HYBRID ANTENNA ARRAY - A LOW-COST ENERGY EFFICIENT PHASED ARRAY

Contact: Professor Xiaojing Huang, Distinguished Professor Jay Guo

Abstract

Owing to their advantages of low cost and low power consumption, hybrid antenna arrays are becoming a major technology for 5G and future wireless communications and sensing systems. We have been pioneering the research and developing hybrid antenna array technologies since 2009. Our IP covers system architecture, hardware implementation and signal processing algorithms.

Introduction

Phase arrays produce steerable beams by employing phase shifters. A major drawback of phased arrays is that typically only one beam can be produced at any given time. On the other hand, digital beamforming serves as the most flexible approach to generating individually steerable and high-quality multiple beams. For many applications, however, a fully digital beamformer can be too costly and too power hungry.

Hybrid beamforming is a strategy that combines the advantages of both analogue and digital beamforming techniques. The hybrid beamforming approach does not treat every antenna element as a completely independent one. Instead, it partitions a large antenna array into smaller subarrays. This type of array is also known in the 5G literature as an array of subarrays (AOSA). Each subarray consists of a conventional analogue antenna array that forms its beam in the analogue domain. The number of sub-arrays into which the whole array is partitioned determines the degrees of freedom of the array. A subarray can also be in other forms such as lenses and reflectors.

When analogue subarrays are employed in a large antenna array, significant cost reductions can be achieved immediately due to the decrease in the number of complete RF chains required to form the beams. However, the number of simultaneously supported data streams or beams in a hybrid array is lower in comparison to a full digital array. In practice, the actual array design depends on the beamforming capabilities required along with the system's total complexity and budget considerations, both issues being influenced directly by factors such as the number of steerable beams and costs. Although reducing the number of RF chains also limits the number of data streams, per-user performance can be designed to come close to that attained with a fully digital beamformer.

System Architecture

Figure 1 shows the basic architectures of both transmitting and receiving hybrid arrays. Their schematics illustrate the whole array being divided into many analogue subarrays. Each subarray includes *N* antennas and a RF/IF (intermediate frequency) unit. These components can be shared by different antenna elements in different ways, depending on their actual implementations. For convenience, we simply denote an array with *M* subarrays with *N* antenna elements in each subarray as an *N*×*M* hybrid array. Typically, given the dimension of the whole array, the decision on the size of the subarray, or the selection of *N* and *M*, is a trade-off between the system cost and performance. If *N* is larger than *M*, a high antenna gain can be achieved at a lower cost. If *N* is too large, however, the number of users the array can support would be limited. The distance between corresponding elements in adjacent subarrays is called the *subarray spacing*. It is determined by the desired multiple beam performance and the allowed physical area of the array. Each subarray is connected to a baseband processor via a digital-to-analogue convertor (DAC) in the transmitter and an analogue-to-digital convertor (ADC) in the receiver. The signals from all of the subarrays are interconnected and processed centrally in the baseband processor.

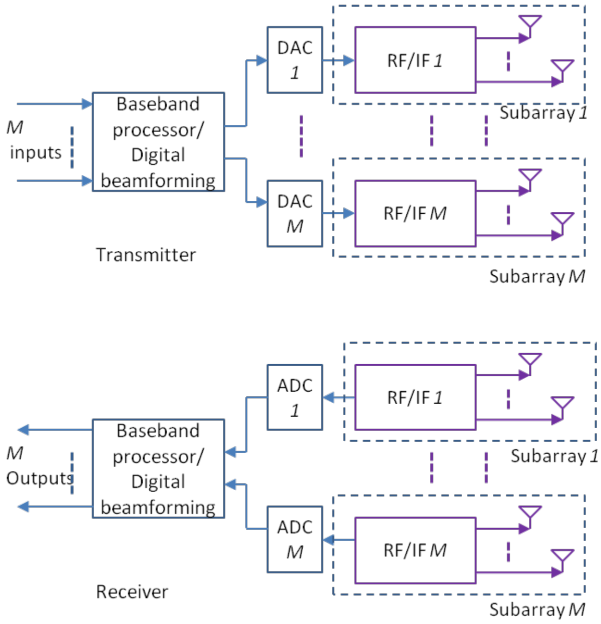

Figure 1 Basic architecture of a hybrid array.

Signals in the analogue subarray and in the digital processor can be processed in different domains and in different ways. A signal in each subarray can be simply weighted in the analogue domain mainly for the purpose of achieving array gain and beam steering. The signal for each antenna element in a subarray can be varied in both its magnitude and phase, typically with limited resolution. In the simplest case, only a phase shifter is applied and the signal is weighted by a discrete phase shift value from a quantized set of values. In the digital processor, signals from/to all of the subarrays are jointly processed. Advanced techniques which are similar to those utilized in conventional MIMO systems, such as spatial precoding/decoding, can be implemented.

The analogue subarrays can be implemented in four different configurations depending on where the phase shifters are placed for beam forming. They are illustrated in Figure 2. Fig. 2(a) shows the conventional phased array architecture for a receive analogue array. Only the phase shifters and antennas are independent; all of the rest of its components are shared by all elements in each analogue subarray. This passive power combining architecture incurs losses in the phase shifters and power combiners which increase with the number of antenna elements and operating frequency. These power losses could make large passive arrays impractical. A modification of this architecture is shown in Fig. 2(b). An individual low noise amplifier (LNA) is applied to each antenna element before the phase shifter. This modification reduces the noise significantly and provides increased receiver sensitivity. This architecture can be implemented using either a shared frequency converter (with individual RF chains combined at the input to the mixer) or individual frequency conversion and combining in the IF unit. Figures 2(c) and 2(d) depict more advanced configurations in which the phase shift is implemented in the IF unit and local oscillator (LO) circuits, respectively. The system configuration in Figure 2(d) is particularly attractive since the devices in the LO path are typically operated in saturation. Consequently, variable losses that typically change with any phase shift are avoided in this scheme.

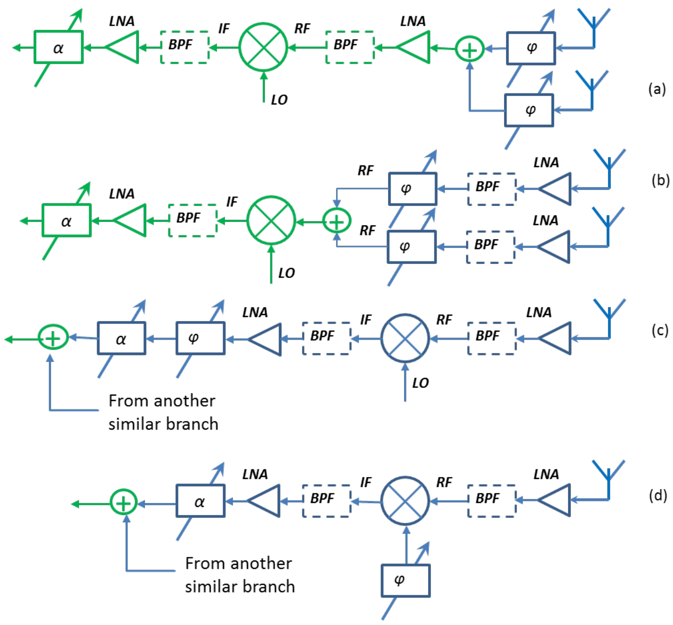

Figure 2 Implementation options of a subarray.

UTS Research Achievements on Hybrid Antenna Arrays

The UTS team pioneered the research on hybrid array, with the publication of several earliest papers in this area [25-27] and the development of one of the earliest prototype systems. The main research achievements can be classified into the following four categories.

- *Precoder and Combiner Optimization*
- *Angle-of-Arrival Estimation*
- *Array Design and Optimization*
- *Prototype Development*

Precoder and Combiner Optimization

Precoder and combiner optimization is one of the most challenging and important tasks in hybrid arrays. This generally involves joint optimization of the digital and analogue precoding and combining matrices. UTS has developed various practical algorithms that can achieve excellent balance between system performance and implementation performance. Examples are the low-complexity hybrid precoder design in [9, 10].

Angle-of-Arrival Estimation

A critical task in an adaptive antenna array system is to track the beam, which is often achieved using angle of arrival (AoA) estimation algorithms. The architecture of a hybrid antenna array varies according to the configuration of the subarray. In general, most traditional AoA estimation methods are not directly applicable. We have developed a number of novel correlation based AoA methods to cater for different analogue subarrays including small arrays [15, 17, 22], lenses and analogue beamforming networks [16. 18]. These methods are not only of low complexity but also Doppler resilient. In particular, we developed several fast AoA estimation techniques [5, 12-15, 21, 22], which can get accurate estimate rapidly instead of coarse ones depending on the beam-scanning granularity in conventional techniques.

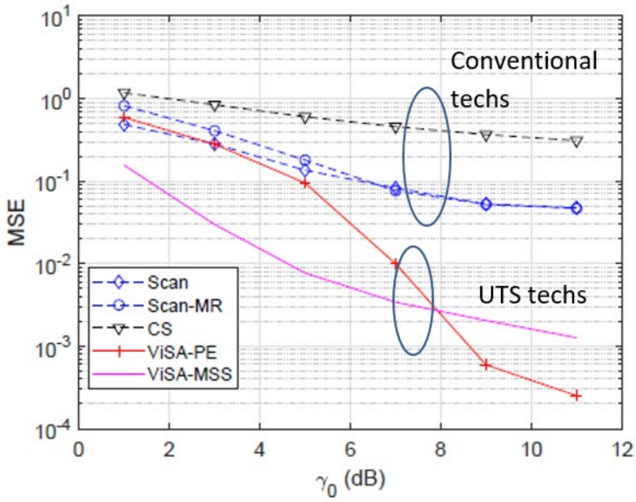

Figure 3 Mean square error of AoA estimation for the work in [12].

Array Design and Optimization

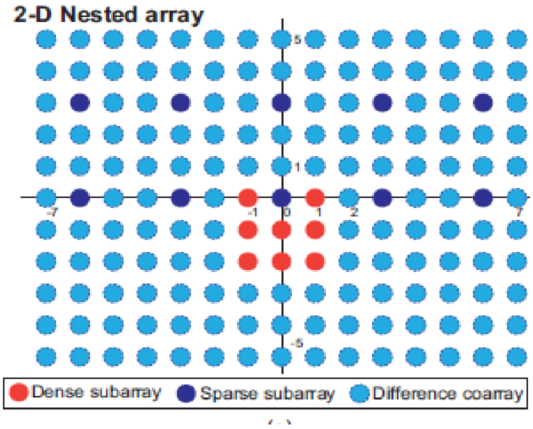

Figure 4 A 2-D nested hybrid cylindrical array designed in [11].

The geometrical form and physical structure have an important impact on the performance of hybrid array systems. The UTS team studied various structures, including the localized and interleaved structure [24], the nested hybrid cylindrical array [6, 8, 11], and the sparse array [10]. These studies reveal the importance of array structure on system performance, and demonstrate how to adapt signal processing techniques to the different structures.

Prototype Development

The UTS team has developed quite a few prototype systems related to mmWave hybrid array, which includes one of the world's earliest prototypes in 2009. Later on, the team has also developed several other mmWave systems since 2012, including some successful field trials. One of the prototype systems has been successfully commercialized. Recently, a mmWave RF chip capable of supporting phased shifting-based hybrid array is also partially developed [7].

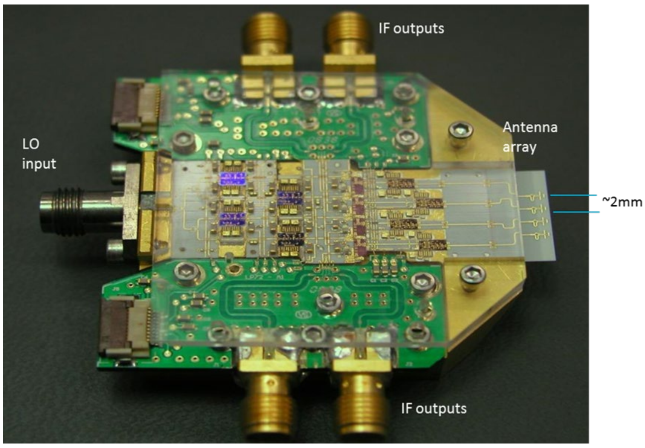

Figure 5 The prototype mmWave hybrid-array system developed by the UTS team in 2009

Conclusions

The UTS team has developed a world-leading technology, hybrid antenna arrays. The hybrid antenna arrays have the advantages of flexibility in producing multiple beams and accommodating different antennas, and are of much lower cost and lower power consumption in comparison to digital beamforming techniques.

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