True Time-Delay Beamsteering for Radar

Matt Longbrake
Wright State University
Air Force Research Laboratory Sensors Directorate
Dayton, OH

***Abstract*—This paper showcases the benefits of true time-delay beamsteering for radar systems. The basics of array factor are reviewed and the problem of beam squint over wide bandwidths is shown. Available technologies to implement time-delay are discussed including RF photonics, MEMS, and MMICs. Finally, measured antenna pattern data from a MMIC-based time-delay module is presented, showing a lack of beam squint across 2 GHz instantaneous bandwidth.**

I. Introduction

Active electronically-scanned arrays (AESAs) are becoming popular for use in radar as well as other RF systems. They allow control of the amplitude and phase of each element, which enables fine manipulation of the beam direction and shape and can be changed much more rapidly than a mechanically steered array. In radar, this makes tracking of multiple spatially diverse targets possible, even while searching for new targets.

As better performing and higher resolution radars are developed, the bandwidth of the radar waveform is necessarily increased [1]. This presents a problem for AESAs that have traditionally been steered with phase shifters because the beam will squint as a function of frequency. For wide instantaneous bandwidth waveforms and narrow beamwidths this beam squint can be enough to steer off of the target, resulting in a greatly reduced return. 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 presented, closing with measured results of an array steered with time-delay units (TDUs).

II. Benefits of Time-Delay Beamsteering

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 $d\sin\theta$ to arrive at each successive element. Assuming free-space, this means the delay in arrival to each element is

$$\Delta t = \frac{d\sin\theta}{c}. \tag{1}$$

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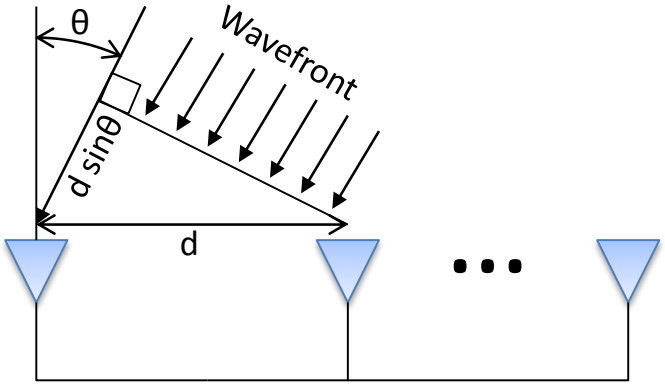

Fig. 1. Illustration of additional travel distance when signal arrives from an angle θ for a linear array with element spacing d.

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:

$$\Delta\phi = 2\pi f\Delta t = \frac{2\pi d\sin\theta}{\lambda}. \tag{2}$$

Skolnik shows in [1] that the array factor of a uniformly spaced linear array is

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

$$= \frac{\sin^2\left[N\pi(d/\lambda)\sin(\theta)\right]}{N^2\sin^2\left[\pi(d/\lambda)\sin(\theta)\right]}. \tag{4}$$

The array can be steered by applying a phase shift such that $\Delta\phi = 0$ at the angle of interest. The desired phase shift can be applied using either phase shifters, which produce a constant phase shift, or time delays, which produce a frequency dependent phase shift. Each method will be explored and the trade-offs explained.

The traditional method of steering a phased array is with phase shifters. To steer the array to a desired angle θ_0 we must choose $\Delta\phi_0$ such that $\Delta\phi - \Delta\phi_0 = 0$. Since the phase shift is fixed, λ becomes a fixed λ_0 and $\Delta\phi_0$ is defined as

$$\Delta\phi_0 = \frac{2\pi d\sin\theta_0}{\lambda_0}, \tag{5}$$

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 $\Delta\phi$ in (3) we obtain the following

expression for the array factor of an array steered with phase shifters:

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

A plot of the array factor for three different frequencies is given in Fig. 2a. Note how the beam position changes with frequency when steered using the phase shifter method.

To steer the array using time-delay, substitute the desired angle θ_0 into (1) to obtain Δt_0. Then, the applied phase shift $\Delta\phi_0$ is given by (2). Again, substituting $(\Delta\phi - \Delta\phi_0)$ into (3) we obtain the expression for the array pattern when steered with time-delay:

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

A plot of the array factor for the same three frequencies as above is given in Fig. 2b. Note how the beams are now all pointing at 20° and it is simply the beamwidth that varies with frequency.

The plots in Fig. 2 clearly show the benefits of true time-delay beamsteering: 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. For example, [2] states that extremely fine-resolution multi-mode SAR systems may use as much as 2 GHz of bandwidth to obtain 0.1 m resolution. 2 GHz of bandwidth is what is shown in Fig. 2. 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 beamsteering.

Time-delay has traditionally been impractical to implement and phase shifter designs are prevalent. This has led to other schemes to reduce the instantaneous bandwidth of the radar signal. For SAR processing, [2] describes a stepped-chirp technique that generates an equivalent wideband LFM chirp from multiple narrowband chirp pulses. Each chirp segment is narrow enough for the beam squint to be tolerable and the array is re-steered for each pulse. Taking this idea one step further, if the array could respond quickly enough, it would be possible to re-steer the array as the wideband pulse is chirping. This is called intra-pulse beamsteering and it is being worked on by the defense industry, though no public references could be found. Even though such workarounds have been developed, they are still not an ideal solution and development of TTD hardware continues.

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 θ_p when $\sin\theta_p/\lambda = \sin\theta_0/\lambda_0$. The beam squint can be defined as the difference between the actual peak and the desired peak:

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

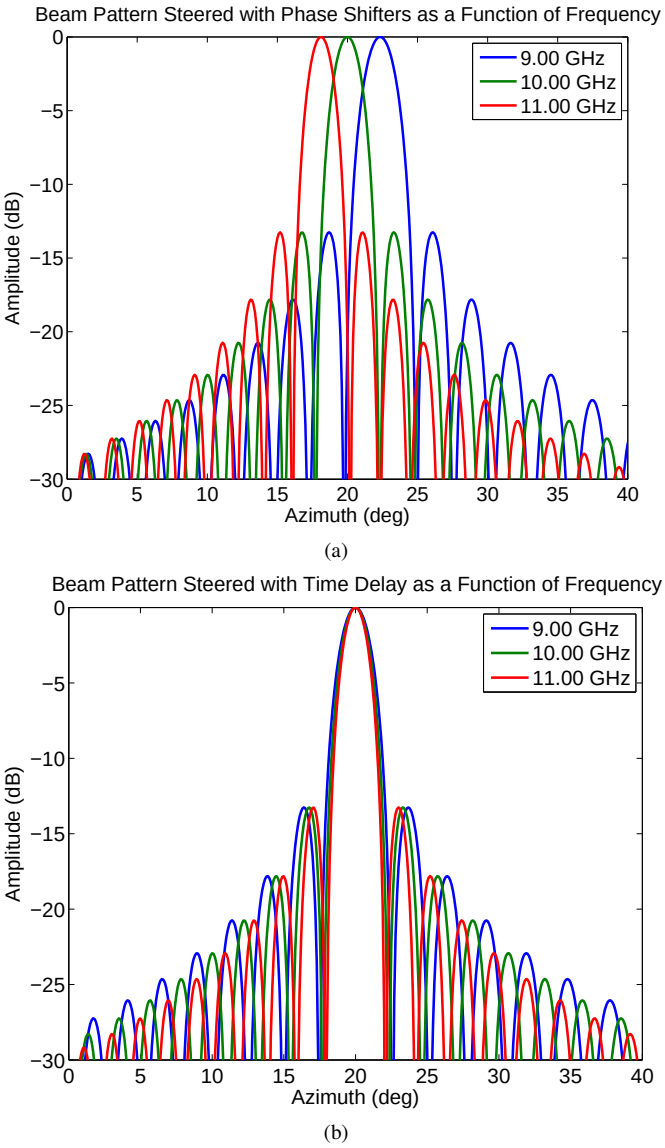

Fig. 2. Comparison between array factors for three different frequencies when steered to 20° using phase shifters, (a), and time-delay, (b). The phase shifter values were computed based on the center frequency of 10 GHz. The simulated array is 64 elements with an element spacing of $\lambda/2$ for 12 GHz.

Skolnik [1] provides an approximate equation for the 3 dB beamwidth of an array, $\theta_{3\text{dB}} = 102/N$, where N is the number of elements in the array. Setting the beam squint in (8) equal to the 3 dB beamwidth and solving for frequency leads to

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

This equation will tell you at what frequencies (above and below f_0) your beam will have moved off the target by the 3 dB beamwidth. A similar equation is derived in [2] by requiring that the beam squint be much less than the beamwidth; the result is a limit on the bandwidth of the system:

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

Note that this equation does not depend on wavelength or frequency, just on the length of the array. Equations (9) and (10) can be used to determine whether exotic techniques like stepped chirp waveforms or intra-pulse beamsteering are needed for a given system.

Finally, it is worth noting that beam squint has not always been a negative thing. In fact, some of the earliest phased arrays used this property to steer the beam in what are called frequency-scan arrays [1]. Frequency-scan arrays choose the beam direction by changing the frequency of the transmitter. This was relatively simple to implement, but results in some problems. Since frequency is used to steer the beam, it cannot be used for other tasks such as improved resolution or moving target detection with Doppler. As a result, frequency-scan arrays are not used much in modern systems.

III. TTD Implementation Methods

There are two basic methods for implementing the delay lines for TTD: optical and electronic. Optical methods modulate the RF signal onto an optical carrier and use long fibers to delay the signal. Electronic methods use traditional microstrip lines or coax cable to delay the signal. This section discusses the two methods and their advantages and disadvantages.

A. Optical Delay Lines

Stimson [3] provides a brief overview of using RF photonics to implement TTD. The basic idea is to modulate the bias current of a laser diode with the RF signal. The light is delayed by a length of optical fiber and then converted back to an electronic signal with a photodetector. It should be noted that the detector only responds to optical power, i.e. amplitude modulation, and therefore there must be a DC bias to the laser in order to allow the intensity to modulate up and down with the RF signal.

In order to obtain a cost-effective variable delay line, multiple fibers whose lengths correspond to a power of two times a basic increment are connected with optical switches. The switches allow switching between the delay fiber and a straight through path for each length increment. Such a configuration is called a binary fiber-optic delay line, or BIFODEL. If the beginning and end of the BIFODEL are co-located, switches can be used to make it bidirectional so it can be used for transmit and receive. Use of the power of two spacing means the number of fiber lengths needed only increases as the logarithm base 2 of the number of delay states.

An alternative to the BIFODEL concept is given in [4]. Each antenna element's fiber link is composed of two parts: a low-dispersion fiber and a high-dispersion (HD) fiber. The group delay of an HD fiber changes with wavelength. The ratio of HD fiber to regular fiber is increased from element to element, but the overall length is kept the same. Thus, at the nominal wavelength the delay of each element is the same, but if the laser wavelength is varied the different amount of HD fiber in each element causes a linear delay progression across the array face, effectively steering the beam. This technique is particularly interesting because the steering is continuously variable rather than in fixed increments.

The primary disadvantage to optical time delay is poor RF performance of the modulator and detector, especially insertion loss. The optical time delays in [5] had an insertion loss of nearly 40 dB without amplifiers or matching networks. Even after those were added, the TTD-steered array had a 13 dB degradation in dynamic range compared to a traditional phase-shifter design.

A thorough review of the challenges of RF photonics and the advances made early in the field is given in [6]. Although digital and RF optical fiber transmission evolved around the same time, different requirements led to different approaches and components for RF over digital. RF photonic signals need high linearity and high dynamic range, as much as 60 dB or more, whereas digital photonic links can achieve good bit-error rates with only 20 dB of dynamic range. To achieve high dynamic range, significant modulation depth is required. This means that the DC bias and overall optical power is significantly higher than with digital links. High power operation requires better components and can limit the transmission distance of the fiber due to nonlinearities.

If the disadvantages of RF optical links can be overcome, advantages include: low loss, low weight, very wide bandwidth, and immunity to electromagnetic interference. Recent advances in RF photonics have aimed at improving on the disadvantages mentioned above. Development of external modulators have allowed the use of high-power, high performance CW laser sources instead of laser diodes. This allows improved dynamic range, but is larger and heavier than a laser diode. An RF photonic link with a high-power laser and Mach-Zehnder modulator was able to show an RF *gain* of 11 dB [7]. Others have focused on using phase or frequency modulation of the optical carrier to improve performance. An RF photonic link using phase modulation and a phase discriminator was shown to have a 6.7 dB improvement in third-order intermodulation distortion performance compared to amplitude modulation with a Mach-Zehnder modulator [8]. As the technology continues to develop, RF photonic links for TTD are now becoming practical.

B. Electronic Delay Lines

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. Such delay lines are typically implemented using smaller, switched power of two lines similar to the BIFODEL. 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 microelectromechanical systems (MEMS) and monolithic microwave integrated circuits (MMICs).

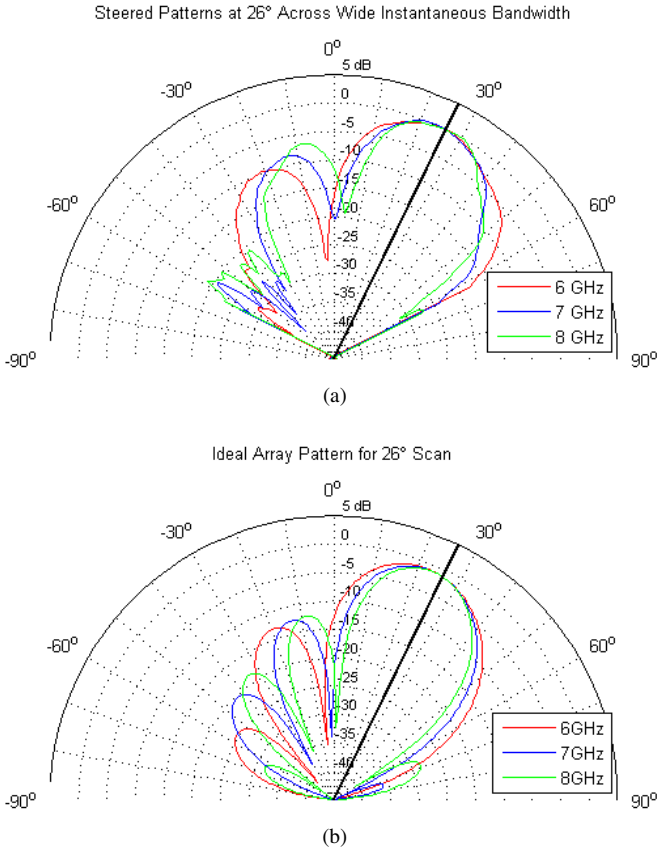

Fig. 3. Plot of antenna pattern steered to 26°. Black line indicates desired beam peak location. (a) Measured results with TELA TDU. (b) Ideal array pattern.

An example MEMS-based TTD module is discussed in [9]. This device is a four-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 beamsteering 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. However, the paper does not mention power handling capability of the MEMS switches. Some kinds of MEMS switches can get stuck when high power signals are passed through them, making them difficult to use in transmit applications.

For comparison, a MMIC-based TTD device is presented in [10]. 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. The paper mentions high losses in the switches. Obviously, passive MMIC TTD modules are impractical for high frequencies.

Active MMIC devices allow the addition of amplifiers throughout the delay line to combat losses and even provide gain. The author was involved in testing such a device built by Cobham [11]. 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 $\times$ 9 mm and also contained a digital IC designed by the Air Force Research Laboratory for control. Measured results of the array steered to 26° using the TDU modules are shown in Fig. 3a. The ideal pattern is shown in Fig. 3b. From the results it can be seen that the beam peak of the TDU-steered array is not moving with frequency and that the TTD concept is working.

Right now there is no obvious choice for electronic TTD. 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. It will be interesting to see what the future holds for electronic TTD modules.

IV. Conclusion

The benefits of true time-delay were shown, along with some of the equations to describe beam squint. Rules of thumb relating instantaneous bandwidth to allowable beam squint were also provided. Two types of delay lines were discussed—RF photonic delay lines and electronic delay lines—and advantages and disadvantages of each were presented. Finally, results from a previous experiment with MMIC TDU modules were presented here to showcase the benefits of true time-delay beam steering.

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