WHITE PAPER

# Smart microwave antennas are a step closer with advanced dual beamforming DAC

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## EXECUTIVE SUMMARY

More and more, the ability to direct and steer RF energy is a critical radio technology. The reason is that free-space RF attenuation increases at higher millimeter-wave frequencies. Those frequencies are used to increase system bandwidth and data throughput, raising the prospect of increased cross-channel interference and lost links without some active steering approach.

A technical collaboration between Teledyne e2v, France, and Fraunhofer IIS, Germany, recently evaluated the performance of a four-channel digitally steered 2.4 GHz planar antenna system. In this, a pair of state-of-the-art, gigahertz capable, digital-to-analog converters (EV12DD700) featuring a slew of novel, on-chip digital beamforming controls delivered digital beam steering control. The aim - to gain further validation of Teledyne e2V's advance towards microwave RF softwarization.

The test results correlated well with the initial design hypothesis. Moreover, the DAC proved highly versatile for specific beamforming functions. The DACs' ability to synchronize, both on-chip and inter-device, was a notable implementation success factor, likely to speed the advancement toward smart antenna deployments over the next few years.

## INTRODUCTION

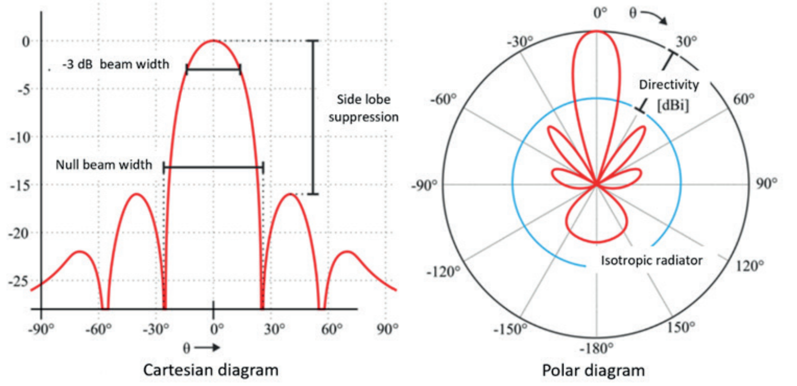
The ever-increasing market demand for radio bandwidth requires new radio approaches and technologies. Using ever higher frequencies with wavelengths in the millimeter range, focusing on reducing interference, and efficiently using radiated power and spectrum are critical technical considerations for improving contemporary radio systems.

For this reason, it is no surprise that digital beamforming arises in most discussions about Massive MIMO, 5G, and satellite communication applications. Beamforming describes steering radiated RF power electronically from a fixed antenna array, enabling the reduction in cross-channel interferers while simultaneously increasing overall transmission quality, data throughput, and connection robustness.

In response to the burgeoning need for more advanced radio control, creating a multi-channel digital beamformer demonstrator relying on a pair of state-of-the-art digital-to-analog converters (EV12DD700) is presented. The novel digital conversion ICs used provide several innovations mainly focused on easing the design of beam-steered systems.

## ISOTROPIC RADIATORS AND BASIC BEAMFORMING

The theoretical isotropic radiator helps simplify antenna design calculations and provides a reference point for measuring the radiation patterns of actual antennas. The blue trace in the polar diagram of Fig. 1 illustrates the idealized radiator. While actual isotropic radiators do not exist, the concept helps us understand general antenna behavior.



Cartesian diagram

Polar diagram

*Figure 1 Antenna performance factors compared to an isotropic radiator (blue line)*

An isotropic radiator is an idealized RF point source radiating electromagnetic energy uniformly within three-dimensional space. Unlike practical antennas with specific radiation patterns with peaks and nulls in specific directions, an isotropic radiator has no directional bias.

Electromagnetic beamforming and steering exploits a key result from the physics of interference theory. When two or more energy sources produce a series of wavefronts, wave patterns emerge that demonstrate constructive or destructive interference. The complex patterns vary in amplitude and phase. A mathematical treatment of this 'superposition' yields that wavefronts have maximum reinforcement when the spacing between point sources are integer multiples of the wavelength of the stimulating signal frequency (assuming coherency between signal sources). You can intuit that a beamforming system arises from the realization that wavefront interference provides a method to direct and steer RF power.

However, the superposition principle neglects electromagnetic coupling between radiator elements and is only an approximation. A more exact representation of antenna radiation can be determined numerically.

There are many possible arrangements of the individual array elements, arrangements which influence radiated behavior. The geometrical distribution, the number of elements, and the distances separating them are all critical design factors. In addition, the magnitude and phase of excitation signals play a role.

### Antenna definitions

**Isotropic gain** is defined as the ratio of the power radiated in a specific direction to that radiated by an idealized isotropic radiator. Expressed in decibels (dBi), isotropic gain is a measure of how well a specific antenna focuses radiated energy directionally.

**EIRP or Effective Isotropic Radiated Power** is the hypothetical radiated power of an isotropic radiator to give the equivalent signal strength as the actual source antenna in the direction of the main beam.

**Beamwidth** is the angular width of the main lobe of the radiation pattern. It provides information about the antennas' directionality. It is measured at the point the output power has fallen by 3 dB.

**Input Impedance** should match the characteristic impedance of the transmission line, ensuring efficient power transfer and minimizing signal reflections.

On point-to-point radio links, high directivity is desirable since the range increases for the same input power. You can achieve this by increasing the physical antenna geometry, but a combination of several elements also leads to an increased effective antenna radiating area.

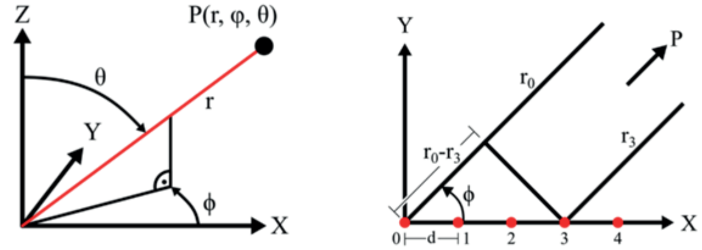


*Figure 2 Spherical coordinate system for a point P (LHS) and far field wavefront path difference of P (RHS*

Superposition is highlighted in Fig. 2. A point P can be visualized at a distance r, removed from the radiator. In Fig. 2 (LHS), polar coordinates locate P in 3D space. In Fig. 2 (RHS) a planar array of five elements is identified with P located in the far-field. By superimposing fields from several individual radiators according to the superposition principle, it can be seen that the resulting far-field radiated signal strength is maximum where the EM waves constructively overlap, i.e., are in phase. This desired behavior can be achieved partially from a clever combination of the individual antenna elements or by controlling the electrical characteristics of the antenna excitation signals (the phase and their amplitudes).
Since this work primarily evaluated the capabilities to control beamforming in a digital system (using advanced broadband DACs), a simple planar radiator arrangement with equally spaced elements. The group factor (a gain multiplier) resulting from such an array arrangement was easily derived.
The resulting array design and its simulated radiation patterns as output from CST Microwave Studio CMS) are shown in Fig. 3.

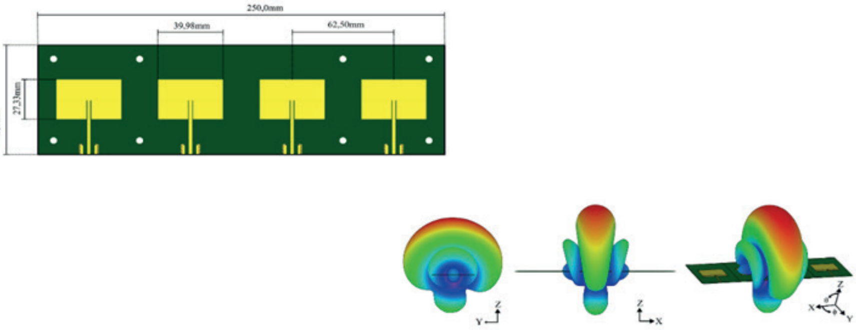


*Figure 3 Experimental 4x1 microstrip antenna shown together with simulated RF field patterns from CMS*

## EXPERIMENTAL RESULTS FOR A SIMPLE MICROSTRIP PATCH ARRAY

The aggregate radiation characteristic of the planar array with n-identical single microstrip elements is expressed as the multiplication of the group factor and the radiation characteristic of a single radiator. Where the individual elements do not have high directivity, this group characteristic dominates as shown in the diagram, Fig. 5. The main lobe power is significantly higher than the three side lobes shown.

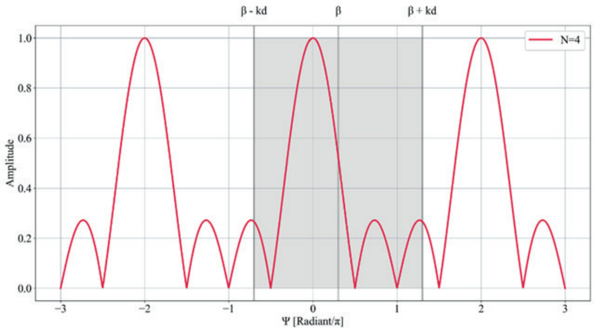


*Figure 4 Main beam and side lobe characteristic of 4x1 patch antenna*

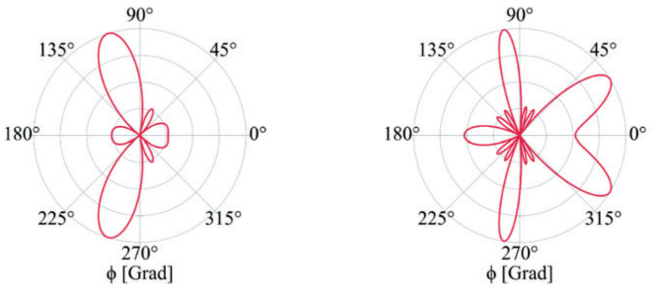


*Figure 5 Polar diagrams of beam and side lobes of antenna with λ/2 (LHS) & λ (RHS) element spacing*

The two polar plots here, Fig. 5, show how different element spacings impact the main beam and sidelobe formation. Fig. 5 details a half-wavelength spacing (on the left). Integer wavelength spacing is shown on the right. In this case, the half-wave spacing is the superior choice, offering fewer and more attenuated side lobes.

## TAPERING

Directional steering works best when side lobe occurrence is highly attenuated: This lowers the probability of interference with other carriers. A simple way to suppress unwanted side lobes is a method known as tapering. Adjusting the input signal amplitude distribution to the linear array can result in a desired, highly attenuated side lobe formation. Two well-known lobe distribution characteristics are Dolph-Chebyshev, which brings all side lobes to the same amplitude, and Taylor, which produces adjustable sidelobe damping, which is especially helpful when deployed with large arrays.

## SYSTEM LEVEL CONSIDERATIONS

Legacy beamforming approaches often turned to analog signal control. In analog beamforming, signals are shifted in phase by individual signal phase shifters. Analog phase shifters use varactor diodes or microstrip lines. The signals are additionally combined appropriately with hybrid couplers to create a series of selectable beams.

Recent digital signal processing advances now mean that gigahertz signals can be processed entirely in the digital domain. The parameters for signals driving each antenna can thus be weighted differently and determined by system calculations. This approach offers significant design and performance advantages. For example:

- A signal can be time-shifted regardless of its frequency
- Beamforming becomes possible even at elevated bandwidths
- Moreover, digital beamformers can exploit multipath propagation and determine channel parameter weightings based on dynamic and direct channel measurement.

Another flexibility presented by digital beamforming is the possibility of simple radio reconfiguration since only the digital processing needs to be modified, leaving the hardware intact. This is one of the primary benefits to derive from RF softwarization. Another flexibility presented by digital beamforming is the possibility of simple radio reconfiguration since only the digital processing needs to be modified, leaving the hardware intact. This is one of the primary benefits to derive from RF softwarization.

### On Multi-channel Synchronization

When operating at ultra-high clock rates (i.e. GHz), how can a system ensure that all signals are sampled at the precise same instant? The 'SYNC chain' is the cunningly simple method used by the EV12DD700.

Teledyne e2v's novel SYNC chain creates a synchronization solution that is easily daisy-chained across a huge number of channels. The SYNC signal source is provided from the signal processing backbone - often an FPGA. The SYNC signal is a one-shot pulse rather than a precision clock, so rooting it across printed circuits is a breeze. Each SYNC signal emerging from a device is re-synchronized based on individual device latency. This method requires an initial set-up calibration, but once executed and, irrespective of the number of devices in a chain, all will have a guaranteed, phase aligned trigger.

## 25 GHZ BROADBAND DACS CREATE NEW MILLIMETER-WAVE BEAMFORMING OPTIONS

The digital-to-analog converters (DACs) arose from the European INTERSTELLAR[1] project. Identified as EV12DD700, they are Ka-band capable dual-core converters. They feature a 3dB bandwidth of 25 GHz. The converters have a switchable 8- or 12-bit resolution and a conversion rate of 12 giga-samples per second. Optimization of output signal power to specific Nyquist zones is enabled by three output modes (NRZ, RF, and 2RF), as illustrated in the characteristic curves of Fig. 6. The RF and 2RF modes extend valid output power projection over a range from 6 to 26 GHz. A high-speed serial lanes interface (HSSL) is implemented for user data transmission using the low overhead and license-free ESIstream protocol. ESIstream ensures low link latency, DC balance, maximum data run lengths, and guaranteed link synchronization.

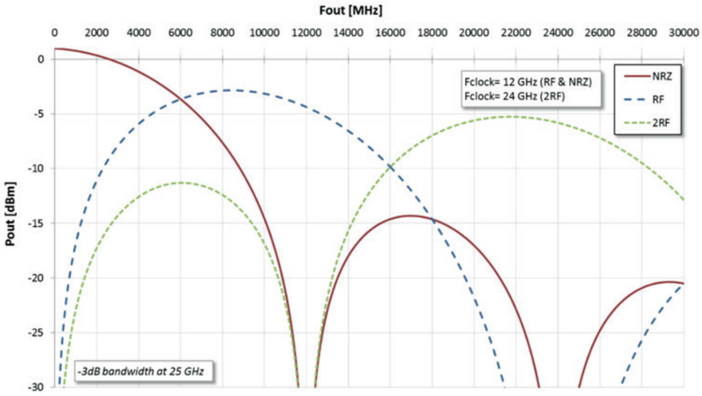


*Figure 6 DAC output characteristics across four Nyquist zones*

In addition, these DACs prove highly attractive for beamforming as they offer several powerful digital signal processing features:

- Digital up-conversion (DUC)
- Frequency hopping and
- Direct digital synthesis (DDS)

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[1] INTERSTELLAR project was a project launched in 2016. It is part of the Horizon 2020 funding program of the European Union. It aimed to strengthen European competitiveness and competence in the field of digital data converters for space applications.

Additionally, the DAC provides a digital Butler matrix – a functional block enabling the adjustment of signal magnitude and phase in the digital domain for individual signal paths. This functional block lies at the heart of enabling digital beamforming. Another critical system-level feature is the synchronization (or SYNC) chain - marked in red in Fig. 7. This signal ensures channel phase synchronization is maintained throughout a massive, multi-channel system (see sidebar) - an obvious benefit where beam steering demands the close tolerance matching of relative signal phasing.

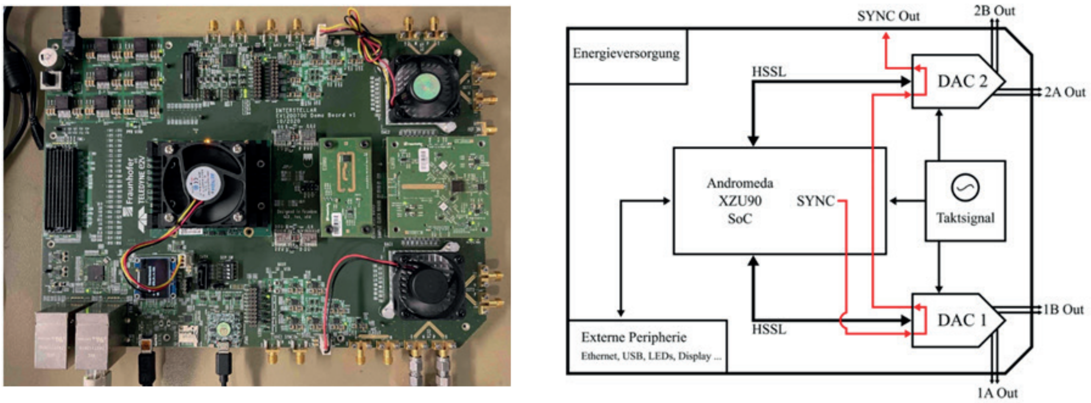

*Figure 7 Evaluation system and block diagram of digital beamformer*

## EXPERIMENTAL BEAMFORMING SYSTEM - COMMUNICATION AND INTERFACES

The Andromeda system-on-chip (SoC) software communicates with a pair of broadband DACs via the Serial Peripheral Interface (SPI). The backend software can also access the General-Purpose Input/Output (GPIO) pins via HSSL links. These provide direct data communication between the FPGA and other peripherals. A master clock provides both the DACs' sample and DSP clocks. The SoC supplies the all-important SYNC signal. Communication with the board is via the backend software that provides an application interface to process commands and arguments, converting them into board and device-specific configurations.

## SPECIAL DAC BEAMFORMING FEATURES

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The EV12DD700 dual DAC contains a complex digital up-convertor (or DUC) combined with direct digital sampling (DDS) capabilities. The DUC implements a signal processing path comprising:

- 4 x interpolations stages (x1, x4, x8 and x16)
- 1x gain and delay stage for beamforming
- 1x SINC compensation
- A frequency-hopping table

Frequency hopping, gain and phase stages, interpolation filtering, and the SINC compensation block are all controlled through SPI.

The complex numerical oscillator (NCO) has a 32-bit frequency resolution. This block also provides a direct digital synthesis (DDS) mode generating either continuous waves or chirp patterns - both are user-selectable. The beamforming control consists of programmable delay stages from -8.5 to 7.5 samples with a 7-bit fractional delay resolution and a programmable gain stage with a range of ± 12.5 % and 10-bit resolution. To compensate for the resulting output pulse shape, the anti-SINC filter offers two programmable coefficients.

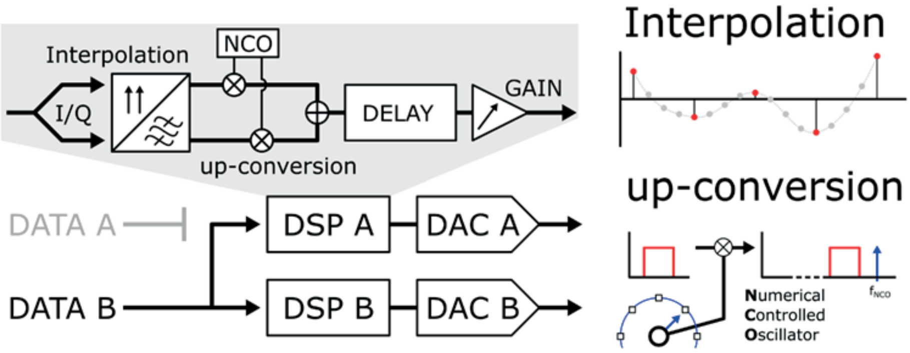

Figure 8 DAC Interpolation and up-conversion functions

Serving the available 25 GHz DAC bandwidth demands high data throughput rates. The DAC is equipped with up-conversion and adjustable interpolation capabilities to ease this potential data bottleneck. Three stages of interpolation can be applied. The data sample rate doubles in each stage by up-sampling followed by digital filtering. A four-stage Farrow filter is implemented to ensure that filter delay matches the interpolation factor of each up-conversion stage. The compound transfer function of the interpolators is shown in Fig. 9. The lower graphic shows an expansion of the passband characteristic.

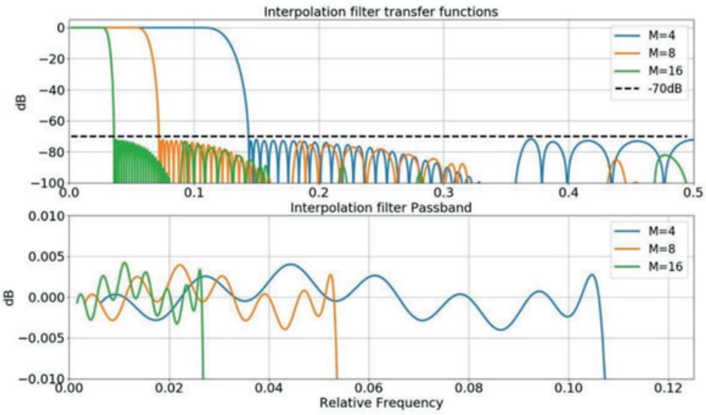

Figure 9 70 dB interpolation filtering (x4, x8 and x16) with expanded passband view

Output signals are supplied to the DACs as digital pattern files. These contain the signal amplitude data per sample. Since the waveform patterns are the same for both channels, data need only be transferred to one core, halving transmit data throughput. Note also that simple test waveforms (sine, square, or triangle) may be generated directly on-board the DACs via the DDS blocks having specified frequency, amplitude, and other signal parameters.

## PRACTICAL BEAMFORMING OPERATION

After system start-up and synchronization, each DAC is ready to receive digital data via the serial data lanes (HSSLs). In beamforming mode, the data for core B is fed to both cores. The essential requirement for using beamforming is the selection of an interpolation level. In doing so, some of the serial lanes can be disabled. This is useful since disabled data lanes reduce the energy draw of the system.

DAC configuration is established via the SPI registers. Registers for signal amplitude and delay setting are available for each DAC core in quadruplicate, allowing storage of four separate signal profiles. If enabled, these pre-loaded ‘zones’ can be rapidly switched through the DAC with a trigger event allowing fast beam hopping. Switching between zones can be either phase-continuous or discontinuous.

The on-board Numerically Controlled Oscillator (NCO) enables digital up-conversion. The NCO generates sinewave functions. In doing this, the NCO uses a combination of look-up table and the CORDIC (COordinate Rotation DIgital Computer) algorithm. A set phase value is added to the on-chip phase accumulator for each clock signal. Higher order bits come directly from the look-up table; lower order bits derive from CORDIC. The DAC thus provides the core digital functionality to control beam steering in the RF domain.

## EXPERIMENTAL FINDINGS

The diagram shows a comparison between the initial simulation and test results. A main beam width of 26 degrees was measured with -13 dB side lobe attenuation. Measured side lobe positioning and signal nulls aligned well with simulation results. The measured signal noise seen at high angles is particularly noteworthy caused by reflections.

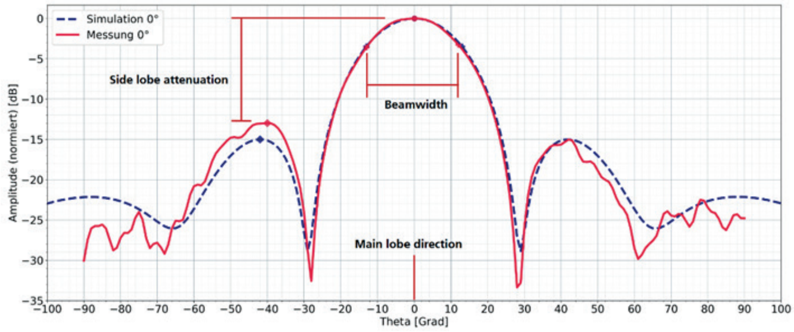

*Figure 10 Comparison of initial test data (red) and simulation (blue trace)*

An evaluation of amplitude tapering was performed. Experimental results demonstrated a further -3 dB of side lobe attenuation could be achieved – see Fig. 11.

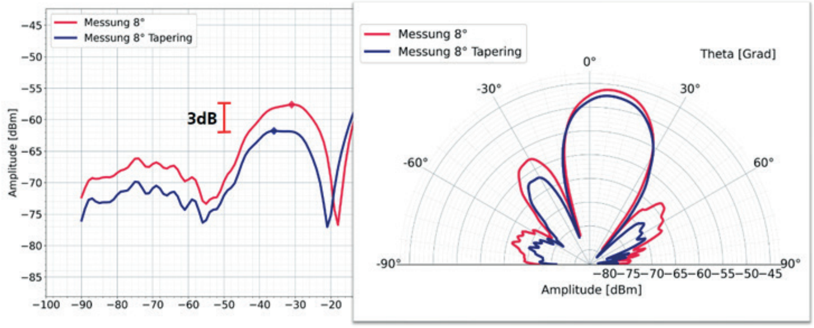

*Figure 11 3 dB side lobe suppression due to tapering*

## CONCLUSION

This project showed that the EV12DD700 provides all the necessary controls to enable RF beam steering of a simple planar microstrip antenna. The project concentrated on simulating the anticipated performance of a modest four-element microstrip array, sourcing the antenna and building a digital control system. The practical implementation exploited the EV12DD700 dual 25 GHz DAC from Teledyne e2v; a device that supplies a full suite of programmable beamforming functions.

RF chamber measurements helped identify discrepancies between modeled and measured performance. Several improvement areas emerged. Overall, there was a good match between the theoretical and practical outcomes. Side lobe attenuation through tapering worked well. Moreover, the granularity of DACs' phase and signal amplitude controls were highly desirable. The test cycle emphasized carefully matching cable lengths to ensure critical signal phase matching across channels. The DAC's embedded phase controls helped here as well.

A noteworthy system benefit derives from the DAC's SYNC chain. While only two devices were synchronized, the daisy-chaining capability was a demonstrable benefit. No doubt, this will prove even more compelling in future large array deployments.

Finally, it is worth highlighting that the DAC, with its 25 GHz bandwidth 12 Gsps sampling, easily projects useful RF power into the Ka-band in 2RF mode. The on-chip digital beamforming features are equally at home at such frequencies. These capabilities signal a new age of microwave RF softwarization, and the arrival of smart, broadband microwave antennas.

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- EV12DD700 Dual channel Ka-band capable 12 GSps DAC Datasheet

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