WHITE PAPER

On the way to RF Softwarization, Teledyne e2v data converters push digital signal processing boundaries with direct access to Ka Band.

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TELEDYNE e2v | Semiconductors
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EXECUTIVE SUMMARY

This article describes market disruptions currently faced by the space industry which may not only upend current commercial assumptions, but herald significant changes in the way that space-borne infrastructure is architected and operated in future. The hypothesis is that market forces and technology trends point to a necessary focus on substantially more flexible multi-mission platforms hereafter. These SoftSats, differ over existing satellites as their operating parameters and air interfaces are soft coded (i.e. determined primarily by software) as opposed to hardwired as is prevalent in today's hardware. In so doing, operators will gain access to resilient, agile platforms that will help protect their technology investment conveying to them greater market responsiveness over time. Moreover, the market will benefit as these innovations are expected to reduce space access costs through more standardization, enhanced flexibility, and system re-use.

A key enabler for SoftSats are new broadband data converters that, for the first time, promise direct Ka-band access eliminating intermediate frequency radio stages and delivering the hitherto impossible promise of RF softwarization to this critical spectral band. The engineering steps towards such complex broadband components are detailed along with initial results from the first two proof of concept designs evaluated under lab conditions. The conclusion is clear, the time is right to reassess architectural choices and prepare for Softsats. Production-worthy sample components will see the light of day in late 2021. Meanwhile current prototypes enable further experimental work to continue apace.

INTRODUCING NEW SPACE AND A FUTURE SOFTSAT VISION

A significant growth opportunity worldwide, with the trend towards new space businesses was identified in a 2019 report[1] for the European Commission on the future of the European space sector. This comprehensive report considers emergent technology trends and highlights leading applications, the extensive risks and challenges to accessing funds.

One outcome of the New Space trend is the imminent arrival of highly flexible satellites. These systems, termed SoftSats in this article, are a class of complex, software-defined space platforms. SoftSats reinvent core space infrastructure and particularly the air interfaces and will almost certainly fuel radical new business models. For Teledyne e2v, SoftSats are a class of satellites combining on-board software defined processing capabilities with agile, direct access soft radios (DASRs) capable of supporting a diversity of missions and switching operating scenarios dynamically to adjust to market demand and operating environment as highlighted in the table (figure 1).

Operation Mode	Service / Waveform	Frequency Bands / Plan
A	SAR EO	C and X-Bands Freq. Plan Nb xyz01
B	Maritime Telecommunication	X-Band Freq. Plan Nb xyz02
C	SAR EO and Telecommunication in Time Division	C and X-Bands Freq. Plan Nb xyz03
D	Telecommunications	Ka-Band Freq. Plan Nb xyz04

Figure 1 - A single SoftSat offers potential multi-client services thanks to RF softwarisation

Twin features of Softsats are their modular, direct access RF hardware enabling the use of RF softwarization combined with an ability for on-the-fly re-configuration. This gives SoftSats mission agility, and multi-mode operation all whilst desensitizing them to future market vagaries.

1. 'The future of European space sector', by The European Investment Bank ©2019

Re-configuration substantially lowers the enormous risks associated with fixed hardware (single mission) payloads. SoftSats allow new radio frequency plans to be dynamically introduced on demand or individual transponders to be reallocated to revised mission profiles. Furthermore, combined with electronically steerable antennas (ESA), service providers gain a versatile, long-life space-borne asset.

SoftSats could drive a wave of standardization, further lowering overall costs. Indeed, this development wave may preface the emergence of 'Satcoms as a service[2]' as recently envisioned by the CTO of Atlas space operations. This may appear far-fetched, but the idea is supported by a new breed of data converters soon to reach the market. For the first time ever, direct access Ka-band conversion will become a reality allowing a rethink of future microwave air interfaces and satellite communication infrastructure.

The rest of this article considers both disruptive technologies and market trends as they affect the space industry before turning to how Teledyne e2v is working to respond.

> According to the ITU's State of broadband report 2019, there are now more than 4980 satellites in Earth orbit, of which 15 % are dedicated to communication.

2. 'The future is Satcom as a service', by Brad Bode, CTO and co-founder Atlas Space Operations Oct. 2nd 2020

MARKET MEGATRENDS: AGGRESSIVE COMPETITION, INSATIABLE DATA GROWTH BOTH IMPACT THE OUTLOOK FOR SPACE INFRASTRUCTURE

Over the last thirty years, communication satellites were generally thought of as highly specialized, single-task platforms, operated either by large enterprises or governments. For example, consider the GEO-based high throughput satellites (HTS) operating as space-based base stations or data repeaters. Much of today's terrestrial data and communications infrastructure relies on such satellite powered networks to close land-based infrastructure loops. We owe much of the last few decade's economic growth to this traditional model, although it is now showing signs of strain. It remains challenging for space-based platform developments to move in step with the pace of commercial progress on the ground; rapid technology enhancements take years to migrate into space, increasing operators' risk. Hardware rather than software defined space-borne assets are all too easily surpassed, increasing operator headaches.

> According to a 2018 forecast by IDC2, data growth is projected at 61% CAGR resulting in up to 175 ZB (1 ZB = 10^21 bytes or 1 trillion GBs) demand by 2025.

Recently, traditional space operators and their clients have sought ways to lower both the operational costs, risks and investments. Simultaneously, entrepreneurship in the space economy has flourished in the last half decade with noteworthy private investments including:

- The 2015 SpaceX announcement of its Starlink program. One intended to place as many as 30,000 satellites in low-earth orbit (LEO), delivering low-latency broadband access to all.

- The OneWeb constellation of an initial 650 satellites was announced almost concurrently to Starlink.

- Jeff Bezos' Amazon Project Kuiper announced in April 2019 with plans to launch 3,236 satellites over the next decade again targeting broadband internet delivery in LEO.

Insatiable data demand has significant impact on satellite capacity planning. Statistics on the topic are eyewatering. The new 5G wireless system and a growing class of IoT applications will drive accelerating data growth. Its pace, illuminated in a IDC forecast[3] in 2018 is staggering. IDC projected data growth at 61% CAGR resulting in up to 175 ZB (1 ZB = 10^21 bytes or 1 trillion GBs) demand by 2025.

Beyond the above, largely commercial motivated data growth are more esoteric applications and needs. Increasingly, governments are re-doubling commitments to space programs in the interests of defense. Some hint at an accelerating arms race built on the development of hypersonic missile technologies, of interest to several global superpowers. Moreover, in a warming world, scientists seek to better monitor climate change impact leading to growing interest in deploying higher resolution instruments including synthetic aperture radar used in earth observation. These fast-changing, data-hungry needs force an industry response. The next decade is ripe for the rapid advancement and commercialization of myriad space capabilities. Thankfully, communication technologies are nearing readiness to help drive this imminent transformation.

[3] 'The Digitization of the World From Edge to Core', by IDC ©2018

Glossary

New Space
A global trend encompassing new space investment philosophy combined with a series of technological advancements leading to a rapidly growing private sector. This trend is set to seed a broader range of projects and developments over the next decade and elevated competition in Space.

SoftSat (Software satellite)
Satellite systems providing both on-board software defined processing capabilities coupled to agile, direct access soft radios (DASRs) capable of supporting a diversity of multi-mode integrated missions (communications, navigation and sensing) and switching operating scenarios dynamically to adjust to market demand. A SoftSat's operating mission and radio interface is defined by the active firmware loaded to the satellite. Though there are no known commercial SoftSats on orbit today, ESA is commissioning OPS-SAT during 2020 which is considered a precursor to full blown SoftSats by the authors.

Direct Access Soft Radio (DASR)
DASRs are intelligent soft radios whose operational characteristics are defined algorithmically. They are largely unconstrained from the limits of conventional hardware and can be dynamically reconfigured by applying new code giving

SEMICONDUCTOR TECHNOLOGY ISSUES HAVE ESTABLISHED A SPLIT IN THE PRODUCT SUPPLY CHAIN FOR THE SPACE BUSINESS

Unless you are well versed in semiconductor technology trends, you may not currently recognize the implications for your future product sourcing strategy caused by disruptions the chip industry faces. There are two key factors:

• Below the 28nm node, the maximum frequency of CMOS process technology has collapsed. The latest nodes thus simply do not support building advanced high frequency sampling systems even though, from the advanced processing perspective RF softwarization benefits.

• The cost to develop next generation, fine-line processes and the products that use them are accelerating at such pace, that they can only economically support the highest volume consumer products.

Increasingly, fine-line processes follow a law of diminishing returns neither yielding significant power improvements nor raised transistor density. Meanwhile development and manufacturing costs grow astronomically.

RF CMOS runs out of steam at just the wrong moment

For the better part of twenty years, software defined baseband radio technology price points have benefited by following the continuous downward price momentum facilitated by Moore's law in high volume core CMOS processes. The iterative innovation caused by the commercialization of each new node has delivered unsurpassed consumer performance, reduced power, and access to an increasingly rich range of applications on the move. For years this seemed like a natural law. Recently however, innovation has stalled as basic device physics upsets the balance of engineering tradeoffs.

A key MOSFET semiconductor figure of merit is fmax (maximum frequency). Fmax informs of raw process performance in terms of high frequency gain. Fmax (figure 2) is the frequency at which transistor power gain drops to one. Over many years, fmax has continued an ascent to ever higher frequencies as gate dimensions shrunk. Unfortunately, frequency scaling has slowed to the point of a reversal. At 28 nm, a peak for fmax was achieved at around 360 GHz. Subsequently, in 14 nm nodes fmax has plummeted to only half that of 28 nm (i.e. 160 GHz). The reasons for dwindling frequency are complicated; down to a mix of both process parasitic resistance and capacitance increasingly dominating the performance budget. Moreover, plummeting threshold voltages impact dynamic range, driver capability and noise levels. How then, is the industry to maintain the pace of innovation when future analog circuits are held back so significantly? In Europe, R&D funds have focused on two prongs of attack:

- DOTSEVEN a three-year, ambitious R&D project targeting the development of Silicon Germanium (SiGe) heterogenous bipolar transistors (HBTs) with fmax around 700 GHz.
- TARANTO aims to break technological barriers in the development of next generation BiCMOS technology, by driving towards the performance improvement of Heterojunction Bipolar Transistors (HBT) with a much higher level of integration.

The direction of travel with these programs is illustrated by the upper red trajectories of figure 2. That is away from core digital CMOS and renewed exploitation of alternate process approaches for radio frequency analog circuits.

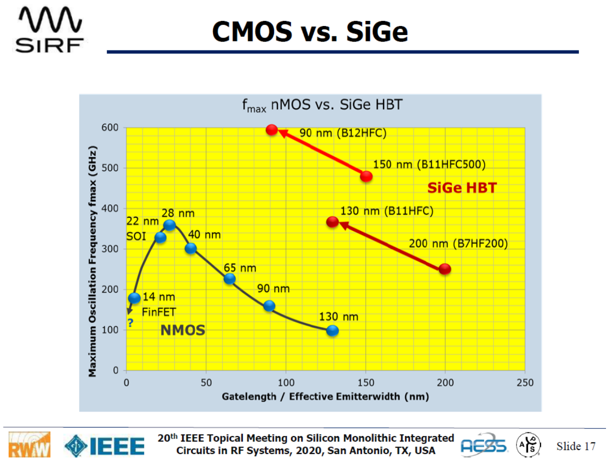

Figure 2 - Progression in fmax for CMOS and SiGe processes, shows the collapse in CMOS performance at gate lengths lower than 28 nm (Source: Infineon, IEEE Radio &Wireless Week Jan. 2020, San Antonio, TX (USA)

The runaway costs of fine-line SoC design demands future alternatives

Silicon design costs have exploded. According to an IBS study[4], IC design costs have jumped from $28.5 at 65 nm to $51.3 million for a 28nm device (i.e. a doubling) and costs accelerate even faster below 28 nm. This economic consideration is largely irrelevant in the context of soft radio design as these costs are already far beyond what specialist markets can bear. The key point to emphasize however is that the space industry has often relied on CMOS scaling and performance benefits derived from designing application specific ICs (ASICs) to deliver future cost reductions and power improvements when building bespoke systems. Increasingly however, much of the specialist analog circuitry either relies on older process nodes or must make the leap to higher frequency devices facilitated by silicon germanium (SiGe) HBTs found on the latest BiCMOS processes.

4. 'Advanced Design Cost (new CPU, GPU or SoC) evolution', by International Business Studies © 2018,

Regaining signal path innovation thus forces a gradual move away from custom ASICs because of the performance challenge highlighted. Future RF signal paths will of necessity split off from bulk CMOS and force a modified architecture where mixed signal front-ends will be teamed with advanced, signal processing capabilities provisioned by the latest field programmable gate arrays (FPGAs). FPGAs will continue unhindered on the bulk CMOS trajectory driving further economy and performance gains. It is in this context that innovators like Teledyne e2v have been investing in manufacturing infrastructure to bring a new class of small, integrated system-in-package solutions or SiPs to market. SiPs are destined to be at the heart of the next phase of RF miniaturizations and be the primary drivers for SoftSat design.

SEMICONDUCTOR TECHNOLOGY ISSUES HAVE ESTABLISHED A SPLIT IN THE PRODUCT SUPPLY CHAIN FOR THE SPACE BUSINESS

What are the necessary advances at the heart of making the SoftSat paradigm a reality? The most important developments center around reprogrammable processing, signal modulation and demodulation, protocol coding, and frequency generation and include:

1. The availability of multi-gigahertz, broadband data converters (ADCs & DACs) with signal bandwidth up to Ka-band (40 GHz) which will surpass the performance achieved by traditional analog RF (bent-pipe) signal chains. Such components will provide increased value add, with on-board digital up and down conversion capabilities and numeric control.
2. Ultra-highspeed interconnect and backplane technologies supporting data rates up to 12 Gbps and beyond including future silicon photonics.
3. Precise time synchronization across multiple channels to ensure sample point synchronization preserving signal phase across the system.
4. New high-performance, low dielectric constant, organic substrates boost the gain and spectral characteristics of SiPs.
5. Space grade or at least 'capable' components.
6. Improved solid state power amplifiers.

Each one of the above has an impact on the ability for the space industry to deliver fully-fledged SoftSats. With only limited space here to cover some of the specifics, the remainder of this article focuses on the top four points.

Setting course towards RF softwarisation of the K-band and beyond

Foundational steps towards building a full Ka-band sampling system were initiated in mid-2019 as an experimental project within Teledyne e2v. The project teamed a highly linear 24 gigahertz signal quantizer (or Track and Hold amplifier – THA) to a then, brand new broadband ADC, the EV12AQ600 as shown in figure 3.

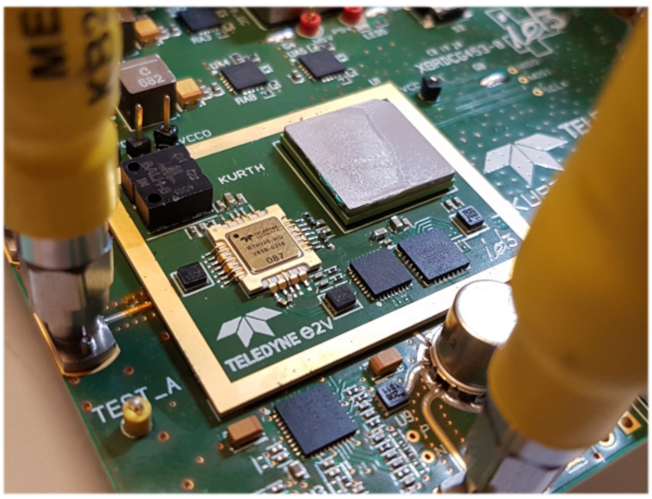

Figure 3 - Image shows the PS620 experimental front-end board

Key parameters of active devices

EV12AQ600 ADC
- Quad 12-bit 1.6 GSps ADC cores supports 1, 2 or 4 channel time interleaving
- Sample up to 6.4 GSps in fully interleaved mode
- 6.5 GHz input bandwidth (-3dB)
- Integrated broadband cross point switch
- Sync chain for multi-channel synchronization

RTH120 THA
- 24 GHz input bandwidth
- Dual THA enables output hold time for more than half a sample clock cycle
- Fully differential design

The resulting PS620 proof of concept combines the microwave THA with a quad cores ADC capable of individually sampling at 1.5 Gsps combined with an internal broadband Crosspoint switch featuring a 6.5 GHz analog input bandwidth. The design of this ADC lends itself to core interleaving. Time interleaving the four cores enables sampling at over 6 Gsps. With the application of Nyquist folding principles applied to the K-band THA and suitable sample frequency selection, it was expected that direct down conversion from the K-band into the baseband 6 GHz range of the EV12AQ600 would deliver useful results. These results were previously detailed in a whitepaper[5] .

The objective of tests performed with the module was to determine the effective limits of direct conversion in the K band (18 to 26.5 GHz) of the above quantizer. Three specific problems were identified from initial spurious free dynamic range (SFDR) testing:

• input signal power substantially influenced raw THA dynamic performance
• significant impact of factory calibration on the ADC 's high Nyquist zone interleaving performance
• the impact of ADC integral non-linearity (INL) errors when sampling in high Nyquist zones

Reporting on initial experiments, several limitations arose. Most notable concerned the calibration of core interleaving (ILG). Initially ILG was rightly optimized for baseband frequencies. However, a spectral analysis clearly indicated that the source of spectral spurs, being centred around Fc/4 had to be interleaved stage offset differences within each individual core.

Unsurprisingly, the offsets were impactful across a range of test frequencies. As a result of iterative tweaking, substantial reductions in Fc/4 spurs were possible (figure 4). With a focus on K-band operation, a 21.5 GHz centered calibration produced particularly encouraging results, gaining almost 15 dB across the K-band.

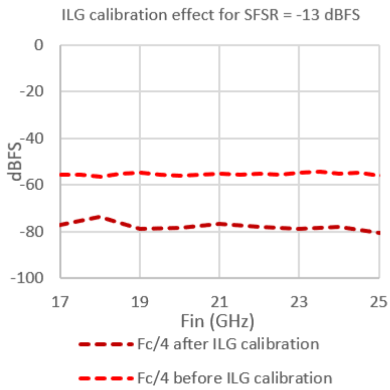

Figure 4 - Impact of high frequency optimized interleaving

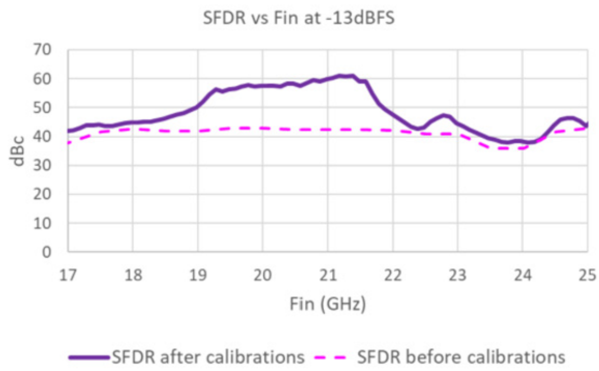

Figure 5 - Experimental K-band SFDR of initial PCB based prototype post - and pre- calibration

Further optimization possibilities seemed limited; however, integral non-linearity (INL) of the converter clearly affected the third harmonic (H3). As with ILG errors, INL calibration is performed for baseband operation at production test. However, test engineers expected a further improvement with a higher frequency calibration. Indeed, a further 3 to 5 dB drop in H3 was observed. These aggregate results (figure 5) helped establish the direct microwave access product plans at Teledyne e2v which will be covered here.

[5] 'Advanced wide band sampling solution for direct digitization of the K-band – extending the boundaries of RF possibility, by Teledyne e2v ©2019.

The emerging microwave direct access product roadmap

Working towards Ka-band direct access, Teledyne e2v planned two further iterations beyond the PS620 proof of concept for a direct access receive path, as shown in figure 6.

Throughout 2020, the capabilities of the first proof of concept have been extended. A second prototype, the PS640, doubles the sample rate by time interleaving a pair of EV12AQ600 ADCs and teams them with a new microwave sampler, featuring a 30 GHz useable bandwidth. This is the first step to reaching beyond the K-band.

Softradio Receive Path Variants	Proto 1 PS620	Proto 2 PS640	Ka-band quantizer
Architecture	RTH120 AQ600	1st gen. µWave sampler AQ600 AQ600	2nd gen. µWave sampler ADxxx
Device structure	MPM - using package parts	MCM - using flip-chip die	MCM - using flip-chip die
Construction	PCB	FC-BGA	FC-BGA
Frequency	Ku-band (upto 24 GHz)	Ka-band	Ka-band
Sampling rate	6 Gsps	12 Gsps	12 Gsps
THA/Bandwidth	Dual clock RTH120 19 to 21.5 GHz	In-house 1st gen. proto upto 30 GHz	In-house 2nd gen. proto upto 40 GHz
ADC	1 x AQ600	2 x AQ600s time interleaved	Enhanced µwave ADC
Power consumed	8 W	14.5 W	TBD
Input signal path	Differential	Single-ended	Single-ended
ENOB	7 bits	6.5 bits	TBD
Status	Proof of concept with test results available today	Encouraging initial results & α-samples available today	α-samples due Q32021

Figure 6 - Teledyne e2v Ka-band Soft radio development roadmap

Initial full Ka-band experimental prototype results

The already encouraging results from the second prototype design are hinted at by the SFDR plot (figure 7). This shows that with25 GHz input signal, sampled at 10 GSps a third harmonic spur is produced at -57 dBFS, equivalent to -51 dBc SFDR when accounting for the input level. This is very encouraging. Unlike the initial PS620 design based on standard packaged components on a RF printed circuit board, the PS640 adopts a new organic, low dielectric substrate with flip-chip components simultaneously improving RF performance whilst reducing real-estate. This 33 x 19 mm SiP assembly is produced by Teledyne e2v and uses a 0.8 mm ball pitch interconnect, totaling 799 nodes. An extra consideration for this module was the desire that both ball and bump interconnections are RoHS compliant in support of future production standards. The resulting, tiny 6.3 mm2 module is the industry's first able to achieve direct Ka-band conversion. A photograph of the finished item is provided here (figure 8).

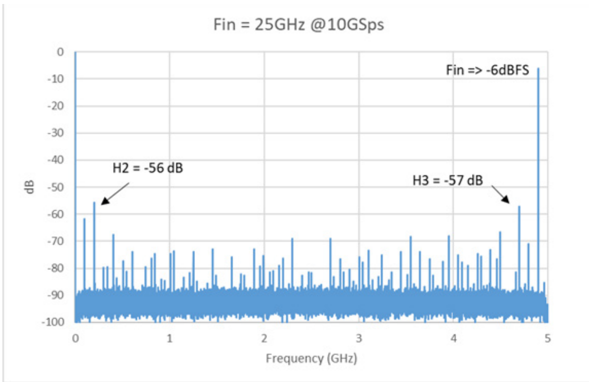

Figure 7 - SFDR obtained with 25 GHz of input frequency continuous wave

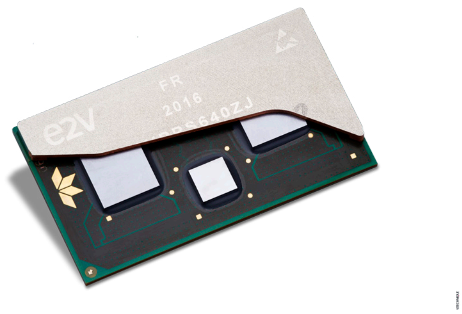

Figure 8 - PS640 Multi-chip module (MCM)

The final piece in the Ka-band puzzle

By the end of next year, initial samples of the third stage of planned innovations are expected. This will be a production ready SiP. It leverages 36 months or more of intensive engineering efforts. It will include a second-generation microwave sampler. The sampler pairs to a next generation ADC core. Whilst remaining tight lipped on the full feature set, Teledyne e2v indicate that the ADC implements several enhancements to improve core time interleaving as well as providing a range of numerical control features to simplify its application in soft radio designs.

A noteworthy architectural choice emerging in the latest developments and a difference marking the move to Ka-band functionality is that Teledyne e2v has ditched balanced differential analog signal and clock lines, in favor of single-ended signal strategy. This move provides some major advantages. Obtaining space qualified components proves challenging and the company notes that finding suitable baluns has been especially tricky. Furthermore, these are expensive, real-estate consuming components. It is a commendable move, given that most microwave sources are single ended.

Section 4.5 – The Ka-band transmit path is developing
Teledyne e2v's development teams are also working on a complementary transmit path solution. A dual 12-bit current-steering RF DAC is being developed supporting synthetic Ka-band frequency generation. A typical broadband output power spectral plot of the device measured in the lab is shown (figure 9).

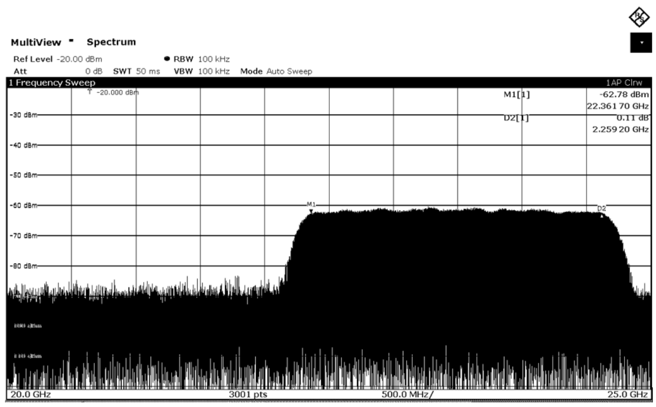

Figure 9 -2.26 GHz multi-tone output power spectrum (Fclk = 20 GSps) in 2RF mode, 4 x Interpolated, ASINC = ON

The EV12DD700 will include a host of advanced features bringing significant flexibility to the transmit side including:
- -3 dB analog bandwidth of 25 GHz
- multiple output modes including 2RF allowing for up-conversion free, synthetic frequency projection at 21 GHz and beyond
- digital beamforming
- a programmable anti-sinc filter
- fast programmable, complex mixer supporting highly agile frequency hopping
- a digital up-converter using a 32-bit NCO
- multi-device synchronization via sync chaining.

The DAC delivers SFDRs of -55 dBc or better. Moreover, it provides specific support for highly agile, rapid frequency hopping including multi-mode hopping (with RTZ, continuous and coherent modes embedded). In common with earlier Teledyne e2v DAC solutions, the product features multiple output coding modes designed to modify the output power characteristics depending on where in the spectrum synthetic signal bandwidth is needed. The 2RF mode peaks output power across the Ka-band (shown by the green dotted curve figure 10).

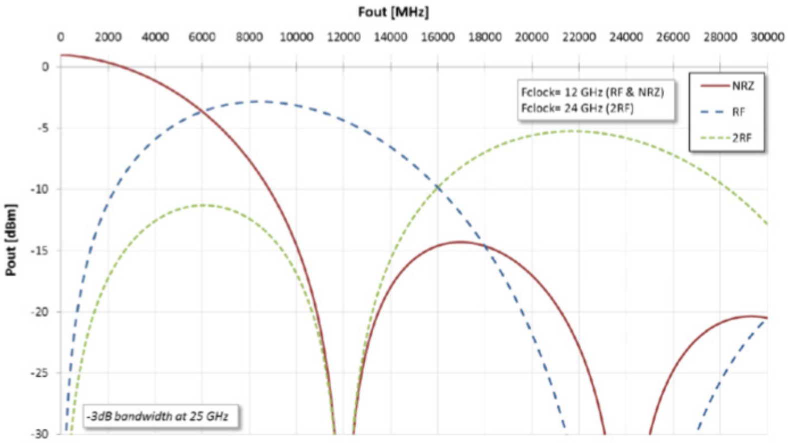

Figure 10 - Simulated three output characteristics of future EV12DD700 dual DAC

Managing high speed data

When using modern data converters, managing the high-speed serial data streams is a challenge. Teledyne e2v products exploit an open source, 12 Gbps link technology called ESIstream (Efficient Serial Interface). This serialized protocol is designed with minimal overhead and delivering simple, license free IP for a range of FPGAs (e.g. Xilinx Kintex Ultrascale and Virtex7, Intel Arria 10).

ESIstream protocol provides data efficiency of 87.5% based on a 14b/16b encoder using a linear feedback shift register (LFSR) scrambler. An added disparity bit ensures DC balanced transmission, and the extra toggle bit enables a synchronization monitor. The link supports multi-device synchronization and deterministic latency via a separate synchronization signal (SYNC) and a simple SYNC triggered counter at receiver side (figure 11). The counter releases data from the ESIstream receive IP output buffers at a user defined time to ensure deterministic link latency.

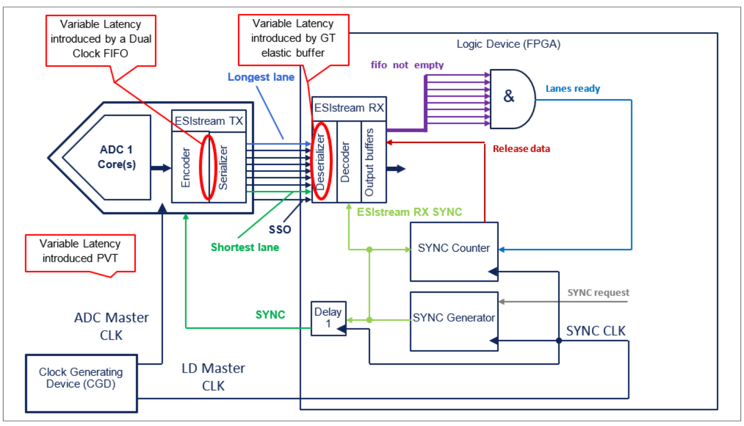

Figure 11 - Single ADC deterministic latency principle supported by ESIstream protocol

Critical timing and the sample synchronization problem

Today, many radio applications use beamforming to improve system performance. Beamforming exploits signal interference to direct signal power spatially. Such systems demand synchronous sampling, where all channels are sampled at precisely the same instant in time. In so doing, signal spatial (or phase) information is preserved across the antenna array. Although there are some penalties such as increased complexity and power, several desirable benefits emerge:

• Higher channel signal to noise ratio (SNR) improves radio link budgeting thus increasing signal range (or reduces the transmit power needed)
• As interference energy comes from a specific direction, beamforming algorithms can use signal nulling to limit or mitigate interferers

However, operating at gigahertz frequencies, signal propagation times are important factors both at the IC device and board levels. Printed circuit board (PCB) traces behave as transmission lines, and it is critical to retaining phase information, that signal trace lengths are matched. A single centimetre of trace adds between 60 to 75ps of signal travel time when compared to a clock period of 166ps (for a 6 GHz clock). Thus, board traces can significantly influence a design, highlighting why PC board layout is a critical success factor for microwave systems.

However, one extra factor hinders good designs and arises in the digital domain. Metastability is an uncertain state in digital systems. As clock frequency increases, it is increasingly likely that a metastable event occurs disrupting system timing A synchronization strategy can counter metastability. That is where Teledyne e2v's SYNC chaining feature comes to the aid of designers.
Delivering deterministic operation in the face of metastability often proves hard to achieve with alternative approaches. The JEDEC JESD204B sub-class 1 approach has left designers with a poor impression given the challenge of getting it to work properly. However, a robust and resilient synchronization is provided by Teledyne-e2v that essentially re-times the master clock at every device using the SYNC signal. Deterministic synchronization is achieved with a pair of event-driven, differential electrical signals; the sync and sync-output (SYNC and SYNCO). Between them, these signals ensure that local timing of a target device is reset and that all digital sub-systems are properly locked to the reference master clock. Moreover, synchronization can then extend, ad nauseum to multiple devices throughout a large multi-channel system.

The benefits of SYNC chaining are:
• Its relative simplicity – no extra clock is needed yet synchronization across many parallel channels over the lifetime of the system is guaranteed.
• A single, one-off training cycle establishes system synchronization.
• Even if environmental conditions (P, V or T) change, timing parameters remain fixed.

The SYNC chain provides a rock solid, trans-system synchronization source.

New high-performance packaging and interconnect approaches

Packaging technology stands out as one of the 'black arts' of microwave system design. And for good reason. For any semiconductor, the package conveys robust mechanical properties. It isolates the semiconductor die from the immediate environment. It facilitates power dissipation and, in many cases, supports a significant number of interconnection nodes in complex designs.

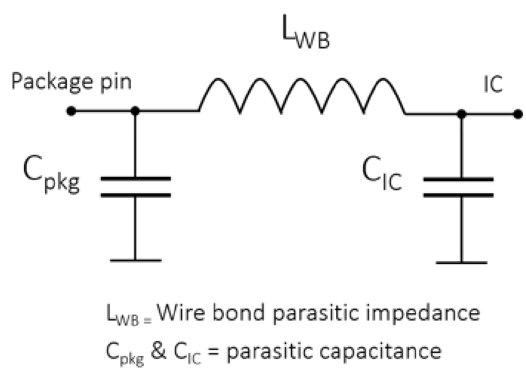

Figure 12 - Lumped model of package pin to IC connection

For microwave ICs, there is an extra dimension critical to achieving optimal performance, and that rests on package parasitics. Parasitics are non-ideal electrical circuit elements due to the package. They arise from individual package material properties. Typically appreciable parasitics at microwave frequencies include wire bond properties of the lead-frame to die attach, material discontinuities between the PC board and the package's connectors. When inspecting IC connections, the lumped model shown in figure 12 is a simplified electrical representation of the interconnect.

This diagram highlights differing impedances resulting from the parasitics and stresses the need for impedance matching as signal frequencies rise. Choice of package materials therefore play a key performance role. Traditionally, many microwave ICs used LTCC (low temperature co-fired ceramic) substrates as the substrate material of choice. However, in migrating up to the Ka-band, key electricals necessitate a move to faster organic substrates highlighted in figure 13.

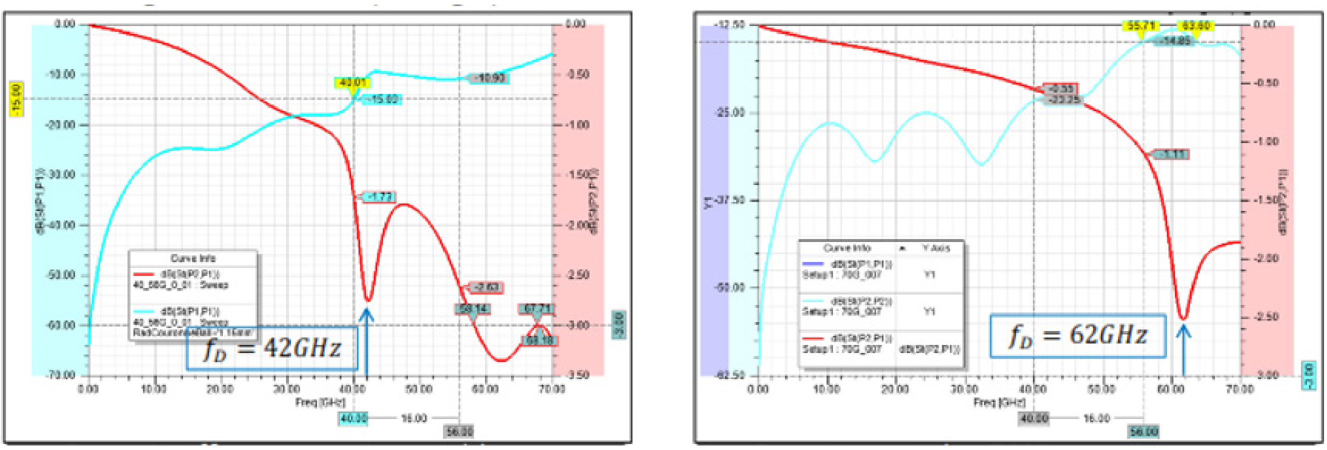

Figure 13 - Frequency characteristic of ceramic (LHS) & organic substrates (RHS) highlighting need to shift to organics

The product development flow included a detailed finite element analysis of package stripline design. High frequency structure simulation (HFSS) simulated the electromagnetic profile of the board-package-silicon interfaces allowing optimization of device electricals. In this analysis, observe the wave propagating from the PCB (bottom left), moving to the Solder Ball (interface between PCB and package), then moving up through the vias into the IC substrate, then on into the silicon through the bumps (i.e. the interface between package and flipped IC). Experimental characterization has subsequently been validated for suitable HF signal connectors at frequencies up to 65 GHz.

A LOOK TO THE NEAR FUTURE OF DISTRIBUTED SOFT RADIO DESIGN

With the technology split discussed earlier (section 3.1), new architectural approaches are demanded. Today, the state of the art, direct access, Ka-band quantizer described reflects a natural progression of current design paradigms as seen in figure 14 . Illustrated is the teaming of RF data acquisition components with signal processing within an FPGA. Each element exploits the optimal process technology choice for the individual tasks. As can be seen, the resulting dense SiP, drives miniaturization whilst minimizing solution cost and device footprint.

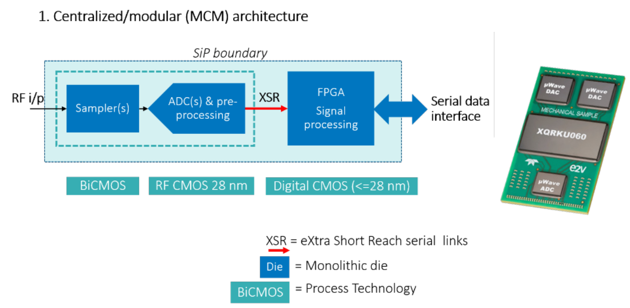

Figure 14 -Modularized Ka-band quantizer and example RF front-end SiP solution from Teledyne e2v on the right

The imminent arrival of silicon photonics heralds a new enhanced design paradigm that will suit a more fundamental, system compatible digital approach to satellite radio architecture. Optical interconnect systems are already codified through the work of the Optical Internetworking Forum[6] who have established an implementation agreement covering serialized interconnects from 6 to 56 Gbps. This will allow a fully distributed future radio architecture (figure 15) where ultrawideband digital converters sit co-located with antennas and exploit digital data over fiber transmission to central processing units. A move that not only facilitates complex algorithmic beamforming but also brings extra design freedom and weight reductions. Moreover, bothersome electronic issues such as signal distortion, noise, and crosstalk should all further benefit.

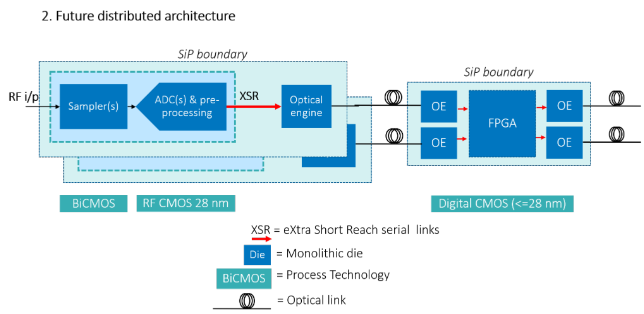

Figure 15 -Future distributed architecture exploits silicon photonics for weight reduction and increased architectural flexibility

[6] 'The OIF-CEI-56G Project, source: OIF Sept. 2015.

ARE YOU READY, SOFTSATS ARE COMING?

This article introduced SoftSats. They are versatile software defined space platforms representing the transformation away from single mission, high cost traditional satellites to substantially more sophisticated options over the coming decade. The twin engines for this change are the emergence of leading-edge data conversion and signal processing semiconductors.

SoftSats combine soft radios for the physical layer air interface together with multi-mission, over-the-air (OTA) re-configurable payloads. Considering current market forces, the case for such migration is crystal clear. Thankfully, this demand is supported by emerging commercially and technically viable direct access, Ka-band soft radios; those powered by a new class of broadband data converters.

Thankfully, this demand is supported by emerging commercially and technically viable direct access, Ka-band soft radios; those powered by a new class of broadband data converters. As reviewed, Teledyne e2v has strategic developments attacking both the receive and transmit signal paths. Over the next year to 18 months, the fruits of this work will emerge. Meanwhile, the company is already giving live demonstrations of state of the art capabilities providing credible proof of the commercial and technical viability of their plans.

> A bridge to SoftSats already on orbit?
>
> ESA's OPS-SAT is a 7 kg, 3U cubesat. It orbits at 515 km and is referred to as a 'software laboratory in space' providing access to a software defined radio and dual core ARM cortex A9. Its designers state that it will be available for in-orbit demonstration of revolutionary control systems and software too risky to evaluate on active satellites. Over 100 European companies and institutions are signed up with experimental project plans for the platform.

Research helping realize the SoftSat vision continues through several ongoing industry efforts and the authors are encouraged that many elements of the SoftSat concept are being mission tested today. One notable project is the European Space Agency's OPS-SAT launched in December 2019 (see side text). Other parallel industry developments add substance to the articulated SoftSat vision which also demands the availability of advanced high-performance digital processing. Thankfully, processors are developing rapidly in support of challenging ground-based problems. Consider for example, the critical image recognition and sensor data fusion challenge presented to developers of autonomous driving solutions along with rapid developments in artificial intelligence (AI) to name but two.

Another key component of SoftSats is better, as in higher efficiency and reduced SWaP (size weight and power) solid-state power amplifier technology. Several companies including Advantech and Tesat are developing these solutions and turning to new gallium nitride (GaN) devices today.

Space projects remain risky, however interest in innovation is growing apace. For this reason, now is a good time to assess how RF softwarisation technology and the SoftSat concept will recast your development plans. Today there is a real risk that slow movers are surpassed by agile entrepreneurs. The early adopters of the SoftSat paradigm are most likely to enjoy considerable market advantages. The time is right to step up to direct access Ka-band technology.

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