

Photorefractive Phased Array Beamforming with True-Time-Delay Processing

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Abstract

We introduce a novel optical beamformer for a large adaptive array that uses a photorefractive crystal for the spatio-temporal weights and two tapped delay lines implemented with an acoustooptic cell and a scrolling image detector.

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We introduce a new optical approach to the problem of implementing true-time-delay (TDD) beamforming for a large N-element adaptive array that requires only 2 tapped delay lines (TDLs) instead of the conventional N TDLs. This new algorithm, BEAMTAP (Broadband and Efficient Adaptive Method for TTD Array Processing) is capable of processing very large phased array radar systems with thousands of receiving elements with GHz of bandwidth [1]. The corresponding digital processing load that would be required to solve such large, broadband adaptive array problems exceeds 10^{15} multiply-accumulate operations per second; well beyond the capability of current electronic systems.

Consider the BEAMTAP algorithm shown in Fig. 1. Each antenna element output $s_i(t)$ is multiplied at each resolved time step by a linear array of weights W_{ij} located along a given row of the weight matrix. Each product is then summed along the column with the corresponding products from the other array elements. The resulting sum is fed into a scrolling delay line with the overall output given by

$$o(t) = \sum_j \int \delta(t' - [t - j\tau]) Y_j(t') dt' = \sum_j Y_j(t - j\tau) = \sum_j \sum_i s_i(t - j\tau) W_{ij}^* \quad (1)$$

The $Y_j(t)$ are the partial sums incident on the tap-in delay line, and the scrolling detector continuously accumulates them. The weights in BEAMTAP are calculated using conventional LMS adaptation [2] [3] but with a reference signal applied to a tap-out delay line as shown. These weights are implemented as holographic gratings in a photorefractive crystal (PRC) volume, and each resolvable hologram acts as an interferometric time integrating multiplier in the form

$$W_{ij}^*(t) = \int_{-\infty}^t s_i^*(t_1) f(t_1 + (j - M - 1)\tau) \tau dt_1 \quad (2)$$

Hence, the resulting LMS output is

$$\begin{aligned} o(t) &= \sum_j \sum_i \int \delta(t' - [t - j\tau]) s_i(t') \int_{-\infty}^{t'} s_i^*(t_1) f(t_1 + (j - (M - 1))) \tau dt_1 dt' \\ &= \sum_j \sum_i s_i(t - j\tau) \int_{-\infty}^t s_i^*(t_2 - j\tau) f(t_2 - (M - 1)\tau) dt_2 \end{aligned} \quad (3)$$

This algorithm is nearly equivalent to the conventional time-delay-beam-forming (TDBF) except for the simple time shift $T = (M - 1)\tau$ in the reference signal $f(t)$ which implies anticipation of the output $o(t)$. This apparent causality problem can be overcome by delaying a copy of the antenna signals $s_i(t)$ by T and using them to write the weights while the undelayed version is used for beamforming. The number of delay lines in this case has been dramatically reduced from N as required by the TDBF to just 2. An optical implementation of the BEAMTAP processor using holographic gratings in a PRC as the adaptive weights is shown in Fig. 2.

A low relative intensity noise (RIN) laser is required to feed an array of electrooptic modulators driven by the outputs of the antennas that convert an incident RF wavefront on each antenna into an optical field. These optical fields are launched by the fiber feed through an optical system and into

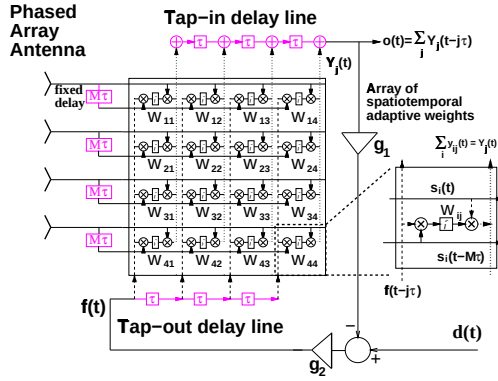


Figure 1: BEAMTAP algorithm for broadband squint-free true-time-delay beamforming using a single output tap-in delay line and a single feedback TDL for adaptive calculation of the weights within the array as integrated correlations. Time delay is not required within the array of weights.

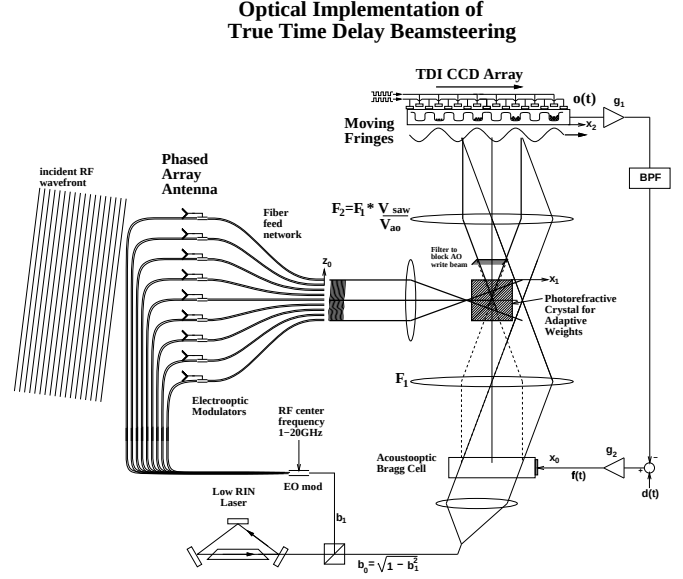


Figure 2: Signal flow for an optical BEAMTAP system utilizing 2 broadband adaptive beamformers that simultaneously form a main beam in the direction of any arriving desired signal $s(t)$ and then null out any narrowband jammers arriving on the sidelobes.

a PRC. Because of fiber length mismatches, the optical phase front is not necessarily planar but the photorefractive hologram can adapt to compensate for this distortion.

It is assumed that we have available a signal of similar correlation characteristics as the desired incident RF signals. The processor output is subtracted from this desired waveform $d(t)$ and applied to the reference AOD. The interference of the spatio-temporally modulated optical field from the fiber bundle with the steering signal in the AOD builds up a dynamic grating throughout the crystal volume that is Bragg matched to the angle-of-arrival of the incident radar signal. In conventional dynamic holography, the diffracted wave is not separable from the write beam. We provide read-write multiplexing by angle and polarization encoding; details of which can be found in [1] and [4].

Hence, any subsequently Bragg matched incident energy is diffracted toward the scrolling output detector where it is interferometrically detected using the undiffracted light from the AOD and time integrated in a traveling wave coordinate system. Hence, at each resolvable time instant, the scrolling detector is read out after a corresponding charge packet has traversed the length of the detector while accumulating charge and being delayed for each position. This scrolling delay line is implemented with a 1-dimensional CCD detector operating in time-delay-and-integrate (TDI) mode. In this mode, each photogenerated carrier is accumulated and shifted along at a constant velocity by the applied clock signal.

Photonic processing of microwave signals is often limited by the conversion of optically modulated signals into high frequency photocurrent usually using high speed point detectors, however, we need a scrolling accumulating detector such as a TDI CCD. GaAs based CCDs promise speeds in excess of 1 GHz while silicon CCDs are still limited to 100 MHz. In addition, all CCDs are inherently prone to bias build up and are full well shot noise limited which may reduce the overall dynamic range of the system. Other promising technologies we are investigating involve replacing the CCD with a traveling fringe detector [5]. In contrast to CCD technology, these traveling wave detectors promise to simultaneously maintain a high saturation level owing to a large detection volume and a high operating frequency well in excess of 1 GHz. Although the instantaneous bandwidth of the AOD and the CCD devices are at best about 1-2 GHz, the

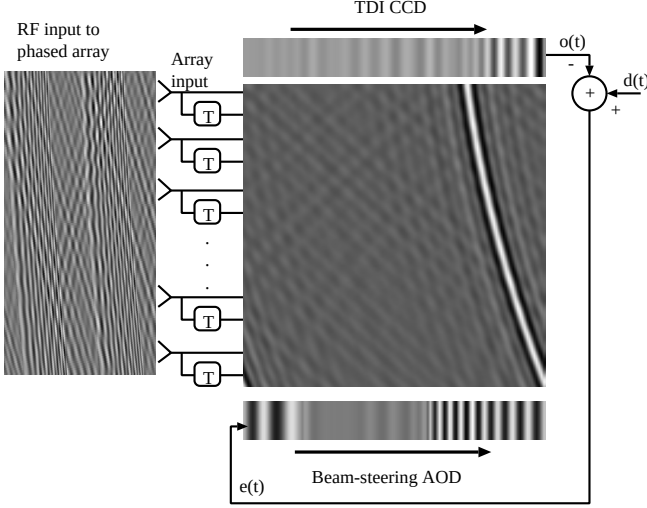


Figure 3: Simulation of BEAMTAP adaptation in the presence of a near-field chirp signal and two jammers: one in the near-field and the other in the far-field.

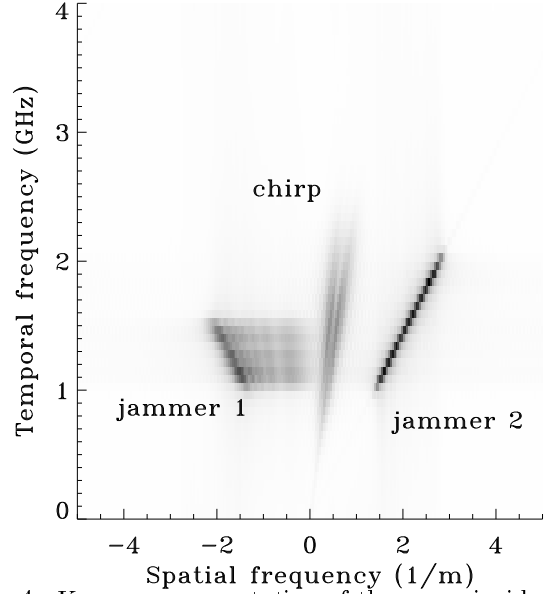


Figure 4: K-space representation of the array incident energy showing the spatio-temporal content of the linear chirp and the two jammers.

BEAMTAP optical system can operate at any 1 GHz bandwidth tunable throughout the bandwidth of the electrooptic modulators, which is typically 20-60 GHz using a single EO device as shown in Fig. 2, without the need for electronic mixers, which can be very lossy at such high frequencies.

A simulation of the BEAMTAP operation with jammer nulling is illustrated in Fig. 3. In this example the input consist of a chirp signal and two jammers. The desired signal is a repetitive near-field broadband spatio-temporal linear chirp spanning from 0.5 GHz to 1.5 GHz, and originating at a distance $5.2L$ from the antenna array, where L is the total array length. The jammers were produced from filtered Gaussian white noise sequences. The first jammer spans the frequency range 1 GHz to 1.5 GHz, located at a distance $L/2$ from the antenna array while the second jammer spans from 1 GHz to 2 GHz, and it is located in the far-field.

A k-space/frequency diagram representing the input signals is shown in Fig. 4. Notice that the chirp signal occupies a broad bandwidth both in time and space, as expected from a near-field source and since it is repetitive, it is sampled in frequency. The near-field jammer signal occupies a large spatial frequency bandwidth, while the far-field jammer occupies a broad time frequency range. Adaptation of our parameters (weights) should provide us detection of the desired output signal and nulling of the jammers for any combination of signal and multiple jammers, as long as their space/time spectra do not overlap and sufficient feedback gain is available.

The graph in the far left of Fig. 3 illustrates the spatio-temporal sequence of the input array signals, linear chirp plus jammers, followed by the graph representing the weights of the adaptive array after $1.02 \mu\text{s}$ of adaptation. 128 antenna elements and 128 time delays on each delay line were used on this simulation, providing us with an array of 128×128 adaptive weights. Their intensity is proportional to the local variation in the index of refraction of the PRC which constitutes the grating. Notice that the time and phase delays caused by the curved wavefronts of the near-field signal are exactly compensated for by the diffraction off of the curved grating slice in the PRC in a fully adaptive fashion. Similar gratings would compensate for delays associated with arbitrary array configuration, such as a conformal or flexible array, or additional delays or phases from the fiber feed network. The thin slice below the weights represents the local variation in the index of refraction in the AOD, which implements the tap-out delay line. The thin slice above the weights represent the accumulated output in the TDI CCD, the tap-in delay line.

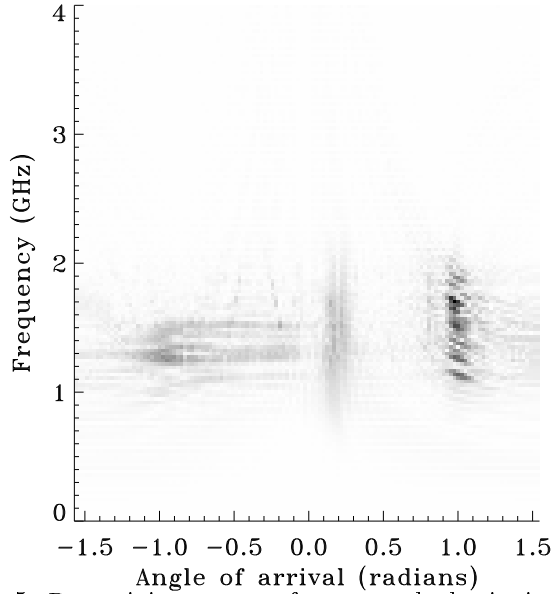


Figure 5: Receptivity pattern of array at the beginning of adaptation.

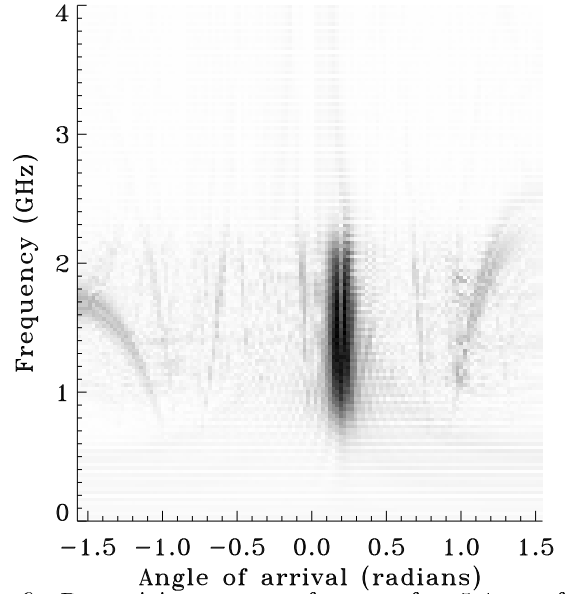


Figure 6: Receptivity pattern of array after 5.1 μ s of adaptation.

Figure 5 shows the receptivity pattern at the beginning of adaptation, where the bright regions represent the combination of angles-of-arrival (AOA) and frequencies of signals to which the antenna array is sensitive. Notice that at first, the adaptive array responds to the presence of all signals. Figure 6 shows the same graph after 5.12 μ s of adaptation. Notice that only the broadband near-field chirp is present, proving the presence of nulls in the space occupied by the jammers. Also notice the absence of beam-squint, indicated by the constant value of the AOA of the receptivity pattern due to the true time-delay signal representation.

For an antenna array with $N = 1000$ elements, bandwidth $B = 1$ GHz and of length $L = N\lambda/2 = 15$ m (requiring $M = BL/c = 50$ taps), this optical processor achieves a throughput of $NMB = 10^{14}$ analog multiplications, which is well beyond the capabilities of electronic approaches, providing strong motivation for the development of these optical techniques.

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1 Conclusion

A novel approach for notching narrowband interferers using digitally tunable filters in a unique space integrating reference tone arrangement was shown to be very effective with minimal correlation envelope distortion required for reliable LPI detection. The processor's performance in the presence of both *in-band* and *out-of-band* NIS cases in addition to broadband noise was studied and the experimental results were found to be consistent with theoretical predictions. A scheme for adaptively identifying the NIS based on an alarm mechanism and notching it was proposed and demonstrated in Sec. 1. It was shown that the error in notching NIS energy peaks at the center of the LPI frequency span and falls off substantially as the NIS location is shifted away from the center. This discrepancy was attributed to the practical limitation of the filters to restrict the notch only to the NIS energy.

2 Acknowledgment

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