GSPS DACs Enable Ultra-Wide Bandwidth Applications

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Introduction

To meet the increasing capacity demand of mobile customers, the emerging E-band market requires wider bandwidth capabilities compared to traditional microwave backhaul wireless architectures. Due to increased capacity, 2-GHz E-band systems will be needed in the near future. This white paper covers the demands of current E-band point-to-point systems, and how Analog Devices' high-speed digital-to-analog converters (DACs) provide the necessary bandwidth and sampling frequencies to support them.

GSPS Converter Market Overview

The increasing popularity of mobile phones, especially smartphones, has grown exponentially over the past few years, and is expected to continue to grow at increasing rates as we move toward 2020. More mobile devices equipped with data capabilities place increasing data demands on the cellular networks that provide the data and create complex problems that service providers need to solve in order to meet the performance expected by their mobile customers.

Cisco's Visual Networking Index report last year predicted that mobile data usage will have a compound annual growth rate (CAGR) of 57% from 2014 to 2019. The main driver in this mobile data increase is the use of smart mobile devices such as smartphones, tablets, and other devices that access these mobile networks.

In 2014, almost half a billion mobile devices and connections were added from the previous year, totaling 7.4 billion devices and connections globally. Of that half-billion growth, 88% were specifically smartphone additions.

In a report from Ericsson, mobile subscribers are expected to grow from 5 billion in 2010 to 9.2 billion in 2020, with 80% of those subscriptions being broadband-capable. The network speed capabilities of these broadband subscriptions will vary regionally depending upon the deployment of more advanced systems over the next few years in different parts of the world. GSM-only subscriptions are the largest percentage of the mobile subscriptions today. However, Ericsson predicts LTE will take over as more LTE systems are deployed into 2020. They predict 85% of mobile subscriptions in North America will be LTE by 2019.

GSPS Converter End Application Markets Overview

Application Market	Channel Bandwidth	Allocation Bandwidth
Cellular Communications (LTE/GSM)	200kHz/20MHz	75MHz/100MHz
Traditional PtP Microwave	3.5MHz-112MHz	500MHz – 3GHz
E-Band PtP Microwave	250MHz – 2GHz	10GHz
Cable Television	6 MHz/8MHz	~1 – 1.4 GHz
Military/Radar	Narrow to wide	~2 GHz to wide
Instrumentation	Narrow to wide	~2 GHz

Figure 1. An overview of the end applications that GSPS converters can support, with allocation bandwidth and channel bandwidth ranges.

Backhaul Solutions

With all the increase in data and capacity demands, this places heavy burdens on the backhaul solutions required to transfer this data throughout the network. Currently, three main mediums are used for backhaul: copper, fiber, and microwave. Microwave is expected to continue to account for at least 50% of mobile network backhaul transmission, with copper slowly being replaced by fiber, where cost and deployment complexity are justified. Regional differences will play into the decision of laying fiber vs. setting up microwave links. Sometimes, areas might already have decent existing fiber infrastructure to utilize, whereas other areas of the world may have limited support, and it may not warrant the cost and time for creating such an infrastructure.

These differences vary drastically across the globe. For example, 90% of the backhaul systems in India and the Middle East are microwave, whereas less than 10% of the backhaul systems in China are microwave due to higher fiber network availability. Overall, microwave systems can provide the high capacity needed for these backhaul systems into the future while being flexible, reliable, and at a low total cost of ownership and quick deployment pace, making them ideal for this fast-growing and demanding cellular network market.

Figure 1 shows the differences in the applications that GSPS converters can support, and the allocation

Microwave Backhaul for Cellular Networks

Today's option when …
➤ Capacity need is < 1-2 Gbps
➤ Fiber or copper are not feasible
➤ Rapid deployment is critical
➤ Future will require > 2 Gbps

Last mile – Daisy Chain

LTE Last mile
Access 1-2 km

Long Haul 20-40 km

Small Cel

How Many …
➤ Millions deployed worldwide
➤ Support 50% of Cell-Sites

Access 1-10 km

Access 1-10 km

Aggregation Site

3G Last mile - Ring
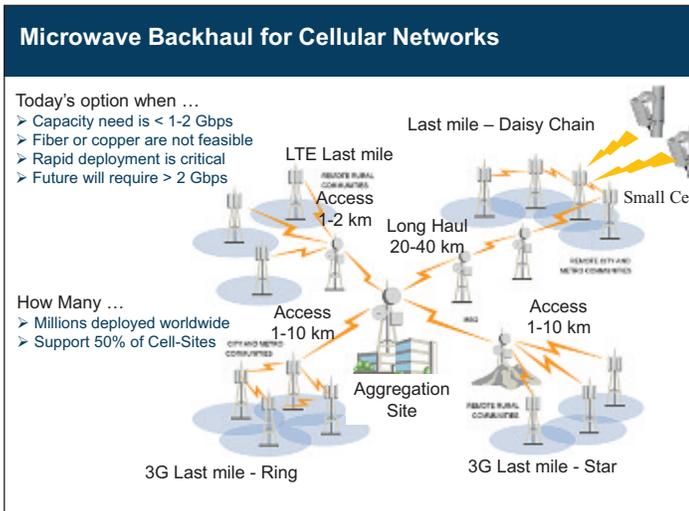
3G Last mile - Star

Figure 2. Microwave backhaul network designs that can be used to transfer data back to the main aggregation base station site.

bandwidth and channel bandwidth ranges. The cellular communications market, along with the traditional or legacy point-to-point (PtP) microwave application, have relatively small channel bandwidth with slightly wider allocation bandwidth possible across operators. The E-band PtP microwave systems are architected for much higher channel bandwidth — up to 2 GHz channel spacing currently — with a very wide allocation bandwidth at the E-band microwave frequencies.

Cable television is similar to cellular communications, with relatively small channel bandwidth; however, the allocation bandwidth is larger. Military and radar technology bandwidth requirements can vary widely, depending on the application. Things like electronic warfare applications or military communications may require very narrow bandwidth for some designs, whereas others will require extremely wideband capabilities. Similarly, the instrumentation market also varies, depending on the end product design. Often the instrumentation needs to follow along with the cellular bandwidth requirements, as they often are driven by test equipment demands for things like FPGA testbeds and other cellular protocol testing.

Overall, the variety of markets that these GSPS DACs can serve require the product to be flexible in how they can be configured to support both narrowband and wideband applications. This discussion will focus primarily on the microwave market segments both for the traditional legacy bands and the E-band PtP application space.

Microwave Backhaul for Cellular Networks

Rapid deployment of network systems is critical to staying competitive and meeting industry needs. Therefore, often fiber or copper are not feasible, given the timescale of these deployment schedules. Figure 2 depicts a variety of different network designs of these microwave systems that can be used to transfer data back to the main aggregation base station site. For the long haul sections, over 10 km distances, typically traditional or legacy bandwidth microwave systems are used for the data transmission. For the shorter haul, traditional band can also be used as well as the higher-frequency architecture like E-band. The E-band systems provide much wider bandwidth and higher data rate throughput than the traditional band systems. Overall, the combination of traditional and E-band microwave systems supports up to 50% of cell sites currently, with millions of these systems deployed across the world.

The traditional microwave bands span from 6 GHz up to 42 GHz, with a 6 to 8 GHz range typically being used for the long haul transmission, and 11 to 23 GHz range used for the short transport and aggregation portions of the network. Due to the increasing demand for data and bandwidth, more bands are gaining popularity in the 26 to 38 or 42 GHz range, as well as to provide additional capacity support in the traditional band.

In the traditional band systems, the individual channel bandwidth varies from 3.5 MHz to 112 MHz. These bands, though relatively narrow, require high-performance components in their systems, as they use high-modulation data transmission schemes that need high signal-to-noise ratio performance. The other frequency ranges at the higher output are V-band at 60 GHz, and E-band at 70 and 80 GHz. The higher microwave frequencies mean the antenna sizes are smaller and their output power is typically lower than the legacy band systems.

Due to environmental factors such as oxygen absorption, weather susceptibility, and fast channel-fading properties at these high frequencies, they tend to only be used for the shorter range or small cell applications covering smaller distances than traditional bands. The channel bands, however, are much wider — up to 1 to 2 GHz bandwidth requirements in E-band, for example. The achievable capacity differences between legacy band and E-band are fairly significant, with E-band being able to potentially deliver up to 10 Gbps throughput rate. Additionally, this range typically has light licensing or no licensing requirements for the operators, which helps for total cost of ownership for these systems.

Point-to-Point Microwave Systems

Point-to-point microwave systems use quadrature amplitude modulation (QAM). The basics important to PtP capacity are shown in Figure 3, which shows a constellation plot for 16 QAM. Four bits are used to describe one symbol in the 16-symbol array. In this case, the L factor is 4. Each symbol has the unique amplitude and phase associated with it, and these are constructed with an in-phase and quadrature phase symbol that is 2 bits in length for each.

The figure shows that impairment in transmission of the signal can cause impairment in the associated symbol, reducing its decision distance and potentially causing an error. As channel impairments increase — such as distance of transmission, lower power transmitters, or amount of noise, for example — the amount of impairment that reaches the receiver increases, and an error is more likely to occur. The red squares describe the decision area around a given symbol. If the actual receive symbol plus the channel impairment exceeds the red boundary, an error will occur.

The need to increase data throughput in PtP systems is large and ever increasing; therefore, operators and equipment makers are working hard to increase the number of bits per symbol that can be transmitted in a given bandwidth. One way to do this is to increase the modulation depth. On the left side is an example given for increasing the level of QAM used in a given bandwidth. When QPSK is used, the number of bits per symbol is only 2 and the constellation would just show 4 points, 1 in each of the four quadrants illustrated. When the modulation level is increased to 16 QAM, L goes from 2 to 4 and the corresponding channel capacity is doubled. The signal now transmits 4 bits per symbol per unit bandwidth, as opposed to 2 bits per symbol per unit bandwidth for QPSK. The tradeoff is that the decision distance from one symbol to the next is reduced twice, therefore requiring 6 dB more signal-to-noise ratio in order to correctly receive the signal.

The example shows that as the modulation depth is increased, the amount of extra capacity achieved is less and less, showing diminishing returns after a point due to the continued requirement of 6 dB more signal-to-noise ratio for each modulation step. As the modulation depth is increased to levels like 1024-QAM or 1k QAM and 4k QAM, the resulting signal becomes more sensitive to other system-level impairments like group delay and phase noise, which causes phase shifts in the constellation. The higher-order modulation also has a higher peak-to-average power ratio requiring higher

Dense QAM Increases Spectral Efficiency

2^L QAM $\leftrightarrow$ L (bits/symbol)

QPSK	L=2
16QAM	L=4
64QAM	L=6
256QAM	L=8
1024QAM	L=10
4096QAM	L=12

↑100%
↑ 50%
↑ 33%
↑ 25%
↑ 20%

Q (quadrature)

$\sin\omega_c t$

symbol impairments

(1011)

(1110)

envelope magnitude

$\cos\omega_c t$

I (in-phase)

envelope phase

Higher QAM Trend
- ✓ **Increased capacity**
- ✗ **Diminishing returns**
- ✗ **+6 dB/step more SNR**
- ✗ **Increased peak-average**
- ✗ **More sensitive to impairments**
- ✗ **Lower system gain**

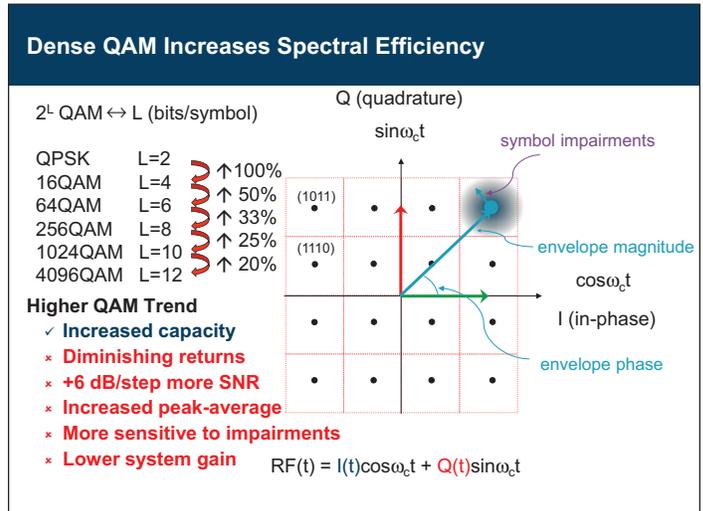$RF(t) = I(t)\cos\omega_c t + Q(t)\sin\omega_c t$

Figure 3. The basics of importance to point-to-point microwave systems using quadrature amplitude modulation (QAM).

levels of backoff at the power amplifier, or means to correct for distortion like digital pre-distortion, both of which cost extra power or hardware, or possibly both. In many cases, when no other options exist, such as the case with fixed frequency allocation in the fixed microwave band, the only way to increase capacity while remaining compatible to the system is to increase the modulation depth, but it comes at a cost.

To a limit, this method is used today in many microwave systems, and high-performance GSPS converters are enabling systems to be designed with higher order modulation like 1k and 4k QAM. Many systems will increase or decrease the modulation depth to adapt to the changing channel conditions to maintain an acceptable amount of signal-to-noise ratio. This, however, will directly affect the amount of capacity and throughput the system can provide.

Bandwidth vs. Channel Spacing

Another concept to understand in PtP systems is channel spacing vs. channel bandwidth or symbol rate — sometimes called baud rate. Figure 4 illustrates the differences between them. In a PtP system, channel spacing is normally allocated by a governing body through licensing. So-called traditional or legacy band licensing ranges from 3.5 MHz up to 112 MHz. In the case of the new E-band, the allocations are given in 250-MHz chunks and can be up to 1 or 2 GHz; 4 or 8 sections of 250 MHz. These allocations are fixed for a given deployment. Signal bandwidth, on the other hand, is determined by the equipment.
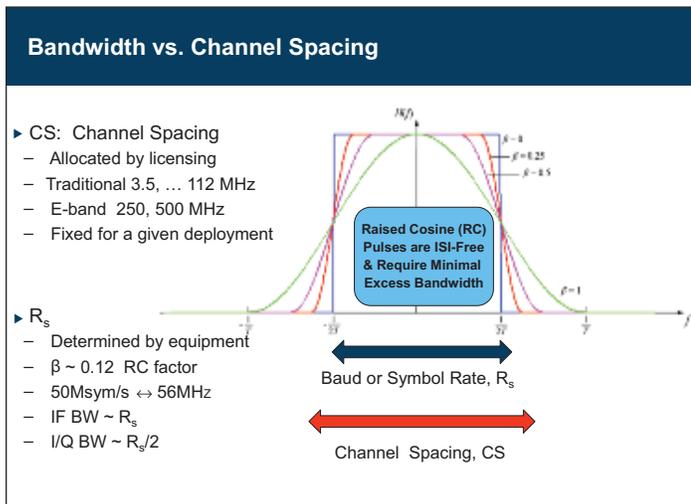
Bandwidth vs. Channel Spacing

▸ CS: Channel Spacing
  – Allocated by licensing
  – Traditional 3.5, … 112 MHz
  – E-band 250, 500 MHz
  – Fixed for a given deployment

▸ R_s
  – Determined by equipment
  – β ~ 0.12 RC factor
  – 50Msym/s ↔ 56MHz
  – IF BW ~ R_s
  – I/Q BW ~ R_s/2

Raised Cosine (RC) Pulses are ISI-Free & Require Minimal Excess Bandwidth

Baud or Symbol Rate, R_s

Channel Spacing, CS

Figure 4. Differences in channel spacing vs. channel bandwidth or symbol rate.

For inter-symbol, interference-free (ISI-free) data transmission, a special class of channel filters known as raised cosine filters is commonly used. These filters have unique properties that minimize the amount of excess bandwidth needed to implement them, while also having the property that all zero crossings in the time domain happen on symbol boundary, thus no symbol interferes with its neighbor, hence the name ISI-free filters. The raised cosine filter can be considered a practical implementation of the ideal brick-wall filter while limiting the pulse response to a finite length in the time domain. This is done by means of the roll-off factor given by the beta term. The higher the beta in the range of 0 to 1, the more excess bandwidth is used, but the shorter the pulse response of the filter. This bandwidth is a premium in PtP systems. The beta factor is small at 0.12, reducing the amount of excess bandwidth to as little as possible while still allowing the filter design that's practical to implement. This example shows the case of a particular system that is designed with a roll-off factor of 0.12. For a 56-MHz channel spacing system, the maximum achievable symbol rate is 50 M symbols/second.

Methods of Multiplying Data Capacity

An additional way to achieve higher capacity other than increasing modulation density or using wider bandwidth is to utilize cross-polarization techniques. There are a few different techniques that can be implemented in these cross-PIC, or XPIC, systems. For an adjacent channel co-polarization system, these radios have the same polarization as each other, but operate in separate, adjacent channel bands and frequencies. The second radio is used for redundancy or can be used to gain capacity at a different operating frequency. However, this requires two different antennas, as they are operating at different frequencies, as well as additional frequency allocation, which can be costly. Adjacent channel alternate polarization utilizes two different frequencies like the co-polarization scheme; however, the second radio is polarized to an orthogonal phase from the first radio to minimize the interference between the two channels. This system, however, still requires two antennas and two frequency allocations, which means additional costs and design overhead.

The more efficient scheme is the co-channel dual-polarization system. For this configuration, both radios are operating at the same frequency, but have different cross-polarizations, minimizing the cross-channel interference. In this setup, only one antenna is needed, as both radios are operating on the same frequency, minimizing system cost. Ideally, for this configuration, if the polarization was completely orthogonal, it would mean both channels are completely isolated from one another. In reality, it is difficult to achieve greater than 25 dB of isolation between the two polarizations due to varying weather conditions and other environment factors that may cause link degradation.

Since the two radios share the same receive signal, it is possible to use digital processing for interference cancellation of these cross-polarized signals in the modem algorithm. This is another way to double the capacity of a system and minimize cost by reducing hardware and using additional digital signal processing as an advantage.

Capacity Estimation

When all of these considerations are taken into account, an estimate of the capacity can be made. The traditional band radio can achieve quite a high raw capacity, but it is using many of the advanced techniques discussed in this paper, and the likelihood of additional capacity gain is very low. The new E-band system, on the other hand, delivers more than 50% higher raw capacity than the optimized XPIC traditional band system with a relatively low-complexity modulation. The key is the 500 MHz of bandwidth in the allocation. There is much more room to grow in raw capacity as the E-band radios become more capable.

The actual payload, or throughput, of these systems is lower than the raw capacity, and is dependent on a number of factors. Forward error correction can be a big one, sometimes consuming as much as 50% of the raw capacity in the case of long distances or difficult radio

transmission environments. There is an overhead of about 5% from network data management, but this can be offset by compression of the data, or traffic headers, or both. The high raw throughput of the new E-band system offers clear advantages for increasing backhaul throughput of 10 GSPS or more.

Microwave Radio Signal Chain and Control Path

In a microwave radio signal chain and control path, like the one shown in Figure 5, the transmit side consists of dual-baseband IQ high-speed digital-to-analog converters whose output enters a quadrature modulator. This output then goes into a block up-converter that performs a single sideband up-conversion up to the microwave frequency output. This microwave signal then gets amplified by a power amplifier and sent through the
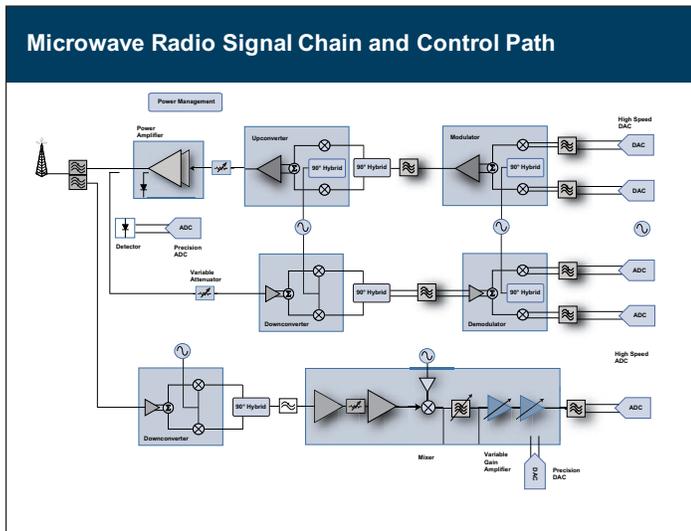

Figure 5. Microwave Radio Signal Chain and Control Path

microwave antenna to be broadcast over the air. For the receive path, the signal chain follows the similar reverse path of the transmit side. The microwave signal is received by the antenna, filtered, and then block down-converted by an image reject mixer to a lower frequency. The signal then passes through a variable gain stage and is again mixed down to a lower frequency. At this point, some channel filtering and initial amplification is done prior to being digitized by the high-speed ADC for digital signal processing in the modem.

Often, these systems will also have a digital pre-distortion (DPD) algorithm to reduce or remove distortion in the transmitted signal caused by running the power amplifier close to saturation. These corrections are needed to improve system performance and prevent

adjacent channel interference. This DPD path taps the output of the power amplifier and routes a copy of the transmitted signal back to the transmitter's processing unit through a receive chain that is sometimes called an observation receiver. The receive transmission can then be used to digitally pre-distort the signal being transmitted in order to correct for imperfections in the transmit path and improve the overall transmit signal chain performance. The full system is sometimes broken up into different equipment pieces in different operator systems.

For legacy band, some systems are split between an indoor unit (IDU) and an outdoor unit (ODU). The typical partitioning between the IDU and ODU is at the data converters and radio boundary. The ODU for a legacy band includes the antenna, through the amplifiers, up/down converters, and RF mixers, where the data is at baseband frequencies, typically around 350 MHz for transmit and 140 MHz for the receive path. This IF data will then go into the IDU through a coaxial cable connection.

With the recent acquisition of Hittite Microwave and the previous Analog Devices RF & Microwave product portfolio, Analog Devices can now cover the entire 6- to 44-GHz PtP legacy spectrum across the entire split ODU. ADI has a wide variety of narrowband and high-integration parts that span the full frequency range for microwave PtP systems. These products include power amplifiers, VGAs, microwave up/down converters, and microwave PLLs with integrated VCO function for high-performance LO generation, as well as RF/IF up/down converters.

The IDU consists of some amplifiers that pre- or post-condition the signal and the data converters along with the modem, FPGA, or ASIC. Analog Devices has a wide variety of converters that can support each of the needed channel bandwidths in PtP systems.

In a full ODU system, the data converters reside in the ODU partition and only the digital ASIC remains in the IDU, and baseband data is passed between them up the pole. ADI produces a mixed-signal front end specifically to support such a system. The ADI converters connect to modulators or demodulators that directly up- or down-convert to and from the desired microwave frequency band, reducing radio complexity by removing all stages of intermediate frequency conversion. This makes for a smaller radio with lower overall size and weight.

In a V-band full ODU with 7 GHz of allocation, there is plenty of bandwidth for use. Wideband GSPS converters can be used. In the case of a single 50-MHz channel, it's more appropriate for the lower-frequency converters to

be considered. If several channels will be aggregated, or several separate channels transmitted at the same time, wideband converters may be more appropriate.

High-Speed ADCs

For a given channel spacing, the required ADC sample rate must be at least double the required channel spacing due to Nyquist sampling theory criterion. The smaller channel space systems of traditional bands for the full ODU or split IDU/ODU systems require a higher effective number of bits (ENOB) to achieve the target QAM densities for these systems. In E-band systems, however, resolution requirements of the system can be relaxed for supporting lower QAM density. They do require a higher sampling ADC to provide the bandwidth requirements of the wider channel separated systems. Depending on these requirements, some ADC products are better suited for certain systems compared to others.

Similar to the ADC sampling requirements, the DAC sampling rate must be at least twice the channel spacing requirement for a given system. The QAM density achievable by the DAC is correlated to the noise spectral density performance of the part: the lower the noise floor of the DAC, the higher the possible signal-to-noise ratio, and therefore the higher the modulation scheme that can be supported. Just like ADCs, the E-band systems require higher sample rate DAC, but do not need the higher noise performance capability that the traditional band systems require.

Next-Generation DAC Technology

With ADI's current portfolio, there is a variety of IF-class DAC solutions that currently only support up to a maximum of 1 GHz channel spacing. There are many industries, especially the microwave and overall cellular communications systems, growing at an explosive rate and requiring even wider bandwidths than what has been investigated to date. For this trend, ADI sees a shift in required technology, moving from the IF-class DAC to the RF-class DAC to provide these higher sampling rates and wider bandwidth.

ADI is developing future RF DACs to have up to 12 GSPS DAC sampling rate and be able to synthesize 6 GHz of complex bandwidth and more, especially for future E-band systems and possible 5G systems.

ADI is aiming to provide customers with the capabilities they need to further improve and stretch the design goals of their systems, and enable them to remain competitive in their markets with this new RF DAC technology.

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