True Time Delay Beamforming for Wideband Active Phased Array

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Abstract **– In AESA for narrowband signals, shifting the phase of a signal has the same effect of delaying the signal. Phase shifters based on such principles provide phase delays. Phase delays for broadband applications result in dispersion of the signal – different frequency components of the signal experience different time delays. Despite of having many advantages such as better directivity, higher gain, and beam-steering, traditional electrical controlled phase array antennas face serious problems working with large bandwidth. One of the most difficult obstacles to overcome is the "beam-squint" phenomenon i.e. beam direction of the array changes across the RF signal's bandwidth. For applications with large bandwidth and high frequency requirements, true time delay beam-forming is a promising candidate. The true time delay chip can delay the signal by discrete amounts of time, with inherent advantages of large bandwidth, compactness and light-weight. More importantly, they can operate squint-free with wideband, high frequency signals, thus avoiding the most significant drawback of the traditional electrical beamformers.**

Keywords: True Time Delay, Beamformer, Phased array, AESA.

I. Introduction

Over the last fifty years, the engineering community recognized the need for true time delay in phased array antennas. However, the subject has become increasingly important in the last decade, as radar systems were required to achieve higher resolution, and wider scan angles. A classic phased array uses a Transmit/Receive module on each of its antenna elements to control the phase (as well as the amplitude) of the transmitted/received elemental wave. This works well for a system with a narrow RF bandwidth (for few MHz). However, when wide bandwidths (short pulses) are involved, a phased-steered array has a frequency dependent beam shape, resulting in wider beams, temporally distorted pulses and loss of gain, as well as spatial and temporal resolutions [1].

Future radar systems will increasingly be applying electronically steering for multi functions and multimode operation. One of them may be re-using of apertures for different applications, including communication and electronic support applications. The scarcity in antenna locations poses further advantages to antenna co-location or antenna sharing. The sharing of antenna apertures by different systems implies that the antenna, including the front-end and beamformer, has to cover the full bandwidth of the systems for which it has to serve. This requirement is in agreement with a further increase in bandwidth of the individual systems, in order to improve performance. A relative bandwidth per system between one and two octaves may be required.

This 'squint' phenomenon, which makes phased-steered antennas unacceptable for many modern and future applications, can be eliminated by replacing the phase delays in the system with true time delays. One of the preferred RF solutions is the Rotman lens [2], which uses RF guided waves in a specially designed geometrical structure to produce these delays for a number of discrete beams. Rotman lenses have been and are still being employed in many radar systems. However, the need for smaller volume and lower weight, as well as for still wider bandwidth, has made this option less attractive. Alternatively, true time delay may be implemented digitally, using fast (many Giga-Samples/sec) Analog to Digital converters on every element with FPGAs based digital circuitry. This power-hungry technology, though, has not yet reached maturity but may become a viable solution in the future.

II. Active Phased Array

Microwave phased-array antennas are important in both military and civilian applications. However, wide bandwidth is not available employing traditional electrical beamforming networks due to their intrinsic narrow band nature. In general, the beamforming of the antenna can be implemented as an optical system, an RF system or as a hybrid system.

A. Wideband Phased Array Beamforming

Consider a uniformly spaced linear array with element spacing d as show in Fig.1. Assuming the array is in the far field of the received signal, the wavefront is approximately planar. Furthermore, if the signal arrives from an angle θ off the antenna boresite, then according to the geometry in Fig. 1

the wave must travel an additional distance d sin(θ) to arrive at each successive element. Assuming free-space, this means the delay in arrival to each element is

$$\Delta t = d\ sin\theta / c \quad \ldots\ldots\ (1)$$

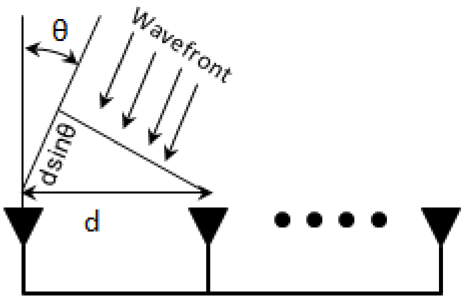

Fig 1. Illustration of additional travel distance when signal arrives from an angle θ for a linear array with element spacing d.

Array theory tends to discuss things in phase rather than delay, so we can convert the delay experienced by the signal into a phase shift at a given frequency

$$\Delta\emptyset = 2\pi f \Delta t = \frac{2\pi d sin\theta}{\lambda} \quad \ldots\ldots\ (2)$$

It has been shows in [3] that the array factor of a uniformly spaced linear array is

$$G_a(\theta,\lambda) = \frac{sin^2\left[\frac{N\Delta\phi}{2}\right]}{N^2 sin^2\left[\frac{\Delta\phi}{2}\right]} \quad \ldots\ldots\ (3)$$

$$G_a(\theta,\lambda) = \frac{sin^2\left[\frac{N\pi d sin\theta}{\lambda}\right]}{N^2 sin^2\left[\frac{\pi d sin\theta}{\lambda}\right]} \quad \ldots\ldots\ (4)$$

The array can be steered by applying a phase shift such that Δø = 0 at the angle of interest. The desired phase shift can be applied using either phase shifters, which produce a constant phase shift, which produce a frequency dependent phase shift.

The traditional method of steering a phased array is with phase shifters. To steer the array to a desired angle $\theta_0$we must choose $\Delta\phi_0$ such that Δø $-\Delta\phi_0 = 0$. Since the phase shift at fixed λ_0, becomes a fixed and $\Delta\phi_0$ is defined as

$$\Delta\phi_0 = 2\pi d\ sin\theta_0/\lambda_0 \quad \ldots\ldots\ (5)$$

where λ_0 is the wavelength this phase shift is based on. Note that for any other wavelength $\Delta\phi - \Delta\phi_0 \neq 0$. If we substitute $(\Delta\phi - \Delta\phi_0)$ in place of in array factor equation we obtain the following expression for the array factor of an array steered with phase shifters:

$$G_a(\theta,\lambda) = \frac{sin^2[N\pi d(sin\theta/\lambda - sin\theta_0/\lambda_0)]}{N^2 sin^2[\pi d(sin\theta/\lambda - sin\theta_0/\lambda_0)]} \quad \ldots\ldots\ (6)$$

The beam position changes with frequency when steered using the phase shifter method.

To steer the array using time-delay, substitute the desired angle $\Delta\phi$ into equation (2) to obtain Δt. Then, the applied phase shift $\Delta\phi_0$ is given by equation (5). Again, substituting $(\Delta\phi - \Delta\phi_0)$ into equation (6) we obtain the expression for the array pattern when steered with time-delay:

$$G_a(\theta,\lambda) = \frac{sin^2[N\pi(d/\lambda)(sin\theta - sin\theta_0)]}{N^2 sin^2[\pi(d/\lambda)(sin\theta - sin\theta_0)]} \quad \ldots\ldots\ (7)$$

A useful computation is to figure out how much deviation from the nominal frequency the system can tolerate before the beam is pointed away from the target. To do this, we first develop an equation for the beam squint as a function of frequency. The squinted beam peak occurs at angle θp when sin θp/ λ = sin θ_0/ λ_0. The beam squint can be defined as the difference between the actual peak and the desired peak:

$$\theta_{BS} = \theta_P - \theta_0$$
$$= sin^{-1}\left(\frac{f_0}{f}\sin\theta_0\right) - \theta_0 \quad \ldots\ldots\ (8)$$

Ref. [1] provides an approximate equation for the 3 dB beamwidth of an array, θ3dB = 102/N, where N is the number of elements in the array. Setting the beam squint equal to the 3 dB beamwidth and solving for frequency leads to

$$f = \left(\frac{f_0 \sin\theta_0}{\sin\theta_0 \pm \frac{102}{N}}\right) \quad \ldots\ldots\ (9)$$

This equation will tell that what frequencies (above and below f_0) beam will have moved off the target by the 3 dB beamwidth. A similar equation is derived by requiring that the beam squint be much less than the beamwidth; the result is a limit on the bandwidth of the system. Note that this equation does not depend on wavelength or frequency, just on the length of the array.

$$B \ll \frac{c}{L sin\theta_0} \quad \ldots\ldots\ (10)$$

B. Time Delay Beamforming

Active phased array architecture with True Time delay behind every radiating element for main beamforming to enable broadband performance is modelled and various radiation patterns have been simulated. This system approach may brings a number of additional requirements for active array subsystems. One of the important requirement is the bandwidth of the active antenna. This bandwidth requirement arises for antenna element, the transmit/receive module components and for the beamformer.

For linear phased array antenna, radiating elements with individual phase control, the far field pattern along the direction of θ can be expressed as

$$E(\theta,t)=\sum_{m=1}^{M} A_m \exp[i(\Psi_m + (f/c)d\, sin\theta)] \ldots\ldots \quad (11)$$

where A_m is pattern of the individual element, Ψ_m is the time delay t, and d is the distance between radiating elements. By varying the progressive time delay excitation, the beam can be oriented in any direction to give a scanning array. For example, to point the beam at angle θ_0 , Ψ_m is set to the following value:

$$\Psi_m = -m2\pi(f/c)d\, sin\theta_0 \ldots\ldots \quad (12)$$

$$t_m(\theta_0) = -m(f/c)d\, sin\theta_0/c \ \ldots\ldots \quad (13)$$

The delay line pitch (length difference of delay lines for adjacent antenna elements) of an equal space interval linear array or the one-dimensional time delay interval of an equal space interval two-dimensional array can be calculated using the following equation

$$\Delta l = d\, sin\theta_0/c \ldots\ldots \quad (14)$$

where c is the electromagnetic wave speed of propagation in the waveguide core material.

III. Implementation Method

Traditional electronic methods can also be used to implement TTD. Coaxial cable can be used for long delays, but loss and cable weight make it somewhat impractical. In addition, it can be expensive to make low-dispersion phase-matched cables. Shorter distances can be made using microstrip lines on circuit boards. This is also fairly lossy, but can be counteracted by putting amplifiers on the circuit boards. Recent advances in semiconductor fabrication have enabled much shorter and finer delays to be manufactured in a very small space, useful for high frequency arrays. Such advances enable TTD using micro electromechanical systems (MEMS) and monolithic microwave integrated circuits (MMICs) [5].

MEMS devices can handle very wide bandwidths but can suffer power handling problems and have moderate insertion loss. Active MMIC devices overcome the large insertion losses but must use power to do so and are limited by the bandwidth of the active devices [5].

An example MEMS-based TTD module is discussed this device is a six-bit TTD module capable of operating from DC to 40 GHz. The delay times range from 106.9 to 193.9 ps at 5.8 ps intervals. This range is suitable to support beam steering at higher frequencies. Insertion loss of the device is fairly well matched among the delay states and averages about 4 dB at 30 GHz, which is quite good. Some kinds of MEMS switches can get stuck when high power signals are passed through them, making them difficult to use in transmit applications [6].

MMIC-based TTD device is considered. This is a six-bit device capable of operation from 2 to 20 GHz. The device achieved a 145 ps total delay with the smallest bit representing 2.5 ps, which is comparable to the MEMS part. Insertion loss of the MMIC device is much worse however, with as much as 25 dB at 20 GHz. Obviously, passive MMIC TTD modules are impractical for high frequencies [7].

Active MMIC devices allow the addition of amplifiers throughout the delay line to combat losses and even provide gain. This device operated over 0.8 to 8 GHz and had 20 dB of gain. It was an 8-bit module with a 4 ps least significant bit and two 256 ps most significant bits. Also included was a 6-bit attenuator for gain matching and array tapering. The whole module was 13 mm × 9 mm and also contained a digital IC designed by the Air Force Research Laboratory for control. Measured results of the array steered to 260 using the TDU modules [8].

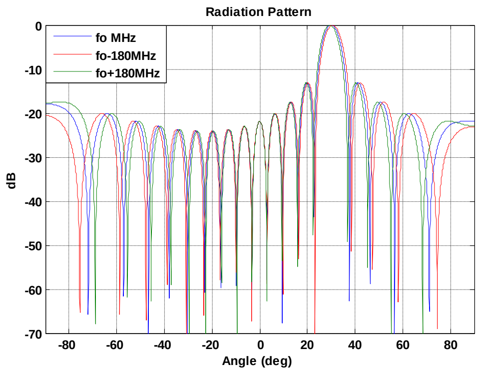

fig. 2. Beam steering with phase shifter for instantaneous bandwidth of ± 180 MHz

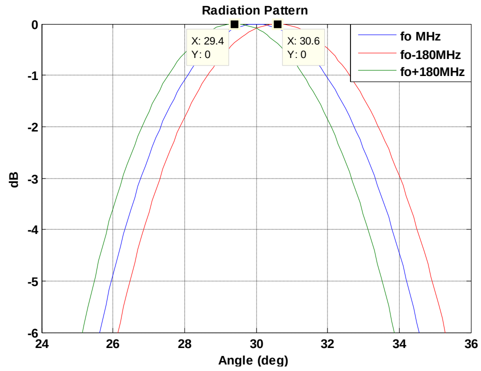

fig. 3. Beam squint of $\pm 0.6^0$ due to frequency dependency of phase shifter for $f_0 \pm$ 180 MHz

If phase shifters are used, the beam would actually steer between three adjacent resolution cells during the pulse, blurring the image. Such applications would obtain a great benefit from TTD beam steering. A plot of the array factor for three different frequencies is given in Fig. 2 for instantaneous bandwidth of ±180 MHz. Note how the beam position changes with frequency when steered using the phase shifter method.

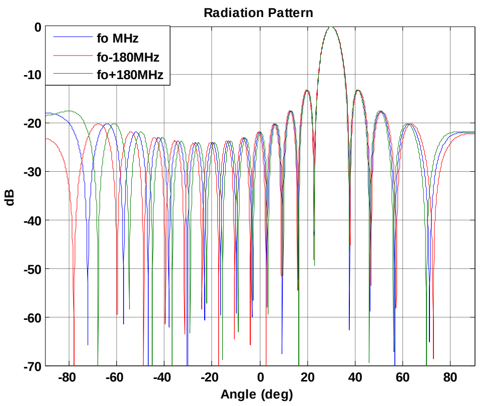

fig. 4. Beam steering with TTD unit for instantaneous bandwidth of ± 180 MHz

A plot of the array factor for the same three frequencies is given in Fig. 4 Note how the beams are now all pointing at 30^0 and it is simply the beamwidth that varies with frequency.

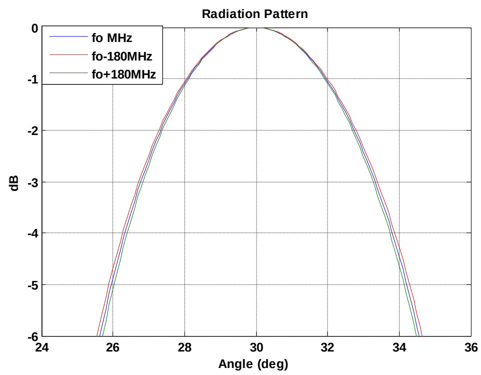

fig. 5. TTD unit is independent of frequency which does not show beam squint problem in phased array

The plots in Fig. 4-5 clearly show the benefits of true time delay beam steering: wide instantaneous bandwidths can be accommodated without beam squint. Since resolution improves with wider bandwidth, imaging radar and SAR tend to use wide bandwidths to improve image quality.

IV. CONCLUSION

Phase delays for broadband applications result in dispersion of the signal – different frequency components of the signal experience different time delays. This paper derives the expressions describing beam squint and shows how the array factor changes when using phase shifters versus time-delay. Then, a discussion of implementation techniques for true time delay (TTD) is conceived, closing with simulated results of an array steered with time-delay units (TDUs). To steer the array using time-delay, Note how the beams are now all pointing at same angle and it is simply the beamwidth that varies with frequency.

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