Microwave DAC promises direct digital synthesis from DC to 7GHz and beyond

A white paper from e2V

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Fast Facts: About this paper

This paper will Introduce you to:

- The baseband limitation of most traditional DACs
- A DAC with a 7 GHz bandwidth
- DAC operation in multiple Nyquist zones
- Up-sampling and how wideband DACs can place synthesised signals into the L-, C- and S-bands
- Pulse shaping as an aid to:
  - frequency planning and
  - output power optimisation
- Novel DAC applications:
  - UWB transmission system e.g. RADAR
  - Arbitrary waveform generation (AWG)

Abstract

'Any sufficiently advanced technology is indistinguishable from magic.[1]'

So said acclaimed sci-fi author, Arthur C Clarke. Magic may not be considered a component of advanced communication engineering and design, but perhaps it is a suitable term to describe the diverse new capabilities enabled by the technology at the heart of the product discussed here.

In this short paper, a new microwave frequency component is introduced that's set to cause a minor stir in several high-end signal processing and instrumentation markets.

The device in question is an ultra-wideband (UWB), 12-bit resolution digital to analog convertor (DAC). It offers the highest levels of spectral purity coupled with a huge analog bandwidth facilitating completely new ways to architect challenging RF and microwave systems. In so doing, it provides design versatility, opens up novel and hitherto unimagined applications and helps to create new price points.

Complex transmit path signal processing is foreign territory to many engineers schooled in baseband radio design. Renewed understanding of the practical implications of sampling theory will show that alias signal imaging can yield beneficial RF design outcomes. Foremost amongst these, is the ability to take a baseband signal, up-convert it, and place synthesised signals directly into wide band RF spectrum whilst eliminating analog mixers.

This paper considers both the dynamic capabilities of the part along with the innovative applications it enables, from complex, agile radar and electronic counter measures to a myriad other advanced RF systems. Leading edge, time domain performance also suits use in high-end testing applications where complex, programmable waveforms are demanded.

Hopefully readers will view sample theory in a positive new light and gain a sense of radical new design possibilities enabled by this novel product.

[1] Clarke, Arthur C, '"Hazards of Prophecy: The Failure of Imagination"' in the collection *Profiles of the Future: An Enquiry into the Limits of the Possible* (1962, rev. 1973), pp. 14, 21, 36.

Introduction

Complex radio and communication systems such as consumer smartphones, mobile phones and even the fixed line network have all benefitted from increasingly sophisticated deployments of high sample rate data conversion combined with digital signal processing (DSP). DSP has helped to push challenging signal processing problems into the digital domain. Because of this, consumers have benefited from an explosion in low cost mobile communication capabilities assisted by Moore's law driving processing costs ever lower.

Less obvious, is the fact that complex signal processing has had a major impact on the radio architectures developed over the last decade. One up-shot of this is that the interface between the 'real world', analog signal domain and the digital processing environment has been pushed ever closer to the antenna.

If only it was possible to take digital signal generation beyond the limited baseband (1.5 GHz) range of today's CMOS DACs. Much complex RF equipment could benefit from direct digital synthesis offered by DSP techniques. This paper explains the technological leap that has been achieved by combining a high performance (non-CMOS) process technology with innovative design. It then goes on to detail the key dynamic specifications of the device and looks at how designers can make use of its flexible output coding modes to assist in frequency planning before focussing on two application examples.

Design features of new microwave DAC

The single largest innovation provided by the EV12DS400 is its broad, synthesised analog bandwidth. To date, most new, high sample rate DACs have exploited CMOS process technology. Although sample rates up to 5 Gsps can be achieved, few of these parts are able to recreate an analog output bandwidth beyond about 1.5 GHz. This is a shame as their RF signal generation capabilities are clearly constrained.

<u>Fast Facts: EV12DS400 Specifications</u>

- 7 GHz -3dB bandwidth
- High spectral purity – 65dBc SFDR @2240MHz
- >47dB NPR in first Nyquist zone
- Synthesis beyond 4th Nyquist zone
- Uses rugged 200GHz SiGeC process

The EV12DS400 takes a different approach to delivering exceptional sample rate performance and high analog bandwidth. The starting point for this DAC was an ultra-fast mixed signal technology – Infineon's designated B7HF200 process. It has been used in rugged GHz frequency applications including automotive 77 GHz safety radar transponders. The process features a blisteringly fast 200 GHz cut-off frequency and delivers this through hetero-junction bipolar transistor (HBT) structures based on the SiGeC technology. Its four layer, copper metallisation helps lower circuit parasitics enabling delivery of a full 7 GHz, -3dB bandwidth. Electrically, the DAC comprises a high speed 4:1 or 2:1 input multiplexer coupled to a 12-bit current steering DAC topology.

Being focused on providing maximum spectral purity, this high speed design shuns time interleaving as a method to increase sample rate and DAC throughput often used in traditional CMOS DAC designs. It relies solely on the benefits of the high speed process. As a result, a single fast quantizer core can deliver un-calibrated 12-bit performance. This helps to guarantee a low signal distortion and eliminate the need for lengthy calibration cycles either at device start-up or during operation. The single core is especially effective in varying temperature environments. Maintaining low distortion over temperature is a challenge for time inter-leaved approaches.

Later, specific device features that help with frequency planning and trimming synthetic carrier placement in up-converted applications will be discussed. But first it is worth recapping sampling theory as it relates to an ultra-wideband operating range.

Spotlight on sampling theory

Potentially, one of the harder aspects of high bandwidth DACs to grasp, is the effect sampling has on image signals (or aliases) produced at the DAC's output. In this section, a light is shone on this process with the introduction of multiple Nyquist zone operation.

Most engineers are aware of the basics of Nyquist sampling theory as it affects digital signal processing. The theorem states that any bandwidth limited signal can be properly reconstructed from time discrete samples, provided that the samples are made at a sample rate in excess of 2 x fa (where fa is the maximum bandwidth of the sampled signal). This is the Nyquist frequency (fc).

When considering the implications of sample theory in terms of the frequency domain performance, interesting things start to happen. A reconstruction DAC provides varying output pulses in response to input sample data provided. Output pulses appear every 1/fc seconds.

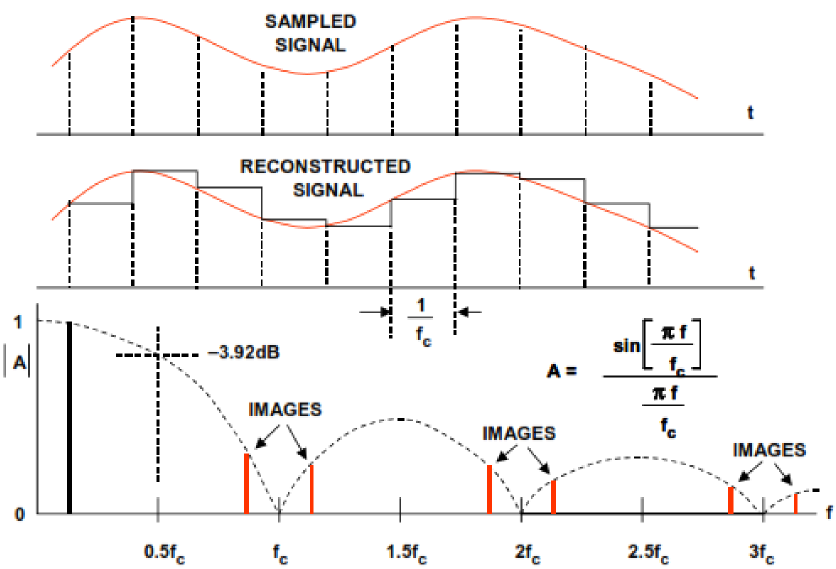

Figure 1 Waveform sampling in the time and frequency domain. Lower plot show alias signals extending out to > 13 GHz.

Figure 1(top) shows the original waveform complete with regular sample points. Figure 1 (middle) shows the DAC output pulses seen in the time domain – note the output signal shows a 'standard', non-return to zero (NRZ) pulse stream. Finally, figure 1 (bottom) shows the frequency spectrum that result from the pulse stream complete with its characteristic sinc(x) attenuation due to the NRZ coded output. The final graph (fig. 1c) shows a fundamental carrier frequency placed at 500MHz together with multiple alias (or images) that appear as a result of sampling at a rate of 4.5 Gsps. The graph maps the frequency domain up to just over 13 GHz (= 3xfc) showing just over six consecutive Nyquist zones, each with a width fc/2. Notice that at integer multiples of the sample frequency fc, a pair of alias signals appear centred around the sample clock (at n x fc ± fa – where fa is the input signal frequency), albeit attenuated by the sinc(x) roll-off.

When considering UWB DACs working with high sample rates, the creation of alias or image signals in the output spectrum of a device in the higher order Nyquist zones clearly has positive system benefits. Simply put, aliasing can be used to directly up-convert based-band signals to microwave frequencies without the need for additional analog mixer circuits. However, because of the standard sinc(x) roll-off, power delivered in high frequency Nyquist zones is often heavily attenuated.

Assuming a solution can be found to counter sinc(x) roll-off, then direct digital synthesis could enable complex direct digital modulation schemes and provide wideband frequency agility to the target system.

<u>Fast Facts: Sampling theory</u>

- Any signal can be reconstructed from time discrete samples if the Nyquist criteria is met
- The Nyquist criteria states the sampling frequency fc > 2 x fa (fa = signal bandwidth)
- A Nyquist zone (NZ) has a width of fc/2 Hz
- For a single tone, alias signals appear at multiples of the sample clock (fc) extending to infinity
- Depending on DAC output coding, output power can alias into high order Nyquist zones
- DAC’s standard NRZ output causes sinc(x) attenuation

By moving transmission modulation into the digital domain, system designers eliminate problems of multiple distortion sources and matching, common in multi-stage analog systems; and gain control over thermal drift; minimise conversion losses improving power efficiency and deliver more compact and reliable equipment. That’s a heady mix of useful possibilities!

Research will show that the topic of high order Nyquist zone operation is rarely described in technical materials supporting high speed DACs, primarily since such discussions are a waste of time given that most existing DACs’ sample rate capabilities outstrip their analog bandwidth. Such DACs’ operation is fundamentally limited to the first Nyquist zone for this reason. This fact is emphasised in the summary of a few modern wideband DACs given in table 2. Of the parts listed here, only four facilitate operation beyond the first Nyquist zone. The last two parts enjoy a significant (3x) bandwidth advantage. Although the AD9129 claims a 5.7 Gsps sampling mode, note that this is in fact an interpolated mode.

Table 1 Examples of modern high sample rate DACs.

Device	Vendor	Resolution	SFDR	Max fc (MHz)	Max Bandwidth (MHz)	Supports multi-nyquist operation	Pulse shaping
DAC39J82	TI	16-bit	66dBc@300MHz	2800	unspecified		•
DAC5670	TI	14-bit	50dBc@500MHz	2400	unspecified		
MAX19692	Maxim	12-bit	70dBc@800MHz	2300	1200	•	
AD9129	ADI	14-bit	55dBc@950MHz	2850 5700*	1425	•	
LTC2000-14	Linear Tech	14-bit	68dBc@DC-1000MHz	2500	2100		
EV12DS130	e2v	12-bit	70dBc@100MHz	3000	7000	•	
EV12DS400	e2v	12-bit	65dBc@2240MHz	4500	7000	•	•
***AD9129 offers interpolated double sample rate output**							

Output coding options

The unadulterated frequency response of a conventional DAC with a standard non-return to zero (NRZ) output is the classic sinc(x) = (sin(π.x)/(π.x)) characteristic. In frequency terms, this response provides the highest signal power and flattest power delivery over the first Nyquist zone – albeit with a small power drop of 3.9dB at the corner of NZ_1.

A disadvantage of NRZ coding is that signal power in the second and third Nyquist zones (and beyond) is severely attenuated due to the notch centred at fs as shown in figure 1c. The sinc(x) notch represents an output power null and means that for standard DACs, their output spectrum can only reasonably be delivered from baseband up to about the mid-point of NZ_2.

To help improve device versatility and output spectrum programmability, the EV12DS400 offers three extra time domain coding modes which enable tailored power delivery across multiple zones. In so doing, the device allows RF engineers to make trade-offs in signal power budget, dynamic performance and carrier placement across the Nyquist zones up to the 7 GHz bandwidth.

Fast Facts: Output coding

- DAC pulse shaping enables frequency planning and dynamic performance optimisation
- EV12DS400 has four output modes:
  - NRZ – non-return to zero
  - RTZ - return to zero
  - NRTZ – narrow return to zero
  - RF mode – broadband operation
- EV12DS400 provides pulse shape trimming

The EV12DS400's four output coding modes are detailed in table 2 and shown graphically in figure 3 on the following page. The ONZ column highlights the optimal Nyquist zones for each operating mode. For all except the NRZ mode, some extra freedom to modify pulse timing is provided by the pulse re-shaping functions (RPW and RPB) accessed by the DAC's 3 wire digital control interface.

Table 2 Four output modes of EV12DS400 compared.

Mode	ONZ*	Advantages	Trade-offs	Pulse shaping features	
				RPB	RPW
NRZ	1st only	Best 1st NZ noise performance	Steep dynamic tailoff > 1st NZ Legacy mode		
RTZ	2nd & 3rd	Best SFDR mode. Extended bandwidth. Possible operation in 4th & 5th NZ	6dB carrier power loss in 1st NZ. Reduced SFDR Strong spur at fclk	•	
NRTZ	1st & 2nd	Peak carrier power in 1st & 2nd NZ Extended 2nd NZ dynamics (better than NRZ)	3rd NZ notch, spur at fclk	•	•
RF	2nd & 3rd	Best for 2nd & 3rd NZ power. Validated operation in 4th NZ. Peak power at fs! Uses 2x rate clock.	Clock spurs at fclk and 2xfclk	•	•
*ONZ = optimum nyquist zone					

The plots in figure 3 show idealised DAC spectral output power distribution enabled by each output mode of the EV12DS400.

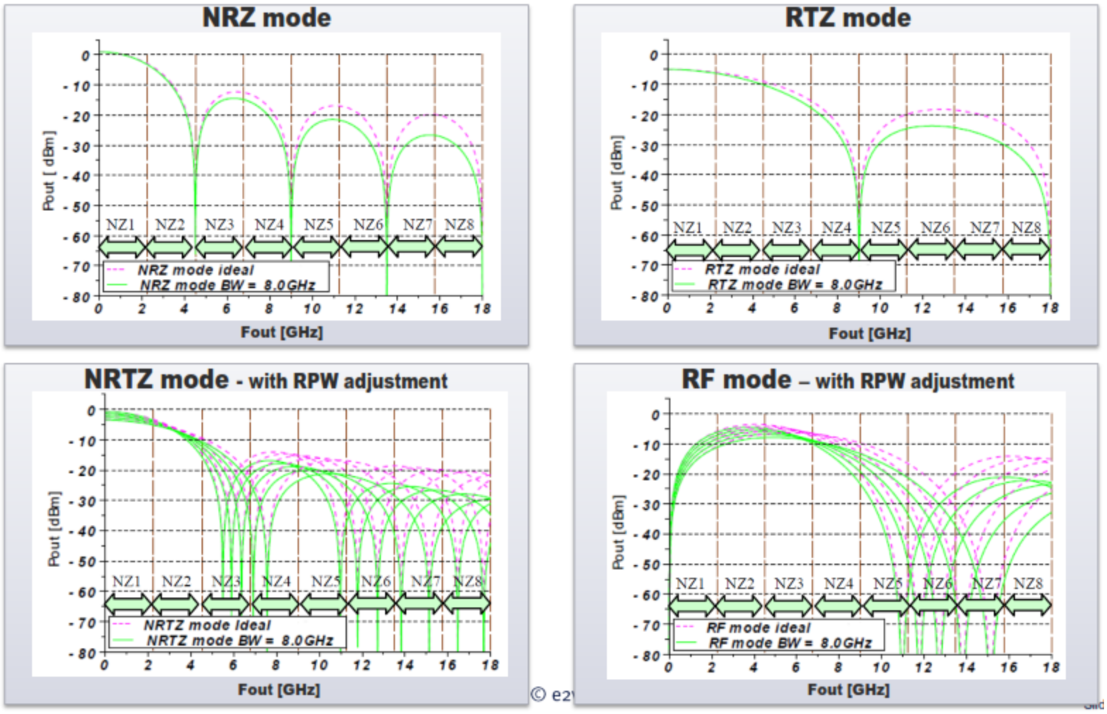

Figure 2 Frequency domain response plots of the four DAC output modes.

Now consider the factors impacting these output characteristics for each mode.

RTZ mode: using a 50% re-sampling clock, the DAC's sinc(x) function is spread over double the frequency band (notch frequency shifts out to 2xfc). The clear benefit is that operation in NZ_2 & NZ_3 is now possible. There is also usable output power in NZ_6 & NZ_7. The downside is a 6dB loss of NZ_1 power.

NRTZ mode: is an e2v patented mode introduced to offer a trade-off between noise performance and bandwidth – taking the best of NRZ and RTZ modes. Clearly for maximum power transfer, intuition suggests that NRZ is the optimum mode for DAC operation. However, by enabling a narrow excursion to zero (NRTZ) every clock cycle, several benefits arise.

- historical information that exists between each NRZ output transition is eliminated – this aids spectral purity at the highest signal frequencies.
- a short pulse to zero provides a null, during which time, internal switching transients can be filtered out, thus helping eliminate transient noise and further improving NPR.

This high resolution pulse control is possible thanks to the excellent switching characteristics of the DAC which allows short duration RTZ excursions in considerably under 100ps ($=100 \times 10^{-12}$ secs).

RF Mode: is the widest band capability offered by the EV12DS400. Here the DAC produces positive and negative going output pulses for each clock cycle which can more than double the output attenuation bandwidth, pushing the second notch to well beyond 2xfc. Note that peak output power is achieved when the carrier signal frequency coincides with the sample frequency fc. Consequently the maximum output power occurs exactly at the boundary between NZ_2 and NZ_3.

For the NRTZ and RF output modes highlighted in figure 2, note that a range of attenuation characteristics with differing notch locations are shown. Actual notch locations are determined by the specific setting of the re-shaped pulse functions (RPW and RPB) described next. Note the purple dotted line indicates the ideal, infinite output bandwidth response and the green curves account for the 7GHz, 3dB frequency roll-off in the DAC.

Pulse re-shaping

As previously noted, being able to modify the DAC output pulse shape has a noticeable impact on the output frequency spectrum. A detailed mathematical treatment of these effects is beyond the scope of this paper, however for the curious, mathematical derivations are given in the EV12DS400 data sheet. What should now be clear, is that designers can select one of four output modes to give an optimum operating point across one of more than four Nyquist zones. This DAC is capable of placing complex signal carriers almost anywhere within its own output bandwidth.

e2v's engineers have provided a re-shaping pulse width feature to supplement the DAC output modes. This sample clock control helps to further optimise the placement of spectral nulls (notches) and maxima when operating in the NRTZ and RF modes.

Distortion reduction via pulse re-shaping

During output edge transitions, the DAC quantizer is settling to a new discrete level and at any moment in time (determined by bit boundaries), small perturbations can appear on the leading and trailing edge of the raw output signal. In figure 3, these quantisation disturbances have been exaggerated to make the point clear.

The re-shaped pulse width (RPW) control introduces a tiny delay period in the sampling clock at sample edge transitions. Re-shaped pulse begin (RPB) sets the centre point of RPW. By careful selection of RPW duration, the edge transitions are optimal as the DAC quantizer can fully settle. The technique yields to a slight loss in signal power, however, eliminating the disturbed output edges, lowers harmonic distortion providing a valuable improvement to SFDR.

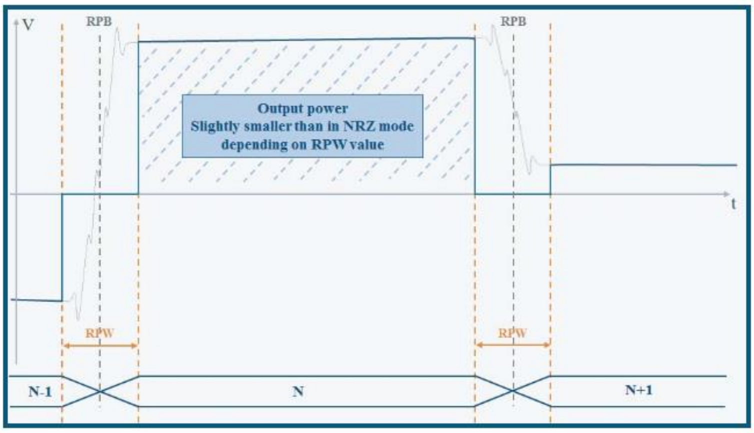

Figure 3 RPW showing optimum pulse duration.

Figure 4 shows an RPW pulse width that is set too narrowly. It leads to slight over and undershoot in the time domain signal and resultant distortion in the frequency response.

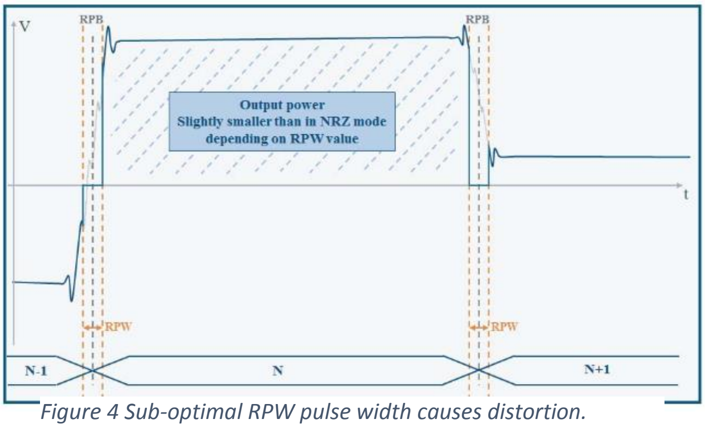

Figure 4 Sub-optimal RPW pulse width causes distortion.

Those seeking to understand the effects of mode control mathematically and how they aid frequency planning, may be interested to know that models that run on the open source Scilab – a numerical computation tool, have been produced and are available on-line at e2v's web site: http://www.e2v.com/products/ev12ds400a/.

Dynamic specifications

Consider the measured single tone SFDR performance of the EV12DS400 shown in figure 5. This highlights the difference between idealised and the real world performance previously shown in Figure 2, where circuit design plays a big role in determining spectral purity of the final product. Note how SFDR varies over frequency and behaves differently for each output mode.

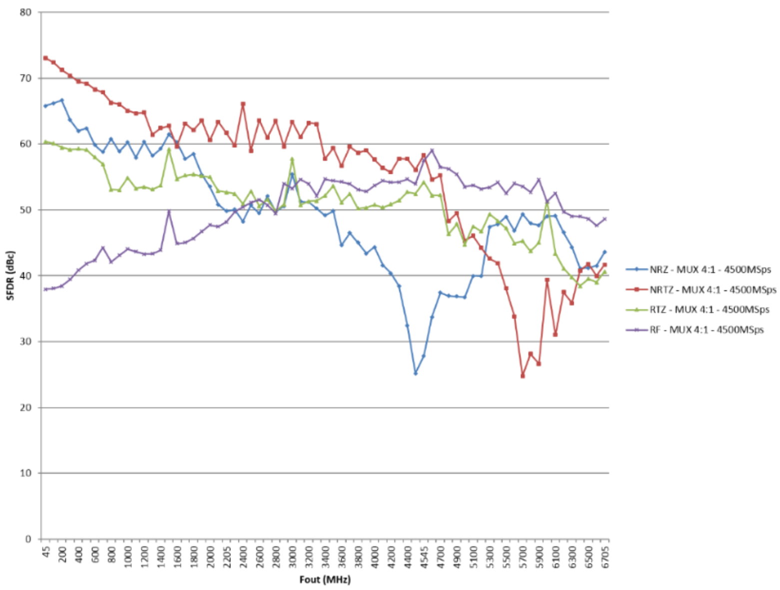

Figure 5 SFDR for each output mode of the EV12DS400.

These results highlight the following conclusions:

- At low frequencies in the first Nyquist zone, NRZ and NRTZ modes clearly offer superior SFDR
- Signal nulls occur at 4.5 GHz (NRZ) and 5.7 GHz (NRTZ) and should be avoided
- From 4 GHz upwards, the RF mode provides superior SFDR

Useable DAC bandwidth is best demonstrated by inspecting noise power ratio (NPR) plots. In the following graphs, carriers can be seen inserted at multiples of 1.125 GHz across a broad frequency range up to 10 GHz. The first plot shows an NRZ coded output response. Here the first notch at 4.5 GHz coincides with the fourth carrier, negatively impacting its NPR.

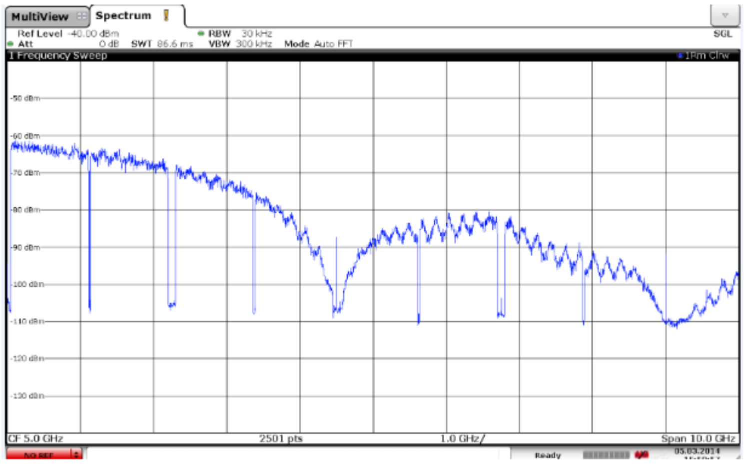

Figure 6 Broadband NPR with NRZ coding (notch at 4.5 GHz)

In the second plot, NRTZ coding is used to push the first notch out to 5.7 GHz resulting in a substantial improvement to fourth carrier NPR. Pre-production testing shows that the EV12DS400 can attain typical NPR values of > 47 dB in the first Nyquist zone rising to 50dB at 3 Gsps.

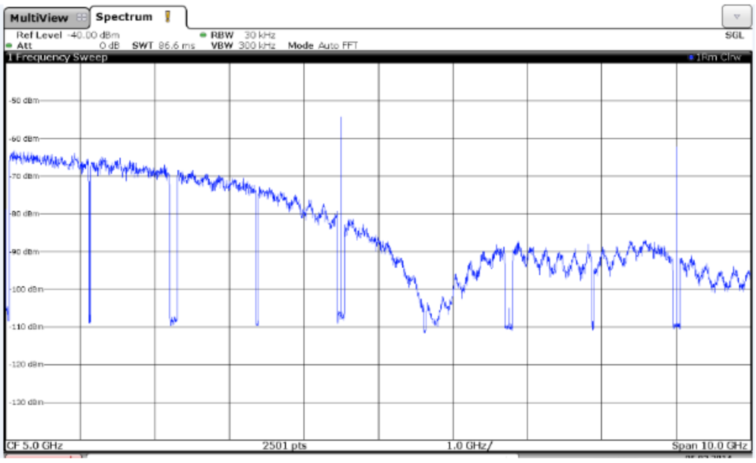

Figure 7 NPR with NRTZ coding (notch shifted to 5.7 GHz).

The DAC's single tone fidelity is illustrated in the next plot (figure 8). Here a single tone at 2.24 GHz is generated with an update rate at 4.5 Gsps using RTZ output coding. The output shows three marked spurs each of which are <-63dB down on the fundamental. Note that this measurement was

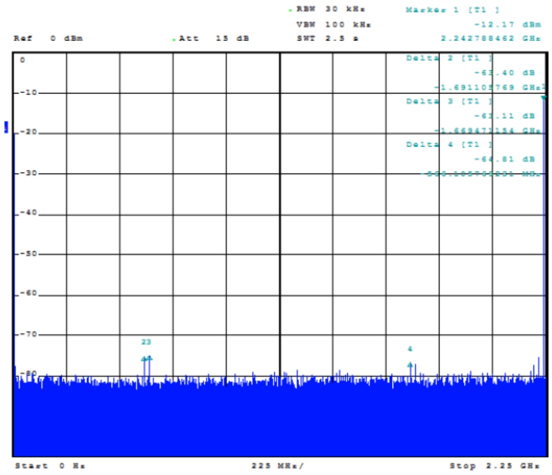

Figure 8 Single tone @ 2.24 GHz SFDR (=63dBc).

optimised using the output pulse shape controls (RPB & RPW).

For multi-tone behaviour, the EV12DS400 provides signal power up to 12GHz evidenced by figure 9. This shows an NRTZ output coded signal. Again, pulse shaping was applied to optimise SFDR.

By necessity, when discussing high bandwidth products, the focus of attention is on dynamic specifications. But before concluding this view of key specifications, it is worth highlighting a fundamental DC characteristic important in ensuring the efficacy of this device. That is gain stability over temperature. In the case of the EV12DS400, it is able to achieve gain stability of ±0.5 dB over its entire operating temperature range. This has a huge impact, ensuring that the device can be used in many challenging thermal environments without needing complex calibration routines to guarantee long term performance.

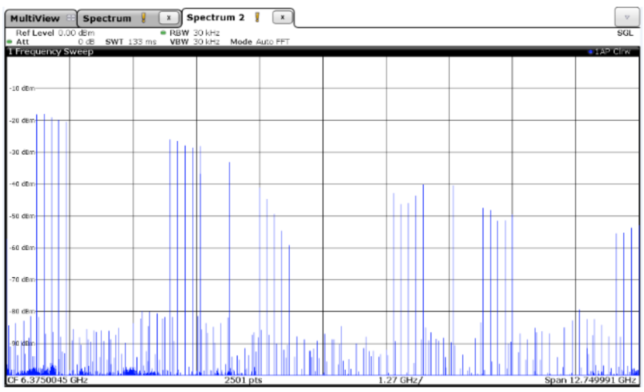

Figure 9 Multi-tone plot with signal maxima out to 12 GHz.

Practical gigahertz applications

Two specific applications present themselves as obvious beneficiaries of microwave capable DAC technology. The first discussed here is a generic, high performance microwave communication architecture.

Multi-channel microwave transmission

Figure 10 shows a traditional multi-channel transmit path based on baseband DACs. Notice the design complexity associated with each channel. Dual DACs are required to generate in-phase and quadrature signal components.

The second IF processing block provides the first step of signal up-conversion with low pass filtering followed by mixing. Following this, we hit the first IF stage which provides the second up-conversion stage to broadband microwave frequencies. The number of transmit carriers needed will determine N, the number of channels and dictate the need for 2N DACs and associated first stage IF elements. Such a system is cumbersome, costly and power hungry. It represents a considerable design challenge to handle issues associated with: inter-channel matching, thermal drift and distortion.

Contrast this analog intensive approach with the much simplified situation represented by deploying a single broadband DAC shown in the lower image (figure 10). Granted, the parametric performance criteria placed on the key components in this modified transmit path are increased in terms of bandwidth, signal purity and clock speeds. Intuitively though, a broadband design delivers a promise

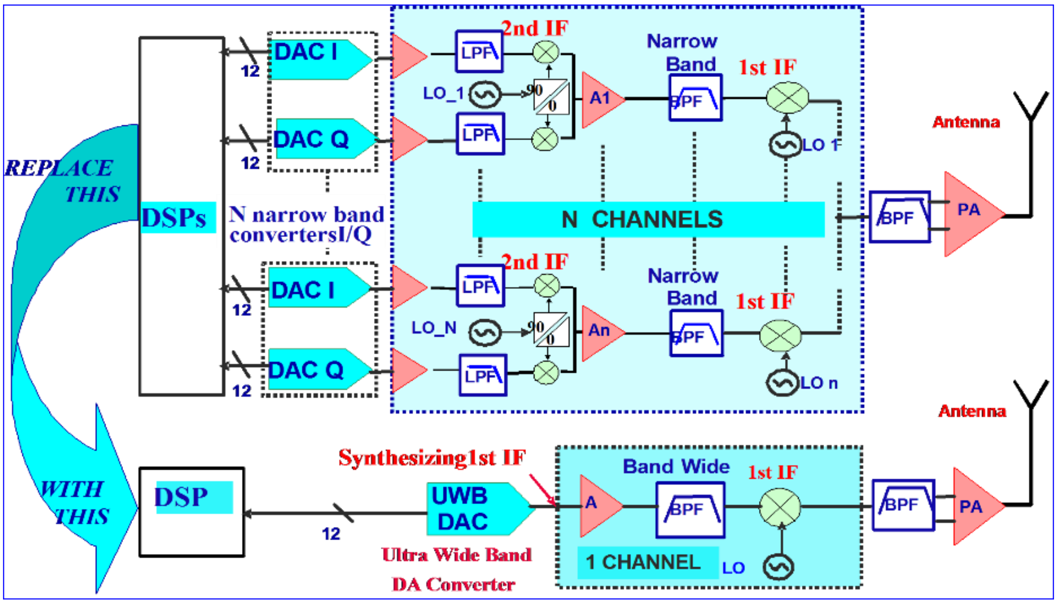

Figure 10 Contrasting a multi-carrier transmit path using baseband DACs (top), with using a single UWB DAC (below).

of multiple system level benefits.

A fair question to consider now would be, can a component like the EV12DS400 deliver enough performance to be useful in a UWB design? Furthermore, what key specifications are demanded to facilitate this design approach?

The answer of course depends on the specific system characteristics to be achieved. To recap, points where the EV12DS400 hit this target include:

- Wide analog bandwidth extends up to the X-band
- Clock spur suppression to better that 80 dB typical
- Multi-Nyquist zone carrier placement beyond 4 GHz, made possible by the RF output mode with trim enabled through fine pulse re-shaping controls (RPW/RPB).
- First Nyquist SFDR in excess of 65 dBc minimises spurious signal generation
- Noise power ratio of > 50dB

Arbitrary waveform generation (AWG)

Arbitrary waveform generation (AWG) roles are a second natural home for a microwave capable DAC. Manufacturers of Automated Test Equipment (ATE) are confronted with the challenge of designing software defined signal generators with performance superior to the devices under test.

Memory testers in particular need to generate stimulus signals with a complex variety of rise and fall time edges with programmable voltage levels for low and high states.

In these applications, the DAC forms a key output element of a system providing versatile and complex, time domain signal generation. Consider for example the data rates delivered by various contemporary digital, serial interfaces including: Serial ATA, HDMI 2.0, USB 3.0 and SMPTE 424M. These standards deliver data rates in the 6 Gbps range, with the exception of the pro-video SMPTE standard at 2.97 Gbps.

Standards compliance testing may not, at first glance appear to need a DAC. After all, can't compliance be established by ensuring interconnected systems work? Alas it is not that simple. Compliance testing assures the inter-operability of systems and requires that equipment properly rejects or accepts 'standard' high data rate signals. In digital serial link testing, the ability to generate dynamic signal patterns within and outside the input level thresholds specified is key (known as V_{OH} and V_{OL} limits). With exceptionally fast, pico-second edge transitions the EV12DS400 is an ideal candidate to drive a complex variety of variable amplitude, test patterns. In this way, it is possible to supply signals allowing bit error rate measurements to be made for next generation serial data standards.

Technical limitations

Irrespective of application, the pressure remains on suppliers of UWB DACs to improve signal fidelity, eliminate distortion artefacts and target the highest possible dynamic range and bandwidth. But improvements happen in an iterative fashion. Today the EV12DS400 already sits on the bleeding edge of mixed signal technology. Its biggest constraint is presented by hitting the limits of current package technology.

Device packaging rapidly becomes a critical success factor in gigahertz electronics. Even tiny amounts of parasitic lead inductance can drastically impact performance. Also, at microwave frequencies device layout considerations are important. Consider that data edge, phase integrity can be compromised just with slightly differing PCB trace lengths between transmit and receive sides of a digital data path.

The EV12DS400 uses a 196 pin plastic ball grid array (BGA) package. This is more than capable of handling the thermal dissipation of the DAC. However, finite bond wire length still means that the top end bandwidth is limited. Future improvements to bandwidth will necessitate a move to a flip-chip package helping minimize interconnection overhead.

Design support resources

In keeping with industry practice, e2v offers developers a full IBIS description and SPICE models for the EV12DS400. In addition, an evaluation system will be available as the device moves in to pre-production. e2v also aims to highlight common, broadband, board design pitfalls as it maintains a design checklist which can be downloaded from the website.

Developers interested to run mathematical simulations to assist their frequency planning can download a Scilab model, which is available on-line from e2v. This will compute the system frequency response given a specific set of design variables. Lastly, talented application and test specialists at e2v are available to assist customers with complex system development.

Conclusion

Until recently, few engineers would have considered using high speed DACs beyond the second Nyquist zone. The reason being that existing CMOS products offer analog bandwidths much lower than their own update rates.

The primary benefit of the EV12DS400 described is that it offers a large, 7 GHz analog output bandwidth, nearly twice its peak sampling rate. Bandwidth that now makes it possible to fully exploit the benefits of up-conversion resulting within discrete time, sampled systems. This DAC can directly synthesise signals well into the microwave spectrum.

A brief review of sampling applied to an UWB frequency space was provided to help those unfamiliar with multi-Nyquist zone operation. It emphasised the potential benefits of operating beyond the first two Nyquist zones. Microwave transmission was proposed as a primary application where the exceptional frequency domain performance of the EV12DS400 stands out. A single UWB DAC can replace many baseband DACs. This translates into cost savings, performance benefits and reduced equipment size suiting many defence applications including: active radar, electronic warfare and electronic counter-measure systems.

The fast time domain performance and pico-second edge transition times of this DAC suits application in advanced test platforms such as AWG and ATE. As indicated, this part can be used for digital serial interface, compliance testing.

Given these outstanding capabilities, the mix of high end specifications, there remains just one question left to consider:

How might you use this DAC in future to help 'Bring life to technology'?

e2V Bringing life to technology

Glossary of terms

ATE – Automatic test equipment

AWG – Arbitrary waveform generator

BGA – ball grid array, a device package format

DAC – Digital to analog convertor

L-, S-, & C-band – Microwave frequency bands. L (1-2GHz), S(2-4GHz) and C(4-8GHz)

NPR – noise power ratio

NRZ – Non return to zero

NRTZ – Narrow return to zero

NZ – Nyquist zone

NZ_n – the n^{th} Nyquist zone

RF – RF mode

RPB – Re-shaped pulse begin time

RPW – Re-shaped pulse width (or duration)

RTZ – Return to zero

SFDR – Spurious free dynamic range

SiGeC – Silicon, Germanium, Carbon process technology (Infineon's B7HF200).

UWB – ultra-wideband