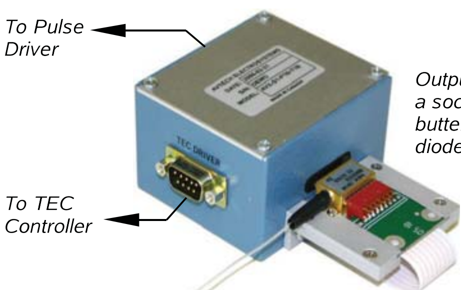
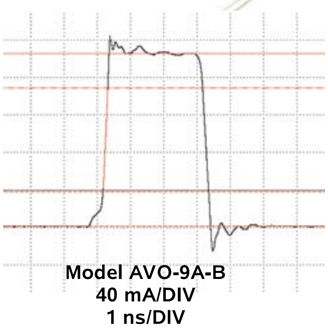
Nanosecond Laser Diode Drivers With Butterfly Diode Sockets



Output module with a socket-mounted butterfly-packaged diode installed.



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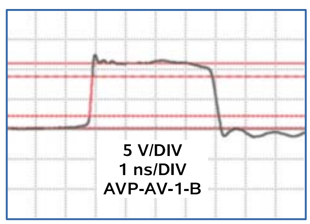

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20 V	120 ps	1 MHz	AVP-AV-HV2-B
20 V	200 ps	10 MHz	AVMR-2D-B
40 V	150 ps	1 MHz	AVP-AV-HV3-B
50 V	500 ps	1 MHz	AVR-E5-B
100 V	500 ps	100 kHz	AVR-E3-B
100 V	300 ps	20 kHz	AVI-V-HV2A-B
200 V	1 ns	50 kHz	AVIR-1-B
200 V	2 ns	20 kHz	AVIR-4D-B
400 V	2.5 ns	2 kHz	AVL-5-B-TR

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Microwaves&RF JANUARY/FEBRUARY 2021

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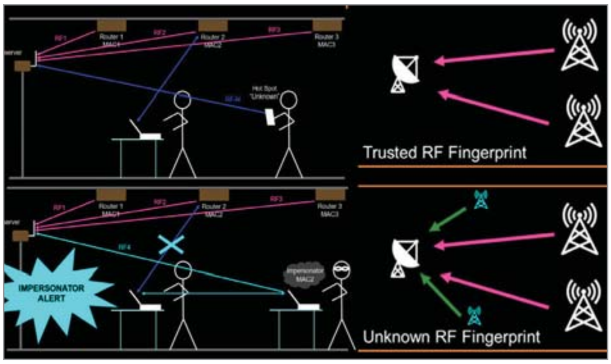
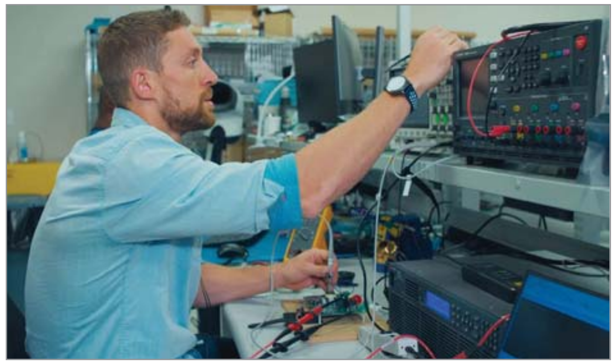


RF Fingerprinting for Trusted Communications Links

Similar techniques to those presented in a previous "Algorithms to Antenna" blog are applied to perform RF fingerprinting to help identify trusted and unknown transmit sources in communications systems.

https://www.mwrf.com/technologies/systems/article/21152806/mathworks-algorithms-to-antenna-algorithms-to-antenna-rf-fingerprinting-for-trusted-communications-links



Not an Afterthought: Why Test is Critical in RF System Development

Demystifying the relationship between RF system design and test can go a long way toward successful product development.

https://www.mwrf.com/technologies/test-measurement/article/21147902/not-an-afterthought-why-test-is-critical-in-rf-system-development

11 Myths About Vehicular IoT

Vehicular IoT design transforms a wide range of vehicles in transportation systems into wireless communications hubs.

https://www.mwrf.com/technologies/systems/article/21146149/laird-connectivity-11-myths-about-vehicular-iot

Caseframe Family of Electronic Chassis and Enclosures Targets 3U/6U Boards

The chassis and enclosures enable users to build application-specific designs, reduce time to market, and help minimize non-recurring engineering costs.

https://www.mwrf.com/markets/defense/article/21153221/verotec-caseframe-family-of-electronic-chassis-and-enclosures-targets-3u6u-boards

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OCTAVE BAND LOW NOISE AMPLIFIERS

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

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

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

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

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

LIMITING AMPLIFIERS

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

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

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

LOW FREQUENCY AMPLIFIERS

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

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News

O-RAN RADIO UNIT
Brings the Outdoor 5G Experience Indoors

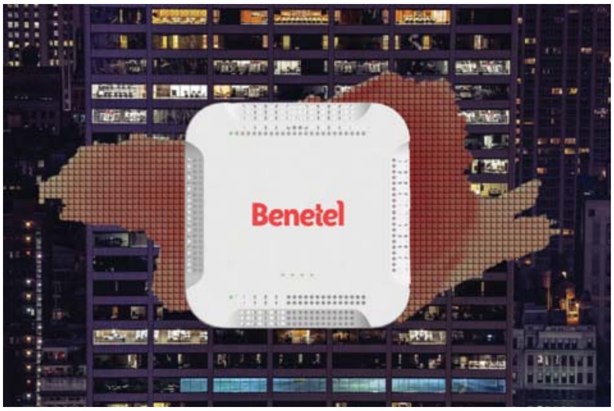
Fully compliant with the latest O-RAN interface specification, these compact, cost-optimized units are specifically targeted at indoor deployment.

The advent of 5G technology promises a great deal to consumers, with greater data speeds, higher capacities, lower latencies, and virtually unlimited connectivity. The technology will enable us to connect more devices to networks at a given time and potentially be able to implement virtual networks.

All the above will certainly come true for the outdoor mobile experience. But what about when we're indoors? Is 5G going to deliver once we're at home, at work, or in some other enclosed space?

That's what Benetel was thinking about in developing its new flagship BNTL-RAN550 O-RAN radio unit (O-RU). This latest addition to the company's RU product family delivers 100 MHz of instantaneous bandwidth, with up to 250 mW of output power per transmitter path.

(Credit: Benetel)



In combining elevated performance parameters, a small form factor, and low total cost of ownership, Benetel has optimized the RAN550 for indoor deployments, which are set to become increasingly commonplace. Enterprises and mobile network operators (MNOs) will both be able to benefit from this solution, using it in access points, private networks, and more.

The BNTL-RAN550's highly adaptable modular architecture is fully compliant with the latest O-RAN interface specification, supporting 7.2 split fronthaul network configurations. It comes equipped with two 10-Gigabit Ethernet ports for fronthaul network interfacing, and the built-in antenna supports 4T4R MIMO operation, which the company believes is the best balance for indoor coverage.

This initial version will support the 5G band n78 (3.3 GHz to 3.8 GHz), with additional frequencies (upper band n77 and band n79) already under development. In this fashion, Benetel hopes to target specific markets around the world in which spectrum is being made available. Other potential derivatives might include units with output power of greater than 250 mW. The modular architecture of the RAN550 easily lends it to adaptation with filtering and power-amplifier matching for given frequency bands.

The company says it's already been approached about the possibility of integrating 4G and 5G operation within the same unit; the design approach they've taken would put such a variant within the scope of the product definition. Interestingly, Benetel has chosen to implement a proprietary indoor solution before announcing an outdoor version, which is in the works.

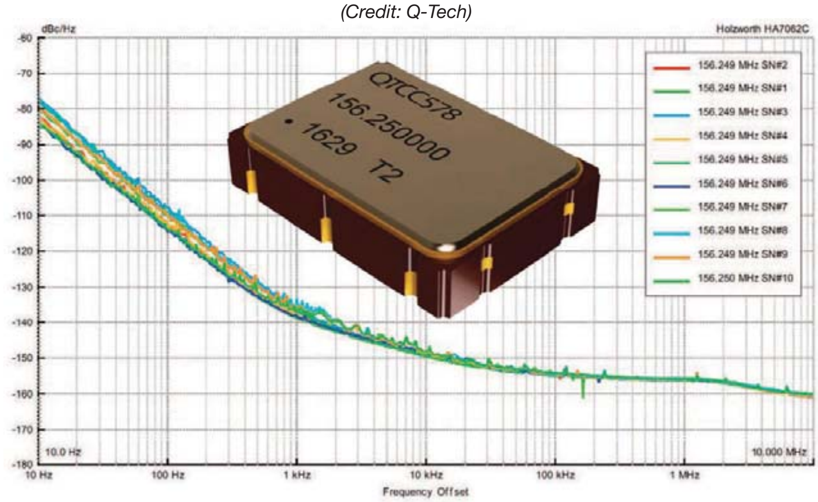
Benetel has been laying the groundwork for this flagship launch for some time. In October, the company joined the Open RAN Policy Coalition, which launched in May with a goal of promoting policies designed to open up the Radio Access Network. That same month of October, Benetel successfully demonstrated multi-vendor O-RAN hardware interoperability at the joint O-RAN Alliance and TIP Plugfest in Berlin. There, they integrated the RAN550 O-RU with Viavi's TM500 O-RU tester.

Available in January 2021, the BNTL-RAN550 O-RUs are designed for ceiling-mount and wall-mount implementations. These CE/FCC-certified units support an operational temperature range of 0° to +45°C and are powered by a 12-V dc supply (or via PoE++). mw

OSCILLATORS CLOSE TO Phase-Noise Floor

LOW PHASE NOISE is important for many receiving systems and it usually starts with a system's crystal oscillator. With a noise floor of -155 dBc/Hz, the QTCC578 series of quartz-crystal oscillators from Q-Tech Corp. keep the noise low while occupying little space in aerospace, commercial, industrial, and military circuits and systems. They are supplied in hermetic ceramic housings measuring only 5 × 7 × 1.5 mm with gold-plated contact pads. Available for supply voltages of +2.5 and +3.3 V dc, the crystal oscillators provide low-voltage differential signal (LVDS) logic outputs at factory-programmable output frequencies from 100 to 250 MHz.

(Credit: Q-Tech)

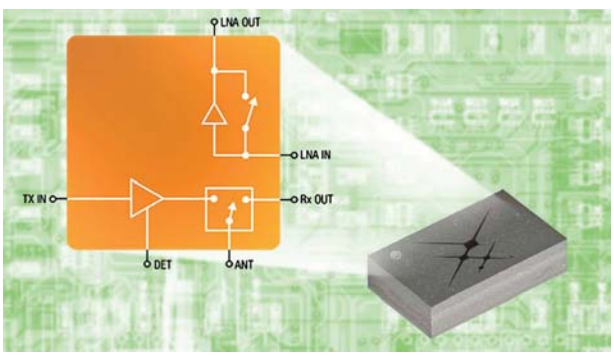


The QTCC578 series oscillators *(see figure)* are lead-free, RoHS compliant and EAR00 classified, available with screening to MIL-STD-55310 requirements for military applications. They can be specified for different operating temperature ranges, with frequency stability of ±25 ppm from -40 to +85°C and ±100 ppm from -55 to +125°C. The effects of ten years of aging are included in the stability specifications. The oscillators have 10-ms maximum startup time with 600-ps rise/fall time and 0.2-ps maximum phase jitter.

Scott Sentz, Q-Tech's director of sales and marketing explains: "This QTCC series answers the demand for low phase noise in a number of commercial applications like fiber channel, telecom, SONET, Ethernet/SynchE and microprocessor clock. This compact, reliable device is also effective in mil/aero applications, such as navigation, avionics and COTS." The clock oscillators are available in tape-and-reel packaging for high-volume, automated-assembly applications. ■

HIGH-POWER FRONT-END MODULE Serves V2V and V2X Applications

ONE OF THE hottest things in 2021 will be automotive applications involving vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) connectivity. To facilitate such applications, Skyworks Solutions has debuted its SKYA21043, a highly-integrated, 5-GHz front-end module (FEM) incorporating a 5-GHz single-pole, double-throw (SPDT) transmit/receive (T/R) switch; a 5-GHz high-gain, low-noise amplifier (LNA) with bypass; and a 5-GHz power amplifier (PA) intended for high-power 802.11p applications and systems.



Said to have the highest power output on the market, Skyworks' FEM has all it needs to propel upcoming V2V/V2X applications from concept to reality.

V2V technology will provide our vehicles with tons of information about the speed and position of other vehicles; the net effect will be to alert drivers to potential dangers down the road and to mitigate accidents and traffic congestion. For its part, V2X encompasses both V2V and vehicle-to-infrastructure (V2I) technology; V2I is part of the U.S. Department of Transportation's Intelligent Transportation Systems initiative that aims to develop better driver-assistance systems for smart parking and autonomous vehicles.

Qualified to AEC-Q104 (Grade 2), the SKYA21043 meets rugged reliability requirements for automotive applications including smart antennas, compensators, and roadside units for automotive infrastructure, backhaul and cellular small cells. The device boasts +29 dBm output power, making it one of the highest power solutions on the market today, Skyworks claims. Its compact, conformally shielded package size will reduce front-end board space by more than 50% and the product is supported by the automotive PPAP process. ■

Fantastic, Yes. Fantasy? Not So Much.

As a viable technology, 6G is quite a way off. But some of the doubts about its feasibility may be overblown. Here's a look at what 6G is, what it might bring to the table, and what it'll take to get there.

Even though 5G is far from being fully realized, researchers throughout the world are already concentrating on the next generation. There's obviously considerable speculation about precisely what 6G will be, and while it's far too early to make precise predictions, it's not too early to see how researchers are approaching the challenges.

When the details and expectations for 5G were released, there were plenty of skeptics—and many remain that way—as the new standard pushes operating frequencies to orders of magnitude higher than 4G. The highest of those frequencies are reserved only for very-short-range variants of Wi-Fi and a few other applications. That said, infrastructure is already being rapidly deployed at 24 and 28 GHz, with higher frequencies following in the coming years.

By the time 6G arrives, more challenges to overcome will emerge, and in some cases, they will be even more difficult than those for its predecessor. There will nevertheless be more opportunities as well, many beyond what 5G will deliver.

More Revolutionary than Evolutionary

If the history of "cellular" generations is used as a predictor, what's been defined in each standard was achieved in part by its succeeding generation. That is, some of what was planned for 2G was ultimately achieved in 3G, and 4G delivered a fuller measure of what 3G was intended to achieve but did not. The goal of each generation was primarily to achieve higher data rates and broader coverage.

That changed with 5G, which might be considered a wholesale reinvention of cellular technology, expanding for the first time beyond smartphones, tablets, and laptops to the far broader landscape under the IoT umbrella. It ushered in the era of software-defined architectures for user equipment, infrastructure, and the entire network, and extended the frequencies used by wireless systems well into the millimeter-wave region.

Any one of those advances would arguably be a major achievement—5G attains them all. When launched around 2030, 6G will attempt to accomplish what 5G did not, whether it's achieving extremely low latency or multi-gigabit speeds in a broad swath of the country.

6G will likely be of the same magnitude as 5G as it reaches frequencies near the light-wave spectrum, drives downlink speeds to 1 Tb/s, and employs technologies that either don't yet exist today or have been in development for years without a market to drive them harder. It will also fully enable applications that require latency much lower than what's ultimately achieved by 5G, and allow for instantaneous communications between consumers, devices, vehicles, and the surrounding environment *(Table 1)*.

However, 6G will offer even more than that, taking advantage of advances in AI and machine learning and enabling such applications as autonomous vehicles, robotic controls, high-definition holographic gaming, and more. All of these apps fit under the categories of wireless cognition, sensing, imaging, wireless communication, and position location and navigation.

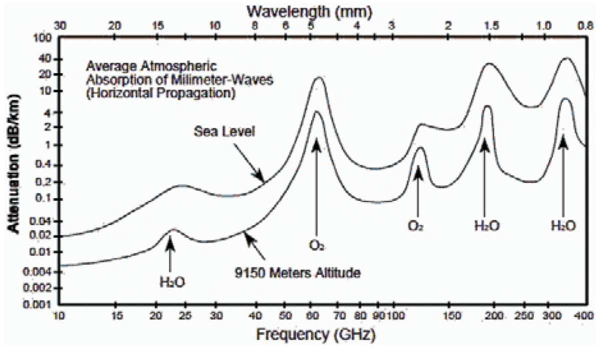
TABLE 1: GENERAL GOALS FOR 6G

Peak data rate	100 Gb/s to 1 Tb/s
Round-trip latency	0.1 ms
System bandwidth	Up to 30 GHz
Device density per m^3	100
Increase in capacity	10,000X
Increase in energy efficiency	10X
Positioning accuracy	10 cm indoors, 1 m outdoors
Battery life for IoT-type device	10 yrs.

6G promises data rates of as much as 1 Tb/s (1 million Mb/s), which is 1,000 times faster than 5G. That will require immense channel bandwidths well north of 1 GHz. The only available spectrum that provides the required bandwidth is between 100 GHz and 3 THz. Not surprisingly, this region has been used only for scientific research, including radio astronomy, the Earth exploration-satellite service (EESS), the space research service (SRS), and to a limited degree, amateur radio.

The FCC recognizes the technological enormity and time required to bring 6G to fruition and, in 2019, initiated a program called New Horizons. It provides an almost rule-free pathway for experimentation at unlicensed frequencies between 95 GHz and 3 THz. Experimental licensing has been employed by the commission many times within its Part 5 Experimental Radio Service (ERS) rules. This time, it creates a new type of license called the Spectrum

TABLE 2: PROPOSED FCC SPECTRUM HORIZONS FREQUENCIES	
Frequency (GHz)	**Available contiguous spectrum (GHz)**
116 to 123	7
174.8 to 182	7.2
185 to 190	5
244 to 246	2



1. Atmospheric impediments to free-space communications aren't linear, and "windows" of opportunity make sub-terahertz wireless capability possible.

Horizons Experimental Radio license (or Spectrum Horizons License).

The goal of the program is to lower the barrier to entry by making experimental licenses easy to obtain, with few of the typical hurdles required in conventional licensing. It provides wide flexibility in specifications such as frequency range, power, and emissions, with the only caveat being that the experimenter must refrain from creating interference to existing services.

More than 21 GHz of spectrum will be available at 116 to 123 GHz, 174.8 to 182 GHz, 185 to 190 GHz, and 244 to 246 GHz *(Table 2)*. Even at lower millimeter-wave frequencies, the available spectrum is immense. For example, the unlicensed band at 60 GHz alone offers available bandwidth equivalent to what's used today by virtually every licensed and license service from above dc to 7 GHz.

The FCC notes that in addition to traditional communications, these frequencies might have use for data links that enable transmission of wideband, uncompressed high-definition video signals and other high-speed data for other types of applications. As an example, the commission specified that Japan's NTT used 120-GHz wireless links to provide live TV coverage of the 2008 Beijing Olympics.

Terahertz Trepidations

The view among many scientists and engineers is that the higher the frequency, the higher the loss through space. Therefore, operation in the terahertz region is a fantasy. This position, along with a lack of suitable semiconductor technologies, is arguably one of the major reasons why millimeter wavelengths haven't been used. However, this is far from a complete picture for several reasons.

First, at the UHF and microwave frequencies currently used for wireless communications, path loss results primarily from molecular absorption that's very low when compared to higher frequencies. But in the higher reaches of the spectrum, other factors come into play as well, such as scattering from precipitation and foliage (and virtually everything else) that significantly impedes range and reliability. So, it might be expected that at 1 GHz where a wavelength measures 0.3 mm, communications would seem, if not impossible, at least impractical for use by traditional wireless services.

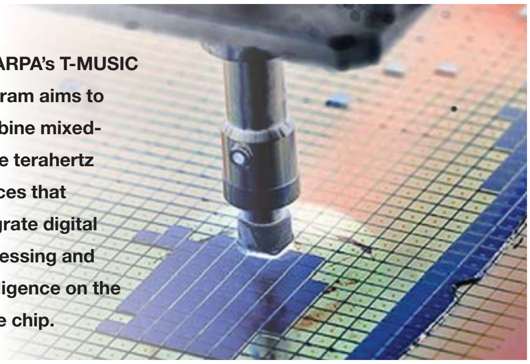
Second, sub-terahertz wavelengths inherently span shorter distances, but the loss from lower to higher frequencies isn't linear *(Fig. 1)*. This is because the resonant frequencies of oxygen, hydrogen, and other gases in the atmosphere absorb more electromagnetic energy than others. This is why the few applications operating at these wavelengths operate at only specific frequencies. It's also why the FCC chose the unlicensed bands it did for Spectrum Horizons.

However, Dr. Ted Rappaport, David Lee/Ernst Weber Professor of Electrical Engineering at the NYU Tandon School of Engineering, founding director of NYU Wireless, and a long-time pioneer in wireless communications, makes an important point: For a given antenna's effective isotropic radiated power (EIRP), path loss through space decreases quadratically as frequency increases if the antenna aperture is the same size (i.e., number of elements) at each end of the transmission path. It's been demonstrated that for the same RF output power when this condition is met, the signal strength at 140 GHz in free space is actually 5.7 dB greater than at 73 GHz and 14 dB greater than at 28 GHz.

In fact, according to Rappaport, many millimeter-wave and terahertz bands have remarkably little loss when compared with sub-6-GHz bands, adding only 10 dB/km of loss at frequencies as high as 300 GHz. These frequency bands could easily be used for high-speed 6G mobile wireless networks with up to km-size coverage range, and perhaps even up to 10 km or beyond in fixed applications. In fact, although much of the spectrum between 600 and 800 GHz suffers from 100 to 200 dB/km attenuation, this is only 10 to 20 dB over a 100-m distance, which is the typical radius of a small cell.

It's been shown that particles such as raindrops, snow, and hail caused substantial attenuation at frequencies above 10 GHz. At 73 GHz, signals attenuate at 10 dB/km in a rain rate of 50 mm/h. Rain attenuation flattens out from 100 GHz to 500 GHz, meaning that rain will not cause any additional attenuation at operating frequencies above 100 GHz.

While all of this may seem to fly in the face of conventional thinking, it considers that at such high frequencies, truly massive amounts of forward gain can be achieved using tiny electronically steered antennas with many ele-



2. DARPA's T-MUSIC program aims to combine mixed-mode terahertz devices that integrate digital processing and intelligence on the same chip.

ments. This would counteract the effect of atmospheric attenuation while maintaining the same signal-to-noise ratio as at lower frequencies. In short, these antennas will allow mobile systems to operate well into the terahertz region.

Challenges and Solutions

Immense challenges must be overcome before 6G can become a reality. They span from the development of semiconductor technologies able to produce measurable power at sub-terahertz frequencies, to the electronically steered, phased-array antennas required to deliver enough gain to overcome the various factors that make communication extremely difficult in this spectral region.

To achieve data rates of about 100 Gb/s, modulation schemes will need spectral efficiency greater than 14 b/s/Hz, well beyond what's available today. RF power amplifiers for this coming generation will require the use of silicon germanium (SiGe), silicon-on-insulator (SOI), and BiCMOS semiconductor technologies, and possibly indium phosphide, too. The space needed for base stations can be dramatically reduced as frequency increases, and the size of an antenna element shrinks, and the distance on the array face between array elements being only a few hundred micrometers even in the lower range of the terahertz regime.

Not surprisingly, DARPA is involved in the development of semiconductor technologies for terahertz applications. The agency's Technologies for Mixed-mode Ultra Scaled Integrated Circuits (T-MUSIC) program is investigating SiGe HBT, CMOS, SOI, and BiCMOS circuit integration in hopes of achieving power amplifiers operating at up to 1 THz. T-MUSIC's goal is to develop terahertz mixed-mode devices that integrate digital processing and intelligence on the same chip *(Fig. 2)*.

The program focuses on advanced materials, device processing, and mixed-mode circuit designs based on an advanced CMOS fabrication platform that it hopes will vastly improve the speed and accuracy of integrated mixed-mode electronics. The T-MUSIC program's participants (BAE Systems, Raytheon, University of California Los Angeles, University of California San Diego, and University of Utah) will develop advanced mixed-mode foundry technologies with transistors operating to at least 1 THz, as well as broadband precision mixed-mode integrated circuits.

An antenna array consisting of 1,000 elements can fit into an area of less than 4 cm^2 at 250 GHz. For user equipment, this means that mobile devices could host several tens of thousands of antennas, and base stations will become tiny cells with a range of 10 m. The pencil-wide beams produced by these antennas can also reduce interference, jamming, and detection.

Coverage extension technology will be necessary to provide services for drones, ships, and spacecraft as their service areas aren't fully covered by conventional cellular networks. To remedy this, geostationary, low-earth-orbit satellites (LEOs), and high-altitude pseudo-satellites (HAPS) may be employed to cover mountainous and remote areas, sea, and space, and to provide communication services to new areas. HAPS are garnering more attention because they can be stationed at a fixed location at an altitude of about 20 km, producing wide coverage with a cell radius greater than 50 km on land. In addition, HAPS offer a solution for providing backhaul service to portable base stations during disasters and possibly for industrial IoT scenarios.

Conclusion

The first tangible evidence that 6G can be achieved is still years away, but with industry, academia, and other entities already fully engaged in development, it will be fascinating to watch how the various elements come together. There's much to be gained when 6G is deployed, well beyond downloading a feature film in two seconds, from extremely precise location and other sensing applications to anti-jam communications where short range is actually desirable, among dozens more.

By 2035, it's likely that huge advances in software-defined hardware, AI, computing power, and other technologies will have taken place. Networks will evolve from purely terrestrial wireless to encompassing satellites that fill in the gaps where earth-bound platforms can't reach, and a long list of other advances will be achieved as well. Time will tell how 6G plays out, but like 5G, what once seemed unlikely is now being deployed. mw

FOR FURTHER READING

"A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," Walid Saad, Virginia Tech; Mehdi Bennis, Centre for Wireless Communications, University of Oulu, Finland; and Mingzhe Chen, Future Network of Intelligence Institute, The Chinese University of Hong Kong, Shenzhen, China and Department of Electrical Engineering, Princeton University.

"Opportunities and Challenges for 6G and Beyond," Theodore S. Rappaport, NYU Wireless, et al., Special Section on Millimeter-wave and Terahertz Propagation, Channel Modeling, and Applications, IEEE Access, June 2019.

"Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence," University of Oulo (Finland), September 2019.

"5G Evolution and 6G," NTT DoCoMo, January 2020.

"Spectrum Horizons, Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band," Federal Communications Commission, Report and Order, March 21, 2019.

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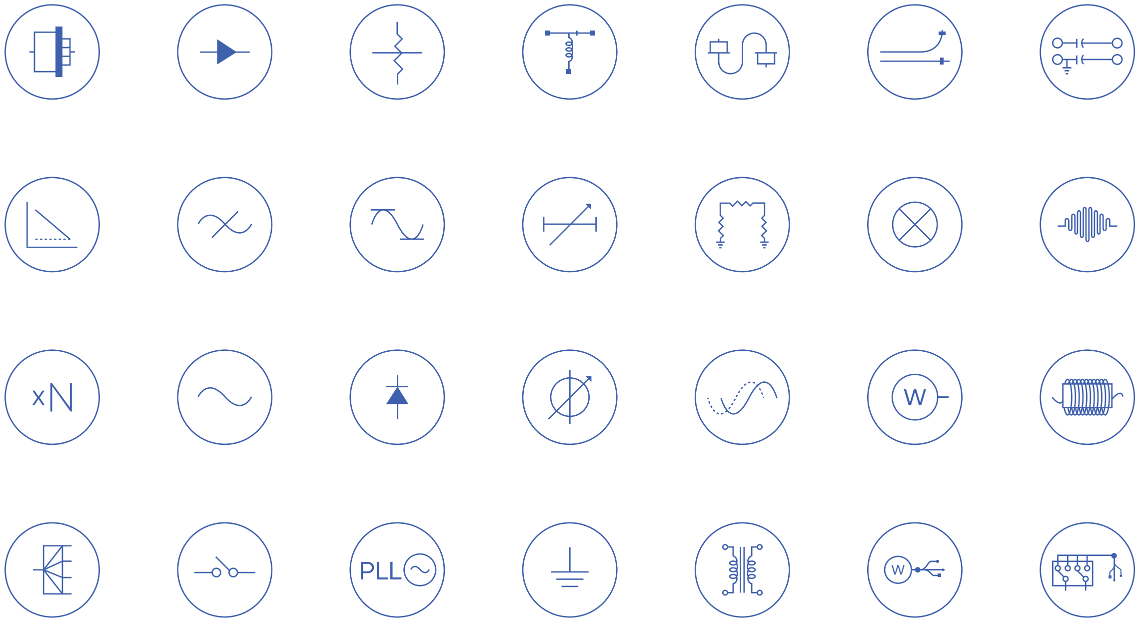

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DAVID MALINIAK | Editor

CAN *CHIP* MAKE THE SEAMLESS *SMART HOME* REAL?

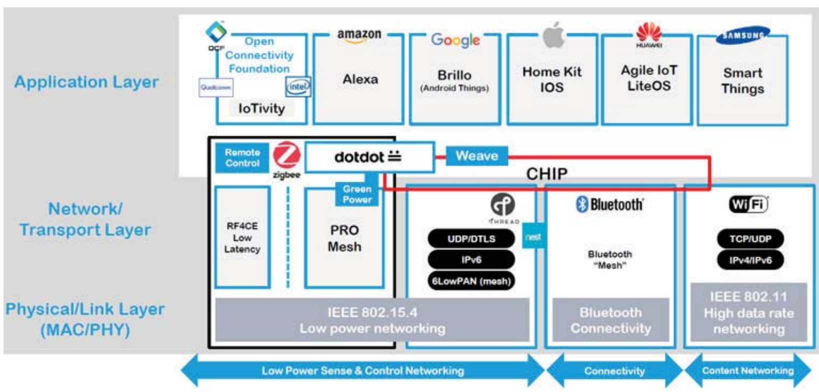
Qorvo's Cees Links discusses where home networks have been, where they are now, and where they're going, and how Project Connected Home over IP is in the mix.

With a Wi-Fi pedigree that stretches back to the "wireless LAN" days and a role in establishing both the IEEE 802.11 standards committee and the Wi-Fi Alliance, Qorvo's Cees Links is well-positioned to opine on the future of the technology he's so closely associated with. Today, Links is general manager of Qorvo's Wireless Connectivity business. In this edited interview, Links discusses how the Zigbee Alliance's nascent Project Connected Home over IP (CHIP) Working Group might catalyze convergence in the smart-home networking ecosystem.

So, how did the wireless networking ecosystem get to where it is at present?

Over the past few years, there have been many networking standards, which meant a lot of fragmentation: Wi-Fi, Bluetooth, Thread, various forms of Zigbee, and so on *(Fig. 1)*. You see application domains, or ecosystems, such as the Open Connectivity Foundation's IoTivity and Amazon's Alexa. Google had Brillo and Weave, Apple had Home Kit, and Huawei was doing Lite OS. Samsung still has Smart Things.

One consequence of this fragmentation was that it kept the market waiting. The feeling over the last, say, two years, is that smart-home networking didn't live up to expectations. On Regis McKenna's innovation hype cycle, we landed with the IoT in the "trough of disillusionment," and now we're trying to climb out of it.



1. The fragmentation of the networking ecosystem has led to a confusing and walled-off landscape in which devices in one silo can't communicate with devices in others.

Late in 2019, the Zigbee Alliance launched a new Working Group called Project Connected Home over IP (CHIP). There were high expectations, and, frankly, a lot of trepidation as well… is this going to work? But after a year of significant effort, CHIP hints at what a convergence point could be *(Fig. 2)*, with roles for Thread, Wi-Fi, Bluetooth, and the IEEE 802.15.4 radio.

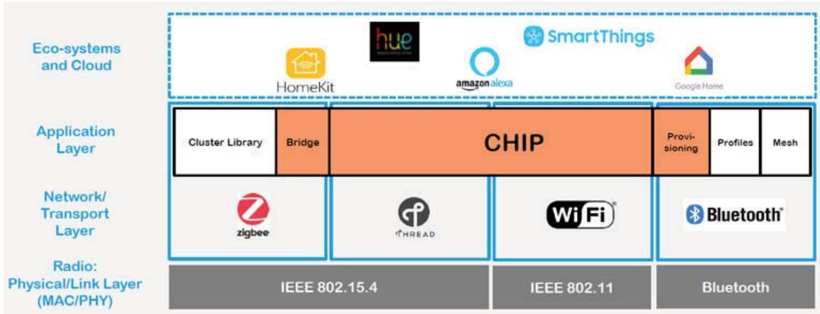
The IEEE 802.15.4, Wi-Fi, and Bluetooth radios are everywhere, and CHIP, as an application-layer protocol, defines a role for all of these radio technologies. To a large extent, Bluetooth is for provisioning: If you can connect with Bluetooth to a sensor over CHIP, then your phone can become the sensor's keyboard and screen. Now you can enter a security key for configuration or settings. When you're happy, you can disconnect your phone from the sensor. With CHIP, you can make that sensor part of a Thread, 802.15.4, or Wi-Fi network.

So that's the convergence point that we see being adopted in the market. Will this be only in the home? Initially, yes, but nothing is carved in stone. The industry is starting to realize that this can be a real convergence point, and other market segments, like building automation, could be very interested.

It sounds like a good vehicle for a lot of disparate devices to talk to each other.

Yeah, now my fridge can talk with my toaster. But there are more interesting problems to solve. My living room has three motion sensors: one each for the lighting, security system, and HVAC. Why? Because there are three ecosystems. We're looking to understand how we can use the IoT and what we expect from certain sensors, controllers, and actuators. It's not about radios or protocols, but about applications that can work together and use data from each other. It requires a sort of openness that the industry is slowly growing into.

Consumers want data from sensors or devices to be shared with other devices doing other applications, and CHIP enables this. Whether it happens depends on Google, Amazon, Apple, and Samsung making data available from their respective devices to be used by applications in the others' devices.



2. With CHIP in the picture, the fragmentation of the networking ecosystem is replaced by a more fluid environment with data shared between once-disparate ecosystems.

I don't know if having my toaster and fridge talking is useful, but if they did, it would have to be in the ecosystems above the communication layer. If the communication layers don't talk to each other, though, then the layers above will do so even less. From that perspective, I think CHIP is a great step forward and that the industry is really starting to coalesce behind it. If Amazon and Google want it to happen, it will happen.

How might this work in an industrial environment?

Consider Wi-Fi, which, initially, was good for consumers. But companies and enterprises, let alone industries, would never adopt Wi-Fi because it was a consumer technology that lacked the required reliability and stamina. Over time, you had enterprise-hardened Wi-Fi, and Power over Ethernet makes enterprise installations very easy. But the industrial environment is extremely conservative and slow in adopting new standards. So, it's a matter of time. Frankly, it may be about a decade out.

The big question is where does this leave Zigbee as we know it today? First, the Zigbee Alliance and its members have realized that something must give to get to one worldwide standard. Over time, Zigbee will fade away. Zigbee's core technologies have largely been implemented in CHIP, including the dotdot cluster library. Many Zigbee Alliance members also participate in the Thread Alliance, which has been working to get the dotdot cluster library running under Thread. So, for the participants, it's quite a natural migration.

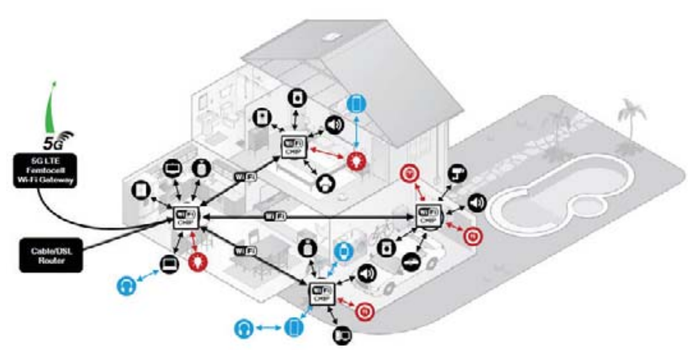
The Bluetooth situation is even more dynamic and interesting. The Bluetooth Alliance is adding meshing capability to compete with CHIP and Zigbee. But the Bluetooth people must realize that Zigbee's meshing is already harmonized under CHIP as well. I expect that Bluetooth Mesh will wither away. Because Bluetooth's Profiles are equivalent to the dotdot cluster library in Zigbee, phones will still have Bluetooth Profiles. But Bluetooth's role in CHIP will become purely one of provisioning.

With CHIP, we'll start seeing some unification, and the fight between Zigbee, Thread, and Bluetooth Mesh will disappear. Eventually, it will propagate from the Connected Home to Connected Buildings and Connected Industries.

Will the Zigbee Alliance continue to maintain and administer it?

Yes, for the time being, Zigbee is still out there and there's no need to move away from Zigbee as such. But will there be a next-generation Zigbee Pro 2.x? I can't speak for the Alliance, but I expect that all future development will be on top of CHIP rather than Zigbee.

> **With CHIP, we'll start seeing some unification, and the fight between Zigbee, Thread, and Bluetooth Mesh will disappear.**



3. CHIP, coupled with Wi-Fi 6's distributed architecture, may finally bring about a truly unified and seamless smart home.

Ultimately, everything depends on the ecosystems sharing their data. Until that happens, I'll still need three sensors for HomeKit, Google Home, and Amazon Alexa. All three sensors probably work with CHIP, and with Thread, and with 802.15.4. But if the data isn't shared, I still have multiple apps on my phone. That's the way you can see it as well.

Standardization starts at the bottom and is slowly crawling up into the value chain. Now, the challenge for the ecosystems is to find a profitable way to share data so that it becomes a rising tide that floats all the boats.

How do Wi-Fi 6 and 6E fit into the picture as we move forward?

We see the world as divided between outdoors and indoors. Outdoors, we use cellular connectivity, with subscriptions and SIM cards. Indoors, we use Wi-Fi, where there are no SIM cards but there's limited range, basically throughout the home. At home, I use my own network and router, my own connectivity, so to speak.

When I'm on the road, I use the cellular infrastructure, so I need a subscription for that. Now, of course, things start blurring, because you need a subscription to get the internet to your front door, but not necessarily throughout your house.

In the past, you had one router at the front door. If you wanted a strong signal throughout the house, you had to install repeaters and fiddle around. The key to Wi-Fi 6, especially now that we all work from home, is that it's a distributed architecture *(Fig. 3)*. You'll go to Best Buy and pick up a Wi-Fi 6 router that will come with two to four satellites. All of these satellites are configured to talk with each other in one network with one ID, one password. That's the starting point for Wi-Fi 6.

Why is this so relevant to the IoT? One of Zigbee's selling points is meshing, but with Wi-Fi 6, Wi-Fi meshing covers the entire home. We believe that in the future, Zigbee (or, if you like, CHIP) meshing will become redundant and wither away. Instead, every CHIP device can find an integrated Wi-Fi/CHIP device in the house and be connected via that device to the network.

In the future, a Wi-Fi pod in a room will connect all devices in the room, but you can also imagine the other way around. My wife hates seeing a router in a room, but if it's built into something like the NetGear Meural digital art canvas, she wouldn't care. Televisions can operate as a Wi-Fi pod, surf all of the devices in the living room, and be itself connected via Wi-Fi to the router. So, there's an interesting kind of future morphing, I like to say, turning things inside out.

The main static devices in the house become Wi-Fi pods for the whole home. Amazon Alexa, or Dot, or a Google device, can function as Wi-Fi pods. The devices will start to absorb the pods and become part of the infrastructure themselves.

That's our vision of Wi-Fi and how IoT/CHIP will merge. Then, there's also Wi-Fi 6E. For 20 years, Wi-Fi has been running on 2 GHz and 5 GHz, but they're running into a wall. Wi-Fi 6E, with the tremendous amount of 6-GHz bandwidth it brings, will open things up again.

Can Wi-Fi and 5G coexist?

My expectation is that Wi-Fi and 5G will continue to coexist, because it's just so close to how people perceive networking and connectivity. Indoors, in your house, with your own network and spectrum, no SIM card is required. And outdoors, with your phone, you need the infrastructure.

I think Bluetooth will also have a long life, because it's a third psychological experience, so to speak. There's indoors and outdoors, and the third experience is what I call the personal bubble. Bluetooth is the connectivity for your bubble. It connects your watch to your phone, your headphones to your phone; you can do all kinds of things in your personal bubble. If I'm on my bicycle, then the speedometer is in my personal bubble, connected by Bluetooth.

So, all of these things, in my personal bubble, are connected. And that's a third radio. In a way, I see Wi-Fi and CHIP merging as indoor wireless technology in license-free spectrum. I see 5G out there and Bluetooth out there. Of course, there will be new technologies and ideas. Nothing is static in this world. But there's some logic in the three radios that we're used to in our phones: a personal bubble, a local home network, and an outdoor 5G subscription network. And the three will coexist in one device. mw

DAVID MALINIAK | Editor

The Future of RF Filtering in a 5G World

The onset of broad 5G and Wi-Fi 6/6E adoption will necessitate a new approach to RF filtering in mobile devices.

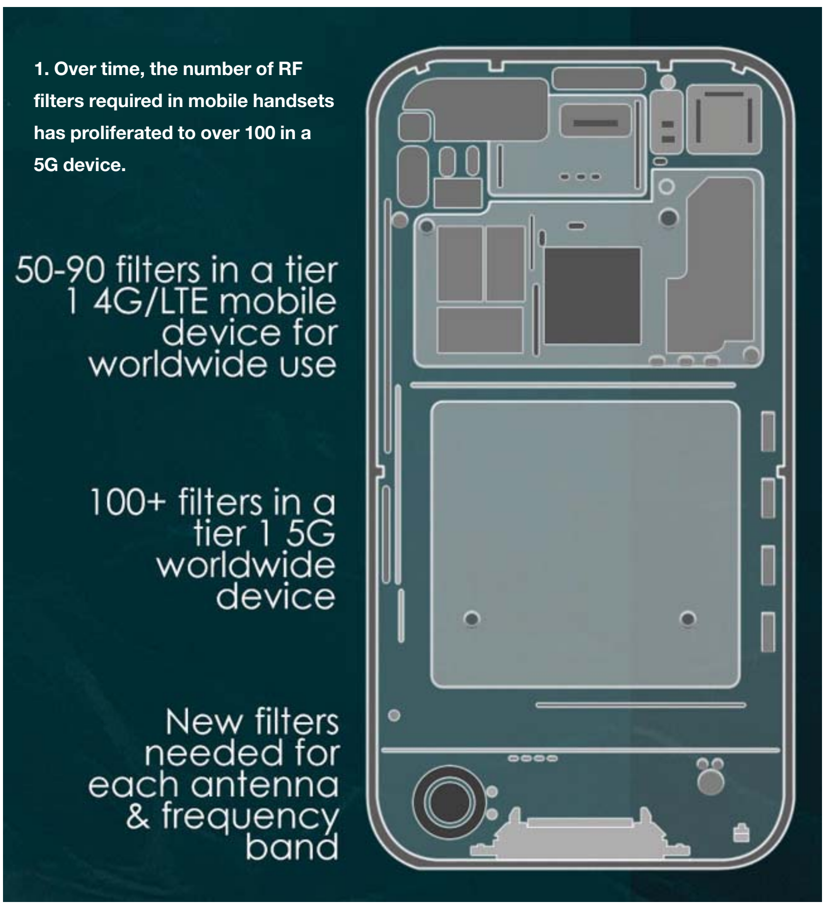
Filters are a critical component—perhaps *the* critical component—of RF and microwave design. Filtering is what enables proper operation of everything from our mobile devices to smart homes/buildings/cities to autonomous and electric vehicles. Put simply, filters let desired frequency elements in and keep undesired elements out of a given device or system. Without filtering to isolate sections of our crowded RF spectrum from one another, interference from, say, the 5G bands to the closely adjacent Wi-Fi spectrum, would wreak havoc. As our mobile devices take on more functionality and comprise multiple radios, the problem becomes insidiously complex. Consider the 1G phones of yore, which didn't even yet have texting capability: These devices required only rudimentary filtering schemes that could be handled by just one or two filters. A 4G/LTE handset for worldwide use contains from 50 to 90 filters.

In contrast, today's emerging 5G phones, which allow you to download a two-hour movie in 30 seconds, can have more than 100 distinct filters *(Fig. 1)*. The more antennas and frequency bands a device covers, the more filters it will require to make everything play nice together.

In such a complex environment, there's necessarily been some advances in how RF filters are designed and implemented. In a design and engineering environment that has seen a great shift toward approaches based on intellectual property (IP), it was inevitable that this approach would make its way into the RF-filtering realm.

RF-Filter Focus

This is where a company like Resonant enters the picture. Resonant is wholly concerned with RF filtering, but it doesn't produce parts or hardware directly. Rather, the company's foundation is a software platform called Infinite Synthesized



1. Over time, the number of RF filters required in mobile handsets has proliferated to over 100 in a 5G device.

Networks (ISN), which uses modeling to rapidly design and simulate filters while also targeting a given foundry's capabilities. The goal is to design the optimal filter for the task at hand while also ensuring that it can be fabricated with reduced prototyping cycles, making the process more cost-efficient.

"What we bring to the table is our ISN software, which performs full finite-element modeling," says Mike Eddy, senior marketing advisor at Resonant. Armed with the material parameters and physical dimensions for a given filter, the software predicts with high accuracy the filter's performance as it would come out of the fab.

Large, vertically integrated players in the RF-filtering market typically approach filter design in an empirical fashion. They create a filter design and prototype it in their fab, evaluate its performance with respect to the performance requirements, and, if necessary, tweak the design and repeat the process. This can result in a lengthy procedure to build a device that meets the specs. "Instead of 12, 15, or 18 iterations, we try to have a spec-compliant part within two or three iterations," says Eddy.

Initially, Resonant developed its ISN software for surface-acoustic-wave (SAW) filters in a process that would minimize variations in frequency response over temperature. Subsequently, the company sought to extend the platform for design of bulk-acoustic-wave (BAW) filters. "But as we looked at doing that, we were also seeing 5G coming along," says Eddy.

5G filter requirements are very difficult from those for 4G, which needed filters with about 60 to 70 MHz in bandwidth at about 2 GHz. In contrast, 5G filtering calls for 600 to 900 MHz of bandwidth at 3 to 5 GHz for operation in the sub-6-GHz bands.

XBAR Resonator

Resonant's next move was to use its own software platform to develop a next-generation resonator as a building block for filters in 5G devices. That resonator, called XBAR, meets not only the requirements of 5G, but also those of Wi-Fi 6/6E.

XBAR resonators generate a BAW, but because of the nature of their structure, they can be fabricated on a simple process like those used for SAW filters. 5G filters must provide high bandwidth at high frequencies while handling higher power to maximize signal coverage. XBAR resonators meet those requirements, and because of the ISN software's ability to factor in process technology, manufacturing a filter using XBAR resonators needs only three to five processing steps. The resonator's simple structure consists of a metal comb line atop a piezoelectric surface with an air gap underneath *(Fig. 2)*.

A prototype of an n79 5G filter was unveiled at the last Mobile World Congress and seized upon by Murata Manufacturing. Murata has since made a strategic investment in Resonant and committed to manufacturing four devices using the XBAR resonator for mobile applications. Today's 5G phones are still being built with integrated passive device (IPD) or low-temperature cofired ceramic (LTCC) filters. Such filtering designs are adequate for now because there hasn't yet been the anticipated explosion in 5G traffic.

But when the 5G bands from 3.3 to 5 GHz do experience that traffic boom, the proximity to the 5-GHz Wi-Fi bands and 6-GHz Wi-Fi 6E bands will result in interference. As a result, IPD or LTCC filters may not provide sufficient rejection of out-of-band signals. That's when higher-performance filters, such as those possible with XBAR resonators, will become essential.

"We see, over the next two to three years, a transition to acoustic-wave filters to manage the looming interference problem," says Eddy. Resonant believes its ISN software will provide value to both vertically integrated filter manufacturers, such as Murata and others, as well as to other companies in the RF/microwave space who don't have access to filters except through foundry partners.

2. The XBAR resonator's structure (right) results in a bulk-acoustic-wave device that requires few manufacturing steps to fabricate RF filters.

JERRY GIPPER | Executive Director, VITA

WHAT'S TRENDING IN **Rugged Board Systems?**

VITA Executive Director Jerry Gipper provides insights about what's on tap and what's coming in rugged hardware design.

What a crazy 2020 we had, and 2021 isn't exactly off to a great start! If you're like me, you're looking forward to a new administration and trying to sort out when you might get your COVID-19 vaccination. Fortunately, life in the standards business is much better!

The VITA community hasn't experienced any significant changes in business. Standards are still being developed, and new products and design wins are being announced at a normal pace. VITA standards meetings since last March have been virtual and well-attended while also very productive.

Members find it easier to participate, especially when all parties are virtual. The face-to-face aspect is still greatly missed in maintaining existing friendships and developing new relationships. Some things are just difficult to do in a virtual environment, despite the clever things that virtual-event tool developers are innovating to engage participants.

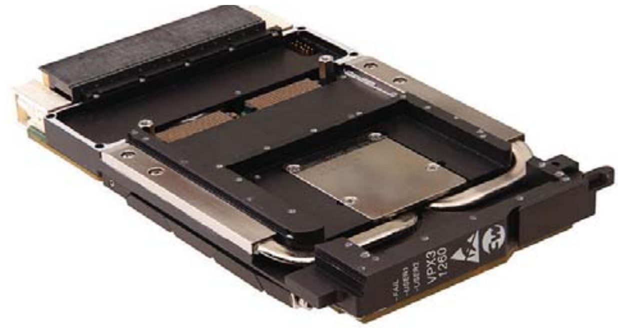
Standard Bearers

We were able to get eight standards through the VITA/ANSI process in 2020, including ANSI/VITA 46.30 and VITA 46.31, which enabled extending the data rate of VPX to the next level of at least 25 Gbaud for protocols such as 100GBASE-KR4 Ethernet and PCIe Gen 4. The higher-data-rate connectors defined in these standards are intermateable to legacy VITA 46.0 connectors and follow the same form factor. The working groups have been focused on this problem for several years *(Fig. 1)*.

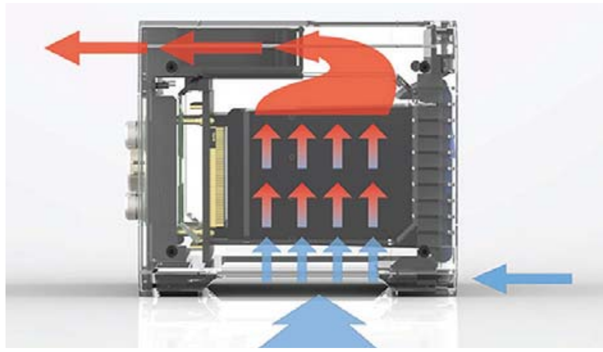
Another challenge met in 2020 was the release of additional ANSI/VITA 67 coaxial interconnect on VPX standards. These standards enable various configurations to support RF connections to a VPX module, extending the use to some interesting applications utilizing RF I/O. This work complements the configurations defined under various VITA 66 VPX optical standards.

A key focus of much of those efforts is trying to strike a balance between flexibility in design options with a push to converge on well-defined configurations. The building-block approach taken in these standards optimizes the balance. The working group focused on fewer, more common standard modules to bring economies of scale, increased interoperability, shorter development cycles, and reduced costs into consideration.

Rounding out 2020 activities was a significant update to the ANS/VITA 48 standards for Ruggedized Enhanced Design Implementation (REDI) mechanical implementations for 3U and 6U in various cooling schemes *(Fig. 2)*. The working group extended the standards to include new air- and liquid-cooling schemes introduced the past few years.



1. VITA 46 is a rugged 3U and 6U board standard that supports high-speed serial interfaces. *(Courtesy of Curtiss-Wright Defense Solutions)*



2. VITA 48 standards include new air- and liquid-cooling schemes to reduce weight while increasing cooling capacity.

Engaging SOSA

Much of the current activity at VITA is driven by user requirements coming out of the SOSA Consortium. They have adopted many of the VPX standards in their documentation. The SOSA Consortium is pushing the envelope on performance and optical/RF connectivity for high-performance embedded computing using VPX as the hardware foundation.

As open standards gain momentum in such demanding applications, the performance envelope will continue to be pushed, leading to more standards to meet these needs. For VITA technology, this means higher data rates, denser optical and RF connectivity, and smaller form factors. All of these areas will likely need to be double or quadruple the levels they are at now within the next three to five years. Study and working groups have been formed to address these areas and I expect work products to roll out in the coming months.

The 2021 Agenda and Bracing for the Unknown

The VITA working groups have a full plate going into 2021. Teams are working on VPX enhancements as mentioned, but others are working on system management, reliability, mezzanine cards, modules for space applications, and circular connectors. New proposals for possible standards efforts are made at nearly every bi-monthly gathering. At last count, there were at least 18 active working groups. Some of the efforts bridge to other standards organizations such as the SOSA Consortium, IEEE, and PICMG.

Unfortunately, the complexity of standards is an increasing challenging for even the most experienced and advanced of the engineering teams. We need to develop ways to make everything from creating to implementing standards more intelligent. We're nearing the cusp of the next generation of "smart" standards that address the increasing complexity that's facing us.

We're in the early stages of exploring possible options that can make creating, implementing, testing, and conforming to standards more manageable. Collaboration between standards organizations for ideas on best practices and tools are needed to speed this effort.

Much of the technology developed on VITA standards ends up in defense applications. The budget allocated to electronics in many programs continues to increase, keeping the demand strong. I don't see this changing anytime soon. New programs, which are being launched at a high rate, should be able to take advantage of open standards for high-performance computing.

A Virtual New World?

I often contemplate "What will business look like when we emerge on the other side of COVID? Will we snap back to the old ways of doing business or will we see a substantial bump in the use of technology to conduct our lives?"

I know that everyone is anxious to get back to life as we previously knew it, but I'm also more convinced that much of it will never be the same. The video technology available today has demonstrated that a lot of routine business travel can easily be replaced with a video conference. Even many routine office meetings with everyone in the same building can be done more productively in a virtual world.

Several companies have come out and stated that more employees will be encouraged, even required to work from home. Brick and mortar will frequently be replaced by green screens and virtual backgrounds. The travel industry is going to have to adjust their model for the potential shift between business and leisure travel.

While VITA may use more virtual-only meetings, at the same time we hope to be back conducting in-person face-to-face meetings by July or September. Our productivity may be great in a structured virtual environment, but we're missing key human elements, especially creativity and innovation, that are strongest when we physically interact!

While we have been discussing the future, the past is just as important. October 2021 celebrates the 40th anniversary of the introduction of VMEbus. Even today, new products continue to roll out and the market remains strong. We look forward to celebrating this historic milestone in embedded computing! mw

PETER DELOS, BOB BROUGHTON, JON KRAFT | Analog Devices

Phased-Array Antenna Patterns (Part 6)—Sidelobes and Tapering

This sixth installment closes out the series on phased-array antenna patterns with a discussion of antenna sidelobes and the effect of tapering across an array.

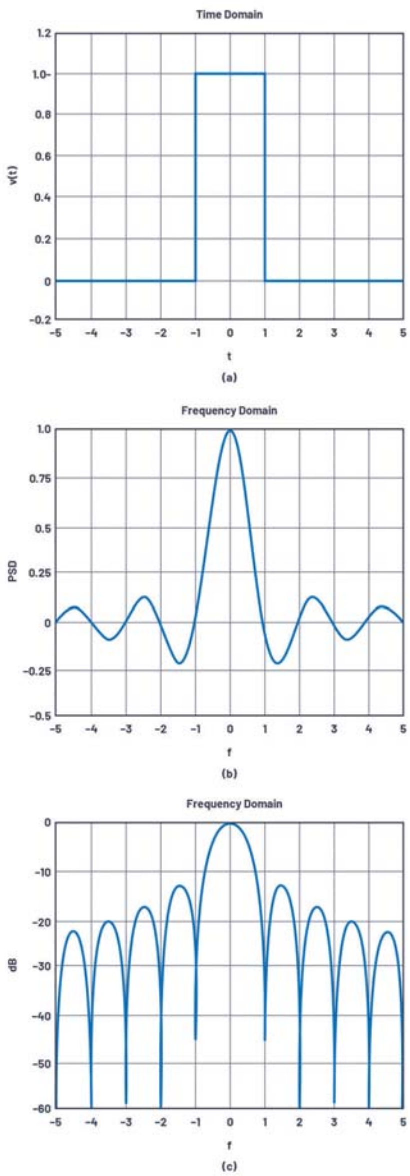
Previously in this series, we introduced the phased-array concept, beamsteering, and array gain. Then we presented the concepts of grating lobes and beam squint. In this final part, we will discuss antenna sidelobes and the effect of tapering across an array.

Tapering is simply the manipulation of the amplitude contribution of an individual element to the overall antenna response. Earlier in the series, no tapering was applied and the first sidelobes were –13 dBc as seen in the figures. Tapering provides a method to reduce antenna sidelobes at some expense to the antenna gain and main-lobe beamwidth. Following an introduction to tapering, we will elaborate on a few points relative to antenna gain.

Fourier Transform: Rect ↔ Sinc

The transformation of a rectangular function in one domain to a sinc function in another domain comes up in different forms in electrical engineering. The most common form is when a rectangular pulse, in time, emits the spectral content of a sinc function. It's also used in reverse, where wideband applications transform a wideband waveform to a narrow pulse in time. Phased-array antennas have a similar property: a rectangular weighting along the planar axis of the array radiates a pattern following a sinc function.

For applications subjected to this property, the sidelobes of the sinc function are problematic with the first sidelobe being only –13 dBc. *Figure 1* illustrates this principle.



1. A rectangular pulse in time yields a sinc function in the frequency domain with the first sidelobe at only –13 dBc.

Tapering (or Weighting)

A solution to the sidelobe problem is to apply a weighting across the rectangular pulse. This is common in fast Fourier transforms (FFTs), and tapering options in phased arrays are directly analogous to weighting applied in FFTs. The unfortunate drawback of weighting is that sidelobes are reduced at the expense of widening the main lobe. Some example weighting functions are shown in *Figure 2*.

Waveform vs. Antenna Analogy

The domain transformation from time to frequency is routine enough that it becomes natural for most electrical engineers to visualize. However, for engineers new to phased arrays, how to use the analogy for antenna patterns may not be initially apparent. To do so, we replace the time-domain signal with the field-domain excitation, and the frequency-domain output is replaced with the spatial domain.

Time domain → field domain
- v(t)—voltage as a function of time
- E(x)—field strength as a function of position in the aperture

Frequency domain → spatial domain
- Y(f)—power spectral density as a function of frequency
- G(q)—antenna gain as a function of angle

Figure 3 illustrates the principle. Here, we compare the radiated energy for two different weightings applied across the array. *Figure 3a* and *Figure 3c* illustrate the field domain. Each dot represents the amplitude of one element in this N = 16 array. Beyond the antenna, there's no radiated energy, and radiation begins at the antenna edge. In *Figure 3a*, an abrupt change occurs in the field, while in *Figure 3c*, there's a gradual increase with distance from the antenna edge. The resulting impact on the radiated energy is shown in *Figure 3b* and *Figure 3d*, respectively.

In the next sections, we will introduce two additional error terms that impact the antenna-pattern performance. The first is mutual coupling. For this article, we merely acknowledge the problem and the amount of electromagnetic modeling used to quantify the impact. The second is quantization sidelobes due to a finite number of bits in the phase-shift control. A more in-depth treatment is given to quantization errors, and quantization sidelobes are quantified.

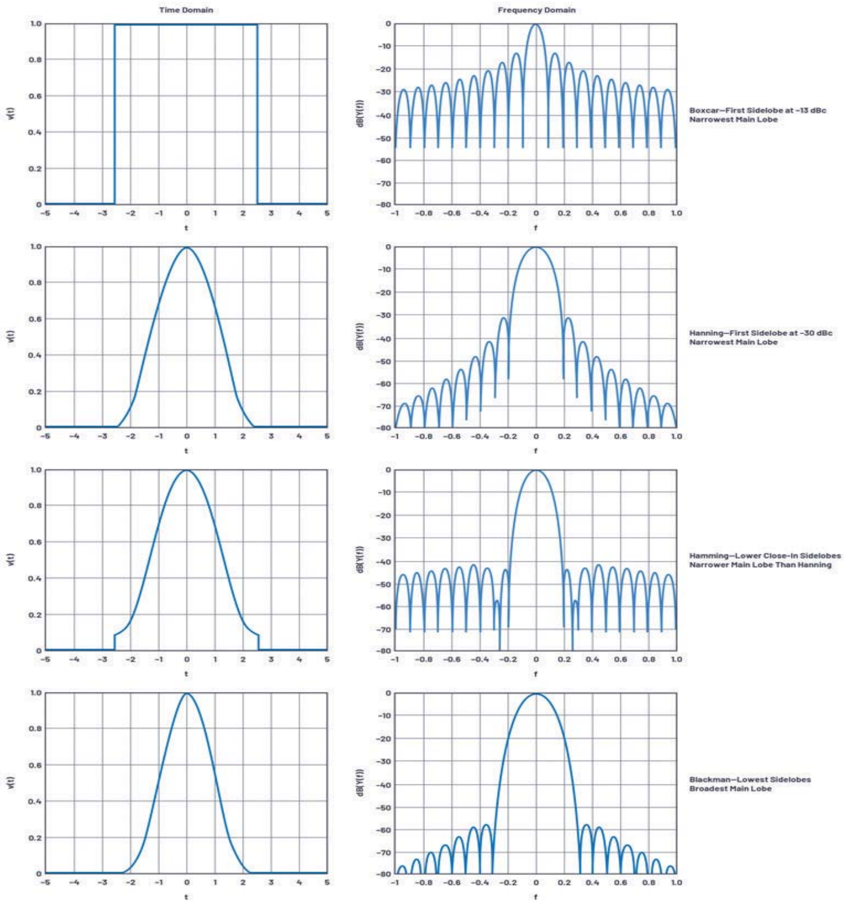
Mutual Coupling Errors

All of the equations and array-factor plots discussed here assume that the elements are identical, and each has the same radiation pattern. In practice, this isn't the case. One of the reasons concerns mutual coupling, which is the coupling between adjacent elements. An element's radiating performance may change significantly when it's widely separated in the array vs. when it's spaced more closely. The elements at the edge of the array have a different surrounding environment than the elements in the middle of the array.

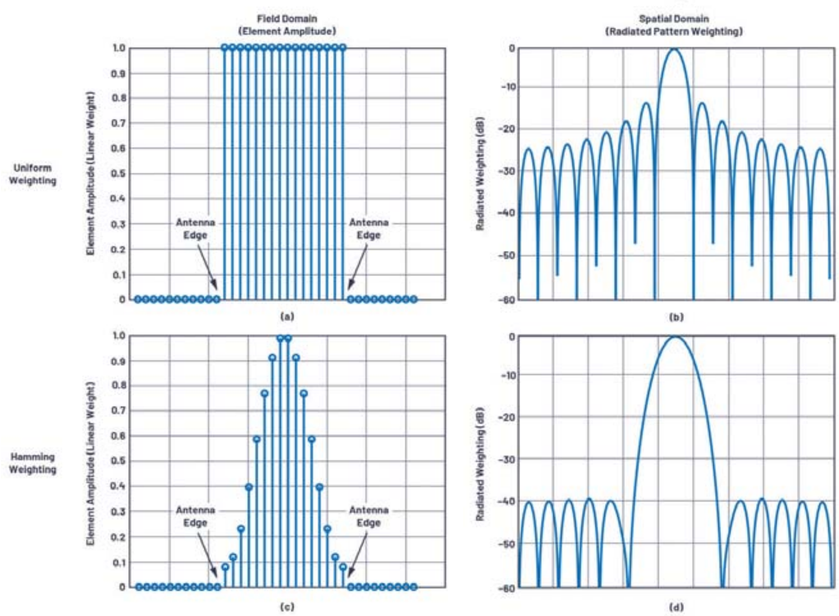
Furthermore, as the beam is steered, it changes the mutual coupling between elements. All of these effects create an additional error term to be accounted for by the antenna designer and, in practice, much effort is spent with electromagnetic simulators to characterize the radiation effects under these conditions.

Beam-Angle Resolution and Quantization Sidelobes

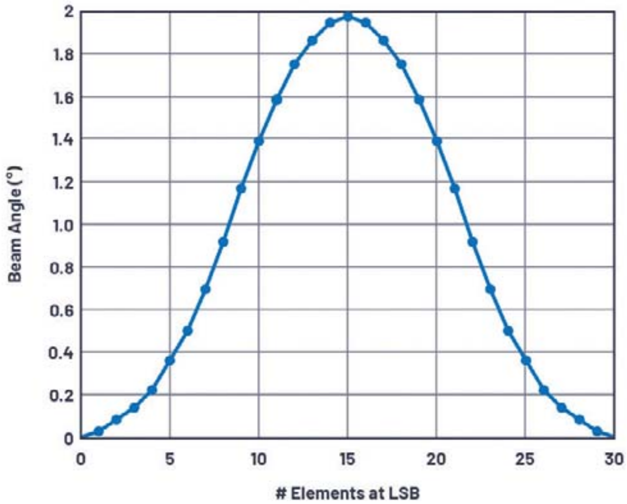
Another practical phased-array antenna impairment stems from the



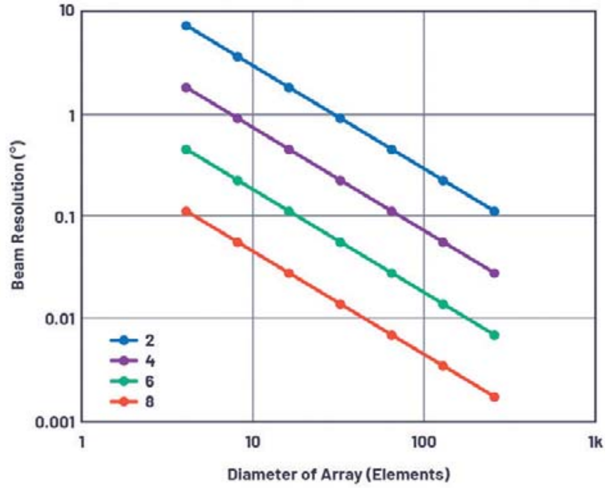
2. Shown are some examples of weighting functions; the unfortunate drawback of weighting is that sidelobes are reduced at the expense of widening the main lobe.



3. These graphs show element tapering transformed to radiated energy weighting: (a) uniform weighting applied to all elements; (b) sinc function radiated spatially; (c) Hamming weighting applied across the elements; and (d) radiated sidelobes reduced to 40 dBc at the expense of broadening the main beam.



4. Shown is a plot of the beam angle for a 30-element array using a 2-bit phase shifter, as the phase LSB is progressively switched into elements from left to right across the array.



5. Here, we plot beam-angle resolution vs. array size for phase-shifter resolutions of 2 bits to 8 bits.

finite resolution of the time-delay unit, or phase shifter, used to steer the beam. This is typically digitally controlled with discrete time (or phase) steps. But how does one determine the resolution, or number of bits, required to achieve the beam-quality goals?

Contrary to common misconceptions, beam-angle resolution isn't equivalent to the resolution of the phase shifters. In Equation 1, we find this relationship:

$$\theta = \sin^{-1} \frac{\Delta\Phi\, \lambda}{2\pi\, d} \qquad (1)$$

We can express this in terms of the phase shift across the entire array by substituting the array width D for the element spacing d. If we then substitute the phase shifter ΦLSB for ΔΦ, we can approximate the beam-angle resolution. For a linear array with N elements spaced at a half wavelength, the resolution of the beam angle is shown in Equation 2:

$$\theta_{RES} \propto \sin^{-1} \frac{\Phi LSB}{N\pi} \qquad (2)$$

This is the beam-angle resolution off boresight and describes the beam angle when one half of the array has a phase shift of zero, and the other half has a phase shift of the LSB of the phase shifter. Smaller angles are possible if less than one half of the array is programmed to the phase LSB.

Figure 4 plots the beam angle for a 30-element array using a 2-bit phase shifter, as the phase LSB is progressively switched into elements from left to right across the array. Note that the beam angle increases until half of the elements are shifted by an LSB, and then returns to zero when all elements are at the LSB. This makes sense as the beam angle changes through a difference in phase across the array. Note that the peak of this characteristic is θ_{RES}, as previously calculated.

Figure 5 plots θ_{RES} as a function of array diameter (at λ/2 element spacing) for different phase-shifter resolutions. This shows that even a very coarse 2-bit phase shifter with a 90° LSB can achieve 1° resolution for an array diameter of 30 elements.

Solving Equation 7 in Part 2 *(go to www.mwrf.com)* of the series for 30 elements at λ/2 spacing, the main lobe beamwidth is approximately 3.3°, suggesting that we have ample resolution even with this very coarse phase shifter.

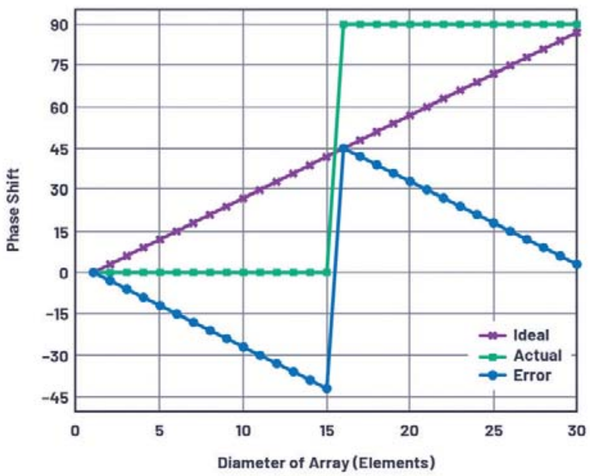
So, what do we get for a phase shifter offering higher resolution? Drawing from analogies between time-sampled systems (data converters) and space-sampled systems (phased-array antennas), a higher-resolution data converter produces a lower quantization noise floor. Higher-resolution phase/time shifters result in lower quantization sidelobe levels (QSLLs).

Figure 6 shows the phase-shifter settings and phase error across the 2-bit, 30-element linear array previously described, programmed to the beam resolution angle θ_{RES}. Half of the array is set to zero phase shift, and the other half is set to the 90° LSB. Note that the error, the difference between the ideal and actual quantized phase shift, has a sawtooth shape.

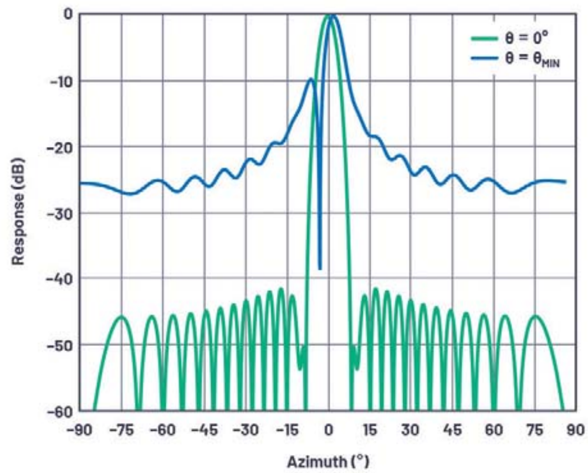
The antenna patterns for the same antenna steered to 0° and to the beam resolution angle are shown in *Figure 7*. There's a severe degradation of the pattern due to the quantization error of the phase shifter.

The worst-case quantization sidelobes crop up when the maximum quantization error occurs across the aperture, when every other element is at zero error and the neighbor is at LSB/2. This represents both the maximum possible

(Continued on page 31)



6. This plot shows the phase-shifter settings and phase error across the 2-bit, 30-element linear array previously described, programmed to the beam resolution angle θ_{RES}.



7. Here are the antenna patterns with quantization sidelobes at minimum beam angle.

quantization error and the maximum periodicity of the error across the aperture. This condition is shown for the 2-bit, 30-element case in *Figure 8*.

Such situations occur at predictable beam angles as presented in Equation 3:

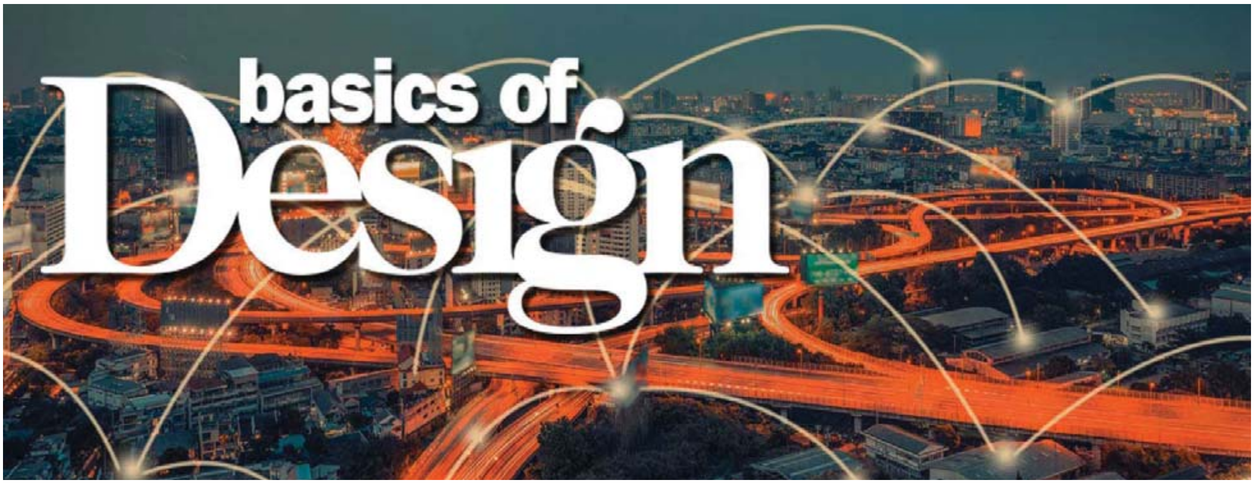
$$\theta_{MAX\ QSLL} = \sin^{-1}\frac{\pm n}{2^{BITS}} \qquad (3)$$

where $n < 2^{BITS}$, and n is odd. For a 2-bit system, this condition is satisfied four times between horizons, at ±14.5° and ±48.6°. *Figure 9* illustrates the antenna pattern for this system for n = 1, q = +14.5°. Note the substantial –7.5 dB quantization sidelobe at –50°.

At beam angles other than the special cases where the quantization error is sequentially 0 and LSB/2, the RMS error is reduced as it is spread across the aperture. In fact, for the angle equation (Equation 3) for even values of n, the quantization error is zero.

If we plot the relative level of the highest quantization sidelobe for various phase-shifter resolutions, some interesting patterns emerge. *Figure 10* shows the worst-case QSLL for a 100-element linear array, employing a Hamming taper so that the quantization sidelobes can be differentiated from the classical windowing sidelobes discussed earlier in this section.

Note that at 30°, all quantization error goes to zero, which can be shown to be a consequence of sin(30°) = 0.5. Notice that the beam angle of the worst-case level for any n-bit phase shifter exhibits zero quantization error at any higher resolution n. The beam angles for worst-case sidelobe levels described here can be seen, as can the 6-dB improvement in QSLL per bit of resolution.



GEOFF SCHULTEIS | RF Antenna Application Specialist, Antenova Ltd.

Integration Tips for FPC Antennas

The smallest antenna may not be the best solution for a design. The FPC antenna can serve as a useful alternative for certain designs.

This article explores the design and integration implications for flexible-printed-circuit (FPC) antennas. The FPC is an alternative to a chip antenna and can be an interesting choice for specific embedded designs.

FPC antennas are thin, typically just 0.15 mm, and have a peel-back strip plus an adhesive area to fix them inside a small electronic device in various configurations *(Fig. 1)*. They're supplied complete with a cable and a connector to attach them to the underside covering or housing of a manufacturer's electronic product. An FPC is lightweight, probably less than 0.5 g.

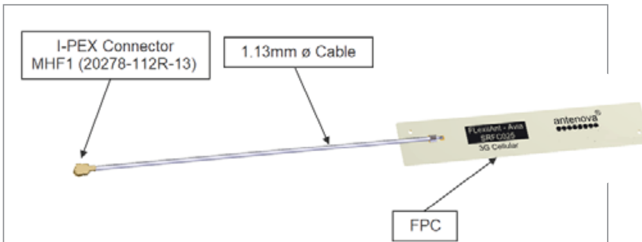
Advantage: No Ground Plane Concerns

The FPC works differently than a surface-mount device (SMD) chip antenna. An SMD antenna, which utilizes the ground plane where it's mounted to radiate, works on the reciprocity principle. A dipole antenna uses two radiators where the length of each radiator is related to the wavelength of the frequency used by the antenna uses. Embedded antennas have one radiator within their mass, and they use an area on the PCB as their counterpoise—commonly referred to as the ground plane.

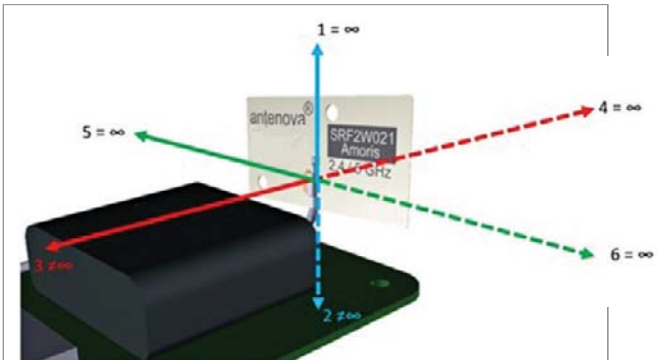
With an SMD antenna, the length of the ground plane is directly related to the antenna's wavelength. The correct ground-plane length must be provided in the design so that the antenna is able to operate and perform with good efficiency.

FPC antennas are different in this respect—they don't require a ground plane to radiate. As such, they allow the designer more freedom to arrange the components in the circuit within the design.

However, it's important to remember that the coax cable becomes part of the antenna. Thus, the routing of the cable should be designed with care to keep this part of the antenna away from other components that might create noise and interference.



1. Shown is the FPC antenna with cable and I-PEX connector.

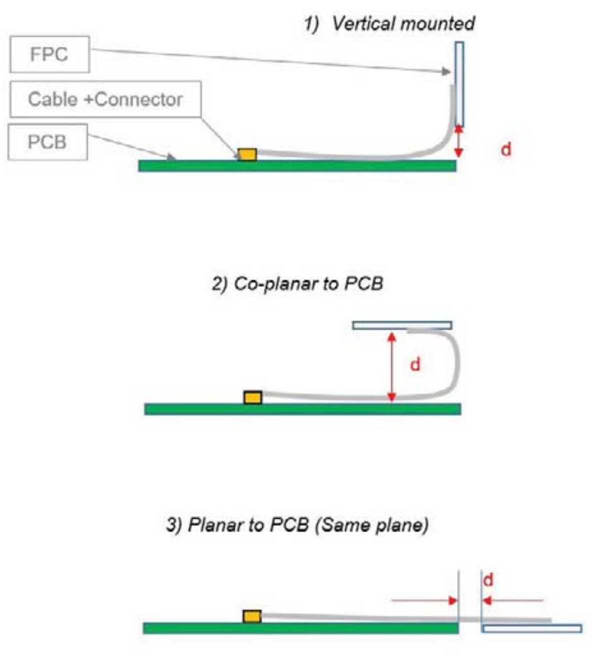


2. Our integration example shows the antenna placed with four spatial directions that are clear of obstructions.

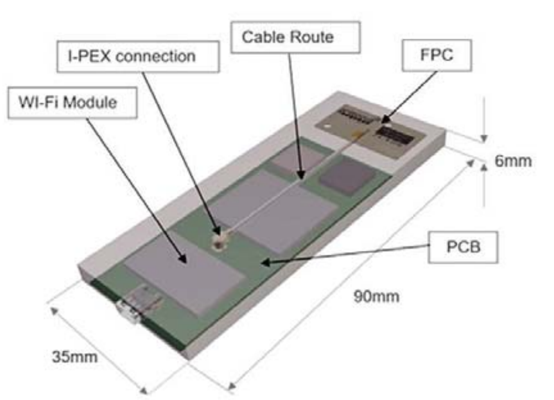
Placement

Because the ground plane isn't a design consideration for the FPC antenna, the size of the host PCB isn't a factor as it is with SMD or chip antennas. However, the placement of the FPC antenna still needs to follow some basic rules, since most antennas are sensitive to their environment.

The antenna will radiate in six spatial directions *(Fig. 2)*. Ideally, a minimum of three to five of these directions should be free from obstructions, which will allow the antenna to operate effectively. For the other directions that have obstacles in the radiation paths, there should still be a minimum clearance, which will be defined in the antenna manufacturer's datasheet.



3. The diagram depicts the three common configurations for the FPC on the host PCB.



4. Here, the FPC is integrated within a narrow device.

The plastic case for the device will not act as an obstruction unless the material used to manufacture the case is glass-filled or if metallic paint has been applied. Metal objects and components such as data cables and printed circuit boards (PCBs) in close proximity to the FPC antenna are usually the culprits that block the signals.

Orientation of FPC

The shape of the device will determine the ideal orientation of the FPC with respect to the host PCB. The antenna's position in relation to the PCB will depend on the proximity of the ground *(Fig. 3)*.

Whichever option is chosen, the distance (d) becomes a critical dimension in the design. This will be specified in the antenna manufacturer's datasheet.

Device Integration Example

Figure 4 shows an integration example for an FPC antenna. The device has the major components within an outer case. The FPC has been adhered to the inside of the device's plastic housing, with the cable routed along the PCB so that it will not interfere with any other component. In this case, the FPC was placed on the same plane relative to the PCB. Due to the slim design of the device, this was the optimal location for the antenna.

The antenna's I-PEX cable connects it into the design. All of the transmission lines within the product are designed to have a characteristic impedance of 50 Ω and should be kept as short as possible. All other parts of the RF system, such as transceivers and power amplifiers, should also be designed to have an impedance of 50 Ω.

We recommend using a commercial RF design package to create the transmission-line layout, taking into account the PCB thickness, copper thickness, and the dielectric constant. The program will calculate the recommended width for the transmission line, and the appropriate spaces between the reference ground plane on either side of the antenna feed trace to keep the 50-Ω system impedance.

Is an FPC Antenna Good for Your Design?

SMD antennas may be the most obvious choice for a small PCB, but FPC antennas are widely used in applications where there's insufficient space for a SMD antenna.

Off-the-shelf FPC antennas aren't recommended for the very smallest devices, but there are plenty of applications where FPCs can work well. They can be a particularly useful choice for those designs where ground-plane length and space are restricted.

Remember that FPCs aren't compatible with pick-and-place machines. However, they're a good choice for lower-volume manufacturing in which devices are assembled by hand. mw

HIGH-POWER GUNN OSCILLATOR FUNCTIONS IN W-BAND

Spacek Labs' Model GW-940-FT is a cost-effective, high-power, W-Band Gunn oscillator with center frequency of 94 GHz and ±250 MHz of bias-tunable bandwidth; other frequencies are available. The output power is 20 mW minimum, stability is 5 MHz/°C, and power stability is specified at -0.04 dB/°C. This model incorporates an InP Gunn diode with an input bias of +5 V dc @ 1 A typical. Heat is dissipated with an integrated heatsink.

SPACEK LABS, www.spaceklabs.com

SP6T SWITCH MATRIX ROUTES DC TO 50 GHz

Mini-Circuits' model RC-1SP6T-50 is a single-pole, six-throw (SP6T) electromechanical switch matrix with a wide frequency range of DC to 50 GHz. Built to last more than 2 million switching cycles per switch position, it is designed in a failsafe, make-before-break configuration ideal for automated test applications. The switch matrix is well matched to 50 Ω, with typical VSWR of 1.30:1 to 40 GHz and 1.60:1 to 50 GHz. It exhibits low loss across its full bandwidth, with typical insertion loss of 0.2 dB or less from dc to 26.5 GHz and 0.4 dB or less from dc to 50 GHz. Isolation between ports is high, with at least 85 dB from dc to 26.5 GHz and at least 75 dB from dc to 50 GHz. The absorptive switch matrix has 50-ms switching speed for an operating temperature range of 0 to +40°C and handles cold-switching input power levels as high as 20 W to 18.0 GHz, 10 W to 26.5 GHz, and 3 W to 50 GHz. It is housed in a compact metal enclosure measuring 5.5 × 6.0 × 2.75 in. with 2.4-mm female RF connectors and USB and RJ45 Ethernet/LAN interfaces for computer control.

MINI-CIRCUITS, https://www.minicircuits.com/WebStore/dashboard.html?model=RC-1SP6T-50

MICROWAVE CABLE ASSEMBLIES OFFER PHASE STABILITY vs. TEMPERATURE

In its UTiPHASE microwave cable assemblies, Carlisle Interconnect Technologies offers products that deliver outstanding electrical phase stability versus temperature without compromising microwave performance. UTiPHASE is ideal for demanding defense, space, and testing applications. The UTiPHASE series builds on the company's UTiFLEX flexible coaxial-microwave-cable technology by combining renowned reliability and industry-leading connector captivation with thermally phase-stable dielectric that eliminates the PTFE "knee." Applications include commercial and military phased-array radars, as well as aerospace SATCOM and Traffic Collision Avoidance Systems (TCAS), synthetic aperture radars, thermal test sets, and any RF/microwave system operating at or near room temperature.

CARLISLE INTERCONNECT TECHNOLOGIES, https://www.carlisleit.com/products/cable-assemblies-harnesses/

LOW-NOISE AMPLIFIER CONTAINS INTEGRATED BIAS-TEE NETWORK

Planar Monolithics Industries' model PE2-30-218-4R0-20-12-SFF-BT is a 2.0 to 18.0 GHz low-noise amplifier that contains an integrated bias-tee network on the output port. This amplifier provides 30 dB of gain while maintaining a maximum gain flatness of ±2.0 dB maximum over the operating frequency. Noise figure is less than 4 dB and current draw is less than 350 mA. This amplifier is supplied in the company's standard PE2 housing that can be used as a SMA connectorized or a surface-mount component.

PLANAR MONOLITHICS INDUSTRIES, https://www.pmi-rf.com/product-details/pe2-30-218-4r0-20-12-sff-bt

(Continued from page 27)

The maximum quantization sidelobe levels, QSLL, for 2-bit to 8-bit phase-shifter resolutions are shown in *Figure 11*, which follows the familiar quantization-noise law for data converters:

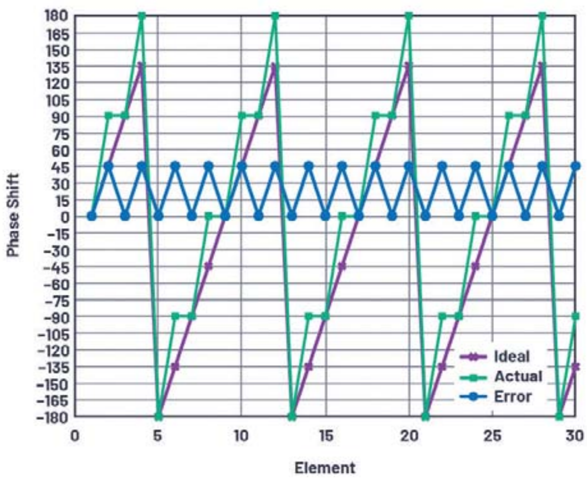
$$QSLL \;\alpha\; 20 \log_{10} 2^{-BITS} \qquad (4)$$

or about 6 dB per bit of resolution. At 2 bits, the QSLL levels are about –7.5 dB, higher than the classical +12 dB for a data converter sampling a random signal. This discrepancy can be viewed as a consequence of the periodically occurring sawtooth error being sampled across the aperture, where the spatial harmonics add in phase. Note that the QSLL isn't a function of the aperture size.

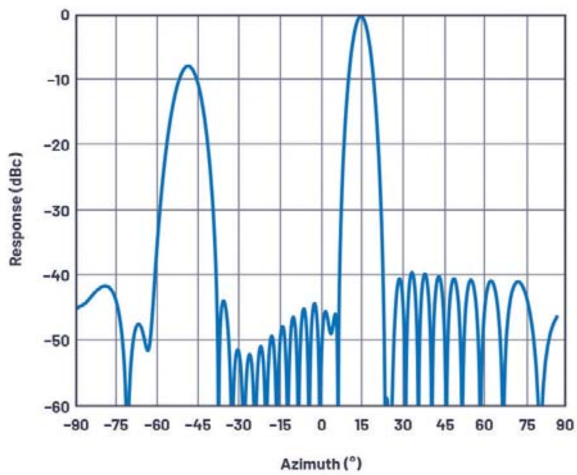
Closing Comments

We can now summarize some of the challenges faced by antenna engineers relative to beamwidth and sidelobes:

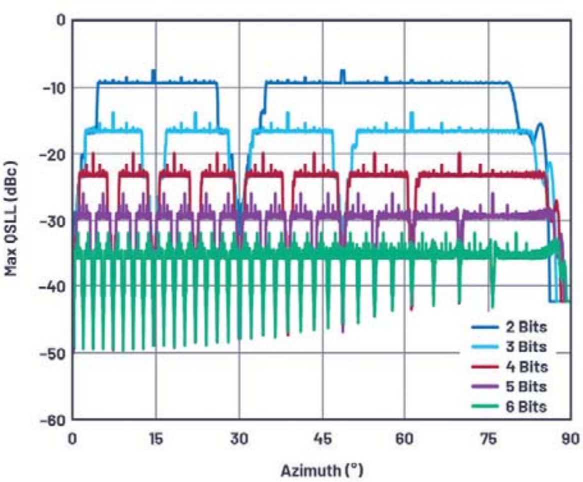
- Angular resolution requires a narrow beam. A narrow beam needs a large aperture, which requires many elements. Furthermore, the beam widens when steered off boresight, so extra elements are needed to maintain the beamwidth as scan angles increase.
- It may seem possible to increase the element spacing to expand the overall antenna area without adding extra elements. This would narrow the beam, but, unfortunately, introduces grating lobes if the elements are uniformly spaced. Reduction of scan angle, along with aperiodic arrays implementing an intentionally randomized ele-



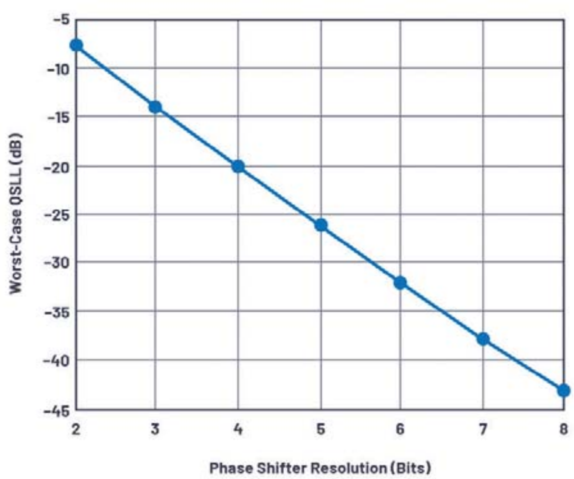
8. The worst-case quantization sidelobes occur when the maximum quantization error occurs across the aperture, when every other element is at zero error and the neighbor is at LSB/2. This condition is shown here for a 2-bit, 30-element case.



9. Here are worst-case antenna quantization sidelobes for: 2 bits, n = 1, 30 elements, and q = +14.5°. Note the substantial –7.5 dB quantization sidelobe at –50°.



10. This graph plots worst-case quantization sidelobes vs. beam angle for phase-shifter resolutions of 2 bits to 6 bits.



11. Shown are worst-case quantization sidelobe levels vs. phase-shifter resolutions of 2 bits to 8 bits.

ment pattern, can be explored to exploit increased antenna area while minimizing the grating-lobe issue.

- Sidelobes are another problem, which we learned can be mitigated by tapering the gain of the array toward the edges. However, tapering comes at the expense of widening the beam, again requiring more elements. Phase-shifter resolution can introduce quantization sidelobes that also must be factored into the antenna design. For antennas implemented with phase shifters, the beam-squint phenomenon causes an angular shift vs. frequency limiting the bandwidth available for a high angular resolution.

This concludes this six-part series on phased-array antenna patterns. We introduced beam pointing, array factor, and antenna gain, then explored imperfections of grating lobes and beam squint. Finally, we discussed tapering and quantization errors. The intention is aimed not for antenna design engineers fluent in electromagnetic and radiating element design, but rather the large number of engineers in adjacent disciplines working on phased arrays who may benefit from an intuitive explanation of the varied impacts affecting overall antenna pattern performance. mw

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