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Performance of Massive MIMO Systems with Transceiver Hardware impairments

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***Abstract*:** *Massive MIMO (multiple-input multiple-output) provides great improvements in spectral efficiency (SE) over legacy cellular networks, by coherent combining of the signals over a large antenna array and by spatial multiplexing of many users. Since its inception, the coherent interference caused by pilot contamination has been believed to be an impairment that does not vanish, even with an unlimited number of antennas. In this paper we study and evaluate the effect of transceiver impairments in massive MIMO Systems and pilot contamination. Also this paper discuss downlink, uplink massive MIMO system and prove that with LMMSE estimator, the SE grows without bound as the number of antennas increases, even under pilot contamination, under a condition of linear independence channels matrices.*

Keywords: *channel estimation ,CSI, Hardware impairments, LMMSE, Pilot contamination,*

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I. Introduction

Massive MIMO is the evolution of MU-MIMO that massively scales up the magnitude of MIMO. In the same time frequency resource tens of terminals are considered to be served with hundreds of base station antennas [1]. Basically massive MIMO will provide all the benefits of conventional MU-MIMO but at a very large scale. Massive MIMO is a technology of future that will provide broadband networks more security, robustness, energy efficiency and efficient use of spectrum. Massive MIMO requires good knowledge about the channel for both uplink and downlink channels for the fact that it uses spatial multiplexing. This can be easily achieved in uplink when terminals send pilots to the base station that can be used to estimate the channel. In the downlink it is more complex. First base station sends pilots to the terminals where they estimate the channel and quantize the so-obtained estimation; this estimation is then sent back to the base station.

Limiting factors of massive MIMO.A lot of research is being carried out in this domain still there are many open research problems that are to be solved yet. Mainly these problems include

1. Channel Reciprocity.
2. Pilot Contamination.
3. Orthogonality of Channel Responses and Radio Propagation.

Pilot contamination is the term associated with the negative effects of reusing pilots in more than one cells. Correlation of pilot se of channel that is contaminated by channels that use the same pilot sequence. Therefore considering downlink beamforming interference occurs in those terminals that have the same pilot sequence similar is the case for uplink transmissions. This interference increases directly with the increase in service antennas [2]. Pilot contamination is not only restricted to massive MIMO it is ageneral phenomenon but it is appears at a high rate in massive MIMOs than ordinary MIMOs [3]. The occurrence of pilot contamination degrades the performance.In this paper we show that performance of Massive MIMO System with the effect of transceiver impairments and the pilot contamination. Also discussed the downlink and uplink massive MIMO system and prove that with LMMSE estimator, the SE grows without bound as the number of antennas increases, even under pilot contamination, under a condition of linear independence channels matrices

1.2 Massive MIMO System Model

In this subsection massive MIMO system is discussed. It is assumed that channel experiences fading properties and hence channel estimation and data transmission are to be done within a specified time interval T_s. Wireless communication channels are random and independent realization between the blocks. Block T duration symbols, system model is

$$Y = \sqrt{\rho}\, HX + V \qquad (1)$$

where Y is representing received signal matrix at BS, X representing transmitted vector with size of T×M, H is channel matrix connected to BS and UE , V is additive white gaussian noise matrix and received expected SNR matrix is ρ. Further, it is assumed that V and H with zero-mean and unit-variance independent complex gaussian values.

1.3 Downlink Channel Estimation

Downlink channel estimation (CE) is evaluated in this subsection. Estimations have done based CSI on the transmitter pilot and send feedback to BS. Number of BS antennas is proportional to CE overheads and inefficient for MU-MIMO systems. Hence, channel reciprocity at BS via UL pilots is considered for CE.

Let τ is duration used for channel estimation and orthogonal pilot sequence of τ symbols where $\tau \geq K$ each user is assigned.

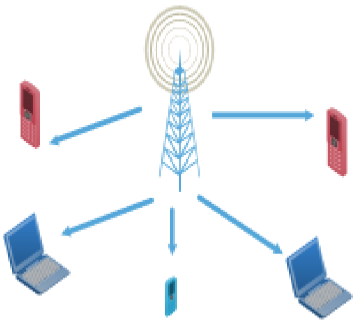

Figure 1 Massive MIMO downlink system

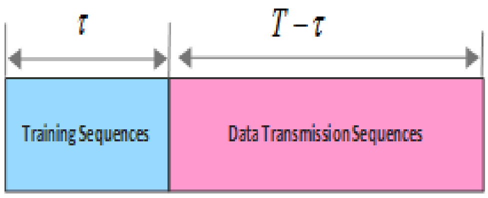

Figure 2 Downlink data transmission protocol

The $M \times \tau$ indicates *BS*received pilot matrix and can be represented as [5]

$$Y_p = \sqrt{p_p}\, H\Phi^T + N_p \qquad (2)$$

where pilot symbols is represented as $\Phi \in \tau \times K$, $N_p \in \mathbb{C}^{M\times\tau}$ is the additive noise at BS, His channel matrix between K users and BS and $p_p = \tau p_u$, where $p_u$is the power transmitting of each user. From (1), the channel can be estimated from [5] as

$$\tilde{Y}_p = \sqrt{p_p}\, H + W \qquad (3)$$

where $\tilde{Y}_p = Y_p \Phi^*$ and $W = N_p \Phi^*$

Let y_k and w_k be the k^{th}columns of $\tilde{Y}_p$ and *W*respectively. Then

$$\tilde{y}_{p,k} = \sqrt{p_p}\, h_k + w_k \qquad (4)$$

Assuming that BS uses MMSE channel estimation, the channel estimate of $h_k$is given by

$$\tilde{h}_k = \arg \min_{\tilde{h}_k \in M} E_{h_k, \tilde{y}_{p,k}}\left[\left\|\tilde{h}_k - h_k\right\|^2\right] (5)$$

Finally, we obtain the channel estimate of $h_k$as

$$\tilde{h}_k = \frac{\sqrt{p_p}}{p_p + 1}\tilde{y}_{p,k} = \frac{p_p}{p_p+1} h_k + \frac{\sqrt{p_p}}{p_p+1} w_k \qquad (6)$$

II. Zeroforcing(ZF) Equalization

ZF algorithm is common scheme popularly used in wireless communication which applies inverse of channel frequency response to receive signal for signal restorationbefore channel. It is corresponds to reduces the ISI to zero noise free environment, ISI more significant when it is useful.

Assuming transmitting antennas M_T is equal to receiving antennas M_R and channel matrix H as a full rank then received symbol is given by

$$Y = HX + N$$

where Y is received Symbol Matrix, H is Channel matrix, X is Transmitted symbol Matrix, and N is Noise matrix. The ZF detector (assuming Wwhich satisfies WH = I) is given by

$$W = \left(H^H H\right)^{-1} H^H \qquad (7)$$

where W is Equalization Matrix, though ZF equalization is simple and easy to implement it is not best possible equalizer as noise is also applied while performing equalization.

2.5 Minimum Mean Square Error (MMSE)

A MMSE estimator reduces the MSE is common measurement quality [7]. ISI does not eliminate completelyby using MMSE equalizer but, reduces the ISI in the output and total noise power.

$$Y = HX + N$$

MMSE approach finds coefficient W such that $E\left\{\left[W_{y-x}\right]\left[W_{y-x}\right]^{H}\right\}$ is minimized.

MMSE detector (assuming matrix W satisfies these condition WH= I) is expressed as

$$W = \left[H^{H} H + M_{T} I\right]^{-1} H^{H} \qquad (8)$$

Mobile channels have faster fading compared to cellular channels due to increase in mobility. Channel estimation schemes help in tracking fast fading channels when required. Linear MMSE estimation is better than the ZF scheme hence LMMSE technique is applied in our work.

III. Raning Based Channel Estimation(TBCE) Scheme

TBCE scheme sends known training sequence from the transmitter. In case of imperfect CSI we estimate the channel matrix when part of the transmitted matrix X is known at the receiver, TBCE schemes have two phases as given below

1) Training Phase: This model is expressed as part of the at the receiver

$$Y_{\tau} = \sqrt{\rho_{\tau}}\ X_{\tau} H + V_{\tau} \qquad (9)$$

$$X_{\tau} \in C^{T_{\tau}\times M}, tr X_{\tau} X_{\tau}^{*} = M T_{\tau}$$

where $Y_{\tau} \in C^{T_{\tau}\times N}$ is received matrix, ρ_{τ} is SNR during training phase, and X_{τ} is the training matrix for the period of T_{τ} and also known to the receiver.

2) Transmission Phase: This model can be written as

$$Y_{d} = \sqrt{\rho_{d}}\ X_{d} H + V_{d} \qquad (10)$$

$$X_{d} \in C^{T_{d}\times M}\ tr X_{d} X_{d}^{*} = M T_{d}$$

where $Y_{d} \in C^{T_{d}\times N}$ is the received matrix, during training phase ρ_{d} is SNR, and X_{d} is training matrix for the period of T_{d}.The above two phases can be combined in to a single model as

$$Y = \begin{pmatrix} Y_{\tau} \\ Y_{d} \end{pmatrix}, X = \begin{pmatrix} \sqrt{\frac{\rho_{\tau}}{\rho}} X_{\tau} \\ \sqrt{\frac{\rho_{d}}{\rho}} X_{d} \end{pmatrix} V = \begin{pmatrix} V_{\tau} \\ V_{d} \end{pmatrix} \qquad (11)$$

SNR and total time represented as $T = T_{\tau} + T_{d}\ \rho T = \rho_{\tau} T_{\tau} + \rho_{d} T_{d}$.

A lower bound is put on the capacity to find out the optimum parameters for obtaining the worst performance of cellular system. As the transmitted and received training sequences influence the accuracy of estimated channel it can be written as $\hat{H} = f\left(X_{\tau}, X_{d}\right)$. For the LMMSE estimated channel is given as

$$\hat{H} = \sqrt{\frac{1}{\rho_{\tau}}}\ \left(\frac{1}{\rho_{\tau}} I_{M} + X^{*}_{t} X_{t}\right)^{-1} X^{*}_{\tau} Y_{\tau} \qquad (12)$$

Now, the channel estimation with transceiver impairments is observed and then multiuser MIMO system performance is analyzed with hardware impairments impact.

IV. Transceiver Hardware Impairments

So far study on MU-MIMO is carried out by considering the ideal hardware. But ideally non impairments create the following disturbances:

1) Produce a divergence between generated signal and transmitted signal.
2) Received signal is distorted in the detecting process.

Wireless communication system has different types of hardware components and each of them has their own distortion and behavior[8]. Recently wireless communication system uses a generalised system for evaluate the effect of hardware impairments at BS and UE. This system can defined as

$$Y = \sqrt{\rho}\left(X + \eta^{UE}{}_t\right)H + \eta_r{}^{BS} + V \qquad (13)$$

In this model have extra two additive noise terms as compared traditional system model $\eta_t{}^{UE} \in C$, $\eta_t{}^{UE}$ and $\eta_r{}^{BS} \in C^{N\times M}$, $\eta_r{}^{BS}$ describe UE and BS different levels transceiver impairments. Covariance matrices for these models can be defines as

$$v_t{}^{UE} = \kappa_t{}^{UE}\rho^{UE}$$

$$\gamma_r{}^{BS} = \kappa_r{}^{UE}\rho^{UE}\ diag\left(\left|H_{11}\right|^2, ...,\left|H_{NM}\right|^2\right)$$

where $\kappa_r{}^{BS}$ $\kappa_t{}^{UE}$ is representing as receiver and transmitter hardware impairments.

LMMSE estimator of this channel model can be defines as

$$\hat{H} = \underbrace{X^*{}_d R\bar{Y}^{-1}}_{W} Y \qquad (14)$$

The covariance matrix $\bar{Y}$ is represented as

$$\bar{Y} = E\left\{YY^*\right\} = \rho^{UE}\left(1+\kappa_r{}^{UE}\right)R + \rho^{UE}\kappa_r{}^{BS}R_{diag} + X + \sigma_{BS}{}^2 I,\ \ R_{diag} = diag\left(r_{11}, ...r_{NN}\right)$$

ThereforeMSE is given by

$$MSE = E\left\{\left\|\hat{H} - H\right\|_2{}^2\right\} = tr\left(Z\right)$$

and covariance of error matrix Z is given by

$$Z = E\left\{\left(\hat{H} - H\right)\left(\hat{H} - H\right)^H\right\} = R - \rho^{UE}R\bar{Y}^{-1}R \qquad (15)$$

LMMSE estimator is in form of $\hat{H} = WY$ and Wminimizes MSE. MSE is given by

$$MSE = tr\left(R - X_d WR - X_d{}^* RW^H + W\bar{Y}^{-1}W^H\right) \ (16)$$

Because of this error decreases accuracy of the channel estimation which will affects the capacity and other useful parameters of the multiuser MIMO systems.

4.1 LMMSE Estimator

Performance of MU-MIMO system LMMSE channel estimator has the form $\hat{h} = Az$ is to be examined. Hence A minimizes MSE given by

$$MSE = tr\left(R - X_d WR - X^*{}_d RW^H + W\bar{Y}W^H\right) (17)$$

The channel rewritten as $H = \hat{H} + \varepsilon$, where $\hat{H}$ is the estimate given in equation (17) and $\varepsilon \in C^{N\times 1}$ is the estimation error unknown at the receiver. Hence a non linear estimator gives best MSEs is compared with LMMSE estimator.MSE performance slight changes, distortion noises are comparatively weak.

Let $R = \lambda I$ and S = 0, then covariance error matrix becomes

$$\Xi = \lambda \left(1 - \frac{p^{UE}\lambda}{p^{UE}\lambda\left(1+\kappa_r^{BS}+\kappa_t^{UE}\right)+\sigma_{BS}^{2}} \right) I \qquad (18)$$

For high SNR,

$$\lim_{p^{UE}\to\infty} \Xi = \lambda \left(1 - \frac{1}{1+\kappa^{BS}{}_r+\kappa_t^{UE}} \right) I \qquad (19)$$

This outcome explains the estimation average error per element in channel matrix which is independent of receiving antennas N. With pilot sequence power $p^{UE} = |d|^2$ estimation error is decreases; it does not reduce to zero as $p^{UE} \to \infty$ for the ideal hardware.

V. Simulation Results

5.1 Transceiver Impairments effect in Massive MIMO

In Fig.3, 50 antennas at the BS (i,e N=50) and zero interference (i.e., S = 0) is considered. The channel *covariance matrix R is generated using (exponential correlation model) [6]. The* $(i, j)^{th}$ *element of R is given by*

$$[R]_{i,j} = \begin{cases} \delta r^{j-i} & , i \le j \\ \delta\left(r^{i-j}\right)^{*}, & i > j \end{cases} \qquad (20)$$

where δ is any arbitrary scaling factor. This is a uniform linear array (ULA) model and correlation factor between any two adjacent antennas is given by $|r|$ for $0 \le |r| \le 1$ and phase of r represents the angle of arrival/departure.

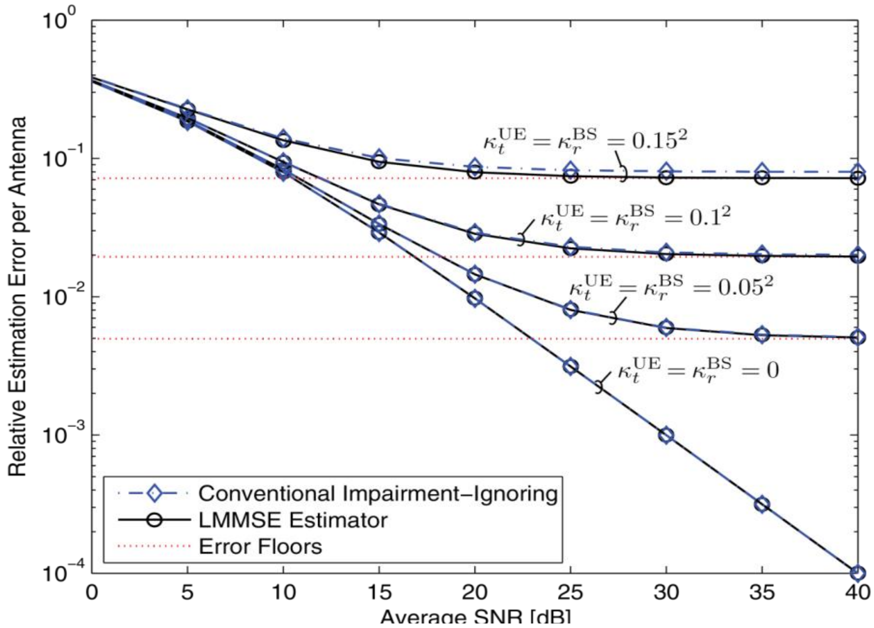

Fig.3: LMMSE estimator for Estimation error per antenna element and the conventional impairment neglecting MMSE estimator

In simulation, a channel with N_t number of transmitters and Nr no. of receivers with varying SNR is studied. Average channel capacity as the number of antennas are varied at the BS with hardware impairments.

Table 1: Error comparison for Different impairments levels

SNR in dB	Error per antenna		
	$\kappa_t^{UE} = \kappa_r^{BS} = 0$	$\kappa_t^{UE} = \kappa_r^{BS} = 0.05^2$	$\kappa_t^{UE} = \kappa_r^{BS} = 0.15^2$
0	$10^{-0.6}$	$10^{-0.6}$	$10^{-0.7}$
10	$10^{-0.9}$	$10^{-1.0}$	$10^{-1.1}$
30	$10^{-1.5}$		$10^{-3.1}$

From Table 2 the capacity limits to a specified value when SNR increases. Table 1 show the simulation results of various levels of impairments. Figure 3 plots the relative estimation error $MSE_{rel} = \frac{MSE}{tr(R)}$ versus average SNR in the uplink, where

$$SNR^{UL} = p^{UE} \frac{tr(R)}{N\sigma_{BS}^{2}} \qquad (21)$$

where p^{UE} is the SNR for the UE, considering various level of impairments.

Error vector Magnitude (EVM) is a common performance measure of transceivers. 3GPP LTE standard specifies that the total EVM should be in the range [0:08; 0:175]. Smaller EVM values support higher spectral efficiencies [4]. For EVM below 0.8 support all standardized modulations, the distortion noise power is non stationary which is proportional to current channel gain $\|h\|_2^2$ and the signal power p^{BS}. Proportionality coefficients κ_t^{BS} and κ_r^{UE} characterize the levels of impairments and are related to EVM. The EVM at the BS is

$$EVM_t^{BS} = \sqrt{\frac{E\left\{\left\|\eta_t^{BS}\right\|_2^2 \middle| H\right\}}{E\left\{\|s\|_2^2 \middle| H\right\}}} = \sqrt{\frac{tr\left(\Upsilon_t^{BS}\right)}{tr(W)}} = \sqrt{\kappa_t^{BS}} \qquad (22)$$

To predict the SE of UL, the impact of estimation error depends on number of antennas at BS. Suppose fraction of data allocated for channel UL transmission i.e. $T_{data}^{UL} / T_{coher} = 0.45$. The UL SE may be defined as

$$0.45\log_2\left(1+\frac{1-MSE_{rel}}{MSE_{rel}+\frac{1}{N_{SNR}^{UL}}}\right) \qquad (23)$$

Where $N_{SNR}^{UL} \to 1$ the SE 1.5 bits/s/Hz, $MSE_{rel} = 10^{-1}$ if the number of antennas is large and 4.5 bits/s/Hz, $MSE_{rel} = 10^{-3}$ respectively.

These bounds for under any CSI H^{BS} at the BS and H^{UE} at the UE lower bounds represent no instantaneous CSI in the decoding step the upper bounds represent perfect CSI. Though the gap between these extremes is large for ideal hardware and small under non-ideal hardware due to finite capacity limit (caused by distortion noise) and the channel hardening makes stochastic inner product (such as h^{Hv}) as deterministic when

N becomes large. If the difference between the upper and lower bounds (is the quality of the CSI) is small the estimation errors impact on the capacity is minor.

Table2: Different number of antennas with Capacity Bounds at BS

S.No	SNR in dB	Hardware impairment of Capacity bounds (bits/sec/Hz)		
		4Antennas at BS	20 Antennas at BS	40 Antennas at BS
1	20	21	40	45
2	30	32	49	55
3	60	32	49	55

The horizontal axis in Figure 4 shows the performance as a function of the relative channel gain of the pilot contaminated interference (with respect to the useful channel). It is observed that the ideal hardware case is sensitive to interference than non-ideal hardware case (due to large number of antennas which decorrelate user channel). Second pilot contaminated interference has a little impact when it passes over a channel which is weaker than the useful one but there appear breaking points where the degradation effect increases suddenly.

These breaking points are approach to $10\log_{10}\left(\kappa_t^{UE}\right)$ that is distortion noise caused by the UE compared to useful signal. This is true when we compare the distortion term $\kappa_t^{UE} E\left\{|\varphi|^2\right\}$ with the interference term in lower capacity bound. As N increases pilot contaminated interference becomes negligible if

$$\kappa_t^{UE} \square \sum_{l\in u}\left(\frac{tr\left(AR_l\right)}{tr\left(AR\right)}\right)^2 \quad (24)$$

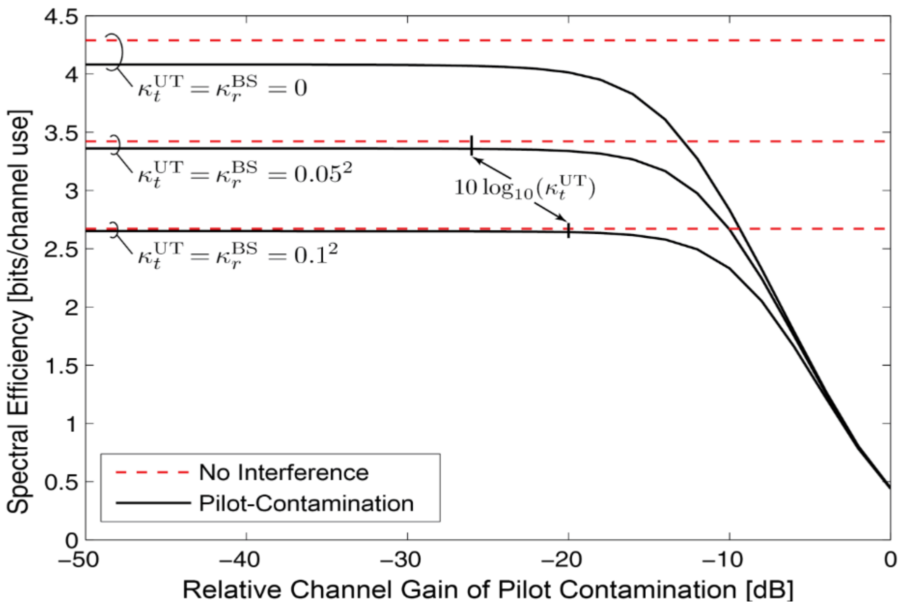

Figure.4: Lower capacity bounds of a user that experiences that pilot contamination

VI. Conclusions

This paper shows that comparison between LMMSE Estimator and conventional impairment-ignoring estimator and observed estimation error per antenna elememnt. Results are shows that there are non zero error floors at high SNRs and error floor increases with the levels of impairments. The value of error floors depends on the uplink SNR, number of antennas. With non ideal hardware, the effect of pilot contamination is less if inter user interference is -10dB weaker than the useful channel which is possible by increasing the number of antennas

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