Introduction to the Issue on Hybrid Analog–Digital Signal Processing for Hardware-Efficient Large Scale Antenna Arrays (Part II)

HYBRID analog-digital (HAD) processing provides a key technology for the coming generations of wireless networks, as a means of obtaining hardware-efficient transceivers. The principle behind HAD is that the transceiver processing is divided into the analog and digital domain, where networks of analog components implement large-dimensional processing at the transceiver front end, allowing for a low-dimensional digital processing which necessitates only a few RF chains. This technology has recently been brought at the forefront of research motivated by the proliferation of millimeter-wave (mmWave) communications, as a solution to circumvent the use of large numbers of expensive mmWave RF components. Its scope however is not limited solely to mmWave, as hardware-efficient transmission is key for small cell deployments in the microwave frequencies and also in emerging applications such as the internet of things (IoT) involving massive connectivity. All these applications still rely on transceivers capable of beamforming, using cheap, low-power, and physically small devices.

Accordingly, the aim of this Special Issue (SI) has been to gather the relevant contributions focusing on the practical challenges of hybrid analog-digital transmission. We received a total of 59 submissions of particularly high quality, spanning a broad range of topics. After a strict review process, we decided to accept 23 papers, which will be published in two issues. The previous first issue contained 12 papers which provided significant solutions with an explicit mmWave component. This second issue contains 11 papers, covering a wide selection of topics as follows.

In the first paper of this issue, X. Jiang *et al.* focus on the issue of channel state information at the transmitter (CSIT) in time division duplex (TDD) systems with hybrid beamforming. They propose a reciprocity calibration scheme that allows to acquire full CSIT. Different to existing CSIT acquisition methods, the approach studied circumvents beam training or selection and acquires CSIT without any assumption on the channel. They illustrate that, by use of full CSIT, TDD hybrid beamforming systems can fully release their beamforming potential.

Liu *et al.* investigate a two-timescale hybrid precoding (THP) where the RF beamformer is set according to the second order statistics of the channel. The authors use stochastic successive convex approximation to design an online algorithm for THP design. The advantage of the proposed method is that it requires outdated perfect CSI samples it is more robust to signalling latency. The proposed solution is applicable to different THP optimization problems such as throughput maximization, fairness and power minimization.

Abdelaziz *et al.* study the problem of digital predistortion (DPD) for hybrid MIMO transmitters. They propose a novel DPD approach per antenna sub-array that involves a combined signal from multiple power amplifier outputs and a decorrelation-based learning rule in order to minimize the nonlinear distortions in the direction of the intended receiver. The technique requires only a single observation receiver and is shown to outperform conventional techniques that rely on a single power amplifier. It is also shown to be robust in terms of amplitude and phase imbalances, and to have low out-of-band emissions in all signal directions.

In the paper titled "Spectral Efficiency Optimization For mmWave Multiuser MIMO Systems", the authors Qingjiang Shi and Mingyi Hong take an optimization approach and analyze the use of penalty dual decomposition method, together with the weighted minimum mean-square error approach, for solving the nonconvex hybrid beamformer optimization problem. The paper also treats the case where the phase shifter is low resolution. The results illustrate the theoretical performance of the optimized hybrid structure as compared to fully digital beamforming.

H. He *et al.* consider a HAD MIMO-OFDM receiver and address the strong non-linearity introduced by low-resolution ADCs. They provide a low-complexity Bayesian optimal detector. they also present an analytical framework to study the theoretical performance of the detector in the large-system limit, which can precisely evaluate the performance expressions such as mean-square error and symbol error rate. Based on this optimal detector, the potential of adding a few low-resolution RF chains and high-resolution ADCs for mixed-ADC architecture is investigated.

Roth *et al.* compare the spectral and energy efficiency of hybrid beamforming and digital beam forming with low resolution ADCs under the effects of channel estimation, transmitter impairments and a wideband multipath model. Their result shows that as the Signal to Noise Ratio (SNR) gets larger the ADC resolution achieving the optimal energy efficiency gets also larger. They also show that in the multiuser scenario digital beamforming is more energy efficient than hybrid beamforming.

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Their results also demonstrate that if mixed ADC resolutions are used we can achieve any desired trade-off between power consumption and rate close to those achieved with only one ADC resolution.

Ding *et al.* consider multiuser massive MIMO channel estimation problem for a system that consists of both hybrid analog-to-digital beamformer and lower resolution ADCs. This structure benefits from low cost and power consumption, however, the hardware constraints impose sever design challenges. By exploiting the sparse nature of mmWave channels in the angular domain, the authors formulate the channel estimation problem in the form of sparse Bayesian learning (SBL) framework. Then, an efficient algorithm is proposed based on variational Bayesian (VB) method. Then, using data-aided channel estimation, they can remove the signalling overhead. The proposed methods can effectively overcome the reduced number of effective and coarser channel measurements due to the use of hybrid beamformer and low resolution ADCs.

In the paper titled "DFT-based Hybrid Beamforming Multiuser Systems: Rate Analysis and Beam Selection", the authors Yu Han, Shi Jin, Jun Zhang, Jiayi Zhang, and Kai-Kit Wong propose an analog Discrete Fourier Transform (DFT) based beam selection algorithm for hybrid beamforming. The algorithm relies on an accurate approximation of the achievable uplink and downlink rates. The main contributions of the paper are an analog beam selection strategy and an achievable rate characterization based on the Rician channel statistics.

The work by Gmez-Tornero *et al.* treats the problem of direction-of-arrival (DoA) estimation by a combination of analog amplitude monopulse radar techniques and digital signal processing of conventional WiFi received signals. The reader architecture comprises two panel antennas that are tilted between them to form the monopulse tilted-array configuration required for the radar-type DoA estimation. A received signal strength indicator (RSSI)-based monopulse function is used for the DoA estimation in the digital domain. The DoA performance is tested over typical indoor scattering environments, whereas, by combining two readers, 2D localization is experimentally demonstrated in an outdoor environment.

C. Zhang *et al.* study the beam-based training and the transmission design design jointly for hybrid massive antenna single-user (SU) and multiple-user (MU) systems based on outage probability.They propose an interleaved training design to concatenate the feedback and training procedures for the SU case, thus making the training length adaptive to the channel realization. They also derive exact analytical expressions for the average training length and the outage probability of the proposed interleaved training. For MU systems, two solutions for the beam assignment are provided with different complexity-performance tradeoff. All proposed schemes are shown to provide significant savings in the training overhead.

In this paper Sohrabi *et al.* consider downlink of massive MIMO system with 1-bit resolution DACs. Firstly, a tight upper-bound for symbol error rate (SER) with low-resolution DACs is derived. Then, in order to minimize the SER, the optimal QAM constellation range of QAM is calculated. Finally, a low-complexity heuristic one-bit symbol level precoder is proposed for both single-user and multiuser scenarios. It is shown that 1-bit precoding requires larger number of antennas to achieve the same performance compared to infinite resolution phase shifters.

This completes the second part of our two-part Special Issue. Our guest editorial team would like to thank the Authors of all published and unpublished papers who contributed their works towards this Special Issue. Our sincere gratitude also goes to our expert Reviewers for their timely and thorough reviews that have significantly improved the quality of the Special Issue.

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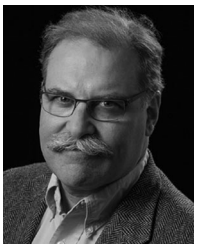

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