High-Resolution Small-Aperture Angle of Arrival Detection using Nonlinear Analog Processing

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***Abstract* — This paper presents a method for obtaining increased functionality in a small antenna array by adding analog nonlinear processing to the receiver circuit. As an example, high-resolution angle-of-arrival detection using a small aperture antenna is presented. In specific, a two-element patch antenna array with a measured directivity equivalent to that of a 5-element array is demonstrated at 2GHz using off-the-shelf components and nonlinear transmission lines for pulse compression.**

I. Introduction and Fundamental Principles

In linear receiver antenna arrays, it is well known that the resolution of an *N*-element antenna array is inversely proportional to *N*. For applications such as small mobile receivers, it is desirable to obtain large-system performance with a small aperture [1]. This paper presents a method to accomplish this task using broadband analog processing. It has been shown in acoustics that a two-element array can perform as an *N*-element array when signal processing gain up to the *N*-th harmonic of the carrier frequency is used [2]. This is less known in the RF domain, as the required bandwidths are generally inaccessible.

If the antenna elements in a uniform array are separated by an electrical distance d/λ at the frequency of the target, they are separated by $2d/\lambda$, $3d/\lambda$,..., Nd/λ at the 2^{nd}, *3d,...,N-th* harmonics of the signal. High resolution can be obtained by processing of the signal and its harmonics in parallel. In this way high processing gain is accomplished by increasing the bandwidth of the system. For example, if the resolution of a 2-element array is increased to that of an *N*-element array, the bandwidth of all associated system components needs to be at least *N* times larger than the signal frequency. At 10GHz, therefore, this would imply receiver electronics bandwidth of 100GHz for a 10-fold increase in directivity (resolution).

In order to mathematically illustrate the principle, consider the *N*-element antenna array in Fig.1 with an incident wave from a source at angle θ off boresite. Upon downcoversion with a common local oscillator, the outputs at the antenna elements are proportional to the cosine of the corresponding phase angle. For example, at the first element the output is proportional to $\cos\phi$, and at the *N-th* elements to $\cos(N-1)\phi$.

Since $\cos(n\phi)$ can be written in terms of Chebyshev polynomials $C_{n,p}$ as

$$\cos(n\phi) = \sum_{p=1}^{n} C_{n,p} \cos^{p} \phi \qquad (1)$$

It is sufficient to have knowledge of $\cos\phi$ and subsequently perform processing of polynomials of this quantity in order to achieve performance of an *N*-element array. The key is that a 2-element array gives $\cos\phi$, and can therefore, in principle, be used to synthesize an *N*-element aperture. Each term in the polynomial expansion has the frequency of the *N*-th harmonic as well. Therefore, to mimic an *N*-element array, the system needs to down-convert the various harmonics, and perform combinations of the terms that will give the phases required to synthesize a large array. In fact, *N* harmonics are needed for an *N*-element array. Following the mathematical procedure in DSP seems complex, inefficient and only applicable to narrowband sources.

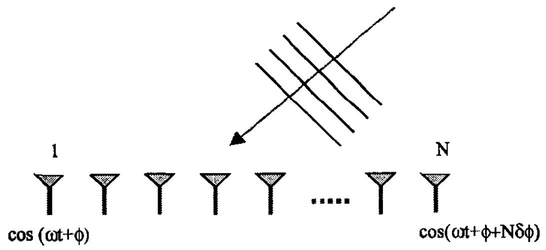


Fig. 1. N-element antenna array with incident plane wave.

As a simple illustration of the required complexity, consider a 2-element array with an incident wave at some angle θ off boresite with a signal strength of unity, Fig.1. The signals received at the two antennas can be written as

$$s_0 = \cos(\omega t + \phi) \qquad s_1 = \cos(\omega t + \phi + \delta\phi) \tag{2}$$

In an N-element array, the N-th element would receive

$$s_N = \cos(\omega t + \phi + N\delta\phi) \tag{3}$$

The goal is to extract all N signals from the two, in order to make a two-element array effectively behave as an N-element array. If s_0 is treated as a reference, then s_1 carries the direction information. Various powers of the received signals need to be considered, e.g.,

$$s_1^2 = \cos^2(\omega t + \phi + \delta\phi) = \frac{1}{2}(1 + \cos[2(\omega t + \phi + \delta\phi])$$
$$s_1^3 = \frac{1}{2}\left\{\frac{1}{2}\cos[3(\omega t + \phi + \delta\phi)] + \frac{3}{2}\cos(\omega t + \phi + \delta\phi)\right\} \tag{4}$$

Notice that, buried in these two signals in Eq.(4), are terms that contain as arguments $2\delta\phi$ and $3\delta\phi$, while higher powers likewise carry the successive terms. By combining a DC term with the first of the equations above, the $2\delta\phi$ term can be isolated, etc. It also becomes clear that the desired $N\delta\phi$ term can be isolated by superimposing the weighted harmonics of the original signal. This example illustrates that Eq.(1) is valid more generally.

One approach that avoids the complicated weighting and processing described above, but performs the same function using analog signal processing, is shown in Fig.2. The signal received at Antenna 1 is amplified and then pulse-compressed by a factor M so that the signal period remains the same, but the energy is now contained in pulses with a duration $(1/2M)T$, where T is the original period. The output is then delayed using a variable delay whose value depends on the incidence angle (phase). The righthand antenna performs the same function, and if the delays are adjusted to correspond to the incident phase, there is an output signal at the mixer (multiplier). A 2-element array has an increased directivity over a single element, and it is therefore expected that the system such as the one in Fig.2 with a compression factor of M will have a directivity comparable to that of a $N=2M$ element array.

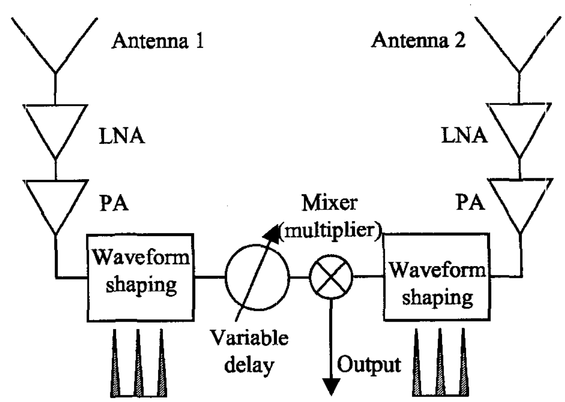


Fig. 2. Block diagram of angle-of-arrival detection system with nonlinear signal processing. In this paper, the system was implemented at 2GHz with low-cost off-the-shelf components.

In this work, the pulse compression circuit is implemented using a single loaded transmission line. Nonlinear transmission lines loaded with varactor diodes have been demonstrated as shock-wave and soliton guiding media well into the millimeter wave range for applications such as harmonic generation and fast sampling [3-6]. When such a line is excited with a sinusoidal wave, it can perform pulse compression, and the level of compression depends on the degree of nonlinearity of the device.

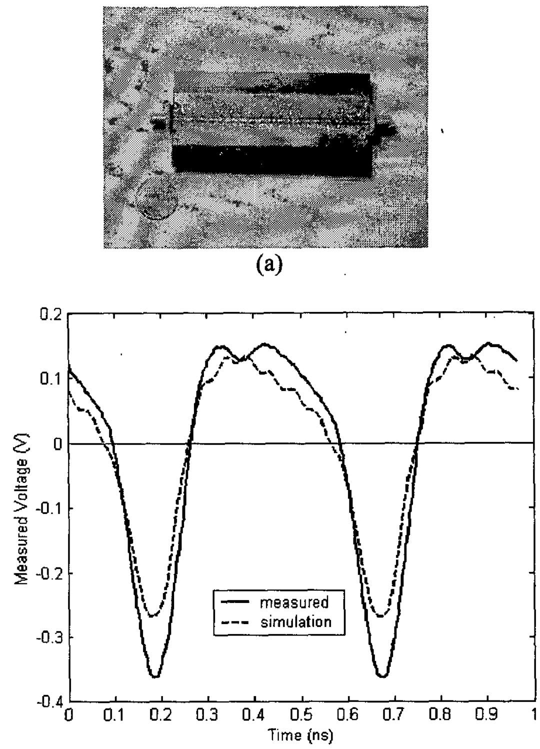
II. Experimental Validation

As a proof-of-principle demonstration, the system from Fig.2 is implemented at 2GHz with inexpensive off-the-shelf components. The feeds of two identical patch antennas fabricated on standard FR4 substrates are connected directly to coaxial MGA-86563 lownoise amplifiers (LNAs) from Agilent Technologies. The pulse compression circuit requires a relatively high voltage input, so the LNAs are followed by Mini Circuits ZVE-8G packaged power amplifiers (PAs) designed to operate from 2 to 8GHz with a gain of 30dB and a 1-dB compressed power of 30dBm. The variable time delay is implemented with a Narda 3752 1-5GHz phase shifter in this narrowband prototype. The phase shifter is designed to have a maximum phase shift of 180° at 1GHz with an accuracy of ± 0.5°/GHz. A 2-6GHz Aertech Industries Orthostar MX4001 mixer is used as the multiplier.

The nonlinear transmission line shown in Fig.3a is implemented in grounded coplanar waveguide (CPW) using 38 Alpha Industries hyperabrupt tuning varactor diodes SMV 1247-079. The grounded CPW transmission line is fabricated on a substrate with a relative permittivity of 2.2 and thickness of 0.508mm, the diode spacing is uniform and equal to $\lambda_g/40$ at 2GHz, and the characteristic impedance of the unloaded line is 52Ω.

The nonlinear line was simulated using Ansoft's Serenade harmonic balance with 11 harmonics taken into account, and with a Spice nonlinear diode model provided by the manufacturer. The simulations indicate a pulse compression level ranging from 2 to 2.5 when the diodes are biased between −2.5 and −5V and with an input power over 20dBm. This level of pulse compression was confirmed with measurements using a HP71500A Transition Analyzer with the diodes biased at −3.5V and a sinusoidal input signal with a power level of 25dBm at 2GHz. The nonlinear CPW line and the measured and simulated normalized time-domain output waveforms showing pulse compression are shown in Fig.3. The nonlinear transmission line is mismatched to the 50-Ω input, and a measurement using a directional coupler indicates that about ½ of the incident power is reflected, and the rest is dissipated in the lossy line or transmitted to the output port. The mismatch is not a fundamental limitation, and in the next iteration the high input reflection can be eliminated and the PA power lowered.

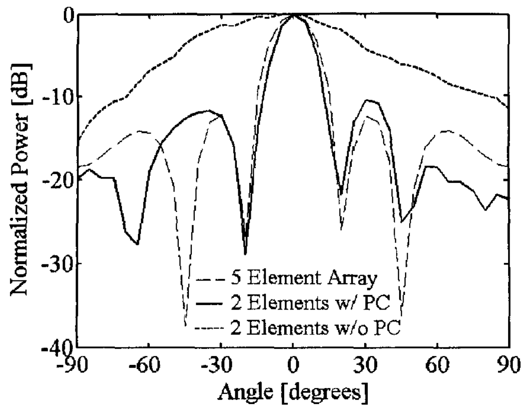
The final validation of the increased resolution in direction of arrival detection is performed with all the components described above connected as in the circuit diagram of Fig.2. The two-antenna system is rotated in an anechoic chamber and the DC signal at the output of the mixer (multiplier) measured as a function of incidence angle of a plane wave on the two-element antenna aperture.



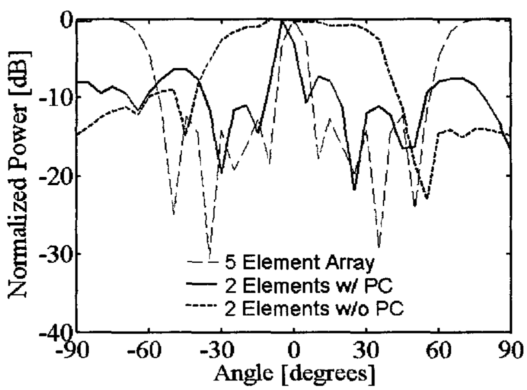
(b)

Fig. 3. (a) Photograph of fabricated hybrid NLTL pulse compression circuit. (b) Measured and simulated normalized time-domain waveforms for a 2-GHz sinusoidal input signal. An HP71500A Transition Analyzer was used for the time-domain measurement.

In the calibration process, the phase shifter value of 100° degrees corresponds to the main beam pointing at boresite, indicating that the two branches of the system are, as expected, not symmetrical due to the large number of individually connected components. The pattern measurements for a source at boresite shown in Fig.4 are compared with theoretical patterns for a uniformly excited 5-element antenna array, corresponding to a pulse compression level of 2.5. Measurements were performed for several different antenna element separation distances, and the results for $0.56\lambda_0$ and $1.03\lambda_0$ are shown in Fig.4a and b.



(a)



(b)

Fig. 4. Measured E-plane radiation patterns of a 2-element antenna system with nonlinear processing (Fig.2). Measured results from antenna element separations of (a) $0.56\lambda_0$ and (b) $1.03\lambda_0$ show good agreement with a uniform 5-element array pattern, corresponding to approximately 2.5:1 pulse compression.

Figure 5 shows the phase shifter calibration curve, measured as the incidence angle of the incoming wave was varied from +90° to -90° in the E-plane.

In conclusion, this paper provides a theoretical basis and simple experimental validation for small-aperture arrays with increased antenna directivity using analog processing at the front end. Although the prototype presented here is only a 2-GHz proof-of-principle demonstration built with packaged components not optimized for size, the entire system is smaller than a 5-element array of patch antennas at this frequency. In the UHF range, the size and weight reduction would be more pronounced. The current system can be considerably reduced in size by using MMIC components and a monolithic nonlinear transmission line.

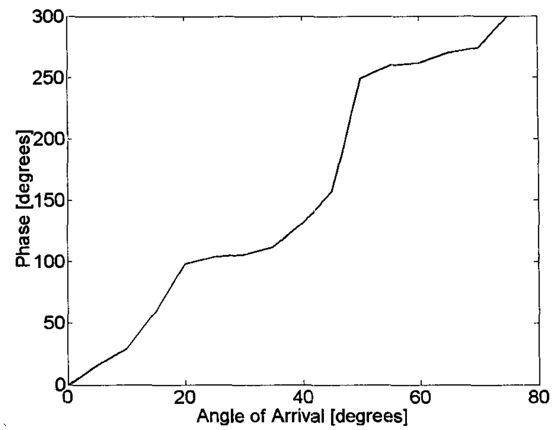


Fig.5. Measured phase shift in the feed of one element of a to-element at 2GHz required to determine directions of arrival for plane waves from 0 to 90° with a receive E-plane directivity corresponding to a 5-element array.

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