Next-generation platforms will demand next-generation antenna performance. (TRW photo)

Digital Beamforming Basics

Hans Steyskal

Antenna performance is steadily increasing as ever more sophisticated information is demanded from radar and communications systems. Digital beamforming (DBF) is a powerful technique for boosting antenna performance. Beamforming in the strict sense corresponds to weighting and summing elemental signals, whereas digital beamforming includes almost any spatial processing of digitized signals from a sensor array. State-of-the-art microwave integrated circuits, signal processing and high-speed digital electronics are now beginning to make DBF feasible for microwave radar and communications. The importance of this technology will continue to grow. This paper describes general DBF concepts and early implementation.

Each element of an array antenna receives or transmits a signal. In the receive mode, analog beamformers output the weighted sum of the sensor signals, reducing the signal dimensionality from the number of elements N to 1. Unlike analog beamformers, DBF arrays digitize received signals at the element level, then process these signals in a special-purpose digital processor to form the desired beam. The total information available at the aperture is preserved and is represented by the N individual element signals.

Once the physical input signals have been properly digitized, they can be manipulated indefinitely, without incurring any further error since a digital representation of the signal is used rather than the real received signal power. As a result, any number of beams can be formed or the signal can be subjected to multiple hypotheses testing.

DBF PROMISES

Digital beamforming is applicable both on transmit and receive, although most of its advantages are realized in the receive mode. The most important advantages are fast adaptive pattern nulling, super resolution and direction finding, antenna self-calibration and ultralow sidelobes, array element failure and pattern correction, closely spaced multiple beams, adaptive space-time processing and flexible radar power and time management. Many of these features have been addressed previously.[1-4] Adaptive space-time processing is a recently proposed technique[5,6] for airborne surveillance radars to suppress ground clutter that is spread over a large Doppler frequency band. DBF in the transmit mode may find its first application in cellular telephone networks.

DBF IMPLEMENTATION

A generic DBF array consists of antenna elements, receiver modules, analog-to-digital (A/D) converters and a digital beamformer and controller, as shown in **Figure 1.** The simple approach of directly sampling and digitizing the incoming microwave signal is not yet practical because of digital hardware speed limitations. Therefore, the

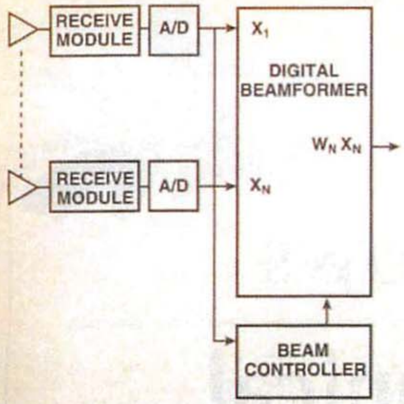

Fig. 1 The generic DBF array.

modules comprise complete heterodyne receivers, performing frequency downconversion, filtering and amplifying to a power level commensurate with the A/D converter, as shown in **Figure 2.** Separate A/D conversion of baseband I and Q signals allows a low sampling rate but requires channel matching. IF sampling and digital I/Q generation avoids this problem at the expense of a higher sampling rate. The equalizer compensates for dispersion differences between individual receivers. The downconversion can be done in one or more steps, which are governed by hardware considerations.

After A/D conversion, the signals enter the actual digital beamformer, a fast parallel processor that forms the inner product beams at a rate commensurate with the signal bandwidth, typically in the MHz range for radar. The weight vector(s) are derived from a separate beam controller. For open-loop adaptive pattern control, the element signals are also input to the beam controller that determines the proper weights via a suitable algorithm. This operation is performed at the much slower rate of the external scenario change, typically on the order of a kHz or less.

FUNDAMENTAL SYSTEM CHARACTERISTICS

Dynamic range and signal bandwidth are fundamental characteristics of microwave systems. In most cases, A/D converters set these parameters for DBF arrays. For adaptive pattern nulling the beam controller characteristics are also important.

Dynamic Range: The system's instantaneous dynamic range is determined by the number of bits N_b of the A/D converters and the number of parallel channels N. For a Gaussian signal, the upper limit is set by N_b and the lower limit by the quantization noise, leading to a dynamic range of approximately $(6\ N_b + 10 \log N)$ dB.[7] Thus the range increases by 6 dB per bit, and the factor N expresses the gain arising from the coherent integration of N element signals. A/D converter nonlinearities may further restrict the usable dynamic range.

Signal Bandwidth: The signal bandwidth of the DBF system is determined by the A/D converter sampling rate and by the beamformer processing. To digitize IF signals with components up to f_{max}, the Nyquist criterion requires an ideal sampling rate of $f_s \geq 2f_{max}$, whereas the same signals at baseband with analog I and Q channels can be sampled with two A/D converters at a rate $f_s \geq f_{max}$. In practice the signals must be slightly over sampled to provide a margin for realistic, finite slope filters.

Despite modern computers' impressive performance, the processing required by digital beamforming may yet be challenging. With N elements, a beam requires N complex multiplies at the sampling rate (approximately B) that brings the total count to approximately NB complex operations per sec (COPS), or about 10^8 COPS, with N = 100 and signal bandwidth B = 1 MHz, which poses no difficulties. However, this hypothetical set does not represent a full-scale radar. A full-scale radar may have several thousand elements and many independent beams, and this load is still challenging. The processing cost becomes an implementation issue.

As an alternative to forming custom beams with individual weight vectors, a fast Fourier Transform (FFT) can be utilized to calculate the entire set of N orthogonal beams simultaneously, assuming the array elements are uniformly spaced. This approach is extremely efficient and uses only $(N/2) \log_2 (N)$-N complex multiplies. However, in application, the FFT and the custom beams are not necessarily equivalent. The custom beams have arbitrary patterns and directions, and the FFT beams have identical patterns and fixed angular spacing.

The beam controller processing capacity depends on the desired control algorithm. As a representative example, consider adaptive nulling via the sample matrix inversion (SMI) method. The formation of the sample matrix and its inversion take approximately $(7/6)\ N^3$ complex operations. With N equal to approximately 100 elements and an update rate of 100 times/sec, this formation leads to approximately 5×10^8 floating point operations (FLOPs), which is currently reasonable. However, for the more ambitious adaptive space-time processing envisioned for airborne surveillance radar, the number of spatial degrees of freedom is multiplied by the number of temporal degrees of freedom, a factor of three. In addition, the update rate needs to be increased. A factor of 10 is reasonable. This increase leads to processing loads on the order of 100 gigaFLOPs, which pose serious difficulties. Due to the N^3 dependence, the number of adaptive degrees of freedom clearly must be kept to an absolute minimum.

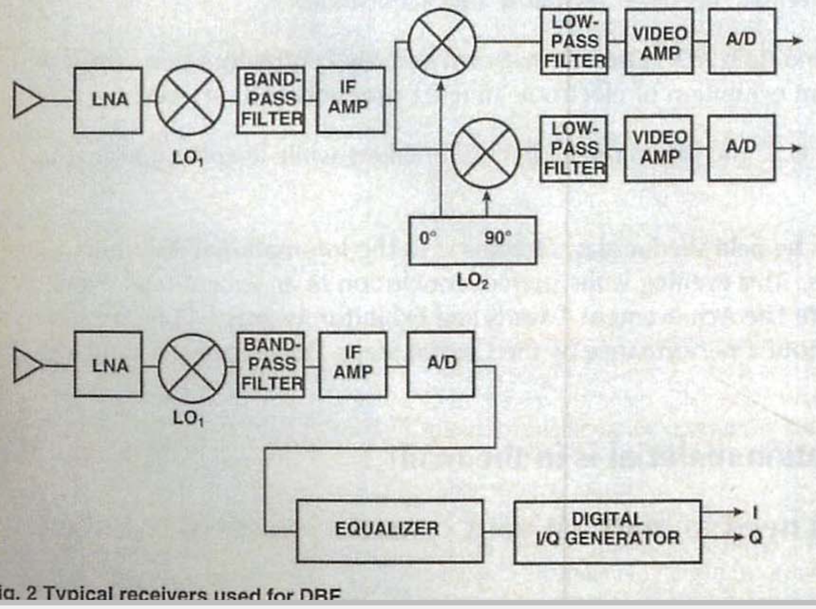

Fig. 2 Typical receivers used for DBF

OTHER IMPLEMENTATION ISSUES

A multitude of system concepts and issues are of interest aside from the basics discussed previously. For instance, as often done in radar, the dynamic range may be extended by coherent integration in time. In effect, this extension allows detection of signals smaller than the least significant bit because of the offset of the zero-mean noise voltage. Based on this concept, an interesting radar has been proposed[8] with 4,000 elements, 32-bit compression code and 32 Doppler output cells, leading to 66-dB processing gain. With an operational dynamic range of 55 dB, the element signals are so far below the noise that a multibit A/D converter seems unnecessary. A 1-bit A/D converter, which simply outputs the plus/minus sign of the input signal, may be sufficient and would result in enormous A/D converter and IF channel savings.

Other computational simplifications may be gained by going from element space to beam space via a spatial Fourier transform. Assuming a scenario where there are signals only in a relatively small number of M directions, then only a correspondingly small number of beams needs to be considered, rather than the large number of N elemental signals. In this case, processing these beams by an SMI or similar adaptive algorithm requires on the order of M^3 rather than N^3 mathematical operations, which usually dramatically reduces complexity. Sophisticated adaptive systems based on this concept have been proposed.[9,10]

DIGITAL BEAMFORMING AT ROME LABORATORY

Early Activities

Digital beamforming has long been used in sonar systems and also for low-frequency over-the-horizon radars, such as the Air Force East Coast Radar System (OTH-B). However, the data rates are much lower than required by modern microwave radars. Serious interest in employing DBF for such systems was first stimulated in the US about 10 years ago by a joint DARPA/US Army MICOM study. Its objectives were to chart potential technical options offered by DBF techniques and to quantify the benefits derived from them in selected applications. Rome Laboratory consulted on its own program.

Hardware Developments and Experiments

An early US Air Force program addressed array calibration, a problem common to all DBF arrays. For this research, a 32-element linear array operating at C-band was built with high-performance commercial components.[11] Triple conversion receivers provided analog I and Q signals that were digitized by a pair of 10-bit/0.5-MHz A/D converters. The array featured a novel self-calibration system that injected an accurate pilot tone immediately behind each antenna element and thus monitored the 32 receive channels. After digital correction of channel imbalances (±2-dB amplitude, random phase) and I/Q and DC-offset errors, the RMS phase error was 2°, consistent with a -45-dB sidelobe level.

Another, separate project was the technology demonstration of a fast digital beamformer[12] with performance compatible with an actual radar system. This successful design has several unique features. Four parallel processors accept 64 complex digital input channels and form four independent inner product beams at a 20-MHz clock rate. Since the bandwidth is excessive for many applications, the design allows flexibility with respect to the number of beams formed. Thus, 4, 8, 16 or 32 beams can be multiplexed with a proportionally reduced bandwidth. The high computational capacity, 5×10^9 complex multiplies per sec, is achieved with a systolic processor architecture based on the quadratic residue number system. This number theoretic approach is highly effective for multiplications and additions and uses integer arithmetic so that round-off errors are avoided. The finite dynamic range is tailored to correspond to the limited range of the quantized input signals. Compared to a conventional approach, this processor has about 40% less complexity (defined as the product of gate count and gate delays).

These two systems coupled with a beam controller (a general-purpose computer) form the major components of the RL/Ipswich antenna site real-time digital beamforming testbed. This testbed was used to study adaptive pattern nulling and super resolution.

Fast adaptive jammer suppression is presently the strongest drive for DBF. Analog systems are usually based on feedback loops and their convergence

slow. Digital open-loop systems need no feedback and are scenario-independent and significantly faster. The SMI algorithm was used to demonstrate open-loop adaptive nulling.

A jammer was placed at -10°, the interference-plus-noise covariance matrix was measured and the adapted weights were computed using a steering vector for a desired-look direction at broadside with a 20-dB Taylor taper imposed. The array was then phase scanned and the received power was measured as a function of scan angle, as shown in **Figure 3.** This pattern represents jammer power only, and obtaining the adapted response in this way provides a direct measure of jammer cancellation. The main beam corresponds to maximum received jammer power and the broadside null to jammer cancellation of 59 dB, which is the full dynamic range of the system.

The resultant adapted pattern does not yield 20-dB sidelobes, which can be explained by an eigen-decomposition of the covariance matrix. It ultimately depends upon the array errors — that is, the DC offset, I/Q, third harmonic and even the differences between the noise figures of the element receivers.[13]

Super-resolution and direction-finding techniques aim to resolve sources closer than the Rayleigh limit. The key lies on the *a priori* assumption that the received array signal vector is generated by a few point sources only, and then the corresponding spatial frequencies in this signal are determined with modern spectrum estimation methods. These methods involve nonlinear signal processing, and the algorithms tend to be highly complex, making a DBF array requisite for their practical implementation. An experiment using the well known multiple signal classification (MUSIC) algorithm was performed in which two uncorrelated sources illuminated the array from directions that were only 1.7° (approximately 0.4 beamwidth) apart. The received signals were analyzed with this algorithm. The response is plotted in **Figure 4.** The sharp peaks correspond exactly to the directions of the two signals. For comparison, the response is shown for the sources when scanned by a conventional beam and a monopulse beam, respectively. Clearly, only the super-resolution algorithm is able to resolve such closely spaced sources, and a sum beam or a monopulse beam fails completely.

And Elsewhere in the World of Antenna Technology

The theory associated with DBF's ability to manipulate the appearance and response of an antenna pattern seems almost mystical, but progress is being made in translating the theory into practice. Several DBF applications and hardware advances in several adjunct fields deserve special recognition.

Andrew SciComm (Garland, TX) has developed various beamforming technologies for both military and commercial applications. An HF Digitally Adaptive Beamforming subsystem is a case in point. This M antenna system is able to null up to M-1 undesired (jamming) signals and form a beam directed at a desired signal location. The typical system consists of four to as many as eight antennas. Current activity is aimed at improving the required algorithms and transitioning to a VXI form factor. VHF and UHF versions of the system are under consideration.

Scientists at Roke Manor (Romsey, Hampshire, England), the research arm of Siemens Plessey, have been involved in advanced antenna beamforming since the early 1970s. Digitally adaptive beamforming has been applied to the Multifunction Electronically Scanned Adaptive Radar (MESAR) developed in conjunction with the UK Defence Research Agency. The MESAR consists of some 1,000 S-band active phased-array elements. While standard phase shifters provide electronically controlled beam steering, each output is then combined into one of 16 subarrays for adaptive beamforming. Each subarray feeds its own receiver channel for conversion to digital I and Q basebands. The 16 I/Q channels are adaptively beamformed using complex weight multipliers to provide protection against up to 15 sidelobe or mainbeam jammers.

Siemens Plessey has also entered into a strategic alliance with the Watkins-Johnson Co. (Palo Alto, CA) to interface advanced communications digital receiver technology into Roke Manor adaptive array processing and DBF algorithms. In this HF communications application, super-resolution DF processing provides improved readability in the direction of signal interest, while nulling other unwanted co-channel signals.

The ability to generate numerous antenna beams in arbitrary directions poses a challenge to measurement instrumentation. Antenna patterns are generally measured with instrumentation receivers that measure the response of the antenna as a function of angle off boresight. Conventional antenna pattern receivers perform a few thousand measurements per sec. For an antenna system capable of synthesizing hundreds of thousands of *different* patterns, however, the measurement time per pattern must be greatly reduced. To fill this need, the Aeroflex Lintek Corp. (Powell, OH) has produced the élan antenna-measurement system. The élan system is capable of collecting four million samples/sec at frequencies from 100 MHz to 100 GHz. This increased measurement speed not only reduces test time but in some cases can lead to new insights, such as a study of the time-varying response of an adaptive DBF antenna as its pattern evolves.

A portable kit of antennas intended for cellular telephone applications in the Nordic 450, AMPS and TACS bands has been introduced by Electro-Metrics (Johnstown, NY). Consisting of directional Yagis and omnidirectional antennas covering the 430- to 470-MHz and 824- to 960-MHz range, along with required preamplifiers, switch, filters and cables, the kit allows antennas to be assembled in the field without tools.

—Don Herskovitz

Circular Array with Frequency-Invariant Pattern

Circular array antennas have a unique capability. They can generate a main beam and sidelobes that are essentially independent of frequency because the far field pattern can be represented in terms of orthogonal phase modes (mode of unit amplitude/linear phase azimuth variation). So long as the relative amplitudes of these modes are constant, the entire pattern is constant with frequency. However, to generate constant amplitudes, the required beamforming network is complicated. For arrays with more than 32 elements, it becomes feasible only with DBF.[14]

The basic pattern synthesis technique has been given previously.[15] On receive, the N element signals are transformed into phase modes by an N X N Fourier transformer, which is followed by in-line filters that remove the frequency dependence of the individual phase modes. Finally, the amplitude and phase taper corresponding to the desired beam shape and look direction are imposed, and the phase modes are summed to produce a frequency-invariant pattern.

The beamwidth is determined by the number of phase modes used in the pattern. For given numbers of elements N and phase modes M, the usable pattern bandwidth is roughly given by M <2ka <N, where ka is the cylinder circumference measured in wavelength. At the lower end, the pattern becomes super directive, and at the upper end the element spacing exceeds half a wavelength, leading to pattern perturbations. The filter responses for the phase modes have to be determined corresponding to the actual array element pattern.

To demonstrate the features of frequency-invariant patterns, a circular array was built with 64 elements composed of monopoles in a parallel-plate region. The electrical design was based on a theoretical analysis[16] that agreed well with measurements. The feeding network was simulated by sequentially switching one digital receiver to the array elements, recording patterns and forming the composite array patterns off line. **Figure 5** shows three 30-dB Chebyshev patterns taken at 4, 5 and 6 GHz, demonstrating stable nulls and no beam squint over a 40% bandwidth.

This study showed that circular arrays with DBF can generate high-quality patterns, with narrow beams and deep pattern nulls, that are stable over large bandwidth. These features are attractive for many applications, including adaptive pattern nulling.

Array Element Pattern Correction

In a small array, all elements have different radiation patterns because of mutual coupling, which may preclude precise pattern control. However, with DBF these adverse effects can be corrected.[17] Rome Laboratory's method is based on the following observation: in the receive mode, the individual antenna element signal has several constituents, one dominant constituent resulting from the direct incident plane wave and several lesser constituents resulting from scattering of the incident wave at neighboring elements. These constituents can be resolved and scattering compensated for by linear transformation, which is accomplished by a matrix multiplication performed on the element output signals. The compensation is scan-independent; the matrix is fixed and applies for all desired patterns and scan directions. The theoretical technique has been verified in a demonstration with an eight-element array, where the initial sidelobe level was reduced from 20 dB to 30 dB, as shown in **Figure 6.**

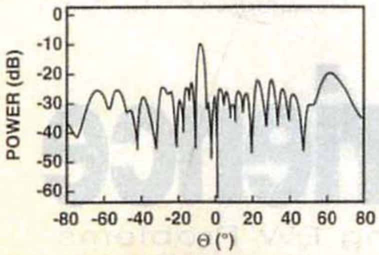

Fig. 3 Adaptive pattern nulling with the SMI

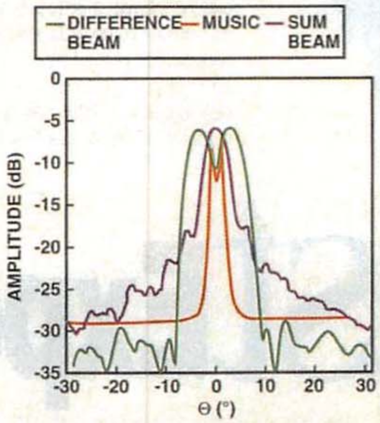

Fig. 4 Super resolution with the MUSIC

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