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NEAR OPTIMAL MULTIPOINT RECEIVE BEAMFORMING WITH FINITE SAMPLES

Receive beamfoming techniques play an important role in MIMO communications systems as means to mitigate interference and enhance the link quality. Multipoint receive beamforming methods are expected to provide additional gains in systems employing advanced coordinated multipoint processing. Due to its importance, receive beamforming has been studied extensively in the literature. The optimal detection schemes are well known in the case of perfect channel knowledge at the receiver. The more realistic case, where the beamformer is constructed using a finite training sequence transmitted by the desired transmitter has also been addressed. The study of the latter case, known as finite sample beamforming, focused on linear detection. In this paper we propose new nonlinear finite sample detection schemes for the case of multiple spatial streams. We show that the proposed schemes significantly outperform the known linear detectors and exhibit near optimal performance. We also show that the complexity of the proposed schemes is very similar to that of standard multi stream MIMO detectors, which makes them ideal for real life systems. We apply the new schemes to uplink space division multiple access and demonstrate the implementation and respective performance gains over standard detectors. Finally, we apply our approach to the case of coordinated multipoint reception where multiple base stations jointly decode multiple spatial streams. We study the tradeoff between performance and backhaul capacity and suggest near optimal finite sample schemes.

Receive beamforming, Finite sample size beam- forming, CoMP, Spatial multiplexing, MIMO systems.

1. Introduction

Multiple input multiple output (MIMO) techniques are an important means to improve the performance of wireless systems and are considered one of the most important technological building blocks underlying 4G. Different MIMO transmission and reception techniques provide various gain. These include diversity gain, array gain, multiplexing gain and interference suppression capabilities [5].

One of the Mima schemes that has drawn considerable attention and has become an integral part of modern communications standards is spatial multiplexing (SM). In SM M transmit antennas transmit independent information simultaneously, using the same time and frequency resource. The signal are received by an array of $N > M$ receive antennas. In uncorrelated Rayleigh and additive white Gaussian noise (AWGN) SM provides multiplexing gain of M, diversity gain of N and array gain of N/M [1]. For example, for $M = 2$ transmit antennas and $N = 4$ receive antennas, SM gives multiplexing gain of 2 together with diversity gain of 4 and array gain of 3dB. With such tremendous gains the advent of SM is no wonder. These gains however, go not come without a price. SM detection is usually an involved task since the optimal decoder is exponentially complex. Moreover, SM operates best at high signal to interference and noise ratio (SINR) [5] so it is rather vulnerable to interference.

Another prominent MIMO technique and one that goes a long way back is receive beamforming (R x BF). RxBF exploits the spatial domain to suppress interference and maximize the SINR respective to a desirable signal [7]. Intuitively, when the number of dominant interference sources is small enough, RxBF techniques focus set of vectors that are orthogonal to the channels from the interferers. The beamformer is the vector that maximized the power of the received signal within that set. This way, using N receive antennas, the beamformer may null out (in some scenarios) significant interference from up to N – 1 sources (spatial nulls).

Since most modern communications systems are interference limited [2, p. 507], the fusion between SM and RxBF is natural. In case of perfect channel knowledge at the receiver the optimal detection schemes for single transmitter and SM are known and simple. The more realistic case, where the beamformer is constructed using a finite training sequence transmitted by the desired transmitters has also been addressed in the literature [3, p. 201]. This case, known as finite sample size beamforming (FSSB), has been a subject for significant study mostly focusing on linear detection and a single transmitter.

In this paper we propose a new near optimal FSSB method tailored for SM. The reuses standard mechanisms and detectors in a new arrangements so its complexity is very similar to that of regular SM detectors, which are designed for AWGN rather than strong interference. We also consider the employment of the new FSSB SM method in a system including coordinated multipoint (CoMP) reception. We discuss fundamentally different scenarios and propose a method that significantly reduces the required backhaul.

The paper is organized as follows. In Section 2 we discuss the optimal detection schemes when full channel knowledge is available. In Section 3 FSSB for single transmitter is presented followed by immediate solution for FSSB SM. In Section 3 the new FSSB SM method is presented. In Section 4 we consider the employment of FSSB SM in a system including CoMP. In Section 5 we give simulation results. Section 5 contains discussion and conclusions.

2. RXBF with Perfect Channel Knowledge

We begin with the a simple flat fading MIMO communications system with a single transmit antenna and N receive antennas. The mathematical model of the received signal $y = (y_1, ..., y_N)^T$ reads:

$$y = hs + \upsilon \, , \tag{1}$$

where h is a channel vector from the desired transmitter, s is the QAM signal transmitted by the desired transmitter and υ is a noise and interference vector. We further assume for simplicity that υ is Gaussian vector with zero mean and covariance matrix C, and that υ is independent of s. The maximum likelihood (ML) estimators $\tilde{s}$ of s reads

$$\tilde{s} = \arg\min_{s \in QAM} \left(y - hs\right)^{*} C^{-1}\left(y - hs\right), \qquad (2)$$

where $(\cdot)^{*}$ denotes conjugate transposition. The ML estimator $\tilde{s}$ may be rewritten as

$$\tilde{s} = \arg\min_{s \in QAM} |\hat{s} - s|^{2}, \qquad (3)$$

where $\hat{s}$ is the global minimizer of the quadratic cost on the r.h.s. of (2)

$$\hat{s} = \frac{h^{*} C^{-1}}{h^{*} C^{-1} h} y \,. \qquad (4)$$

The resulting row vector beamformer

$$\omega_{\mathrm{MVDR}} = \frac{h^{*} C^{-1}}{h^{*} C^{-1} h}, \qquad (5)$$

is known as the minimum variance distortionless response (MVDR) beamformer [4, p. 80]. Using the matrix inversion lemma, we arrive at an alternative expression for the MVDR

$$\omega_{\mathrm{MVDR}} = \frac{h^{*} R^{-1}}{h^{*} R^{-1} h}, \qquad (6)$$

where R is the covariance of y

$$R = C + hh^{*}. \qquad (7)$$

The expression (7) may be useful when explicit knowledge of interference and noise covariance C is not available, but knowledge of measurements covariance R is. We further note that the MVDR beamformer is a scaled version of the minimum mean square error (MMSE) beamformer.

$$\omega_{\mathrm{MMSE}} = h^{*} R^{-1}. \qquad (8)$$

so the MMSE beamformer is also optimal.

We continue with the more involved case of multiple $M > 1$ transmitters and $N > M$ receive antennas. Here M independent QAM symbols $s = \left(s_1, \ldots, s_M\right)^{T}$ are transmitted simultaneously in a spatial multiplexing (SM) fashion. This corresponds for example to uplink (UL) space division multiple access (SDMA) with M users, each transmitting from a single antenna. The mathematical model of the received signal is

$$y = Hs + \upsilon. \qquad (9)$$

In this case the ML estimator ss of the transmitted vector s is

$$\tilde{s} = \arg\min_{s \in QAM^M} (y - Hs)^* C^{-1} (y - Hs) . \quad (10)$$

Similarly to (3), the ML estimator may be written as

$$\tilde{s} = \arg\min_{s \in QAM^M} (\hat{s} - s)^* H^* C^{-1} H (\hat{s} - s), \quad (11)$$

where $\hat{s}$ is the global minimizer

$$\hat{s} = (H^* C^{-1} H)^{-1} H^* C^{-1} y, \quad (12)$$

and $H^* C^{-1} H$ in (11) is the inverse of the error covariance respective to $\hat{s}$.

$$E\{(\hat{s} - s)(\hat{s} - s)^*\} = (H^* C^{-1} H)^{-1}. \quad (13)$$

The matrix

$$W_{MVDR} = (H^* C^{-1} H)^{-1} H^* C^{-1}, \quad (14)$$

is the MVDR beamforming matrix. This means that in the presence of interference, SM detection sums up to per-user beamforming (12) followed by a nonlinear $M \times M$ ML decoder (11) which requires knowledge of the post beamforming error covariance.

Note that in this case of multiple users, a straight forward solution which lacks optimality is to apply the MVDR to each user independently, treating the signals transmitted by other users as interference. This solution is denoted as *per user MVDR*. Specifically, focusing on the detection of s_1, the model (9) is rewritten as

$$y = h_1 s_1 + \sum_{i=2}^{M} h_i s_i + \upsilon = h_1 s_1 + \upsilon_1 , \quad (15)$$

where the interference and noise term υ_1 is *approximated* by a complex normal vector with zero mean and covariance

$$C_1 = C + \sum_{i=2}^{M} h_i h_i^* . \quad (16)$$

It follows that the approximate beamformer for the detection of s_1 is

$$\omega_{\text{MVDR}}^1 = \frac{h_1^* C_1^{-1}}{h_1^* C_1^{-1} h_1} . \quad (17)$$

3. Finite Sample Size Beamforming

In practice, however, the receiver is not equipped with full knowledge of the channel and the covariance of the noise and interference term. These are usually estimated at the receiver using known pilots signals. This problem is known as FSSB.

In the case of single transmitter, corresponding to (1) we assume K pilot signals p_i, ..., p_K are transmitted, resulting in the K measurements vectors y_1, ..., y_L. The FSSB problem may be formulated as finite sample minimum average square error problem [3, p. 201]

$$\hat{\omega} = \arg\min_{\omega} \sum_{k=1}^{K} \left|\omega y_k - p_k\right|^2, \tag{18}$$

with the solution′

$$\hat{\omega} = \hat{R}_{py} \hat{R}_{yy}^{-1}, \tag{19}$$

where $\hat{R}_{py}$ and $\hat{R}_{yy}$ are the empirical cross covariance vector and covariance matrix

$$\hat{R}_{py} = \frac{1}{K}\sum_{k=1}^{K} p_k y_k^* \ , \ \hat{R}_{yy} = \frac{1}{K}\sum_{k=1}^{K} y_k y_k^* \ . \tag{20}$$

Thus, in the case of a single transmitter, the FSSB method above suggests replacing the full channel statistics (as in (8)) with their empirical estimates.

When turning to the case of SM we have the following immediate solutions: First, similarly to the per user MVDR, we may construct a per user FFSB beamformer for each of the *M* users and detect each of them independently. However, this linear, zero forcing like approach, would lead to significant degradation in performance. Alternatively, we may create an empirical estimate $\hat{C}$ of C ,whiten the the interference and noise term and continue with a regular AWGN receiver. This solution is also problematic as it requires "quiet" zones in which no transmission from the desirable users is present [4, p. 201].

4. A New FSSB Method for SM

The new FSSB method is based on the application of the single transmitter FSSB discussed above to each of the users independently, followed by joint nonlinear ML detection. Note that the linear independent per-user FSSB may result in significantly correlated errors (non diagonal error covariance matrix). Thus, this error covariance is estimated, using the pilots and serves as an additional input to the ML detector.

Specifically, the i–th user transmits the pilots sequence p_1^i, ..., p_K^i , such that the vector $p_K = \left[p_K^1, ..., p_k^M\right]^T$ is transmitted in an SM fashion by all M users simultaneously. The corresponding received signal is

$$y_k = Hp_k + \upsilon_k \, . \tag{21}$$

The independent per-user FSSB for the *i*-the transmitter is

$$\hat{\omega}_i = \hat{R}_{p^i y} \hat{R}_{yy}^{-1}, \tag{22}$$

where $\hat{R}_{p^i y}$ is

$$\hat{R}_{p^i y} = \frac{1}{K} \sum_{k=1}^{K} p_k^i y_k^* . \tag{23}$$

Aggregating over all users, the beamforming matrix $\hat{W}$ is

$$\hat{W} = \left[\hat{\omega}_1^T \ \hat{\omega}_2^T \cdots \hat{\omega}_M^T \right]^T . \tag{24}$$

The post beamforming error covariance is estimated by reconstruction of the pilots. We apply the beamforming matrix □ to the y_k to reconstruct p_k

$$\hat{p}_k = \hat{W} y_k , \tag{25}$$

and subtract the known pilots vector p_k to estimate the error

$$\hat{e}_k = \hat{p}_k - p_k , \tag{26}$$

which leads to an estimate of the post beamforming error covariance

$$\hat{\Sigma} = \frac{1}{K} \sum_{k=1}^{K} \hat{e}_k \hat{e}_k^* . \tag{27}$$

Equipped with an estimate of the post beamforming error covariance, we conclude with joint $M \times M$ ML detection

$$\tilde{s}_{FS} = \arg\min_{s \in QAM^M} (\hat{s}_{EM} - s)^* \Sigma^{-1} (\hat{s}_{EM} - s) . \tag{28}$$

Where $\hat{s}_{EM}$ is the per user FFSB or empirical MSE estimator

$$\hat{s}_{EM} = \hat{W} y . \tag{29}$$

Using the Cholesky decomposition of the $M \times M$ covariance matrix Σ^{-1}

$$Q^* Q = \Sigma^{-1} . \tag{30}$$

The $M \times M$ ML detection problem (28) may be rewritten as

$$\tilde{s}_{FS} = \arg\min_{s \in QAM^M} (\hat{s}_{EM} - s)^* Q^* Q (\hat{s}_{EM} - s) = \arg\min_{s \in QAM^M} \left\| Q \hat{s}_{EM} - Qs \right\|^2 , \tag{32}$$

so it may be implemented using a regular $M \times M$ ML detector designed for white noise, where $Q \hat{s}_{EM}$ plays the role of the measurements vector and Q plays the role of the MIMO channel.

5. Multipoint FSSB for SM

When CoMP reception is applicable, multiple base stations (BSs) may jointly decode the information transmitted by the users. Coordinated reception is plays an important role in RxBF as the number of receive antennas determines the number of available spatial nulls. Specifically, when receiving M users in an SM fashion, an array of $N > M$ antennas can create up to $N - M$ spatial nulls [1, p. 945].

Considering for example a scenario including 2 BSs, each endowed with 4 receive antennas, 4 users transmitting in an SM fashion and 2 dominant interference sources. In this scenario each of the BSs cannot create any nulls by itself so the the interference suppression capability of each BS is poor. However, with coordinated reception, the total array has 8 receive antennas so the formation of 4 nulls is possible and the reception performance may significantly enhanced (a lot more than the 3dB implied by enhanced array gain). In a scenario that differs only in the number of users transmitting in an SM fashion, for example 2 users, the situation is different. Here each BS may create 2 nulls so they may suppress much of the interference independently.

We understand from the examples above that in case the BSs cannot suppress much of the interference independently, the beamformers should be computed jointly so rather raw data (e.g., the output of the FFT is OFDMA/SC-FDMA) should be passed from the collaborating BSs to an entity performing the joint detection.

In contrast, in case the BSs have sufficient number of antennas and can suppress much of the interference independently, much looser collaboration may suffice. For example, each collaborating BS may compute the log likelihood ratios (LLRs) of the transmitted bits independently and pass these to an entity performing the joint detection. Joint detection in this case may be approximated by LLR summation.

In order to quantify the difference in backhaul capacity requirements we focus on an LTE resource block (RB) including 84 resource elements (REs)or subcarriers (SCs) out of which 12 are pilots [6]. We further assume each BS has 4 receive antennas and 2 users transmit in an SM fashion. Finally we assume a fixed point implementation of 12 bit per I/Q at the FFT output and an LLR representation of 6 bits.

Following these assumption, joint computation of the beam-formers requires 84 [REs] · (12 + 12)[I and Q] · 4 [antennas] = 8,064 bits/RB. This number is independent of the modulation and the number of users. In case of QPSK, the LLR summation method requires 72 [data REs] · 6 [bits/LLR] · 2 [LLR/QPSK] · 2 [users] = 1,728 bits/RB and therefore 3,456 bits/RB and 5,184 bits/RB for 16 QAM and 64 QAM respectively. This means that the LLR summation method may significantly reduce the backhaul capacity requirements in case each BS in endowed with enough antennas to independently suppress much of the interference.

6. Simulation Results

In order to evaluate the performance of the proposed schemes we conducted a Monte Carlo simulation study. We started with the case of a single BS equipped with 4 Rx antennas and a single dominant interferer. The two desired users transmitted uncoded QPSK in SM fashion, including a training sequence of 32 pilots, and the interferer transmitted independent Gaussian noise so that the signal to interference ratio (SIR) was -10dB. All spatial channels were complex normal with zero mean and unit variance. The BS spatial correlation matrix used was

$$R_{BS} = \begin{bmatrix} 1 & 0,5 & 0,3 & 0,2 \\ 0,5 & 1 & 0,5 & 0,3 \\ 0,3 & 0,5 & 1 & 0,5 \\ 0,2 & 0,3 & 0,5 & 1 \end{bmatrix}, \tag{32}$$

and the users were assumed spatially independent, so the MIMO 8 x 8 correlation matrix was the Kronecker product

$$R_{MIMO} = I_{2\times 2} \otimes R_{BS} . \tag{33}$$

The BER curves corresponding to the optimal decoder (11), the optimal per user MVDR (2) which considers the other transmitting user as interference, the per user FSSB (8) and the proposed FSSB for SM (24) are given in Fig. 1.

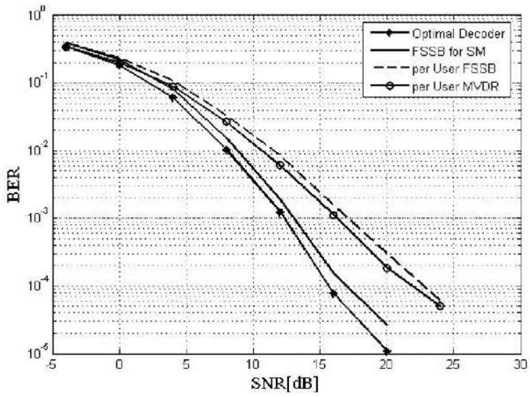

Fig. 1. BER curves for the case of a single BS with a single dominant interferer

We note that the DO of the optimal decoder is 3 and that of the per user MVDR is 2. Due to the large number of pilots (32), the BER curve of the proposed FSSB for SM is very close to that of the optimal decoder. Similarly the curve of the per user FSSB is very close to that of the per user MVDR. The difference in DO between the FSSB for SM and the per user FSSB results in a significant performance gain at low BER values (e.g., approx. 6 dB at BER = 10^{-4}).

The BER curves corresponding the scenario of 2 dominant spatially independent interferers are give in Fig. 2.

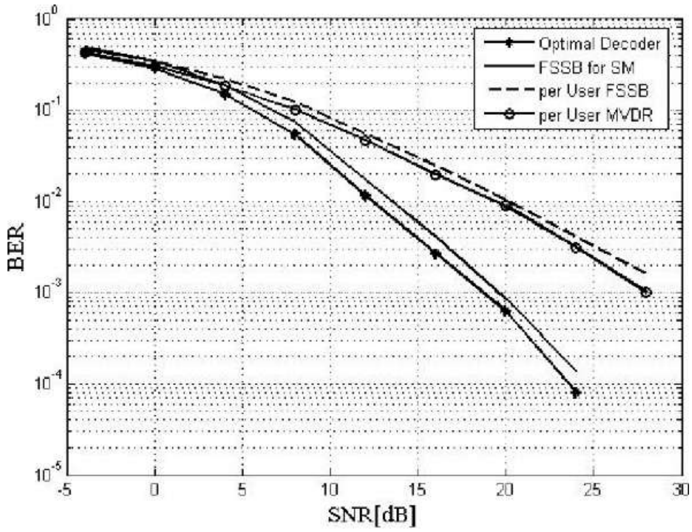

Fig. 2. BER curves for the case of a single BS with two dominant interferers

Here too the SIR is -10 dB taking both interferers into account. The DO of the optimal decoder and the FSSB for SM is 2 and that of the per user MVDR and FSSB is 1. The more significant difference (2 vs. 1 in this case compared with 3 vs. 2 in the case of a single interferer) in DO between the FSSB for SM and the per user FSSB increases the performance gap.

Turning to the case of multiple BSs with independent spatial channel (to capture the geographical separation), we considered two scenarios. In the first, the number of interferers is small enough (2 interferers) to allow decoding at each BS independently with reasonable performance. In the second, the number of interferers (3 interferers) does not allow decoding with reasonable performance at each BS independently and joint decoding should be considered.

The BER curves corresponding the scenario of 2 BSs and 2 dominant spatially independent interferers are give in Fig. 3.

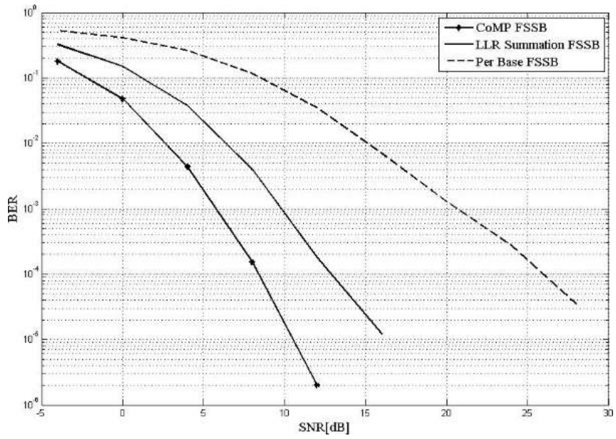

Fig. 3. BER curves for the case of a two BS with two dominant interferers

The DO of the CoMP FSSB decoder,which uses all 8 reception antennas for beamforming, is 6 and that of the per BS FSSB is 2. The DO of the LLR summation combiner is approx. 2.5 and shows significant performance gain over the per BS FSSB. The BER curves corresponding the scenario of 2 BSs and 3 dominant spatially independent interferers are give in Fig. 4.

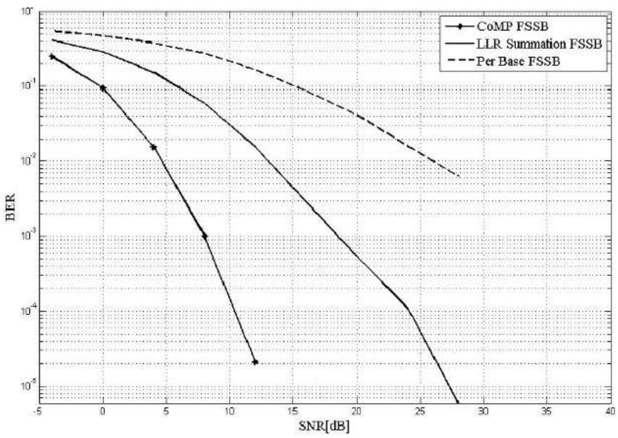

Fig. 4. BER curves for the case of a two BS with three dominant interferers

The DO of the CoMP FSSB decoder is 5 and the per BS FSSB does not decode with reasonable performance. In this case the LLR summation combiner also gives poor results (though better than that of the per BS FSSB).

7. Discussion and Conclusions

In this paper we proposed a new FSSB scheme for SM which employs per user FSSB followed by error covariance estimation and ML detection. We also considered the application of the proposed scheme to CoMP reception end considered several joint detection options, each requiring different backhaul capacity.

The proposed method is attractive since it exhibits performance that is very close to the optimal decoder in the presence of strong interference, offering a very significant performance gap over the linear per user FSSB. Moreover, the complexity of the proposed method is similar to that of the ordinary per user FSSB plus that of standard ML detection. When CoMP is applicable and the number of interferers is sufficiently low, simple low complexity and low backhaul capacity coordinated detection is possible, leading to significant gains over independent BS processing.

More advanced issues, including an analysis of the rate of convergence in the proposed method compared to «quiet zone» methods, and analysis of LLR summation method performance will be given in a forthcoming paper.

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