As we usher in the age of large capacity wireless access systems demanding high spectral efficiencies, array antennas are playing an increasing role. MIMO antenna arrays have become integral to the standards for cellular and wireless local area networks. These active antenna arrays will play an equally important role in next-generation high throughput satellite (HTS) communications. Also, the large low Earth orbit (LEO) and medium Earth orbit (MEO) constellations planned by companies like OneWeb, Telesat, SES and SpaceX will need ground terminal antennas that track multiple satellites. This convergence of trends is driving a shift from passive antennas with static fixed beam patterns to fully steerable, active smart antennas.

In this article, we discuss the advantages of digital beamforming (DBF) for capacity, control and flexibility. Until now, DBF was largely a concept because of the cost and complexity to implement a usable solution. We will describe a commercial ASIC implementing DBF with true time delay (TTD) that realizes its potential. DBF combined with an integrated RF front-end (RFFE) enables modular electronically-steerable multi-beam array (ESMA) antenna systems for a wide range of applications.

Mobile wireless communications systems require increasingly high data rates with virtually worldwide coverage. Because terrestrial networks do not cover the globe, high data rate services are not available in remote areas or onboard ships and aircraft. SATCOM and SATCOM-on-the-move (SOTM) are essential capabilities to achieve high capacity communications with global coverage. With large capacity wireless access requiring high spectral efficiency, array antennas have emerged as a key architecture for wireless communication systems, and MIMO antenna arrays are included in the standards for cellular and wireless local area networks. These active antenna arrays will play an equally important role in next-generation HTS communications. The development of large LEO and MEO constellations, planned by companies like OneWeb, SES and SpaceX, will require ground terminals able to track multiple satellites. Parabolic dish antennas have been the defacto design for SATCOM Earth antennas. They have advantages such as good performance, power consumption and cost, yet they are stationary and have lower efficiency. In comparison, electronically-steerable antennas have many benefits: self-installation, multi-SATCOM, satellite tracking and their payloads can be more flexible, enabling techniques such as multi-beam, beam hopping and flexible beam shaping. All-electronic control eliminates mechanical parts, which are slow and more likely to malfunction.
**Beamforming Options**

Antennas convert RF signals into electromagnetic transmission and vice versa. Each antenna has a radiation pattern defining the direction of the energy radiated by the antenna. An antenna’s gain and directivity go hand in hand: the greater the gain, the more directive the antenna. It is this feature of the antenna that has become the focus for increasing capacity, particularly with the next-generation of wireless communications systems for both SATCOM and 5G.

Beamformers comprise an array of antennas making the combined aperture directive. They control the radiation pattern through the constructive and destructive superposition of signals from the different antenna elements. In general, beamforming can be classified as passive and active. Passive beamformers are fixed directive antennas made of passive components, such as transmission lines, that point the beam in a fixed direction. Active beamformer antennas—commonly known as phased arrays—have active phase shifters at each antenna element to change the relative phase among the elements; because they are active, the beam can be dynamically steered. Electronically-steerable antennas can adopt one of three approaches to beamforming: analog, digital and hybrid (see Figure 1).

### Analog Beamforming

Analog beamforming (ABF) can be implemented in three ways: RF, local oscillator (LO) and analog baseband.

With RF beamforming, phase shifting is implemented in both the RF Rx and Tx paths prior to the mixer. Reduced component cost is one of the reasons for its popularity, particularly at mmWave, where the small size of the phase shifter allows better integration in the RFFE. However, phase shifter precision and noise figure degradation due to the phase shifters are performance challenges for this technique. Also, the phase shifters and beamforming network (BFN) must be designed for the frequency of operation.

LO beamforming uses the LO distribution network for phase shifting, addressing the noise figure challenge by shifting the phase shifter from the signal path to the LO path. However, this increases power consumption, and the complexity scales with the size of the antenna.

With analog baseband beamforming, beamforming occurs in the baseband, after down-conversion and before up-conversion, enabling use of higher precision phase shifters. However, the size of the phase shifters and the complexity of the BFN—mixers in each RF chain and a network of baseband splitters and combiners—are challenges.

### Digital Beamforming

With digital beamforming (DBF), beamforming is performed digitally at baseband, requiring one beamformer and RFFE at each antenna element. Offering a high degree of control, DBF is considered the most flexible beamforming approach and superior to ABF for receiving and transmitting wideband signals and, more importantly, for multi-beam applications. The digital implementation has greater reconfigurability and enables treatment of RF impairments at each antenna element. However, it requires data converters and RFFE for each antenna element, increasing the complexity and power consumption. Fortunately, recent advances in silicon processes have reduced the complexity, power and cost of digital beamforming, making it feasible for some phased arrays.

### Hybrid Beamforming

Hybrid beamforming uses the best of both alternatives: analog and digital. To reduce the complexity of digital beamforming, requiring control at each antenna element, the hybrid approach uses “two stage” beamforming—the concatenation of analog and digital beamforming—and provides a reasonable compromise between performance and complexity. Each analog beamforming network serves as a subarray for the next level of digital beamforming, forming a more directive “super element” whose signal is coherently combined in the digital domain with the signals from the other super elements. Hybrid beamformers provide limited multibeam capability, although the performance is sub-optimal compared to digital beamforming.

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<table>
<thead>
<tr>
<th><strong>Feature</strong></th>
<th><strong>Diagram</strong></th>
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<tr>
<td>Analog RF (a)</td>
<td><img src="image1" alt="Analog RF Diagram" /></td>
</tr>
<tr>
<td>Digital (b)</td>
<td><img src="image2" alt="Digital Diagram" /></td>
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<tr>
<td>Hybrid (c)</td>
<td><img src="image3" alt="Hybrid Diagram" /></td>
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*Fig. 1 Analog RF (a), digital (b) and hybrid (c) beamformers.*
**Technical Feature**

**DIGITAL BEAMFORMING WINS**

Given the ongoing improvement in silicon technology, DBF is the preferred approach for phased array antennas. It offers:

- **Wideband signal reception and transmission**: Wider signal bandwidth improves the spectral efficiency of the system, increasing the capacity of the terminal. DBF enables ready implementation of high precision phase shifters and delay compensation (TTD), so the array can operate over a large signal bandwidth without beam squint.

- **Ability to scale to build large antennas**: To build large antennas, the beamformer architecture should be modular to enable relatively simple scaling. To reduce beam squint, large antennas need to correct for the delays from scanning and system routing, which becomes more challenging with large antennas. DBF supports modular design and can easily scale while maintaining performance.

- **Large number of beams**: MIMO with multi-beam capability is the most effective way to increase channel capacity. With SATCOM, it enables simultaneous communication with multiple satellites. DBF supports large numbers of beams using the entire antenna aperture, which provides the same antenna gain and directivity for each beam.

- **Fast beam steering**: DBF supports fast beam switching and steering, i.e., within microseconds. This enables fast acquisition and tracking in high dynamic channel environments.

- **Flexibility**: Active beamforming with flexible reconfiguration enables the array to adapt for multiple applications, such as online calibration, configuring dynamic subarrays and monitoring processing and synchronization.

- **Precise beamforming and nulling**: With precise control of the phase and gain, DBF enables fine control of the radiation pattern, including side lobes, null depth and null positioning. This fine control can form the radiation pattern to meet regulatory masks and suppress unwanted directional interference, maintaining a high signal-to-noise ratio (SNR).

- **Antennas on conformal structures**: The ability of DBF to calibrate and compensate for phase and delay allows decoupling the antenna’s geometry from its performance, making conformal antennas feasible, i.e., unrestricted to a 2D plane. Geometric shapes such as hemi-spheroidal 3D antennas or other conformal shapes can be implemented using DBF.

**TTD BEAMFORMING**

As shown in **Figure 2**, with a uniform linear array, the incident wavefront at an angle \( \theta \) results in a delay \( \tau \) for the signals arriving at different elements. This delay causes the antenna array to have a pattern depending on the frequency. To have a flat pattern over the desired frequency range, the antenna’s coherent bandwidth should be greater than the bandwidth of the signal. This implies that \( N \tau < T_s \), where \( T_s \) is the duration of the symbol. This condition requires the system to have the capability to perform delay compensation to coherently combine signals.

**Figure 3** shows the beam squint resulting from the frequency selectivity of an array, which does not occur with TTD beamforming. The relationship \( N \tau < T_s \) indicates the antenna’s delay spread can become very large relative to symbol duration if either the antenna is very large (\( N \)) or the symbol duration is very small (\( T_s \)), i.e., the bandwidth is very large. This point is illustrated in **Figure 4**.

SatixFy has developed the industry’s first TTD DBF in a form that is efficient in power and cost (see **Figure 5**). The Prime ASIC has a modular and flexible architecture supporting real-time reconfiguration, online calibration and the scalabil-
Technical Feature

Figure 4: Maximum signal bandwidth vs. number of elements in a uniform linear array.

Figure 5: SatixFy Prime DBF ASIC.

Figure 6: Prime DBF capability: number of beams vs. bandwidth.

Figure 7: SatixFy Beat Ku-Band front-end.

Figure 8: Block diagram of a single element, circularly polarized Tx (a) and Rx (b).

Microchip’s Prime is a versatile phased array solution that enables the construction of large antennas. Prime digitizes the signal at each antenna element with high-speed analog-to-digital converters (ADC) and digital-to-analog converters (DAC), processing more than 2 Tbps data rates. Prime connects to RFFEs containing the RF transceivers via a high bandwidth I/Q interface. Within each DBF, the ADCs and DACs are connected to high-resolution digital phase shifters and digital delay circuits which implement TTD to avoid beam squints, enabling wideband signal transmission and reception. The DBF chips are connected to each other via a high-speed digital serial bus (SERDES), which enables a highly integrated, controllable and scalable antenna system. The key features of the Prime DBF are:

- Over 1 GHz instantaneous signal bandwidth.
- Multi-beam capability: up to 32 beams with independent phase, gain and delay control for each beam (see Figure 6).
- Equalization/pre-equalization and digital predistortion for each beamformer chain.
- 2 GHz analog baseband interface.
- Tight integration with SatixFy’s Sx3000 modem via SERDES interface.
- Support for an external modem with an L-Band interface.
- Very high speed beam tracking and beam steering.
- Linear and circular polarization control.
- Self-calibration with internal synchronization engines.
- Antenna control integrated with the Sx3000 modem.
- Power saving modes and configurations tailored to the application.

RF Transceiver

A companion to the Prime DBF, SatixFy’s first-generation RFFE is...
a Ku-Band RFIC which links the Prime’s I/Q signals with the Ku-Band antenna elements (see Figure 7). Called Beat, the RFFE integrates the transmit driver and power amplifier, transmit up-converter, receive low noise amplifier, receive down-converter and antenna polarization control, either linear or circular (see Figure 8). A single Beat supports four Ku-Band antenna elements operating in half-duplex mode.

Figure 9 shows the block diagram of a fully integrated ESMA system composed of the Prime DBF, Beat RFFE and the antenna panel. The Prime DBF at the heart of the electronically-steerable antenna is connected to the Beat RFFE via an analog I/Q interface and to the Sx3000 modem via high speed SERDES. This level of integration enables a highly configurable antenna supporting different applications. Within this architecture, the DBF is band-agnostic, meaning to build phased array antennas for different satellite (Ku-, Ka- or X-Band) or 5G (sub-6 or 28 GHz) bands, only the RFFE and antenna panel need to be modified. The backbone of the BFN remains the same, greatly simplifying antenna designs for different applications and frequency bands. For phased array antennas at VHF and UHF, Prime can be used with an LNA and PA without up- or down-converters.

The modular architecture of the ESMA enables it to be scaled to larger arrays by tiling. An example is shown in Figure 10, where a single tile of 32 antenna elements requires eight Beats and one Prime. The tiles are daisy-chained via high speed SERDES, which provides both data and the control plane to and from the antenna controller.

SatixFy recently introduced the world’s first fully digital 256-element ESMA for Ku-Band SATCOM (see Figure 11 and Table 1). The ESMA antenna can serve both as a standalone IoT terminal or a build-
ing block for a larger array. The antenna is a single board design with a shared aperture antenna (Rx and Tx), operating from 11 to 12 GHz for Rx and 13.75 to 14.5 GHz for Tx. The 256-element ESMA comprises eight Primes daisy-chained and 64 Ku-Band Beats. The antenna can simultaneously point, track and manage multiple beams with multiple polarizations. Figure 12 shows the antenna radiation patterns, measured in an anechoic chamber.

**APPLICATIONS**

The flexible ESMA architecture enables low-cost, adaptive and steerable antenna system with low weight and power consumption. This makes this system viable and attractive for various applications:

**IoT**

In rural areas, satellites can provide the missing coverage to connect sensors and other entities to the cloud, such as sensors for agriculture, water metering, weather, petrol and gas metering. The ESMA enables compact, low-cost and low-power IoT antennas that can automatically search, acquire and track satellites. Advantages of the ESMA include eliminating bulky mechanical structures and self-installation and tracking, which significantly reduce installation cost and enables mobile applications on vehicles, ships, aircraft and drones. The small antenna size is feasible using appropriate waveforms, making it possible to communicate at very low SNR.

**Broadband Communications for Land, Maritime and Aeronautical Applications**

High capacity GEO networks and new constellations of LEO and MEO satellites will help serve the demand for broadband access, both for fixed terminals in remote areas and SOTM applications. During the past decade, the demand for broadband connectivity and in-flight entertainment on commercial airlines has demonstrated the need for low drag and highly reliable antenna systems, making a conformal antenna based on ESMA a good solution. The simultaneous multi-beam capability enables simultaneous connectivity with multiple satellites and make-before-break connections to ensure seamless connectivity—particularly when switching beams with LEO satellites at high speed. These same benefits extend to land mobile and maritime applications, where ESMA based SATCOM links can co-exist with terrestrial wide area communications. The ESMA can be scaled according to the required link budget, physical size, weight and power consumption constraints of the platform.

**5G Fixed Wireless Access**

The jump in 5G data rates, compared to 4G, relies on smart

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**TABLE 1**

<table>
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<tr>
<th><strong>Ku-BAND ESMA</strong></th>
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<td><strong>Topology</strong></td>
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<td><strong># Beams</strong></td>
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| **Frequency Coverage** | Rx: 11 to 12 GHz  
Tx: 13.75 to 14.5 GHz |
| **# Elements**   | 256 |
| **# DBFs**       | 8 Primes |
| **# RFICs**      | 64 Beats |
| **RF Bandwidth** | 1 GHz |
| **Channel Bandwidth** | 880 MHz |
| **Tx Antenna Gain** | 28 dBi |
| **Rx Antenna Gain** | 26.5 dBi |
| **Modem**        | Sx 3000-Based Modem |
| **Digital Interconnectivity** | 4 SerDes Lanes at 9.4 Gbps/Lane |
| **Terminal Functionality** | Self-Sufficient System, Single Board Design, Minimal External Interfaces |
antennas with multiple, wide-band, directive beams. ESMA’s beamforming capability can increase spectrum utilization by up to two orders of magnitude. The high precision phase shifters and TTD in the DBF makes it suitable for the both mmWave and sub-6 GHz arrays. The ESMA’s flexibility enables dynamically reconfiguring the beams, combined with 1D and 2D dual-polarized scanning for both line-of-sight and non-line-of-sight channel conditions. With TTD beamforming, high gain and squint free antenna patterns can be achieved across the entire cellular band.

**SUMMARY**

This article introduced a scalable ESMA with two building blocks: a digital ASIC (Prime) with TTD, which performs the signal processing and beamforming, and an RFFE containing the RF amplification and up- and down-conversion, which is the interface between the DBF and the antenna element. The chipset enables a flexible and scalable architecture, with the resulting ESMA achieving extremely small size, low power consumption and low-cost, compared to other approaches. Products based on ESMA will support a wide range of applications, including SATCOM (GEO, LEO and MEO) and 5G.

**References**