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Phased Array Architectures and Beamforming Techniques

1. Introduction

Phased arrays have historically been critical components in military radar applications. Due to mechanically-steered antennas' being prone to mechanical failure of wear-out over time, military radar installments usually utilize the so-called electronic beam steering through phased arrays [1]. In commercial applications, phased arrays are implemented rarely due to their cost and complexity. However, with new IC fabrication techniques and more sophisticated CMOS architectures, they are starting to be more prevalent. Especially with the emergence of 5G communications, commercial phased array architectures are being implemented to scan the environment and track wireless devices to increase channel capacity and range [2].

Phased arrays utilize an array of antennas that radiates phase-shifted waves, whose constructive and destructive interferences generate a wavefront or a beam in a particular direction. This allows for electrically steering the beam in any direction without the need for physically moving the antennas in the direction the beam is needed to be directed towards. Beamforming through phased arrays is a technique that is theoretically achievable in all the frequency bands. However, size and cost constraints limit the frequency range the phased arrays are viable for to the high end of the RF spectrum, namely UHF and microwave bands (>300 MHz) [2].

2. System-Level Design

Phased array architectures can be split into two main components: the antennas and the feed network. The feed network is comprised of active and passive devices that are used for impedance matching, power splitting/combining, and most importantly, phase shifting. On the other hand, the antennas serve as an electromagnetic interface between the signals from the feeding network and the electromagnetic waves radiated into the environment. The antennas and feeding networks could be fabricated on a single chip or a printed circuit board to match the process variation of all the fabricated components, but they could also be printed on separate boards to be stacked on top of each other depending on the application [2]. In the following sections, different feed architectures and techniques that determine the design specifications and the complexity of a phased array will be summarized.

3. Feed Networks

3.1. Active Feeding

Active phased arrays utilize a power amplifier and a phase shifter for each antenna in the array. This allows the phase shifters of each antenna to process only a fraction of the power than their counterparts used in passive feeding, improving the bandwidth and precision of the phase shifters. Furthermore, power amplifiers amplify the signals radiated by the antennas, increasing the directivity and the gain of the individual antennas and the array overall [2] [3]. However, implementing active power amplifiers for each antenna element also comes at a cost. Power amplifiers are costly to fabricate and take up space, complicating the design and increasing its cost [4].

3.2. Passive Feeding

3.2.1. Constrained Feeds

Constrained feeds utilize power splitters/combiners to split the power coming from a singular RF source and phase shifters to control the phase shift of each signal. These phase shifters utilize transmission lines of different lengths and add different phase delays for different beam angles. Length of the transmission line is usually controlled by an RF switch, such as a PIN diode or a MEMS switch, which switches the incoming signal to a longer or a shorter path. While these networks are straightforward and less costly to implement, they are bulky and don’t have high precision over the phase shift of each signal, limiting the angle precision of the steered beam. To improve the precision, metamaterials or temperature control on the transmission lines could be utilized [2] [4]. While this entails the overall technique used by constrained feeds for beamforming, there are also special types of constrained feed networks that bring along different advantages to a phased array system.

3.2.1.1. Butler Matrix

Butler matrices utilize 45-degree phase shifters, hybrid couplers, and crossover structures to efficiently isolate the signals between ports and add appropriate phase shift to each line. Phase shifters are controlled in the same way as described in 3.2.1. They pose as a low-cost, less-bulky, and straightforward feed network that could be utilized in low-cost applications [2] [6].

3.2.1.2. Rotman Lens

Rotman lenses utilize a parallel-plate waveguide connected to an array of antennas to add spatially-varying phase shifts to signals between the feeding ports and the antenna ports. The lens is a single electromagnetic structure that removes the need for any lumped phase shifter element, reducing the cost and complexity of the system [2] [7].

3.2.2. Space-Fed Lens and Reflectarrays

Space-fed lens and reflectarray antennas utilize a single antenna that radiates towards a lens array or a reflectarray that generates a wavefront as the waves pass through or reflect off them (see Fig. 2). These lens and reflectarray structures utilize controlled phase shifters on their surface that vary the surface impedance at localized points to add phase shift to the incoming signals [5]. This technique is used in applications where the radiating source needs to be compact or lightweight [2].

3.3. Digital Beamforming

All the other beamforming methods described so far have been types of analog beamforming. However, analog beamforming is not the only way to steer a beam in phased array systems. Digital beamforming is another method to form and steer beams that allow phased array systems to take advantage of digital signal processing. Digital beamformers utilize analog-to-digital converters (ADCs) to convert the incoming analog signals to their I/Q components and add appropriate phase shifts digitally [2]. The high dynamic range of the ADC allows the signals to be copied, phase-shifted with high precision and amplified without the disadvantages of noise and distortion usually present in analog beamformers [4]. However, while digital beamformers prove to be superior in terms of their signal processing capability, they are hard to implement on a single chip or board due to their size. Moreover, since conventional digital beamformers utilize an ADC for each antenna element, they are costly to fabricate. Therefore, most modern phased array systems utilize a combination of analog and digital beamforming techniques in their system implementation [9].

4. Conclusion

While this summary doesn’t cover all different types of beamforming techniques and phased array architectures, it touches on the most common ways to electrically steer a beam utilized in military and commercial applications. Furthermore, there are instances in which different architectures and techniques are used simultaneously to take advantage of each architecture’s strength [9].

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