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Base Station Coordinated Multi-user Detection in Multi-cell MIMO Cellular Systems

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Abstract: In order to effectively cancel Co-Channel Interference (CCI) and reduce Bit Error Rate (BER) in multi-cell MIMO cellular systems, performance of several Multi-User Detection (MUD) techniques based on coordinated multi-point processing (COMP) is studied. Several neighboring base stations coordinate with each other and form a virtual antenna array, serving for users in the coordinated region. Receivers of Zero Forcing (ZF), Minimum Mean-Square-Error (MMSE) and their combination with Successive Interference Cancellation (SIC) are designed and adept by the coordinated base stations and BER of above methods is studied. Simulation results show that BER performance of those COMP methods significantly outperforms single cell processing when interference is considered and is even better than it when interference is free at medium to high SNR. Furthermore, MMSE outperforms ZF and performance is even better when combined with SIC and will still increase with the number of antennas. Finally, MMSE-SIC COMP is shown to be most feasible and effective for interference cancellation in multi-cell MIMO cellular systems.

Key words: Co-channel interference, multi-user detection, interference cancellation, coordinated multi-point, single cell processing

INTRODUCTION

It is well known that MIMO systems have remarkable capacity potential (Goldsmith *et al*., 2003). However, in realistic multi-cell multi-user MIMO cellular systems, the advantage of MIMO may be greatly decreased, because of co-channel interference caused by the sharing of common system resources and frequency reuse among adjacent cells. It has been indicated that MIMO system is even ineffective in an interference-limited environment (Catreux *et al*., 2000). Therefore, in multi-cell MIMO systems, the application of MUD which can effectively suppress CCI has been widely researched (Huaiyu *et al*., 2004; Andrews *et al*., 2007). However, the design of MUD for downlink mobile stations (MSs) is still very difficult to implement, because of the increased complexity of MUD receivers. So, the idea that moving the CCI cancellation to the base stations (BSs) side naturally arises.

Base station coordination is proposed in 2001 (Shamai and Zaidel, 2001), also named as coordinated multi-point processing (COMP) by 3GPP LTE-A. Recently, many researchers have already proved the feasibility of coordinate approaches, including the obtaining of Channel State Information (CSI), information exchanging between coordinated points and so on and studied the capacity of coordination. Studies (Zhang and Dai, 2004; Foschini *et al*., 2006) show that CSI can been obtained at the BSs either by uplink channel estimation or through a feedback channel. Moreover, in current cellular systems, BSs are connected by high-speed wired backbones, so information can been exchanged reliably among them. Furthermore, under strong interference environment, MSs can communicate with several adjacent BSs, such as when soft handoff takes place in current CDMA systems. Therefore, base station coordination transforms interference into constructive signals, which will bring large performance gain (Simeone *et al*., 2009).

Recently, there are already some papers studying uplink MUD using base station coordination approaches. Some of them only make a simplifying assumption to the channel matrix (Khattak *et al*., 2006; Khattak and Fettweis, 2008). Some only focus on the rate region of joint detection (Marsch and Fettweis, 2008). Most of them do not consider the performance under a realistic system model, including large scale fading. Therefore, we build a more realistic system model and performance of several base station coordinated MUD schemes is studied based on this model.

In this study, several base station coordinated MUD schemes, including ZF COMP, MMSE COMP, ZF-SIC COMP, MMSE-SIC COMP, are studied in multi-cell MIMO systems and their BER performance is compared with corresponding single cell processing with and without interference. Simulations show that these schemes can significantly decrease bit error rate, improve system performance and effectively mitigate co-channel interference.

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SYSTEM DESCRIPTION

It is well known that spatial multiplexing can significantly improve spectral efficiency and channel capacity of MIMO systems. Currently, one of the main spatial multiplexing techniques is Bell Labs Space-Time (BLAST) architecture. BLAST can be described as the following: First, the input original data stream is converted into several data streams by serial-to-parallel conversion. Then, data streams are distributed to the N_t transmitting antennas following certain rules. Finally, antennas in the receiver obtain the combination of the sending signals and need to separate all the data streams in order to resume the original data stream. The key of the receiver is the design of data stream separation. There are many types of receivers, including Maximum Likelihood (ML), ZF and MMSE receiver. The complexity of ML receiver increases exponentially with the number of data streams. So generally we use simpler structures such as ZF and MMSE, which will be studied in this study.

Single-cell single-user MIMO system: Assuming there is 1 MS with N_t transmitting antennas, 1 BS with N_r receiving antennas in the system and flat channel condition with channel matrix H. Then, the received discrete signal vector can be written as:

$$y=\sum_{i=1}^{Nt} h_i x_i + w \qquad (1)$$

where, h_i, $(i = 1,..., N_t)$ is the column of H. Data streams of different transmitting antennas $\{x_i\}$, $(i = 1,..., N_t)$ are independent with each other. For data stream j, Eq. 1 can be rewritten as:

$$y = h_j x_j + \sum_{i\neq j} h_i x_i + w \qquad (2)$$

It can be seen that, data stream j will experience interference from other data streams.

Multi-cell MIMO system with single cell processing: Here, assuming the number of BSs is B and MSs is K. BS b_k means the BS which servers MS k. Then, the received discrete signal vector of BS b_k can be written as:

$$y_{b_k} = a_{b_k,k} H_{b_k,k} X_k + \sum_{l\neq k} a_{b_k,l} H_{b_k,l} X_l + n_{b_k} \qquad (3)$$

where, $b_k = 1,2,...,B$, $k = 1,2,...,K$. $a_{b_k k}$ means large scale fading from MS k to BS b_k,

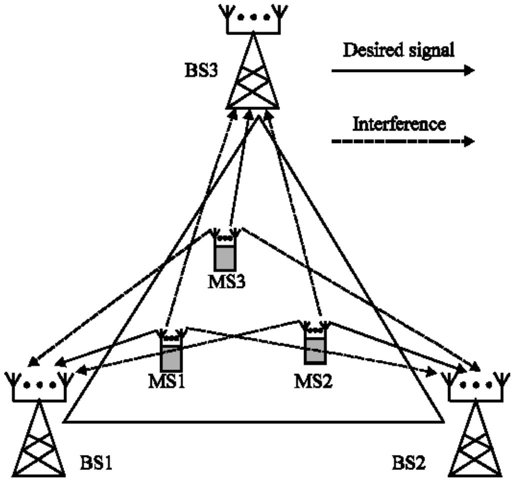

Fig. 1: System model of single cell processing

$$a^2_{b_k,k} = PL_{b_k,k} S_{b_k,k}$$

$$PL_{b_k,k} = d^{-a}_{b_k,k}$$

represents the path loss, with $d_{b_k k}$ the normalized propagation distance between MS k and BS b_k, α the path loss exponent. While $S_{b_k k}$ denotes the shadow fading, typically modeled as a log-normal random variable with standard deviation σ. $H_{b_k l}$ means $N_r \times N_t$ channel matrix between MS1 and BS b_k. $X_{b_k l}$ is $N_t \times 1$ transmitted signal vector of MS1. n_{b_k} is circularly symmetric complex Gaussian white noise, with covariance matrix $\Phi_n = N_0 I$, where I denotes an identity matrix. For single cell processing we assume that $N_r \geq N_t$.

It can be Fig. 1 that taking a 3 cell cellular system as an example, when we use single cell processing, signals from other cell users are regarded as serious interference, especially when required user is located at the cell edge.

Multi-cell MIMO system with COMP: Figure 2, now all the antennas of all the coordinated BSs can form a $BN_r \times KN_t$ virtual antenna array, serving for all the MSs. Assuming $BN_r \geq KN_t$, then signals transmitted by different MSs also can be treated as independent data streams. Therefore, the received discrete signal vector by all the antennas of all the coordinated BSs can be written as:

$$y = H_E X + n \qquad (4)$$

$$H_E = \begin{bmatrix} a_{b_1,1} H_{b_1,1} & a_{b_1,2} H_{b_1,2} & \cdots & a_{b_1,K} H_{b_1,K} \\ a_{b_2,1} H_{b_2,1} & a_{b_2,2} H_{b_2,2} & \cdots & a_{b_2,K} H_{b_2,K} \\ \vdots & \vdots & \ddots & \vdots \\ a_{B,1} H_{B,1} & a_{B,2} H_{B,2} & \cdots & a_{B,K} H_{B,K} \end{bmatrix} \qquad (5)$$

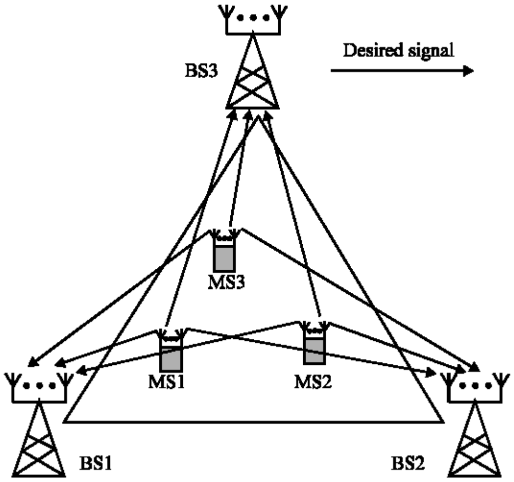

Fig. 2: System model of COMP

where, y is the $BN_r \times KN_t$ received signal vector, H_E is the $BN_r \times KN_t$ channel matrix, X is the$KN_t \times 1$ transmitted signal vector and n is circularly symmetric complex Gaussian white noise.

Through Base Station coordination, all the signals can be exploited as desired signals, rather than treated as noise, so performance can be significantly improved.

PERFORMANCE ANALYSIS

Here, we analyze the performance of MUD COMP schemes. First, several single-user receiver structures are introduced, including ZF, MMSE and their combination with SIC. Then, based on these receivers, design of single cell processing and COMP in a multi-cell MIMO cellular system are introduced and their performances are analyzed.

Single-cell single user receivers: A ZF receiver can be expressed by the pseudo-inverse of channel matrix:

$$H^+ = (H^*H)^{-1} H^* \tag{6}$$

Decorrelator of the j-th data stream is the j-th row of the pseudo-inverse matrix H^+.

ZF receiver can eliminate the interference between data streams completely and guarantee maximum output signal to noise ratio (SNR). However, under low SNR environment, interference between data streams is not a major factor, so performance of ZF is not good enough. Therefore, we can consider a receiver structure which can achieve optimum compromise between interference of data streams and background noise, in order to make sure that output signal to interference plus noise (SINR) is max, under any SNR circumstances. Proper proportion transforms of these receivers can achieve the minimum mean-square-error when estimating x, so it is also called MMSE receiver. Now the effective channel of the j-th data stream is:

$$y = h_j x_j + z_j \tag{7}$$

where,

$$z_j = \sum_{i \neq j} h_i x_i + w$$

If the power allocate for data stream j is P_j, then the covariance of z_j can be calculated:

$$K_{z_j} = N_0 I_{N_r} + \sum_{i \neq j}^{Nt} P_i h_i h_i^* \tag{8}$$

So, the j-th stage of the linear receiver can be expressed as:

$$\left(N_0 I_{N_r} + \sum_{i \neq j}^{Nt} P_i h_i h_i^* \right)^{-1} h_j \tag{9}$$

In order to further improve performance, successive interference cancellation can be considered: Once the data steam is successfully resumed, it can be subtracted from the received vector. This method can be combined with ZF and MMSE, denoted as ZF-SIC and MMSE-SIC. Now, we take MMSE-SIC as an example. Figure 3: MMSE receiver 1 decodes data stream 1, then subtracts this data stream from the received vector. If data stream 1 is decoded successfully, MMSE receiver 2 only needs to handle interference streams 3,...,N_t, because data stream 1 has already been subtracted. Repeat this process until the last MMSE receiver dose not need to handle any interference.

Single cell processing in multi-cell MIMO system: In a multi-cell MIMO system, when using single cell processing, we can still use above single-user receivers, but at this time, we regard

$$\sum_{l \neq k} a_{b_k,l} H_{b_k,l} X_l$$

together with n_{b_k} as background noise at the receiver of BS b_k. Therefore, this will bring serious interference and performance of detection will be significantly degraded, especially when interfering signal strengths are comparable with required signal.

COMP in multi-cell MIMO system: At this time, under the assumption that $BN_r \geq KN_t$, the above single-user

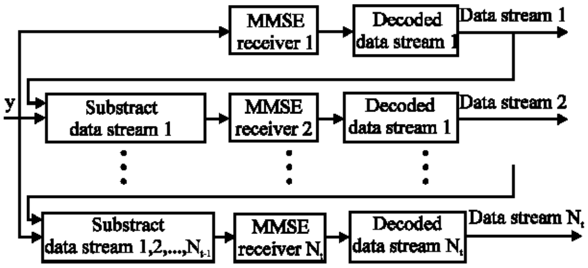

Fig. 3: Structure of MMSE-SIC receiver

channel matrix H can be expanded into multi-user channel matrix H_E, so the single-user receivers can also be expanded into coordinated MUD schemes, denoted as ZF COMP, ZF-SIC COMP, MMSE COMP and MMSE-SIC COMP. So we can still use Eq. 5 and 8 as design of the receivers, just replace channel matrix H by H_E.

When we use single cell processing, signals from MS l, $l \neq k$, are regarded as interference at the receiver of BS b_k, seriously affect performance of the required signal. While, adopting base station coordination can convert interference into useful signals, because all the users signals are treated as independent data streams and can be detected using the above receivers.

NUMERICAL RESULTS

In the simulations, BER performances of COMP schemes are obtained by changing the received SNR at the base stations. And effect of different number of antennas on the performance of base station coordination is also studied.

Assume that the MIMO network includes 3 cells, B = 3, cell radius is 1 km, each has 1 base station. At each time slot only 1 user can be served by each cell, K = B. All the devices have same number of antennas, $N_t = N_r$. Links between users and base stations are flat. The path loss exponent α is 3.8. Standard deviation of lognormal shadowing is 8 dB. Elements of channel matrix H are Rayleigh fading coefficient, obeying complex Gaussian distribution, with 0 mean and variance of 1. To obtain the average values, each data stream has 1×10^5 bits, with BPSK modulation.

Figure 4 gives bit error rate performance by changing variable received SNR. Performance of ZF COMP and ZF-SIC COMP are simulated and compared with single cell processing with and without interference. $N_r = N_t = 1$, so we also call it 1 by 1 MIMO cellular systems. It can be seen that, when serious interferences exist, single cell processing is almost failed to detect the required signals. While, ZF COMP can greatly improve the performance. ZF-SIC COMP is much better and even outperforms when there is no interference in the system, at higher SNR.

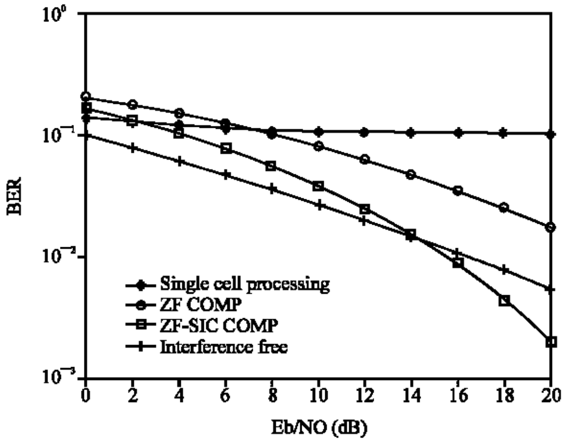

Fig. 4: BER of ZF in 1 by 1 MIMO cellular systems

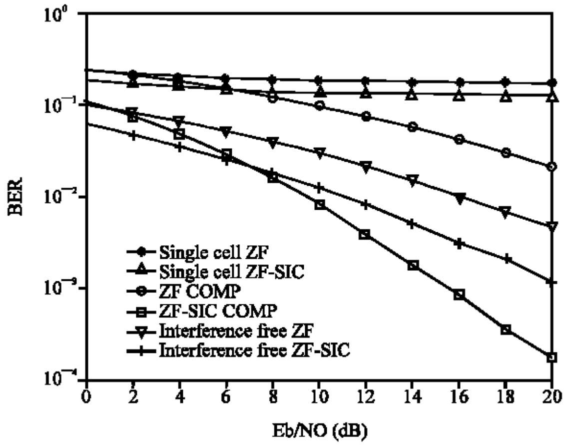

Fig. 5: BER of ZF in 4 by 4 MIMO cellular systems

Figure 5 shows performance of 4 by 4 MIMO cellular systems under different uplink channels. Performance of ZF COMP and ZF-SIC COMP are also simulated and compared with single cell processing with and without interference and we will come to the similar conclusions.

Figure 6 gives BER performance under different received SNR, using MMSE receivers, in 1 by 1 MIMO cellular systems. Performance of MMSE COMP and MMSE-SIC COMP are simulated and compared with single cell processing. It can be seen that, performance of MMSE COMP is better than single cell processing and MMSE-SIC COMP even outperforms interference-free circumstances at medium to high SNR.

Figure 7 shows performance of 4 by 4 MIMO cellular systems using MMSE receivers. It also can be seen that, performance of MMSE COMP and MMSE-SIC COMP are much better.

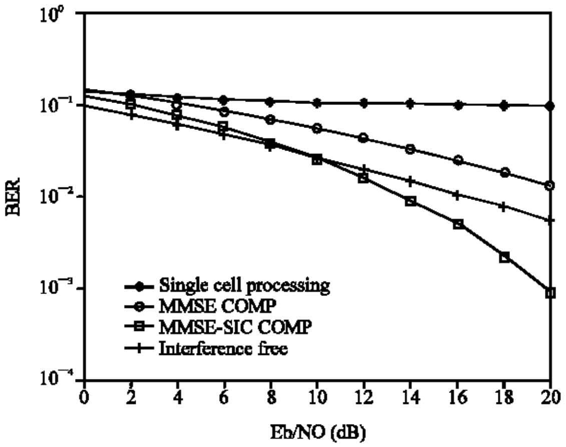

Fig. 6: BER of MMSE in 1 by 1 MIMO cellular systems

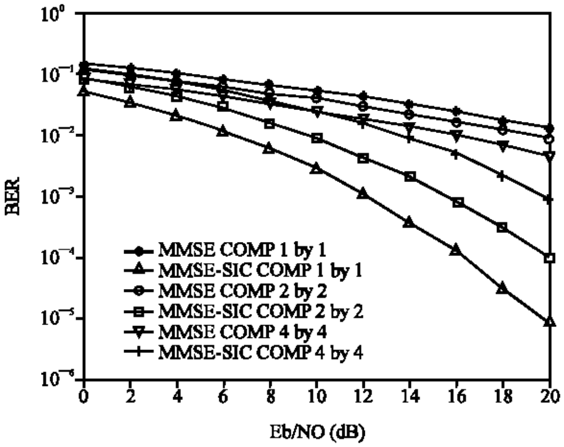

Fig. 8: Compare of different antenna numbers

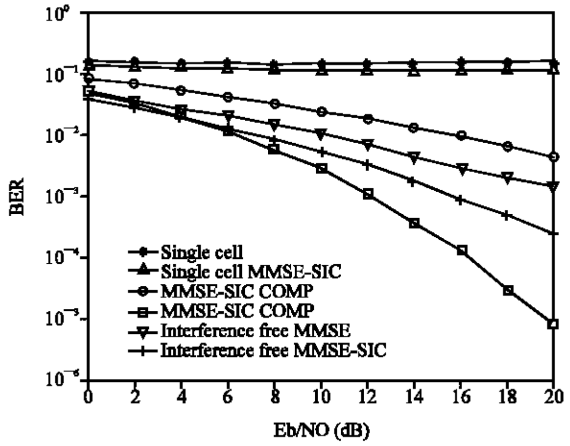

Fig. 7: BER of MMSE in 4 by 4 MIMO cellular systems

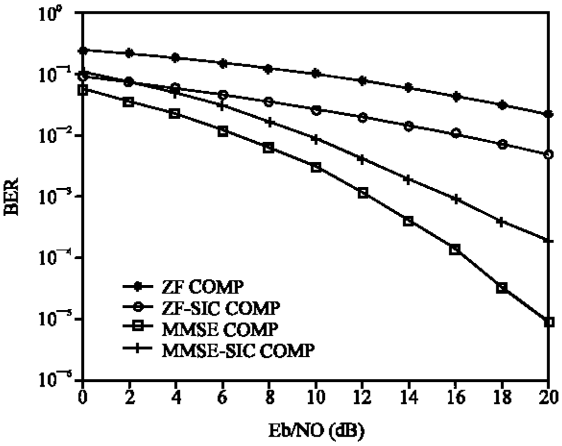

Fig. 9: Compare of different COMP schemes

Figure 8, we choose MMSE receivers for an example and performances of different antenna numbers are simulated. We compare BER of 1 by 1, 2 by 2 and 4 by 4 MIMO systems and come to the conclusion that performance of COMP schemes will significantly increase with the number of antennas, especially combined with SIC.

Figure 9, performance of different COMP schemes are compared with each other in 4 by 4 MIMO cellular systems. From the simulation results, we can see that MMSE COMP outperforms ZF COMP, performance of ZF-SIC is better than MMSE COMP and MMSE-SIC COMP is the best. So we believe that MMSE-SIC COMP is most feasible and effective for interference cancellation in multi-cell MIMO systems.

Through the results in Fig. 4-9, we can find that the COMP schemes can improve BER performance in multi-cell MIMO cellular systems. It means that it can effectively eliminate CCI and obtain higher spectral efficiency. The major contribution of this study is that we build a more realistic channel model in coordinated multi-cell MIMO systems and design several coordinated MUD schemes, including ZF COMP, ZF-SIC COMP, MMSE COMP and MMSE-SIC COMP. Then, we analyze the BER performance of each scheme and compare them with single cell processing under both interference and interference -free environment. Finally, we come to the conclusion that COMP schemes exhibit great advantage over single cell processing in multi-cell MIMO systems, especially MMSE-SIC COMP and the more antennas are employed, the better performance can be achieved. However, there are still some practical problems to be solved in the future for base station coordination, such as the problem of asynchronous interference, accurate channel estimation, numerous information exchange between coordinated base stations and so on, which also direct our future work.

CONCLUSION

Several base station coordinated multi-user detection schemes are studied in this study. Through coordination, all the antennas of coordinated base stations will form a virtual antenna array and co-channel interference can be exploited rather than treated as noise, so performance can be significantly improved compared with single cell processing. Moreover, performance of MMSE COMP is better than ZF COMP and is even better when combined with SIC. Simulation results also show that performance of all the coordinate schemes will increase with the number of antennas. So the MUD COMP schemes, especially MMSE-SIC COMP can effectively cancel co-channel interference in multi-cell MIMO cellular systems and will become a promising technique for next generation mobile communications.

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