1-Bit Massive MIMO Transmission: Embracing Interference with Symbol-Level Precoding

Ang Li, Christos Masouros, A. Lee Swindlehurst, and Wei Yu

ABSTRACT

The deployment of large-scale antenna arrays for cellular base stations (BSs), called massive MIMO, has been a key enabler for meeting the ever increasing capacity requirement for 5G communication systems and beyond. Despite their promising performance, fully digital massive MIMO systems require a large number of hardware components including radio frequency chains, power amplifiers, digital-to-analog converters (DACs), and so on, resulting in a huge increase in terms of the total power consumption and hardware costs for cellular BSs. Toward both spectrally-efficient and energy-efficient massive MIMO deployment, a number of hardware limited architectures have been proposed, including hybrid analog-digital structures, constant-envelope transmission, and the use of low-resolution DACs. In this article, we overview the recent advances in improving the error rate performance of massive MIMO systems with 1-bit DACs through precoding at the symbol level. This line of research goes beyond traditional interference suppression or cancellation techniques by managing interference on a symbol-by-symbol basis. This provides unique opportunities for interference-aware precoding tailored for practical massive MIMO systems. In this article, we first explain the concept of constructive interference (CI) and elaborate on how CI can benefit the 1-bit signal design by exploiting the traditionally undesired multi-user interference as well as the interference from imperfect hardware components. We then overview several solutions for 1-bit signal design to illustrate the gains achievable by exploiting CI. Finally, we identify some challenges and future research directions for 1-bit massive MIMO systems that have yet to be explored.

INTRODUCTION

Massive multiple-input multiple-output (MIMO) is an attractive technology to support the desired 1000-fold system throughput improvements for fifth generation (5G) cellular communication systems. By deploying large-scale antenna arrays at base stations (BSs) or access points (APs), massive MIMO systems are able to spatially multiplex multiple data streams during the same time and frequency with near-orthogonal transmission simultaneously, offering significant gains in data rates compared to classical small-scale deployments. More importantly, the channel hardening effect further simplifies the channel estimation and power allocation procedure for massive MIMO. Nevertheless, the above potential benefits are premised on ideal fully digital massive MIMO BSs with infinite-precision digital-to-analog converters (DACs), where losses or signal distortions are not present. In practice, this would require a radio frequency (RF) chain, a highly linear power amplifier (PA), and a pair of DACs per antenna element (higher than 6 bits), and such deployments would result in significant hardware complexity and costs. Furthermore, the large number of RF components required by massive MIMO systems significantly increases the total BS power consumption. This is especially true for the downlink, where the PAs and DACs account for the bulk of the power dissipated by the BS. Transmission of signals with a wide dynamic range requires linear PAs with large backoff, which further reduces energy efficiency. The power consumption of the DACs is linear in bandwidth, but increases exponentially in the bit resolution.

All of the issues mentioned above have made fully digital massive MIMO systems prohibitive to deploy in practical wireless communication systems. Toward practical massive MIMO deployment, hardware-efficient massive MIMO architectures, which can balance the trade-off between performance, hardware complexity and cost, and power consumption, have attracted increasing research attention. Existing solutions include analog-only precoding, hybrid analog-digital (HAD) architectures in the millimeter-wave (mmWave) band (defined as FR2 in 5G), and constant-envelope (CE) transmission, to name a few [1]. More recently, the use of low-resolution DACs has attracted research attention as a promising solution for hardware-efficient massive MIMO in both the sub-6 GHz band (defined as FR1 in 5G) and the mmWave band, which is the focus of this article.

Compared to the HAD architecture and CE transmission, which reduce the hardware complexity by reducing the total number of RF chains, implementing low-resolution DACs retains the benefits in degrees of freedom for massive MIMO, while reducing the hardware cost, complexity, and the resulting power consumption on each RF chain [2]. Given that two DACs are required per RF chain, the aforementioned three factors can be greatly alleviated through the implementa-

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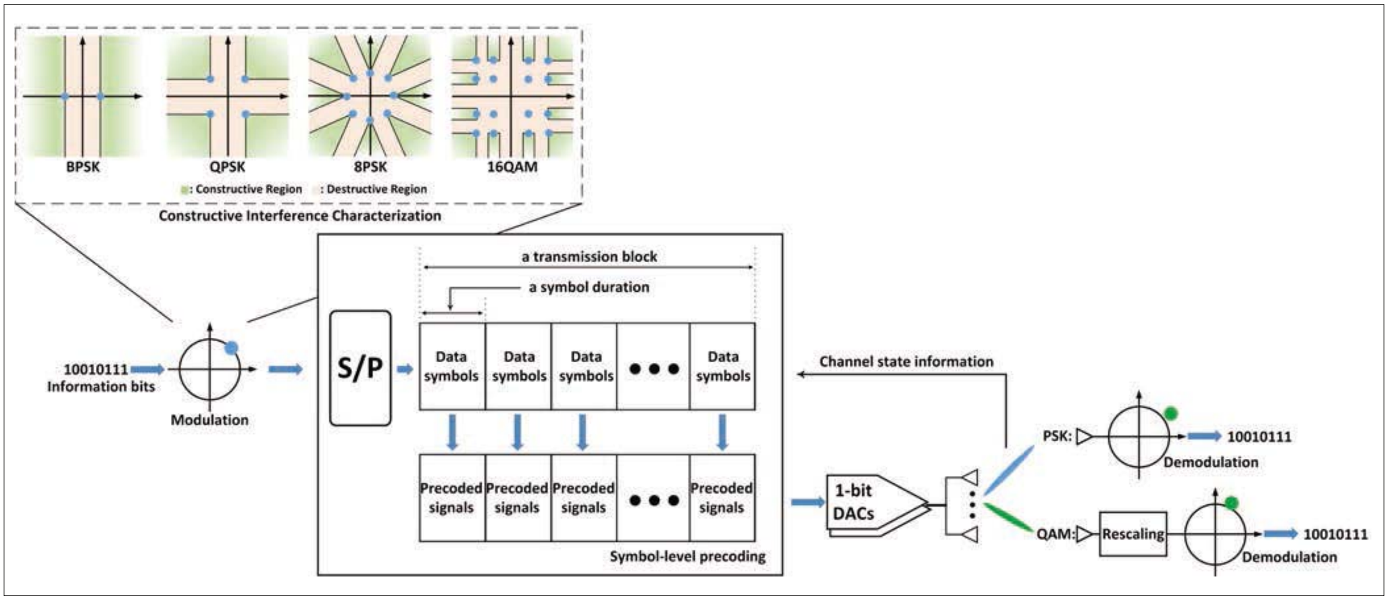


FIGURE 1. A generic framework for 1-bit massive MIMO communication systems based on constructive interference.

tion of DACs with low resolution, especially 1-bit DACs. Meanwhile, similar to the case of CE transmission, which enjoys low peak-to-average-power ratio (PAPR) transmission, the 1-bit DAC outputs also meet the CE requirement, which enables the deployment of the most power-efficient PAs at each antenna port to improve energy efficiency. Toward the design of 1-bit precoding, the main difficulty lies in the constraint incurred by the 1-bit DACs, which force the transmit signals on each antenna to be selected from the set $\{\pm 1 \pm j\}$. Such highly non-convex constraints have made it difficult to find the optimal solution for 1-bit precoding. In the following, we overview the precoding approaches for 1-bit DAC transmission based on the mean squared error (MSE) metric, and further highlight the opportunities and benefits of interference exploitation.

Classical 1-Bit DAC Transmission: MSE-Based Approaches

Precoding design for 1-bit DACs ranges from adaptation of traditional linear precoding to optimization-based nonlinear methods. Of these, the simple adaptation of traditional linear zero-forcing (ZF) precoding and MSE-based approaches, which apply a closed-form precoding matrix to a stream of data symbols over time in a transmission block (a block of symbols), within which the wireless channel remains constant, requires the lowest computational complexity. These techniques yield poor error rate performance due to the severe signal distortions from the 1-bit DACs, which cannot be compensated for with block-level precoding. [3].

Providing reasonable performance with 1-bit DACs necessitates a signal design symbol by symbol (i.e., symbol-level precoding). Different from traditional block-level precoding designs in which precoding matrices depend only on the channel state information (CSI), in symbol-level precoding the signals to be transmitted are directly designed by exploiting the knowledge of both CSI and data symbols, as shown in Fig. 1. Given that the precoding matrices for symbol-level precoding may not have explicit expressions and the precoding procedure may not be linear, in the 1-bit precoding literature they are often referred to as "nonlinear precoding" methods. In one line of research along this direction, [4] uses a least square approach to minimize the symbol-level MSE between the intended data symbols and received symbols subject to the 1-bit constraint, where the biconvex relaxation framework is adopted for 1-bit precoding design, and the resulting biConvex 1-bit PrecOding (C1PO) algorithm is shown to be superior to the 1-bit linear approaches. For very large multi-antenna systems, [4] further provides a low-complexity alternative to the 1-bit C1PO algorithm based on forward-backward splitting, referred to as 1-bit C2PO. Near-optimal 1-bit precoding solutions relying on the semidefinite relaxation (SDR) method as well as the adaptation of sphere decoding have been employed in [5], both of which are applicable to small- and moderately sized systems. For quadrature amplitude modulation (QAM), [7] proposes a 1-bit precoding framework for symbol error rate (SER) minimization via the combination of a novel penalty method and an inexact majorization-minimization process. In these traditional MSE-based 1-bit precoding solutions, interference has been regarded as a detrimental factor that is minimized using the MSE metric.

While the works mentioned above focus on optimization techniques for finding the appropriate transmit signals for fixed constellations, an equally important dimension in 1-bit precoding is constellation design. The 1-bit precoding problem can be thought of assigning $\{\pm 1 \pm j\}$ to each of the transmit antennas so that for the given channel, a desired constellation point is synthesized at the receiver. It turns out that in the regime of a large-scale transmit antenna array, it can be shown that restricting the transmit signal to be $\{\pm 1 \pm j\}$ as with 1-bit DACs only provides $\sqrt{2/\pi}$ or 80 percent of the dynamic range at the user side compared to the case of infinite-resolution transmit signals [6]. As long as the constellation range is reduced to about 80 percent of the infinite-resolution case, the 1-bit precoder design problem becomes considerably easier — heuristic greedy and exhaustive search algorithms can already do

1-Bit precoding scheme	Design principle	Methodology	Linear or nonlinear	Error rate	Complexity	Feature
1-bit ZF	Block-level ZF	Direct 1-bit quantization	Linear	Poor	Low	Closed-form precoding matrix
1-bit MMSE [3	Block-level MMSE					
1-bit C1PO [4]	Symbol-level	Biconvex relaxation + alternating optimization	Nonlinear (symbol-level)	Good with PSK signaling	Moderate	Applicable to all modulations
1-bit C2PO [4]		Forward-backward splitting method		Good with PSK signaling	Moderate, less than C1PO	Strong connection with C1PO via series expansion
1-bit SDR [5]		Semidefinite programming and relaxation		Near-optimal	High	Only applicable to moderate-sized systems
1-bit SQUID [5]		Douglas-Rachford splitting		Promising	Moderate	Comparable performance to SDR with low complexity
1-bit SP [5]		Sphere precoding + tree search		Near-optimal	Prohibitive	Only applicable to small-sized systems
1-bit-greedy [6]		Greedy + exhaustive search		Near-optimal	Moderate	With proper constellation range design and with large antenna array
1-bit MM [7]	SER minimization	Penalty method + majorization-minimization		Promising	Moderate	QAM only, applicable to 1-bit DACs, continuous and discrete CE transmission
1-bit BB [8]	CI	Full branch-and-bound	Nonlinear (symbol-level)	Optimal	Prohibitive	PSK only, only applicable to small-sized systems
1-bit LP [9]		Linear programming formulation		Good with PSK signaling	Moderate	Applicable to both PSK and QAM
1-bit SS [2]		3-stage algorithm		Good	Moderate	PSK only
1-bit IST [10]		Iterative soft thresholding + bit flipping		Promising	Moderate	PSK only, allows zero-power allocation
1-bit P-BB [11]		Partial branch-and-bound		Near-optimal	Moderate	Applicable to both PSK and QAM

TABLE 1. A summary of linear and nonlinear 1-bit precoding schemes in the current literature.

well if the scale of transmit antennas deployed at the cellular BS goes large [6].

We refer the readers to Table 1, which provides a thorough summary of representative 1-bit precoding schemes in the current literature. Compared to linear closed-form 1-bit methods, nonlinear 1-bit precoding schemes are shown to offer significant error rate improvements, but require increased complexity since an iterative optimization problem must be solved at the symbol rate [5].

1-BIT DAC TRANSMISSION: THE SCOPE FOR INTERFERENCE EXPLOITATION

While the linear and nonlinear 1-bit precoding techniques mentioned above both have their distinct benefits and drawbacks, we note an important feature that has been neglected in these 1-bit precoding designs: When we shift the precoding design from the traditional block level to the symbol level, the MSE-based approach shown in Fig. 2, which aims to suppress all interference, is no longer optimal. As explained in the following, interference need not be constrained in all directions around the intended data symbol. Instead, interference exploitation techniques through the characterization of constructive interference (CI) and destructive interference (DI) are able to exploit beneficial interference inherent in multi-user transmission and the interference artificially introduced from 1-bit quantization. This factor was not fully explored in the traditional MSE-based 1-bit precoding solutions mentioned above, where all the interference is minimized and can yield additional performance improvements [1], as shown later.

With the above motivation, this article provides an overview of CI-based symbol-level precoding designs tailored for 1-bit massive MIMO systems. We begin by characterizing the notion of CI and explain how it can benefit 1-bit transmission. Subsequently, we discuss the extension of interference exploitation to 1-bit massive MIMO systems by describing several CI-based 1-bit solutions.

CI CHARACTERIZATION

We begin by introducing the concept of CI, followed by the description of CI signal design for downlink 1-bit massive MIMO.

The essential idea behind the CI-based signal design is aimed at exploiting interference instead of suppressing it via symbol-level precoding, pushing the received symbols as far as possible from their corresponding decision boundaries. The resulting increased distance to the decision boundaries translates into an increase in the received SINR, thus leading to improved performance for each receiver.

THE CONCEPT OF INTERFERENCE EXPLOITATION

Information theory and the notion of dirty-paper coding indicate that known interference does not degrade the capacity of the wireless broadcast channel when CSI is available, and that it is optimal to use interference-cognizant coding rather than just cancelling it. In addition to CSI, the data to be transmitted is also available at the BSs, but such information is not fully exploited by traditional block-level precoding methods. This is the idea behind CI exploitation, as illustrated in Fig. 2 for the $1 + j$ constellation point of quadrature phase shift keying (QPSK) modulation. In this case, QPSK's constellation decision boundaries are formed by the real and imaginary axes, and we can define CI as the interference that is able to push the received signal farther away from these axes. Such "interference" becomes beneficial to decoding as it increases the power of the useful signal [12]. As a toy example, consider a two-user scenario in which the desired and interfering data symbols are $s_1 = 1$ and $s_2 = -1$, respectively, both drawn from a binary PSK (BPSK) constellation. For simplicity, assume that the channel between the transmitter and receiver is $h_1 = 1$, and the interfering channel is $h_2 = \rho$. When $\rho > 0$, the received signal $r = h_1 s_1 + h_2 s_2 = 1 - \rho < 1$, which means that the received symbol is pushed closer to the decision boundary by the interfering signal, and hence destructive interference is observed. On the contrary, when $\rho < 0$, the received signal $r = h_{1s1} + h_2 s_2 = 1 - \rho > 1$, and the received symbol is pushed farther away from the decision boundary by the interfering signal, in which case constructive interference is observed.

Interference exploitation is achieved by controlling the interfering signals' magnitude and phase through symbol-level precoding, and all of the interfering signals can be made constructive to the signal of interest, allowing the received signals to locate inside the constructive area of the constellation instead of the MSE region and move farther from the decision boundaries of the constellation, leading to improved performance. Consequently, the MSE metric that aims to minimize the difference between the received and transmitted symbol as in Fig. 2 is sub-optimal. Given that the interference due to 1-bit DACs is a symbol-level phenomenon and that the existing 1-bit precoding solutions mentioned above neglect the use of CI to further benefit the 1-bit precoding, the concept of interference exploitation finds particular application to 1-bit transmission.

SIGNAL DESIGN

The essential idea behind CI-based signal design is aimed at exploiting interference instead of suppressing it via symbol-level precoding, pushing the received symbols as far as possible from their corresponding decision boundaries. The resulting increased distance to the decision boundaries translates into an increase in the received signal-to-interference-plus-noise ratio (SINR), thus leading to improved performance for each receiver.

Recall Fig. 1, where we depict the CI-based 1-bit precoding procedure for a generic multi-user transmission scenario. Based on the modulation type, the constructive region within which all the interfered signals achieve CI is determined, depicted as the green shaded areas shown in Fig. 1. For example, since the decision boundary for BPSK modulation is only the imaginary axis by definition, an interfering signal becomes constructive as long as its real part shares the same sign as the real part of the intended signal. Interference can be similarly characterized for higher-order PSK modulations and QAM, and we refer readers to [1] for more explicit descriptions and mathematical formulations. Subsequently, given that both the data symbols and CSI are available at the BS, symbol-level precoding techniques design the transmit signal vector such that all the interfering signals for each user are simultaneously made constructive to the signal of interest. By exploiting CI, the interfering signals that were harmful to the wireless transmission now become beneficial. Moreover, the transmit power that was used to suppress interference in traditional block-level precoding methods can now be used more judiciously via symbol-level precoding. The above two effects jointly offer a performance gain in terms of signal-to-noise ratio (SNR), which is over 7.5 dB for PSK modulations and 5 dB for QAM modulations compared to traditional ZF and MMSE precoding methods with a 10^{-3} uncoded bit error rate (BER) target in a typical small-scale 12 × 12 MIMO system [1].

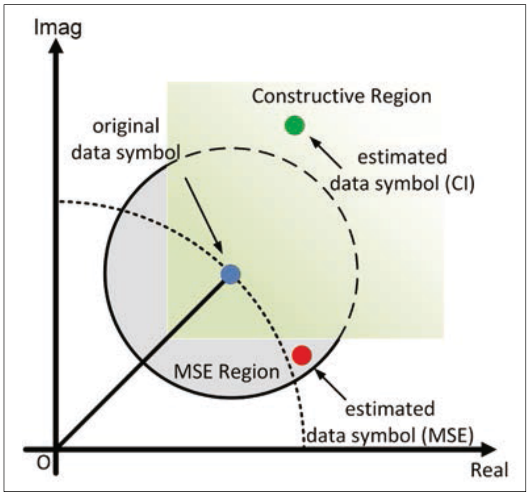
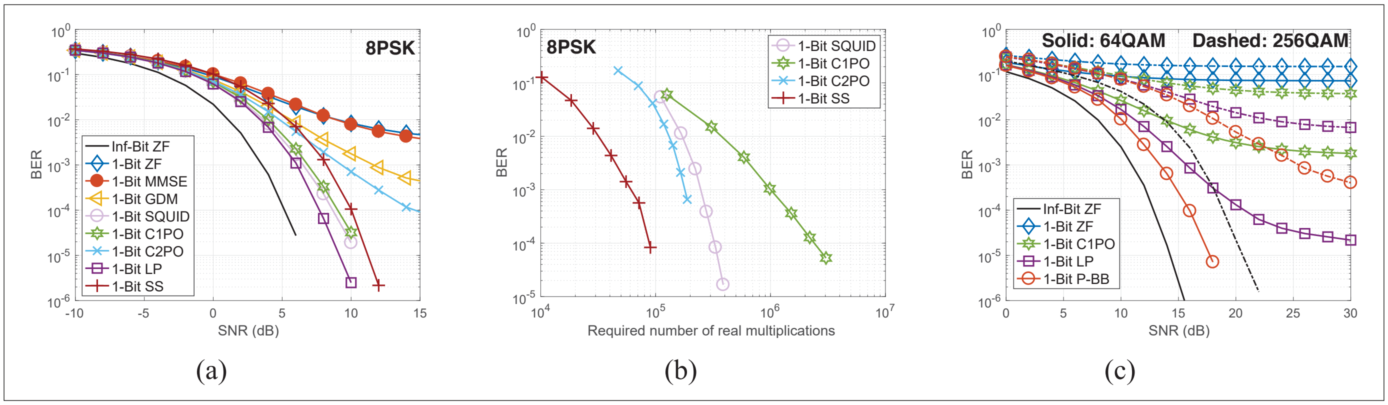


FIGURE 2. An illustration of the advantage of the CI metric compared to MSE.

Similarly, for 1-bit precoding, in addition to the inter-user interference that is inherent in wireless transmission, there is also artificial interference introduced by the coarse quantization of the 1-bit DACs. In this rich interference environment, both sources of interference can be made constructive to the users, as discussed in the following.

CI-BASED 1-BIT PRECODING SOLUTIONS

Several CI-based 1-bit solutions have already appeared in the literature of precoding, adopting the CI concept either implicitly or explicitly. For example, [8] proposes the optimal 1-bit solution through the use of the branch-and-bound (BB) framework, which applies to small-sized MIMO systems due to the prohibitive computational costs of the BB operations. In addition, [10] enables zero-power allocation for some of the antenna elements in 1-bit precoding design, and has shown that such an approach enables further



(a)

(b)

(c)

FIGURE 3. Numerical comparison of CI-based and MSE-based 1-bit precoding in the literature;standard uncorrelated Rayleigh fading channel, max iteration number for "1-Bit SQUID," "1-Bit C1PO," and "1-Bit C2PO" is 50, 20 and 20, respectively [2, 11]: a) Uncoded BER v.s. SNR, 8PSK, $N_T = 128$, $K = 8$; b) Uncoded BER v.s. complexity, 8PSK, $K = 8$, SNR=10dB; c) Uncoded BER v.s. SNR, 64QAM and 256QAM, $N_T = 128$, $K = 8$.

performance improvements under certain scenarios. It should be mentioned that although the concept of CI is not mentioned explicitly, the problem formulation in the two works above coincides with the symbol-scaling formulation in [2]. Below, we highlight some representative CI-based 1-bit precoding designs.

LINEAR-PROGRAMMING-BASED SOLUTION

We first introduce a computationally efficient 1-bit precoding solution based on the linear programming (LP) formulation. This approach is formulated in [9], and designs 1-bit precoding that aims to maximize the safety margin (the constructive area defined in the CI concept shown as the green shaded region in Fig. 2) to the decision thresholds by incorporating the classical CI constraint into the 1-bit precoding optimization problem. As opposed to traditional CI precoding for fully digital MIMO systems where the formulated problem is a second-order cone programming (SOCP), a simple LP formulation can be obtained by relaxing the discrete 1-bit constraints to inequality constraints on the real parts and imaginary parts for the transmit signal, and the solution is then obtained by enforcing a 1-bit quantization on the result of the LP optimization. The performance gains of the CI-based 1-bit LP solution includes promising error rate performance with low computational complexity, obtained by exploiting interference rather than minimizing it. To illustrate the corresponding error rate performance, Fig. 3a presents the BER result with an increase in the SNR at the transmitter side in a typical massive MIMO scenario. Standard uncorrelated Rayleigh fading channels are considered, and there are K = 8 single-antenna users in the scenario with N_T = 128 transmit antennas at the BS, benchmarked by several linear and nonlinear 1-bit solutions in the current literature. Since DACs perform in the baseband, 1-bit precoding schemes apply to both the sub-6 GHz and millimeter-wave (mmWave) bands, although standard uncorrelated Rayleigh fading channels are adopted to generate the numerical results in Fig. 3 as a representative example. As observed, the "1-Bit LP" [9] exhibits the best BER result compared to other benchmark schemes, and the SNR loss compared to unquantized ZF precoding is less than 3 dB when the BER target is 10^{-5}, bearing in mind that only 1-bit DACs instead of high-resolution ones are employed.

SYMBOL-SCALING-BASED SOLUTION

We next illustrate an alternative low-complexity 1-bit precoder based on symbol scaling. Conceptually, the symbol scaling performs a decomposition for both the data symbols and the 1-bit transmit signals along the decision boundaries (the real and imaginary axis in Fig. 2 for QPSK modulation as an example). The mathematical relationship between these approaches is formulated in [2], along with a three-stage algorithm based on this idea, referred to here as 1-bit SS. In particular, the values of the precoded signals for some antennas are allocated in the first stage following a specific criterion based on the data symbol and CSI. The second stage allocates the 1-bit signals for the residual entries of the transmit signals based on two different design criteria. The final stage includes a refinement process that performs a greedy algorithm to see if the CI effect can be further improved by modifying the sign of each precoded signal. The superiority of the 1-bit SS scheme lies in its performance-complexity trade-off, achieved using an efficient iterative algorithm instead of solving an optimization problem. To illustrate the favorable performance-complexity trade-off offered by the proposed 1-bit SS scheme, Fig. 3b plots the BER against the analytical complexity for K = 8 users with a transmit SNR of 10 dB, where the number of transmit antennas varies from 32 to 128. As can be observed, the 1-bit SS scheme is superior to 1-bit algorithms in the existing literature, requiring only 10 percent of the complexity at the cost of only slight BER losses.

P-BB-BASED NEAR-OPTIMAL SOLUTION

Next we describe a near-optimal 1-bit solution that leverages a partial branch-and-bound (P-BB) framework, applicable to both PSK and QAM modulations. This method is based on the fact that most entries in the 1-bit transmit signal of the solution to the LP formulation discussed already satisfy the 1-bit requirement, and the quantization losses are due to the relatively small portion of entries that fail to obey the 1-bit constraint [11]. The approach in [11] leaves the entries already satisfying the constraint unchanged, and only applies the BB procedure to those for which the constraint is inactive. As a result, the complexity relative to previous BB approaches is

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significantly reduced; meanwhile, the error rate performance has been improved over the 1-bit LP method because the introduced P-BB framework returns a near-optimal solution. To numerically demonstrate the performance gains, in Fig. 3c we depict the BER result for both 64-QAM and 256-QAM modulation as the transmit SNR increases, where it is observed that the performance of the traditional interference suppression approaches degrades severely, although they exhibit competitive error rate performance when PSK signaling is employed. The P-BB-based 1-bit design exhibits an SNR gain of more than 4 dB for 64-QAM and 6 dB for 256-QAM over existing 1-bit precoding designs, validating its superiority.

Open Challenges and Future Works

Hardware-efficient massive MIMO systems based on CI are still an open and ongoing research topic for 5G and future wireless communication systems. Some interesting research directions in the future are identified in the following.

CI Precoding for Different DAC Architectures

One of the potential future works in this field is the study of alternative DAC architectures. A representative work uses a spatial version of Sigma-Delta modulation with 1-bit precoding in [13], which leads to simplified optimization problem formulations for 1-bit precoding by transforming the complicated binary optimization into peak amplitude constraints and better control over the 1-bit quantization for massive MIMO. In addition to the above, using DACs with more than one bit per dimension can be another option, which leads to improved error rate performance and even approaches the ideal unquantized case, at the expense of increased hardware costs. This problem was considered for the LP approach in [9] for the case of polar DACs, where the CE property of the transmit signal is maintained by distributing the quantization points around the unit circle. For such studies, a natural question arises: what is the optimal bit resolution for DACs that should be adopted at low, medium, and high SNR regimes regarding the BER, hardware efficiency, and energy efficiency trade-off? The literature would benefit from an analytical performance study of massive MIMO with low-resolution DACs, founded on which practical block/symbol-level few-bit-DAC precoding designs could be developed.

Task-Based Quantization

Recently, a new concept referred to as task-based quantization (TBQ) has emerged in the signal processing community as a counterpart to traditional quantization methods [14]. The TBQ technique considers the specific task of the system in the quantization design, leading to improved performance compared to traditional quantizers that only aim to accurately represent the underlying signals. The superiority of TBQ over traditional quantization techniques is analogous to that of CI-based 1-bit precoding designs over traditional MSE-based designs, since it takes into account how the signals are processed post-reception. While TBQ has been shown to be a promising technique for channel estimation in the uplink when few-bit analog-to-digital converters (ADCs) are deployed at massive MIMO arrays, this combination of the TBQ concept with interference exploitation has stimulated new research directions for the data transmission of massive MIMO in the downlink.

Effect of Nonlinear Power Amplifiers

Practical wireless communication systems often operate the PAs in the nonlinear region near saturation in order to improve power efficiency, which generally works well with CE transmissions such as CE precoding (CEP) or 1-bit DACs, as described above. However, if few-bit DACs are employed at cellular BSs and the transmit signals are no longer CE, the input signals with increased PAPR may incur severe in-band distortion and out-of-band radiation that further deteriorate the system performance. Thus, the effect of imperfect nonlinear PAs must be taken into account if the focus is shifted to higher-order DACs in future works, which would require a rethinking of the communication model that takes into account the resulting signal distortion of the nonlinear PAs. This will potentially lead to a joint optimization problem on the DAC resolution, precoded signals, and their corresponding peak power values, which need to be carefully designed for a promising performance trade-off.

Machine-Learning-Based 1-Bit CI Transmitter

The solutions discussed above for the precoded signal design for 1-bit DACs are all based on model-based approaches, where the intended precoded signal is obtained either by solving an optimization problem or through an (iterative) algorithm, both featuring system parameters that are tuned manually. Recently, machine learning and deep neural networks have been discussed extensively in the literature for their potential applications in wireless communication systems. Machine learning has already found applications in image/audio processing, social behavior analyses, and economics and finance, and has been shown to be particularly effective in the field of pattern recognition and natural language processing. The application of machine learning and deep neural networks (DNNs) to 1-bit precoding has already started to emerge [15], especially utilizing the concept of auto-encoders to model the end-to-end 1-bit precoding procedure as a DNN. A key advantage of such an approach is that the channel uncertainty can be taken into account in the training process for the auto-encoder. By using a data-driven approach, neural-network-based encoders and decoders, along with optimized constellations, can be designed in a manner that makes the overall system robust to the changing channel propagation conditions.

Conclusions

This article has given an overview of the potential of employing interference exploitation in hardware-constrained massive MIMO systems. We have discussed how interference can be characterized as either constructive or destructive and how interference artificially introduced in downlink 1-bit massive MIMO systems can be manipulated to further benefit the system performance. The overviewed solutions offer prominent gains in terms of the BER performance, validating the potential by exploiting CI to guarantee both energy-efficient and hardware-efficient massive MIMO architectures. Still, there are a number of open challenges that have yet to be addressed, opening a broad and exciting new research area for the years to come.

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BIOGRAPHIES

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> The overviewed solutions offer prominent gains in terms of the BER performance, validating the potential by exploiting CI to guarantee both energy-efficient and hardware-efficient massive MIMO architectures. Still, there exist a number of open challenges that are yet to be addressed, opening a broad and exciting new research area for the years to come.