Phased Array Beam Steering Through Serial Control of the Phase Shifters

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Abstract **─** The commands to control the phases shifters in a phased array can be sent through a parallel or serial channel. Parallel commands simultaneously change the phase shifters, allowing the beam to nearly instantaneously hop from one direction to another. If a serial channel is used, then the commands are sequentially sent to the phase shifters. The sequential approach causes the beam to gradually move from one position to another, rather than the quick hop encountered with a parallel channel. This paper shows simulated results of the behavior of the array factor due to serial phase shifting and effects the element sequence has on that behavior and a method to optimize the command sequence.

Index Terms **─** Antennas, beamforming, genetic algorithm, linear array, phase steering, phased array, planar array.

I. INTRODUCTION

Phased arrays steer the main beam of the antenna by placing a linear phase shift across the elements. When the signals from all the elements add in phase, then this coherent addition results in a main beam peak. Phase steering began in the early 1930's when, the nulls of a two element array were steered by using a calibrated variable phase changer in order to determine the direction of arrival of a signal [1]. Today's digitally controlled phased arrays use state-of-the-art MIMC technology with phase shifters, amplifiers, and attenuators in the same module [2].

Commanding the phase shifters, especially for a large array, is a very complex engineering design. The commands may be sent to the element phase shifters over a parallel or serial control channel [3]. If the commands are sent in parallel, then all the phase shifters change at once. Serial phase shifting switches one phase shifter at a time in the array. Parallel phase shifter control is generally much faster than serial control, because a serial link transmits less data in one clock cycle than a parallel link. Unlike parallel control, serial control requires less hardware, is cheaper, occupies less space, has less crosstalk, and being asynchronous, clock skew is not an issue. Implementing serial phase shifting in place of parallel phase shifting may save cost and complexity for an array.

This paper explains the implications of serial phase shifting upon the array pattern during beam steering by a phased array. Mutual coupling, element patterns, phase shifter quantization, and bandwidth are ignored in order to isolate the effects on the array factor due to strobing one phase shifter at a time. The next section describes the effects on the array pattern of serial phase shifting in linear and planar arrays. Section III has an example that demonstrates how to reduce the main beam wandering due to serial phase shifting by sending nonsequential commands to the phase shifters. The order of the commands can be further optimized to reduce main beam wandering.

II. SERIAL PHASE SHIFTER CONTROL IN LINEAR ARRAYS

The effects of serial and parallel phase shifting can be demonstrated using the array factor formulation. An N element uniform linear array factor is given by:

$$AF = \sum_{n=1}^{N} e^{j(n-1)kd\sin\theta} e^{-j(n-1)kd\sin\theta_s} , \qquad (1)$$

where $d =$ element spacing, $\theta_s =$ steering angle, $k = 2\pi /$ wavelength, and $\theta =$ angle off boresight.

If all phase shifters receive their steering phase simultaneously, then the beam jumps from one steering angle, θ_s^A, to another, θ_s^B. If the phase shifters receive commands from a serial data connection, then the antenna elements receive their phase shifts one at a time. Consequently, the main beam does not jump from one direction to another, but morphs from a main beam pointing at θ_s^A to a main beam pointing at θ_s^B.

Serial phase shift commands go first to element 1, then element 2, then …, finally to element N. Serial commands split the array factor into two contiguous parts with the left n elements receiving a linear phase shift that steers the beam to θ_s^A, and the right part of N-n elements having a main beam that points to θ_s^B. The array factor for a uniform array becomes a

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superposition of the two parts of the linear array:

$$AF = \overbrace{1+\cdots e^{j(n-1)(\psi+\psi_A)}}^{A} + \underbrace{e^{jn(\psi+\psi_B)}+\cdots e^{j(N-1)(\psi+\psi_B)}}_{B}. \quad (2)$$

When all the phase shifters receive commands to point at θ_s^A, then only term A in (2) exists. Steering the beam to θ_s^B causes term B to emerge in (2). If the phase shifts are delivered to the elements starting with element 1 and going in sequence to element N, then the array factor is a superposition of an n element uniform array factor pointing at θ_s^A, and an $N-n$ uniform array factor pointing at θ_s^B the new steering direction. The examples that follow demonstrate the beam transition from θ_s^A to θ_s^B.

Assume a linear array has 20 isotropic point sources spaced $\lambda/2$ apart, and the elements receive phase shift commands sequentially from element 1 to element 20. The commands are separated by a time Δt_s. Figure 1 shows a plot of the array factor starting at broadside ($\theta_s^A = 0^o$ and $t=0$) and ending when the beam reaches the desired steering angle at $\theta_s^B = 0.5^o$, ($t = 20\Delta t_s$). The main beam at broadside slowly steers to $\theta_s^B = 0.5^o$, so serial beam steering seems to work well for small beam steering increments (about a quarter of a 3 dB beamwidth or less).

Figure 2 shows a plot of the array factor starting at broadside ($\theta_s^A = 0^o$ and $t=0$) and ending when the beam reaches the desired steering angle at $\theta_s^B = 45^o$, ($t = 20\Delta t_s$). The main beam at broadside gradually degrades, while the main beam at $\theta_s^B = 45^o$ gradually emerges. Beam steering with parallel commands skips the distorted array factors for $\Delta t_s \le t \le 19\Delta t_s$.

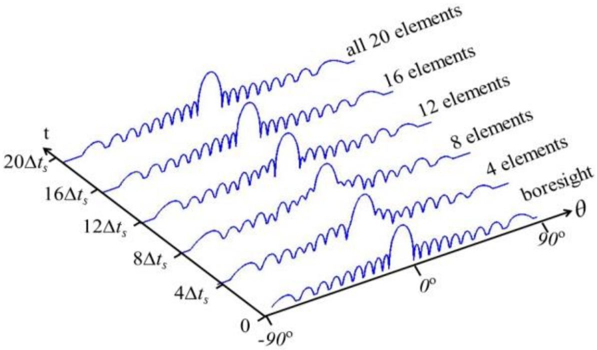


Fig. 1. Array factors as a function of time when steering a 20 element uniform linear array from boresight to 0.5^o.

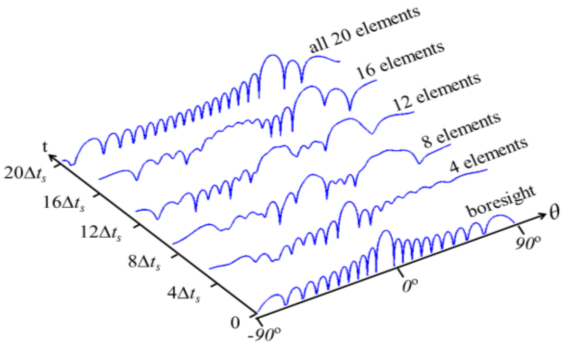
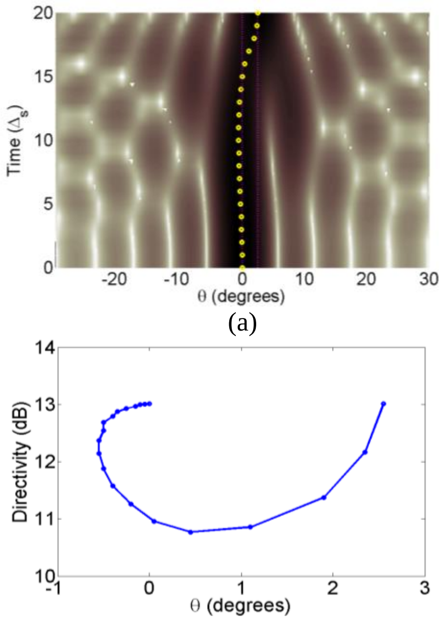


Fig. 2. Array factors as a function of time when steering a 20 element uniform linear array from boresight to 45^o.

The effects of serial steering on the array factor depend upon how far the beam is steered. The 20 element uniform array has a 3 dB beamwidth of 5.1^o and a null-to-null beamwidth of 11.4^o. Steering from $\theta_s^A = 0$ to $\theta_s^B = 3^o$ keeps the peak of the main beam near the 3 dB beamwidth of the broadside beam. Figure 3 (a) is a plot of the array factor after each phase shifter receives its steering command. At first, the broadside beam starts moving in the negative θ direction, while the new main beam begins to emerge at about $t = 8\Delta t_s$. The broadside main beam and the emerging main beam steered at $\theta_s^B = 3^o$ eventually merge into one beam at $t = 20\Delta t_s$. Figure 3 (b) is a plot of the maximum directivity, and its location in θ as the beam steers from broadside to $\theta_s^B = 3^o$. This plot confirms that the main beam starts moving in the negative θ direction before moving to $\theta_s^B = 3^o$. Along the way, the peak directivity decreases by 3 dB.

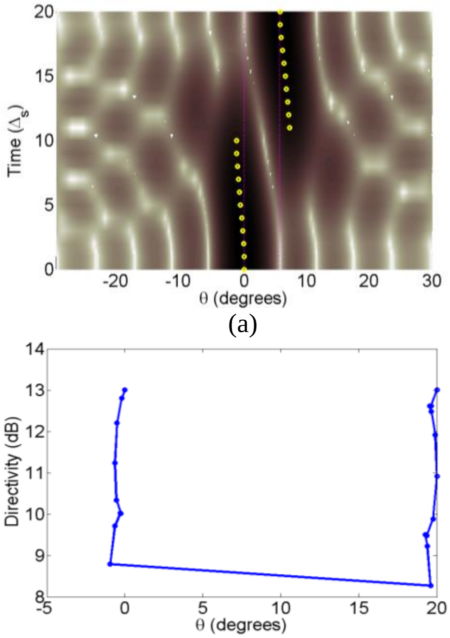
Increasing the beam steering to $\theta_s^B = 5.7^o$ puts the steered beam at the peak of the first sidelobe of the broadside pattern. Figure 4 (a) is a plot of the array factor after each phase shifter receives its steering command. The directivity of the broadside main beam decreases until it becomes the first sidelobe of the main beam steered at $\theta_s^B = 5.7^o$, while the first sidelobe of the broadside beam becomes the main beam at $\theta_s^B = 5.7^o$. Figure 4 (b) is a plot of the maximum directivity and its location in θ as the beam steers from broadside to $\theta_s^B = 5.7^o$. The maximum directivity shifts from $\theta = 0^o$ to $\theta = -1.2^o$ at the same time the directivity decreases over 3 dB. At the half way point, the peak gain dramatically shifts from $\theta = -1.2^o$ to $\theta = 7.3^o$. It then slowly gains directivity as it moves to the desired steering angle at $\theta_s^B = 5.7^o$.



(a)

(b)

Fig. 3. Array factor as a function of time for a 20 element uniform linear array when serially steering from $\theta_s^A = 0^o$ to $\theta_s^B = 2.5^o$. (a) Circles indicate the main beam peak. (b) Location of maximum directivity.

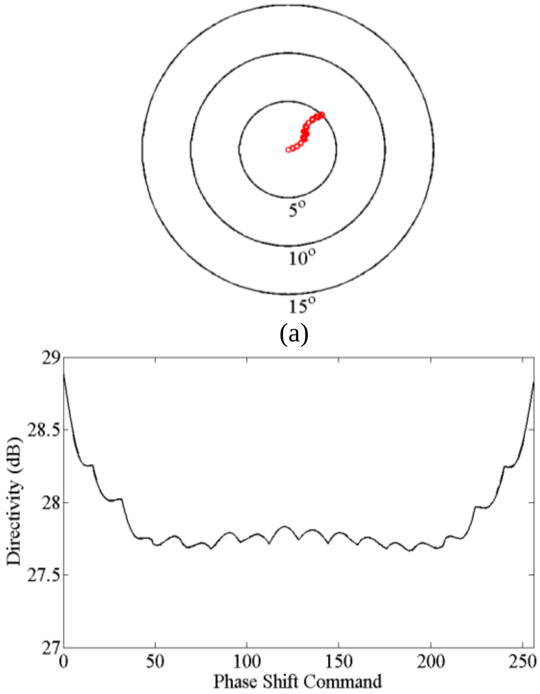


(a)

(b)

Fig. 4. Array factor as a function of time for a 20 element uniform linear array when serially steering from $\theta_s^A = 0^o$ to $\theta_s^B = 5.7^o$. (a) Circles indicate the main beam peak. (b) Location of maximum directivity.

As with the linear array, the main beam directivity of a 16×16 uniform planar array decreases while the main beam peak wanders in space when steering from one location to another. Figure 5 (a) shows the location of the main beam peak as it is serially scanned from $\left(\theta_s^A, \phi_s^A\right) = \left(0^o, 0^o\right)$ to $\left(\theta_s^B, \phi_s^B\right) = \left(5^o, 45^o\right)$. As with the linear array, the peak does not travel in a straight line from the initial angle to the desired steering angle. Instead, it wiggles about $\phi = 45^o$ as it goes from $\left(\theta_s^A, \phi_s^A\right) = \left(0^o, 0^o\right)$ to $\left(\theta_s^B, \phi_s^B\right) = \left(5^o, 45^o\right)$. The corresponding change in the peak directivity is shown in Fig. 5 (b). The main beam loses over 1 dB along its steering path.



(a)

(b)

Fig. 5. Array factor as a function of time for a 16×16 element uniform planar array when serially steering from $\left(\theta_s^A, \phi_s^A\right) = \left(0^o, 0^o\right)$ to $\left(\theta_s^A, \phi_s^A\right) = \left(5^o, 45^o\right)$. (a) Circles indicate the main beam peak. (b) Location of maximum directivity.

III. NONSEQUENTIAL SERIAL PHASE SHIFTING

Sending the commands one phase shifter at a time in sequence from element 1 to element N has some undesirable consequences, such as the main beam peak moving to angles other than the starting and ending pointing directions. This section explores sending the phase shift commands to elements nonsequentially in order to prevent main beam wandering.

It is possible to reduce the main beam wandering due to serial phase shifting by not sending the phase shift commands to the elements in a random order. A random order for sending the phase shift commands was found by minimizing the maximum main beam deviation using a genetic algorithm from either θ_s^A or θ_s^B over 5^o increments of the scan range: 16, 19, 4, 14, 8, 11, 5, 17, 9, 3, 12, 6, 18, 15, 1, 2, 13, 10, 7, 20. Figure 6 compares sequential and nonsequential beam steering for $\theta_s^A = 0^o$ to $\theta_s^B = 2.5^o$. The nonsequential path for the main beam does not go below 0^o or above 2.5^o at any time. Sequential steering, on the other hand, steers the peak of the main beam below -0.5^o. The tradeoff with nonsequential steering is that the maximum decrease in the directivity is an additional 1 dB.

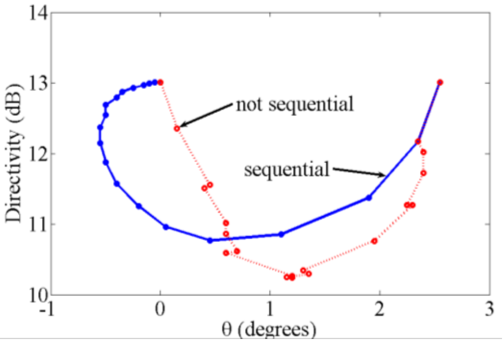


Fig. 6. Location of main beam peak vs. angle as a function of time as the main beam scans from $\theta_s^A = 0^o$ to $\theta_s^B = 2.5^o$.

IV. CONCLUSIONS

The main beam of a phased array can be scanned by sending the phase shifts to all the phase shifters, then changing their phase simultaneously, or by sending the phase shifts one at a time and changing the phase whenever the phase shifter receives the command. The simultaneous phase shift quickly moves a beam from one location to another. A serial phase shift, however, results in the main beam traveling a path from its present position to its desired new position with accompanying sidelobe level distortions. Serial commands can be sent to phase shifters and buffered (if there is available memory) until a strobe signals causes all the phase shifters to change at once, much like parallel phase shifting but slower. The beam wandering resulting from sequential serial phase shifting for beam steering greater than a fraction of a beamwidth can be limited by sending the phase steering commands in a random or optimal nonsequential order. There is a greater loss in directivity, though.

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