Hybrid beamforming for 5G MIMO arrays

Rick Gentile - February 14, 2018

All 5G systems networks are going to use MIMO (massive input, massive output) antenna arrays and beamforming. Many 5G systems will operate in millimeter wave (mmWave) spectrum. Designing MIMO arrays that operate at millimeter wave frequencies is challenging for multiple reasons. System-level design is going to be the best approach for meeting those challenges.

Millimeter wave signals have difficult propagation conditions and greater path loss. 5G networks will need to maintain maximum system flexibility in multiuser applications.

It will be easier to meet these and other system-level performance requirements if each of the subsystems, from the antenna array through the RF chain to the signal processing, are tuned as a system during the design process.

Designers have two options for beamforming, one more practical than the other. If cost and power were not constrained in 5G systems, dedicated receive and transmit paths could be added for each MIMO array element. This type of “all digital” beamforming architecture would provide the most flexibility from a system-level standpoint to form beams in large multiuser scenarios.

Cost and power are constrained, however, and that leaves hybrid beamforming – “hybrid” in that analog phase shifters are integrated with the digital circuitry. And whenever digital and analog are integrated, that’s another place where a system-level approach to design is recommended.

The need for hybrid beamforming

The main objective of a hybrid beamforming design is an architecture that is properly partitioned between the RF and digital domains. The design also includes the sets of precoding weights and RF phase shifts needed to meet the design goal of improving virtual connections between the base station and the user equipment (UE).

From a system standpoint, the balance comes in finding optimal partitioning between RF and digital beamforming. Partitioning is possible, and engineers can efficiently build a system without implementing an individual mapping between the MIMO array elements and the transmit/receive (T/R) signal chains. Sufficient flexibility can still be achieved to satisfy a multiuser scenario.

One of the advantages of moving to mmWave frequencies is that antenna element sizes scale with wavelength. This approach enables a very large number of elements in a reasonable physical size.

The tradeoff is that more elements and more RF connections for each element add complexity. The array design must allow for MIMO operations to support spatial multiplexing, which in turn enables the higher channel capacity. These factors all increase complexity because more hardware and
controls are needed. With the large numbers of antenna elements in a MIMO array, the design must also account for the reality of mutual coupling between antenna elements.

Hybrid beamforming designs are developed by combining multiple array elements into subarray modules. A T/R module is dedicated to a subarray within the larger array, and therefore fewer T/R modules are required in the system. The number of elements, and the positioning within each subarray, can be selected to ensure that system-level performance is met across a range of steering angles. This approach translates directly into less system hardware.

A MIMO array implemented with hybrid beamforming enables a range of spatial processing capabilities. Signal processing algorithms including direction of arrival estimation, beamforming, and spatial multiplexing all make the end application possible. These algorithms also help characterize the channel between the base station and the UE.

For a hybrid beamforming design, it is also important to include the full set of system components in the system model to ensure optimized link-level system performance. Understanding how design choices affect bit error rate (BER), spectral efficiency, and channel capacity before systems are fabricated is critical. It is also important to have the option to perform signal processing where it is most effective. Having a model for each portion of the system makes system design easier. Ideas can be tried at the lowest cost point in the project life cycle.

From an architectural perspective, hybrid beamforming partitioned systems can take shape in a variety of ways. Figure 1 shows the typical, high-level configurations.

![Figure 1] Possible partitioning strategies. Source: The MathWorks

In Figure 2, we can see that on the transmit side, the number of T/R switches, \( N_{\text{TRF}} \), is smaller than the number of antenna elements, \( N_T \). To provide more flexibility, each antenna element can be connected to one or more T/R modules. In addition, analog phase shifters can be inserted between each T/R module and antenna to provide some limited steering capability.
Figure 2 Hybrid beamforming example with RF and digital steering. Source: The MathWorks

The configuration on the receiver side is similar, also as shown in Figure 2. The maximum number of data streams, \( N_{\text{v}} \), that can be supported by this system is the smaller of \( N_{\text{TRF}} \) and \( N_{\text{RRF}} \). In this configuration, it is no longer possible to apply digital weights on each antenna element, as it was in the all-digital case. Instead, the digital weights can only be applied at each RF chain. At the element level, the signal is adjusted by analog phase shifters, which only change the phase of the signal. Thus, the precoding and combining is done in two stages. Because this approach performs beamforming in both digital and analog domains, it is referred to as hybrid beamforming.

5G MIMO array development is challenging, but the required hybrid beamforming system designs can be modeled prior to any hardware being built. This modeling work can save hardware costs, as well as time in the design and development process. Design issues can be identified at the earliest stages, where they are the most cost effective to correct. The resulting system designs can achieve full system-level requirements.

You can view a detailed design example of the hybrid beamforming workflow, including the beam pattern view, weighting, and phase shift computations, here. Also, the white paper Hybrid Beamforming for Massive MIMO Phased Array Systems illustrates a process to design hybrid beamforming in massive MIMO antenna arrays for 5G, using features available with MATLAB and Simulink.

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