A Literature Survey on Transceiver Designs in Multiple-Input Multiple-Output and Orthogonal Frequency Division Multiplexing Systems

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Abstract —All kinds of wireless communication systems face the difficulties of multipaths, signal fading, increasing interference, and limited spectrum. A productive approach to protect against deep fade is to utilize different diversity techniques. The primary idea behind all diversity techniques is to provide multiple uncorrelated replicas of the same information bearing signal over multiple independently faded paths. There are different types of diversity schemes that are applied upon the characteristics of the channel and additionally the transceiver structures. Some common diversity techniques that have been applied in practice include time diversity (e.g., channel coding, interleaving), spatial diversity (e.g., Multiple-Input Multiple-Output (MIMO) systems), and a combination of multipath and frequency diversity (e.g., Orthogonal Frequency Division Multiplexing (OFDM) systems). In order to exploit the benefits of MIMO and OFDM systems, precoding and/or joint precoding and decoding design for MIMO and OFDM systems is of great meaning and has been widely studied. The major aim of this survey was to show the advantages of applying various precoding and/or decoding methods to enhance the performance of the system in terms of both the bit error rate (BER) and the capacity. Also, this survey considers the various assumptions about the Channel State Information (CSI) as the performance of MIMO and OFDM systems depending on the availability of either perfect or imperfect CSI and channel correlation information (CCI).

Index Terms—MIMO, OFDM, diversity, CSI.

I. Introduction

A. MIMO Communication System Model

In the last few years, Multiple-Input Multiple-Output (MIMO) systems have risen as a standout among the most guaranteeing methodologies for high data rate and more solid wireless communication systems. These systems have multiple antennas deployed at both the source (transmitter) and the destination (receiver). The capacity of the MIMO system increases linearly with the increase of the number of transmit and receive antennas. The multiplexing gain (data throughput), diversity gain, and coding gain (link reliability) of MIMO systems are essentially higher than those of conventional Single-Input Single-Output (SISO) systems. The performance improvement in terms of either data throughput or link reliability of the MIMO systems depends on the presumption of CSI at the transmitter (CSIT) and/or state information available at the receiver (CSIR). In practice, getting the perfect CSI is impractical because of the dynamic nature of the channel and the channel estimation errors. Thus, it is important to outline a system sufficiently enough to imperfect CSIT and/or CSIR. A MIMO systems can be subdivided into three fundamental classifications: spatial diversity, spatial multiplexing, and beamforming.

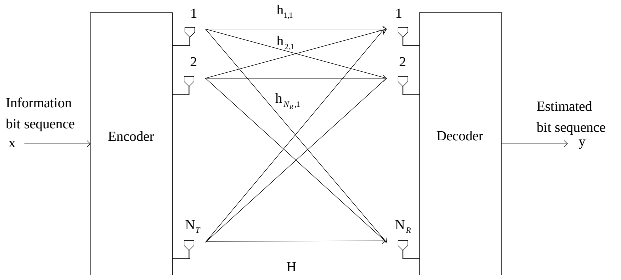

Fig. 1. Block diagram of MIMO systems.

The basic structure of a MIMO system model is illustrated in Fig. 1. Thus, let N_T denote the total number of antennas at the transmitter, N_R denote the total number of antennas at the receiver, $\boldsymbol{x}$ be a vector of size N_T containing the transmitted values, and $\boldsymbol{y}$ be a vector of size N_R containing the received values. The channel transfer matrix $\boldsymbol{H}$ is defined as

$$\boldsymbol{H} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,N_T} \\ \vdots & \ddots & \vdots \\ h_{N_R,1} & \cdots & h_{N_R,N_T} \end{bmatrix} \tag{1}$$

The received signal can be written as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}, \tag{2}$$

where $\boldsymbol{n}$ represents additive noise.

B. Spatial Multiplexing

In order to achieve a multiplexing gain in a spatial multiplexing system, a high-data-rate signal is divided into different lower-data-rate signals, and each datum is transmitted from different transmit antennas in the channel with the same frequency. On the other hand,

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when these signals are received at the multiple receive antennas with sufficiently distinctive spatial marks, the receiver will separate these streams and create free parallel channels. Spatial multiplexing is a method capable of increasing the link capacity at high signal-to-noise ratios (SNRs). The quantity of parallel spatial streams is restricted by the low number of transmit or receive antennas. The Bell-Labs Layered Space–Time (BLAST) architecture is the most popular spatial multiplexing system, which was proposed by Foschini [1]. The accomplished increase in terms of data rate is called multiplexing gain. The spatial multiplexing system can be implemented either with or without CSIT.

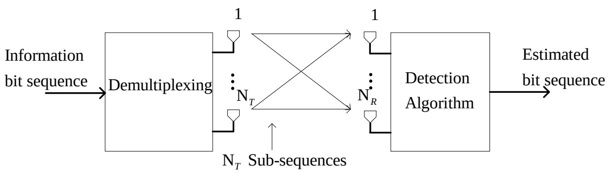

Fig. 2. Block diagram of the spatial multiplexing system.

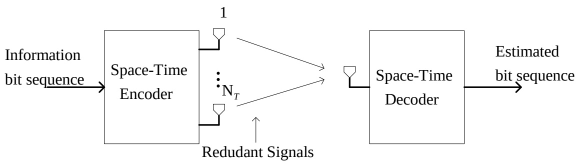

Fig. 3. Block diagram of the space–time coding system.

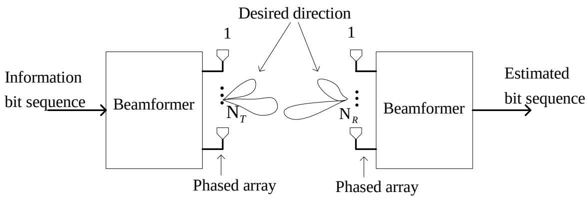

Fig. 4. Block diagram of the beamforming system.

The basic block diagram of a spatial multiplexing system is provided in Fig. 2. In the event that the transmitter is outfitted with N_T antennas and the receiver has N_R antennas, the maximum spatial multiplexing order is denoted as

$$\boldsymbol{N_S} = min(N_T, N_R). \tag{3}$$

C. Spatial Diversity

Spatial diversity techniques are used when only the transmitter is aware of the CSI. They are used to increase the performance of the system in terms of the error rate, just like channel coding, and they operate under the principle of transmitting and/or receiving redundant signals representing the same information sequence. In spatial diversity, only one stream is transmitted; however, the signal is coded by utilizing a technique known as space–time coding. Orthogonal coding principles are used to transmit signals from each of the transmit antennas. This may be either full- or near-orthogonal coding. The signal space diversity can be enhanced by exploiting the independent fading within the multiple antenna. Since there are channel data, it is not possible to achieve beamforming or array gain from diversity gain. Alamouti's transmit diversity scheme [2] and space–time trellis codes [3] are well-known spatial diversity schemes. The basic block diagram of a space–time coding scheme is shown in Fig. 3.

D. Beamforming

The beamforming technique works under the principle that the same signal is transmitted from all transmit antennas with particular phase weighting that can increase the signal power at the receiver input. The main advantage of beamforming is that it maximizes the signal gain using combining methods that diminish the multipath fading impact. Without scattering, beamforming brings about an overall characterized directional pattern; however, conventional beams are not suitable for typical cellular systems. The transmit beamforming technique cannon simultaneously increases the signal strength at each receive antenna when the Single-Input Multiple-Output (SIMO) design is used. Spatial diversity techniques are used when only the transmitter is aware of the CSI. They are used to increase the performance of the system in terms of the error rate, just like channel coding, and they operate under the principle of transmitting and/or receiving redundant signals representing the same information sequence. In spatial diversity, only one stream is transmitted; however, the signal is coded by utilizing a technique known as space–time coding. Orthogonal coding principles are used to transmit signals from each of the transmit antennas. This may be either full- or near-orthogonal coding. The signal space diversity can be enhanced by exploiting the independent fading within the multiple antenna. Since there are channel data, it is not possible to achieve beamforming or array gain from diversity gain. Alamouti's transmit diversity scheme [2] and space–time trellis codes [3] are well-known spatial diversity schemes. The basic block diagram of a space–time coding scheme is shown in Fig. 3.

E. Multiuser MIMO Communication

Multiuser MIMO (MU-MIMO) systems have attracted incredible attention recently mostly because of their ability to provide enhancements to the capacity and reliability of data transmission over wireless channels. In the case of MU-MIMO, the base station (BS) is connected with different antennas, and while communicating with multiple mobile stations (MSs), each of these MSs is additionally outfitted with multiple antennas. Multiple users are allocated in one time–frequency resource endeavor multiuser diversity in the spatial area, which brings about significant increases over SU-MIMO, particularly in spatially correlated channels. There are two scenarios connected with MU-MIMO:

1. *Uplink (Multiple Access Channel, MAC).* This is a wireless network with multiple senders to a single receiver. For uplink MU-MIMO systems, the BS (receiver) handles a significant part of the handling, and here the BS is needed to know the CSI. Estimation of the CSIR is less difficult than estimating the CSIT, yet it requires noteworthy levels of uplink ability to transmit the dedicated pilots from every MS. However, uplink MU-MIMO systems perform better than SU-MIMO, especially if the number of receive antennas is more prominent than the number of transmit antennas at every MS.
2. *Downlink (Broadcast Channel, BC).* This is a wireless system with a single transmitter to multiple receiver systems. Transmit handling is needed for this, and it is ordinary as precoding and SDMA downlink user scheduling. The BS (transmitter) needs to know the CSIT. It empowers enormous throughput enhancements over that of traditional point-to-point MIMO frameworks, particularly when the quantity of transmit antennas surpasses that of the antennas at the MS (receiver).

MU-MIMO offers some significant advantages over other techniques:

- It empowers a level of immediate gain to be acquired in a multiple access capacity emerging from the multiuser multiplexing schemes. This corresponds to the number of transmit antennas at the BS.
- It gives off the impression of being less influenced by some propagation issues that affect SU-MIMO systems. These incorporate channel rank loss and antenna correlation; the channel correlation still affects the diversity per user basis, but it is not a real issue in multiuser diversity.
- It allows spatial multiplexing gains to be attained at the BS without requiring multiple antennas at the MS, and it considers the creation of cheap remote terminals; the intelligence and expense are incorporated inside the BS.

F. OFDM System Model

An Orthogonal Frequency Division Multiplexing (OFDM) system is one of the widely used multicarrier systems dealing with frequency-selective fading as well as achieving high-speed data transmission. The principle of the OFDM technique is to split a high-speed data stream into narrow-band data streams and then simultaneously transmit them on a number of orthogonal subcarriers. Furthermore, since the subcarriers are orthogonal, there is essentially no cross talk between signals, which simplifies the detection process. Orthogonality is kept up during channel transmission. This is accomplished by adding a cyclic prefix (CP) to the OFDM packet to be sent. This duplicates the end segment of an Inverse Fast Fourier Transform (IFFT) packet to the start of an OFDM symbol. In order to completely suppress the Intersymbol Interference (ISI) in the OFDM systems, the length of the CP must be longer than the duration of the dispersive channel. In Fig. 5, the OFDM modulation in a transmitter includes the IFFT operation that converts the signal from the frequency domain to the time domain and CP insertion. At the OFDM receiver, the CP is removed before the packet data is sent to the FFT for demodulation.

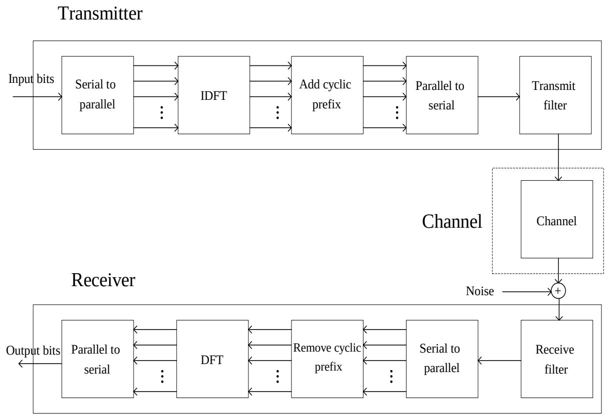

Fig. 5. Block diagram of a basic OFDM system.

II. Literature Review

A. Background of MIMO

The idea of MIMO was initially presented by Jack Winters of Bell Laboratories [4] when there was a need for a higher information rate with a constrained amount of bandwidth. In [5], the concept of spatial multiplexing using MIMO was proposed to achieve the multiplexing gain. In [1], a well-known spatial multiplexing scheme, Bell-Labs Layered Space–Time (BLAST) concept, was introduced to achieve higher bit rates. The capacity of the fading Gaussian MIMO channel was exhibited in [6] to demonstrate that the capacity of the channel is increased when the number of transmit or receive antennas is increased. The capacity of the multipath channel can be increased by planning an appropriate communication structure of multipath signal propagation [7].

Channel fading can be combated by increasing the diversity order using the multiple antenna techniques. It can also be used to improve the error performance. The various independently faded replicas of the data symbol can be acquired at the recipient end, by sending signals that carry the same data through different ways. A few cases of MIMO schemes that fall in this classification are space–time block codes (STBCs), space–time trellis codes (STTCs), and STBC from orthogonal designs [2, 3, 8]. The concept of the transmit diversity scheme was created with three research works [9–11] that autonomously proposed a core strategy called delay diversity. Nonetheless, the primary transmit diversity for two transmit antennas was introduced in [2]. Two-dimensional coding schemes for multiple antennas at the transmitter based on STTC were proposed in [3]. Alamouti's transmit diversity and delay diversity methods provide solely a full diversity gain with respect to the number of antennas at the receiver and transmitter, but the STTC can provide both a diversity gain and a coding gain.

It was indicated in [3] that STTCs provide a good performance of the outage capacity limit. Nevertheless, this performance was achieved at the cost of a comparatively high complexity in decoding. The orthogonal space–time block codes (OSTBCs) were acquainted [8] with attaining a straightforward receiver structure, which constitutes a speculation of Alamouti's schemes to more than two transmit antennas. The STTC and OSTBC were joined with the antenna selection method at the receiver and were studied in [12], [13], respectively.

The beamforming methods that utilize multiple antenna techniques are used to enhance the SNR at the receiver and to smooth the cochannel interference (CCI) in a multiuser situation along with increased data rate. Such SNR gains due to the beamforming techniques are frequently called array gains. Initially, this beamforming concept was introduced in [14]. A full diversity can be achieved using the transmit beamforming technique along with receiver combining techniques, and this has been discussed in [15–18]. In contrast with space–time codes [2, 3, 8], beamforming and receiver combining techniques give a similar diversity order with a significantly higher array gain [19] at the cost of making CSI available at the transmitter as the transmit beamforming vector.

As mentioned above, the SU-MIMO and MU-MIMO systems are used for beamforming, diversity, or spatial multiplexing. A transmission technique can be designed to achieve one or a combination of three different gains. Both the diversity and the multiplexing gain can be all the while gotten, yet there is a trade-off in how much gain any MIMO technique can extract. A complete investigation of this trade-off was given in [20, 21].

B. Impact of Channel Knowledge on MIMO System Designs

The MIMO system's performance generally depends on the amount and nature of the CSI available at either CSIR or CSIR. CSIR is customarily procured by means of a training sequence that permits the channel estimation. In addition, the CSIT can be acquired either by the method of estimation and feedback from the receiver or based on the existing estimates, if the channel has some correspondence. The CSI at both ends comprises the estimated channel information and the information about the channel connection. For diverse sorts of CSI, distinctive transmit systems ought to be utilized. The situation in which the perfect CSI is known to both the receiver and the transmitter has been studied in [6, 22, 23]. Spatial multiplexing frameworks [5] and space–time coded frameworks [3] do not require the CSIT, whereas others (e.g., transmit beamforming [24, 25] or generalized beamforming frameworks [22, 23]) were assumed to have a perfect CSIT.

It is impractical to get the perfect channel information either at the transmitter or at the recipient because of the time changing nature of the wireless channel. Hence, it is important to plan a framework that is sufficiently vigorous for imperfect CSI. The capacity of SISO channels for imperfect CSI at the receiver with and without feedback to the transmitter was studied [26]. Systems for accomplishing incomplete CSI have been proposed in [27], [28]. The ideal transmission procedures for MIMO systems with imperfect CSIT were studied in [29], [30]. The impact of imperfect CSI at both the transmitter and the recipient for MIMO systems has been analyzed in [31], [32]. A pilot-based transmission in a MIMO system with imperfect CSI and correlation information at the transmit antenna was considered in [33, 34].

Two distinctive methodologies are utilized to model and manage the instability of the CSI. One methodology models the error in the CSI as obscure yet deterministic and limited to a particular region. To ensure a least reliability level, the worst-case optimization scenario is utilized in [35], [36]. Be that as it may, a worst-case design is somewhat conservative, since it occurs with a low likelihood [37]. Hence, another approach that models the uncertainty by its first-order and second-order statistics [38]–[41] is exceptionally compelling and has been adopted. A design focused on statistical channel data is known as a stochastic robust design [42].

With the extent of statistical vulnerability models that are involved, the channel correlation information (CCI) is obtained from the propagation geometry and the channel mean information (CMI) is obtained from the channel estimation [40]. The CCI and CMI can be conveniently exploited by utilizing precoding or joint transceiver designs. Specifically, a linear transceiver is preferred, because of the complexity constraint, particularly for MSs.

Feedback is required to make the estimated CSI at the receiver available at the transmitter side, but the feedback is not frequent in the slow fading channels. It will be more fitting to utilize the limited feedback channel if the feedback link is bandwidth-constrained [18, 28]. By and by, the general stochastic robust designs generally prompt arrangements that plainly depict system structures and subsequently give direct information on how weaknesses, for example, erroneous channel estimation and channel correlations, influence the performance of the system. The results of the general designs are likewise useful in distinguishing key channel parameters that ought to be quantized and exchanged again with the transmitter, and in evaluating the performance of low feedback system designs. Accordingly, it is of incredible vitality to analyze a MIMO system model with imperfect CSI modeled statistically.

Here, the simulation results are presented to show the effect of CSI in downlink MU-MIMO system designs. From the simulation parameters, the total number of MSs is $\boldsymbol{K} = 3$ and the number of antennas at the transmitter is $N_T = 6$, whereas the number of antennas at the receiver is set to be $N_R = 2$. Figure 6 shows the performance of the joint precoder/decoder design for downlink MU-MIMO with perfect and imperfect CSI. In addition, it compares the performance downlink MU-MIMO systems with BPSK and 4-ASK modulations. It is observed that the MU-MIMO system has a much better bit error rate (BER) performance in perfect CSI, and the errors in the channel estimation lead to a massive performance loss.

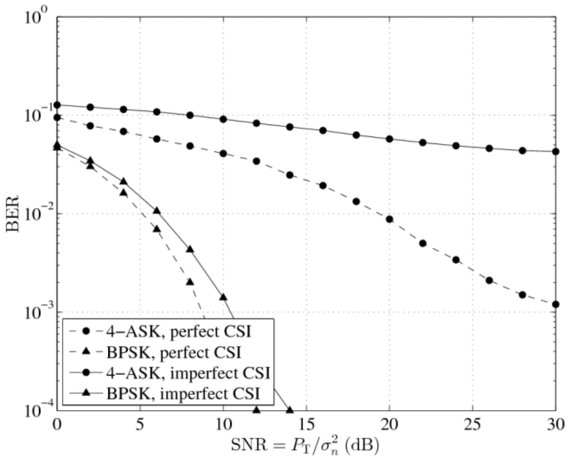

Fig. 6. Effect of perfect and imperfect CSI on the performance of the downlink MU-MIMO transceiver design for BPSK and 4-ASK.

C. Precoder and Decoder Designs in SU-MIMO Systems

In SU-MIMO systems, diversity can be obtained through the utilization of space–time codes [2], [3]. In order to accomplish full diversity, transmit beamforming with receive combining was one of the least difficult methodologies [17], [24], [43]. To enable spatial multiplexing in SU-MIMO systems, appropriate transmit precoding designs or joint precoder/decoder designs were proposed under a variety of system objectives and different CSI assumptions in [21], [44]. Another beamforming method utilizing Singular Value Decomposition (SVD) for closed-loop SU-MIMO systems with a convolution encoder and modulation techniques, for example, M-quadrature amplitude modulation (M-QAM) and M-phase shift keying (M-PSK), over Rayleigh fading has been proposed in our past work [45]–[47].

As far as spectral effectiveness is concerned, an SU-MIMO system is intended to approach the capacity of the channel [48], [49]. In light of this perception, a frequency-selective MIMO channel can be managed by taking a multicarrier approach, which is a well-known capacity lossless structure and allows us to treat every carrier as a flat MIMO channel [49]. A capacity achieving design manages to make the channel matrix at every carrier diagonalized; afterwards, a water-filling power distribution must be utilized on the spatial subchannels of all carriers [48], [49]. Note that this makes CSI available at both the receiver and the transmitter.

As design criteria, different performance measures are considered, for example, weighted MMSE [22], TMSE [23], and least BER [42], [50]. From the signal processing point of view, to minimize the information estimation error from the received signal, TMSE is a critical metric for transceiver design and has been embraced in SU-MIMO systems. The joint transceiver design for SU-MIMO frameworks, utilizing an MSE paradigm, was given in [22].

The schemes introduced in all the above works are considered few optimization criteria like high data rate, low BER, and MMSE. The issue of designing an optimum linear transceiver for an SU-MIMO channel, possibly with delay spread, utilizing a weighted MMSE paradigm subject to a transmit power constraint, is discussed in [22]. These studies assumed that the perfect CSI was available at the transmitter side. However, in practical communication systems, the propagation environment may be more challenging, and the receiver and transmitter cannot have a perfect knowledge of the CSI. Imperfect CSI may emerge from an assortment of sources, for example, outdated channel estimates, error in channel estimation, and quantization of the channel estimate in the feedback channel [51].

To obtain a robust communication system, the MIMO systems' design with imperfect CSI is an important issue to investigate. The optimal precoding strategies in the SU-MIMO systems were proposed under the assumption that imperfect CSI is available at the transmitter and perfect CSI is available at the transmitter [29], [52]. The robust joint precoder and decoder designs to reduce the TMSE with imperfect CSI at both the transmitter and the receiver of SU-MIMO systems were proposed in [53], [54].

In [55], a novel precoding technique to enhance the performance of the downlink in MU-MIMO systems is studied with an improper constellation. Precoding that was designed in [55] is more appropriate for a MIMO system with an improper signal constellation. The MMSE and modified Zero-Forcing (ZF) precoder designs are demonstrated to accomplish an unrivaled performance compared with the routine linear and nonlinear precoders [55]. Both instances of imperfect and perfect CSI are considered, where the imperfect CSI case considers the correlation data and channel mean.

The joint precoder and decoder designs under the minimum TMSE measure produce an exceptional BER performance for proper constellation techniques (e.g., M-PSK and M-QAM) [56]. Then again, when applying the same outline to the improper constellation techniques (e.g., M-ASK and BPSK), the performance gets fundamentally corrupted. The minimum TMSE design for SU-MIMO systems with improper modulation techniques was proposed in [55] and was indicated to provide a predominant performance in terms of BER, compared with the traditional design in [56]. The optimum joint precoder and decoder designs for the SU-MIMO frameworks which utilize improper constellation strategies, under either the imperfect or the perfect CSI, were proposed in [57]–[59]. In both instances of imperfect and perfect CSI, a minimum TMSE measure is created and used to develop an iterative design technique for the optimum precoding and decoding matrices [57]–[59].

D. SVD-Based Transmit Precoding in SU-MIMO Systems

Here, we consider the SU-MIMO systems with N_T antennas at the transmitter and N_R antennas at the receiver. The Rayleigh fading channel is utilized for information transmission and is expected to have perfect CSI at both ends. The framework is comprised of beamforming precoding at the transmitter and diversity combining at the recipient. The transmit bits $\boldsymbol{s} = \{s_1, s_2, \ldots, s_K\}$ are encoded by the convolutional encoder, and all of these encoded bits are modulated to produce the symbol vector of length K, $\overline{\boldsymbol{x}} = \{\bar{x_1}, \bar{x_2}, \ldots, \bar{x_K}\}$.

Transmit beamforming is performed by applying the transmit symbol $\boldsymbol{s}$ to the beamforming matrix, and the precoded symbol vectors $\boldsymbol{x} = \{x_1, x_2, \ldots, x_K\}$ are transmitted over the fading channel. The received symbol vector can be expressed as

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{n}, \tag{4}$$

where $\boldsymbol{x}$ is a $1 \times N_T$ size vector that contains the transmitted symbols, $\boldsymbol{H}$ is a channel matrix of size $N_T \times N_R$, and $\boldsymbol{n}$ is a vector of AWGN on the receive antenna of size $1 \times N_R$.

In general, The transmitted symbols are multiplied with an appropriate beamforming vector at the transmitter and receiver to perform beamforming. Here, we assume that the perfect CSI is available at both the transmitter and the receiver. In that case, the beamforming vectors are acquired by performing the SVD of the MIMO channels [45–47]. The SVD of the channel is

$$\boldsymbol{H} = \boldsymbol{U\Sigma V}^H, \tag{5}$$

where $(.)^H$ denotes the conjugate transpose, $\boldsymbol{U}$ are unitary matrices of size $N_T \times N_T$, $\boldsymbol{V}$ are unitary matrices of size $N_R \times N_R$, and $\boldsymbol{\Sigma}$ is the $N_T \times N_R$ diagonal matrix with nonnegative real numbers on the diagonal; that is, $\boldsymbol{\Sigma} = diag\{\lambda_1, \lambda_2, \ldots, \lambda_{N_R}\}$. $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_{N_R} > 0$ are singular values. The SVD is used to decompose the MIMO channel into multiple independent subchannels.

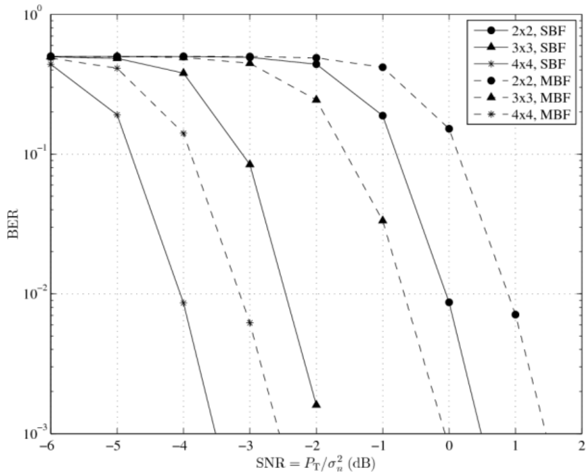

Fig. 7. Performance comparison of the single beamforming and multiple beamforming with a convolution encoder for BPSK.

E. SVD-Based Single Beamforming (SBF)

In the instance of SBF, the subchannel with the largest gain is used to carry only one symbol at a time. $\boldsymbol{H}$ may be deteriorated into various free orthogonal modes of excitation, which is alluded to as an eigenmode of the channel. At the transmitter, transmit information $\boldsymbol{x}$ is multiplied with the precoding matrix $\boldsymbol{V}$ before sending to the transmit antennas. At the receiver's end, the received signals gotten at every antenna are multiplied by the decoder lattice $\boldsymbol{U}^H$. The general transmission relationship between the input signal $\boldsymbol{x}$ and output signal $\boldsymbol{y}$ is written as

$$\boldsymbol{y} = \boldsymbol{U}^H(\boldsymbol{Hx} + \boldsymbol{n}) \tag{6}$$

$$= \boldsymbol{U}^H(\boldsymbol{U\Sigma V}^H\boldsymbol{x} + \boldsymbol{n}) \tag{7}$$

$$= \boldsymbol{\Sigma}\bar{\boldsymbol{x}} + \bar{\boldsymbol{n}} \tag{8}$$

where $\bar{n} = \boldsymbol{U}^H\boldsymbol{n}$ is the multiplication by a unitary matrix with noise. The ideal beamforming vectors to be utilized at the transmitter and receiver side are the first column of $\boldsymbol{U_1}$ and $\boldsymbol{V_1}$ corresponding to the biggest singular value of H. At that point, the received signal for SBF can be expressed as

$$\boldsymbol{y} = \bar{\boldsymbol{x}}\,\boldsymbol{U}_1^H\boldsymbol{H}\boldsymbol{V}_1 + \boldsymbol{U}_1^H\boldsymbol{n}) \tag{9}$$

$$= \boldsymbol{\lambda_1}\bar{\boldsymbol{x}} + \boldsymbol{n_1} \tag{10}$$

where $\boldsymbol{\lambda_1}$ is the largest singular value of $\boldsymbol{H}$.

F. SVD-Based Multiple Beamforming (MBF)

Numerous symbols transmit over distinctive subchannels at the same time. The ideal vectors to be used as weights on the transmitter side and receiver side are the first $\boldsymbol{S}$ columns of $\boldsymbol{U}$ and $\boldsymbol{V}$ related to the first $\boldsymbol{S}$ bigger singular values of $\boldsymbol{H}$, when the $\boldsymbol{s}$ subchannel is utilized at the same time. At that point, the received signal for MBF can be written as

$$\boldsymbol{y}_i = 1\Big/\sqrt{\boldsymbol{S}_i}\;\boldsymbol{\lambda}_i\boldsymbol{x}_i + \boldsymbol{n}_i, \tag{11}$$

where $\boldsymbol{\lambda}_{\mathrm{i}}$ is the ith largest singular value of $\boldsymbol{H}$. Figure 7 shows the performance comparisons of the SVD-based SBF and MBF under BPSK with a convolution encoder for $M_T = M_R = 2, 3,$ and 4. It is observed that increasing the number of antennas at the transmitter and receiver leads to a better performance in terms of BER, and it is also shown that SBF has a much better BER performance than MBF.

G. Precoder and Decoder Designs in MU-MIMO Systems

Intensive research efforts have been exploited in SU-MIMO system designs [44, 60]. MU-MIMO systems have attracted incredible attention, primarily because of their ability to acquire a high system capacity and good spectrum utilization [53, 61–65]. MU-MIMO-OFDM wireless systems were proposed to improve the system performance by achieving a multiuser multiplexing gain, where multiple users were transmitted simultaneously in an orthogonal frequency band under the interference limit required [66]. The capacity region of a downlink MU-MIMO system was obtained in [67, 69] by means of a nonlinear transmission technique known as dirty paper coding (DPC) [70], and the capacity analysis of an uplink MU-MIMO system was obtained in [6, 71].

Linear precoding methods usually search optimal beams for each user's data streams under some given criteria, such as signal-to-interference-plus-noise ratio (SINR) balancing [61, 72], ZF precoding [73], and block diagonalization (BD) precoding. Due to the fact that optimal beam vectors for each user are highly coupled and thus difficult to solve directly, some researchers utilize the duality [74] between the uplink and the downlink to find the precoding matrix in a relatively easier way.

The performance of MU-MIMO systems relies on the availability of the CSIT and recipient. Without CSIT, various antennas can be utilized for spatial multiplexing [1], or for space–time to accomplish the diversity gain [2, 3]. When the CSI is available at the transmitter, the full benefits of CSI are exploited by precoding techniques. In such cases, designing an appropriate precoding method has been concentrated on for various types of goals [22, 23, 44]. The impact of CSIR on MU-MIMO frameworks was additionally studied in [75]. Different performance measurements have been considered to design the joint transceiver structures for both uplink and downlink MU-MIMO systems, for example, maximum sum capacity, MMSE, and minimum BER. The MSE from all the information streams was a standout among the essential performance measures in MU-MIMO systems [76, 77]. Channel quantization and transceiver design for downlink MU-MIMO systems with restricted feedback were analyzed in [78].

The SVD-assisted MU-MIMO downlink transmission is proposed in [79]. When the BS obtains the perfect CSI of all MSs and each MS has its own specific perfect CSI, the SVD-assisted method can decouple the multiuser channel into multiple independent SISO subchannels. Although equal power allocation (EPA) is employed in [79] with perfect CSI, a more efficient Transmit Power Allocation (TPA) scheme should be used to further enhance the system's performance under the practical scenario.

For uplink and downlink MU-MIMO systems, a joint linear transceiver design with the minimum TMSE has been examined in [80, 81]. It is assumed that perfect CSI is available at both the transmitter and the receiver. The estimation of the channel must be performed at the receiver and sent back to the transmitter to empower precoding [80]. Due to the channel estimation error and feedback delay, the feedback information to the transmitter is not perfect. For both uplink and downlink MU-MIMO systems, the TMSE minimization based joint precoder and decoder were designed under the assumption of imperfect CSI.

Mainly, in [82–84], the MU-MIMO systems design focused around the MMSE criteria was developed as a nonconvex optimization problem under an average transmit power constraint. An iterative structure based algorithm is used to design an optimum linear precoder and decoder for both the uplink and downlink systems. In [82–84], the MU-MIMO system with imperfect CSIT or receiver was considered by including the impact of channel estimation error. The CCI available at the receiver for the downlink and at the transmitter for the uplink is considered in [82–84], whereas [32] analyzed both transmit and receive correlations. For the purpose of simplicity of investigation, the feedback data were assumed to be error-free. In [85], both linear and nonlinear precoder and decoder designs for flat fading channels have been analyzed under the presumption that the CSI is available at the transmitter. All in all, the linear structure is favored in the transceiver design because of its lower computational complexity, in contrast with nonlinear designs. In order to evade the computational complexity in iteration-based algorithms, the computationally complex noniterative SVD supported uplink and downlink MU-MIMO frameworks with proper modulations were proposed with perfect CSI in [79].

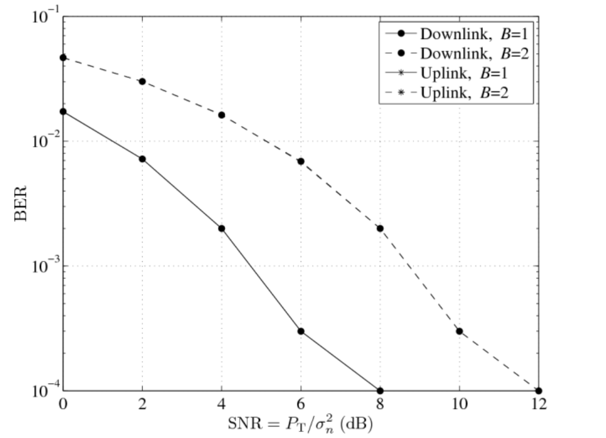

Fig. 8. Performance comparison of the proposed downlink and uplink transceivers with B = 1 and B = 2 for BPSK.

For the special case of improper modulation techniques employing SU and MU-MIMO systems, a novel precoding design that performs better than existing linear precoders that are only optimum for proper modulation techniques was proposed in [55]. Such superior performance was acquired by focusing on the precoder designs that consider the unique properties of improper signal constellations. It developed for both perfect and imperfect CSI. An iterative joint linear transceiver design for both downlink and uplink MU-MIMO systems under improper constellations was proposed in [86–89], and the problems of noniterative SVD-based precoder and decoder for uplink MU-MIMO systems with improper constellations are also examined in [90]. It focuses on the case of both perfect and imperfect CSI. Figure 8 illustrates the performance of the joint precoder and decoder design for both the downlink and uplink MU-MIMO systems in [86] for BPSK. It is observed from the simulation results that the BER performances for both uplink and downlink transmission are almost identical, and also it is shown that the performance improves when the number of data streams $\boldsymbol{B}$ is reduced.

H. Precoder Design in OFDM Communication Systems

OFDM is one of the multicarrier modulation techniques that transmit signals through various subcarriers. These carriers have distinctive frequencies, and they are orthogonal to one another [91]. OFDM counteracts ISI by embedding a Guard Interval (GI) utilizing a CP, and it moderates the frequency selectivity of the multipath channel with a straightforward equalizer [92]. The peak-to-average power ratio (PAPR) was one of the real downsides of the OFDM frameworks [93]. Numerous PAPR decrease strategies were proposed in the literature, for example, constellation shaping [94], stage streamlining [95], nonlinear companding transforms [96], and precoding-based techniques [97, 98].

A significant issue in the design of a communication system is to manage multipath fading, which causes greater performance degradation in terms of both the reliability of the connection and the data rate. A productive approach to battle fading is to apply diversity techniques. LCP, otherwise called signal space diversity, is an influential method to endeavor the variety of high diversity order channels [99, 100]. Applications of LCP have been considered in different OFDM frameworks [101, 102], with and without channel coding. Uncoded multidimensional modulation schemes with an intrinsic diversity order, which accomplishes a significant coding gain over fading channels, were proposed in [100]. Modulation diversity can be expanded by applying a particular pivot to a classical signal constellation in such a way that any two points accomplish the greatest number of distinct components. Specifically, subcarrier grouping was acquainted [101] with partitioning the set of subchannels into subsets. Inside every subset, a linear constellation specific precoder was then designed to boost both the multipath diversity and the coding gains. Likewise, precoding over groups of subcarriers permanently diminishes the complexity of the receiver.

The OFDM system has the problem of ICI, which results from the loss of orthogonality between the subcarriers because of the carrier frequency offset (CFO). So, it needs to reduce the ICI. Several methods [103, 104] have been developed to show the effect of ICI on the performance of OFDM systems. In [103], upper and lower bounds on ICI power of OFDM in uniform scattering and Gaussian scattering channels are analyzed. In [105], an analytical BER of OFDM systems with pulse shaping for ICI reduction employing selective diversity and Maximal Ratio Combining (MRC) diversity in Rayleigh fading environments is proposed. In [106], precise closed-form BER expressions for BPSK OFDM frameworks disabled by the frequency offset are determined for both flat and frequency-selective Rayleigh fading channels.

To benefit frequency diversity inherent in a multipath fading channel, the technique of LCP has been introduced for OFDM [100, 107, 108]. Furthermore, LCP can be implemented in conjunction with subcarrier grouping in order to maximize both diversity and coding gains [109]. If properly designed, subcarrier grouping can diminish the complexity of the receiver without influencing the maximum diversity and coding gains.

In LCP [110–112], the data bits are initially mapped to different symbols having a place with a regular constellation. These various symbols are accordingly rotated (i.e., multiplied) by a square spreading lattice. Then, subcarrier grouping is applied to split the set of associated subchannels into subsets of uncorrelated subchannels. The complexity of the precoder and decoder designs is greatly simplified when subcarrier grouping is performed. The fundamental downside of the subcarrier grouping proposed in [109] is that the solution is just accessible when the group size is equivalent to the quantity of channel taps. Moreover, the procedure suggested in [109] is not unique when the group size is more important than the number of channel taps. It was later indicated in [102] that the maximum diversity gain increase can be accomplished with any subcarrier grouping scheme; the length of its group size, F, is at least the number of valid resolvable paths, L. It ought to be called to attention that both references [109] and [102] just consider linear constellation spreading.

A novel nonlinear constellation is precoding (NCP) technique based on the maximum distance separable (MDS) codes has been recently proposed in [113]. This new procedure has the adaptability of supporting any number of diversity channels and craved diversity order. In general, the diversity order is expressed as the minimum Hamming distance between any two coordinate vectors of constellation points, although the coding gain is the minimum product distance between any two constellation points. The code is known as an

MDS code if it attains the Singleton bound [114] and it can augment the minimum distance between codeword sets. Compared to linear constellation precoding techniques, the nonlinear precoding method based on MDS codes always has its precoded symbols residing on the smallest possible regular constellation so that the average transmitted power for all the diversity channels stays the same. Furthermore, the linear constellation is spreading methods proposed in [109] and [102] use the ML decoding, whereas the nonlinear MDS precoding method can be used with the DCS decoding method [113]. The DCS decoding method has a much lower computational complexity at the cost of marginal performance loss.

Reference [115] investigates the performance of an OFDM system over a Rayleigh fading channel in which the novel NCP technique is implemented along with subcarrier grouping. The novel NCP method is designed on the basis of the MDS codes to maximize both the diversity and the coding gains. It will be shown that nonlinear precoding leads to a significant performance improvement over the linear method [102]. The advantage of using subcarrier grouping together with the nonlinear constellation precoding is illustrated in [115]; in addition, the effect of ICI induced by CFO in the proposed NCP OFDM systems is analyzed.

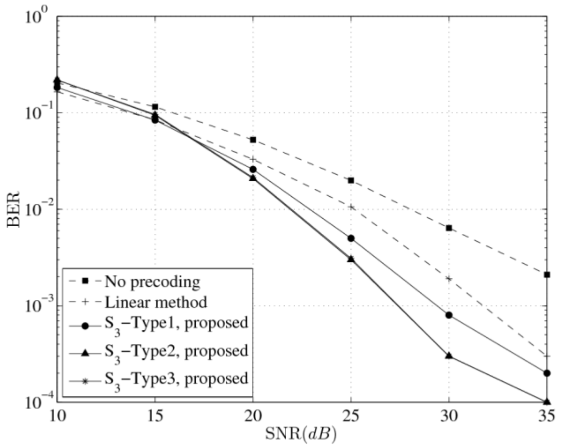

Fig. 9. Performance comparison of precoding and without precoding in the OFDM system under a correlated fading channel and ML decoding.

Here, we present the simulation results to show the advantage of using precoding techniques in OFDM systems [115]. Figure 9 displays the BER performance of the novel NCP based on MDS codes such as $\boldsymbol{\zeta_{S_3}} -$ ***type1***, $\boldsymbol{\zeta_{S_3}} -$ ***type2***, and $\boldsymbol{\zeta_{S_3}} -$***type3*** in OFDM for ML decoding algorithms under a correlated fading channel. It compares the performance of the nonlinear based precoding technique with a linear based precoding technique which has a diversity order of 2. The LCP method utilizes a 16-QAM constellation to have the same throughput as three-diversity channel joint modulation techniques in OFDM systems (*3-DCJMT-OFDM*), and *3-DCJMT-OFDM* utilizes a 64-QAM. It is clear from Fig. 9 that a performance improvement is accomplished using either the linear or the nonlinear precoding techniques in OFDM contrasted with or without precoding.

I. Problems and Possible Solutions in Precoder and Decoder Designs in MIMO and OFDM Systems

In order to exploit the benefits of MIMO systems, precoding or joint transceiver design for SU-MIMO or MU-MIMO systems is of great meaning and has been extensively studied [116–118]. Optimum precoder and decoder designs can significantly improve the performance of the MIMO system and can even reduce its sensitivity to channel estimation errors. From different design purposes or to tackle different problems, the criteria of transceiver design can be various. In general, the transceivers are designed for two main purposes: (1) to improve the capacity and (2) to minimize the MSE of output data. The capacity improvement mainly focuses on increasing the throughput between the transmitter and the receiver. Usually, it is aimed at the problem of how much information can be transmitted over the wireless channel under a transmit power constraint. On the other hand, the minimum MSE design criterion aims to solve the problem of how accurately a transmitted signal can be recovered from the received signal.

In order to minimize the information estimation lapse from the received signal, minimum MSE is a vital parameter for transceiver designs [22, 42, 119]. To avoid the implementation complexity of nonlinear transceiver designs, a linear minimum MSE (LMMSE) based transceiver design is used. Along these lines, the LMMSE transceiver design for MIMO frameworks has been broadly studied in different situations in the past decade [22, 42, 119].

With joint linear transceiver designs, a MIMO framework exploits the spatial diversity or spatial multiplexing that enhances both the SNR and the throughput. The SNR improvement is also attained by means of beamforming. Gains in terms of beamforming are called array gains or antenna gains. For joint precoder and decoder designs of MIMO systems, different performance measures have been viewed as, for example, minimum weighted MSE [22], maximum mutual information [23], minimum TMSE from all data streams [23], minimum Euclidean distance between received signal points [120], and minimum BER [121]. Out of all the criteria, the minimum TMSE criterion prompts a lower BER. Subsequently, the TMSE transceiver design for MIMO frameworks has been widely considered in different situations in the previous decade [119, 122].

Precoders or linear precoders and decoders have been planned under different presumptions of CSI. Most of the past MIMO frameworks are designed by utilizing proper modulations [56] with the suspicion of perfect CSIR and/or CSIT. Just few studies have considered imperfect CSI and the effect of channel estimation error and additionally channel correlation at both the transmitter and the recipient. Then again, in many cases of practical interest, the symbol arrangement was an improper random process. All things considered, when applying the conventional transceiver design to the improper modulation schemes, the BER performance gets fundamentally corrupted. In the case of OFDM, the cost paid for OFDM's simplicity is the loss of multipath diversity, due to the fact that every symbol is transmitted over a single flat subchannel and due to the inability to ensure improper modulation schemes when channel nulls happen on those subchannels. The LCP is proposed in the OFDM framework to endeavor the multipath diversity [123, 124]. LCP can be executed in conjunction with subcarrier grouping, keeping in mind the end goal of attaining both the diversity and the coding gains [125–127].

III. Conclusions

In this survey, precoder or joint precoder and decoder designs for SU-MIMO, MU-MIMO, and OFDM systems are analyzed under both imperfect and perfect CSI. The optimum precoder and/or transceiver have been obtained from different performance measurements, such as weighted MMSE, minimum BER, and minimum TMSE. It was found that, among all these performance measurements, the minimum TMSE criterion leads to a better performance in terms of BER. Additionally, the precoder or joint precoder and decoder designs have been studied under different presumptions of CSI. Because of the time-shifting nature of the wireless channels, acquiring the CSI at the receiver and then providing it as feedback to the transmitter can be troublesome. Normally, the obtained CSI is not the same as the original CSI. It was additionally suggested that a superior precoder and decoder design can be obtained by considering the error in channel estimation. This precoder or joint precoder and decoder design criterion is ideal for systems with proper modulation techniques. The current SU- and MU-MIMO systems are not suitable for systems employing improper modulation techniques, and their performance can be enhanced by outlining the MIMO system with modified cost functions and by exploiting the properness of signal constellations. The computation complexity of iteration-based algorithms was additionally uprooted by proposing another non-iteration-based algorithm in MIMO systems.

For the instance of OFDM systems, a novel nonlinear signal space diversity method focused on MDS codes joined with subcarrier grouping is proposed to replace the current LCP scheme. A massive performance increase of all the precoding-based OFDM designs without precoding OFDM designs in terms of the system's BER has been completely exhibited with simulation results. This section introduces some of the issues that remain to be investigated, in addition to conceivable future exploration points propelled by the consequences of this overview.

- For diminishing design complexity, an SVD-based beamforming system with a convolutional encoder can be stretched out for another beamforming structure focused around transmit MRC that joins adaptive bit loading and power allocation.
- The noniterative algorithm based joint precoder and decoder can be designed for SU-MIMO systems with both perfect and imperfect CSI.
- The noniterative SVD-based joint precoder and decoder designed for uplink MU-MIMO systems can be easily extended to downlink MU-MIMO systems with both perfect and imperfect CSI.
- A joint precoder and decoder design for SU- and MU-MIMO systems employing improper constellations can be extended to a transceiver for LTE SC-FDMA systems using improper constellations.
- In order to maximize both the diversity and the coding gains in MIMO-OFDM systems, the proposed novel NCP technique based on MDS codes in OFDM systems with subcarrier grouping can be extended to the MIMO-OFDM systems.

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