Wideband Analog and Digital Beamforming

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Abstract – High quality beamforming is necessary for the integrity of phased arrays and accuracy of monopulse direction finding systems. Traditionally, beamformers are realized as hybrid or monolithically integrated analog sub-systems. Their wideband operation is plagued by higher loss, amplitude and phase misbalances, weight, complex integration, etc. All these factors contribute to the errors in beam-pointing and geo-location, as well as antenna pattern contamination. This paper compares the performance of analog and digital beamformers realized for wideband operation through HF/VHF range. Recent advances in digital integrated circuits have contributed to not only improved performance of analog to digital (ADC) and digital to analog (DAC) converters and field-programmable gate arrays (FPGAs) but also to their reduced cost. Thus, we are now able to realize complete beamforming functionality in a digital domain and thus enhance the performance of beamformers. Modelling, performance, and realization of analog and digital beamformers for the mode 1 operation of a 4-arm spiral are discussed and relevant conclusions drawn.

Keywords – Spiral antenna, Multi-arm spiral, Beamforming Network, Digital beamformer, FPGA.

I. INTRODUCTION

Compared to the more common two-armed spiral antenna, multi-armed spiral antenna apertures inherently produce far-field patterns with a high degree of modal purity, and with correspondingly low levels of axial ratio (AR) and azimuthal gain variations (often denoted as WoW). The performance improvements including the use of absorber free cavities and ability to add increased number high-power sources (one per each arm), are now for the first time enabling a consideration of spirals for electronic attack and similar applications [1]. The additional arms improve the performance by suppressing the radiation of spurious modes [2]. However, the important benefits of a multi-armed aperture will not be completely realized unless it is paired with a high-quality beam-forming network (BFN). Therefore care must be taken to ensure that the BFN ports are properly amplitude- and phase-balanced, potentially over multidecade bandwidths, while maintaining acceptable size and weight of the BFN. In analog BFNs, component parasitics and overmoding limit performance at high frequencies, while size and weight limit performance at low frequencies.

This paper demonstrates two types of BFNs that together address low- and high-frequency performance. The paper is organized as follows. First, we discuss the effects of BFN errors on the pattern characteristics. Next, we demonstrate a digital BFN constructed using commercial components such as a field-programmable gate array (FPGA), analog to digital converter, and digital to analog converter. We conclude by comparing the far field characteristics produced by each BFN when paired with a typical four-armed spiral aperture.

II. EFFECTS OF BEAMFORMER ERRORS

A spiral antenna analog BFN is constructed from a combination of wideband hybrid components that typically have individual amplitude and phase imbalances of about 0.8 dB and 5°, respectively. Figs. 1 and 2 show the effects of these individual errors, distributed to produce spurious Modes -1 and 3, on the far field of a four-armed spiral antenna. At commercially available hybrids. Then, we demonstrate a digital BFN constructed using commercial components such as a field-programmable gate array (FPGA), analog to digital converter, and digital to analog converter. We conclude by comparing the far field characteristics produced by each BFN when paired with a typical four-armed spiral aperture.

Fig. 1 Broadside axial ratio (AR) as a function of frequency, highlighting the effect of typical beam-forming network (BFN) amplitude and phase errors

Fig. 2. Azimuthal gain variation (WoW) at 30° from broadside, highlighting the effect of typical beam-forming network amplitude and phase errors

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low frequencies any presence of spurious Mode -1 degrades the broadside AR (Fig. 1), until Mode +3, which has the same excitation, is able to radiate efficiently beyond 3\(f_0\). However, radiation of Mode +3 causes degradation of off-broadside WoW (Fig. 2). Both of these parameters are important in typical applications, so proper design of the BFN is of critical importance.

III. ANALOG BEAMFORMER

The analog BFN used for this paper consists of 90° and 180° hybrids from Pulsar Microwave, arranged as in Fig. 3. A low frequency band, 100-500MHz, uses the QE-18-412 90° hybrid and the high frequency band, 500-1000MHz, is constructed with the QS2-01-464 90° hybrid. Both bands use the same JT-06-411 180° hybrid which is rated to operate from 20-1000MHz. Individually these components are rated no worse than 1.2dB magnitude misbalance, 7° phase misbalance, and 1.5dB of insertion loss over their operating frequency ranges [4-6].

The baseline analog BFN that is also used to develop a digital counterpart is shown in Fig. 3. In the figure the connecting lines between the hybrids are phased matched. A 2 port Agilent 8719ES network analyser was used to measure the 5 port response, where unused ports were terminated in the 50Ω loads. The ideal response of this network is four equal magnitude outputs, -6dB for the lossless case, with a 90 degree phase progression on the output ports 2-5.

Fig. 4 and Fig. 5 show the results for the misbalances in magnitude and phase respectively. In both plots there is a discontinuity at 500MHz where the two measurement setups overlap accounting for the vertical lines in the results. From the output magnitude data all ports are within -8.13±1.13dB, thus accounting for nominal loss of 2.13dB. This loss is proportional to the rated loss of the 180° hybrid, 1.5dB max, plus the loss through a single 90° hybrid, 1.2dB max. The magnitude misbalance figure shows that the maximum misbalance for this analog network is within 1.75dB. This value is also proportional to the rated misbalance of the individual components. Phase misbalance is within 10° of the desired 90° phase progression on the output ports. This comes from phase misbalance in the hybrids, 3° and 7° for the 90° and 180° hybrids respectively, as well as some mismatch with the two connecting cables.

In order to evaluate the effects of BFN nonidealities on multi-armed spiral performance, a moment method model [3] of a 0.5 m diameter four-armed self-complementary spiral aperture (\(f_0 = 191 \text{ MHz}\)) was excited using the BFN outputs as weights. The resulting broadside AR is shown in Fig. 6, where the BFN errors have their greatest effect at frequencies below 3\(f_0\). Fig. 7 shows the effect of BFN errors on WoW at 30° from broadside, which worsens as higher order spurious modes begin to radiate efficiently at higher frequencies.
IV. DIGITAL BEAMFORMER

The appeal of a digital beamformer is that all the data is stored as samples and can be manipulated without any loss. The mode 1 operation of a 4-arm antenna requires four signals, one at each of the following phases 0°, 90°, 180°, and 270°. In a digital system, it is very easy to produce a 180° phase shift. With the simple assumption that the signal is a sine wave centered around zero then the negative of that signal is also the 180° phase shift. The simplest method to negate a digital sample is to negate all the bits within the sample. With this 180° shift capability of the digital system, we can create the four required phases from two inputs, one at 0° and the other at 90°. Fig. 8 shows a possible realization of a beamformer using both analog and digital components. The analog components are the initial 90° phase shift block and the 4-arm antenna and the digital component is the FPGA. The interface between the digital and analog domains is carried out by utilizing analog to digital converters (ADC) and digital to analog converters (DAC).

ADCs sample an analog signal and convert it into a digital representation using a number of bits. For an 8-bit ADC there are $2^8 = 256$ discrete values that can be represented. The ADC will specify an input voltage range for the analog signal which will then be equally divided into the 256 values. DACs perform the conversion in the opposite direction, i.e., from digital to analog domain. Each sequence of bits taken as an input into DAC is converted into an output analog signal within a specified range. FPGA is usually used to implement a user defined logic function, which makes it fairly easy to create a design where the FPGA can perform nearly any digital operation the user desires. For our purposes the FPGA is programmed with a design that reads data values from the ADC and then creates the two desired outputs for the DAC, one at 0° and the other at 180°. The other reason the FPGA is useful is its ability to do parallel operations, so we can have two chains of 180° phase shift as shown in Fig. 8.

The analog input is sampled at a constant rate to create a digital stream of 8-bit samples. The stream is then manipulated and output at the sampling frequency to recreate the 0° signal and produce the 180° signal. The sampling frequency plays a big role in the capability of the digital BFN because of the sampling theorem. The sampling theorem by Nyquist states that the maximum frequency present in an analog signal must be half the sampling frequency in order to have an accurate representation of the signal in the digital domain.
The beamforming system shown in Fig. 8 was built and tested using a sampling frequency of 500MHz. The analog branch line hybrid has bandwidth of 100-500MHz, so the effective range of the hybrid BFN is from 100-250MHz. Fig. 9 shows the magnitude misbalance of the system over a range of frequencies that includes the effective range. As seen, about 1dB amplitude misbalance is obtained. This variation could theoretically be removed by using the FPGA to multiply up the amplitude by a correction factor which is frequency dependent. Fig. 10 shows the phase misbalances between the different phases. As seen, a fairly large drift between phases is obtained. This result is caused by the unequal routing on the fabricated printed circuit board (PCB). The electrical length of the traces carrying clock signal is slightly different for each of the DAC chips, thus leading to a small linear phase between the channels. A closer look at the graphs shows several spikes in the plots at certain frequencies, which are likely due to the chosen sampling frequency.

V. DIGITAL/ANALOG COMPARISON

Comparing the digital BFN to the analog BFN shows that the digital system performs better as far as magnitude misbalance, but the phase misbalance of the analog system is superior. From Fig. 4 and Fig. 9 the magnitude misbalance is ±2dB for the analog system compared with ±1dB for the digital system. It is important to notice that the performance of the digital BFN is also heavily influenced by the quality of the analog branch-line hybrid. At the moment, the digital realization of a frequency independent branch-line counterpart is under development and when realized it will significantly improve the performance of the digital beamformer. Fig. 5 and Fig. 10 show that the analog BFN is better for phase misbalance with 90°±8° while the digital BFN is 90°±28°. Layout of the digital board is a likely cause for most of the phase distortion and can be mitigated with greater care on phase matching on the PCB.

One of the other big differences between the analog and digital BFNs is that the analog is completely passive while the digital is active. The digital BFN shown here consumes approximately 10 W. While this needed power may be undesirable in some applications, it also enables enhanced range of system level capabilities. Specifically, the FPGA allows us to have intelligence within the BFN, so we can control a number of things such as the manipulation of various waveforms, control the system operation over a serial communications link, etc.

VI. CONCLUSION

This paper initiated the discussion on ramifications of using analog and digital beamformers for mode 1 operation of four-arm spiral antennas. Effects of amplitude and phase misbalances at the beamformer outputs on the unloaded spiral’s far-field purity are demonstrated. Two beamformer networks are designed, fabricated, measured and compared. Results presented here show that the analog/digital hybrid beamforming network can be designed and realized to outperform the traditionally used completely passive analog counterparts.

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