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Information aging in massive MIMO systems affected by phase noise

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Abstract

In massive MIMO systems, phase noise can spoil the performance of the usual receiver techniques. The problem arises because of the aging of phase-noise information based on pilots. In this paper, in a realistic 5G uplink scenario, we quantify the impact of information aging and we propose an iterative receiver based on expectation-maximization (EM). Simulation results show that the iterative receiver is robust to information aging related to phase noise.

1 Introduction

Massive multi-input multi-output (MIMO) is a key technology to support high data rates in 5G cellular systems. In massive MIMO systems, the base station (BS) is equipped with many antennas, allowing to communicate to several multiantenna users sharing the same time-frequency resources. With ideal channel state information (CSI), in the uplink, the symbols coming from all users can be correctly demodulated by properly filtering the received signal, in order to reduce the interference among different users.

The crucial problem for massive MIMO systems is thus acquiring a sufficiently good CSI, which is a nontrivial task, due to the large number of antennas involved both at the transmitter and at the receiver side. Typically, pilots are periodically transmitted to estimate the channel, and the latest available channel estimation is used to filter the received signal and demodulate the user symbols. Consequently, if the channel changes (due to, e.g., mobility) between two successive pilot transmissions, data are demodulated based on obsolete CSI, i.e., *information aging* takes place.

This is especially true whenever phase noise at the transmitter and at the receiver side affects the signal. Phase noise typically has a faster dynamics than channel fading, and its impact on the performance of filtering at the BS may impair correct data demodulation. It becomes thus of paramount importance to evaluate the impact of CSI aging due to phase noise. This is the subject of several works from the literature, in different scenarios ([1]-[3]). However, most of such works do not propose phase-detection techniques to mitigate the effect of phase noise.

In this work, we investigate the application of the iterative phase detector described in [4] to the uplink of massive MIMO systems. Since the phase detector is applied at the BS receiver, we assume that it is able to cope with the additional computational burden. By simulation, we show the benefit of phase recovery and the impact of the model parameters to the overall performance.

The remaining of the paper is organized as follows. In Section 2, we describe the massive MIMO system and the frame structure. In Section 3, we introduce the EM-based iterative receiver. In Section 4, we show simulation results to assess the performance of the proposed receiver. Finally, in Section 5, we draw some conclusions.

2 System description

Consider an $N_t \times N_r$ massive MIMO channel with O_t oscillators at the transmitter and O_r oscillators at the receiver. Each transmit-side oscillator feeds $N_{o,t} = N_t/O_t$ antennas, while $N_{o,r} = N_r/O_r$ receive antennas are fed by the same oscillator. Different oscillators introduce independent phase noise. The input-output relationship at time $n = 1, 2, \dots$ is given by

$$\mathbf{y}[n] = \Phi_R[n]\,\mathbf{H}[n]\,\Phi_T[n]\mathbf{x}[n] + \mathbf{z}[n] \qquad (1)$$

where:

- $\mathbf{H}[n]$ is the $N_r \times N_t$ channel matrix at time n;
- $\Phi_T[n] = \text{diag}\left(e^{j\phi_1[n]}, \dots, e^{j\phi_{O_t}[n]}\right) \otimes \mathbf{I}_{N_{o,t}}$ and $\Phi_R[n] = \text{diag}\left(e^{j\phi_{O_t+1}[n]}, \dots, e^{j\phi_{O_t+O_r}[n]}\right) \otimes \mathbf{I}_{N_{o,r}}$ are the diagonal matrices of transmit and receive phase-noise coefficients at time n, respectively, assumed to be unknown at both sides;
- $\mathbf{x}[n]$ and $\mathbf{y}[n]$ are the column vectors of the N_t transmitted symbols and N_r received samples at time n, respectively;
- $\mathbf{z}[n]$ is a size-N_r vector of zero-mean, circularly-invariant Gaussian-noise samples, with variance σ^2 per real dimension, which are supposed to be independent across time and receive antenna.

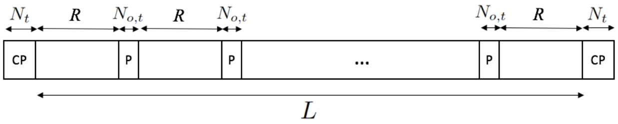

Figure 1. Frame structure.

For the phase-noise samples, time dependency is kept into account by assuming Wiener phase-noise processes:

$$\phi_i[n] = \phi_i[n-1] + w_i[n], \; i = 1,\dots,O_r+O_t, n = 1,2,\dots \tag{2}$$

where $\phi_1[0],\dots,\phi_{O_r+O_t}[0]$ are independent and uniformly distributed over $[0,2\pi)$ and $w_i[n],\dots,w_{O_r+O_t}[n]$, are independent zero-mean white Gaussian processes with power ρ^2 (all processes have the same power).

Let us notice that each tap of the MIMO channel is affected by a *sum* phase-noise process:

$$\phi_{ii'}[n] = \phi_i[n] + \phi_{O_t+i'}[n], \; i = 1,\dots,O_t, i' = 1,\dots,O_r \tag{3}$$

which is the sum of one transmit and one receive *atomic* phase-noise process. We define for future use the size-(O_t+O_r) vector $\phi[n]$, whose i-th element is $\phi_i[n]$, $i = 1,\dots,O_r+O_t$.

2.1 Pilot-based channel estimation

Fig. 1 shows the structure of the transmitted frame. Every L channel uses, channel estimation is performed through the transmission of N_t channel pilots (labelled "CP" in the figure). The channel matrix $\widehat{\mathbf{H}}$ estimated at the beginning of a data frame is used for the whole frame, although the channel may experience variation between two channel estimation stages.

Every R data channel uses, other pilots are transmitted (labelled "P" in the figure), which are used for phase detection only, since phase noise is assumed to vary much faster than channel coefficients. Such pilots take O_t channel uses, during which only one group of transmit antennas fed by the same oscillator are switched on, while the others are switched off.

The parameter R must be chosen according to a trade-off between two conflicting exigences. R should be chosen as large as possible in order to increase the transmission efficiency, defined as

$$\eta = \frac{R}{R+O_t} \tag{4}$$

On the other side, as shown in Figures 3-4, phase-noise information aging takes place between two successive phase estimation stages, and the larger R, the more relevant is the impact of this information aging on receiver performance. So, R should be kept not too large in order to avoid exceeding a prescribed value of the *Age of Information* (AoI), defined in this paper as

$$\text{AoI} = \frac{R\rho^2}{1 \text{ degree}^2} \tag{5}$$

The above definition, which is equal to the variance of the Wiener increment of phase noise between two successive pilot transmission stages, is proposed to take into account both the inter-pilot data burst length and the phase noise dynamics.

3 EM-based receiver

Suppose a frame of L symbol vectors $\mathbf{X} = (\mathbf{x}[1],\dots,\mathbf{x}[L])$ is transmitted through the channel described by (1) and let $\mathbf{Y} = (\mathbf{y}[1],\dots,\mathbf{y}[L])$ be the channel output. Also, define $f_A(\Phi)$ the a priori distribution of $\Phi = (\phi[1],\dots,\phi[L])$. As in [4], we consider an EM-based iterative receiver, whose block scheme is shown in Fig. 2.

At iteration l, $l = 1,2,\dots$, the EM algorithm performs the following two steps:

E step: The average over transmitted symbols is computed as follows:

$$h^{(l)}(\Phi) = E_{\mathbf{X}}^{(l)} \log \prod_{n=1}^{L} \Pr\{\mathbf{y}[n]|\mathbf{x}[n],\phi[n]\} \tag{6}$$

where the average is performed according to the distribution $\Pr\{\mathbf{X}|\mathbf{Y},\widehat{\Phi}^{(l-1)}\}$ for $l > 1$ and to the a-priori symbol distribution $\Pr\{\mathbf{X}\}$ at the first iteration.

M step: The following maximization problem is solved:

$$\widehat{\Phi}^{(l)} = \arg\max_{\Phi} \left(h^{(l)}(\Phi) + \log f_A(\Phi) \right) \tag{7}$$

For the channel model in (1), apart from an inessential additive constant, (6) becomes:

$$h^{(l)}(\Phi) = \sum_{n=1}^{L} \frac{\Re\{\widetilde{\mathbf{x}}^H[n]\Phi_T^H[n]\widehat{\mathbf{H}}^H\Phi_R^H[n]\mathbf{y}[n]\}}{\sigma^2} \tag{8}$$

where $\widetilde{\mathbf{x}}[n] = E_{\mathbf{X}}^{(l)}\mathbf{x}[n]$.

The a-posteriori probability on input symbols $\Pr\{\mathbf{X}|\mathbf{Y},\widehat{\Phi}^{(l-1)}\}$ is approximated through standard demodulation and possibly (if the transmitted message is encoded) decoding, for the current estimated value of phase noise. More precisely, we suppose that demodulation is performed by first applying a linear minimum mean-square error (LMMSE) filter in order to reduce the multiuser interference, and then by single-user demodulation of the LMMSE output. The LMMSE filter matrix at the l-th iteration is given by:

$$\mathbf{M}^{(l)} = \left(\widetilde{\mathbf{H}}[n]^{\mathsf{H}}\widetilde{\mathbf{H}}[n] + \sigma^2\mathbf{I} \right)^{-1} \widetilde{\mathbf{H}}[n]^{\mathsf{H}} \tag{9}$$

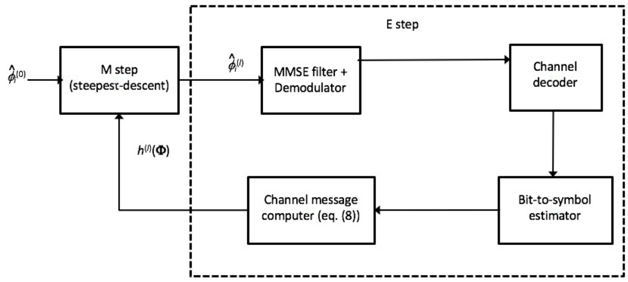

Figure 2. Block scheme of the proposed EM receiver.

where

$$\widetilde{\mathbf{H}}[n] = \widehat{\mathbf{\Phi}}_R^{(l)}[n]\widehat{\mathbf{H}}\widehat{\mathbf{\Phi}}_T^{(l)}[n] \tag{10}$$

As in [5], the maximization involved in the M step is approximated through the steepest-descent algorithm. Let $\widehat{\Phi}_m^{(l)}$ be the estimate of $\widehat{\Phi}^{(l)}$ after m steepest-descent iterations. Let the starting point be $\widehat{\Phi}_0^{(l)} = \widehat{\Phi}^{(l-1)}$ for $l > 1$ and $\widehat{\Phi}_0^{(1)} = \widehat{\Phi}_P$, where $\widehat{\Phi}_P$ is an initial estimate based on pilots (see [4] for more details). Then:

$$\widehat{\Phi}_{m+1}^{(l)} = \widehat{\Phi}_m^{(l)} + \lambda \nabla_{\Phi} \left(h^{(l)}(\Phi) + \log f_A(\Phi) \right) \Bigg|_{\widehat{\Phi}_m^{(l)}} \tag{11}$$

where λ is the step size of the steepest-descent algorithm and can be optimized numerically. See [4] for the explicit computation of the above gradient.

4 Simulation results

In this section, we show simulation results for the system described in the previous sections and higlight the benefit in terms of information aging due to the adoption of the EM-based receiver.

We consider a system with $K = 16$ users, each equipped with a two-antenna user equipment. Thus, we have $O_t = K = 16$ independent oscillators, each feeding $N_{ot} = 2$ antennas, for a total of $N_t = 32$ transmit antennas. The BS is equipped with $O_r = 8$ oscillators, each one feeding $N_{or} = 8$ antennas, for a total of $N_r = 64$ receive antennas.

Each user encodes its information bit stream with a 5G NR LDPC code of type 2 and lift factor $Z = 2$, with a length $N = 104$ bits and a rate equal to 0.8 [6]. Each frame transmits 1000 LDPC codewords. The employed modulation format is 256-QAM. The transmit power is normalized to 1 so that the signal-to-noise ratio on the channel is $E_s/N_0 = (2\sigma^2)^{-1}$.

In the simulations, we will suppose that the channel matrix is fixed for the whole frame and that channel estimation is perfect, i.e. $\widehat{\mathbf{H}} = \mathbf{H}$. Regarding phase-noise processes, the standard deviation of the increment is equal to $\rho = \sqrt{0.2}$ degrees. As a consequence of channel estimation, we can safely set the phase-noise values to zero at the beginning of the frame, i.e., $\widehat{\phi}_i[0] = 0$, $i = 1, \ldots, O_r + O_t$.

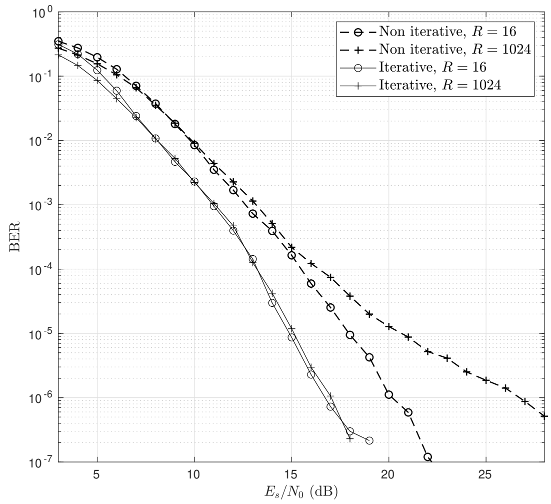

Figure 3. Performance of the proposed EM receiver with different values of R. AWGN channel.

At the receiver, the LDPC decoder implements the optimal BP algorithm with at most 50 iterations and genie-aided stopping rule. The phase detector performs at each receiver iteration 5 steps of the steepest-descent algorithm with a step size $\lambda = 2.5 \times 10^{-4}$. The computation of (8) is slightly simplified by substituting $\widetilde{\mathbf{x}}[n]$ with the hard estimates $\widehat{\mathbf{x}}[n]$ of the transmitted symbols. This simplification has been shown in [4] to have a negligible effect on performance. The decoder performs at most 10 iterations of the EM algorithm, but it stops earlier if the LDPC decoder triggers its stopping rule. For each E_s/N_0 value, we count 100 frame errors.

In Fig. 3, we show the performance of the receiver on the AWGN channel (solid lines), for different values of R, the length of the inter-pilot data burst. All entries of the channel matrix have magnitude 1. The line with circles is for $R = 16$, which corresponds to a low efficiency $\eta = 50\%$ and a low AoI $= 3.2$. The line with crosses is for $R = 1024$, corresponding to a high efficiency $\eta = 98.5\%$ and a high AoI $= 204.8$. The increase in AoI is well tolerated by the system as the performance degradation in passing from $R = 16$ to $R = 1024$ is less than 1 dB. As a comparison, in the figure, we have also plotted (dashed lines) the performance of a scheme in which we simply estimate the phase noise on the basis of pilots, without any feedback from the decoder to the phase detector. The results show that, in this case, information aging is apparent not only in the E_s/N_0 loss, but also in a lower slope of the $R = 1024$ curve with respect to the case $R = 16$.

In Fig. 4, we show the performance of the receiver on a Rice-fading channel with a Rice factor $K = 0$ dB. The channel matrix is constant for the whole frame. We can

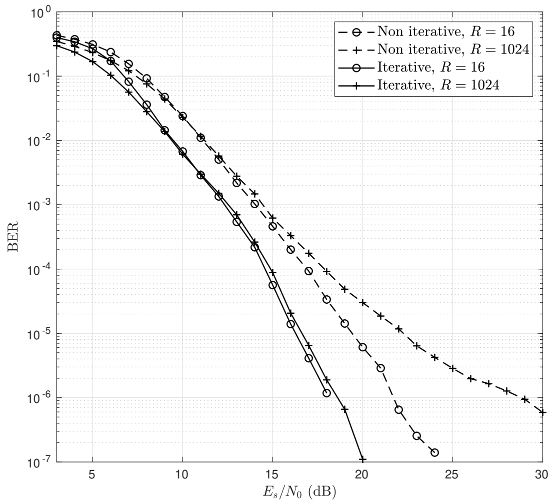

Figure 4. Performance of the proposed EM receiver with different values of R. Rice-fading channel with $K = 0$ dB.

draw the same conclusions as for the AWGN channel. The dashed curves, which correspond to the non iterative receiver, show the dramatic effect of information aging in going from $R = 16$ to $R = 1024$. The iterative receiver is much more robust to information aging, with the more efficient $R = 1024$ case losing only a fraction of dB with respect to the other. Comparing Fig. 4 with Fig. 3, we can see that the iterative receiver loses only a couple of dB due to fading.

5 Conclusions

In this paper, we have quantified the impact of information aging in a realistic massive-MIMO 5G uplink scenario. We have also proposed an iterative receiver based on expectation-maximization (EM), robust to information aging related to phase noise.

Future work can consider the impact of imperfect channel estimation on the system performance, the optimization of the receiver parameters, the performance analysis and the scaling law of performance with the number of antennas.

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