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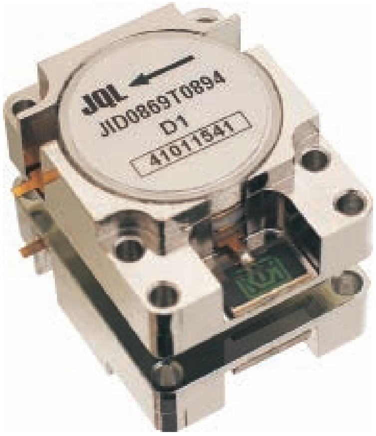

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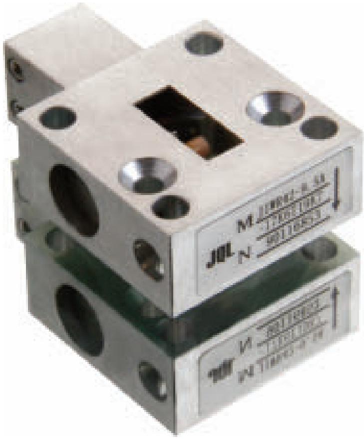

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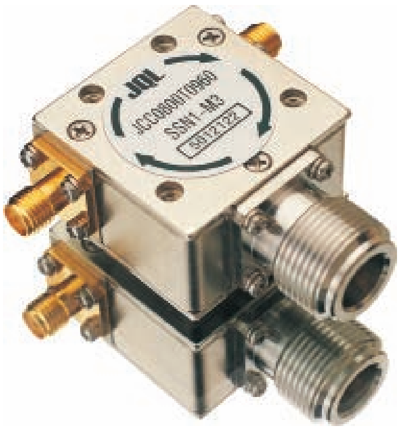

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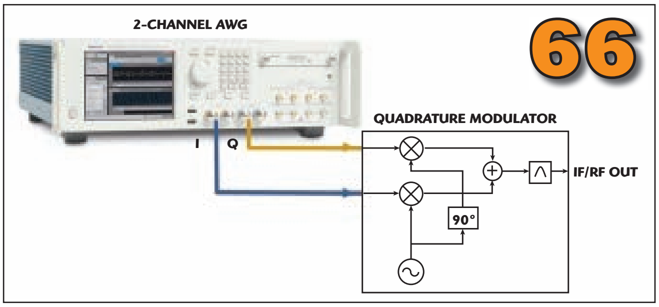

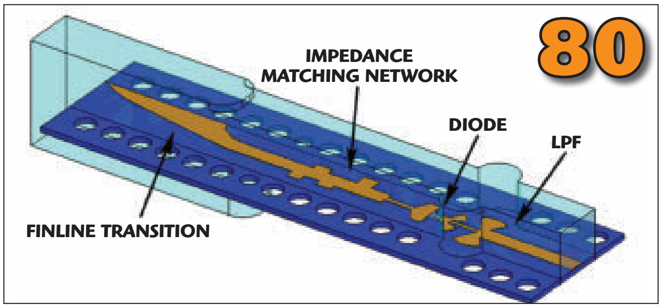

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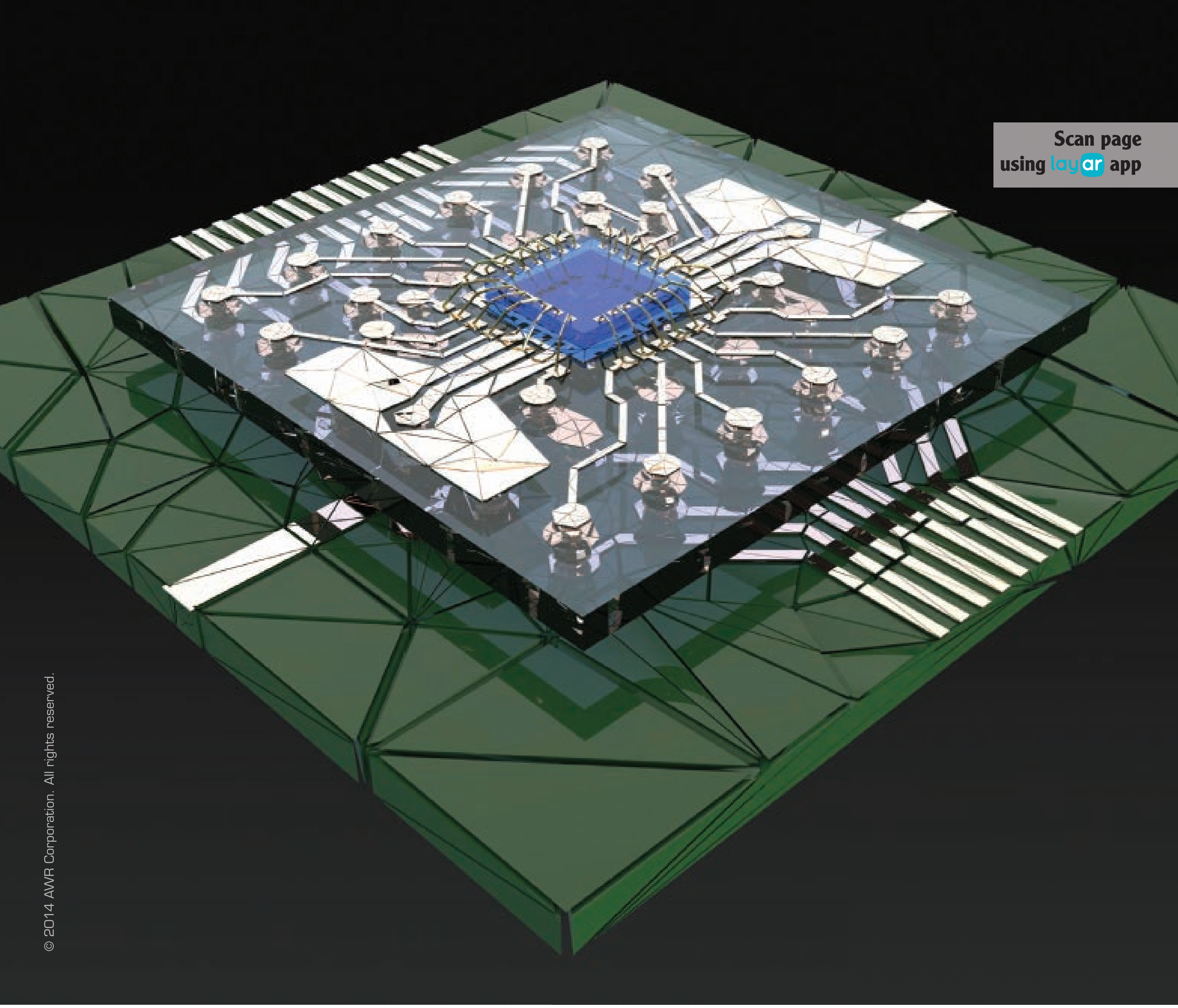
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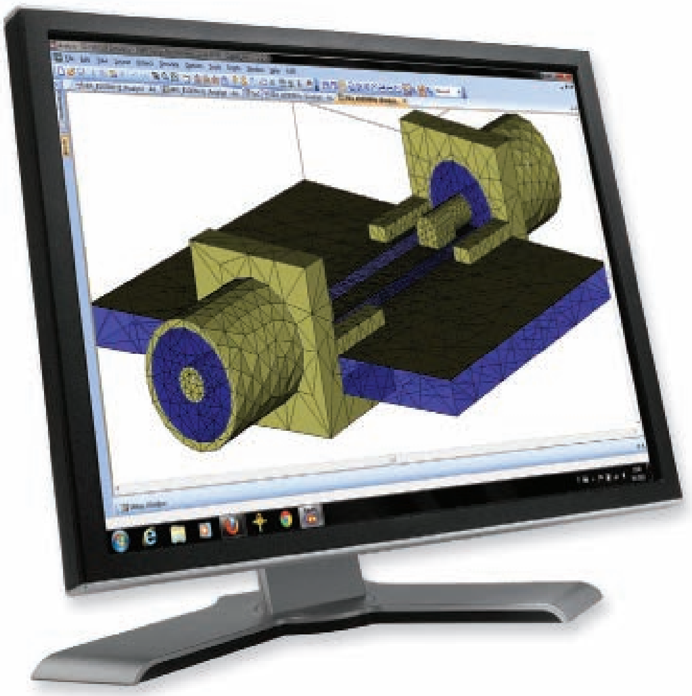

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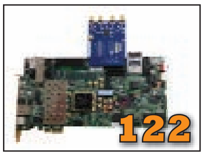

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Microwave Journal (USPS 396-250) (ISSN 0192-6225) is published monthly by Horizon House Publications Inc., 685 Canton St., Norwood, MA 02062. Periodicals postage paid at Norwood, MA 02062 and additional mailing offices.

POSTMASTER: Send address corrections to *Microwave Journal*, PO Box 3256, Northbrook, IL 60065-3256 or e-mail mwj@omeda.com. Subscription information: (847) 291-5216. This journal is issued without charge upon written request to qualified persons working in the RF & microwave industry. Other subscriptions are: domestic, $120.00 per year, two-year subscriptions, $185.00; foreign, $200.00 per year, two-year subscriptions, $370.00; back issues (if available) and single copies, $10.00 domestic and $20.00 foreign. Claims for missing issues must be filed within 90 days of date of issue for complimentary replacement.

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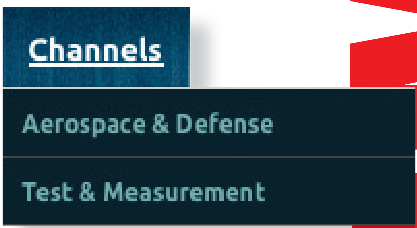

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Reality Bytes

CARL SHEFFRES
Microwave Journal Publisher

I have the distinct pleasure every January of informing our readers of the latest offerings from *Microwave Journal*. It's been a fun exercise, especially during recent years with the ever-evolving media landscape. There's much more to talk about these days, as we leverage the latest technologies to deliver your information on new platforms and in enhanced formats.

Two years ago, we announced the launch of our redesigned website. The new site organizes content by technology and products "channels," allowing users to better locate information relevant to their needs. The site also provides an archive of white papers, webinars, videos and a robust Buyer's Guide. We've just added a "Classifieds" section, where you'll find job postings and products for sale. If you haven't visited lately, I encourage you to do so.

Last year, we announced the MWJ Mobile App, which provides the latest issue of the magazine, archived issues, a news feed, executive interviews and blogs. Almost 5000 subscribers have downloaded the free app to date, with new users signing on daily. Recently, we launched a video series titled "Frequency Matters" in which MWJ editors David Vye and Pat Hindle discuss current articles in the magazine, the latest industry news and events. It's a quick and casual format that I hope you find informative and entertaining. 2013 also featured the debut of the Electronic Design Innovation Conference (EDI CON) in Beijing, China. This industry-driven event attracted nearly 2000 engineers in the growing Chinese RF/microwave industry with presentations from international and domestic experts and exhibition participation from many of the world's leading manufacturers. Lastly, our social media platforms continue to expand, especially the "RF and Microwave Community" on LinkedIn, which just surpassed 20,000 members.

I am really excited about this year's news and this issue in particular. I'm pleased to announce the first-ever "Augmented Reality" issue of MWJ. For those of you unfamiliar with the term, the basic idea of augmented reality is to superimpose graphics, audio, video and other sensory enhancements over a real-world environment in real time. A simple example might be the super-imposed first down line that appears on televised U.S. football games. A more complex example would be Google Glass, which will display augmented reality in a smartphone-like, hands-free environment. With *Microwave Journal*, this technology allows you to bridge the print world to the digital world like nothing before. By using the Layar App and your mobile device, you can scan the augmented pages and video and other rich media spring to life. It's really incredible stuff and very easy to access.

I hope that you enjoy this issue as much as we've enjoyed producing it for you. As always, I welcome your feedback.

On behalf of the entire MWJ team, we wish all of our readers a happy, healthy and prosperous New Year.

Check out the next two pages for the simple instructions on how to access and use the augmented content in this issue. You'll also find a snapshot of the advertisements and editorial that has been augmented. Or, you can scan this page to view a video of yours truly explaining the process.

Microwave Journal

Frequency Matters.

Microwave Journal unveils its first augmented reality issue. This issue showcases how mobile technologies can make printed pages interactive for an enhanced reader experience.

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ISSCC 2014
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SPACOMM 2014
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February 23–27, 2014 • Nice, France
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MWC 2014
Mobile World Congress
February 24–27, 2014 • Barcelona, Spain
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NATE UNITE 2014
Annual Conference for the National Association of Tower Erectors
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MARCH

ISQED 2014
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SATELLITE 2014
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DPC 2014
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March 10–13, 2014 • Fountain Hills, AZ
www.imaps.org/devicepackaging

TAEECE 2014
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March 18–20, 2014 • Kuala Lumpur, Malaysia
www.sdiwc.net/conferences/2014/taeece2014

Microwave & RF 2014
March 19–20, 2014 • Paris, France
www.microwave-rf.com

ACES 2014
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www.aces-society.org/conference/2014

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www.gomactech.net

APRIL

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MAY

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RTH26007-10	2610 ~ 2690	13	38.5	46.5	45	31 / 0.53

Cover Feature
Invited Paper

Next Generation Affordable Smart Antennas

J.R. Guerci, *Guerci Consulting LLC, Arlington, VA*
T. Driscoll, R. Hannigan, S. Ebadi and C. Tegreene, *Intellectual Ventures, Seattle, WA*
D.E. Smith, *Duke University, Durham, NC*

A confluence of advances in low cost digitally controllable RF metamaterial-based apertures and real-time embedded cognitive signal processing has afforded a new opportunity to realize a distinctly new and affordable low SWAP smart antenna capability for a multitude of demanding applications from communications to radar. This article provides an overview of these enabling advances, their synergistic combination, and the new markets that are emerging as a result.

MOTIVATION FOR NEXT-GEN SMART ANTENNAS

From wireless communications to RF sensing (radar, SIGINT), operating environments are becoming ever more challenging due to a multitude of factors from the "spectrum crunch" resulting from a global proliferation of wireless and RF sensing systems, to complex clutter and multipath/propagation backgrounds[2,3] (see ***Figure 1***). This emerging challenge is concurrent with continual demands for greater performance from end users. Consequently, there is a perennial need for systems that can adapt continuously to an ever changing transmission channel in an "intelligent" and sophisticated way.

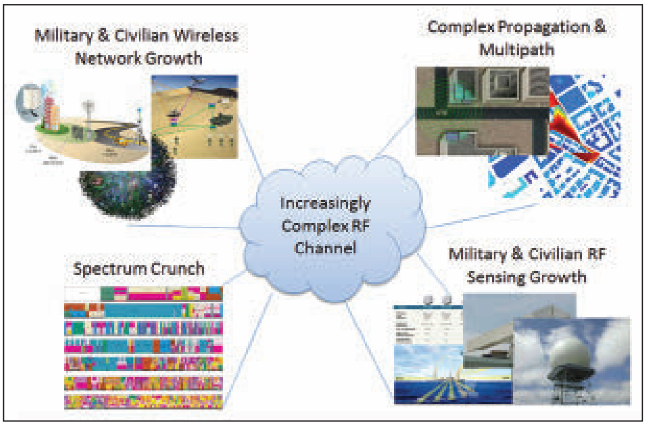


Fig. 1 A confluence of stressing factors is conspiring to create significant challenges to next generation RF systems.

Theoretically, one path forward is through real-time spatio-temporal adaptivity powered by flexible RF hardware and back-end cognitive signal processing.[4] While there has been steady and measureable progress in real-time software that powers cognitive software defined radios (SDR) and radar,[5,6] the analog hardware "in front of the analog-to-digital-converter (ADC)" has remained a stubborn challenge due to inherent physical and cost challenges.[7]

However, recent breakthroughs in affordable software defined apertures (SDA) enabled via new RF metamaterial designs are opening up both new levels of adaptive antenna affordability as well as performance and control. Though the functionality of the SDAs is similar to electronically scanned antennas (ESA), the former term can be used to reflect the significantly distinct architecture. In particular, the metamaterial SDA can be considered a dynam-

ically tuned but passive antenna, due to the absence of power amplifiers and distinct radio modules distributed throughout the aperture.

In this article, we provide an overview of the latest advances in new affordable ESA technologies, and the real-time cognitive signal processing that can take maximal advantage of the available adaptive degrees-of-freedom (DoF). Also discussed are the latest breakthroughs in RF metamaterials that are enabling an entirely new generation of affordable low size, weight, power and cost (SWaP-C) SDAs for a variety of applications. Then the state-of-the-art in cognitive signal processing and real-time embedded computing—the "smarts" behind smart antennas—is reviewed. Finally, it is all put together exploring the many problems to which next generation affordable smart antennas can be applied.

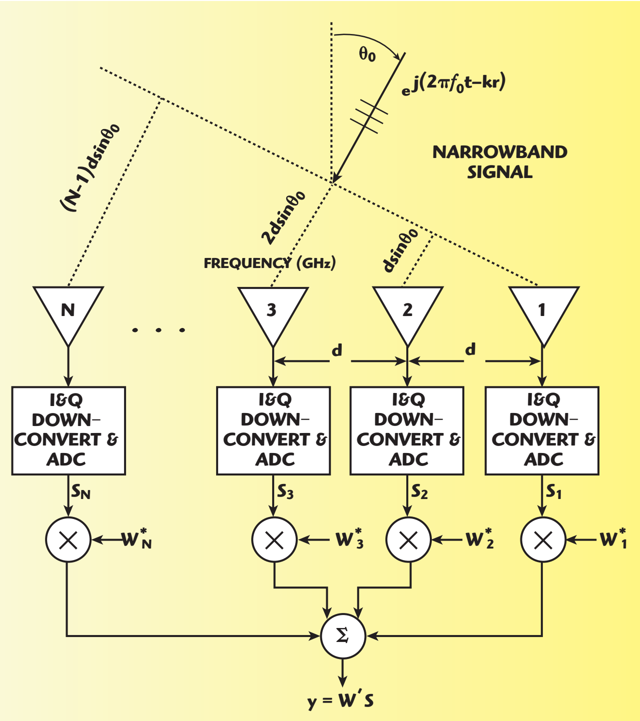
NEXT GENERATION LOW SWAP-C ESAs

Electronically scanned antennas have enabled countless RF applications where fixed beam and/or mechanically gimbaled apertures are not viable solutions. Interestingly, achieving electronic scan capability from the very beginning utilized phased array concepts,[8] which of course is just one way to achieve electronically controlled scanning. In a phased array (see ***Figure 2***), the constructive/destructive property of electromagnetic (EM) waves emanating from different subapertures is exploited to shape the composite antenna pattern. For a passive ESA, this is achieved by transmitting an identical waveform (possibly amplitude tapered for sidelobe control), emanating from a single high power source, from different subapertures with an appropriate phase shift (narrowband) or time delay (wideband) to achieve a desired beam shape.

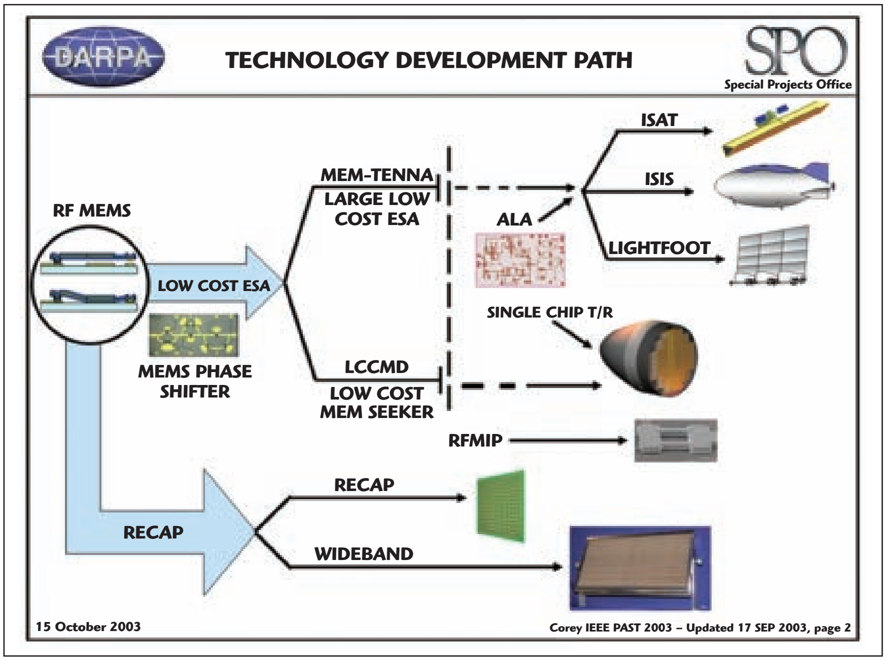
In an active ESA (AESA), each subaperture is capable of transmitting as well as receiving. Note that the physics of this approach, as well as numerous practical considerations and constraints, often results in a relatively large SWaP-C footprint. For example, if one desires a high gain mainbeam with low sidelobes, as well as adaptive beamforming to spatially filter interference, a generally complex ESA is required with a relatively large number of independent subapertures and channels.[1] Moreover, the full power of an ESA is only realized if it can be digitally controlled which, unfortunately, leads to the requirement for separate ADCs in each receive channel. Realizing that the number of channels tends to grow in proportion to the area of the antenna leads inexorably to an approach whose SWaP-C does not scale well as requirements grow.

Guerci has first-hand experience with the difficulties of achieving a low SWaP-C ESA. During his seven years with the Defense Advanced Research Projects Agency (DARPA), numerous advanced projects were executed precisely to achieve low SWaP-C antennas for everything from low cost cruise missile defense (LCCMD) to multi-function RF and MEMS based phase shifters (see ***Figure 3*** and reference 9). While these projects achieved modest success, in the end, it was mostly due to leveraging the major advances taking place in the commercial wireless RF sector.[9] The "DARPA-esque Holy Grail" of achieving an order of magnitude reduction in SWaP-C remained elusive.

In hindsight, the reasons are obvious: An ESA approach that is based



▲ *Fig. 2 Example of a modern digital phased array antenna (receive) illustrating the need for independent RF and digital channels (Courtesy of reference 1).*



▲ *Fig. 3 An excerpt from a presentation by Dr. Larry Corey (DARPA/SPO) overviewing the multipronged approach to achieve lower cost yet high performance ESAs (reference 9).*

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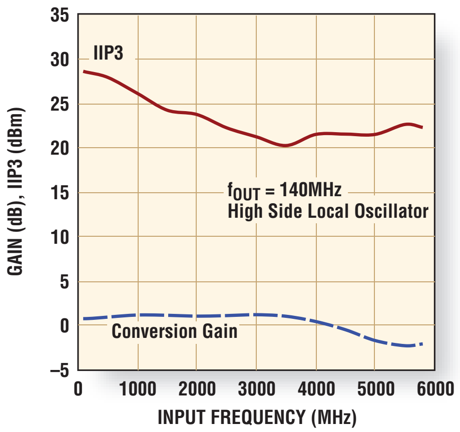

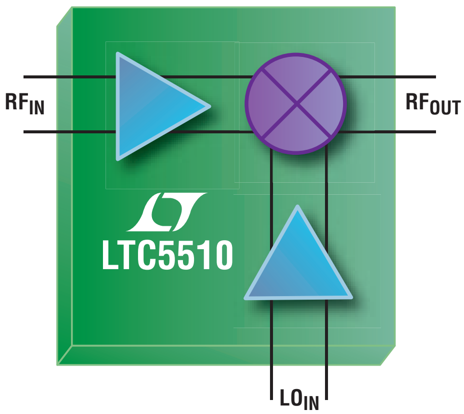

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	LTC5569	Dual +26.8dBm IIP3, Low Power Mixer		LTC5587	6GHz 40dB Dynamic Range RMS Detector + ADC
Amplifier	LTC6430-15	+50dBm OIP3 @240MHz, 15dB Gain Differential Amplifier	VGA	LTC6412	31dB Gain Control, Analog VGA with +35dBm OIP3
	LTC6431-15	+47dBm OIP3 @240MHz, 15dB Gain Single-Ended Amplifier		LT®5554	16dB Gain Control, 0.125dB/Step Digital VGA
ADC	LTC2158-14	Dual 14-Bit, 310Msps ADC	Oscillator	LTC6946	Low Phase Noise Integer-N PLL + VCO
	LTC2209	16-Bit, 160Msps ADC		LTC6945	Low Phase Noise Integer-N PLL

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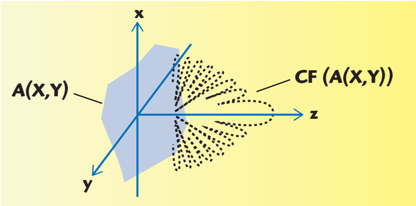


Fig. 4 Under fairly general conditions, the far field antenna pattern is proportional to the Fourier transform of the CF (•) aperture function A(x, y) (Fraunhofer approximation[10]).

on multiple independent RF channels can only be made so cheap and compact. Ironically, if one consults an elementary text on EM theory to determine how to achieve a desired antenna pattern from first principles, one finds a much more general solution than a phased array. Specifically, and without going into too much detail, the far field antenna pattern is the Fourier transform of the RF aperture distribution (see ***Figure 4***).[10] This naturally begs the question: "How can one digitally control the aperture distribution without the use of phased array approaches?" One answer, the use of RF metamaterials, has proven to be remarkably successful.

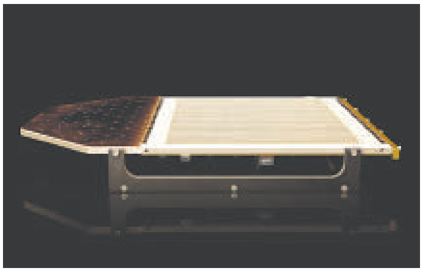


Fig. 5 Sample MSA-T ESA for satellite communication applications (see www.kymetacorp.com).

Beginning in the 1990s, researchers began to explore RF metamaterials that could exhibit properties not found in naturally occurring substances—such as so-called "negative refractive index" materials.[11] Of course, the usual "Hype Curve"[12] kicked in with exaggerated hopes and expectations. Within the past few years however, solid applications exploiting RF metamaterials have emerged and have even led to commercial product lines.

One particular application of metamaterials for SDAs that function as low SWaP-C ESAs is being developed by engineers and scientists at the Metamaterials Commercialization Center

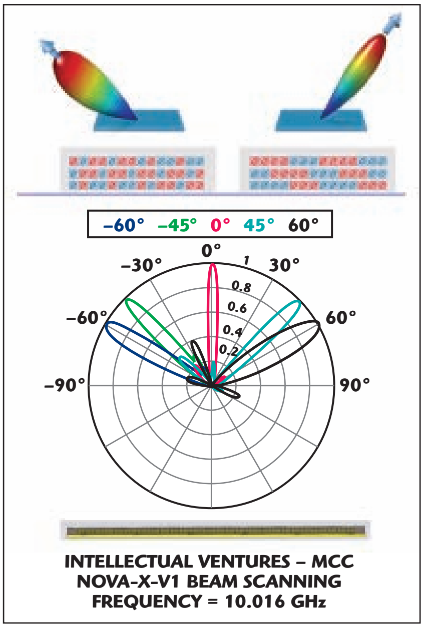


Fig. 6 Illustration of the RF metamaterial SDA. By judicious digitally controlled tuning of the resonant elements, an arbitrary steerable antenna beam (or beams) can be formed.

(MCC) that is a part of Intellectual Ventures (IV), working in cooperation with Duke University.[11] ***Figure 5*** shows an example of IV's metamaterials surface antenna technology (MSA-T) as applied to a commercial satellite communications application. Electronic scan capability (transmit or receive) is achieved by launching a wave across a surface with embedded RF resonant elements as shown in Figure 5. By a judicious selection of digitally controlled resonant elements, and spacings, any desired antenna pattern can be formed with the available DoF as shown in ***Figure 6***. It should be noted that this approach can be more efficient than so-called "leaky" waveguide approaches.[13]

Some of the key advantages of the MSA-T SDA approach include:

- Eliminates the need for multiple independent RF channels and associated phase shifters or time delay units (TDU) (i.e., it is not a phased array approach).
- Large electronic scan angles (±60°) are possible (see Figure 6), unlike traditional leaky wave antennas.
- Can be synthesized using conventional printed circuit board (PCB) manufacturing methods (see Figure 5).
- Additional adaptive DoFs can be introduced without introducing more RF channels (just more low power digital control lines and resonant elements).

TABLE I

MAPPING OF BIOLOGICAL COGNITIVE PROPERTIES TO A COGNITIVE RF SYSTEM (COMMS/RADAR/ETC.)

Cognitive Property	*Cognitive RF Equivalent*
Perceiving	Sensing (onboard/offboard, networked)
Thinking, reasoning, judging, problem solving	Expert systems, rule-based reasoning, knowledge-aided (KA) processing, adaptive algorithms and computation
Remembering	Memory, environmental and systems databases, cloud resources

- Inherently low physical volume and, especially, low profile (e.g., a few mm thick).
- Inherently low cost due to aforementioned architecture and PCB compatibility.
- Can realize radiation efficiencies comparable to parabolic dish and other conventional antennas.
- Enables the potential for delivering a true conformal aperture that performs just as effectively as a planar aperture (to within projected aperture constraints).

A "digitally" controllable, adaptive and flexible aperture is certainly a necessary prerequisite for a smart antenna—but not sufficient. Next we survey the latest advances in the back-end signal processing that is the "brains" of smart antennas.

NEXT GENERATION INTELLIGENT SIGNAL PROCESSING

The original term "smart antenna," as coined by Winters,[14] referred to spatial diversity and adaptive beamforming. Of course the "smarts" were achieved via real-time adaptive digital signal processing (DSP). In the past 10 years or so, even more sophisticated real-time adaptive processing has been developed that from an "input-output" perspective exhibits a very high degree of machine intelligence and environmental awareness. It has thus become necessary to develop newer nomenclature such as "cognitive processing" (e.g., cognitive radios,[15] cognitive radar,[5,16] etc.) to make clear the significant advancements that have been achieved.

A definition of cognition that has surprising engineering applicability is afforded by the National Institute of Health (NIH):[17]

Cognition: Conscious mental activity that informs a person about his or her environment. Cognitive actions include perceiving, thinking, reasoning, judging, problem solving and remembering.

If we replace "person" with "system," and "his or her" with "its," we can readily map the above attributes into those associated with machine intelligence as in ***Table 1***.[5] The goal of any intelligent RF system is to optimize system performance based on ever changing knowledge of the RF channel and user demands. In general, the biggest challenge is real-time channel knowledge due to the extreme nonstationary and complex nature of a realistic RF channel due to highly complex multipath scattering and terrain interaction, as well as highly chaotic electromagnetic interference (EMI).

The importance of knowing the RF channel is easily illustrated with a relatively simple signal-to-interference-plus-noise ratio (SINR) optimization problem. ***Figure 7*** shows that a simple forward RF channel model consists of an N-dimensional complex valued transmit signal $\mathbf{S} \in C^N$, a signal-to-receiver multi-input, multi-output (MIMO) stochastic transfer function represented by $\tilde{H} \in C^{N\times N}$ (which in the case of radar includes a target transfer function), and additive interference $\tilde{\mathbf{n}} \in C^N$ with associated covariance $R \in C^{N\times N}$. The goal of the receiver, represented by $\mathbf{w} \in C^N$, is to (for example) maximize the output SINR. Details of the solution can be found in reference 5, which are stated here:

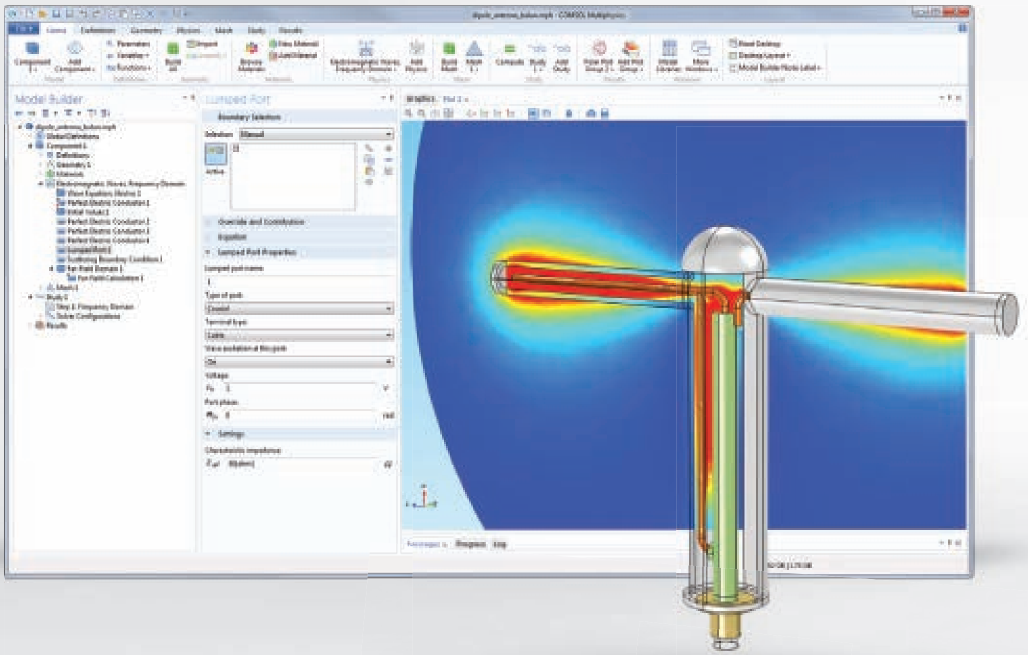
$$\left(H_+^{'}H_+\right)S_{opt} = \lambda_{max} S_{opt}$$

Optimum Transit Solution (1)

$$w_{opt} = R^{-1}(Hs)$$

Optimum Receiver Solution (2)

where $H_+ = H_w H$, and H_w is the "whitening filter" ($H_w = R^{-1/2}$).[18] The key take away from these two fun-



damental equations is the need for knowledge of the channel propagation and interference. How does one get this knowledge in a rapidly varying environment and act on it in real time? This is indeed the raison d'être for cognitive RF systems.

INTELLIGENT CHANNEL ESTIMATION

In both wireless communications and radar, there are two fundamental contributors to the time-varying channel parameters: (1) Propagation; and (2) Co-Channel Interference. Traditionally, relatively simple adaptive signal processing techniques, coupled with basic statistical models, were employed to estimate both (1) and (2). Suffice to say these approaches have run their course—hence the emergence of so-called cognitive radio/radar. There is now a variety of new "intelligent" signal processing methods emerging for both propagation and interference channel estimation. We will highlight some of the more advanced techniques.

What if a radio knew ahead of time that it was about to hit a significant fade? Or conversely be blasted by a co-channel interferer? Or if it knew that steering its antenna pattern 20° to the left would result in a 10 dB improvement in SINR? In many applications, events like this can be the result of complex terrain/multipath interactions. In principle, if a radio knew its precise location and had accurate 3D knowledge of its surroundings and possibly relevant meteorological data, it could "calculate" the propagation channel and thus predict a multitude of important effects. To do this in practice, however, the radio would need to perform complex electromagnetic ray tracing and wave propagation calculations, and have access to digital terrain databases, etc. Additionally, if propagation measurements were routinely performed and stored, then over time a historical database could be created and likewise utilized to predict performance. Why not combine both these approaches?

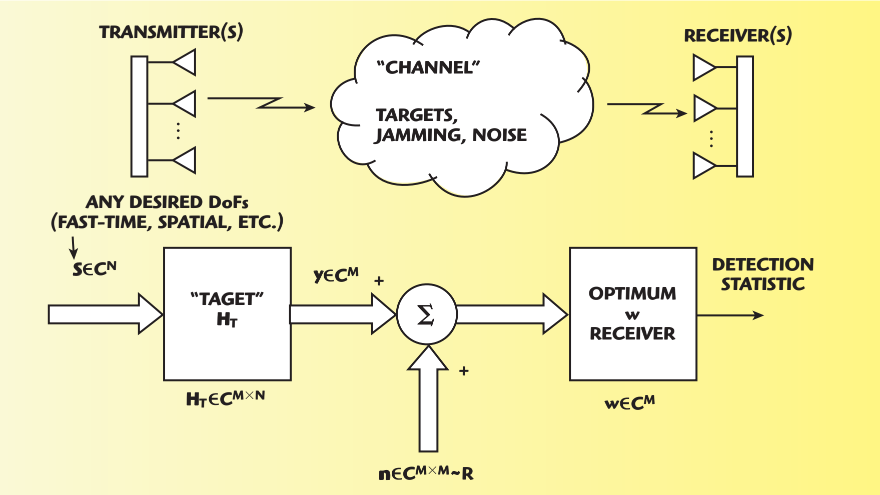


Fig. 7 Example of a MIMO forward path problem where it is desired to jointly optimize both the transmit and receive functions to maximize SINR.

In the early 2000s, DARPA started a major project to do just that for radar. Dubbed the KASSPER project (Knowledge-Aided Sensor Signal Processing and Expert Reasoning),[19] the goal was to achieve an order-of-magnitude or better detection performance improvement in a challenging ground moving target indicator (GMTI) application (a good example of a major GMTI radar is the U.S. Air Force's JSTARS[20]). Though there are many intricate details, the crux of the KASSPER concept can be illustrated with a relatively simple mathematical example.

One of the specific key goals of KASSPER was to achieve significantly better clutter cancellation performance. In particular, improvement was sought in the space-time adaptive processing (STAP) filter.[1] Without belaboring the details, a STAP filter is essentially an adaptive multichannel finite impulse response (FIR) filter whose optimum weights ("taps")

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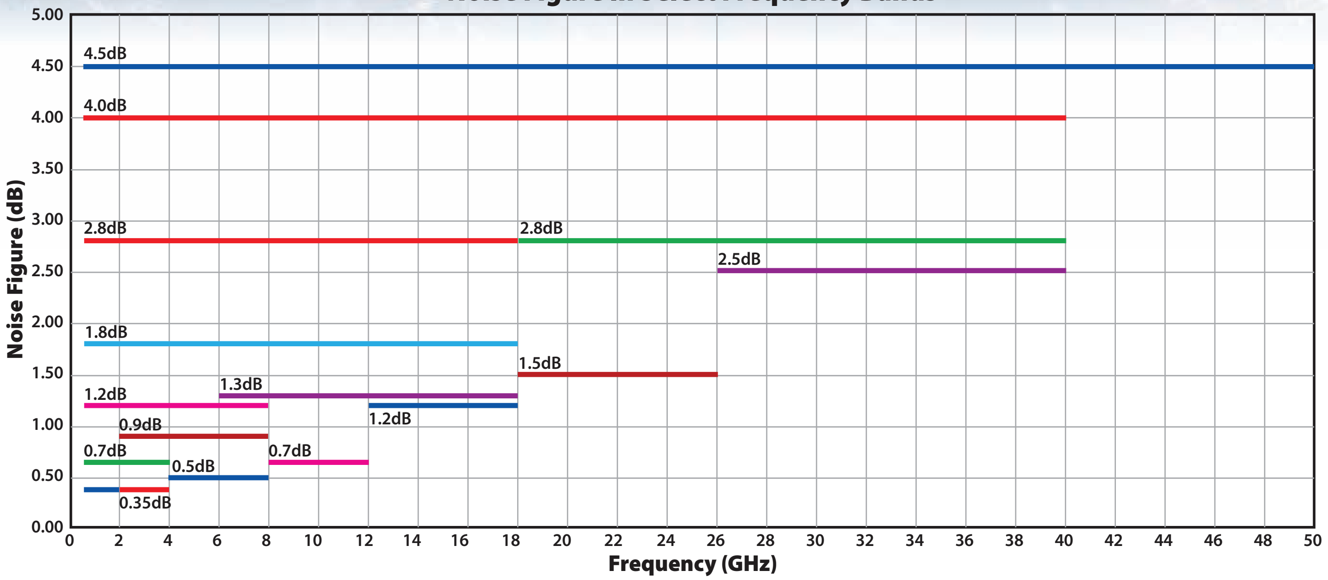

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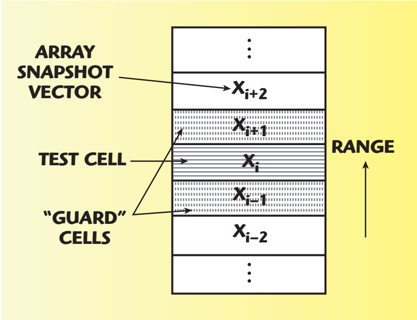
$\mathbf{w} \in C^N$ obey the well-known Wiener-Hopf equation:[1]

$$\mathbf{w} = R^{-1}\mathbf{s} \tag{3}$$

where $R \in C^{N \times N}$ is the interfering clutter plus noise covariance matrix, and $\mathbf{S} \in C^N$ is the desired target ("steering vector") of interest (i.e., direction, Doppler, etc.). In STAP applications, the dimensionality of R can be relatively large, and thus require a lot of training data to estimate. For example, a bedrock of STAP is the so-called maximum likelihood estimate (MLE) which substitutes an estimate of R in the filter equation, denoted as $\hat{R}_{MLE}$, given by

$$\hat{R}_{MLE} = \frac{1}{K}\sum_{k=1}^{k} X_i X_i' \tag{4}$$

where the K samples $\{\mathbf{X}_i \in C^N\}$ correspond, for example, to the space-time signals received by the radar over K range bins[1]. An illustration



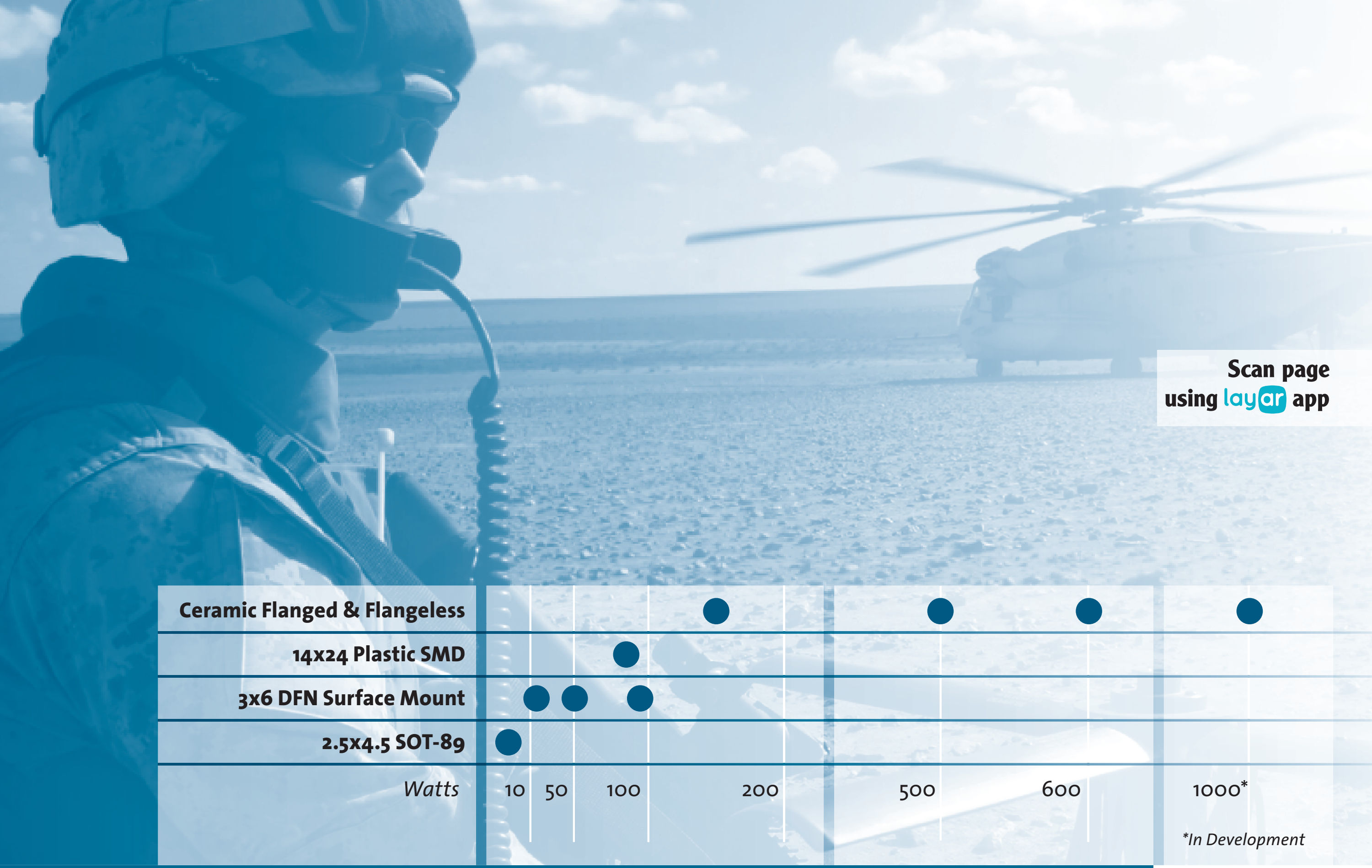
▲ *Fig. 8 Illustration of a popular training strategy for computing the requisite statistics in STAP applications (Courtesy of reference 1).*

of this training approach is shown in ***Figure 8***. If one is fortunate enough to be operating over homogenous clutter terrain, than the "stationarity" assumption implicit in this sample matrix approach works very well, and near optimal clutter cancellation performance is achievable. Of course in the real world, radars can be operating in extremely complex clutter terrains, such as urban settings resulting in very suboptimal performance that has been well documented in the literature.[1,21] How did the KASSPER project remedy this with cognitive signal processing?

The approach that resulted in the best overall performance averaged over a number of different scenarios had a structure in the form of:

$$\hat{R} = \hat{R}_{MLE} + \hat{R}_{KA} \tag{5}$$

where $\hat{R}_{MLE}$ is as before but with far fewer training samples that are much closer to the range bin of interest—and thus very representative of the actual clutter, and $\hat{R}_{KA}$ is the knowledge-aided (KA) estimate of the clutter covariance obtained from a variety of model-based and cognitive signal processing techniques. In some variants, it has a very similar mathematical form as the MLE estimator, but instead of using measured range samples, synthetic samples were generated using either ray tracing or synthetic aperture radar (SAR) images of the region of interest. The former is an example of the model-based ray tracing approach while the latter is an example of the database approach where the SAR image acts as the "database."[5] Thus the best overall intelligent signal processing approach was a blend of "live" data, model based predictions and historical databases—hard to argue with. Indeed without getting too



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philosophical, it's a lot like the way we interact with the world—prior experience, problem solving and learning, hence the term cognitive.

This is all well and good but the astute reader is by now no doubt wondering about the potentially daunting computational burden associated with this approach for real-time applications. Indeed, when the KASSPER project was started over 10 years ago, it was the challenge of trying to implement these ideas in a high performance embedded computer (HPEC) that was the true crux of the project. This was before the advances in FPGAs, ASICs and multi-core GPUs for embedded applications over the past decade, that have greatly expanded the range of cognitive techniques that can be implemented in real-time.[5] Nonetheless, the non-device specific techniques developed under KASSPER for achieving real-time performance are still very applicable and often still necessary. We will briefly discuss two of the methods developed under KASSPER.

The first method for reducing real-time KA processing is simply prioritization based on relatively simple knowledge and ownship kinematic knowledge. For example, if a radar knows where it will be located, say, a few seconds into the future (if it doesn't, it has far bigger problems), it can perform a "look-ahead" function in parallel with the real-time processing and search the terrain database for "troubled" spots. In the case of GMTI radar, these might be regions of complex terrain, land-sea interfaces, or very large reflectors (known as "discretes"). Not all "inhomogeneities" have the same deleterious impact on performance. Thus a natural rank ordering of the trouble spots emerges. This can then be subjected to a resource allocation function that decides how to best use onboard computational resources. Keep in mind that this is all happening "in the future," i.e., in a predictive mode. The radar has not yet encountered the next scene—but it can easily anticipate it a few seconds into the future, often even longer. This look-ahead approach is also essential when interacting with onboard databases that reside in memory. There is simply no way for a highly vectorized real-time processor to interact with slower memory and keep up. An analogous prioritization scheme is easily developed for a variety of non-radar applications such as wireless mobile communications where, for example, prior knowledge of impending channel changes can be used to again optimize resources and performance.

The second method developed under KASSPER for achieving real-time KA processing was to perform the necessary calculations BEFORE the radar returns arrive. This was again achieved using the aforementioned look-ahead approach, but it also utilized the radar resource scheduler to obtain critical and necessary information such as what operating frequency, waveform/bandwidth, polarization, scan angle and patterns will be used in the future. With this information, the aforementioned synthetic KA covariances could be calculated and literally "appended" to the actual real-time data stream.[1,5] Thus in short, the seemingly insurmountable obstacles associated with performing KA and cognitive functions were overcome with prior knowledge,

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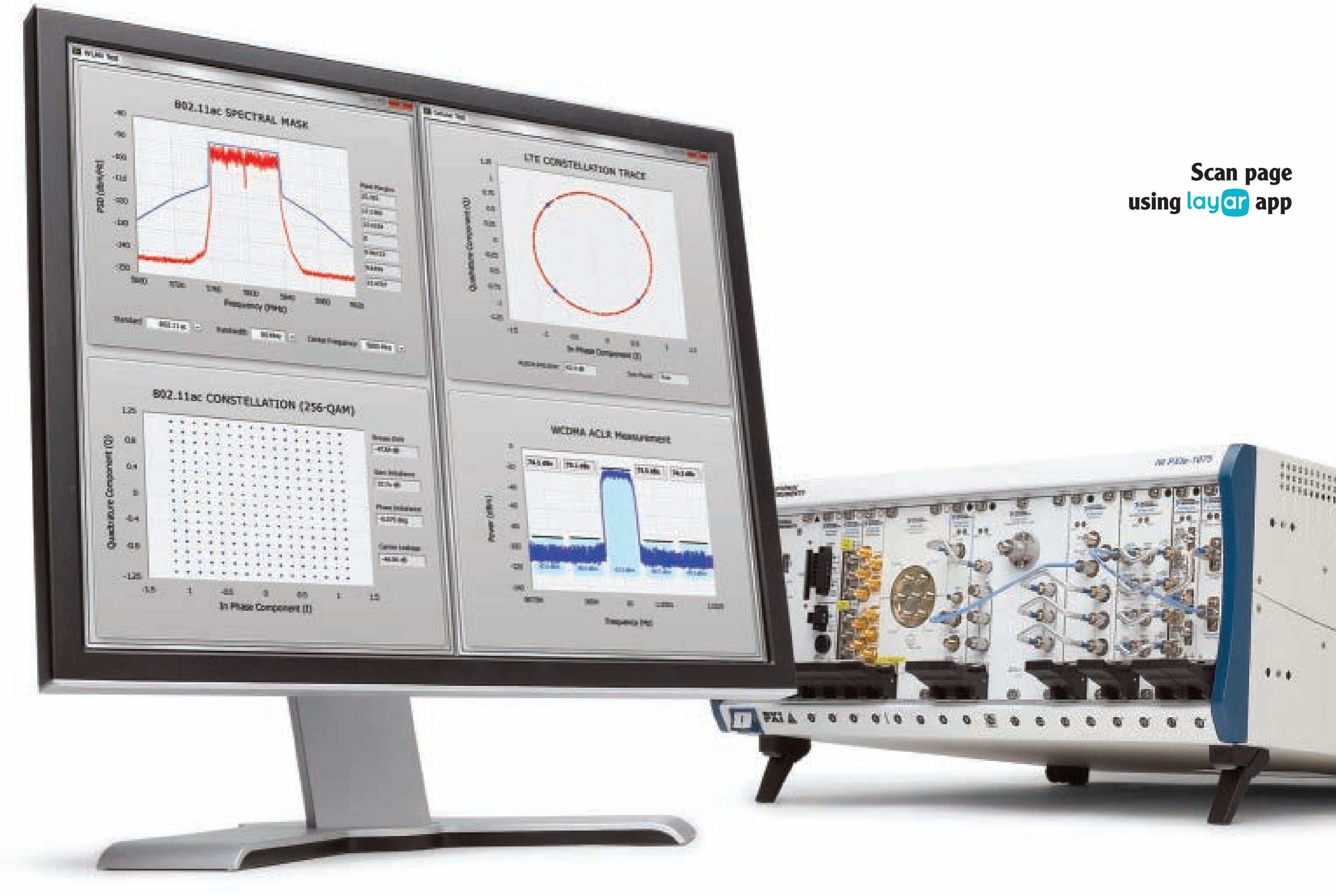

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physics calculations and ownship resource scheduler knowledge.[5]

A third method for achieving real-time KA/cognitive capabilities had nothing to do with KASSPER. It is simply the result of the advances achieved in the past decade with embedded ASICs, FPGAs, multi-core CPUs and especially general purpose GPUs. Indeed it is rather ironic that the "real-time" graphical rendering and ray tracing requirements of video games has ushered in entirely new ways to perform real-time sensor and communication signal processing exploiting the very same types of calculations. Thus from an algorithmic/software and real-time hardware stance, the technical excuse is "off the table." It is now absolutely possible to implement truly "intelligent" real-time sensor/comms signal processing that knows where it is in relation to its environment, has access to a plurality of knowledge and modeling sources, and can act on the knowledge in a way that for all intents and purposes mimics cognitive abilities.

PUTTING IT ALL TOGETHER: THE PATH AHEAD

While cognitive RF systems have been successfully demonstrated with high-end adaptive antenna systems (e.g., the DARPA KASSPER project), it is now possible to leverage these techniques and advances in low SWaP-C HPEC and SDAs and apply them to a whole range of heretofore cost and SWaP prohibitive applications. For example, UAVs are inherently SWaP-C limited due to both their relatively small size and need to maximize their operational flight envelope (speed, altitude, range). Nonetheless, there are countless missions and demands that UAVs are poised to fulfill if only they could maximize their payload effectiveness in a cost effective way. For example, there is great interest in outfitting UAVs with GMTI radars. While large UAVs such as the Predator and Global Hawk can support reasonably powerful systems with conventional AESAs, the vast majority of smaller UAVs must settle for far less powerful and capable radars. Indeed due to the relatively high SWaP-C nature of AESAs, static or mechanically steered antennas are often utilized which lack the necessary DoFs to fully exploit cognitive signal processing. Fortunately, with maturation of the aforementioned metamaterial SDAs, it now appears that technical obstacle has been removed. Moreover, even larger UAVs may want to take a second look at replacing their AESAs with metamaterial ESAs—SWaP-C is still very much a major concern no matter what the class of UAV (see ***Figure 9***).

As mentioned at the beginning of this article, the term "smart antenna" originally referred to ESAs (or multi-antenna) wireless communication sys-

Fig. 9 UAVs represent one of the most demanding and growing applications for a multitude of low SWaP-C electronically scanned antennas.

tems. However, over the years, only a modest rollout of AESAs for communications has been achieved again due to their inherently high SWaP-C nature. Here again is another opportunity to re-visit a multitude of wireless applications armed with next gen low SWaP-C powered by state-of-the-art embedded cognitive processing.

Lastly, but by no means least, RF spacecraft payloads represent a major class of severely SWaP-C constrained applications. Every pound of payload costs $10,000 to boost into low Earth orbit (LEO), and every cubic foot takes up precious space in the rocket faring.[21] Extremely low SWaP-C ESAs powered by onboard intelligent embedded processing open up entirely new application possibilities from remote sensing, surveillance and satellite communications.

In summary, a confluence of advances in low SWaP-C digitally controllable SDAs and real-time embedded cognitive signal processing has afforded a new opportunity to realize a distinctly new affordable smart antenna capability for a multitude of demanding RF applications from communications to radar. The sky's the limit—or perhaps even beyond! ■

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Phased Array Radar
At the Intersection of Military and Commercial Innovation

Glen Fields, Director, Aerospace and Defense, MACOM, Lowell, MA

Accelerating innovation in phased array radar design and manufacturing is transforming our military radar infrastructure, enabling the achievement of unprecedented size weight and power (SWaP) profiles that in turn facilitate greater radar system accuracy, mobility and deployment flexibility for an ever widening range of ground-based, airborne and seaborne applications. This has enhanced the military's ability to equip existing ships, aircraft and vehicles with new high-performance, ultra compact radar systems while introducing new multi-function radar capabilities for a new generation of radar systems and a new era of deployment modes.

As phased array radar technology becomes ubiquitous for defense applications – driven by the military's significant and sustained investment in this field – the associated innovation has naturally flowed into the commercial domain, where today it's being adopted for applications spanning weather tracking to perimeter protection to air traffic control and beyond. This growing adoption of phased array radar for civilian applications has in turn yielded commercial-scale cost and component manufacturing efficiencies that are – in full circle – flowing into the military domain, where increasing reliance on COTS radar components and commercial manufacturing techniques is promoting leaner cost structures and eliminating cumbersome 'chip and wire' assembly approaches. This convergence of military and commercial innovation and best practices is driving greater SWaP optimization and cost efficiencies across both of these domains, unlocking the full potential of phased array radar technology.

WEATHER AND SAFETY APPLICATIONS AT THE FOREFRONT

The early adoption of phased array radar for non-military uses has been most prominent in weather and safety applications, particularly early warning detection of severe impending weather. New X-Band radar systems, networked across multiple nodes, are providing greater understanding of weather patterns like hurricanes and wildfires in real-time as they develop.

New weather radar initiatives such as the Collaborative Adaptive Sensing of the Atmosphere (CASA) Weather Radar Program – a multi-sector partnership among academia, industry and government – are emerging to better protect people and property and mitigate damage through improved weather sensing. X-Band radar networks developed via the CASA program detect the region of the lower atmosphere currently below conventional radar range, providing the ability to map storms, wind, rain,

temperature, humidity and the flow of airborne hazards.

The development of the Multi-function Phased Array Radar (MPAR) panel, a dual-polarized S-Band system, is an example of defense-caliber phased array radar technology applied to weather tracking and air traffic control applications simultaneously. MPAR panels were co-developed by MACOM and the Massachusetts Institute of Technology Lincoln Laboratory under sponsorship from the Federal Aviation Administration (FAA) as a next generation alternative to the existing civil radar network currently supplying air traffic and weather surveillance. MPAR panels consolidate eight separate radar systems that currently perform four unique missions – terminal air surveillance, en-route air surveillance, weather radar and terminal Doppler radar. This enables increased resolution and faster operation, providing improved data for weather forecasting together with advanced air traffic control capabilities. An MPAR system is constructed of multiple MPAR panels functioning in concert to radiate and receive pulses of radar energy used to detect, locate and track aircraft and weather features.

Other safety-driven applications of phased array radar for non-military purposes include radar-assisted search and rescue operations for disaster victims, including those trapped under rubble or underground by earthquake or landslide conditions. This capability requires high frequency radar to detect movement, which opens the door to additional non-weather-related safety applications like perimeter security and border protection.

FROM AIRBORNE TO UNDERGROUND

Another prominent example of phased array radar technology applied to commercial interests is the recent effort to begin transmitting high-speed Internet/voice data between airborne aircraft and ground stations via Ku-Band active phased array antenna or communication AESA, bringing broadband Internet access to in-flight passengers. Qualcomm has proposed an air-to-ground backhaul communication system of this nature, and has submitted a plan to the FCC that would leverage the 14 to 14.5 GHz band and a network of 150 ground stations to move this initiative forward.

At the infrastructure level, this would shift in-flight Internet traffic from satellite-based networks to terrestrial-based systems, which could potentially introduce significant cost efficiencies. This proposed system would boost current in-flight Internet capacity from 10 to 300 Gbps, enabling video streaming, gaming and other rich multimedia access for planes at altitudes of several miles.

The combination of ground penetration and range sensing capabilities enabled by phased array radar systems have shown considerable promise for the energy and mining sectors. Radar-assisted range sensing can be used to monitor and gauge fluid levels in underground pipelines and aboveground oil tanks. It can also be employed for mine exploration and mineral detection applications.

MILITARY AND COMMERCIAL CONVERGE

Just as the commercial domain is leveraging the military's heavy investment in phased array radar technology to drive innovation and cost-efficiencies for civilian applications, the military is increasingly adopting commercial design and manufacturing best practices to achieve cost and process efficiencies of its own. Consider, for example, the X-Band Core Chip designed by MACOM and FIRST RF Corp. for the common leg circuit in CASA-optimized radar systems. This integrated, surface mount solution enables high-yield automated assembly, smaller footprint design and improved reliability. The plastic packaged, 7 × 7 mm X-Band Core Chip for the 8 to 11 GHz range integrates a CMOS logic driver with a GaAs Transmit/Receive (T/R) MMIC within a single QFN package. The ability to offer a full SMT solution for demanding X-Band phased array radar applications combines the best of military radar innovation and high volume commercial manufacturing expertise in a bi-directional value proposition.

MACOM's work on the aforementioned MPAR program is another example of the use of commercial manufacturing practices for a technically demanding radar architecture originally developed for military purposes. In addition to meeting the exacting technical demands, the MPAR design team needed to achieve an order of magnitude or more reduction in cost compared to earlier military-class phased array radar systems. To meet these challenges, MACOM designed and manufactured highly integrated MMICs that would minimize total part count and simplify manufacturing and assembly, and packaged these MMICs in industry-standard surface mount plastic packages. This effort also included the design and manufacturing of PCB T/R modules to facilitate automated assembly and test, and a PCB-based line replaceable unit (LRU) which forms the fundamental RF building block for the system.

For phased array radar system OEMs, the convergence of military radar innovation and commercial cost efficiencies better enables them to serve both markets simultaneously with generic products assembled at high-volume via a common manufacturing platform, enabling significant cost savings. These OEMs must ruggedize their commercial products for use in high-reliability military applications if they are to effectively cross-purpose their product lines, and this ultimately relieves some of the high-reliability testing and screening burden that drives up costs for military systems – further promoting cost efficiencies for both domains.

The cross-domain flow of military investment and commercial best practices is lowering development and manufacturing costs for phased array radar systems while unlocking new application opportunities. Leveraging the volumes of both the commercial and defense applications will produce economies of scale further enhancing the cost equation. The continued erosion of cost barriers on both sides of the customer/supplier equation will ultimately accelerate the pace of innovation and adoption for phased array radar into the future. ■

Semiconductor Technology Drives the EDI CON 2014 Technical Program

David Vye, Microwave Journal *Editor*

The dust has settled on the final rush for turning in materials before the submission deadline for the peer-reviewed technical program at EDI CON 2014, to be held this April in Beijing, China. With an emphasis on high frequency and high-speed electronic design, this year's crop of papers reflects many industry trends that define the state-of-the-art in RF, microwave and high-speed digital design, measurement, simulation and components. The focus of this industry-driven event is to educate attendees on the latest techniques, tools and devices available to help engineers achieve their goals, whether that is to optimize their amplifier's linearity and efficiency, improve the dynamic range of their receiver chain or address any number of electronic design challenges. In addition, the conference will examine evolving technology in the context of those communication systems driving development and investment.

China's size and rapid economic growth left little doubt that it would become the world's largest mobile market. Despite a downturn in the Chinese mobile infrastructure in the first half of 2013, Infonetics Research reported a strong overall market for hardware thanks to China Mobile's massive TD-LTE rollout of 20,000 base stations and the Chinese government's awarding of 4G licenses. As elsewhere, high-speed data is driving the growth of the mobile business and radio spectrum is a finite resource in great demand. As a result, several talks in the system track will consider spectrum management and radio monitoring, addressing topics such as opportunistic spectrum access, interference control and mitigation techniques, and spectrum efficiency. Experts will discuss detection, location and analysis of radio signals, signal intelligence and analysis, receivers and antenna technologies. Further LTE related topics will include carrier aggregation, CoMP, MIMO and over-the-air testing.

In addition to system level testing, papers submitted to the measurement and modeling track cover a range of topics specific to device and material characterization and design verification as well as the test and simulation techniques that ensure accurate results. Device modeling via measurement or EM simulation is a critical part of the design process and experts from leading test equipment and software vendors will cover a host of these modeling challenges from characterizing device nonlinear behavior to studying materials in the free-space mm-wave and THz-regions.

Integrated circuits and semiconductor technology are critical to the overall performance of electronic systems, whether the application is for mobile communications, radar or satellite navigation. The design track reflects the industry's focus on recent advances in design technology with an emphasis on specific components such as filters and power amplifiers. Doherty and class F PA architectures along with techniques such as digital pre-distortion and envelope tracking that are garnering so much industry attention at the moment will be among the hot topics presented in the field of power amplifier design. Presentations focused on semiconductor devices from GaN, CMOS and RF SOI technologies were equally popular among submitting authors. Related papers will look at thermal heat-sinking materials and techniques in support of high-power transistors. In addition to talks on amplifier technology, submitted design papers focus on filters, antennas, sources (VCOs/PLLs), receivers and data converters.

Success as an engineer requires ongoing skill development throughout one's career. The Journal supports this effort with our publication each month and we are pleased to once again help organize an event where working engineers can learn from experts and share their knowledge with colleagues face to face. The papers submitted to each of the four main EDI CON technical tracks (Design, Measurement/Modeling, System Engineering and Commercial Resources) are a faithful representation of the design methods, semiconductor technology and engineering tools that defines where we are in 2014 and establishes our foundation on which to build the future. ■

Smart Weapons Market Worth $5335.1M

According to ASDReports, the global smart weapons market is valued at $3621 million in 2013 and is expected to register a CAGR of 8.06 percent to reach $5335.1 million by 2018. The cumulative market across the forecasted period is estimated to be $26.73 billion.

U.S. is the most attractive market for smart weapons. It is a matured market with most of the market leaders situated in this country. The U.S. smart weapons market is valued at $1593.3 million in 2013 and is expected to register a CAGR of 2.6 percent to reach $1817.5 million by 2018. The second-largest market is the Middle East, where the market is expected to increase from $350.9 million in 2013 to $712.1 million in 2018.

Recent conflicts across the globe have emphasized the need for precision attacks and stand-off surgical strikes. There is an imperative need to avoid collateral damage and at the same time provide combatant commanders with a weapons capability that could create an immediate positive effect on the battlefield. These needs are met by smart weapons that are increasingly being added to the inventory of the armed forces. Given the need for such systems, the demand is expected to increase during and after the period under study.

Recent conflicts across the globe have emphasized the need for precision attacks and stand-off surgical strikes.

Smart weapons range from precision-guided artillery rounds and precision-guided bombs to precision-guided stand-off missiles. Anti-armor weapons comprise of anti-tank and anti-structure missiles. Lately, multi-mission capable missiles, which could be used in a variety of operations, are widely developed and produced, thus reducing logistics and providing single, easy-to-use solutions for a variety of missions. Guided munitions are bombs that are fitted with any one of the following guidance systems: inertial navigation system, global positioning system, laser beam guidance, terrain mapping, radar guidance, infrared imaging and video guidance systems.

These guidance systems can be used individually or by combining two different guidance mechanisms; thus creating a hybrid navigation system that helps in improving all weather targeting and attacking capabilities for war fighters. Joint Direct Attack Munition (JDAM) by The Boeing Company, Paveway by Raytheon and AASM by Sagem of France are a couple of widely procured guided munitions. The demand for precision/surgical strikes has led to an increased demand for these systems, and western companies, who dominate this market, are expected to strengthen their market position across the globe in the coming decade or at least until a credible domestic capability is built by the procuring nations.

The need to provide precision fire capabilities to soldiers operating in squad and platoon levels has led to the development of guided projectiles and is being inducted by all major armed forces. The precision effect offered by these projectiles—apart from offering a reliable first-shot, first-hit capability—also reduces the logistics burden. The advancement of technology means that the unit cost of such systems will be further reduced, thus making it even more attractive and affordable.

DARPA Selects Rockwell Collins to Develop Prototype for Next Gen SDRs

Rockwell Collins has been selected by the Defense Advanced Research Projects Agency (DARPA) to develop a direct conversion digital receiver based on photonic technology. The three-year contract for the DISARMER program is valued at up to $8.5 million.

RF sensor systems on the modern battlefield must cover many RF and microwave bands, and deliver accurately processed information. Rockwell Collins seeks to apply the photonic analog to digital converter (ADC) technology developed under the recently completed DARPA RADER program to create a digital receiver that can accommodate X-Band frequencies.

"This technology will provide the Department of Defense with the networking capability that it has been seeking for the last decade..."

"This technology will provide the Department of Defense with the networking capability that it has been seeking for the last decade to assure spectrum superiority on the battlefield," said John Borghese, vice president of the Rockwell Collins Advanced Technology Center. "Our overall goal is to develop a first-of-its-kind radio to digitize signals at higher frequencies and with more resolution than ever before, allowing a much quicker assessment of threats."

A single DISARMER digital receiver may replace multiple pieces of equipment, enable field reconfiguration and reduce the size, weight, power and cost of both military and commercial radio systems.

U.S. Navy Accepts MUOS-2 Satellite, Ground Stations After LM's Successful On-Orbit Testing

Lwwockheed Martin has completed on-orbit testing of the second Mobile User Objective System (MUOS) satellite and handed over spacecraft operations to the

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U.S. Navy. The handover also includes acceptance of three MUOS ground stations that will relay voice and high-speed data signals for mobile users worldwide.

MUOS-2 was launched July 19, 2013 aboard a United Launch Alliance Atlas V rocket from Cape Canaveral Air Force Station FL. The system dramatically improves secure communications, delivering simultaneous and prioritized voice, video and data for the first time to users on the move.

"MUOS-2 benefits from continuous improvement. We completed our baseline on-orbit testing in half the time compared to MUOS-1," said Iris Bombelyn, vice president of narrowband communications at Lockheed Martin. "We look forward to supporting the Navy's test and evaluation phase to demonstrate the total capability of the Mobile User Objective System. When commissioned, the full digital data and flexible network management capabilities will be available to users for both MUOS-1 and MUOS-2."

The Naval Satellite Operations Center will soon begin relocation operations to place MUOS-2 in its operational slot. There, it will undergo testing and evaluation prior to formal government commissioning in 2014.

MUOS satellites are equipped with a wideband code division multiple access (WCDMA) payload that provides a 10-fold increase in transmission throughput over the current Ultra High Frequency (UHF) satellite system, which is also on board. The WCDMA payload gives users the advantage of high-speed data and priority access that legacy systems did not.

Lockheed Martin's MUOS operations team conducted the on-orbit deployment and checkout of all spacecraft systems over a four month period. Government testing will take place before MUOS-2 is turned over to U.S. Strategic Command for operational use.

U.S. Navy photo courtesy of NASA by Patrick H. Corkery

Horizon 2020 Launched with €15B Over First Two Years

On 11 December 2013 the European Commission, for the first time, presented calls for projects under Horizon 2020, the European Union's €80 billion research and innovation programme. Worth more than €15 billion over the first two years, the funding is intended to help boost Europe's knowledge-driven economy and tackle issues that will make a difference to people's lives. This includes 12 areas that will be a focus for action in 2014/2015, including topics such as smart cities and digital security.

For the first time, the Commission has indicated funding priorities over two years, providing researchers and businesses with more certainty than ever before on the direction of EU research policy. Most calls from the 2014 budget are now open for submissions, with more to follow over the course of the year. Calls in the 2014 budget alone are worth around €7.8 billion, with funding focused on the three key pillars of Horizon 2020: Excellent Science – around €3 billion, Industrial Leadership – €1.8 billion to support Europe's industrial leadership in areas like ICT, nanotechnologies, advanced manufacturing, robotics, biotechnologies and space, and Societal Challenges – €2.8 billion for innovative projects addressing Horizon 2020's seven societal challenges.

At the launch European Research, Innovation and Science Commissioner Máire Geoghegan-Quinn said: "It's time to get down to business. After all the talk and the seemingly endless negotiations around the EU budget, today we are starting to put that money to good use.

> "It's time to get down to business."

"This is funding that is sorely needed. It is funding that is needed by researchers, who in many countries are finding national science budgets squeezed, and little money available for pan-European cooperation. It is funding that will be welcomed by businesses – both big and small, who need research and innovation to remain competitive in global markets.

"Above all this funding is for citizens, because only by investing in research and innovation will Europe find solutions to the big challenges that our societies face, and only by investing in research and innovation will we generate good, sustainable jobs in our economies."

GSA Confirms 244 LTE Networks Commercially Launched

The latest update of the Evolution to LTE report from the Global mobile Suppliers Association (GSA) confirms that 244 operators have commercially launched LTE services in 92 countries. 98 LTE networks had been commercially launched in 2013 at the time that the report was published (December 5, 2013). GSA forecasts that there would be 260 LTE networks in commercial service by the end of 2013.

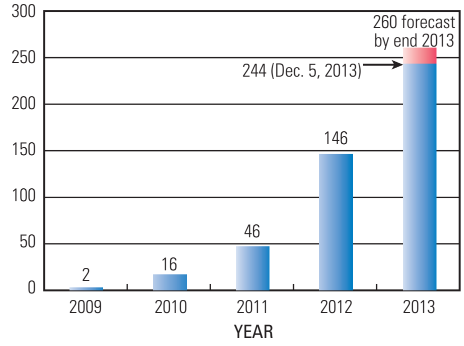
The report confirms that 499 operators are investing in LTE in 143 countries. This is made up of 448 firm operator commitments to build LTE networks in 134 countries, plus 51 additional operators engaged in various trials, studies, etc., in a further nine countries. From amongst the committed operators, 244 have commercially launched services, which is 78 percent more than a year ago.

The majority of LTE operators have deployed the FDD mode of the standard. The most widely used band in network deployments continues to be 1800 MHz which is used in over 44 percent of commercially launched LTE networks. 108 operators worldwide have launched LTE1800 (band 3) systems, 157 percent more than a year ago, in 58 countries, either as a single band system, or as part of a multi-band deployment. The next most popular contiguous bands are 2.6 GHz (band 7) as used in 29 percent of networks in commercial service, followed by 800 MHz (band 20) in 12 percent of networks and AWS (band 4) in 8 percent.

Interest in the TDD mode continues to strengthen globally ahead of large-scale commercial deployments in China. Worldwide, 25 LTE TDD (TD-LTE) systems are commercially launched in 20 countries, of which 12 are deployed in combined LTE FDD and TDD operations.

The report also confirms how voice service has moved up the agenda for many LTE operators as network coverage has improved (nationwide in many cases) and as the penetration and usage of LTE-capable smartphones has increased. VoLTE services have been launched by operators in Asia, Europe and North America.

Commercial LTE Network Launches Cumulative Totals



Source of data: GSA's Evolution to LTE report – December 5, 2013
Global mobile Suppliers Association www.gsacom.com

New ETSI Standards for Wireless Devices

Reacting to the fact that the number of wireless devices using technologies such as WLAN, Zigbee or Bluetooth® has grown rapidly over the last few years, the European Union has changed two important Europe-

For More Information Go to mwjournal.com for more international news items an Telecommunications Standards Institute (ETSI) standards, mandatory for market access in Europe.

The utilization of the unlicensed 2.4 GHz wideband has increased dramatically and problems such as interference are increasing. The EU has therefore updated the standards that devices using the 2.4 GHz band have to adhere to. The target is to improve the usage and quality of data transmission within the 2.4 GHz band. The new ETSI EN 300 328 V1.8.1 version will become mandatory in the beginning of 2015.

The 5 GHz band is increasingly popular especially for devices using WLAN technology, as it provides additional bandwidth and can carry a greater number of non-overlapping channels than the 2.4 GHz band. However interferences also play a role here and automated adaptivity of devices to the most suitable channels is a must. The new ETSI EN 301893 V1.7.1 takes this into consideration. It has made test cases proving adaptivity mandatory for all wireless devices using the 5 GHz band.

UK Centre Stone-Laying Launches ECSAT

The first stones of ESA's new establishment in the UK were laid by Director General Jean-Jacques Dordain, UK Minister of Universities and Science David Willets and the first ESA Director General, Roy Gibson. While placing one of the stones in a sculpture that will later grace the establishment's courtyard, Dordain revealed that the first building of ESA's European Centre for Space Applications and Telecommunications (ECSAT), scheduled for completion in 2015, will be named after Gibson.

> "...UK is taking a stronger role in the European Space Agency..."

Dordain noted: "I stand here next to the man who drove ESA at the very beginning of its history, and with the symbolic representation of ESA's future building. The UK space sector has been around for as long as ESA, and it is fitting that our first ever Director General hailed from this country and ECSAT is marking the renewed ambitions of the UK in using space for competitiveness and growth, in particular within the ESA framework.

Gibson responded: "I am honoured to be part of this celebration of ESA in the UK. It has been a particular pleasure of mine to see how ESA has developed over the years, and particularly in recent times how the UK government is working more closely with ESA."

Minister Willetts stated: "The UK is taking a stronger role in the European Space Agency and this new centre is an embodiment of our intention to work more closely together. I have high hopes that this centre will allow us to maximize the potential of space for future economic growth, keeping the UK at the forefront of the global science race."

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USB-1SPDT-A18	1	0.25	1.2	85	10	385.00
USB-2SPDT-A18	2	0.25	1.2	85	10	685.00
USB-3SPDT-A18	3	0.25	1.2	85	10	980.00
USB-4SPDT-A18	4	0.25	1.2	85	10	1180.00
USB-8SPDT-A18	8	0.25	1.2	85	10	2495.00
NEW USB-1SP4T-A18	1 (SP4T)	0.25	1.2	85	2	795.00

NEW USB and Ethernet Control Switch Matrices

Model	# Switches (SPDT)	IL (dB)	VSWR (:1)	Isolation (dB)	RF P_{MAX} (W)	Price $ (Qty. 1-9)
RC-1SPDT-A18	1	0.25	1.2	85	10	485.00
RC-2SPDT-A18	2	0.25	1.2	85	10	785.00
RC-3SPDT-A18	3	0.25	1.2	85	10	1080.00
RC-4SPDT-A18	4	0.25	1.2	85	10	1280.00
RC-8SPDT-A18	8	0.25	1.2	85	10	2595.00
RC-1SP4T-A18	1 (SP4T)	0.25	1.2	85	2	895.00

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*The mechanical switches within each model are offered with an optional 10 year extended warranty. Agreement required. See data sheets on our website for terms and conditions. Switches protected by US patents 5,272,458; 6,650,210; 6,414,577; 7,633,361; 7,843,289; and additional patents pending.

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CommercialMarket

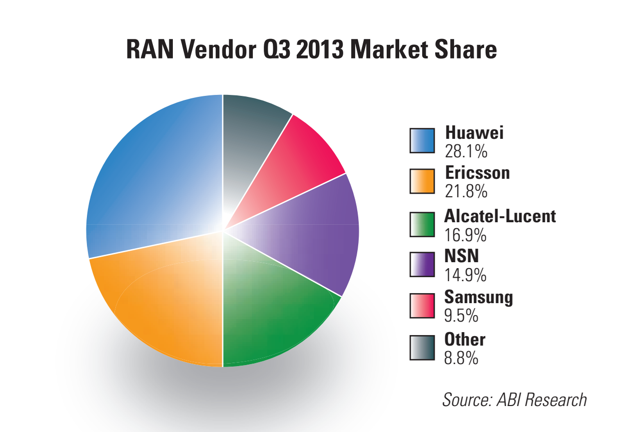
Cliff Drubin, Associate Technical Editor

Huawei Holds #1 Position in RAN Market

For the third quarter of 2013, Huawei maintained its #1 rank in RAN market share at 28.1 percent, down 3 points from 2Q 2013 and up 3.8 points from the year-ago quarter. Meanwhile Alcatel-Lucent increased its RAN revenue by 20.1 percent sequentially to gain the #3 spot ahead of NSN which dropped to #4 with RAN revenues slightly ahead of normal seasonality for the market. Ericsson maintained its #2 rank position with RAN revenues in line with normal seasonality.

According to ABI Research, estimates Samsung posted the largest sequential growth in RAN revenues this quarter at 44.6 percent which is also 101.4 percent ahead of the year-ago quarter.

"Alcatel-Lucent's results were due to strong growth in LTE driven by the U.S. market in addition to positive trends in both the APAC and EMEA regions with LTE revenues more than doubling year-over-year, thanks to the company's LTE overlay strategy," says Nick Marshall principal analyst.



Multimode Femtocell Shipments to Increase by 350% in 2014

While 3G is still the predominant access technology, and is expected to remain so for the next five years, LTE and 3G/LTE multimode femtocell are showing significant growth in shipments as well.

In 2014, standalone 4G LTE femtocells will show a more pronounced presence in the market following the general development of the LTE market, but the key player is expected to be 3G/LTE multimode. The number of shipments is likely to increase by 350 percent in 2014 and a compound annual growth rate (CAGR) of 198 percent is estimated between 2013 and 2018. "3G and 4G will coexist for a long period of time just like the previous generation 2G and 3G technologies did. The introduction of 3G/4G multimode femtocells will allow smoother transition and faster adoption of 4G," comments Ahmed Ali, research analyst.

Femtocell access points implemented by end users require a level of built-in intelligence in contrast to easy-access macro cell sites. The femtocell market is currently focused on developing access points' capabilities like Self-Organizing Networks (SON) and interference management mechanisms. Nevertheless, femtocell management systems are also an important and essential piece for a successful deployment. With the standardization of management system interfaces, vendors are looking to go beyond basic management functions and integrate advanced features in order to provide operators with a higher level of control, easier management, and room to implement additional services.

> "The introduction of 3G/4G multimode femtocells will allow smoother transition and faster adoption of 4G..."

"While today's voice services continue to be provided by the 3G network and data by 4G, a converged management system is a must for every successful femtocell deployment. We believe this gives operators headroom to gracefully extend their network to 4G and plan future enhancements," says Nick Marshall, principal analyst.

While the femtocell market is still developing, operators are exploring ways to generate revenue out of their femtocell networks. Indoor location-based services are increasingly in demand and are expected to become a crucial aspect of femtocell services. "The Service Manager or Service Enabler module is an essential component in today's femtocell management systems and is a key element in differentiating a femtocell solution," adds Ali.

These findings are part of ABI Research Enterprise and Consumer Femtocells Research Service.

M2M Connections to Hit 2.9 Billion by 2022

A new study from Strategy Analytics, "M2M Connections by Industry Vertical and Bandwidth," predicts machine-to-machine (M2M) connections will grow from 368 million in 2013 to 2.9 billion by 2022. Of those connections, 78 percent will be on 3G or faster networks by 2022.

Key factors such as M2M platform evolution, application and analytics developments, regulation as well as the creation of new business opportunities and avoiding obsolescence are all factors driving M2M to an expected growth in connections of 23 percent CAGR growth between 2013 and 2022.

M2M service platforms that increasingly support connectivity, as well as application development for building "turnkey" customer solutions, remain critically important in offering affordable solutions. Regulations remain a driver of M2M, with the Affordable Care Act (ACA, "Obamacare"), eCall compliance in 2015, and the European Energy and Efficiency Directive all helping to drive M2M deployments going forward.

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> "The 2G sunset in the U.S., shift to LTE, and the long lifecycles in many M2M markets, will see an accelerated shift towards 3G and 4G connections..."

"Regulation has always been a key driver pushing M2M forward, whether it's the emergence of the ACA ("Obamacare"), or smart metering initiatives in Europe or China," said Andrew Brown, Director of Enterprise and M2M research at Strategy Analytics and author of the study.

"However, it is also the investment from industrial giants like GE and pressure from "kick-starter-funded" companies pursuing "over-the-top" initiatives for the "Internet of Things" that are providing the impetus and competition that will also help customers find an increasing range of relevant, tailored solutions," he added.

"The 2G sunset in the U.S., shift to LTE, and the long lifecycles in many M2M markets, will see an accelerated shift towards 3G and 4G connections in the next few years. This will only be enhanced by richer applications such as streaming video and digital signage, culminating in 78 percent of M2M connections being 3G or faster networks by 2022," added Gina Luk, senior analyst enterprise research and M2M at Strategy Analytics.

One in Three Commercial Fleet Telematics Units Shipped Based on Consumer Smartphone Platforms by 2018

With today's mobile and cloud-based technology, commercial fleets no longer need to fit expensive hardware on their new trucks and the availability of consumer mobile devices with increasingly sophisticated capabilities means that smaller fleets are embracing commercial telematics.

Most fleet operators are already using smartphones as service access devices to monitor their fleets remotely. Now commercial telematics service providers are increasingly adapting their core applications including track & trace/route planning, driver behavior and fuel management solutions to run on consumer-grade smartphone and tablet devices.

"With GPS and accelerometer functionality, plus the power and flexibility of a sophisticated computer, smartphones and tablets are already important platforms for telematics applications," comments Gareth Owen, principal analyst at ABI Research. "As sensors continue to develop, and new technologies such as voice and gesture recognition improve further, smartphone and tablet-based applications will become even more compelling for fleet telematics."


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Around the **Circuit**

Laura Glazer, Staff Editor

MERGERS & ACQUISITIONS

M/A-COM Technology Solutions Holdings Inc. (MACOM) announced it has entered into a definitive agreement to acquire **Mindspeed Technologies Inc.**, a supplier of semiconductor solutions for communications infrastructure applications, for $5.05 per share in a cash tender offer. The companies' combined trailing twelve months (TTM) revenue is approximately $451 million with non-GAAP gross margin of approximately 50 percent, excluding Mindspeed's wireless business. The cash transaction is valued at $272 million for Mindspeed's $132 million in TTM revenue (excluding wireless business and non-recurring revenue from sales of intellectual property) and $26 million of cash and cash equivalents at September 27, 2014.

An agreement-in-principle has been reached between **Altair** and **EMSS**, pursuant to which Altair will acquire 100 percent of EM Software & Systems – S.A. (Pty) Ltd. and its international distributor offices in the United States, Germany and China. The agreement is expected to close early in 2014. Altair offers OptiStruct®, RADIOSS®, MotionSolve® and AcuSolve® within the HyperWorks suite of engineering simulation software. The addition of EMSS' comprehensive electromagnetic solver FEKO® will enhance the capabilities of the Altair offering, enabling further solver functionality for customers, particularly in the aerospace, automotive and shipbuilding industries.

COLLABORATIONS

MaxLinear Inc. announced a collaboration with **Peregrine Semiconductor Corp.** to produce a dual-RF-input digital TV (DTV) front end reference design. Television sets incorporating this front end will support reception of both digital terrestrial TV and cable TV for seamless channel browsing. The reference design pairs MaxLinear's MxL600 family (MxL601 and MxL661) of software-programmable, low power, global hybrid-television tuners with Peregrine's low power PE42750 RF switch in a fully tested, end-to-end solution including complete schematics, bill of materials and the Gerber files required to quickly implement a high-performance DTV solution.

Soitec (Euronext) and **SunEdison Inc.** announced that they have entered into a patent cross-license agreement relating to silicon-on-insulator (SOI) wafer products. The agreement provides each company with access to the other's patent portfolio for SOI technologies and ends all outstanding legal disputes between the companies. It also covers the manufacturing of existing engineered unpatterned handle-substrates, such as partially depleted SOI, fully depleted SOI and radio-frequency SOI as well as advanced FinFETs, as well as the right to use the companies' respective wholly owned patents for research and development purposes.

Rohde & Schwarz and **NTT DOCOMO** have joined forces to develop an interoperability test package. NTT DOCOMO has now validated the package as NTT DOCOMO approved test equipment (D-ATE). The D-ATE test package from Rohde & Schwarz provides the internal certification labs of wireless device and chipset manufacturers as well as test houses with a comprehensive, customized solution for testing the interoperability of their products with NTT DOCOMO's 3G and 4G networks. NTT DOCOMO also uses the test solution in its product development lab.

Selex ES, a Finmeccanica company, and **BAE Systems** have signed a teaming agreement that will see the two companies working together to provide Electronic Warfare Operational Support (EWOS) for Eurofighter Typhoon customers. The work will initially focus on current and potential future export campaigns and the Eurofighter Typhoon core programme where appropriate. Under the agreement, Selex ES and BAE Systems will work closely together to design, develop, deliver, integrate and support a potential export customer's EWOS requirements, providing them with a sovereign EWOS capability.

Alcatel-Lucent will enable **YooMee Africa**, previously known as 4G Africa, a high-speed Internet service provider in Cameroon, to expand into new African markets by offering TDD LTE ultra-broadband wireless access. The operator has targeted deploying TDD LTE in its new markets within the next six months and expects to build out in average 35 to 50 sites per capital city before deploying in remaining cities of the countries it operates in. Alcatel-Lucent will deploy a complete end-to-end TDD LTE solution consisting of eNBs, wireless backhaul and the Evolved Packet Core (EPC).

NEW STARTS

CTS Electronic Components Inc. announces the addition of frequency related semiconductors to its product offering. CTS' new line of high speed, low noise integrated circuits, available in Q1 of 2014, includes buffers and dividers, capacitive tuning, cable driver and PECL/ECL logic that are complementary to their current frequency control portfolio.

ACHIEVEMENTS

The **U.S. Army** and **Northrop Grumman Corp.** have successfully demonstrated a warfighter-focused, net-centric battle command system for integrated air and missile defense (IAMD). The Army demonstration, conducted from Oct. 24 to Nov. 8 at Redstone Arsenal, AL, employed Northrop Grumman's IAMD Battle Command System (IBCS) software and hardware components to highlight critical capabilities tied to objectives established by warfighters. Key objectives include demonstrating the IBCS tactical air defense planner and the IBCS graphical user interface (GUI). In addition to showcasing capabilities, the IAMD demonstration served as the mechanism to execute detailed test plans, procedures, processes and data collection plans for upcoming developmental and operational testing.

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CONTRACTS

The **Raytheon Co.** and **Lockheed Martin** Javelin Joint Venture received a $176 million contract for the production and delivery of 842 Block I Javelin missile rounds and 120 command launch units (CLU). The missiles will be provided through the U.S. government to the U.S. Army, U.S. Marine Corps and three international customers: Oman, Jordan and Indonesia. Funded with Special Defense Acquisition Funds, the CLUs will be delivered to the U.S. Army beginning October 2014.

Defence and security company **Saab** has signed a framework contract with the **Swedish Defence Materiel Administration** (FMV), for maintenance and upgrades of mobile airbase solutions for the Swedish Air Force. The contract comprises maintenance, change management and upgrades of communication platforms and mobile airbase solutions for the Swedish Air Force. The order is expected to be 150 million SEK over the contract period. The initial contract is for three years, with options for up to four more. The first order within the contract will be received and delivered in 2014.

Northrop Grumman Corp. has been selected by the **U.S. Navy** to conduct a study that explores the replacement of the SPS-48 and SPS-49 air surveillance radars currently on board U.S. Navy amphibious ships and aircraft carriers. The $6 million, 18-month Enterprise Air Surveillance Radar (EASR) study, sponsored by the Office of Naval Research under its Integrated Topside program, will examine how an existing radar concept can be evolved to meet the EASR requirements. Northrop Grumman will be leveraging the capabilities, affordability and maturity of the existing AN/TPS-80 Ground /Air Task-Oriented Radar (G/ATOR) for the EASR study.

Astrium is now delivering to the **UK Ministry of Defence** (MoD) enhanced overseas tactical, land and maritime communications capability, which directly links to Astrium Services' new IP core based modular infrastructure. This capability allows UK Armed Forces to securely connect their users to one core defence infrastructure – supporting all voice and data traffic with encryption from tactical, land and maritime operations across the globe – rather than having to recreate a network of services. The company is delivering the first two Deployable Maritime Milsat (DMM) SCOTPatrol terminals now. Further terminals are on order and will be delivered in the next year.

PEOPLE

▲ *Frank Ohnhäuser*

Georg Schmidt, CEO and CVO of **eesy-ic**, announced that he has transferred the technical management of eesy-ic to Dr. **Frank Ohnhäuser** (CTO and CEO). Ohnhäuser is the ideal fit due to his wide experience in the development of integrated circuits, Schmidt says. Beside Ohnhäuser's long list of patents and applications, he previously opened a design center for Burr-Brown/Texas Instruments in 1999 and drove it successfully. Furthermore, Ohnhäuser is teaching analog

Around the **Circuit**

IC design at the University of Erlangen-Nuremberg, which will enforce the close cooperation between eesy-ic and the university to ensure dynamic growth.

▲ *William F. Dinardo*

Remtec Inc. has appointed **William F. Dinardo** to the new position of business development manager. Dinardo has served in senior management positions where he has directed sales, marketing, new product development, marketing research and new business development for glass-to-metal, ceramic packaging, advanced materials and microelectronic companies. Dinardo graduated with a BS degree in marketing and a master's degree in business administration from Southern New Hampshire University.

▲ *Brian Rowe*

Integrated Microwave Technologies LLC (IMT) announced that **Brian Rowe** has been appointed business development manager for its Intelligence, surveillance and reconnaissance (ISR) programs. With more than 20 years of sales and business development experience in the RF industry, Rowe will be responsible for managing IMT's relationships with its government agency clients, commercial organizations and OEMs responsible for designing, acquiring, and operating ISR systems.

▲ *Ajay Poddar*

Dr. **Ajay Poddar**, Synergy Microwave chief scientist and IEEE Northern New Jersey vice-chair, joined the ***Microwave Journal* Editorial Review Board**. Poddar, whose expertise is in the areas of low noise signal sources, high performance active and passive mixers circuits and RF MMIC/MEMS enabled devices for communication systems, will work with the MWJ editorial staff to vet technical content from contributing authors.

REP APPOINTMENTS

San-tron Inc. announced the hiring of two new sales representatives. **McLane Associates** will handle sales in Upstate NY while **Amplitude Technical Sales** will cover the Eastern PA and Southern NJ territories.

Spacek Labs has appointed **Southeast Atlantic Sales LLC** of Fort Pierce, FL to represent Spacek Labs in FL, GA, NC, SC, AL, MS and TN.

ECM announced a new authorized franchise distribution agreement with **Times Microwave Systems Inc.** to supply the manufacturer's line of connectors, cable and cable assemblies for high performance reliable RF/microwave solutions.

Vaunix Technology Corp. announced the hiring of a new sales representative, **Northtree Associates**, to handle customer relationships in IA, WI, IL, KS, MI, ND, SD, IN and MO.

Generating Radar Signals with an Arbitrary Waveform Generator

Chris Loberg
Tektronix, Beaverton, OR

The generation of signals for radar system testing is challenging due to the complexities associated with carrier frequency generation, intricate modulation schemes and periodic (pulsed) waveforms; while the ability to accurately emulate real-world targets and conditions is essential to the thorough evaluation of radar devices and designs. Historically, radar signal generation has been accomplished with a baseband signal generator and an RF/microwave modulator. With up to 50 GS/s sampling rate at 10 bits vertical resolution, however, today's new arbitrary waveform generators (AWG) offer the performance needed for direct generation of fully modulated RF/microwave signals. Before looking more closely at the use of AWGs for radar testing, let's first explore some of the characteristics of radar signals.

RADAR SIGNAL CHARACTERISTICS

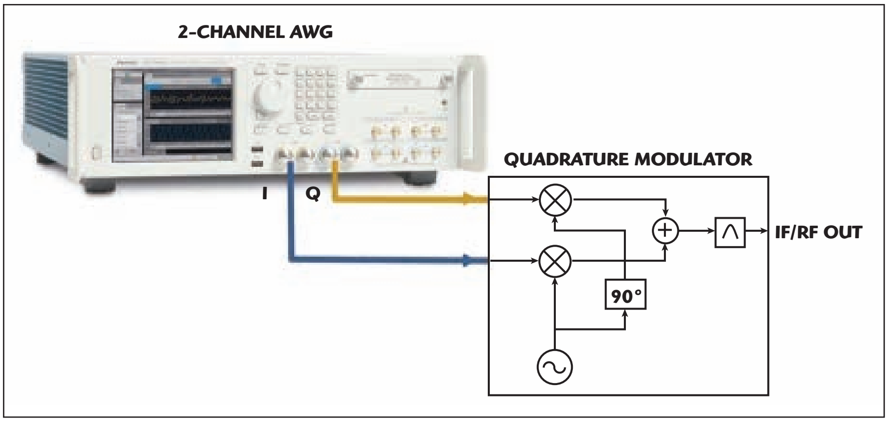
Carrier frequencies used in radar systems cover most of the usable radio frequency spectrum, ranging from very low frequencies required for long range and over-the-horizon surveillance radar up to millimeter wave used in some high-resolution, small size military and civilian radar. Most radar systems, however, operate at frequencies less than 18 GHz (Ku-Band).

Signal types may be divided into the two main groups:

- Pulsed RF: The signal consists of periodic bursts of an RF carrier, modulated or not (simple pulse radar systems). The rate that pulses are generated is known as the pulse repetition frequency (PRF) and the period (1/PRF) is known as the pulse repetition interval (PRI).
- Continuous Wave (CW): The RF signal is continuous and range is established through time markers carried by the transmitted signal. FM modulation is a popular way to measure distance, as the instantaneous frequency received from the target depends upon its range from the transmitter.

For pulsed RF radars, PRF may be fixed or it may vary over time for a number of reasons, which may include:

- Resolving echo (range) ambiguity. The ability to unambiguously determine the range of a target is limited by the PRI. A target located at a distance for which the round trip time of a transmitted pulse exceeds the PRI can be mistakenly positioned in range relative to the nearest transmitted pulse. This can be resolved by varying the timing of consecutive pulses, changing the position of subsequent radar returns.
- Overcoming the "Doppler Dilemma." Ra-



▲ *Fig. 1 Baseband generation of radar signals.*

dar systems use the Doppler effect to measure target velocity and/or reduce interference due to clutter. The physics behind the Doppler effect produces "blind speeds" for specific target velocities. Changing the PRF can change the location of these "blind speeds," enabling the detection of previously invisible targets. Some radar systems switch between a high PRF to avoid blind speeds for expected target velocities and a slower one optimized to avoid range ambiguity.

- Protecting against jamming. A variable PRI, often combined with complex stagger sequences, allows easier discrimination between echoes caused by a given radar and those created by other radars operating in the same frequency band or by interference caused by intentional jamming.

For pulsed RF radar waveforms, the transmitting frequency may be fixed or variable (frequency agile). This takes the form of frequency hopping patterns. These patterns are complex, non-predictable, and typically non-repeating (or repeating over extremely long periods of time). The carrier frequency may even change for each transmitted pulse.

Since radar range is maximized as power increases while spatial resolution improves as pulses become narrower, pulse-compression techniques are widely used. The pulse compression techniques increase range resolution by transmitting longer pulses (increasing average power for a given peak power), while echo processing at the receiver results in much better spatial resolution by "compressing" the pulse through correlation or dispersion processing. There are two main pulse compression techniques:

- FM chirp. This consists of fast frequency sweeps that may be linear (LFM) or nonlinear (NLFM). NLFM has some advantages regarding bandwidth, resulting in better sensitivity and lower noise levels at the receiver.
- Phase modulation. Each pulse is composed of a series of shorter pulses where the carrier phase is controlled by some low autocorrelation binary sequence of symbols. While average power is controlled by the total duration of the sequence, spatial resolution depends on the duration of each symbol. In binary-phase coding, the carrier phase changes between 0 and 180 degrees; the Barker code is a very popular example. Polyphase pulse compression applies the same basic idea but the carrier phase takes on more than two values.

An important issue for some radar systems is carrier phase coherence. In some systems, such as those employing a high-performance coherent Moving Target Indicator (MTI) architecture, phase coherence must be preserved between consecutive pulses. Regardless of the phase characteristics of the transmitted pulse, returning echoes are a superposition of signals with a variety of relative phases. There are multiple target echoes with arbitrary delays, multiple echoes from the same target with different time of arrival due to multi-path, all kinds of

clutter, and frequency shifts caused by the Doppler effect. The instantaneous amplitude and phase for a given echo is also influenced by a target's shape and size. No matter the complexity of the transmitted signal, the reflected signal will be much more complex.

AWG SIGNAL GENERATION

AWGs can generate radar signals in three ways:

- Baseband generation. The AWG generates a time-domain signal that is applied to an external RF modulator.
- Intermediate frequency (IF) direct carrier generation. In this case, the AWG generates a modulated signal at a relatively low carrier frequency. In some cases, this signal is applied directly to a signal-processing block in the receiver or the transmitter. In other cases, it is applied to an up-converter block to reach the final RF/microwave carrier frequency.
- RF direct carrier generation. The AWG generates a modulated carrier at the final RF/microwave frequency, requiring no additional signal-processing blocks other than filters or amplifiers.

Baseband and IF generation can be implemented with a moderate performance AWG for most signals; however, in both cases, the modulation bandwidth of the final RF/microwave signal will be limited by the characteristics of the modulator or up-converter. Direct RF signal generation, on the other hand, requires an extremely fast AWG with a sampling rate at least 2.5 times higher than the maximum RF frequency component of the signal. The latest generation of AWGs offers 10 bits of resolution at speeds up to 50 GS/s, opening the door for direct signal generation beyond Ku-Band (12 to 18 GHz).

BASEBAND SIGNAL GENERATION

Baseband signal generation may appear relatively straightforward because modulation and up-conversion are performed externally. The modulation device may be a simple amplitude (AM) modulator for basic pulsed RF signal generation, however some baseband signals require a suppressed carrier, which is not supported by most AM modulators, as the instantaneous phase can take two values (0° and 180° or BPSK). Baseband generation of FM chirps, QPSK/QAM and UWB OFDM signals requires a two-channel AWG and an external quadrature modulator (see ***Figure 1***) as both the instantaneous amplitude and phase of the carrier must be controlled. Sampling rate requirements depend on the modulation bandwidth which is limited by the modulator. Similarly, emulation of realistic radar echoes incorporating the effects of the target characteristics, multi-path, Doppler shifts, noise and jamming also requires quadrature modulation and a two-channel AWG.

Generating good quality wideband modulated signals using this approach is not an easy task. Frequency responses of both baseband generators and RF modulators are not flat and group delay is not constant over the bands of interest when signal band-

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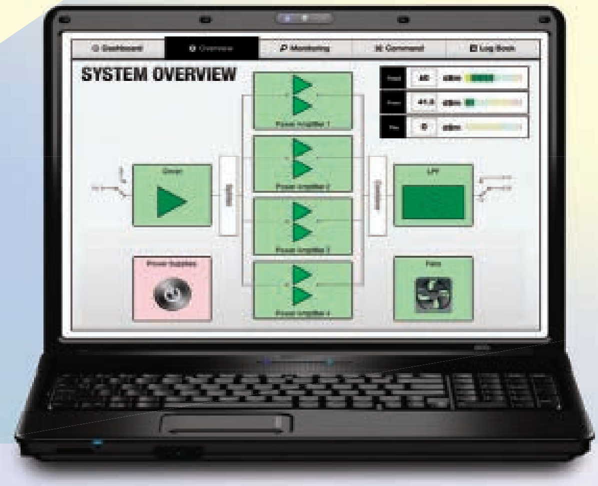

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widths are high. Even a perfect AWG incorporating ideal digital-to-analog converters (DAC) will show a zeroth-order hold response:

$$H(f) = \mathrm{sinc}(\pi f/Fs) = \sin(\pi f/Fs)/(\pi f/Fs),\quad Fs = \text{Sampling Frequency} \qquad (1)$$

This introduces linear distortion to the RF pulses, altering the shape of the transitions and modifying rise and fall times. The analog frequency response of the AWG and cabling, and the modulator's frequency response adds to these distortions. Unwanted images resulting from the sampled nature of signals generated by AWGs can also affect signal quality, and the limited time resolution available in any AWG may result in undesired levels of pulse-to-pulse jitter.

Fortunately, AWGs can generate either undistorted or intentionally distorted signals. Predistortion mathematically applied to waveforms stored in the generator's memory may be designed to compensate for external distortion. After careful calibration of the overall frequency response it is possible to design a compensation filter that improves flatness and group delay response. Typically, the compensation filter takes the form of a pre-emphasis filter to correct the signal generation system's overall lowpass frequency response.

For quadrature-modulated radar signals such as FM-chirps, two baseband signals, the I and Q components, feed the external modulator. These two components are generated independently and synchronously by a two-channel AWG or by two properly synchronized single-channel AWGs. Quadrature error and imbalance cause unwanted images to appear at the RF and at symmetric frequency locations, resulting in higher noise and reduced modulation quality. While AWGs can generate a differentially corrected signal, one should be aware that generating quadrature-modulated signals with an AWG and external modulator involves a time-consuming calibration process as well as additional equipment (typically a high-end real-time oscilloscope, a wideband vector signal analyzer, and supporting software).

DIRECT CARRIER GENERATION

AWGs can produce any signal from DC up to half the sampling rate (Fmax = Fs/2). With a high enough sampling rate, it is possible to directly generate a modulated RF signal. Previously, relatively low sampling rates and poor spurious-free dynamic range (SFDR) limited the capability of AWGs to generate carriers up to only a few GHz. With improved DAC performance, AWGs can now be used for direct generation of wideband signals with carriers up to 20 GHz and with almost unlimited modulation bandwidth. Direct generation offers a number of advantages over the traditional baseband/external modulator combination:

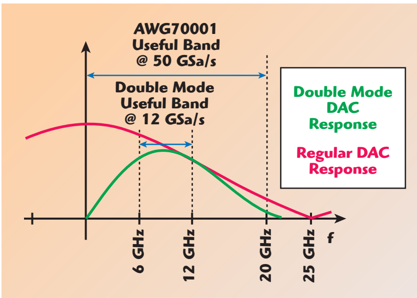
- Baseband generation and quadrature modulation are performed mathematically. As a result, there are no unwanted quadrature imbalances or errors. This approach yields higher quality and more repeatable test signals.
- No additional equipment is required, saving cost when multiple synchronous signals are required

(i.e., for MIMO radar or phased array emulation).

- Direct, nearly unlimited, frequency agile radar signal emulation is possible.
- One single AWG can generate multiple dissimilar carriers or wideband noise for more realistic test scenarios.
- Calibration procedures are simplified, where only the amplitude and phase of the more stable AWG must be verified.

The implementation of direct carrier generation has its challenges, as well:

- For a given record length (RL) and sampling rate (Fs), the maximum time window (TW) = RL/Fs. As sampling rates for direct RF generation tend to be higher than those for baseband signal generation, the same record length translates to shorter realizable time-windows. Record length is also crucial for a realistic emulation of complex radar systems incorporating staggered pulse sequences, frequency hopping patterns or time varying echo characteristics caused by target movement or antenna vibration.
- An alternative method to extend the carrier frequency range for a particular AWG is to use an image in the second Nyquist zone, between Fs/2 and Fs. The usability of the image can be improved by filtering out the fundamental signal located in the first Nyquist zone. The quality of this signal is more limited given the much lower amplitude and the steeper roll-off in the AWG frequency response.
- Some signal generators incorporate DAC working modes to improve second Nyquist zone performance. Doublet-mode DACs (also known as Mix-Mode DACs) generate a higher amplitude image and a reduced amplitude fundamental signal while removing the first null of the zeroth-order hold response of a regular DAC. However, maximum modulation bandwidth and the capability to generate multiple carriers are still limited to less than half the sampling rate and this is only possible when the carrier frequency is located in the middle of the valid Nyquist zone (see ***Figure 2***). In this example, the Doublet DAC mode boosts images in the second Nyquist zone and attenuates the direct signal located in the first Nyquist zone. This extends the frequency coverage of a 12 GS/s AWG but limits its carrier frequency range and modulation bandwidth compared to the regular DAC response. AWGs designed to generate signals in the first Nyquist zone do not have these limitations.
- Another way AWGs obtain higher effective sampling rates is by interleaving two DACs (see ***Figure 3***).



▲ *Fig. 2 Doublet DAC mode.*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This is effectively a two "true-arb" model with odd and even samples stored in each channel's memory. Since switching DAC outputs creates noise and reduces effective bits performance, an interleaved DAC architecture is used that adds the outputs from both channels with a channel-to-channel delay of half the sampling period (1/2SR). This architecture, when used in a high-speed AWG, effectively doubles the Nyquist frequency to 2×SR.

- Although direct carrier generation does not suffer any quadrature impairment due to I/Q mismatch, wideband signals may need some linear distortion to compensate for flatness and phase linearity issues, including those created by cabling and interconnections. Applying corrections based only on the amplitude response improves modulation quality, although phase response compensation is also required for optimal performance. Direct carrier generation also requires stable sampling clock jitter performance as this translates directly to phase noise in generated carriers.

SIGNAL CONSISTENCY

Continuous signal generation with an AWG requires seamless cycling of the contents of the waveform memory through the DAC. In order to obtain useful signals, consistency of the signal around the wrap-around event must be preserved. Timing characteristics of radar signals are especially important:

- An integer number of PRIs must be stored in the waveform memory. Otherwise abnormal pulse timing (longer or shorter than required) will occur every time the waveform is cycled.
- For coherent radar emulation, the phase of the carrier must be preserved. This condition can be met if record length and sampling rate are selected in such a way that the resulting time window is an exact multiple of the carrier frequency period.
- Echo consistency requires that multi-path, filtering effects and echoes beyond the unambiguous range propagate from the end of one cycle to the next. These effects may be seen as the convolution of the transmitted signal with the target system impulse response. Applying circular convolution to consistent transmitted data will result in an echo emulation signal without any discontinuity or abnormal behavior that could confuse a radar receiver under test.

CALIBRATION AND SIGNAL CORRECTION

AWGs are typically flatness-corrected up to a certain frequency. Beyond that point, signal generators exhibit relatively gentle roll-off responses (see ***Figure 4***). Moderate attenuation allows the direct generation of usable radar signals at higher frequencies. In order to improve modulation quality at those frequencies, the frequency response can be corrected or calibrated to compensate. Real-time oscilloscopes are ideal calibration tools as they show flatness and phase linearity over their full bandwidths with accurate channel-to-channel alignment. Once the correction filter response is determined

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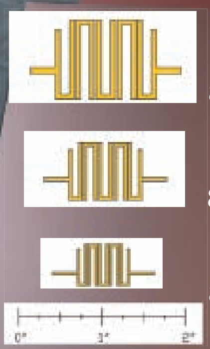

$\varepsilon_r = 3.0$

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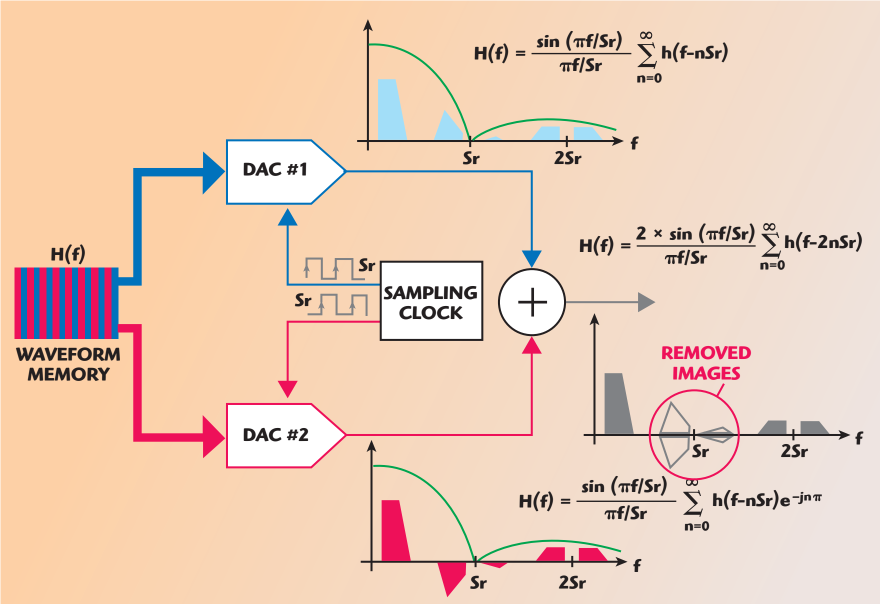
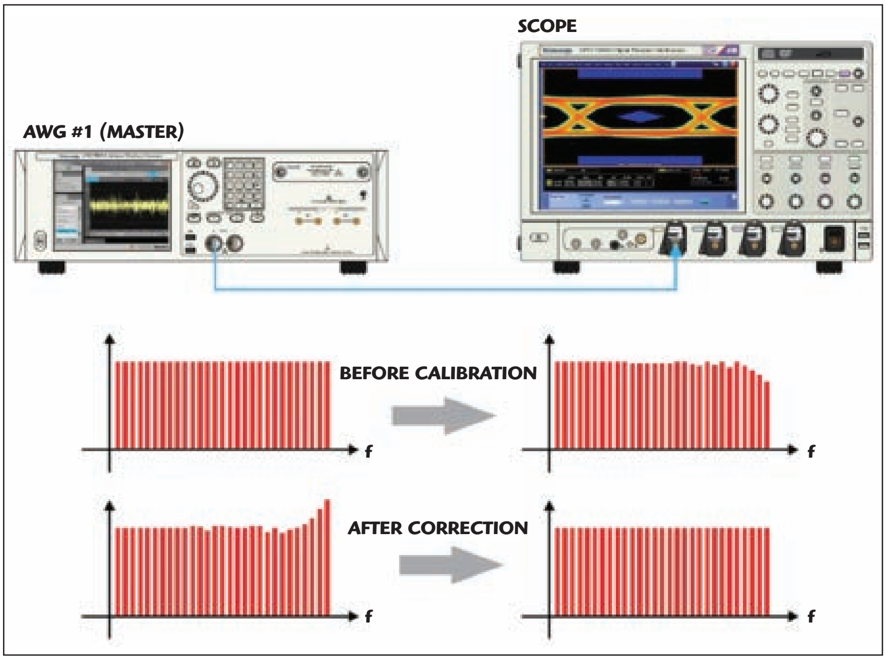
$\varepsilon_r = 10.2$



▲ *Fig. 3 An interleaved DAC architecture.*



▲ *Fig. 4 Calibration using a real-time oscilloscope.*

in the frequency domain, it is applied to the original, uncorrected waveform through convolution. Convolution must be circular when signal looping is required.

CONCLUSION

Arbitrary waveform generators allow for the direct generation of complex radar signals at carrier frequencies up to 20 GHz. This is made possible by improved DAC performance and by the use of an interleaved DAC architecture. Some of the most complex frequency-agile or MIMO radar systems can be now be emulated using direct RF generation techniques. ■

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MWJ REVIEW BOARD APPROVED

W-Band Radiometer Front End Module for Real-Time Imaging

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University of Electronic Science and Technology of China, Chengdu, China

This direct detection W-Band radiometer front end module for real-time imaging employs a monolithic microwave integrated circuit (MMIC) low noise amplifier (LNA), a highly sensitive detector and a video amplifier. The detector has a responsivity of 1000 mV/mW over a 21 GHz bandwidth. The compact module (measuring 13 × 20 × 56 mm) achieves a temperature sensitivity of 0.83 K with an integration time of 2.3 ms over a 22 GHz bandwidth. It is a candidate for large imaging array applications.

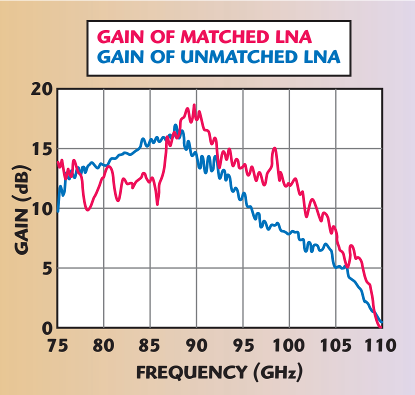
Millimeter-wave (MMW) imaging research and system design for remote sensing has gained much interest in recent years. Compared to active imaging systems, passive imagers have simpler and lower-cost hardware architectures and can detect contraband (for example), often with good fidelity and free of speckle or interference effects.[1] W-Band has important applications in passive millimeter-wave (PMMW) imaging under poor atmospheric conditions such as fog[2] and dust which generally limit the performance of visible or infrared sensors.

In 1997, Northrop Grumman Corp. developed a direct detection, 1040 channel PMMW imaging receiver array.[1] Each channel contained PHEMT LNAs, on-chip switches and a detector diode. It worked at 89 GHz center frequency with a bandwidth of 10 GHz, a temperature sensitivity of 2 K, and a 30 Hz display rate. In 2009, a single channel receiver for PMMW imaging was developed[3] with a bandwidth of 17 GHz (85 to 102 GHz) and temperature sensitivity of 1.5 K. In 2010, a direct-detection RFIC for W-Band PMMW imaging was reported.[4] It achieved a bandwidth of 20 GHz (83 to 103 GHz) with a temperature sensitivity of 0.69 K. These developments, however, were either physically large,[3] or were one of a kind.[1,4]

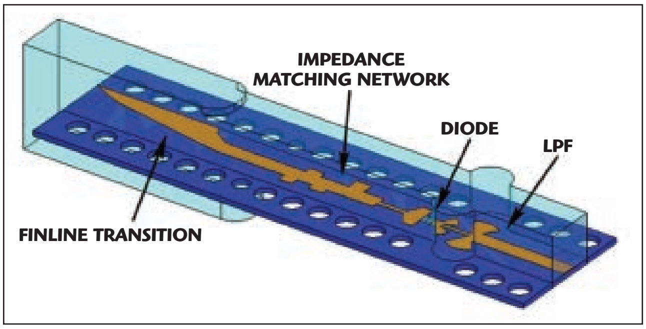
In this article, we describe the design of a compact wideband W-Band radiometer front end module with high sensitivity and a 22 GHz bandwidth for real-time PMMW imaging using commercially available components. Due to the lack of on-chip measurement capabilities, separate LNA and detector modules with waveguide interfaces are assembled for design verification. Much work has been done to expand the bandwidth for a higher sensitivity.

FRONT END DESIGN

Millimeter wave energy can be rectified directly producing a proportional DC voltage (square law detection), or downconverted to a lower intermediate frequency before detection. For large real-time imaging radiometer arrays and for applications where there is no



▲ *Fig. 1 Measured gain comparison of a matched and unmatched LNA.*



▲ *Fig. 2 HFSS model of the W-Band planar detector.*

special requirement for spectroscopic resolution, reduced hardware size, mass and complexity takes precedence over other considerations. For these applications, direct detection is usually a better choice. The temperature sensitivity for a total-power radiometer is given by

$$\Delta T = \frac{T_s}{\sqrt{B\tau}} \quad (1)$$

where ΔT is the temperature sensitivity, B is the RF bandwidth, τ is the integration time and T_s is the system noise temperature.[5] Because requirements for real-time imaging places limits on integration time, increased sensitivity must be achieved through broadening the front end bandwidth.

LNA

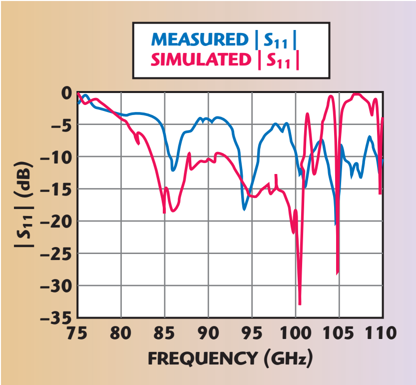
An amplifier with low noise, high gain and wide bandwidth at the first stages of the radiometer front end can lower system noise. Even though this design is based on the use of commercial MMIC chips, performance is optimized through the use of multiple bond wires for low impedance, and a broadband external matching network. An antipodal finline transition provides a broadband transition from waveguide to microstrip. A complete LNA module with a standard W-Band flange interface was designed. The LNA's output impedance matching circuit was optimized and the LNA designed using Ansoft HFSS and Ansoft Designer.

The performance of two LNAs (one matched and one unmatched) is compared in ***Figure 1***. Through appropriate impedance matching, the gain of this single stage LNA is improved by approximately 1 to 7 dB in the upper half of the band, so that the bandwidth, at 10 dB gain, is broadened by about 7 GHz.

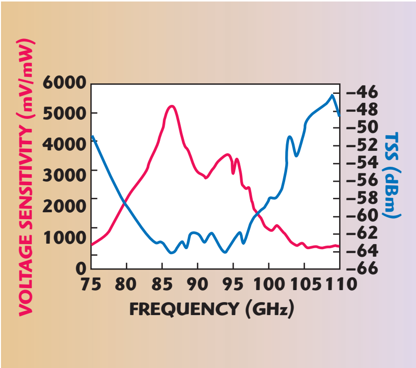
Detector

The detector module includes a standard waveguide input flange to interface with the LNA. It consists of a waveguide-to-microstrip transition, impedance matching network, detector diode and output low pass filter (LPF). The design goal was to achieve both wide bandwidth and high sensitivity. An LPF is necessary to extract the quasi-DC information from other abundant spectral components at the output of the detector diode. We selected a structure based on a stepped-impedance of three orders. A radial stub in place of the traditional uniform width transmission line stub broadens the bandwidth of the frequency response and makes the whole circuit more compact. The system bandwidth is maximized when the mismatch over the operating band of the LNA and detector is minimized.[6] The center frequency of the detector is set to 89 GHz, in alignment with the LNA. The HFSS physical model of the detector is shown in ***Figure 2***.

The return loss (reflection coefficient), voltage sensitivity (or responsivity) and tangential signal sensitivity (TSS) are the main figures of merit. The measured reflection coefficient is compared with simulated results in ***Figure 3***. There is good agreement, not only at the center frequency and the two adjacent zeroes (85 and 95 GHz), but also at zeros near 100 and



▲ *Fig. 3 Comparison of the detector simulated and measured* $|S_{11}|$.



▲ *Fig. 4 Voltage sensitivity and TSS of the detector.*

105 GHz at the high end of the frequency band. The measured values, however, are greater by 5 dB or more than the simulated results below 100 GHz and lower by several dB at higher frequencies. This may be due to circuit discontinuities where the detector diode interfaces with the impedance matching network and the LPF. At the highest frequencies, the effects of parasitic capacitance in the simulation become worse, and some potential higher order modes due to the construction of the model may adversely affect the accuracy of simulation.

Responsivity measures the ratio of output voltage to input millimeter wave power and is expected to remain constant in the square law region which is the normal operating range of the detector. Up to 1000 mV/mW responsivity over 78 to 99.5 GHz is measured, with a peak value more than 5200 mV/mW at 86 GHz (see ***Figure 4***).

A tangential signal sensitivity (TSS) measurement is most commonly performed to estimate noise equivalent power (NEP). NEP is the lower limit of the detectable power. TSS is defined as a signal pulse whose bottom level coincides with the top level of the noise on either side of the pulse. The detector's NEP is related to TSS by

$$NEP = \frac{TSS}{2.5\sqrt{\Delta f}} \quad (2)$$

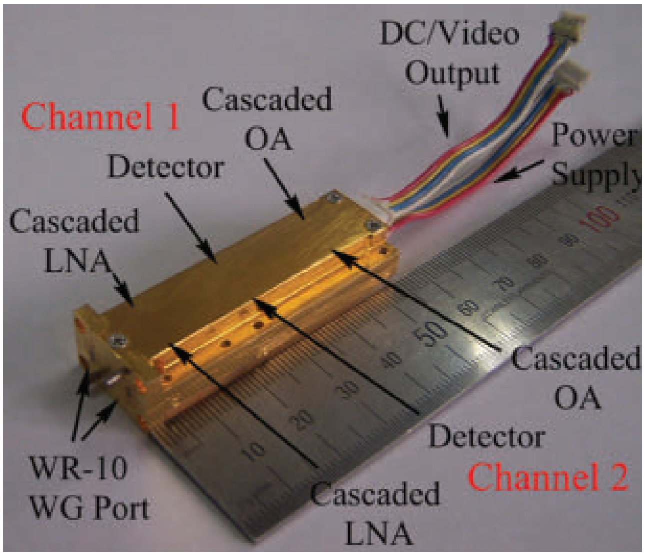
where f is the video bandwidth of the video amplifier following the detector.[7] A pulse train with a pulse width of 30 ms and a period of 60 ms simulates the source, and the bandwidth of the video amplifier is approximately 70 Hz. Figure 4 shows that the TSS of the detector is better than –58 dBm over the band from 79 to 100 GHz. The minimum value reaches –64 dBm at several frequency points. According to equation 2, the NEP of the detector is lower than 76 $pW\sqrt{Hz}$.

Table 1 lists the performance of several detectors reported in recent years. Except for NEP, which is main-

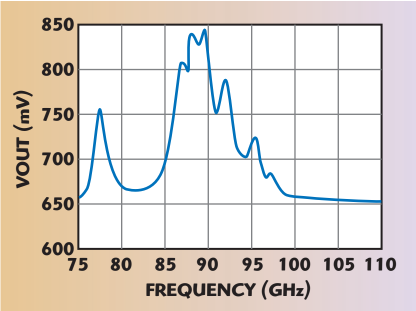
TABLE I

VOLTAGE SENSITIVITY AND NEP COMPARISON OF SOME DETECTORS

Reference Year	Voltage Sensitivity (mV/mW)	NEP ($pW/\sqrt{Hz}$)	Diode	Bandwidth (GHz)
2007[8]	2000	1.5	VDI BLK109 Schottky	30
2010[9]	850	370	HSCH 9161 Schottky	20
2010[10]	500	unknown	VDI Diode Schottky	35
This work	1000	76	HSCH 9161 Schottky	22



▲ *Fig. 5 Compact dual-channel front end module.*



▲ *Fig. 6 Frequency response of the radiometer front end module.*

ly limited by the detector diode itself, this detector's performance is comparable to that of Virginia Diode Inc.'s advanced products, which satisfies requirements for high sensitivity and broad bandwidth. Because it is made with commercially available components at a relatively low cost, it is a very competitive candidate for large array applications.

Module Integration

Based on separate evaluation of the millimeter wave components, the integrated front end module was designed and is shown in ***Figure 5***. The MMW circuits of each channel are separated in different chambers to minimize mutual interference. Two operational amplifier (OA) stages, along with RC integration circuits, constitute the main structure of the video amplifier section. A differential OA is chosen as the second stage, converting the single ended input to a balanced output in order to suppress common mode interference. The link gain is adjusted so that the output voltage level is placed in the required range for A/D conversion. Power supply components are located on the bottom side of the module.

It has been previously demonstrated that in the presence of a highly directional antenna, only when the sampling rate slows down from 0.5 wavelengths (Nyquist sampling density) to larger than 3.13 wavelengths per sample, is there a perceived reduction of target sharpness.[11] Therefore, the spacing between adjacent module channels is chosen as 9.96 mm to make the module design easier and decrease the number of elements of the array for a given aperture. The module has regular shape and is no larger than 13 × 20 × 56 mm. This compact size makes it applicable for miniaturization and modularization.

MEASUREMENTS

Frequency Response

Since the interface of the two waveguide ports is not a standard W-Band flange, a specially designed connector is introduced to provide matched interface for measurement. The input power is set to produce a maximum power without driving the video amplifier into saturation. This is about –72.5 dBm. The measured frequency response (see ***Figure 6***) shows that the radiometer front end module has a response above 650 mV in over a bandwidth of at least 22 GHz and a peak value appearing near 89 GHz. This verifies the design predictions.

Calibration

A set of W-Band standard hot-cold calibration sources is introduced to measure the temperature sensitivity based on the two-point calibration equation,[12]

$$T_A = \frac{T_A^h - T_A^c}{V_{out}^h - V_{out}^c} \cdot \left(V_{out} - V_{out}^c\right) + T_A^c \qquad (3)$$

TABLE II

COMPARISON OF BANDWIDTH AND TEMPERATURE SENSITIVITY

Reference Year	Bandwidth (GHz)	Temperature Sensitivity (K)	Renormalized Temperature Sensitivity ($K/\sqrt{Hz}$)	Circuit Type
1997[1]	10	2	unknown	MMIC
2009[3]	17	1.5	unknown	HMIC
2010[4]	20	0.69	0.12	MMIC
This work	22	0.83	0.04	HMIC

where T_A^h/T_A^c corresponds to the antenna temperature of the hot/cold calibration source, respectively, (80°C/6°C) and V_{out}^h / V_{out}^c represents the output voltage of the front end (–186 mV/–400.59 mV) over integration time τ (2.3 ms, the same as that in the measurement of the individual detector module). Then the deduced calibration equation (V in mV and T in K) is obtained as:

$$T_A = 0.345V_{out} + 401.702 \quad (4)$$

With the root mean square (RMS) voltage of the observed data equal to 2.4 mV, the calculated sensitivity of the radiometer is about 0.83 K. The renormalized system sensitivity to integration time is about 0.04 $K/\sqrt{Hz}$.

Table 2 lists the recently reported performance of several W-Band direct detection type radiometers for comparison. Due to the compact structure and on-chip interconnects between the LNA and detector and other circuits integrated in a single chip, carefully designed MMICs often tend to have intrinsically lower noise and smaller internal insertion loss than Hybrid Microwave Integrated Circuit (HMIC) counterparts. This design, however, has achieved comparable performance and some improvements in bandwidth and sensitivity at relatively low cost—based on the use of commercially available components.

CONCLUSION

A compact wideband W-Band radiometer front end module for real-time imaging is designed, demonstrating at least 22 GHz bandwidth and a sensitivity of 0.04 $K/\sqrt{Hz}$. Subsequent single channel scanned imaging experiments have been conducted, showing that the W-Band radiometer system can produce a passive planar image, thus validating its practical value in large arrays for PMMW imaging. Fur-

ther performance improvements are possible through refinements of the diode model.[13] ■

ACKNOWLEDGMENTS

This work is supported by the State Key Program of National Natural Science Foundation of China (No. 60632020) and the National High Technology Research and Development Program of China (863 Program, NO.2007AA061903).

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Tuning Speed	1usec
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Harmonics	-30dBc Max.
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Prototyping Massive MIMO

James Kimery and Ian Wong
National Instruments, Austin, TX

The rapacious demand for wireless data has spurred researchers to search for new technologies to expand wireless data capacity and network capability. Industry experts universally agree that even with current and planned infrastructure rollouts, data demand will continue to outpace capacity and the debate has shifted from "if" to "when" this event will occur. Wireless service providers plan to furiously upgrade their networks to 4G LTE, LTE-Advanced (LTE-A) and beyond, introducing new innovations such as small cells, heterogeneous networks, and carrier aggregation along the 3GPP roadmap. However, it is clear that the current technology trajectory produces a capacity slope that is still flatter than the demand line. Embracing the challenge, the 3GPP standards body recently adopted a goal of increasing data capacity "1000× by 2020" acknowledging the need for evolutionary or revolutionary ideas.

One such concept entails the deployment of base stations with very large scale antenna arrays encompassing perhaps hundreds of transceiver elements. This concept is referred to as Massive MIMO.[1] Indeed, Massive MIMO departs from current network topologies and could be a key to solving our wireless data challenges; however, another interesting question is posed through the process of understanding the effectiveness and/or feasibility of Massive MIMO for wide spread deployment – just how does one go about creating a prototype to truly see whether it will work? After all, creating a prototype with hundreds of antenna elements creates several engineering challenges not the least of which include cost and time.

MIMO BACKGROUND

MIMO relies on multipath to enhance the reliability and the effective data rate of a wireless data link using multiple streams typically through several separate antennas. Multipath propagation, a formidable challenge to robust communication systems, is actually exploited with MIMO using a variety of techniques including space-time coding and/or spatial diversity.[2] The 4G cellular standard LTE-A specifies a maximum of eight antennas for use in a MIMO configuration. The IEEE 802.11n/ac standards and the actual commercialization of those standards are the predominant use cases of MIMO in practice.

Basically, more antennas yield more degrees of freedom of the propagation channel delivering improved performance in terms of data rate and/or link reliability. However, the overall data rate is still constrained by the Shannon-Hartley theorem. In a network with multiple users, one way to increase the overall network throughput

is through multi-user MIMO (MU-MIMO), where multiple users can simultaneously access the same time-frequency resource, but it is separated through the multiple "spatial dimensions" created by multiple antennas.

MORE ANTENNAS, MORE CAPACITY, ENHANCED RELIABILITY

Scaling up MU-MIMO to a large scale, classified as Massive MIMO, potentially offers higher network capacity, better reliability and increased energy efficiency of the Massive MIMO base station by lowering the overall transmitted power in a cell or served region. Theoretically, the transmitted power per antenna could be less than the transmitted power of a single antenna serving a designated cell or region with the same data rate. That is, the overall power given by

$$PTot_{MM} \sim P_T\, N_T$$

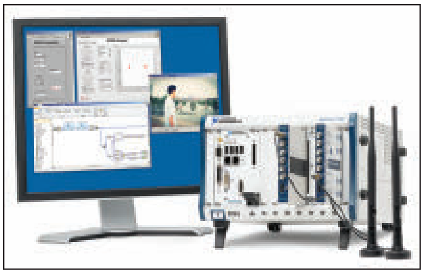
where $PTot_{MM}$ is the total transmitted power per region, P_T is the power per antenna, N_T is the number of transmit antennas, and $PTot_{MM}$ is less than PTot of a single antenna system. A Massive MIMO cellular topology could potentially reduce the overall transmitted power in a sectorized region compared to the power needed in a single antenna system to achieve the same reliability and/or throughput because of the increased capability of the Massive MIMO base station to focus its emitted energy to the desired users through its increase in degrees of freedom. In addition, the probability of the correct bits being transmitted from a transmitter to a receiver increases when multiple antennas are deployed, since

$$\text{Link Outage Probability} \sim 1 / \text{SNR}\, N_T\, N_R$$

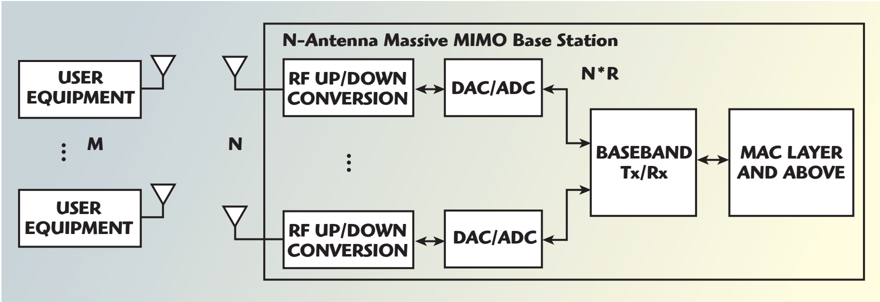
where SNR is the signal to noise ratio, N_R is the number of receive antennas and N_T is the number of transmit antennas. As the number of antennas increase in a system, the probability of a link outage decreases thus increasing the communications link reliability.[2]

Large scale MIMO antenna arrays build on the fundamental concepts presented here, behind the theory that antenna deployments in the hundreds scale to realize better efficiencies than current MIMO point-to-point deployments. Specifically, with hundreds of antennas, the antenna aperture and deployment grid will have a much finer resolution. Combined with beamforming, the antenna lobes can be more finely controlled to reduce power in the channel.

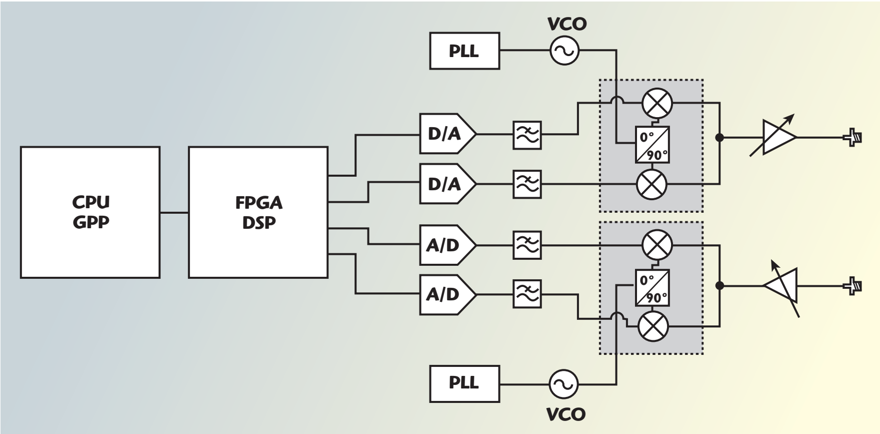
Massive MIMO systems are not without their challenges. One challenge includes finding a way to communicate the channel state information from the receiver to the transmitter for precoding. With hundreds of antennas, the number of pilot signals needed to derive the channel state is really not practical. Massive MIMO in its current incarnation is hence only practical in a time-division-duplexed (TDD) system which relies on the reciprocity of the channel, but to determine the feasibility of this approach more research is needed. Some initial research has also proposed



▲ *Fig. 1 Two-antenna MIMO transceiver.*



▲ *Fig. 2 M-user, N-antenna Massive MIMO system.*



▲ *Fig. 3 Typical 1×1 software defined radio architecture.*

that the thermal noise in the system is less of a concern with so many antennas, and the impact of interferers becomes more of an issue. These challenges and others can be explored with real world waveforms once a working prototype has been developed.

PROTOTYPING A MASSIVE MIMO SYSTEM

The task of prototyping a Massive MIMO system requires a lot of up front work to carefully and properly design an actual working system. Most researchers may find that even prototyping a minimally configured two antenna MIMO transceiver system can be challenging (see ***Figure 1***). To begin the task of designing a Massive MIMO prototype, let's first sketch a diagram of the system (see ***Figure 2***). For the purposes of this exercise, we will use N number of antenna elements at the base station to be 128 to achieve a 128 × 128 MIMO configuration. The configuration does assume M mobile users using SISO antennas.

There are many items to consider when designing a large scale MIMO system, including RF system parameters such as transmit power, adjacent channel interference, conformance to spectrum mask and so on. However, a key parameter to consider in a large scale MIMO system is the digital data throughput to and from each antenna. From Figure 2, one of the most challenging aspects of the system is aggregating all of the received samples into a common processing subsystem. Unlike simple transmit and receive communications using a SISO radio, Massive MIMO requires high speed data throughput between transmit and receive elements and the baseband – an order of magnitude higher than today's currently deployed systems.

Processing the data streams in a distributed fashion to the nodes located close to the antenna is an option, but in order to recover the received signals from, or effectively precoding the signals to the different users, the data streams from each antenna must be aggregated at a common location in order to extract the best performance. Taking a closer look at the throughput and data requirements, we break down the system into their fundamental elements. Thus, we can quantify the data rates into the actual building of the prototype and explore tradeoffs that can impact system design, integration, power and ultimately cost.

BASELINE SYSTEM PARAMETERS

A typical SISO radio is depicted in ***Figure 3***. In this diagram, the RF signal is downconverted or mixed down, filtered and then amplified before being converted to digital data. The transmit operation uses the reverse flow. A Massive MIMO system encompasses hundreds of these fundamental SISO elements.

In order to use off-the-shelf equipment to lower cost and expedite prototype development, it is assumed that each In Phase (I) and Quadrature (Q) sample is 16 bits. The number of bits determines dynamic range and in effect may be more than enough for the prototype. Fewer bits of resolution can reduce the data throughput significantly especially when aggregating so many channels. Although 16 bits increase the data path and ultimately the data throughput requirements – more bits lead to wider data paths and increased data throughput requirements – off-the-shelf components and programming architectures handle 16-bit samples easily without customization.

Next consider the sampling rate. Each analog-to-digital converter (ADC) in the receive chain must sample the downconverted waveform at a rate greater than the bandwidth of the channel consistent with the Nyquist theorem. This example will focus on using LTE as a baseline, a common cellular scenario, where each converter samples the received waveform at a sample rate of 30.72 MS/s. In fact, the converter may oversample the signal to increase resolution but may increase the signal processing to convert the data rate to a data stream that a standard signal processing block can accept. The data throughput can be derived using the following equation:

(2 samples) (16 bits per sample or 2 bytes/s) (sample rate)

For the example described above:

(2 samples) (2 bytes/s) (30.72) = 122.88 MB/s

TABLE I

SURVEY OF COMMERCIALLY-AVAILABLE BUS TECHNOLOGIES

Bus Technology			Latency	Raw Data	MBytes/s per Lane	Aggregate Rate (MB/s)	Typical (MB/s)
PCIe	Gen 1	×4	µsec	2 Gb/s	250	1000	900
	Gen 2	×8	µsec	4 Gb/s	500	4000	3600
	Gen 3	×8	µsec	8 Gb/s	1000	8000	
1 GE			msec	1 Gb/s	125	125	112.5
10 GE			msec	10 Gb/s	1250	1250	1125

For the example system description, the aggregate data throughput for one channel equals 122.88 MB/s.

To scale to a Massive MIMO system, the effective rate can be calculated as follows:

Total System Throughput (TST) = (Throughput rate/channel) (number of antennas)

TST = (122.88 MB/s) (128)

TST = 15.7 GB/s

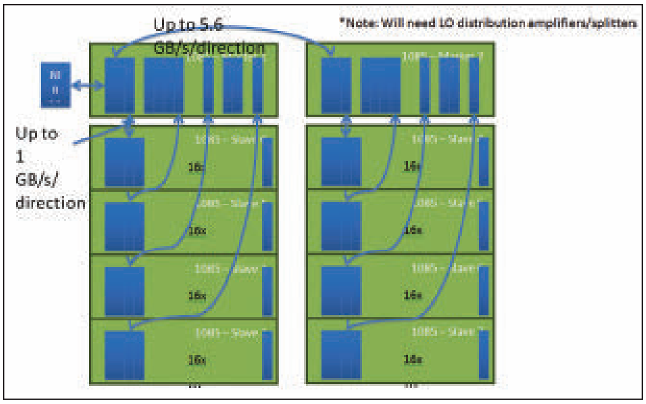
Thus, if all channels were either transmitted or received simultaneously, then the data throughput to the central processing system would be 15.7 GB/s. In addition, aggregating all of this data into the central processing system requires a processing engine capable of accepting this massive amount of data and the capacity to further process the data in order to produce a communication link.

Two challenges are revealed through this brief analysis. First, there are few, if any, low-cost commercially-available technologies that can address these requirements. Second, the data rate for the prototype requires exploration of alternative partitioning of the signal processing chains including distributed and parallel implementations.

Reviewing the available technologies for prototyping, we present a brief survey of high speed serial buses that potentially can be used as the data framework for constructing the Massive MIMO prototype.

Table 1 presents an overview of some high-speed commercially-available bus technologies today. There are other buses, of course, but this table presents a guideline of many of the popular buses today that are open standard and not proprietary. In addition, these bus technologies are used in many of today's modular architectures such as PXIe, which is fundamentally based on the PCIe standard.

One specification that should be considered is latency. Latency describes the turnaround time between a transmit and receive operation. If the prototype is for a unidirectional link, then latency is of less importance. However, for a true TDD Massive MIMO prototype, latency must be considered as it is critical for the turnaround time to be shorter than the coherence time of the wireless channel so that the downlink precoding is not based on outdated channel



▲ *Fig. 4 Example implementation using PXIe.*

information. The latency specification given here is an approximation. However, in general, Ethernet latency is non-deterministic and can vary significantly. On the other hand, Ethernet implementations tend to be lower cost.

It should be noted that PCIe Gen 3 implementations are just now appearing on the market and measured actual throughput data was not available. It should also be noted that although maximum/peak data rates are widely available, typical implementations where the bus is actually implemented vary due to cost, IP core size and power. The typical numbers are provided as a guideline as few, if any, implementations will achieve the maximum published rates.

Figure 4 shows an example system configuration using PXIe. In this configuration, a total of 10 chassis are used to achieve a 128-antenna Massive MIMO system. The system employs two "Master" chassis to aggregate the data and eight slave chassis housing 128 transceivers (NI 5791 RF transceiver) capable of transmitting and receiving in the cellular bands. The data backbone uses PCI Express Gen 2 × 8 to easily capture and transmit 20 MHz of RF bandwidth data with appropriate partitioning.[3,4]

CONCLUSION

Massive MIMO is just one of many new technologies being explored for 5G communications. However, with new technology, a bottleneck between theory and standardization can be prototyping. Massive MIMO's system parameters push the envelope in terms of requirements to actually test the theory and expedite commercialization. Although there are many commercially available technologies, PCI express appears to have an optimal combination of sufficient data throughput and low latency to truly test the effectiveness of Massive MIMO in practice. Of course building a complete system requires further work, but one of the central challenges to building such a prototype pertains to the careful analysis of the data throughput, latency and signal processing which are addressed in this article. ■

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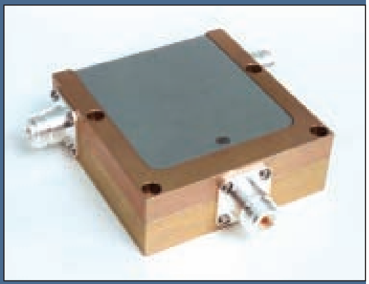

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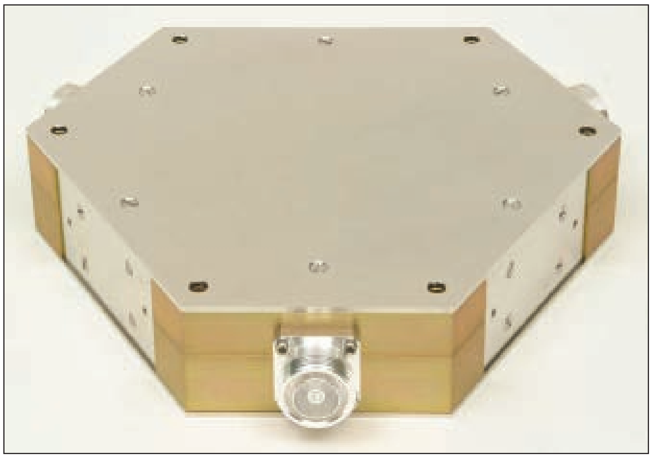

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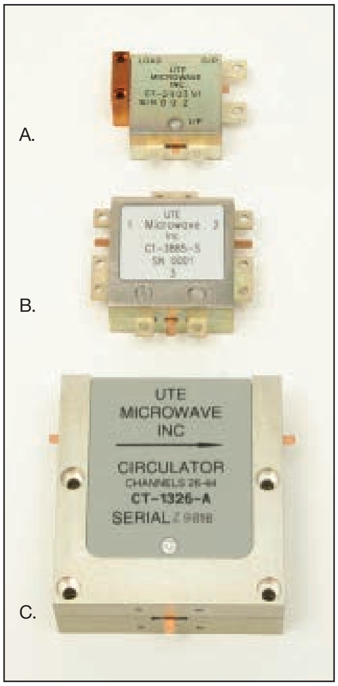

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CT-3838-N	5 Kw Pk 500 W Av	N Conn.	2.7–3.1 GHz
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A Method to Design an Aperture-Tuned Antenna Using a MEMS Digital Variable Capacitor

Paul Tornatta
Cavendish Kinetics Inc., San Jose, CA

This article describes a method for designing a frequency-tunable antenna using a microelectromechanical system (MEMS) digital variable capacitor (DVC) as the tuning element in the antenna aperture. The design example targets a smartphone where the low frequency response of the antenna is tunable from 700 to 960 MHz while the high frequency response from 1710 to 2170 MHz remains fixed. Significant performance improvement is shown when compared to an impedance tuning approach.

Smartphone industrial design is trending toward larger screens, larger batteries, flatter designs, multiple cameras and metallic cases. In addition, wireless network operators are moving to LTE requiring 2×2 MIMO, as well as carrier aggregation (combined frequency bands) supported in LTE-Advanced. Carrier aggregation requires the RF front end to operate over multiple, widely-spaced frequency bands or over very wide frequency ranges. These trends are making space-constrained, cost-effective front ends more difficult to design. One approach is to use additional components with complex switching networks adding signal loss, cost and complexity. A better approach is to use tunable components including filters, power amplifiers and antennas.[1]

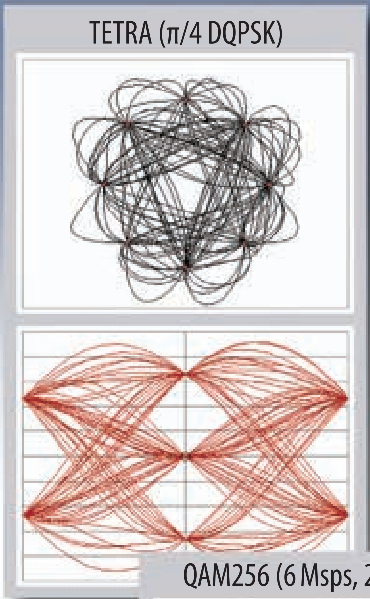
Considerable effort is being spent on improving the entire RF chain, including broadband, tunable power amps, tunable filters and tunable matching networks. While tunable matching networks can deliver more power to the antenna, a much more significant improvement is possible by improving the radiation efficiency of the antenna, particularly with antenna frequency tuning (AFT), which tunes the antenna in the aperture. ***Table 1*** shows typical losses attributed to components in the RF front end. Reducing losses in the antenna can have a significant impact on overall efficiency.

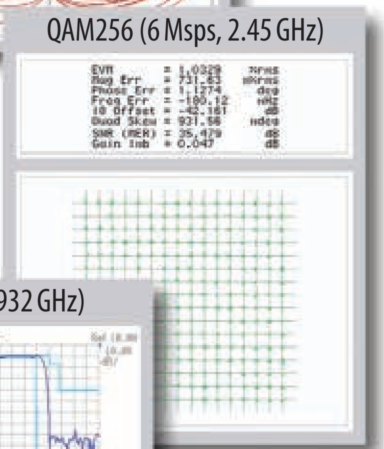
Antenna radiation efficiency is affected by physical size of the antenna and the instantaneous bandwidth required. To cover a wide frequency band, it must be large or the efficiency will be low; yet the antenna's physical size is constrained by industrial design trends. This makes the cellular antenna system a good candidate for tuning.

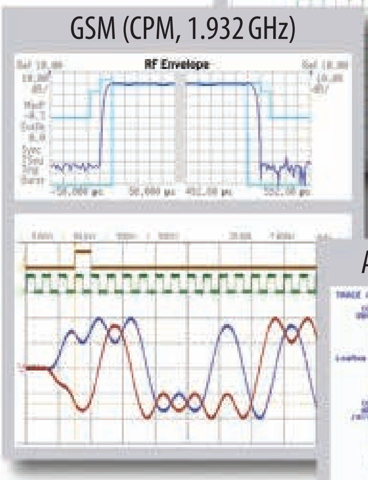
TABLE I
RF FRONT END LOSSES

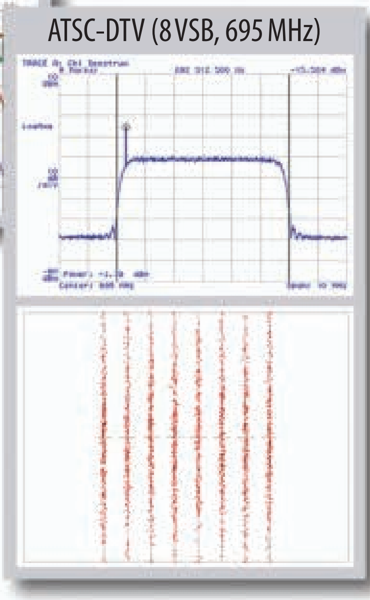
	Filters	Switches	Fixed Matching	Antenna
Loss (dB)	1.0 to 2.0	0.5 to 1.0	0.25 to 0.50	3 to 8
Loss (%)	20 to 37	10 to 20	6 to 10	50 to 85

Vector Signals at the touch of a button









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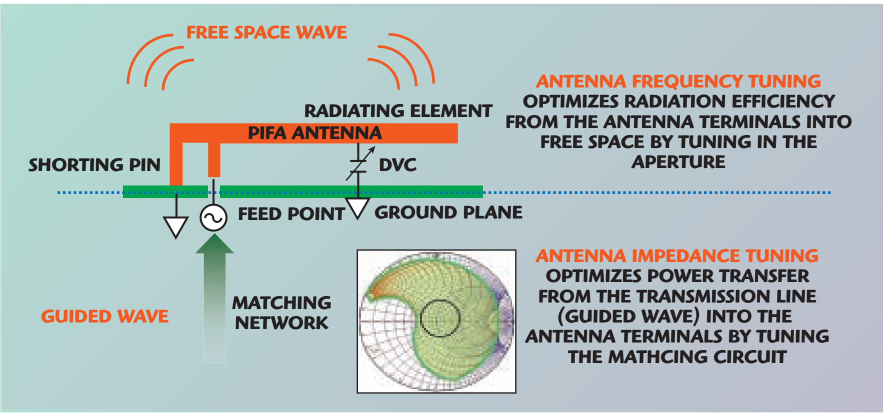
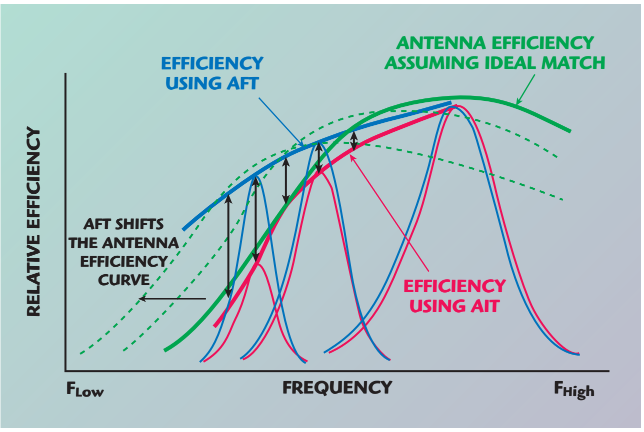


▲ *Fig. 1 Two types of antenna tuning.*



▲ *Fig. 2 AFT compared to AIT.*

TABLE II

KEY DEVICE CHARACTERISTICS FOR AFT

Performance Metric	*Impact*	*Tuning Device Requirements*	
Antenna Efficiency	Total Radiated Power (TRP), Total Isotropic Sensitivity (TIS)	Low C_{min} Low ESR High Q	C_{min}<0.5 pF ESR<0.5 Ω Q>150 @ 2 GHz Q>225 @ 750 MHz
Tuning Range	Band Coverage	C-range High SRF	C range: 0.5 to 1.5 pF SRF>8 GHz
Low Noise	TIS	High IIP3 Low Harmonics Low Parasitics	IIP3 > 65 dBm Tx spurious < -85 dBm Rx spurious < -120 dBm

ANTENNA TUNING

Antennas are transition devices (transducers) between guided waves and free space waves. There are two forms of tuning in antennas: 1) Antenna frequency tuning (AFT), as mentioned earlier, and 2) Antenna impedance tuning (AIT) executed by adjusting the feed point match. ***Figure 1*** illustrates the difference between AFT and AIT.

AFT optimizes the radiation efficiency of the antenna system, while AIT optimizes the power transfer between the transmission line feeding the antenna and the antenna terminals. AIT uses variable reactive components at the antenna feed point to adjust the power transfer. It is effective over narrow bands, but has limited impact when the frequency tuning range is several hundred megahertz because the antenna itself cannot be both high efficiency and broadband. AFT allows the resonance of the antenna structure to be changed, which optimizes the radiation efficiency over much wider bandwidths than AIT.

Figure 2 shows the difference in efficiency between AFT and AIT. In this example, AFT shifts the total radiated efficiency curve for each tuning state, resulting in higher peak efficiency, whereas AIT follows a single antenna efficiency curve for each tuning state. Using AFT, the antenna can have 2 to 3 dB better efficiency than an antenna tuned using AIT, alone.

DESIGN METHOD

The design method described in this article is for a multiband smartphone antenna and assumes that:

- Coverage is 700 to 960 MHz in the low band and 1710 to 2170 MHz in the high band.
- The low band is tuned while the high band is fixed.
- The antenna is a Planar Inverted F Antenna (PIFA), the most common for smartphones.
- The impedance match is fixed.

KEY DEVICE CHARACTERISTICS

AFT is commonly used in military, civil and land mobile radio applications to tune narrowband antennas over wide frequency ranges. In these applications, the reactive elements are either variable capacitors or variable inductors and are typically large and expensive. For consumer electronic products, there are several device types that are candidates for tunable elements. They fall into two categories: variable capacitors and switches. Variable capacitance devices include varactor diodes, barium-strontium-titanate (BST) capacitors and MEMS devices. Switches include silicon on insulator (SOI), silicon on sapphire (SOS), gallium arsenide (GaAs) and MEMS devices. Switches can be used with discrete capacitors or inductors to create variable reactances or can be used to connect different antenna structures. A quick internet search will yield a large number of variable capacitors; however, due to the nature of these devices, there are no high performance, cost-effective, small, variable inductors on the market. This article focuses on using a variable shunt capacitor for antenna frequency tuning.

A device used for a frequency-tuned antenna in a smartphone must have the characteristics shown in ***Table 2***. The two key characteristics that drive antenna efficiency are ESR and C_{min}.

The Effect of ESR

The most important characteristic is low ESR. An ideal antenna with 100 percent efficiency will radiate all the power available at its input terminals without any losses. In practice, however, antennas have several loss mechanisms. Non-tunable antennas have losses due to impedance mismatch, conduction losses and dielectric losses. Tunable antennas have additional loss from the tuning devices. The goal is to minimize all of these losses. It is essential for the tuning capacitor to have the highest possible Q and the win SEMICONDUCTORS

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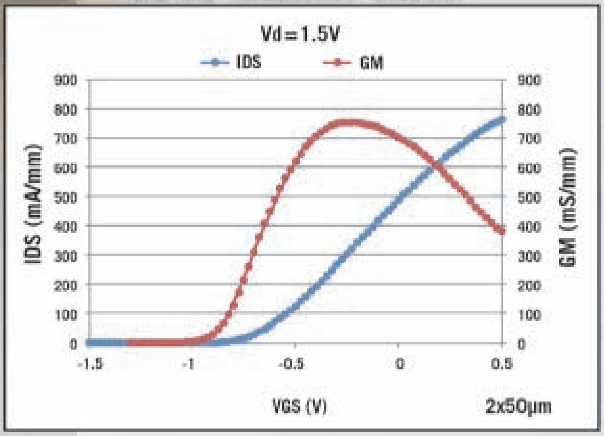
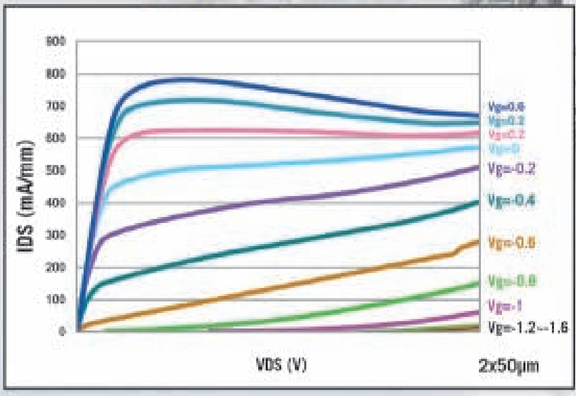
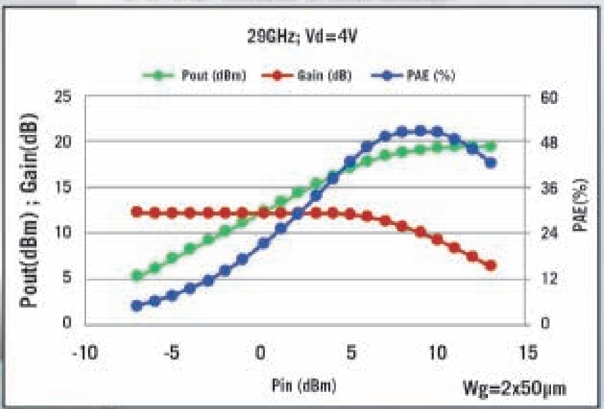


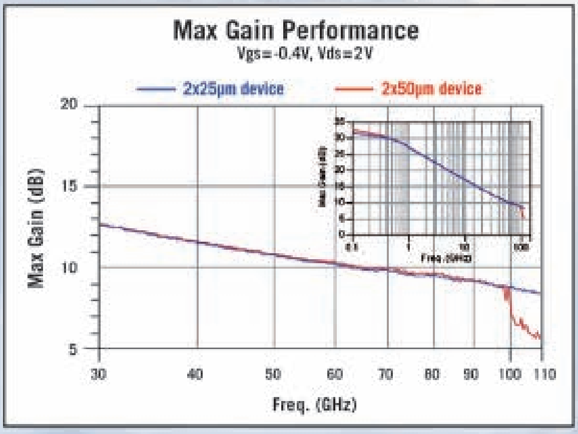
PP10 I-V Curves



PP10 Load Pull Data



PP10 Max Gain



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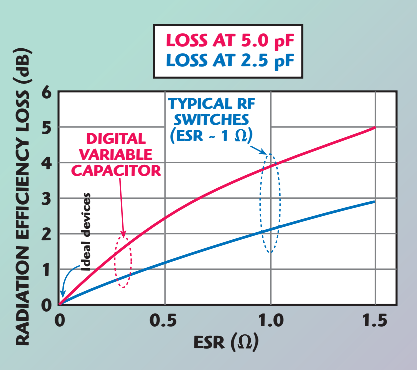
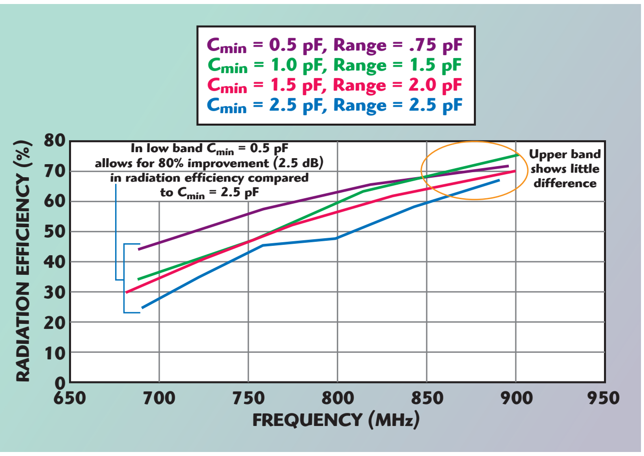
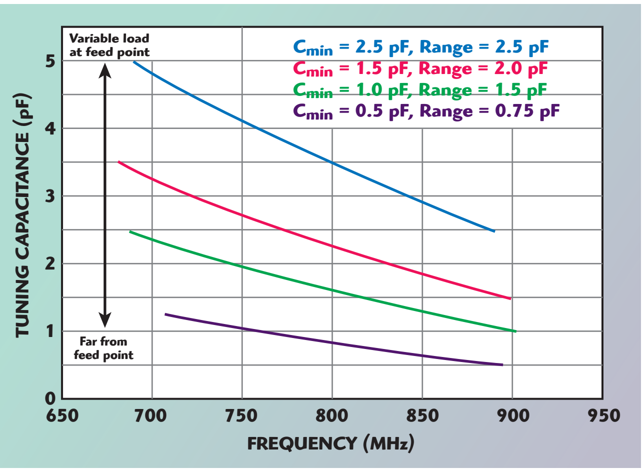


▲ *Fig. 3 Losses due to ESR and capacitance.*

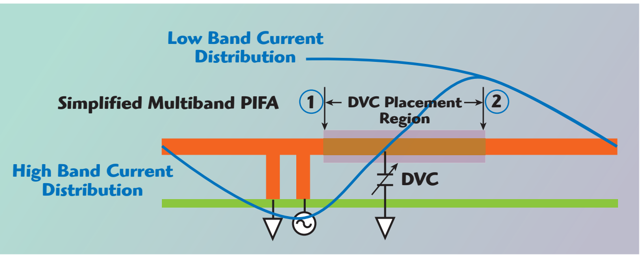
lowest possible ESR. The lowest losses require both low ESR and low capacitance. As shown in ***Figure 3***, an ideal device (ESR = 0 Ω) adds no additional loss. Only one ohm can produce 2 to 3 dB of additional losses making ESR a critical parameter.



▲ *Fig. 4 Impact of C_{min} on radiation efficiency.*



▲ *Fig. 5 Required C range for a 200 MHz tuning range at various tuning locations.*



▲ *Fig. 6 PIFA structure. Location 2 provides a wider tuning range than 1.*

Figure 3 also shows that lower capacitance loading further limits losses.

The Effect of C_{min}

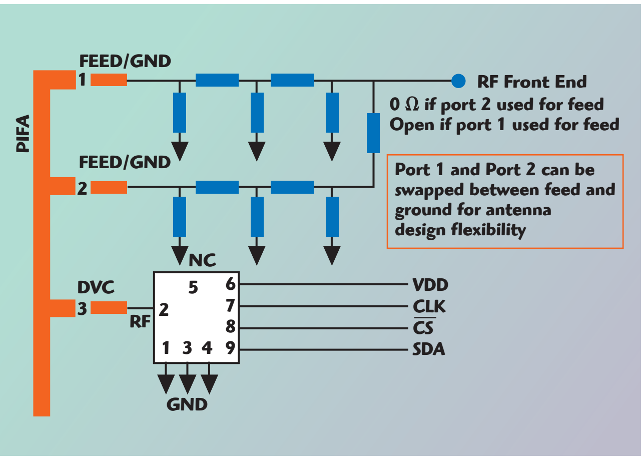
In addition to low ESR, the device must have low minimum capacitance (C_{min}). Loading the antenna aperture with capacitance lowers the resonant frequency, making it appear electrically longer. To compensate, the antenna must be physically shortened. This shortening reduces radiation efficiency. Using the smallest amount of capacitance to load the aperture will result in the largest physical resonant structure and highest radiation efficiency. ***Figure 4*** illustrates the importance of low C_{min} and its effect on radiation efficiency. Lower C_{min} improves radiation efficiency significantly in the lower band.

The Effect of C Range

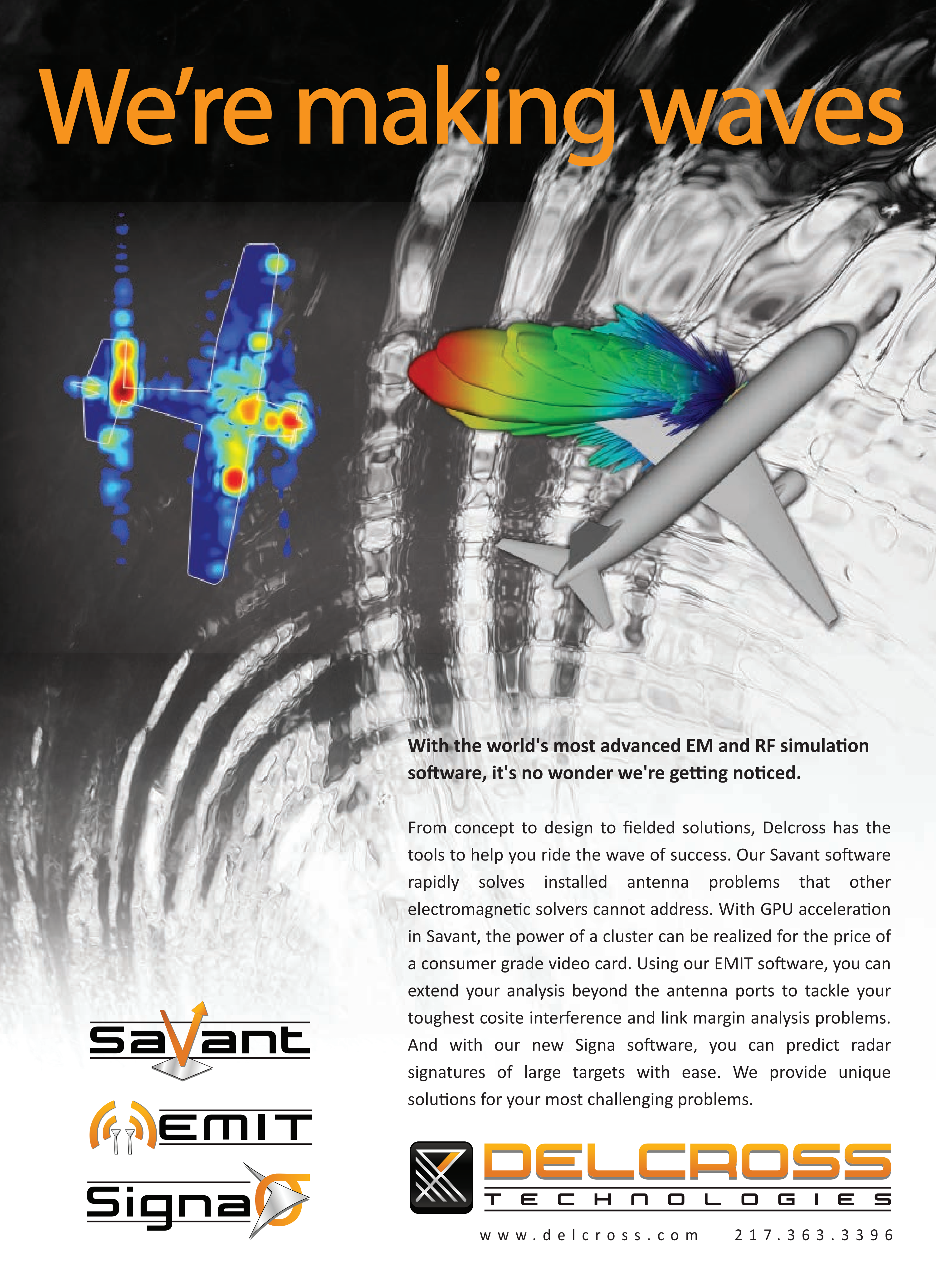
Tuning range is generally considered to be a key characteristic of a variable capacitor. For antenna frequency tuning, however, the capacitor tuning range is not so important. ***Figure 5*** shows how an antenna can be designed to have the same frequency tuning range with a variety of capacitor tuning ranges. This is because the desired frequency tuning range is a design parameter that can be adjusted by selecting the capacitor location on the antenna aperture.

FEED, GROUND AND DIGITAL VARIABLE CAPACITOR LOCATION

Figure 6 shows a sketch of a simplified multiband PIFA structure. Several parameters must be simultaneously optimized to produce a good frequency-tuned antenna design. The first is the location of the antenna feed point. Feed and ground locations are usually determined very early in the design phase and are dictated by industrial design constraints and available printed circuit board (PCB) real estate. The feed geometry is generally determined long before the antenna is designed, sometimes resulting in compromised performance. The best process to mitigate the risk of picking the wrong feed geometry is to make the layout as generic as possible. ***Figure 7*** shows a general schematic diagram allowing the feed and ground points of the antenna to be swapped during the antenna design phase. This layout gives the designer the choice of a normal or reverse-fed PIFA.



▲ *Fig. 7 PIFA schematic allowing feed and ground to be swapped.*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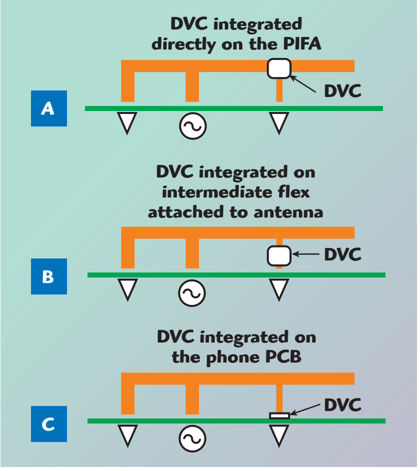


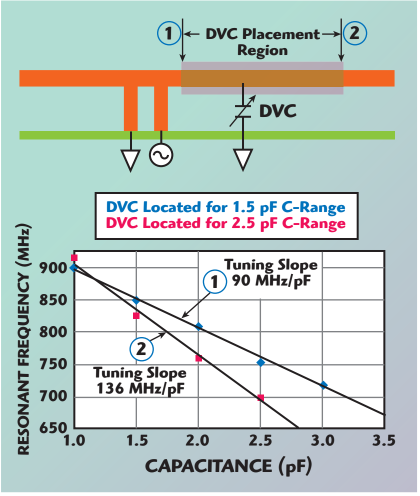
▲ *Fig. 8 Methods for connecting the digital variable capacitor to the antenna.*

VARIABLE CAPACITOR CONNECTION TO ANTENNA

The location of the tuning element is important and is also generally determined before the antenna design is complete. There are three basic methods to connect the tuning element to antenna (see ***Figure 8***). Method C is the preferred method for connecting the capacitor because it is generally close to the antenna feed and ground due to industrial design and PCB layout constraints. This usually results in a suboptimum location, for which the antenna design can usually compensate.

VARIABLE CAPACITOR TAP POINT

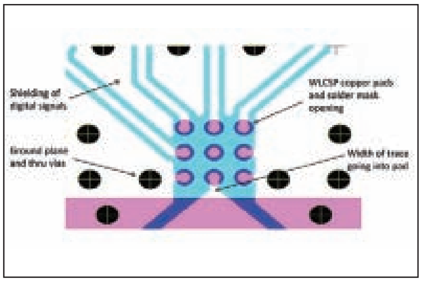
The variable capacitor location affects how much the frequency tunes



▲ *Fig. 9 Change in tuning slope relative to DVC placement.*

with capacitance variation. The tap point can be modified by changing the location and length of the line that runs from the variable capacitor interconnect point to the PIFA low-band arm. ***Figure 9*** illustrates the change in tuning slope relative to variable capacitor location. The farther out the capacitor is on the radiating element, the faster the frequency will change with capacitance.

Variable capacitor location also affects how the high band (1710 to 2170 MHz) reacts with changing capacitance. It is possible to find a location on the antenna where tuning the low band will have no effect on the high band. Radiation efficiency, low-band tuning range and high-band perfor-



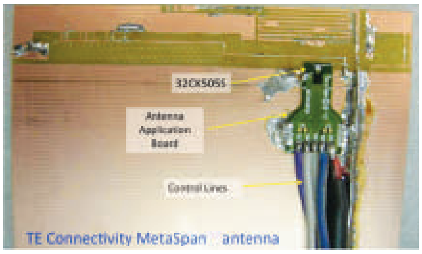
▲ *Fig. 10 PCB layout that minimizes parasitics.*

mance are iterated to find the best antenna performance.

IMPEDANCE MATCHING NETWORK DESIGN

After determining an optimum device location, a fixed matching network is added at the feed point to optimize power transfer between the transmission line and the terminals of the antenna. The matching network is designed by measuring the complex impedance at several frequency points in the bands of interest using a vector network analyzer. The most effective frequency points to choose for optimization are the band edges and at least one point in the middle of each band to ensure that the matching network does not introduce unwanted narrowband behavior. The measured impedance values are entered into impedance-matching optimization software to obtain the best three-, four- or five-element match across the frequency bands of interest.

TABLE III SUMMARY OF MEASURED PASSIVE ANTENNA PERFORMANCE				
Frequency Band (MHz)	*Tuning State*	*Average Return Loss (dB)*	*Average Efficiency (dB)*	*Average Efficiency (%)*
B12 (698-746)	Cmax	–10.3	–2.5	56
B17 (704-746)	Cmax	–11.1	–2.5	56
B13 (746-787)	C21	–9.9	–2.6	55
B5 (824-894)	C10	–7.1	–2.6	55
B8 (890-960)	Cmin	–7.9	–2.9	51
Upper 3G Legacy Bands (1710-2170)	Any	–11.3	–1.9	65



▲ *Fig. 11 Frequency tuned antenna using a DVC driven by an applications board.*

PCB LAYOUT CONSIDERATIONS

Since antenna performance is dependent on reactive loading, it is important to minimize parasitic capacitance and inductance between the device and the antenna. This can be done by following good RF PCB layout practices. ***Figure 10*** shows an example of proper PCB layout around a variable capacitor.

MUTUAL COUPLING

Another parameter that must be considered is coupling between multiple antennas. MIMO operation in 4G systems requires at least two antennas. The interaction between antennas operating in close proximity to one another is called mutual coupling. In a MIMO system, the mutual coupling can be large because both antennas are operating at the same frequency at the same time. Energy coupled from one antenna to another cannot be recovered and lowers the efficiency of both antennas. In a MIMO system it is important to have high isolation between antennas.

Frequency tuning both the primary and secondary antennas in a MIMO system allows both antennas to be tuned and/or detuned to improve the isolation, lowering the mutual coupling and improving the efficiency. Tuning the main and diversity antenna separately can provide a large benefit in data rate throughput since the diversity gain is proportional to antenna isolation.

MEASURED RESULTS

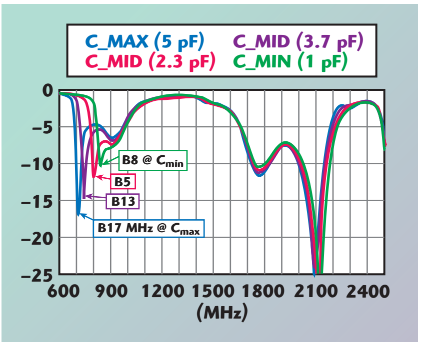
The key performance parameters for passive antenna evaluation are return loss and average gain (efficiency). Passive antenna parameters are shown in ***Table 3*** for a multiband tuned antenna structure. For carrier qualification, the relevant active performance parameters are total radiated power (TRP) and total isotropic sensitivity (TIS). These measurements are taken on the completed phone assembly and are usually done in a controlled environment, such as an anechoic chamber. The phone is placed in the chamber and a call is initiated with a base station simulator (call box). Data is taken over a complete sphere to evaluate phone performance in all directions. The measurements are performed using phantom heads and hands to simulate the loading effects of the human body. At this stage of qualification, it is often necessary to tweak the antenna to optimize performance. This is where tunable antennas provide a big advantage. During active testing, tuning of both the primary and secondary antennas can be adjusted to optimize TRP and TIS. The tuning can also be adjusted to compensate for variations in the device usage model, mitigating head and hand detuning effects. The

antenna tuning settings for various usage models can be stored in look-up tables and recalled during normal phone operation.

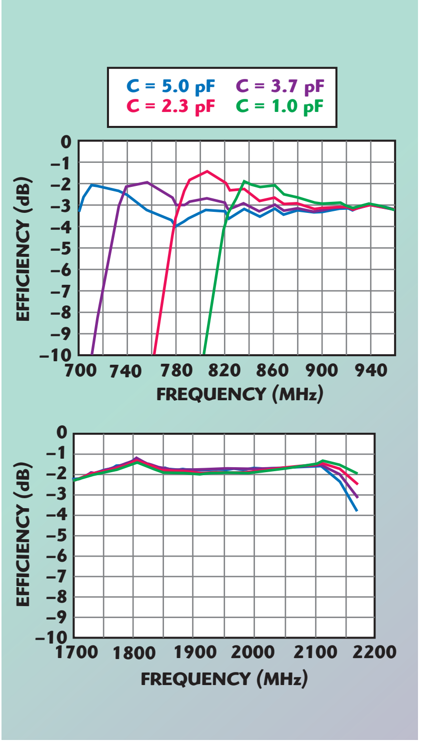
PASSIVE TESTING

Figure 11 shows a frequency-tuned antenna structure developed by TE Connectivity using the Cavendish Kinetics digital variable capacitor model 32CK505S. The antenna is on the edge of a 100 × 60 mm ground plane. Antenna dimensions are 60 × 10 mm. The 32CK505S is mounted on an antenna applications board which is soldered to the main board ground plane.

Figure 12 shows the return loss for the antenna and *Figure 13* shows the measured efficiency. Table 3 summarizes the measured return loss and radiation efficiency for different frequency bands and capacitor settings. The data shows the low band of the antenna tuning from C_{min} – Band 8 with a high-band edge frequency of 960 MHz down to C_{max} – Band 17 with a low-band edge frequency of 704 MHz. As the low band is tuned, the high band from 1710 to 2170 MHz remains unchanged, demonstrating that a frequency-tuned antenna can have a tunable low band while keeping the high band fixed.



▲ *Fig. 12 Return loss of TE Connectivity MetaSpan Antenna.*



▲ *Fig. 13 Measured efficiency of TE Connectivity MetaSpan Antenna.*

ACTIVE TESTING

Industrial design features, such as the size of the display and battery, the thickness of the phone and the location of cameras and connector ports have a significant effect on antenna performance. The measured data shown in *Figure 14* is a summary of the TRP from a complete smartphone assembly comparing AIT and AFT. The baseline performance identified as 100 percent on the chart is the performance of AIT in Band 17 and Band 5. The AFT

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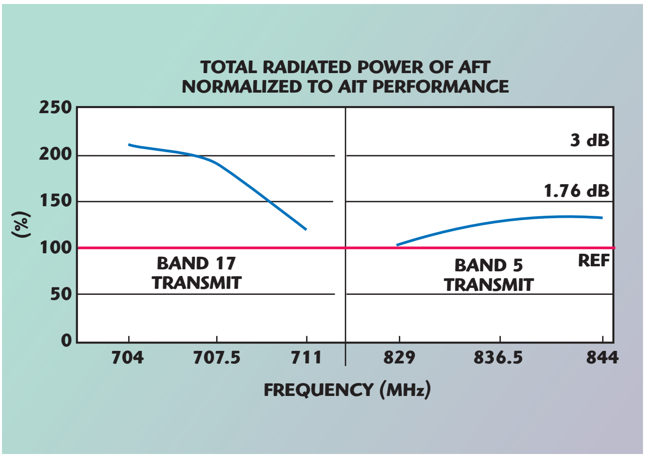


▲ *Fig. 14 Active measured data comparison between AFT and AIT in a smartphone platform.*

performance is better in both Band 17 and Band 5. The performance in Band 17 (lower frequency band) is better than Band 5 due to the optimization of the fundamental antenna resonance in Band 5. This is similar to the performance shown in Figure 2.

CONCLUSION

Operator qualification requirements, industrial design constraints and consumer demand for high-speed data are driving the need for tunable RF front ends in smartphones. Antenna radiation performance is strongly dependent on smartphone industrial design constraints and is limited by the physical volume for antenna implementation making the antenna a good candidate for tuning. AFT (where the tuning element is part of the antenna aperture and is used to optimize radiation efficiency) is an effective form of antenna tuning; however, to tune the antenna and achieve a measureable benefit, the tuning element must have very low ESR (high Q), low C_{min} and good tuning range.

Several key design variables must be considered to design a good tunable antenna including feed, ground and tuning element location, tuning element connection to the antenna, tuning element tap point on the antenna, impedance matching network design, PCB layout to minimize parasitics, and mutual coupling to diversity and MIMO antennas. Measured data from a smartphone equipped with a DVC-enabled tunable antenna shows significant performance margin. ■

Reference

1. P. Carson and S. Brown, "Less is More: The New Mobile RF Front-End," *Microwave Journal*, Vol. 56, No. 6, June 2013.

Paul Tornatta *has more than 25 years of experience in the aerospace, wireless, telecommunications and automotive industries. Before joining Cavendish, he served as CTO of Skycross, a leading mobile antenna supplier. Prior to that, he served as vice president of the automotive business unit at Radiall Corp., a leading supplier of RF interconnect products. He also served in a variety of leadership positions at Larsen Antenna Technologies, Metricom and Lockheed Martin. Tornatta earned a bachelor's degree in electrical engineering from New Mexico State University. He has written articles on RF design and electromagnetics for a variety of RF trade publications. He is a member of IEEE.*

A Very-Near-Field Measurement Technique to Test Large Antennas in the Lab

Ruska Patton
EMSCAN, Calgary, Canada

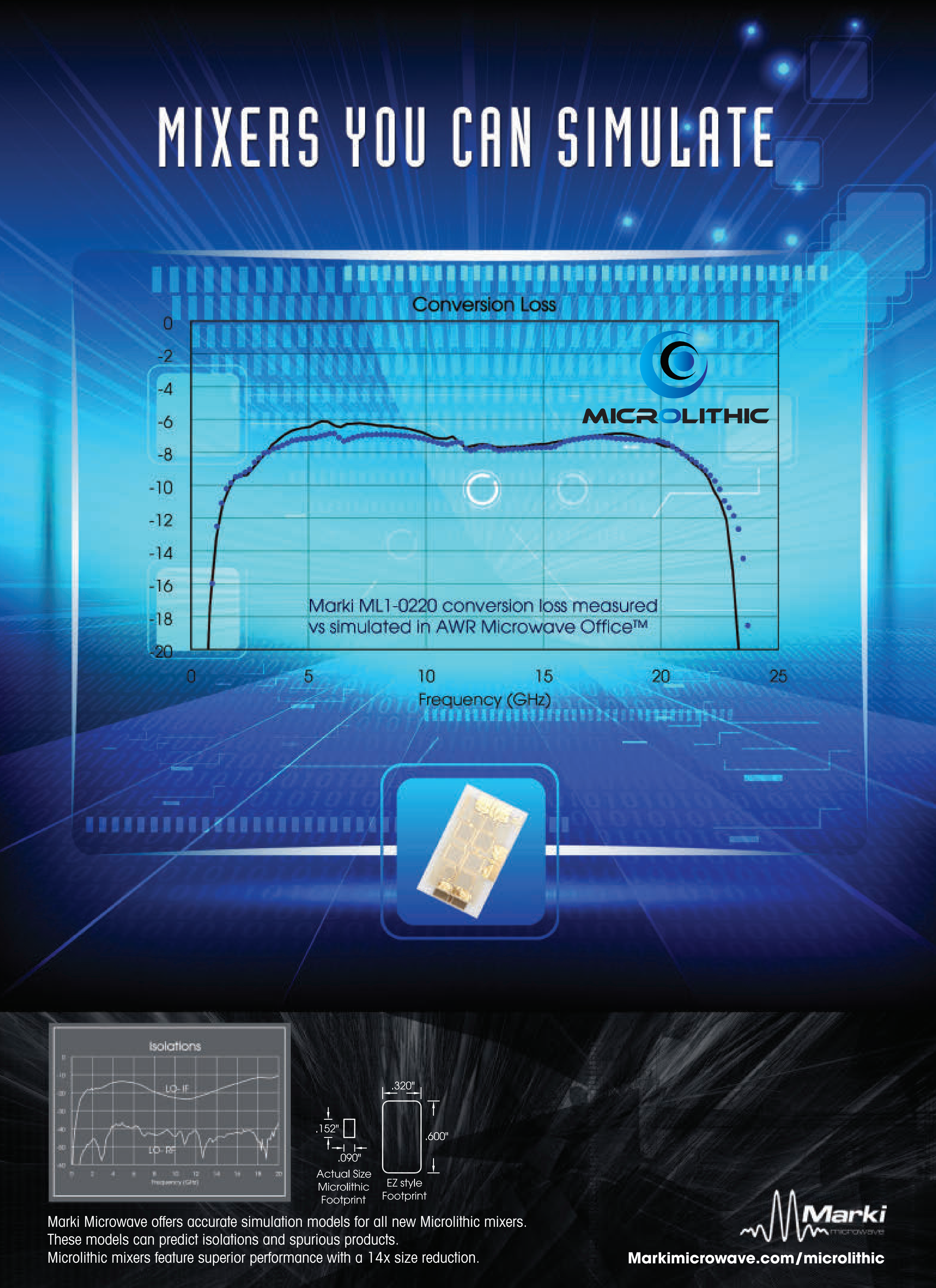
Far-field characterization of antennas that are both electrically and physically large can be a challenging task since the far-field region of these antennas can be quite long. A good example of this is a base station antenna at 700 MHz. The rule of thumb for the boundary of the far-field region in this situation is

$$d = 2D^2/\lambda \quad (1)$$

where D is the largest dimension of the antenna and λ is the free space wavelength. A base station antenna might be 1.2 m long and at 700 MHz, the free space wavelength is 0.42 m. Hence, the far-field region for such an antenna begins approximately 13.6 m from the antenna. This means specialized test sites would likely be required.[1,2] These test facilities can have long lead times to schedule testing. On top of this, many base station antennas have mechanical tuning that requires multiple measurements. Characterization of these antennas in the far-field region can be time consuming and very costly.

There is an alternative to direct far-field measurement, which is based on very-near-field measurement. The very-near-field measurement approach has already been successfully commercialized for small antennas.[3] The implementation of this method is based on an array of small magnetic field probes which sample the fields in the very-near-field region of the antenna. Algorithms can then transform these measurements to far-field data in a matter of seconds. Theoretically, this method can be scaled to arbitrarily large antennas. However, increasing the size of the array of probes has serious practical limitations.

To overcome these limitations, a method has been developed to combine multiple very-near-field measurements to form a larger synthetic measurement area. This method will divide the desired very-near-field region into tiles, each the same size as the array of probes. The measurement array will sequentially measure the fields in each of these tiles. If the resulting very-near-field tiles are properly combined together like puzzle pieces, the transformation to the far-field will provide ac-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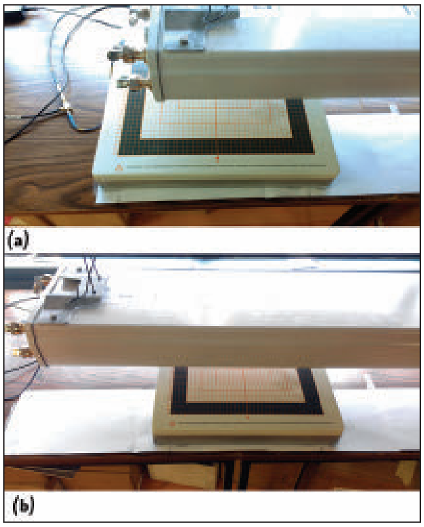
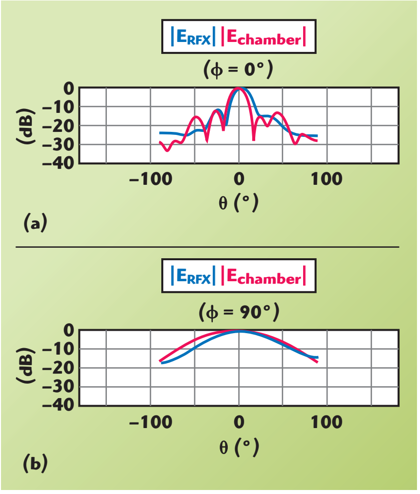
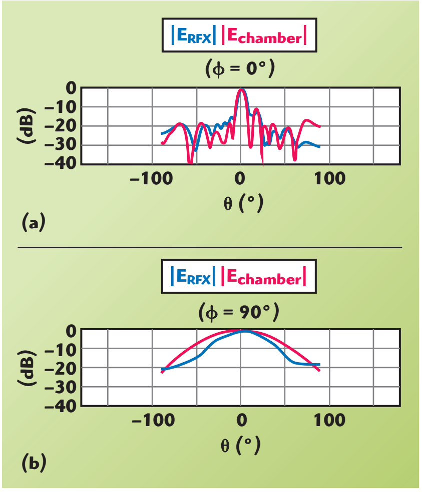


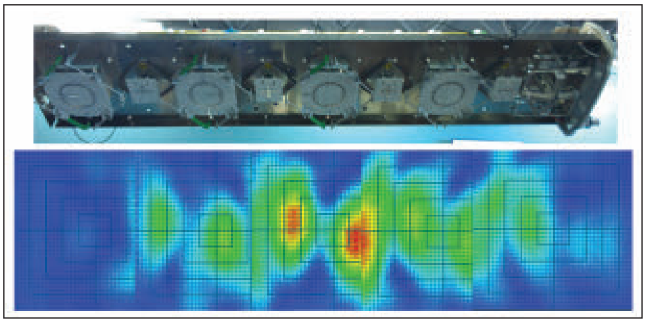
▲ *Fig. 1 Very-near-field array in the first position (a) and in the next position (b).*



▲ *Fig. 4 Base station antenna radiation pattern at 700 MHz for elevation (a) and azimuth (b) cuts.*



▲ *Fig. 5 Base station antenna radiation pattern at 1950 MHz for elevation (a) and azimuth (b) cuts.*



▲ *Fig. 2 The magnetic very-near-field intensity right below the base station antenna.*

▲ *Fig. 3 Absorber placed between the measurement array and the antenna under test.*

curate results for the entire synthetic measurement area.

This article will show sample results for what is called the multi coplanar approach. This approach combines multiple planar very-near-field tiles and provides the far-field radiation pattern for arbitrarily large antennas.

VERY-NEAR-FIELD SNAPSHOTS

To capture the multiple measurements, a very simple setup is needed. First the antenna under test (AUT) is positioned close to the surface where the very-near-field measurements are to be taken. ***Figure 1*** shows a base station AUT. The antenna is simply suspended over a table in the lab and the very-near-field measurement array is placed in various positions below the antenna to sample the magnetic field radiating in the downward direction. Figure 1a shows the array in the first position at the corner of the desired measurement area. This overall measurement surface is carefully chosen to capture all significant very-near-field radiation under the antenna. In Figure 1b, the array has been moved to the next position such that no gap in the measurement area exists. This move and measurement process continues until the entire scan area has been covered. In this case, five tiles of the 0.40 × 0.40 m measurement array are required.

After the separate measurements are combined together, the resulting very-near-field distribution should be almost as if a single large array were used. The combined very-near-fields of the base station antenna are shown in ***Figure 2***. The antenna, with its cover removed, is shown for reference above the field strength plot. In this way, the correlation between the antenna elements and the field hot spots can be seen.

The combined very-near-field plot depicts some pattern distortion at the seams. This is mainly due to the interaction between the measurement array and the AUT not being constant as the measurement array is moved. It will be shown that despite this field distortion, the far-field results are still very accurate. If greater accuracy is required, this effect can be reduced by placing absorbers between the antenna and the measurement array as shown in ***Figure 3***. However, de-embedding the effect of the absorber on the measurement results is not a trivial task.

TRANSFORMATION TO THE FAR-FIELD

If the measurement array provides polarized magnetic field measurements with phase information, a simple algorithm can be used for transformation of the measured data to far-field data.[4,5] For correct estimation of the far-field radiated power, the mutual coupling effect (loading) of the measurement array needs to be taken into account when doing the transformation.

The far-field radiation pattern of the base station antenna is shown at 700 MHz in ***Figure 4*** and at 1950 MHz in ***Figure 5***. These show a comparison between the pattern calculated from the very-near-field results and the pattern provided by the manufacturer that was measured in an antenna range. The calculated results are labeled as E_{RFX} in this case and show a good correlation with the far-

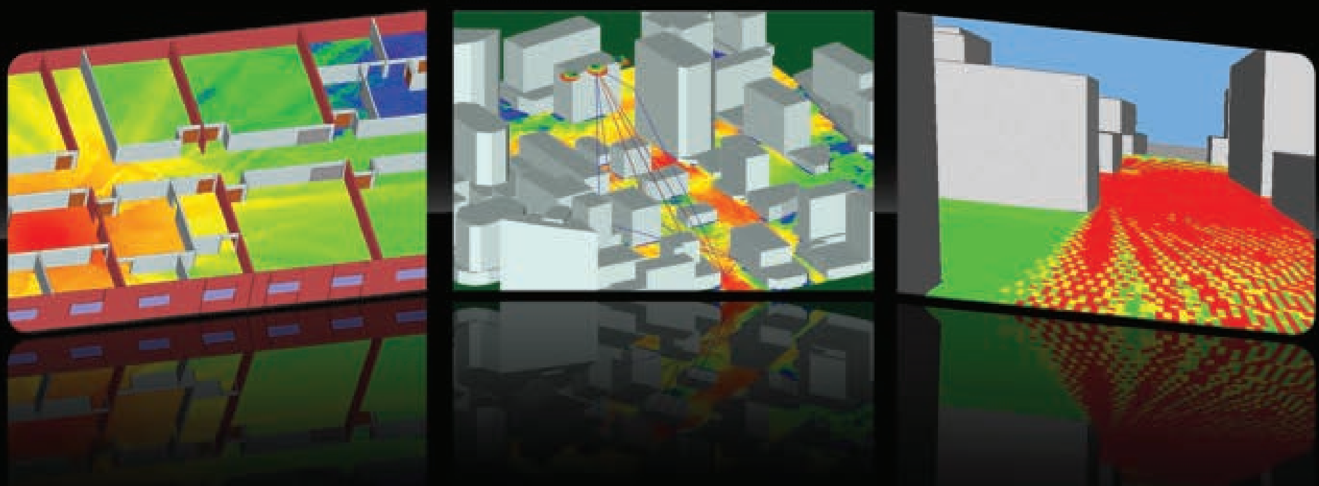


TABLE I

COMPARISON OF THE CRITICAL RADIATION PATTERN PARAMETERS AT 700 MHz

	Multi Co-planar Results	*Datasheet*
Vertical 3 dB Beamwidth	6.35°	6.3°
Horizontal 3 dB Beamwidth	52°	66°
Gain	19.87 dBi (D_{max})	18.2 dBi
Downtilt	2°	0-10°

TABLE II

COMPARISON OF THE CRITICAL RADIATION PATTERN PARAMETERS AT 1950 MHz

	Measurement Results	*Datasheet*
Vertical 3 dB Beamwidth	4°	4.2°
Horizontal 3 dB Beamwidth	28°	33°
Gain	23.55 dBi (D_{max})	23.4 dBi
Downtilt	1°	0 and 2°

field range results, especially for the main lobe in the elevation cut. This is the narrow lobe at 0° that contains most of the energy in the pattern. In this application, knowing the beamwidth and downtilt is critical. The downtilt is how much off center the peak of the main lobe is.

A second set of results is given for a different base station antenna and the beamwidth and downtilt are highlighted (see ***Tables 1*** and ***2***). The results for the multi co-planar approach show very close agreement in the vertical (elevation) beamwidths as well as downtilt. The horizontal (azimuth) beamwidth could be improved by increasing the number of multi co-planar samples in the horizontal direction.

CONCLUSION

When measuring the magnetic very-near-field of an antenna, it is fast and easy to obtain accurate estimates of the radiation pattern and power levels. By combining smaller snapshots of the very-near-field, a reasonably sized measurement array can also quickly measure very large antennas in the lab setting and get good estimates of the critical parameters. This solves the very expensive and time consuming problem of measuring arbitrarily large antennas in very large chambers or outdoor ranges. ■

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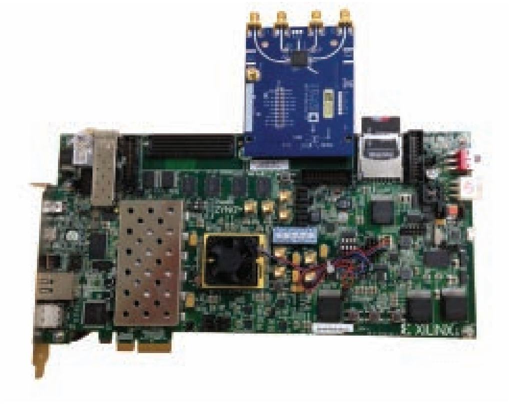

Advanced RF Transceiver Meets the Demands of SDR Applications

Analog Devices
Norwood, MA

Peter Real, vice president of high speed products and technology, Analog Devices.
Visit www.mwjournal.com to read this in-depth interview.

ExecutiveInterview

The astonishing, sometime bewildering array of available wireless standards, with their different frequencies, bandwidths, protocols and formats, has given users unprecedented connectivity and access. But it has also meant that engineers of wireless systems are faced with severe challenges when designing or investigating issues, performance and options.

The solution seems obvious: minimize use of dedicated hardware and instead rely on a software-defined radio (SDR) to implement and manage as much of the transmitting and receiving functionality as possible. Today's high-performance, low-power processors, including FPGAs, and their ability to execute complicated algorithms at high speed make such real-time implementation practical.

But there is a real-world impediment to this solution: it is difficult to design wideband analog circuitry for the receiver and transmitter signal paths. As a result, most broadband SDRs use a set of overlapping, parallel analog channels, each optimized for a specific slice of the overall band, and with bandwidths matched to the signals of interest in each segment. While this approach is technically effective, it requires considerable hardware, PC board real estate, power and, of course, cost.

▲ *Fig. 1 The Maveriq™ Multichannel Reconfigurable RF Transceiver.*

That's the dilemma Epiq Solutions (Schaumburg, IL) faced as it developed its latest SDR unit, the Maveriq™ Multichannel Reconfigurable RF Transceiver (shown in ***Figure 1***), an advanced platform combining multiple RF transceivers, an internal solid state drive (SSD) for data recording, an on-board Intel ×86 CPU running Linux, and a gigabit Ethernet interface for high-speed data access. It offers significant SDR capability in a small package and covers a tuning range from 100 MHz to 6 GHz. As designers and builders of state-of-the-art, reconfigurable radio systems for mission-critical applications, the company's objective was to deliver a more powerful multi-channel version of its existing Matchstiq™ SDR.

Despite its advanced features and capabilities, Maveriq is a portable, low-power platform, while previous solutions required large and bulky hardware configurations. Combined

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45	1.20	1.3
90	1.20	1.3
160	1.20	1.3
200	1.22	1.3
225	1.28	1.3

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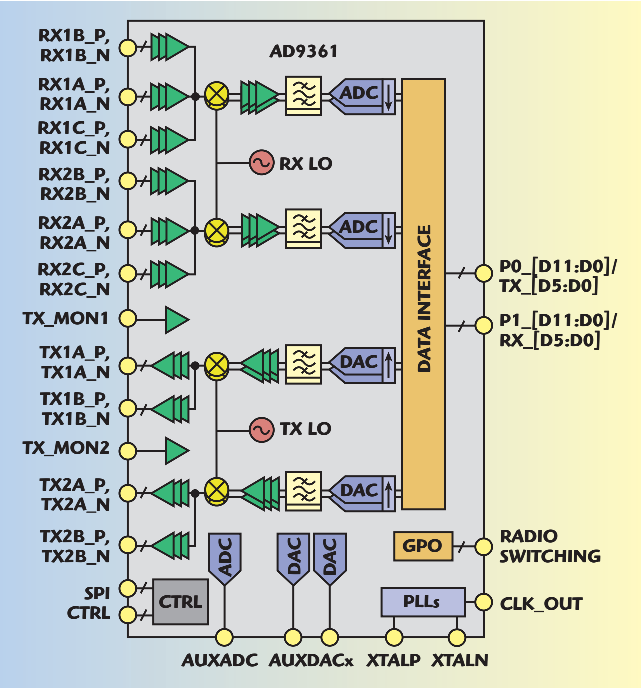


▲ *Fig. 2 Analog Devices' AD9361 RF Agile Transceiver IC block diagram.*

with a library of ready-to-run specialty software applications, Maveriq can immediately be used to solve challenging signal-processing requirements. These include scanning and decoding cellular radio signals from both base stations and mobile phones; recording wideband RF to its internal hard drive (SSD) as well as RF playback; and implementing 2 × 2 multiple input, multiple output (MIMO) waveforms.

ENABLING A NEW DESIGN APPROACH

What allowed the engineers at Epiq to pack this much performance into a small, low-power unit was the availability of a new IC, the AD9361 RF Agile Transceiver from Analog Devices, specifically tailored for SDR applications. According to John Orlando, Epiq's CEO and system architect, "The AD9361 provides the RF flexibility and integration needed to enable our next generation SDR platform."

This 10 × 10 mm chip-scale device with dual independent channels, as shown in ***Figure 2***, has user-tunable bandwidth from 200 kHz to 56 MHz, and 12-bit A/D and D/A converters operating up to 61.44 MSPS, along with other features and the performance that are needed to build a signal chain spanning 70 MHz to 6 GHz. Critical operating parameters are user-adjustable "on the fly" for optimum matching to the application requirements. Using this component reduced the overall footprint of the entire analog front end (AFE) while keeping power consumption for this portion of the design in the 1 W region — essential to stay within the product power budget.

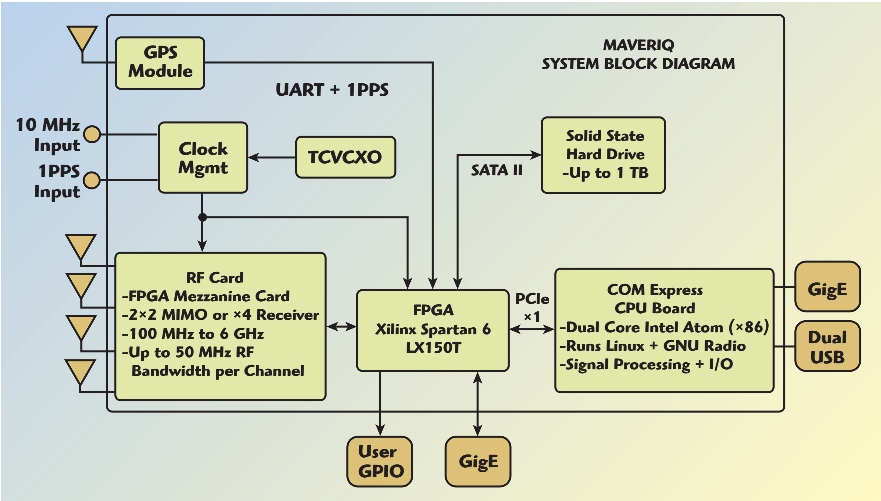
The overall Maveriq unit, shown in ***Figure 3***, supports 2×2 MIMO or 4-channel receiver configurations via a pair of AD9361s, with an RF tuning range from 100 MHz to 6 GHz, 1 kHz step size, and 2 msec tuning time. It includes an integrated GPS receiver with 1 PPS performance, up to a 1 TB internal SSD supporting data recording 100+ MB/sec (sustained), and gigabit Ethernet for interfacing to external systems.

The processing function is centered on a dual-core Intel ×86 CPU running Linux plus an FPGA for signal-processing tasks, along with runtime loadable/executable software applications, all supported by an available software-development kit (SDK) for custom applications. The entire unit is 9.1" × 6.6" × 1.7" (23 × 16.7 × 4.3 cm), weighs 1.9 lbs (0.9 kg) and dissipates 15 W (depending on FPGA and I/O usage).

Of course, processing power is inadequate without suitable RF performance. The receiver has a typical noise figure of less than 8 dB and typical IIP3 of –10 dBm. Transmit-side performance parameters (such as bandwidth, tuning and speed) complement the receive side numbers, along with output power of +5 dBm.

Although the AD9361 IC was a key enabler for this design, additional improvements are always on the horizon. Certain applications require stretching the RF performance down to the 20 MHz range and below, which is beyond the reach of the AD9361. Further, selection of RF components such as low noise amplifiers (LNA) capable of operating down to 20 MHz can also be a challenge, especially for size and power constrained designs. It is simplistic to think that advances in low-power processing coupled with the availability of large amounts of memory plus high-speed digital I/O and connectivity — all driven by Moore's law — are sufficient for a viable small, high-performance SDR. The reality is that the front end channel for both receive and transmit paths is just as important, and developments in RF ICs that combine analog processing, filtering and conversion not only minimize the algorithm burden, but make much of the actual SDR performance possible.

**Analog Devices,
Norwood, MA,
www.analog.com/
ad9361rftransceiver.**

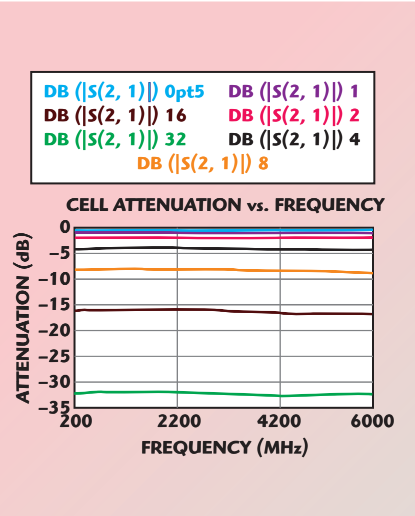


▲ *Fig. 3 The Maveriq unit simplified system block diagram.*

The Next Evolution of Digital/ Programmable Attenuation

Aeroflex / Weinschel
Frederick, MD

At the heart of this digital attenuation solution is a series of USB/TTL controlled MMIC digital attenuators and Ethernet controlled rack mountable subsystems that is suitable for a multitude of RF and microwave applications up to 6 GHz. Designed with budget and performance concerns in mind, these devices offer superior RF characteristics and performance suitable for automated bench testing in wireless backhaul, fading simulation and other high performance wireless applications. All of these models are RoHS compliant.



▲ *Fig. 1 Attenuation versus frequency plot.*

The USB/TTL controlled MMIC digital attenuators, Model 4205 Series, are available in three attenuation configurations up to 95.5 dB in 0.5 dB steps and operate over the 0.2 to 6 GHz frequency range. These devices are supplied with both parallel-TTL and USB 2.0 interfaces. The mode of operation is determined by the source of DC power to the unit. Note: The two interfaces cannot be used in a simultaneous use configuration.

TTL Control: Two pins are specified for supply voltage and ground. The remaining pins will accept TTL control signals to activate or de-activate a particular attenuation cell. A TTL high will energize a cell to the high attenuation state, whereas a TTL low will maintain a cell in its zero attenuation state. The TTL control connector is an AMP-Latch 10-pin ribbon cable connector that mates with AMP P/N 746285-1, which is supplied with each device.

USB Control: The USB interface is compatible with standard USB 2.0 interfaces. In USB mode, DC power to the attenuator is provided by the host USB connection. The attenuator operates as a USB CDC device and accepts simple ASCII text commands. This allows the unit to be controlled from any system capable of sending data via a standard COM

port-style interface. The USB port is a 5-pin female series B mini socket and mates with most standard USB 5-pin male series B mini plug connectors.

These devices offer uninterrupted RF when changing attenuation dB values with excellent solid-state repeatability and performance. Available in three ranges of 0 to 31.5 dB, 63.5 dB and 95.5 dB configurations (see ***Figure 1***). ***Tables 1*** through ***4*** show the performance specifications.

Control software is also included with each device. Aeroflex / Weinschel's LabVIEW based USB Control Center Software (AUCS) can also be used in the operation of this series of digital attenuators. The AUCS will allow the user to set up, control and perform test and measurements using these digital attenuators over a standard USB 2.0 communication interface.

The low profile design of the Model 4205 Series and convenient 12 mounting holes on the front, sides, top and bottom allow for mounting in any subsystem or rack configuration. With this in mind, Aeroflex / Weinschel offers a standard line of half-rack (Model 8320) and full 19 inch rack turn-key solutions (Model 8321 and 8331) containing these devices that offer USB, Ethernet control or front panel operation. Attenuation matrices and custom configurations can also be designed using these building block components. These units are also supplied with LabVIEW-based control software. These devices are already employed in specific applications that include simulation of the cell phone-to-base station RF link; simulation of the WiFi client-to-access point RF link; precise power level control of RF and microwave signal generators.

VENDORVIEW

Aeroflex / Weinschel,
Frederick, MD
(301) 846-9222,
www.aeroflex.com/Weinschel.

TABLE I

SPECIFICATIONS FOR THE MODEL 4205 SERIES

Nominal Impedance	50 Ω
Frequency Range	0.2 to 6 GHz
Power Rating	+23 dBm maximum
Switching Speed	1 μsec maximum
Control Logic	TTL or USB
Operating Voltage	+5 V @ 50 mA
Temperature Range	0° to + 70°C

TABLE II

ATTENUATION ACCURACY (dB)

dB Range	*4205-31.5*	*4205-63.5*	*4205-95.5*
1 to 7.5 dB	±0.5	±0.5	±0.5
8 to 11.5 dB	±1.0	±1.0	±1.0
12 to 31.5 dB	±1.25	±1.25	±1.25 or 4%
32 to 63.5 dB	—	±1.25	±1.25 or 4%
64 to 85 dB	—	—	±1.25 or 4%
86 to 95 dB	—	—	± 5%

TABLE III

MAXIMUM INSERTION LOSS (dB)

Frequency (GHz)	*4205-31.5*	*4205-63.5*	*4205-95.5*
0.2 to 3	3	4.5	6.5
3 to 6	4	6	8

TABLE IV

MAXIMUM SWR

Frequency (GHz)	*4205-31.5*	*4205-63.5*	*4205-95.5*
0.2 to 0.8	1.50	1.80	2.00
0.8 to 5	1.50	1.50	1.60
5 to 6	1.70	1.50	1.90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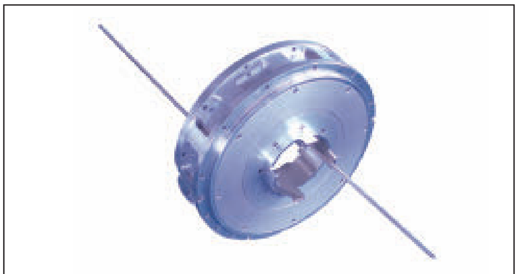
Hybrid Rotary Joints for Radar Applications

SPINNER GmbH
Munich, Germany

Surveillance radars employ multichannel rotary joints as transition gears between the transmit/receive equipment and a directional antenna that is rotating around its azimuth. The task of the rotary joint is to enable low-loss transmission channels between stator and rotor for various electrical and optical signals and also for electrical power and media, if necessary.

Transmission channels can be divided into four different categories according to their primary function: RF channels (high and low power signals), power channels (for power supply of electrical equipment), media channels (cooling media, dry air, etc.) and data channels (optical, Ethernet, RS232, RS422…). SPINNER has built up increasingly complex hybrid rotary joints to serve all those customer requirements. Here, a range of the latest transmission paths that have been developed for radar applications is described.



▲ *Fig. 1 Modular RF channel rotary joint for L-Band secondary radar.*

DATA CHANNELS

The basic function of a classical low power RF joint is the submission of data that is collected by the antenna. ***Figure 1*** shows an L-Band medium power channel rotary joint with a relatively large center opening. It has a frequency range of 1 to 1.1 GHz, an average power rating of 500 W, typical insertion loss of 0.5 dB and a 70 mm diameter.

A higher data rate can be achieved with a contactless fiber optic rotary joint. Optical rotary joints are available as single mode as well as multi-mode solutions with up to 20 channels. SPINNER's new optical rotary joint family is available with four mechanical housings: A single channel joint, a dual channel joint, a small multichannel housing with space for up to six channels (shown in ***Figure 2***) and a large mul-

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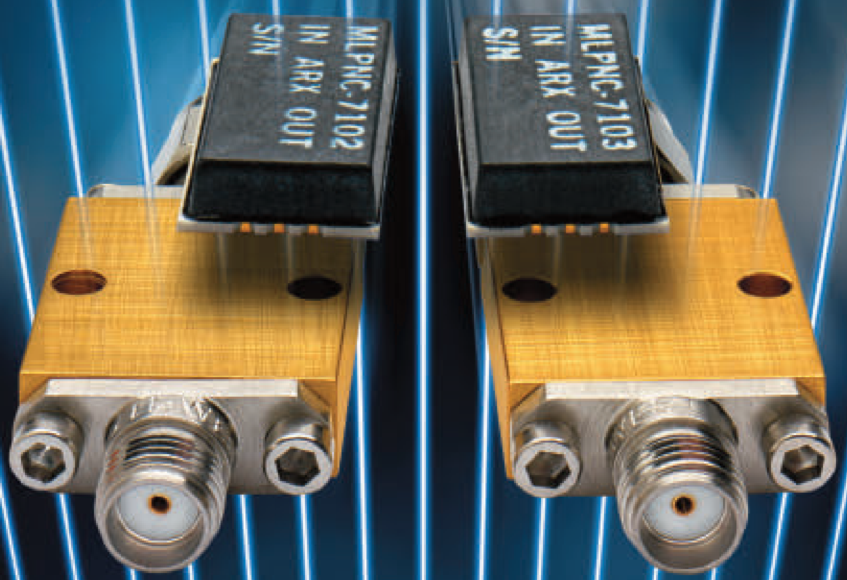

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Non-linear-transmission-line (NLTL) GaAs Comb Generators

Part Number	Power (dBm)		Output Harmonics (dBm)*		
	Minimum	Maximum			
MLPNC-7100-SMA850	20 @ 100 MHz	24 @ 400 MHz	> -8 @ 4 GHz	> -18 @ 12 GHz	> -35 @ 20 GHz
MLPNC-7100-SMT680	20 @ 100 MHz	24 @ 400 MHz	> -8 @ 4 GHz	> -18 @ 12 GHz	> -35 @ 20 GHz
MLPNC-7102-SMA800	21 @ 400 MHz	23 @ 600 MHz	> -8 @ 4 GHz	> -16 @ 12 GHz	> -20 @ 20 GHz
MLPNC-7102-SMT680	21 @ 400 MHz	23 @ 600 MHz	> -8 @ 4 GHz	> -16 @ 12 GHz	> -20 @ 20 GHz
MLPNC-7103-SMA800	21 @ 800 MHz	23 @ 1300 MHz	> -5 @ 6 GHz	> -15 @ 18 GHz	> -20 @ 30 GHz
MLPNC-7103-SMT680	21 @ 800 MHz	23 @ 1300 MHz	> -5 @ 6 GHz	> -15 @ 18 GHz	> -20 @ 30 GHz

* Contact the factory for additional information or for products not covered in the table.

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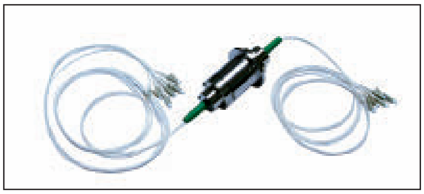
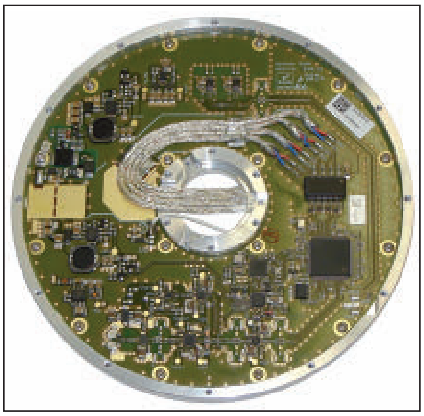
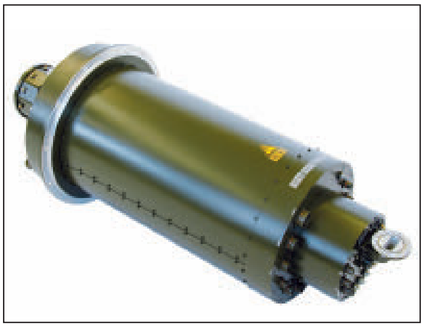
TABLE I TECHNICAL DATA OF THE MEDIA MODULE		
	Channel 1	*Channel 2 + 3*
Medium	Dry air	60% glycols, 40% H_2O
System pressure	2.5 kPa	800 kPa
Flow rate	30 l/min	30 l/min
Pressure difference at max. flow rate	1.5 kPa	100 kPa



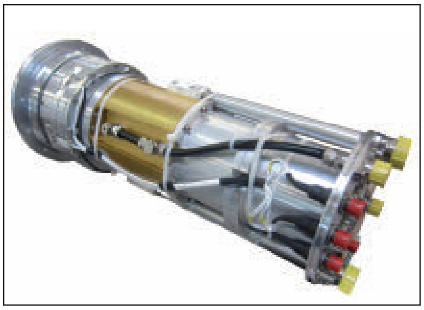
▲ *Fig. 2 Small multichannel FORJ housing with six channels including input and output fibers.*



▲ *Fig. 3 A Gigabit single module.*



▲ *Fig. 4 Multichannel rotary joint.*



▲ *Fig. 5 Hybrid unit including a media joint.*

tichannel housing with up to 20 channels. All optical rotary joints represent a high technical standard with a large temperature range, a high mechanical capability against vibration, shock and bump, as well as very attractive optical parameters.

A newly developed module for contactless bidirectional data transmission with an Ethernet interface is shown in ***Figure 3***. The standards it supports are: 10BASE-T, 100BASE-TX and 1000BASE-T. This module automatically recognizes and selects the connected devices' current Ethernet standard and duplex mode (full or half). All Ethernet modules can be stacked directly and will be attached together to an Ethernet unit which can be implemented into a rotary joint assembly.

MEDIA ROTARY JOINT

Modern radar antennas generate the RF power directly on the rotating part. This process calls for a cooling liquid which needs to be transmitted up and down. In total, three media channels, one dry air and two cooling media, are needed for a typical modern rotary joint. The essential technical data is summarized in ***Table 1***.

The technical data has been chosen in such a way that they meet the customer requirements for a large number of applications. The module was thoroughly tested in SPINNER's test facility and all data stated could be proven in the tests.

When developing the media module, care was taken so that it can also be used in a wide range of other joints. The mechanical flanges allow for virtually any integration into any hybrid joint. In addition to this module, a second module is currently being developed that has an identical technical design, but allows a considerably higher flow rate for cooling water.

The lifetime of a rotary joint is normally limited by the mechanical wear of the sliding contacts. In order to reduce maintenance and increase reliability of a rotary joint, it is necessary to reduce the number of sliding contacts. To eliminate wear completely, contactless systems need to be used. Contactless systems are available for RF channels (choke systems with limited bandwidth), data channels (Ethernet and optical joints), media and some power transmission in the range up to 1 kW.

HYBRID JOINTS

Several rotary joints with multiple transmission paths have been realized. The multichannel rotary joint in ***Figure 4*** is used for a radar employing a passive electronically scanned array (PESA). On the antenna unit, which rotates at a speed of up to 30 RPM, digital interface signals as well as the electrical power supply necessary for feeding active electronics and elevation drives are needed. Four Gigabit-Ethernet channels are realized in a contactless way, whereas the power supply is realized with a classical slip ring module.

In 2013, SPINNER developed and manufactured the first hybrid rotary joint not serving an RF path. The media joint was designed for a customer project, in which a phased array antenna is used. In order to cool the electronic components, the supply antenna is supplied with the corresponding coolant.

In ***Figure 5***, the integrated media joint is shown in the assembly process prior to the final completion with the power and signal slip ring module. The elements for the different transmission channels, such as the modules of non-contacting Ethernet transmission, cooling water and air, are clearly identifiable. In addition, there is a 20-channel fiber optic multimode rotary joint as well as a 14-bit encoder system inside the hybrid system.

As can be seen, the SPINNER portfolio of hybrid rotary joints for radar applications is comprehensive and expansive, meeting all requirements, in any format. The range continues to expand and 2014 will see new products enter the market.

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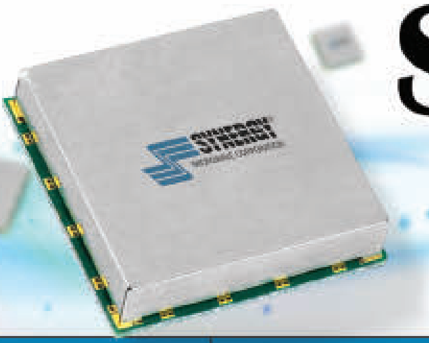

RoHS

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Model	Frequency (MHz)	Tuning Voltage (VDC)	DC Bias VDC @ I [Max.]	Phase Noise @ 10 kHz (dBc/Hz) [Typ.]
HFSO640-5	640	0.5 - 12	+5 @ 35 mA	-151
HFSO745R84-5	745.84	0.5 - 12	+5 @ 35 mA	-147
HFSO776R82-5	776.82	0.5 - 12	+5 @ 35 mA	-146
HFSO800-5	800	0.5 - 12	+5 @ 30 mA	-146
HFSO914R8-5	914.8	0.5 - 12	+5 @ 35 mA	-139
HFSO1000-5	1000	0.5 - 12	+5 @ 35 mA	-141
HFSO1000-12	1000	0.5 - 12	+12 @ 35 mA	-141

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Planar 808/1 characterizes S-parameters in a wide variety of presentation formats. In addition to the traditional frequency domain measurements of S-parameters, it has time domain with gating, embedding and de-embedding, and frequency offset mode for mixer/converter testing.

As a four-port VNA, the Planar 808/1 can be used to measure balanced or differential networks. The Planar 808/1 fixture simulation feature supports testing DUTs with single ended inputs and balanced outputs, balanced inputs and single ended output, and balanced inputs and outputs. Multiport analyzers are also well-suited for testing multiport DUTs such as combiners and duplexers, reducing or eliminating reconnection steps from the testing process. Unlike other four-port VNAs, the Planar 808/1 incorporates two independent generators, providing greater flexibility for advanced test scenarios.

The Planar 808/1 is fully compatible with the ACM8000T automatic calibration module, enabling full four-port calibration with as few as four connection and four disconnection steps. Automatic calibration is particularly time-saving in production environments or other scenarios where frequent recalibration is required. Or, the Planar 808/1 can be calibrated with any commercially available 50 Ω mechanical calibration kit.

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Planar 808/1 can fit into applications needing automation – it is fully programmable by SCPI commands from any programming environment supporting COM/DCOM – including C++ , Visual Basic and LabVIEW. Automation enables remote instrument control and automatic exchange of data among components in an integrated ATE station.

Copper Mountain Technologies,
Indianapolis, IN
(317) 222-5400,
www.coppermountaintech.com.

Enhanced Spectrum Analyzer Performance of Mixed Domain Oscilloscopes

The Tektronix MDO4000B series of mixed domain oscilloscopes now features significantly enhanced spectrum analyzer performance and, when used with Tektronix SignalVu-PC, the widest bandwidth vector signal analysis capability and deep support for WLAN 802.11 a/b/g/j/n/p/ac testing.

The Tektronix mixed domain oscilloscopes are the only oscilloscope with an integrated spectrum analyzer that can capture time-correlated analog, digital and RF signals for a complete system view of a user's device. At its core, a mixed domain oscilloscope combines the functionality of Tektronix' popular mixed signal oscilloscopes (MSO) with a powerful spectrum analyzer in a single instrument. With the introduction of the MDO4000B, Tektronix has significantly enhanced the performance of the MDO's spectrum analyzer compared to the original MDO4000 instruments. These enhancements include the following:

- Spurious Free Dynamic Range (SFDR) has improved to 60 dBc guaranteed and 65 dBc typical (from 55/60 typical) giving users higher confidence while performing spurious searches.
- Phase noise performance has improved as much as 20 dB enabling close-in spurious measurements and phase noise evaluation.
- Vector calibrated I&Q data enable high-accuracy modulation and vector measurements.
- Maximum RF acquisition time has been doubled from 79 to 158 ms enabling longer time correlation with the rest of the system as well as the capture and analysis of multiple bursts of modulated data.
- Lower frequency limit has dropped from 50 to 9 kHz enabling EMI diagnostics over the frequency range specified by internal regulations.

When used with SignalVu-PC vector signal analysis (VSA) software, the MDO4000B offers the industry's widest bandwidth (≥1 GHz) vector signal analyzer, making this combination well-suited for such RF test and measurement tasks as general modulation analysis, pulse analysis, frequency and phase settling, radar and spectrum management.

Tektronix Inc.,
Beaverton, OR,
www.tektronix.com.

Low Cost X-Band Phased Array Weather Radar

FIRST RF and Raytheon have partnered with the University of Massachusetts at Amherst to create an X-Band phased array radar for use in weather measurements. This radar has been deployed to Australia and has been used for weather and bushfire studies since January 2013. Additional units are being used at the University of Massachusetts for weather research. This weather radar provides a low cost tool for demonstrating the use of X-Band frequencies in studying weather phenomena and to explore the operational and maintenance implications of small form-factor phased array technology for weather surveillance.

The prime purpose of this radar is to investigate the feasibility of a low infrastructure, low maintenance, and low cost technology for a variety of weather applications including: airport weather surveillance, hazard detection and monitoring, future operational radar in regions such as mountainous terrain or in the Arctic, and process and precipitation studies. This product represents an early commercial offering of the LPAWR series and is considered an experimental system that includes the following components:

- Up-down converter, antenna controller and radar backend assembly (including DREX)
- Integrated weather-resistant phased array antenna assembly
- Host PC, display, software, power supply and cables

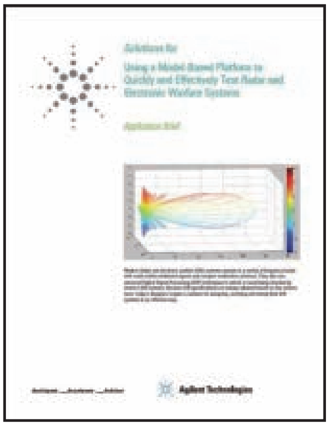
The FRF-166 low power X-Band phased array weather radar antenna is designed as a low cost, low power solution that supports high beam update rate in the azimuth plane, where the weather community needs performance, and saves cost and complexity by offering an optional mechanical tilt capability in the elevation plane. It is a solution for many weather applications including: wind shear monitoring at airports, wind turbine mitigation, gap-fill and other high-resolution weather sensing needs.

FIRST RF Corp., Boulder, CO, products@firstrf.com, www.firstrf.com.

CatalogUpdate

Model-Based Platform App Note

VENDORVIEW

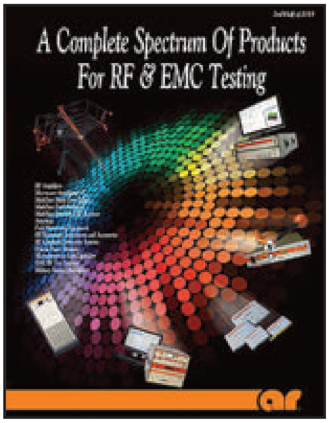


EW systems operate in complex environments with multi-emitter input signals from radar, military and commercial communication systems. This complexity poses a number of challenges when designing and testing Radar and EW systems. The application note "Using a Model-Based Platform to Quickly and Effectively Test Radar and Electronic Warfare Systems" shows how to gain access to a true design-oriented value proposition to shorten the development cycle – saving time and money by minimizing field tests.

Agilent Technologies Inc.,
www.agilent.com.

Product Catalog

VENDORVIEW

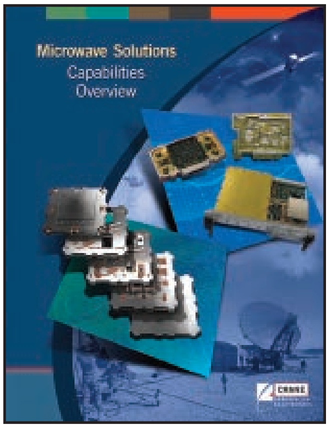


AR has completed another revision of its sought after full line product catalog. Many new products have been included and various sections were updated to provide you with the information required to make your equipment search easier and more in depth. The catalog is easy to use, with "find-it-fast" charts and color coding to help get right to whatever you need for RF & EMC testing.

AR RF/Microwave Instrumentation,
www.arworld.us.

Microwave Capabilities Catalog

VENDORVIEW



Crane Aerospace & Electronics Microwave Solutions has an updated microwave capabilities catalog that features a wide range of product solutions from component-level devices to complex, advanced integrated microwave assemblies. Products are illustrated from major product areas and represent the breadth of technical capability of Crane. Crane's microwave brands include Merrimac, Signal Technology and Polyflon.

Crane Aerospace & Electronics Microwave Solutions,
www.craneae.com.

EM Simulation for Defense Catalog

VENDORVIEW

Electrically large structures such as aircrafts, ships, land vehicles and satellites exist within complex electromagnetic (EM) environments. The advanced EM simulation tool, CST STUDIO SUITE®, is used by government agencies and defense contractors worldwide to address the broad range of problems encountered in the design process of defense technology. This catalog outlines applications of the software, including the analysis of: antenna placement, co-site interference, electromagnetic environmental effects and radar. Download the brochure on the company's website.

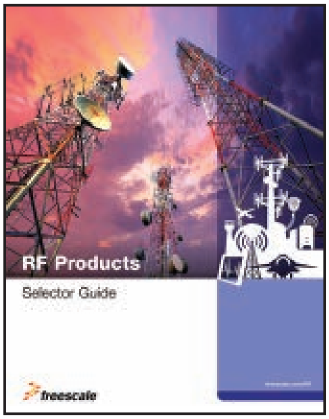
CST-Computer Simulation Technology AG,
www.cst.com.

Finite-Element Software Catalog

Field Precision's Finite-Element Software Catalog describes the basis of finite-element analysis as well as available products. Field Precision creates high-performance 3D finite-element software for Windows. Application areas include high-voltage engineering, microwave devices, magnet design, electron/ion guns, accelerators, X-ray sources and simulations of X-ray imaging. The programs are designed for top speed on multi-core computers. Textbook-quality instruction manuals and libraries of prepared examples are included for quick learning.

Field Precision LLC,
www.fieldp.com.

Product Selector Guide



Freescale Semiconductor's RF Product Selector Guide offers RF products ranging from less than 100 mW to 1.25 kW using GaAs and LDMOS technologies. These products are designed for communication and industrial applications serving wireless infrastructure, broadcast, aerospace, land mobile communication and industrial, scientific and medical (ISM) markets. Freescale offers the broadest portfolio of RF power transistors. Download the Freescale RF Product Selector Guide at www.freescale.com/RFSelectorGuide.

Freescale Semiconductor,
www.freescale.com.

CatalogUpdate

Air Traffic Control Brochure

The rapidly growing air traffic density requires the highest standards of quality and reliability for flight control systems and their components. According to these high demands, HUBER + SUHNER developed a specific range of radio frequency cables, connectors and assemblies, as well as EMP and lightning protectors. All of them have been collected in the new brochure Air Traffic Control, which provides an excellent overview on the product portfolio as well as guidelines for making a proper selection according to your needs.

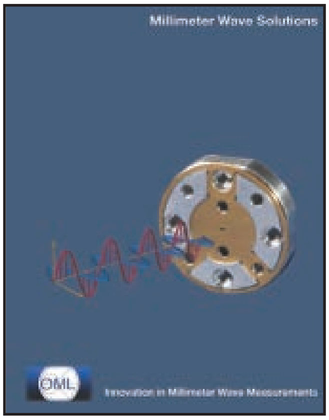
HUBER+SUHNER AG,
www.hubersuhner.com.

Rapid PCB Prototyping Catalog

The LPKF Laser & Electronics In-House Rapid PCB Prototyping Catalog features not only the milling and laser systems the manufacturer has become known for, but also its complete line of through-hole, multilayer and SMT/finishing equipment. LPKF is the only company to provide the full line of equipment necessary to complete in-house PCB prototypes up to eight layers in-house. To learn more about LPKF's in-house PCB prototyping technology, visit the company's website.

LPKF Laser & Electronics,
www.lpkfusa.com.

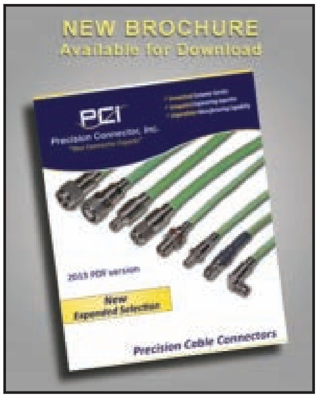
Millimeter Wave Solutions Brochure



OML offers a new solutions brochure summarizing the available millimeter wave accessories for microwave vector network analyzers, spectrum analyzers and signal generators. The solutions span the 50 GHz to 0.5 THz spectrum. The brochure is available for free download on the company's website.

OML,
www.omlinc.com.

Cable Connector Brochure



Precision Connector Inc. has released a new updated Precision Cable Connector Brochure for 2013. The new eight-page brochure features an expanded offering of male and female precision cable connectors designed for low VSWR and insertion loss. These connectors are grouped and matched to specific low loss cables offered by leading cable manufacturers: Harbour Industries, Semflex, Times Microwave, Dynawave Cable, IW Microwave, ATM and Pic Wire & Cable. Also included are various semi-rigid cable sizes in standard RG, low loss and armored versions.

Precision Connector Inc.,
www.precisionconnector.com.

Test & Measurement Catalog

VENDORVIEW

The Test & Measurement Catalog 2013/2014 from Rohde & Schwarz supplies more than 200 pages full of information about the company's test & measurement instruments, systems and software. It includes a short description and photos of each product, the most important specifications and the ordering information. You can download this catalog as a PDF from the Rohde & Schwarz website or order from customer support (order number: PD 5213.7590.42).

Rohde & Schwarz GmbH & Co. KG,
www.rohde-schwarz.com.

Connector Series Application Note

SV Microwave has released a new application note for the SMP, SMPM and SMPS connector series. The SMP connectors operate at high frequencies of DC to 40 GHz; the SMPM connectors operate at high frequencies of DC to 65 GHz; and the SMPS connectors operate at high frequencies of DC to 100 GHz. Please visit the website or email marketing@svmicro.com for more information.

SV Microwave,
www.svmicro.com.

360° e-scan Radar

Consuming less than 100 W of power and with a 38 kg mast payload, the Blighter® Revolution 360 mobile e-scan radar detects small and slow moving targets – even in cluttered environments – due to the radar's coactive frequency modulated continuous wave (FMCW) Doppler fast-scan processing. It can detect a walking person at 7.4 km or a large moving vehicle at 22 km. The system is deployable on vehicle or trailer masts.

Blighter Surveillance Systems,
www.blighter.com.

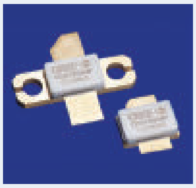
SSPA

Comtech PST introduced a new high power density solid state RF module quickly becoming available in today's marketplace. Comtech's latest development continues to expand on its proven innovative integrated RF GaN power amplifier designs by further increasing the RF power density. Consistent with its planned technology development roadmap, Comtech introduces the latest in GaN-based 6 to 18 GHz RF amplifier. This highly integrated design is ideal for use in communication, electronic warfare, and radar transmitter systems where space, cooling and power are limited.

Comtech PST,
www.comtechpst.com.

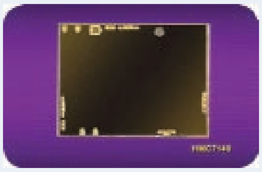
GaN HEMT

Cree's CGHV35150 is a 150 W, 50 V gallium-nitride (GaN) high electron mobility transistor (HEMT) designed specifically with high efficiency, high gain and wide bandwidth capabilities, which makes the CGHV35150 ideal for 2.9 to 3.5 GHz S-Band radar-amplifier applications. The transistor is supplied in a ceramic/metal flange and pill package. It features 13.5 dB power gain, and 50 percent typical drain efficiency. It is specified at 85°C case and features <0.3 dB pulsed amplitude droop.



Cree Inc.,
www.cree.com.

GaN MMIC PA



Hittite Microwave announced a new 10 W GaN MMIC power amplifier product that offers significant performance, size and durability advantages for communications, test instrumentation and radar systems operating in the 6 to 18 GHz frequency range. The HMC7149 typically provides 20 dB of small signal gain and +40 dBm of saturated output power. The amplifier draws 680 mA quiescent current from a +28 V DC supply and features RF I/Os that are matched to 50 Ω for ease of use.

Hittite Microwave Corp.,
www.hittite.com.

Pulsed Power Transistor

MACOM introduced a new ceramic GaN on SiC HEMT power transistor for avionics applications. The MAGX-001090-600L00 is a gold-metalized, matched GaN on silicon carbide, RF power transistor optimized for pulsed avionics applications, such as secondary surveillance radar in air traffic control systems. The MAGX-001090-600L00 provides 600 W of output power with a typical 21.4 dB of gain and 63 percent efficiency. The device has very low thermal resistance of 0.05°C/W and best-in-class load mismatch tolerance of 5:1.

MACOM,
www.macomtech.com.

GaN Transistors

Microsemi's six new sets of transistors with peak output powers ranging from 20 to 1000 W, all designed for 50 V drain bias operation. The total of 24 transistors are designed using the latest in GaN on SiC HEMT proven high voltage wideband gap technology, delivering the best performance and reliability available in today's RF and microwave power transistor market. Microsemi customers will welcome these new design solutions for the most demanding pulsed avionics and radar applications.

Microsemi,
www.microsemi.com.

Termination

For high-power testing of cellular, satellite, radar or military applications, take a look at Mini-Circuits' TERM-500W-14N+ termination. This design can handle up to 500 W RF power at 1 GHz, with a return loss of 17 dB or higher from 0.5 to 18 GHz. It features wideband coverage of 0.7 to 10 GHz, an operating temperature of -10° to 50°C, a storage temperature of -10° to 70°C, DC supply voltage +24 ±2 V, current (for fan) of 310 mA and a rugged construction.

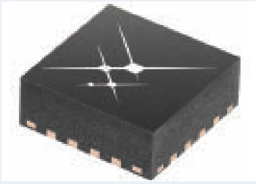
Mini-Circuits,
www.minicircuits.com.

Ku-Band BUC

RADITEK's Ku-Band block upconverter family is so compact, its small size and weight facilitate direct antenna feed mounting. It weighs only 5.5 lbs, with up to 40 W (rated power), and has a built-in AC (90-265 VAC 50 to 60 Hz auto-ranging) power supply, with -48 V (DC) optionally available, too. These BUCs have best-in-class RF performance, including: internal output isolator and Internet-based monitor and control, with both serial and analog interfaces. Ideal for any VSAT application.

RADITEK Inc.,
www.raditek.com.

SPDT Switch



RFMW Ltd. announced design and sales support for Skyworks SKY12215-478LF, a 125 W SPDT switch covering 0.9 to 4 GHz. Based on silicon PIN diode technology, it features low insertion loss of 0.4 dB, minimizing receiver noise figure in Rx applications. 43 dB antenna to receiver isolation provides protection from large transmitter output signals enabling this switch to operate in T/R and failsafe high power switching applications. Typical switching speed is 250 nS making it well suited for a variety of telecommunications systems.

Skyworks Solutions Inc.,
distributed by RFMW Ltd.,
www.skyworksinc.com.

High Resolution Synthesizer

The MTS2500-200400-10 is a high resolution synthesizer that combines the latest in DDS and multi-loop synthesizer technologies with a high performance VCO to generate frequency signals from 2 to 4 GHz with as low as 1 Hz step size. It also features ultra low phase noise, wide bandwidth performance and low spurious, while permitting for faster settling time and higher stability under vibration. This product is ideal for applications in imaging equipment such as radar and magnetic resonance, DVB transmitters, satellite ground station equipment, test equipment and control links for UAVs.

Synergy Microwave Corp.,
www.synergymwave.com.

S-Band Radar LNA

The TriQuint TGA2613 is a balanced S-Band high linearity low noise amplifier. The balanced configuration provides return loss and improves robustness into non-ideal loads. The TGA2613 operates from 2.5 to 4 GHz. It typically provides 2.5 dB of noise figure, 29 dBm of ITOI, 29 dBm of P1dB and 12.5 dB of small signal gain. Fully matched to 50 Ω with integrated DC blocking caps on both I/O ports, the TGA2613 is ideally suited for radar and satellite communications.

TriQuint Semiconductor,
www.triquint.com.

Components

Coaxial Adapters

AtlanTecRF has introduced its range of high grade, yet affordable, coaxial adapters in the popular SMA and Type N series of interconnects. Suitable for use to 18 GHz and in some cases to 26 GHz, these professional quality adapters are available from stock and feature materials well suited to commercial, defense and aerospace environments. The connector combinations include all male/female types, both in-series and between-series, as well as the classic mount options of bulkhead female and four-hole flange.

VENDORVIEW

Atlantic Microwave Ltd., www.atlantecrf.com.

Power Inductors

Coilcraft CPS has announced its new AE425PJB series of low-profile power inductors that meet NASA low outgassing specifications. The AE425PJB is just 1.8 mm high with a footprint of 3.9 mm square. It features a special suspended core construction, allowing it to pass vibration testing to 80 G and shock testing to 1000 G and making it ideal for a variety of mission-critical military, aerospace and handheld medical device applications. High-temperature materials allow operation in ambient temperatures up to 155°C.

Coilcraft CPS, www.coilcraft.com.

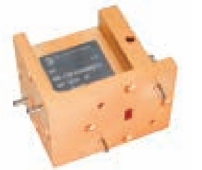
SMA Male RF Connector

Coaxicom's 3183-1 is a very small, versatile SMA plug with an overall length of 0.330". It

is used with 0.141 SR, RG402, Mil 17/130 and Ultra-Flex (Hand-Formable) cables. Manufactured from type 303 stainless steel, it can be ordered with a passivated stainless steel coupling nut or a gold plated coupling nut; the body is always gold plated. The connector is small enough to allow for very tight bends obviating the need for a conventional right angle connector or a swept right angle connector.

Coaxial Components Corp., www.coaxicom.com.

Balanced Mixers



It is always a concern at high millimeter-wave band that there is not enough power to drive the mixer, especially full waveguide band. Model FDB-XX-E1 series externally biased, balanced mixers is especially developed for this purpose. The mixers are offered in four waveguide bands to cover frequency spectra from 50 to 140 GHz. These mixers employ high performance GaAs Schottky beamlead diodes and balanced configuration to produce superior performance with a very low LO pumping level.

Ducommun LaBarge Technologies, www.ducommun.com.

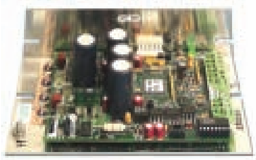
DC/DC Controller

Linear Technology introduced the LTC3774, a current-mode dual output synchronous step-down DC/DC controller that enables the use of very low DC resistance (DCR) power inductors by enhancing the current-sense signal. Power inductor DCRs down to 0.2 milliohms can be utilized to maximize converter efficiency (up to 95 percent), increase power density and reduce the output ripple voltage in high current applications. This new DCR sensing technique also reduces the switching jitter normally associated with low DCR resistance applications.

VENDORVIEW

Linear Technology Corp., www.linear.com.

Temperature Controller



Oven Industries' 5R7-001 temperature controller creates a seamless transition between heating and cooling devices, as it serves as the commander of thermoelectric modules. With a bi-directional or unidirectional H-bridge configuration, the temperature controller has many benefits: it delivers a load current of 0.1 to 25 amps, is RoHS compliant, allows for a set temperature range of -40° to 250°C, has a large program memory space for customization, is PC programmable and has 0 to 36 V DC output using a split power supply system.

Oven Industries, www.ovenind.com.

Broadband Capacitor

PPI's 0201BB104KW160 is intended primarily for coupling RF signals or bypassing them to ground over extraordinarily large RF bandwidths. It is a 100 nF capacitor and offers resonance-free, low loss operation from 16 KHz (-3 dB point) to >50 GHz at 16 V with an insertion loss of <1 dB. The applications for which these parts are intended require small, SMT devices with low insertion losses and reflections across RF frequencies extending from the tens of KHz to the tens of GHz.

Passive Plus Inc., www.passiveplus.com.

Single Pole Single Throw Switch

PMI Model No. P1T-9D25G-90-T-SFF is a high speed, solid state, single pole single throw

switch capable of switching within 20 ns. The frequency range is 9.25 GHz (±30 MHz) with > 90 dB of isolation. Learn more about this switch at www.pmi-rf.com/Products/Switches/P1T-9D25G-90-T-SFF.htm.

VENDORVIEW

Planar Monolithics Industries Inc., www.pmi-rf.com.

Drop-In Isolator

Renaissance developed a new drop-in isolator to handle 25 W of reflected power in a compact size of 0.5"× 0.75" at X-Band frequencies. Covering 7.9 to 8.4 GHz, this isolator provides a VSWR of 1.25:1 at input and output ports with loss of 0.5 dB and isolation of 20 dB over -40° to +85°C. It is specifically designed for mobile satellite architecture.

VENDORVIEW

Renaissance Electronics & Communications LLC, www.rec-usa.com.

Continuously Variable Attenuators

Trilithic announced its new CVA series of continuously variable attenuators available in octave bands over the frequency range of 1 to 18 GHz. The CVA series is currently available with 0 to 8 dB attenuation range over 1 to 2 GHz and 0 to 20 dB attenuation range over 2 to 4 GHz, 4 to 8 GHz, 8 to 12.4 GHz, and 12.4 to 18 GHz. Trilithic's CVA attenuators feature a turns counting dial with locking lever, the non-translating dial is not direct reading in dB; 50 Ω impedance, average power: 5 W.

Trilithic Inc., www.trilithic.com.

Amplifiers

RF Gain Blocks

Richardson RFPD Inc. announced immediate availability and full design support capabilities

for four new broadband RF gain blocks from Analog Devices Inc. The new gain blocks are single-ended RF/IF gain block amplifiers that operate from 30 MHz to 6 GHz and offer up to 24 dB gain and 40 dBm OIP3. They are stable over frequency, temperature and power supply, enabling high performance with low power consumption. The gain blocks feature integrated bias control circuits and are fabricated on an InGaP HBT process.

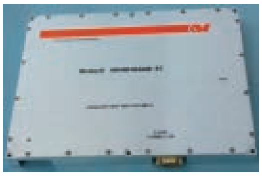
VENDORVIEW

Analog Devices Inc., distributed by Richardson RFPD Inc., www.analog.com.

Hybrid Amplifier

Model 50HM1G6AB-47 is a compact, wideband, Class AB solid state hybrid power amplifier module that instantaneously covers 1 to 6

NewProducts

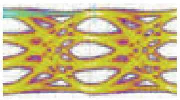


GHz. It operates from a single DC voltage and provides 48 dB of typical gain with excellent gain flatness, noise figure and low intermodulation distortion for military and wireless applications.

VENDORVIEW

AR RF/Microwave Instrumentation,
www.arworld.us.

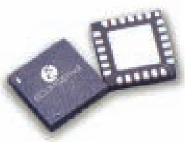
IC Chip Set



The OA3MM2C from Centellax is an amplifier IC chip set containing one input amplifier chip and one output amplifier chip. The small footprint, superb performance and low cost is perfect for transponder integration. A user could assemble multiple channels to meet application integration needs by using the chip set as a building block. The OA3MM2C has gain and power levels that are ideally suited for advanced optical modulation formats such as DP-16QAM at 32 Gbaud and beyond.

Centellax,
www.centellax.com.

General Purpose LNA



Eclipse Microdevices' EMD1710 is a GaAs MMIC PHEMPT distributed general purpose low noise amplifier. This LNA has a small signal gain of 12 dB with noise figure less than 2 dB at 10 GHz. It is ideal for applications that require a typical P1dB output power of +18 dBm up to 12 GHz, while requiring only 83 mA from a +5 V supply. The EMD1710 comes in an RoHS compliant 4 mm QFN leadless package.

Eclipse Microdevices,
www.eclipsemicrowave.com.

Ultra-Wideband PA

Giga-tronics introduced the GT-1000B option 06 and the GT-1050B/GT-1051B solid-state ultra-wideband power amplifiers that cover 100 MHz to 20 GHz and 10 MHz/2 GHz to 50 GHz respectively, with high output power, low noise figure and low harmonics in a single amplifier. Designed using broadband MMIC technology, the GT-1000B option 06 provides 5 W from 100 MHz to 18 GHz and the GT-1050B/GT-1051B provides 0.5 W (+27 dBm) at 40 GHz and 0.25 W (+24 dBm) at 50 GHz.

VENDORVIEW

Giga-tronics Inc.,
www.gigatronics.com.

Low Noise Amplifiers

MITEQ's SAFSW series of K-Band waveguide amplifiers offer very low noise figure (1.25 dB at +25°C from 18 to 21 GHz) operation in extreme airborne environments. An integral transmit band filter can also supply 60 dB minimum of rejection at 30 GHz. MITEQ's design can be powered by either +12 to +15 V DC or +5 V DC for minimum power dissipation. DC power can also be supplied over the RF coaxial outdoor connector for use in high signal strength environments where EMI is a concern.

MITEQ,
www.miteq.com.

LDMOS RF Power Transistor

Designed for tough engineering environments, the BLF188XR(S) LDMOS RF power transistor provides high output powers and simplified design, while enabling lower system cost and eliminating the use of hazardous substances. It is claimed to have excellent stability under severe mismatch conditions (VSWR greater than 65:1 at P3dB) and improved Class-C operation due to new dual-sided ESD diode structure with a larger negative voltage range. Key applications include terrestrial broadcast systems, ISM applications, igniting plasmas and lasers, synchrotrons and MRIs.

NXP Semiconductors,
www.nxp.com.

Sources

PLL-Based Crystal Oscillators

The SG3225 is a new family of small, accurate, high-frequency differential-output PLL-based crystal oscillators that support frequencies up to 700 MHz, with a 3.2 × 2.5 mm footprint. The product family also includes the SG5032 and SG7050, which come in popular sizes of 5.0 × 3.2 mm and 7.0 × 5.0 mm, respectively. With a frequency tolerance of ±20 × 10^{-6} and low phase jitter of 270 femtoseconds, these oscillators offer accuracy and stability and have a wide operating temperature range (-40° to +85°C).

Seiko Epson Corp.,
www.global.epson.com.

Broadband Waveguide Noise Sources

QuinStar Technologies Inc. introduced the QNS-FB15LE series of waveguide noise sources, which come in standard (Q,U, V, E and W) full waveguide bands. The QuinStar QNS series noise sources have 15 dB ENR with 0.015 dB/°C of noise power output stability over temperature and 0.15 dB/1 percent over bias voltage. Typical ENR flatness is ±0.5 dB over any 10 GHz region and ±1.25 dB over the full band. QuinStar also offers QIF series full band matching isolators.

QuinStar Technologies Inc., www.quinstar.com.

Test Equipment

DC Power Supplies

The Advanced Power System (APS) family, designed for ATE applications, consists of 1 kW and 2 kW system DC power supplies, the N6900 and N7900 that deliver a new level in power supply performance enabled by Agilent's exclusive VersaPower architecture. The APS family was designed to help you overcome tough power test challenges by delivering industry-leading specifications and innovative features in an integrated solution for advanced automated test equipment (ATE) power testing needs.

VENDORVIEW

Agilent Technologies Inc., www.agilent.com.

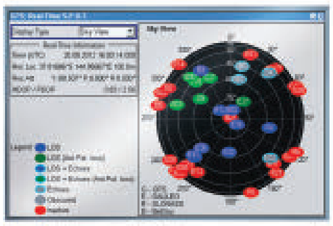
PIM Measurement Options

Anritsu Co. introduced three frequency options for its industry-leading PIM Master MW82119A Passive Intermodulation (PIM) high-power, battery-operated, portable PIM test analyzer. The new options provide wireless field engineers and technicians with the first battery-operated handheld analyzers that can accurately conduct "top of the tower" PIM measurements in the LTE 800 MHz and UMTS 2100 MHz bands, in addition to the LTE 2600 MHz band. The new options have been specifically developed to address the top bands planned for LTE network deployments.

VENDORVIEW

Anritsu Co., www.anritsu.com.

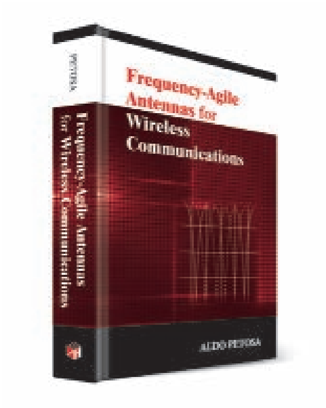
GNSS Simulator



The functionality of the R&S SMBV100A vector signal generator has been extended by adding BeiDou/Compass capability to its integrated GNSS simulator. With the R&S SMBV-K107 option, the GNSS simulator now covers the Chinese BeiDou standard as well as the GPS, Galileo and Glonass satellite navigation systems. The R&S SMBV-K107 allows users to generate realtime scenarios with up to 24 BeiDou satellites. It supports all possible BeiDou orbits and can simulate satellites that are not yet in orbit.

VENDORVIEW

Rohde & Schwarz, www.rohde-schwarz.com.



Frequency-Agile Antennas for Wireless Communications

Aldo Petosa

Mobile data subscriptions are expected to more than double and mobile wireless traffic to increase by more than tenfold over the next few years. Proliferation of smartphones, tablets and other portable devices are placing greater demands for services such as web browsing, global positioning, video streaming and video telephony. Many of the proposed solutions to deal with these demands will have a significant impact on antenna designs. Antennas with frequency agility are considered a promising technology to help implement these new solutions.

This book describes the capabilities of frequency-agile antennas (FAA), the methods for achieving tunability, the current achievable performance and the challenges still facing FAA designs. It explores the many aspects of FAAs, including an examination of the metrics used to evaluate their performance, a review of the most commonly used antenna elements, the wide variety of mechanisms for achieving tunability and a survey of examples of FAA designs. The general categories of tuning techniques covered include frequency tuning, mechanical tuning, tunable substrates and integrated devices.

The main focus is on FAAs for wireless mobile communications with applications including handsets, laptops, wireless machine-to-machine communications, as well as larger, fixed designs such as cellular base station antennas. The book is comprehensive in coverage of this topic and has an extensive list of references at the end of each chapter. It starts with a good introduction to the topic so it is appropriate for most readers with a technical background in this area and is a good reference piece for this subject area.

To order this book, contact:

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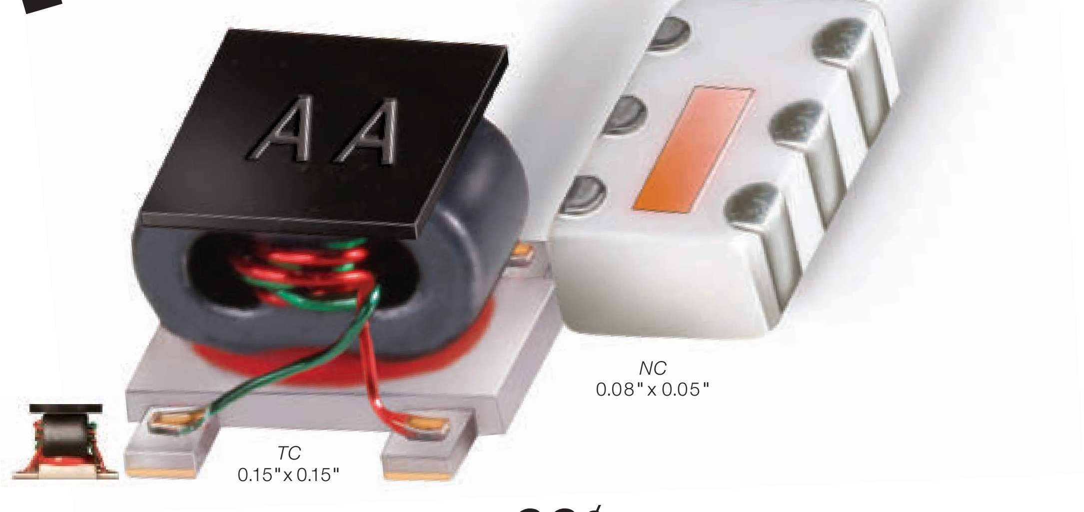
TINY Wideband Transformers



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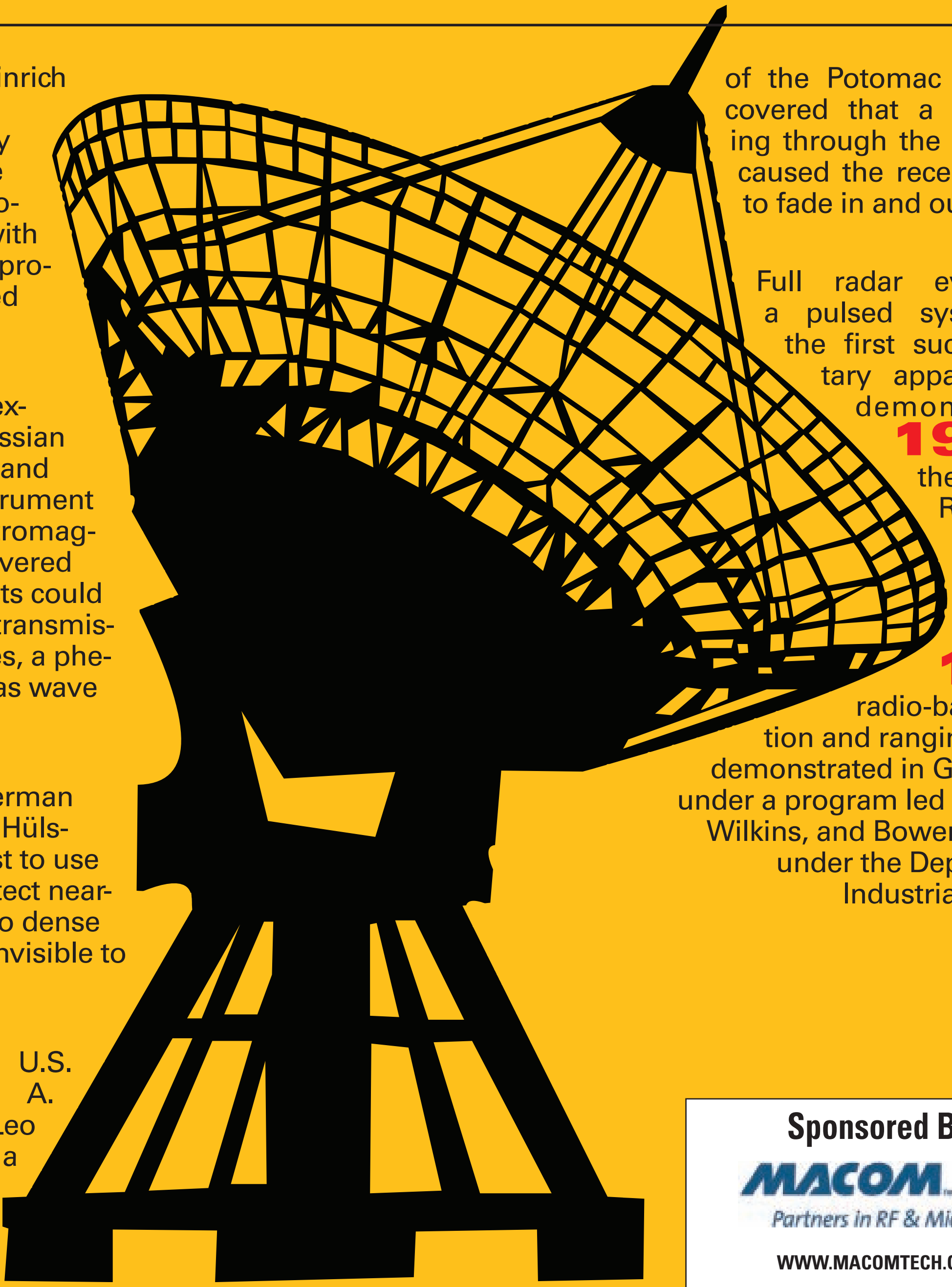
ra·dar [re-dahr]

The term RADAR was coined in 1940 by the United States Navy as an acronym for RAdio Detection And Ranging, marking an important milestone in the use of reflected radio waves to detect remote objects.



In **1886** Heinrich Hertz proved Maxwell's equations by demonstrating the presence of electromagnetic waves with an apparatus that produced and detected VHF/UHF signals.

In **1897**, Alexander Popov, a Russian physics instructor and inventor of an instrument that detected electromagnetic waves, discovered that metallic objects could interfere with the transmission of radio waves, a phenomenon known as wave reflection.

In **1902**, German inventor Christian Hülsmeyer was the first to use radio waves to detect nearby ships in a fog so dense the vessels were invisible to the naked eye.

In **1922**, U.S. Navy researchers A. Hoyt Taylor and Leo C. Young, using a transmitter and a receiver on opposite sides of the Potomac River, discovered that a ship passing through the beam path caused the received signal to fade in and out.

Full radar evolved as a pulsed system, and the first such elementary apparatus was demonstrated in **1934** by the American Robert M. Page.

On June 17, **1935**, radio-based detection and ranging was first demonstrated in Great Britain under a program led by Watson-Wilkins, and Bowen operating under the Department of Industrial Research.

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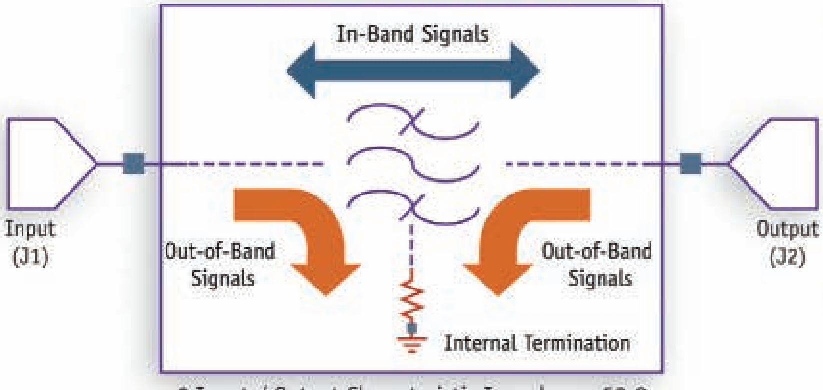

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AF9680	Low Pass	10-520	1040-3000	540	160	10	0.6	1.25:1	1.45:1
AF9313	Low Pass	10-870	1700-4000	1340	100	10	0.6	1.30:1	1.60:1
AF9349	Low Pass	10-150	270-1500	200	500	100	0.4	1.35:1	1.45:1
AF9255	Low Pass	10-170	300-1500	220	100	10	0.5	1.25:1	1.60:1
AF9705T	Low Pass	10-320	620-3000	500	150	25	0.5	1.25:1	1.45:1
AF9350	Low Pass	10-500	750-3000	540	400	100	0.5	1.25:1	1.50:1
AF9187	Low Pass	450-490	850-3000	620	100	10	1.0	1.40:1	1.60:1
AF9681	Low Pass	500-2500	4000-6000	2700	160	10	0.5	1.50:1	10:1

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