

All-optical antenna array adaptive processing system

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ABSTRACT

We present an all-optical architecture for a fully adaptive antenna array processor capable of optimally processing the signals from very large arrays in the presence of high frequency and wideband signals. A modified version of the least mean square (LMS) algorithm is employed using the BEAMTAP (Broadband and Efficient Adaptive Method for True-time-delay Array Processing) architecture. A dynamic photorefractive volume hologram is used for the adaptive weights and two cohered fiber arrays are used as tapped-delay-lines at the output and feedback paths, allowing for the processing of signals at bandwidths exceeding 10 GHz. The optical cohering of the fiber arrays is discussed and simulations are shown which describe the performance of the proposed architecture in the presence of broadband signals and multiple broadband jammers.

Keywords: Adaptive phased arrays, true-time-delay, BEAMTAP, optical processing.

1. INTRODUCTION

In adaptive antenna array processing, antenna array parameters are algorithmically adjusted in order to modify the input signals to accomplish a desired task. Truly adaptive implementations of these systems require a specific adaptation algorithm,¹⁻³ such as the least mean squares (LMS) algorithm,^{1,4} to perform this task. However, the digital implementation of these algorithms becomes difficult when the signal environment becomes complex enough to require the use of very large arrays to optimally preform the beamforming and jammer nulling operations typical of these adaptive antenna arrays. The high degree of parallelism of optical processors, therefore, lends itself to the optical processing of these antenna signals when the number N of antenna elements is large.⁵⁻⁷ The LMS algorithm is specially useful for optical implementations since it requires the evaluation of a convolution-correlation integral. Conventionally, the algorithm has been implemented using one tapped-delay-line per antenna element; however, this can be both technologically challenging and expensive. The BEAMTAP architecture⁸ overcomes this problem by moving the tapped-delay-lines (TDLs) to the output and feedback arms of the processor, requiring the use of only two TDLs instead of N .

Previous versions of the proposed implementation of the BEAMTAP architecture require the use of acousto-optic devices (AODs) or time-delay-and-integrate charge-coupled-devices (TDI-CCDs),⁹ and are thus limited to the detection of signals with a BW of only 500 MHz. In this paper, we discuss a new implementation of the BEAMTAP architecture in which an array of linearly increasing fiber lengths are used as the tap-in and tap-out delay lines necessary for the processing of signals at very high center frequencies and GHz of bandwidth. Section 1 provides a short overview of adaptive array processing architectures. Section 2 then explains the need for time-delay-and-sum broadband signal processing and the need for fully adaptive arrays when dealing with broadband noise and multiple jammers. Section 3 presents the BEAMTAP implementation of the LMS algorithm, and Section 4 explains the proposed optical architecture. Finally, Section 5 presents simulations showing the adaptive capabilities of the proposed architecture in the presence of broadband signals and jammers, with Section 6 providing the concluding highlights and technical advantages of this optical architecture.

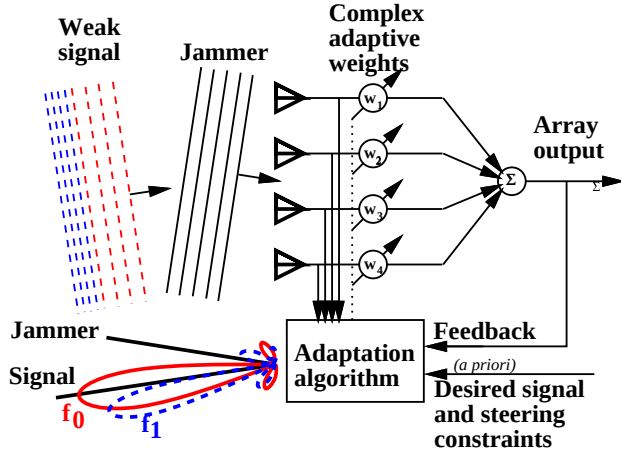


Figure 1. Narrowband adaptive array in the presence of broadband signals.

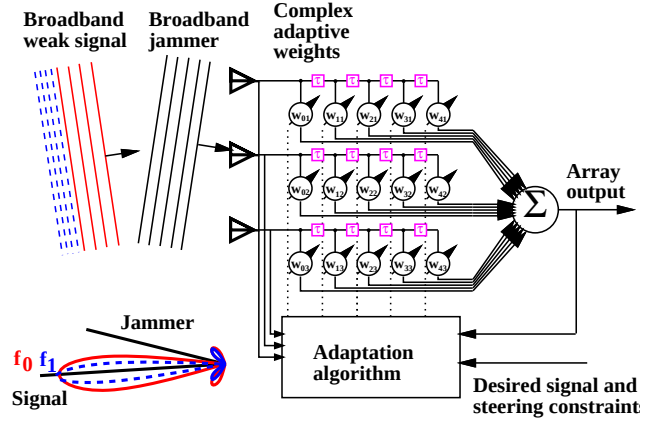


Figure 2. Time-delay-and-sum adaptive array capable of broadband signal detection and jammer nulling.

2. ADAPTIVE ARRAY PROCESSING

A general application of adaptive antenna arrays consists of the optimum detection of desired signals constrained by the rejection of undesired signals (i.e. noise sources, intentional jammers, neighboring interference, multipath interference, etc). We will simply refer to the undesired signals as *jammers*. Adaptive antenna arrays containing N elements do not require the use of true-time delay (TTD) or time-delay-and-sum techniques in order to steer its antenna function to detect the desired signals and null out potential jammers when the signal environment is restricted to the presence of N narrowband signals. As shown in Fig. 1, a single complex weight per antenna element provides the necessary number of degrees of freedom for adaptation—hence, the capacity to better null most of the jammer power while detecting as much of the desired signal power as possible is proportional to N . However, if one of the input signals (desired or jammer) occupies a significant amount of bandwidth, different signal frequencies will experience different directivity gains, since when no TTD is present, the antenna directivity scales with frequency. This effect is known as *beamsquint*. To compensate for the RF propagation delay, extra degrees of freedom in the temporal domain are required in order to synchronize signals arriving on different antenna elements, as shown in Fig. 2.

Fig. 3 depicts two broadband signals being detected by an antenna array, where t_p and t_j are the propagation delay between antenna elements for the signal and jammer, respectively. The RF signals are converted to the optic domain using electro-optic (EO) modulators, which produce optic wave fronts displaced in time by t_p or t_j . In order to coherently adapt to both signals, it is not enough to process the input at one single instant of time. Instead, it is necessary to delay the input signals in order to compensate for the propagation delay incurred by the time required for the signals to propagate across the array elements. This is done by using a tapped-delay-line with a total delay of at least dN/c , where d is the element spacing and c is the speed of light, for angles of arrival (AOAs) up to $\pm\pi/2$. Each individual time delay is chosen to be $\tau = 1/2f_{max}$, where f_{max} is the maximum signal frequency. Therefore, the minimum required number of time delays must be $M = 2dNf_{max}/c$.

3. ADAPTIVE ARRAY ALGORITHM

Let us first analyze the conventional adaptive array processor, from which the BEAMTAP method is derived. The diagram in Fig. 4 illustrates conventional time domain adaptive array processing using the conventional LMS time-delay-and-sum algorithm. The signals $s_n(t)$ from each of the N antenna elements are delayed by N TDLs, producing signals $s_n(t - m\tau)$, where m is a temporal index ranging from zero to $M - 1$, and τ represents the time delay between taps, as defined in Sec. 2. For simplicity of notation we define $M' = M - 1$, the total number of time delays on each delay line, where the maximum time delay is given by $T \equiv M'\tau$.

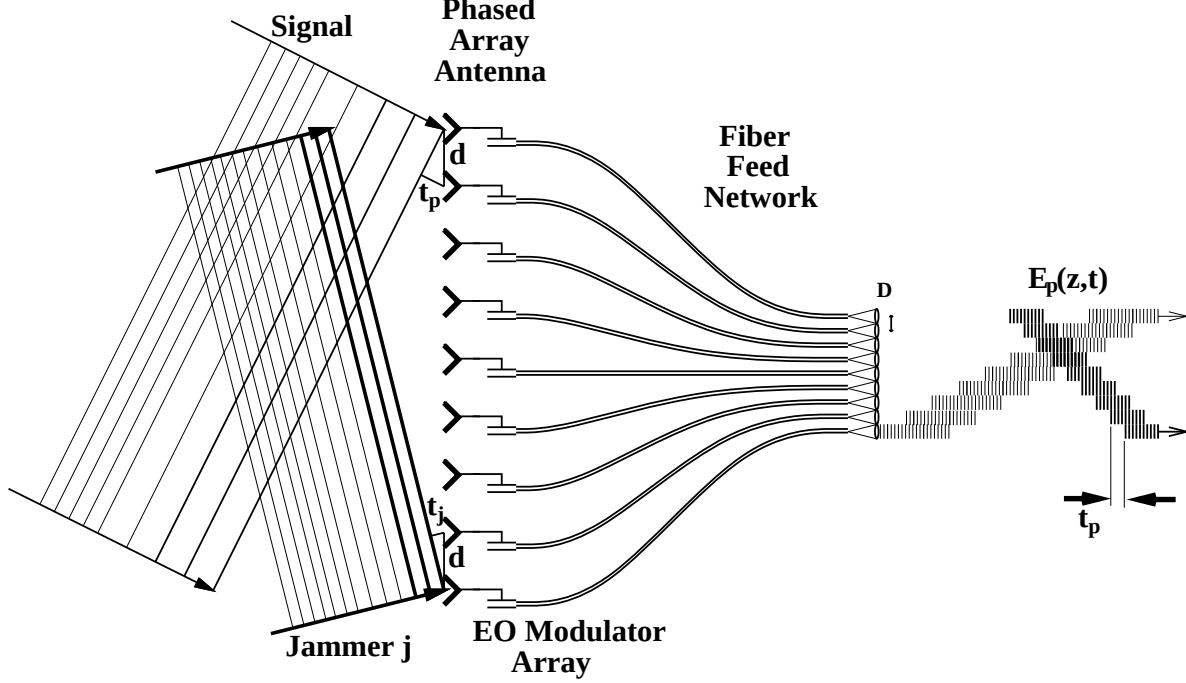


Figure 3. Detection of two RF signals and conversion to the optical domain using electro-optic modulators at each antenna element, illuminated by a single coherent laser source. Different angles of arrival across the RF signals translate into different time delays of the optic wave fronts.

The output of the processor is given by the weighted sum of delayed versions of the inputs,

$$o(t) = \sum_{n=1}^N \sum_{m=0}^{M-1} W_{mn}^* s_n(t - m\tau). \quad (1)$$

Performing continuous-time, gradient descent supervised learning using the LMS algorithm to minimize the error signal $f(t) = d(t) - o(t)$, the weight adaptation is given by the correlation between each delayed antenna signal and the feedback error signal $f(t)$

$$W_{mn}^* = \int_{-\infty}^t f(t_1) s_n^*(t_1 - m\tau) dt_1. \quad (2)$$

Thus,

$$o(t) = \sum_{n=1}^N \sum_{m=0}^{M-1} s_n(t - m\tau) \int_{-\infty}^t s_n^*(t_1 - m\tau) [d(t_1) - o(t_1)] dt_1. \quad (3)$$

Since the time variation of the weights due to adaptation is small (the weights are essentially constant over the duration of the convolution), the output signal can be solved for using a frequency domain approach which results in a power nulling spatio-temporal filter. In Sec. 3.1 we will show a nearly identical output for our new BEAMTAP beamformer that requires only 2 TDLs in comparison with the N TDLs required by this LMS time-delay-and-sum conventional approach.

3.1. BEAMTAP

In the BEAMTAP architecture, shown diagrammatically in Fig. 5, the instantaneous input signal $s_n(t)$ is simultaneously multiplied by each of the adaptive weights with the tap-in delay line delaying the products from each corresponding column such that the signal at the m th column is given by

$$Y_m(t) = \sum_{n=1}^N W_{mn}^* s_n(t). \quad (4)$$

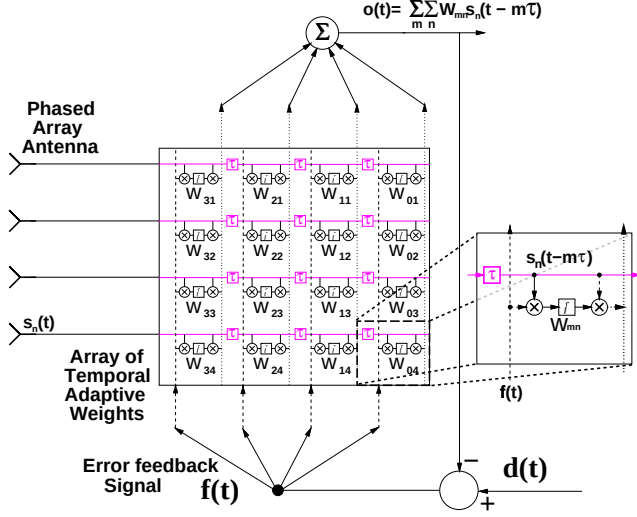


Figure 4. Conventional time-delay-and-sum approach to adaptive array processing for broadband squint-free true-time-delay beamforming using least-mean-square (LMS) adaptation based on a desired signal and a simple correlation-cancellation-loop feedback, where the desired signal d_t is subtracted from the output signal o_t to produce the feedback signal f_t .

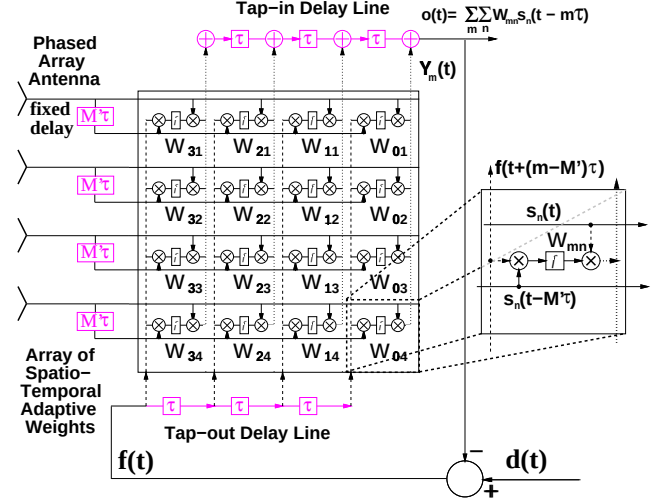


Figure 5. BEAMTAP algorithm for broadband squint-free true-time-delay beamforming using a single output tap-in delay line. For adaptive calculation of the weights within the array, the additional input tapped-delay-line is also required. The desired signal d_t is again subtracted from the output signal o_t to produce the feedback signal f_t .

At the output of the tap-in delay line we have an accumulation of delayed versions of the products of the M columns such that

$$o(t) = \sum_{m=0}^{M-1} Y_m(t - m\tau) = \sum_{m=0}^{M-1} \sum_{n=1}^N W_{mn}^* s_n(t - m\tau). \quad (5)$$

Thus, from any antenna element there is a path to the delay line such that its corresponding output has the correct amount of delay required to synchronously sum the antenna element output signals $s_n(t)$. This operation is exactly equivalent to the conventional time domain beamformer given by Equ. 1, but only requires one TDL. We have commuted the delay-and-sum operation of multiple TDLs which have one weighted output from each tap position (Fig. 4) into a single multiple input delay line which accumulates and shifts the partial sums from each column (Fig. 5).

In BEAMTAP adaptation, the feedback signal is delayed instead of the input signals. Column m of the weight matrix is multiplied by the feedback signal $f(t)$ delayed by $(M' - m)\tau$, where the amount of delay is such that the total loop delay is always $M'\tau = T$ for every column. Each multiplication is accumulated over time, providing us with the following weight adaptation equation:

$$W_{mn}^*(t) = \int_{-\infty}^t f(t_1 - (M' - m)\tau) s_n^*(t_1 - M'\tau) dt_1. \quad (6)$$

Note that m varies from 0 to M' and, therefore, the argument of f varies from $t_1 - T$ to t_1 , and is always causal. The signal $s_n(t)$ must be delayed by $T = M'\tau$ in order to synchronize the input signal with the total loop delay $M'\tau$, since the weights should be modified by a product between the feedback error signal and the corresponding input signal $s_n(t - M'\tau)$. Notice that this is a bulk delay with a single output, such as provided by a fiber loop, and no tapped-delay lines are necessary at the input of the array. Thus, we obtain the following expression for the output:

$$o(t) = \sum_{n=1}^N \sum_{m=0}^{M'} s_n(t - m\tau) \int_{-\infty}^{t-m\tau} s_n^*(t_1 - m\tau - M'\tau) f(t_1 - M'\tau) dt_1$$

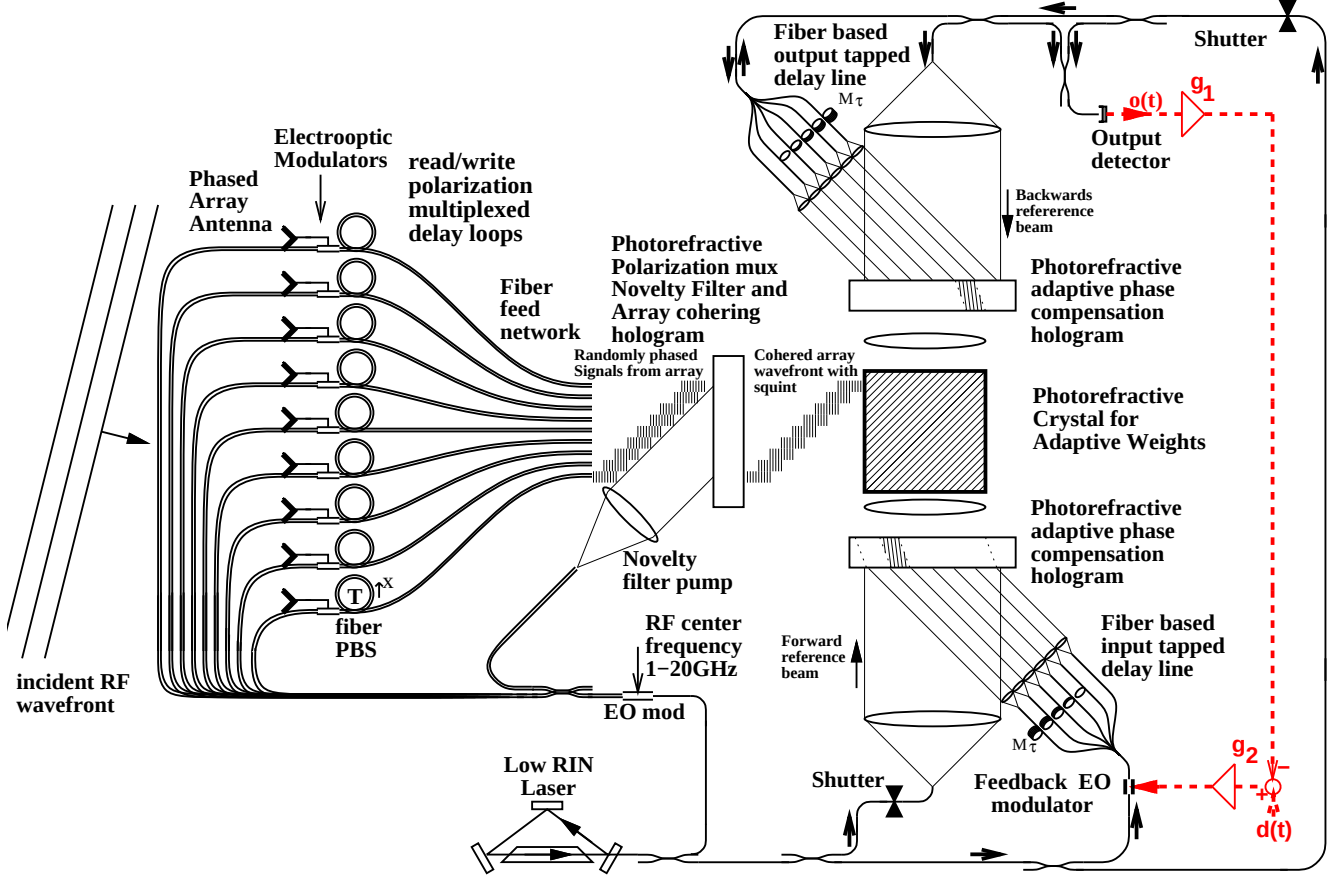


Figure 6. All-optical BEAMTAP system using cohered fiber tapped delay lines. A photorefractive crystal is used to implement the adaptive weights and a novelty filter is used for removing the carrier from the modulated input signals. Cohered fiber arrays implement the tapped-delay-lines. The dotted line represents electronic signals.

$$o(t) = \sum_{n=1}^N \sum_{m=0}^{M'} s_n(t - m\tau) \int_{-\infty}^{t-T} s_n^*(t_2 - m\tau) [d(t_2) - o(t_2)] dt_2. \quad (7)$$

The output signal provided by the BEAMTAP approach is equivalent to the one provided by the conventional LMS delay-and-sum adaptive algorithm shown in Equ. 3. The only difference is the upper limit of the integral, which show that the weights are being adapted by the delayed product of $s_n(t)$ and $f(t)$, which is inconsequential for input signals whose statistics vary slowly compared to the convergence rate of the algorithm.

4. COHERED FIBER TIME DELAY BEAMTAP PROCESSOR

Optical architectures have been proposed for the implementation the BEAMTAP algorithm⁸⁻¹¹ utilizing acousto-optic devices (AODs) and TDI-CCDs for the two required tapped-delay-lines. However, these architectures were limited by the bandwidth of existing AODs and the bias build-up inherent to heterodyne detection on TDI-CCDs. The new all-optical approach achieves high frequency and wideband operation using cohered fiber TDLs consisting of a coupler (or cascaded couplers) which splits the signal from its input fiber to M output fibers. Each of the fibers are cut at an incremental length, such that the propagation time through the fibers provides the M delayed versions of the signal. Figure 6 depicts such a system.

Optical convolvers based on fiber TDLs can weight and sum wideband modulated optical signals emerging from an array of fibers with linearly increasing time delays.¹² These fiber tapped-delay-lines can be used for incoherent optical signal processing applications by cutting the fiber lengths to an accuracy given by a small fraction (typically 1/4 to 1/10) of the highest RF frequency times $c/n_g \approx 2 \times 10^{10}$ cm/sec. Thus for a system with 10GHz bandwidth,

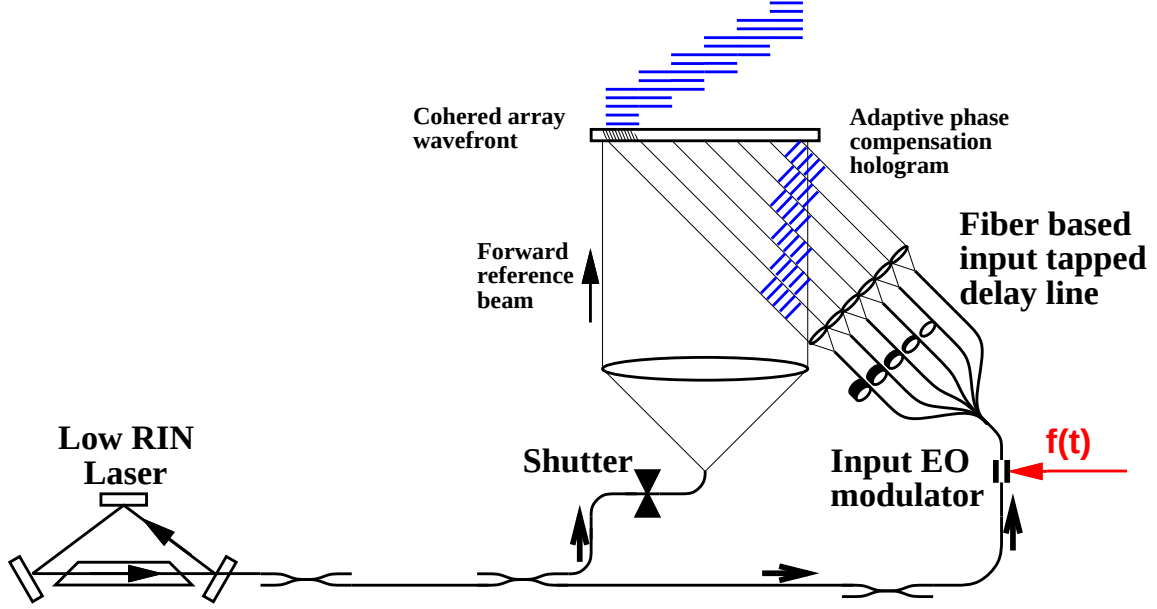


Figure 7. Cohering of the feedback tapped delay line. The reference signal and the unmodulated component of the delayed feedback signal write a grating in the adaptive phase compensating hologram. When the feedback signal is diffracted from that grating it acquires the planar phase front of the reference beam. A shutter is used to control holographic recording.

the fiber lengths should be cut to an accuracy of a few mm and lengths of 1-10m, which can be readily accomplished. Such incoherent signal combination systems achieve a gain N proportional to the number of signals added, but substantially larger gain of N^2 can be achieved by coherently combining these signals (eg adding the field amplitudes and detecting the resulting intensity instead of simply summing intensities). However, for coherent optical signal combination the length accuracy must instead be a small fraction of an optical wavelength (well under 100nm) and this must be maintained even when the fiber flexes or its temperature varies. This represents a fractional length change of 10^{-5} or less and clearly can not be maintained without active correction and compensation. Although fiber stretchers can be servoed using closed loop feedback circuits,¹³ when more than a few fibers are required this discrete component approach becomes impractical. For this reason, we instead utilize a dynamic hologram to sense the phase of each fiber and compensate for any errors in its phase by interfering the output of an array of fibers cut to approximately the correct array of lengths (within 1mm or so) with a plane wave reference beam, as depicted in Fig. 7. When the beams coming out of the fiber array are diffracted by the dynamic hologram their phase fronts are transformed into the same as that of the reference beam, thereby correcting for phase distortions experienced by the signals in the fibers while still preserving their respective time delays. Therefore, as long as the dynamic hologram responds at least as fast as the phases in the fiber drift, this cohered-fiber TDL can be used for coherent optical processing. The shutter shown in the figure is opened whenever re-cohering of the fiber array is necessary, which rewrites the adaptive hologram, and is closed during processing.

The reference beam and the delayed feedback signal interfere in the phase compensating hologram writing a grating given by

$$g_h(x) = \int \left| \frac{E_o}{\sqrt{M}} \sum_{m=0}^{M'} e^{i[\omega_l(t' - m\tau - e_m) - kx \sin \theta]} a(x - md') \left[1 + \eta f_m(t - m\tau) e^{i\omega_{rf}(t' - m\tau - e_m)} \right] + E_r e^{i\omega_l t'} \right|^2 dt', \quad (8)$$

where $a(\cdot)$ represents the spatial profile of the feedback signal after the lenslet array with spacing d , where $d' = d / \cos \theta$, θ is the angle between the feedback signal and the reference beam, e_m represents random phase differences which vary from fiber to fiber, η is the EO modulator efficiency, ω_l is the optic carrier and ω_{rf} is the RF carrier. Note that the reference beam $E_r e^{i\omega_l t'}$ is only coherent with the optic carrier of the feedback beam, $e^{i\omega_l(t' - m\tau - e_m)}$. The other cross-terms wash out and do not write a grating. The output of the fiber TDL diffracted by the hologram

is given by

$$E_h(x, t) = \eta_h \frac{E_o}{\sqrt{M}} \sum_{m=0}^{M'} e^{i\omega_l t} |a(x - md')|^2 \left[1 + \eta f_m(t - m\tau) e^{i\omega_{rf}(t - m\tau - e_m)} \right]. \quad (9)$$

Notice that the random phase delay experienced by the optic carrier has been removed, whereas the random time delay experienced by the RF carrier remains. As an example, consider a fiber length mismatch of ± 0.1 mm at 10 GHz. Without cohering the fibers, the phase error is given by $(\omega_l + \omega_{rf})e_m = \pm 282\lambda$, which would make it impossible to perform coherent optical processing. After cohering the fibers, however, the phase error is reduced to $\omega_{rf}e_m = \pm \lambda/200$, which is well within acceptable limits.

The adaptive array architecture depicted in Fig. 6 operates as follows: the top delay line is used to delay the input antenna signals diffracted by the adaptive weight hologram in order to implement forward propagation and produce the output signal $o(t)$, as dictated by Equ. 5. The bottom delay line is used to modify the photorefractive adaptive weights as a temporal correlation between the feedback signal and the array signals, as dictated by Equ. 6. Coherent optical processing requires that a single powerful laser be utilized and split into several paths: an array of beams which are then modulated by RF signals from the antenna array, a signal for the feedback TDL, references for cohering both delay lines, and a reference for interferometric detection of the output. Each of the modulated signals from the array is transmitted from the modulators at the phased array through the fiber feed network to an array of terminated fibers. The terminated fibers can be in any topological arrangement (1-D linear array, 2-D hexagonal array, circular array, random, etc). They may have present an arbitrary permutation with respect to the spatial topology of the phased array, as well as lengths that may be cut arbitrarily to within $\tau/2$. The modulated signals from the fiber feed network are then imaged or focused into the photorefractive crystal.

Figure 6 also depicts the analog feedback gains g_1 and g_2 , responsible for controlling the total feedback loop, which affects the convergence rate of the system, as explained in Section 3. The feedback signal given by the amplified difference between the desired signal and the processor output, $f(t) = g_2(d(t) - g_1 o(t))$, is applied to the feedback EO modulator in order to control the adaptive weights. The modulated signal is distributed through the fiber TDL and launched as an array of beams with linearly increasing delays, which are corrupted by unavoidable random optical phases. However, the diffraction of this array of delayed beams off the cohering hologram produces a phase compensated and appropriately time delayed array of beams that can then be used to adapt the photorefractive weight hologram. The adaptive weights are recorded as the interference between this time delayed array of beams and the fiber remoted RF modulated signals from the phased array (corrupted by their random phase and time delays). The diffraction of the phased array signals off this holographic weight matrix compensates for the random phase delays due to the array fiber feed, and produces the diffraction at respective spatial positions corresponding to the relative time delays between the array signals and feedback signals. These adaptively weighted diffracted beams are re-diffracted by the output delay line cohering hologram (which precompensates for the random phases of the output fiber tapped delay lines) towards the output fiber TDL, so that at the M -port star coupler the weighted and delayed signals recombine coherently. Interferometric detection of this signal on a single high speed photodetector produces the heterodyne output signal $o(t)$. Closed loop adaptation drives the adaptive weights to the desired optimal beamforming and nulling solution. When the fiber TDLs are perturbed or when they drift, the cohering holograms must be re-adapted by opening the shutters.

Figure 8 explains in more detail the input section of the all-optical adaptive array processor. As we have seen in the previous section, the adaptive weights must be adapted with a delayed version of the input signal $s_n(t)$. This delay can be provided by fixed length fiber loops with a re-entrant fiber beam splitter on each input fiber. Polarization multiplexing is used in order to separate the delayed and undelayed versions of the signal and a Rochon prism angularly separates the two beams. A quarter-wave plate (QWP) and a polarizer are used to transform both signals to the same polarization, so that they can efficiently undergo 2-wave mixing with the cohering reference beam at the first photorefractive (PR) crystal. The purpose of this crystal is to adjust the phase fronts of the two beams so that the read beam (in black, not delayed) can read out the grating written in the adaptive weight PR written by the write beam (in gray, delayed) in conjunction with the feedback beam. However, the first PR also has the effect of amplifying the unmodulated power of the optical carrier. This large carrier is deleterious to the system since it only contributes to the erasure of the grating written in the adaptive weight PR crystal. The second crystal implements a novelty filter which removes this spectral component. An unmodulated reference beam is used as the weak signal for 2-wave mixing with the phase-cohered input beams. Since all signals have the same carrier, they will write a grating such that the reference beam will be diffracted and constructively interfere with the undiffracted carrier from

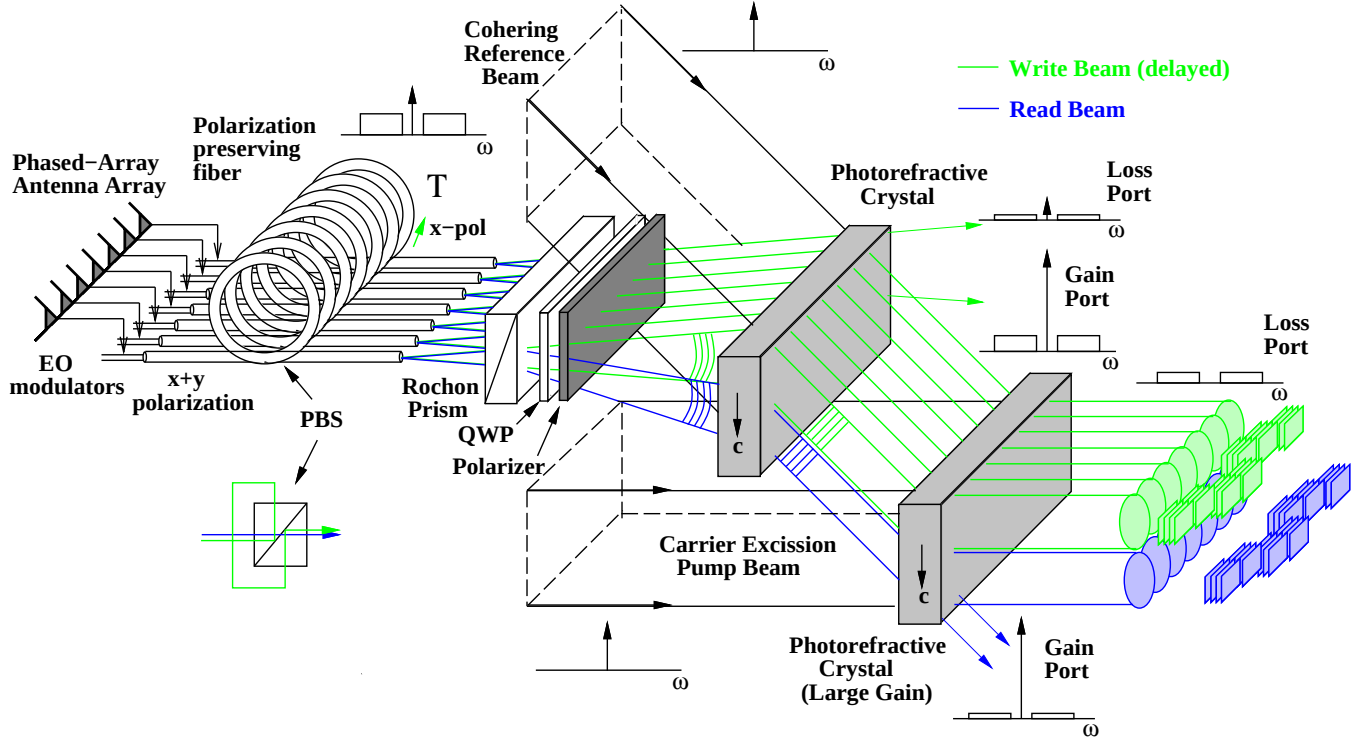


Figure 8. Input to the all-optical adaptive system shown in detail. The RF input signals modulate $\hat{x}\hat{y}$ polarized reference beams. The $\hat{x}$ polarized beam undergoes a time delay of T and is spatially separated from the undelayed beam by a Rochon prism. A quarter-wave plate and a polarizer are used to bring both beams to the same polarization. A cohering PR crystal is used to cohere the phase of the delayed and undelayed beams and a PR novelty filter is used to remove the RF carrier from the modulated beams.

the signal beam at the gain port, and the undiffracted portion of the reference beam will destructively interfere with the diffracted carrier from the signal beam such that the loss port will have the side bands of the modulated signal with very little of the carrier left. Notice that the crystal orientations were chosen so that both PR crystals could be implemented by a single, larger one with different portions illuminated by the two distinct reference beams.

The beam combination and coherent detection schemes utilized in this architecture raise some interesting issues. The cohering of the output fiber delay line allows the recombination of the different delayed fibers at the $1 : M$ coupler coherently, thereby avoiding the normal $1/M$ constant radiance fan-in loss. In addition it also provides a selective filtering which suppresses unwanted jammers diffracting off of a main beam sidelobe since they will not be correctly phased and will instead produce a poorly coupled speckle pattern at the single mode fiber input. Because of the time delayed fan-in to the output detector, this accomplishes the necessary spectral filtering. Furthermore, this coherent combination of desired signals occurs even for large AOAs for broadband signals because the propagation-induced time delays are compensated for by the fiber feed network. The coherent signal summation produces a superposition of the modulated signals from each antenna and the residual unmodulated carriers. For beamforming an array of signals with linearly increasing delays $s_n(t) = d(t - t_n)$, this signal summation produces an output with compensated time delays which, neglecting array apodization, can be represented as

$$o(t) = \left| r + \sum_n (\eta s_n(t + t_n) + b) \right|^2 = (r + Nb)\eta N d(t) + \eta^2 N^2 |d(t)|^2 + cc + \text{bias},$$

where r is an optional additional reference, η is the EO modulation depth (typically very small), $b = \epsilon \sqrt{1 - \eta^2}$ is the unmodulated carrier, where ϵ is the carrier excision ratio in the 2-wave mixing system of Fig. 8. The second term is an unwanted signal self mixing term that must be eliminated. In octave bandwidth limited scenarios it can be eliminated by bandpass filtering. For super-octave applications either the additional reference beam r must be very

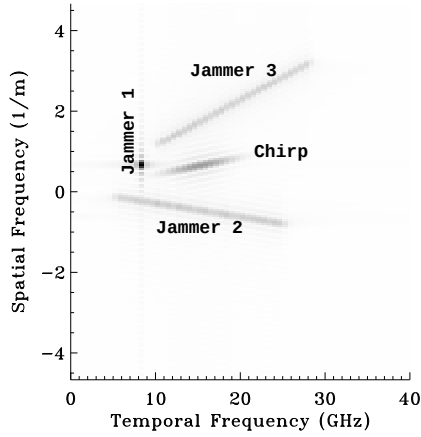


Figure 9. Fourier-space representation of the input signals used in the computer simulation: a Gaussian chirp (the desired signal), one narrowband jammer (jammer 1) and two broadband jammers (jammers 1 and 2).

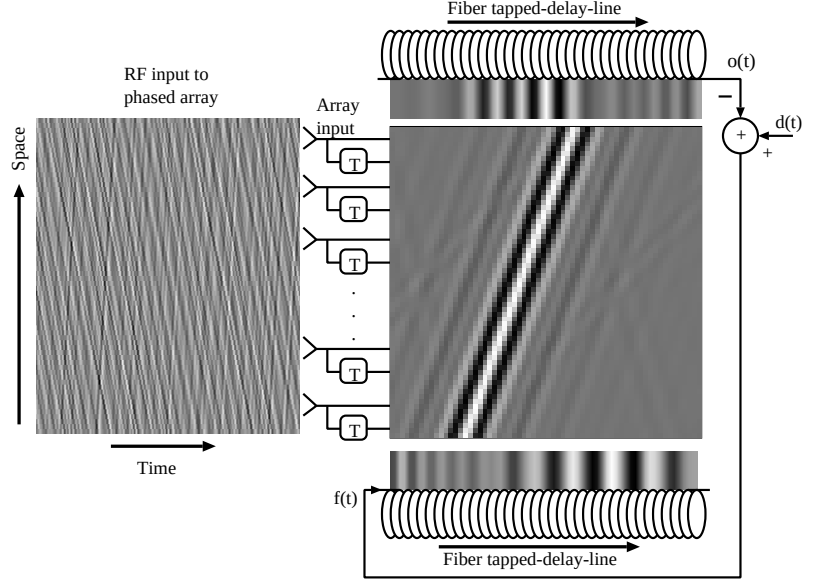


Figure 10. Diagram illustrating the operation of the simulation of the BEAMTAP architecture. The input signal is represented by the spatio-temporal signal at the left. At every time-step an instantaneous slice of the input is detected by the antenna arrays and it is propagated through the adaptive weight matrix (center of figure) and the product of the input vector with the weight matrix is diffracted vertically, delayed and coherently detected. The output $o(t)$ is subtracted from the desired signal $d(t)$, generating the feedback error signal $f(t)$, which is fed through the error feedback delay line. An outer-product between the feedback signal and a delayed version of the input adapts the weights.

large or the modulation depth of the EO modulators in the array must be very small so that $b = \sqrt{1 - \eta^2} \gg \eta$, in which case the self mixing term can also be neglected. Thus, when we do not use the external reference, the output signal can be seen to be proportional to $o(t) \propto N^2 d(t)$, which provides the full coherent array gain rather than the electronically combined signal processing gain of only N in conventional intensity modulated fiber remoted arrays.

5. BEAMTAP SYSTEM SIMULATIONS

Figure 9 characterizes the input signals used in a computer simulation of the all-optical implementation of the BEAMTAP architecture, shown in spatio-temporal Fourier-space with transverse spatial frequency along the vertical axis and single sided temporal frequency along the horizontal axis. The desired signal is an ultra broadband Gaussian chirp whose $1/e$ width is from 11 GHz to 19 GHz. Its angle of arrival (AOA) is set at 0.25 radians. Jammer 1 is a narrowband sine wave at 8 GHz with an AOA of 0.5 radians. Jammers 2 and 3 are broadband filtered Gaussian white noise signals. Jammer 2 spans the frequency range from 5.0 GHz to 20 GHz, with an AOA of -0.2 radians. Jammer 3 spans the frequency range from 10 GHz to 28 GHz at an AOA of 0.75 radians. The power of each jammer is set to be one thousand times stronger than the power of the desired signal during adaptation. However, the power of all signals was normalized in Fig. 9 in order to make them all equally visible.

The diagram shown in Fig. 10 illustrates some of the signals calculated during the simulation. The leftmost array shows the spatio-temporal RF field amplitude sampled at 8 GHz along the horizontal time axis and detected by the 64 antenna array elements along the vertical spatial axis. Notice that only the jammers are visible, since they are much stronger than the signal. The final weight values after adaptation for $102\mu s$ are shown in the central array on the left. Notice the tilted stripe, resulting from the correlation between the feedback error signal $f(t)$ (the difference between the output and the desired chirp signal) and the input signals $s_n(t)$ (chirp and jammers) whose

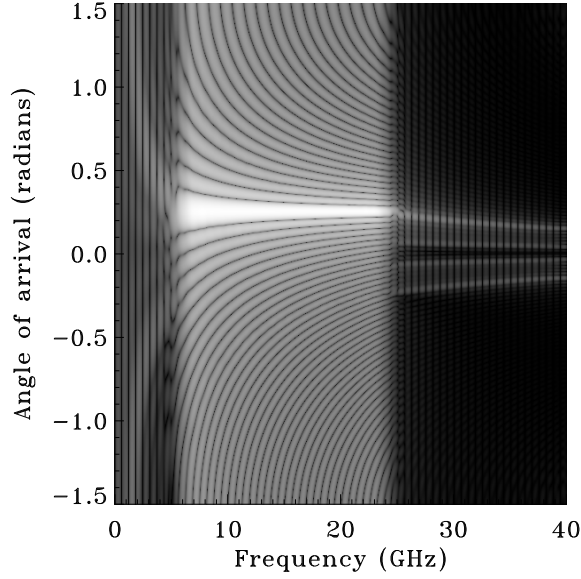


Figure 11. Receptivity pattern after adaptation in the presence of only the desired signal. Notice that the main lobe does not vary its center position with frequency, the result of true-time-delay beamforming.

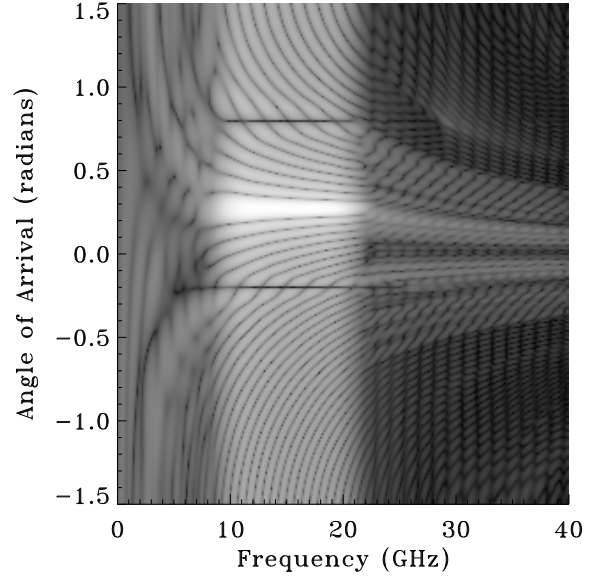


Figure 12. Receptivity pattern after adaptation in the presence of the desired signal and strong jammers. Notice the long and deep nulls in the direction of the broadband jammers. Also, the bandwidth of detection of the desired signal has been reduced because of the presence of the narrowband jammer at 8 GHz.

tilt is an indication of the angle-of-arrival of the desired signal. Weak sidelobes seen in the weight matrix are due to a cross-correlation between the signal and jammers and are responsible for the manipulation of the antenna nulls to point towards any undesired jammers. The instantaneous input signal vector from the array is multiplied by this weight matrix, deflected vertically and summed in the fiber TDL at the top, thereby compensating for the previously unknown time delays between the signal out of each antenna element and the desired chirp signal. The upper part of the figure shows the signals as they are propagating through the fiber TDL at an instant in time. The lower part of the figure shows the contents of the fiber tap-out delay line at this instant in time. An outer-product between this signal and a version of the input signal delayed by T is used in order to adapt the weights. This simulation used 64 taps in the delay line, providing us with an array of 64×64 adaptive weights.

Figures 11 and 12 show the receptivity pattern of the system for two different cases. In Fig. 11 beamforming is performed only with the desired repetitive chirp in the input, without the jammers. Notice the strong response in the direction of the desired signal (0.25 radians), over almost the entire chirp bandwidth (5 GHz to 25 GHz). Note that, even though the chirp has a Gaussian window, the system transfer function is almost flat over the full bandwidth of the signal. This is because the system adapts in order to produce an output that resembles the desired signal as closely as possible. Since both the input and desired signals are Gaussian chirps, it is to be expected that the system response should be flat over the entire signal bandwidth. Also note that the maximum receptivity describes a straight line at a constant angle, verifying that there is no beam-squint, as desired for a time-delay-and-sum beamformer.

In Fig. 12 both the signals and jammers are present in the signal environment so beam forming and jammer nulling are performed simultaneously. Notice the changes compared to Fig. 11. The main lobe's bandwidth has been slightly reduced. This reduction was adaptively obtained by the BEAMTAP algorithm in order to optimize the response of the array to the desired signal in the presence of the narrowband jammer at 8 GHz, which was placed on the position where the first sidelobe of the main beam would be located if no jammers were present. Since the spatial sidelobe of this jammer extended onto the main beam and throughout its sidelobes, an improved error performance was adaptively obtained by producing a null in that frequency which spans a wide span of angles of arrival, without substantial detrimental effect on the signal. The wideband jammer 2 caused the appearance of

a long and thin null, located exactly at its AOA (-0.2 radians) and spanning its complete bandwidth without any squint. Similarly, jammer 3 also caused the appearance of a long and deep null at its AOA (0.75 radians) spanning its complete bandwidth. The array frequency response in the direction of jammer 1 is 79 dBs below the signal response. The response at the directions of jammers 2 and 3 are at least 56 and 59 dBs below the signal response, respectively.

6. SUMMARY

We have presented a new approach to all-optical true-time-delay beamforming based on the BEAMTAP method (Broadband and Efficient Adaptive Method for True-time-delay Array Processing) that reduces the number of TDLs required for time-domain adaptive beamforming of a broadband N -element antenna from the conventional value of N to only 2. We have shown how to implement these delay lines using cohered broadband fiber delay lines. The all-optical implementation of the BEAMTAP architecture is ideally matched to the strengths of optical phased array processing systems. For large arrays the decreased number of delay lines represents a dramatic hardware savings that will allow the implementation of broadband adaptive phased arrays in sizes that were previously impractical. We have presented an optical architecture based on this new hardware-efficient TTD algorithm that utilizes a fiber-remoted coherent phased array, a photorefractive crystal, and two holographically cohered fiber tapped delay lines, and a single high speed photodetector whose electronic output represents the adaptively beam-steered and jammer-nulled output. Simulations were presented that verified this operation for broadband desired signals in the presence of broadband jammers.

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