Performance, Power, and Area Design Trade-offs in Millimeter-Wave Array Architectures

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RESEARCH OBJECTIVES

Millimeter wave (mmWave) communications is viewed as the key technology in 5G cellular networks due to vast spectrum availability that could boost peak rate and capacity. Due to increased propagation loss in mmWave band, it is required to use transceivers with massive antenna arrays to meet the link budget, but their power consumption and cost become limiting factors for commercial systems. Radio designs based on hybrid digital and analog array architectures together with radio frequency (RF) signal processing have emerged as potential solutions to improve power and cost. In particular, hybrid array architecture is the favorable candidate in both next generation of cellular system (5G-NR) and mmWave WLAN (IEEE802.11ay). In this work, we provide a comprehensive overview of the state-of-the-art mmWave massive antenna array designs, and comparison among three common array architectures: digital array, partially-connected hybrid array (sub-array), and fully-connected hybrid array. The comparison in terms of performance, power and area is performed for three typical 5G downlink use cases which cover a wide range of pre-beamforming signal-to-noise-ratios (SNR) and multiplexing regimes. This is the first study to realistically model and quantitatively analyze all design aspects and criteria including: 1) optimal beamforming precoder, 2) quantization accuracy in digital-to-analog converter (DAC) and phase shifters, 3) local oscillator signal and RF signal distribution losses, 4) power and area based on state-of-the-art mmWave circuits including high-speed DACs, mixers, phase shifters, and power amplifiers.

RESEARCH APPROACH

There are many works on comparative analysis of different mmWave array architectures. However, works that focus on signal processing commonly overlook the necessity of optimizing system design options, including array size and required specification of each circuits block. On the other hand, works that focus on mmWave circuits design often ignore key aspects of communication systems design, including mmWave channel characteristics, link budget, and necessary array processing to achieve rate and throughput requirement.

In this work, we present a novel comparison framework that provide a comprehensive understanding of different array architectures for the future mmWave network systems. Specifically, we aim to connect the mmWave hardware (HW) specifications and state-of-the-art communication and signal processing techniques (CSP) separately considered in the state of the art literature. Our comparison is based on target rate and throughput requirement in typical 5G-NR use cases. The comparison is fair in a sense that we optimize the key circuits design parameters, including array size, DSP computation precision, and data converter quantization levels in each architecture, such that all architectures reach the same targeted communication system performance. State-of-the-art circuits design figure-of-merit (FOM) is used in computing power consumption of each circuit block. Moreover, we take a closer look at insertion loss of signal distribution network, an essential but often overlooked component in hybrid arrays. Additionally, the necessary compensation networks are taken into account in our work.

PRELIMINARY FINDINGS AND FUTURE DIRECTIONS

Our preliminary research provides analytical comparison for mmWave transmitter array in typical 5G-NR use cases. Power consumption and required circuits area of the key system blocks in three array architectures are estimated. These blocks include baseband precoding in DSP, high throughout wire-line data link for signal distribution (SerDes), DAC, LO and mixer, RF signal distribution and gain compensation network, and power amplifiers. The results in dense urban use cases are shown in Fig. 1. The analysis shows that the hybrid architecture provides marginal, if any, benefits over the digital array architecture. Large array size allows the digital transmitter array to relax specification of circuits blocks, including precision in DSP and DAC. Our results reveal the bottleneck of hybrid architecture. The sub-array has reduced array gain as compared to other architectures due to antenna sub-grouping, and thus additional elements and PA power are required for target performance requirement. On the other hand, fully connected hybrid array has excessive signal insertion loss in RF splitting and combining. An expensive and power hungry compensation amplifier network is required to deliver signal to antennas. This work has been conducted in collaboration with RF circuits designer at MaxLinear Corp, Carlsbad. All circuits specific performance metrics are extracted from recent literature in RF and integrated circuits conferences. More complete analysis of several use cases and discussion of the scalability of each architecture for future requirement are summarized in our paper that is submitted to IEEE circuits and system magazine 1.

Our ongoing work is focused on: 1) more comprehensive physical layer procedure, beamforming training and tracking, and their impact on different array architecture; and 2) receiver array architectures and their power, cost and performance trade-offs.

Figure 1 Total power consumption for three architectures operating in the dense urban use case. For each array architecture with varying array size, other design options, including precoder design, output power in PA, DSP and DAC precision, are optimized such that throughput demand is equal in all scenarios. Processing powers (excluding non-silicon PA) per array element are listed in subfigures.