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A Tradeoff among Fsc and Csi in Multiple Networking Systems

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Abstract: *In a multiple transmit antenna, single antenna per receiver downlink channel with limited channel state feedback, we consider the following question: given a constraint on the total system-wide feedback load, is it preferable to get low rate / coarse channel feedback from a large number of receivers or high-rate/high-quality feedback from a smaller number of receivers. Acquiring feedback from many receivers allows multiuser diversity to be exploited, while high-rate feedback allows for very precise selection of beamforming directions. In terms of system design, this corresponds to a preference for acquiring high-quality feedback from a few users on each time-frequency resource block, as opposed to coarse feedback from many users on each block.*
Keywords: *antenna, feedback, beamforming, multiuser*

I. Introduction

The use of antenna arrays at both the transmitter and the receiver has received significant attention as a promising method to provide diversity and/or multiplexing gain over wireless links. Multiple antennas create extra dimensions in the signal space which can be used in different ways. The receiver can be provided with replicas of the same data to increase the reliability of signal transmission which results in spatial diversity gain.

The spatial dimensions can also be used to carry independent data streams to increase the data rate which results in spatial multiplexing gain. This collective improvement associated with spatial multiple-input multiple-output (MIMO) channels is based on the premise that in the wireless system with enough separation between antennas in an array, a rich scattering environment provides different channels between each transmit and receive antenna which are statistically uncorrelated to some extent. As the demand for high data rate applications like video and audio streaming, VoIP, video conferencing are increasing, future wireless systems should be able to provide high speed broad band services for mobile users with sufficient quality of service (QoS) support. As the bandwidth and power are scarce or limited resources, techniques which lead to efficient utilization of these resources are quite necessary in the next generation wireless systems. At the same time the wireless channel creates a challenging environment because of variety of channel impairments.

Thus, future wireless systems are to be designed taking all these factors into consideration. For scenarios with a large number of users to be served in one cell, high capacit ygains can be achieved by transmitting independent data streams to different users sharing thesame time-frequency resources. This technique is referred to as multi-user multiple-input multiple-output (MU-MI MO) [1]. It is one of the techniques which can be used in cellular systems to increase spectral efficiency .

In the downlink channel, there is one multi-antenna transmitter which communicates with several non-collocated users having one or more antennas. From research point of view downlink channel, also known as MIMO Broadcast Channel (BC), is much more interesting and received a lot of attention in last few years or so and is also the focus of this thesis. The challenges in downlink MU-MIMO system stem from the fact that the users cannot cooperate hence the multi-user interference should be taken care of at the transmitter side. It is important to note that the channel state information at the transmitter (CSIT) is required for MIMO downlink, which is used to separate signals for different users in the spatial domain.

Long term evolution (LTE) and its successor LTE-Advanced (LTE-A) are some of next generation wireless systems, which use advanced features like MIMO, link adaptation, orthogonal frequency division multiplexing (OFDM) and many other techniques to help in achieving high spectral efficiencies.

Conventional wisdom has been that RBF could compensate for coarse feedback through multi-user diversity and outperform ZF if there were enough users. But on the contrary, we find that RBF achieves a significantly smaller sum rate than a ZF-based system with highly accurate CSI, when both systems have the same aggregate feedback load, T_{fb} bits. This is true even when T_{fb} is extremely large, in which case the number of users feeding back under RBF is also very large, and thus multi-user diversity is plentiful.

II. Mimo System

Figure 2.1 shows MIMO system where there are M (>1) antennas at the BS and N (>1) antennas at the MS.

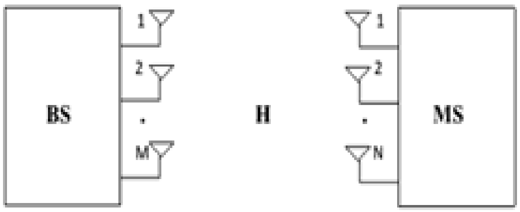

Fig 1 MIMO system

The wireless channel matrix H can be expressed as

where hij is the channel gain from ith receive antenna to the jth transmit antenna. In case of MIMO systems along with diversity , spatial multiplexing can also be exploited which refers to breaking the incoming high rate data stream into M independent data streams. Assuming that the streams can be successfully decoded, the nominal spectral efficiency is thus increased by a factor of M. This is certainly exciting which implies that adding antenna elements can greatly increase the viability of the high data rates desired for wireless broadband access. The MS has to estimate $M\times 1$ transmit vector from $N\times 1$ receive vector. In order to adjust the number ofstreams, some sort of pre-processing also called precoding is done before actual transmission, which can be thought as a kind of beamforming. More insights about MIMO can be found in reference [2]. MIMO systems can be classified as:

- **Single-user or Multi-user**

When a single-user is scheduled in a dataregion it is referred as single-user MIMO (SUMIMO). If more than one user is scheduled in a dataregion then it becomes MU-MIMO. These two are differ in terms of precoding and scheduling. The number of streams allocated to each user is configurable.

- **Open loop or Closed loop**

When the precoders are fixed to subbands and chosen from a codebook which is known to BS and MS is referred as Open loop MIMO (OL-MIMO). If the precoders are formed by the scheduler based on the preferred matrix index (PMI) feedback from each of the MSs, then it is called Closed loop MIMO (CL-MIMO). From the above classification, there are four possible MIMO configurations:

- **OL-SU-MIMO (2) OL-MU-MIMO (3) CL-SU-MIMO (4) CL-MU-MIMO.**

III. Mu-Mimo

In MU-MIMO more than one user can be served in the same bandwidth using appropriate precoders at BS. This technique is just like SU-MIMO where one or more streams transmitted at a time using multiple antennas belonging to the same user . In MU-MIMO each stream could belong to a different user i.e., instead of stream multiplexing, MU-MIMO does user multiplexing. For scenarios where large number of users is to be served in one cell or to serve a limited number of users with increased throughput, MU-MIMO can be used.

The three gains that are useful in increasing the performance of MU-MIMO systems are defined as follows [11].

A Spatial diversity gain

This is the technique for improving communication quality by transmitting and receiving with multiple antennas. Each pair of transmit and receive antennas provides a signal path by sending signals that carry the same information through different paths. Hence multiple independently faded replicas of the data symbol can be obtained and more reliable reception is achieved.

B Spatial multiplexing gain

This is the performance improvement derived from using multiple antennas to transmit multiple signal flows through space in parallel. For a MIMO system with Nt transmitting antennas and Nr receiving antennas, the maximum achievable spatial multiplexing gain is minimum of Nt and Nr.

C Multi-user diversity gain

The improvement in system throughput derived from using a scheduler which exploits the disparities fading and interference characteristics between users. The first two (spatial diversity gain, spatial multiplexing gain) can be typically achieved using precoders at the transmitter side by using the feedback information sent by UE and using multiple antennas. But the latter can be achieved by using proper scheduling techniques.

As UE feedback quantized channel information, the users will not be perfectly orthogonal to each other so some remnant inter user interference will be seen by each of the users who are paired. This can be minimized by using a minimum mean square error (MMSE) receiver at UE to minimize the effect of multilingual user interference (MUI) on capacity [17] . The main advantages that lead to MIMO paradigm shift to MU-MIMO from SU-MIMO communications are

1. **MU-MIMO** schemes allow for direct gain in multiple-access capacity (proportional to number of transmit antennas) because of multiplexing of data of several users in the same radio channel.

2. **MU-MIMO** schemes are more immune to loss of channel rank because of line of sight (LOS) conditions or antenna correlation, which is a major problem that causes performance degradation in SU-MIMO communications.

C Challenges of MU-MIMO

MU-MIMO has tremendous benefits which are achieved by overcoming some challenges. Multiple users using the same resources at the same time would lead to several issues that need to be considered, some of them are mentioned here.

D Interference

When multiple users are using the same resources at the same time, there would be severe interference between their signals. Each user should be capable of decoding his respective stream by reducing the interference due to other stream. This can be achieved by careful pre-processing at the transmitter and post-processing at the receiver .

E Post-processing

In single-user transmission, MIMO could be used for spatial multiplexing, where multiple symbols are transmitted to the same user . For example, consider a 2×2 single-user system, in which the received vector can be represented as

$$y = Hx + n \qquad ()$$

where the transmitted 2×1 vector x represents 2 symbols that are transmitted simultaneously to a particular user , thus doubling the user throughput. In order to decode the 2 symbols from the received 2×1 vector y, a simple approach would be to build a linear receiver that diagonalises the system, i.e., multiply the received vector y by H^{-1}. This decouples the system and we get back the two transmitted symbols.

In the MU-MIMO case, the effective received vector y, is a concatenation of the symbols received by geographically separated users, and post processing must be done in such a way to reduce the interference from the other user . Several receiver configurations such as MMSE, maximum ratio combining (MRC) and ZF are possible but MMSE receiver is shown to reduce the interference effectively .

a Pre-processing/precoding

Because of this limitation on the interference cancellation that can be done at the MS, good precoders need to be designed, such that we beamform efficiently towards the two users. However this would require good knowledge of the channels to both users at the BS, which requires heavy amounts of feedback. So we would need to come up with the best possible precoders to use at the BS, with a limitation on the feedback rate.

b Channel Quality Indicator (CQI) modeling

CQI is a feedback by the user in frame (n), for the allocation of modulation and coding schemes in frame (n+1). CQI modeling is to be done so that the user experiences a good throughput. In the single input single output (SISO) case, CQI is a function of the channel to a particular user , which (for low Doppler's shift) does not fluctuate much between adjacent frames. But in case of MU-MIMO, in addition to being a function of the channel to the user , CQI is also a function of the precoder used at the BS. Hence, better the precoding is lesser is the interference and higher CQI will be.

c Scheduling

When we have a number of users contending for same resource, throughputs can be increased by scheduling those users who experience a good channel. This increase in system performance merely because of scheduling the best-set of users at any point of time is known as multi-user diversity . However , maximizing system throughput must not come as a result of cell-edge users (who face poor channel conditions) never being scheduled. System performance must be maximized and at the same time a certain amount of fairness must be ensured among the users in the system. A multi-user scheduler that meets these demands needs to be implemented.

IV. System Model

We consider the downlink of a cellular system where a transmitter has M antennas and K users have one antenna each, i.e. N = 1. Transmission is performed in time slots of size T and in each time slot users feed back a partial CSI, which is used by the transmitter to schedule downlink transmissions and design the beamformer. The transmitted signal x and the signal received by user k, y_k, are modelled as in (2.2) and (2.1), respectively, with Lk= 1 for each selected user. Since N = 1 we denote the channel and beamformer of user k as the 1 × M vector hk(n) and the M × 1 vector gk(n), respectively. From (2.2) and (2.1) the achievable SINR for user k is given by

$$SINR_k(n) = \frac{|h_k(n)g_k(n)|^2}{1 + \sum_{i \in S(n) \setminus \{k\}} |h_k(n)g_i(n)|^2} \quad (1)$$

Under Gaussian codes and minimum-distance decoding, the achievable rate for user k is given by

$$R_k(n) = \log(1 + SINR_k(n)) \quad (2)$$

and ii) a channel quality information (CQI) related to the user's achievable rate or equivalently its SINR. Each user feeds back to the transmitter a quantized version of the CDI and the unquantized CQI assuming a zero-delay and error free uplink control channel. The CDI FB consists of B bits per slot, used at the transmitter to reconstruct user's channel vector . The channel reconstruction algorithm depends on the FB strategy adopted at receivers. For instance, for the basic FB (BFB) strategy the channel direction is quantized according to minimal chordal distance using a codebook with 2B unit-norm codewords. In this case the index of the best codeword is fed back to the transmitter as quantized CDI and the reconstructed channel is simply the best codeword. More details about the proposed FB strategies are given. We note that the unit-norm reconstructed channel vectors of all users are stored at the transmitter into the matrix

V. Zero-Forcing Beamforming

Let us denote with H(S) the matrix containing as rows the reconstructed channel vectors of the selected users. By denoting with W(S) =H(S) the right pseudo-inverse of H(S) the ZF transmit matrix is given by

$$G(s) = W(s)diag(p)^{1/2} = \bar{H}(S)^H \left(\bar{H}(S)\bar{H}(S)^H \right)^{-1} diag(p)^{1/2} \quad (3)$$

where p is the vector of power normalization coefficients imposing the power constraint P on the transmitted signal. Under the assumption of equal power distribution across users, p has elements

$$p_k = \frac{P}{|S| . \|w_k\|^2} \quad (4)$$

VI. Mmse Beamforming

Differently from ZF BF, MMSE BF aims at minimizing the sum mean square error (MSE) of the received signals. To this end, we first decompose the channel vector relative to user k into two orthogonal vectors f_k and ϱ_k, parallel and orthogonal to h_k, respectively, with

$$h_k = \|h_k\| (f_k + \in_k) \quad (5)$$

VII. Channel State Information

It is to be noticed that the precoding techniques and user scheduling discussed in the previous sections all depend on the availability of CSI at the transmitter. As said before, this is in contrast to the single user MIMO where the availability of CSI is only optional. For the multi-user MIMO systems if the CSI is completely absent then no multiplexing gain can be realized since the degrees of freedom provided by the multiple antennas are completely lost. In the presence of full CSI, the capacity scales as min(NT, max(N, K)) in high-SNR regime where N = Nk is the number of antennas at each user. This means that the capacity scales linearly with transmit antennas and number of antennas at receiver side ave no significant bearing on the capacity scaling. In the presence of the large number of users the capacity scales like NT log log KN which indicates the full multiplexing of NT as well as the multi-user diversity gain of log log KN .

However, in practice perfect knowledge of CSI is not available at transmitter. The transmitter can collect the CSI implicitly through reciprocity in TDD systems or explicitly through user feedback in FDD systems. The availability of CSI at the transmitter is even worse in the case of high mobility environment or frequency selective channels. This means that the transmitter has to live withthe partial or imperfect CSI. An approach where the users feedback their quantized CSI through a rate limited dedicated backhaul is commonly termed as limited rate feedback. In this scheme the users quantize their channel to one of the 2B code words, where B is the resolution of the quantizer, and feedback the corresponding index. The quantized feedback is usually of the channel directional information (CDI). It is shown that the number of feedback bits per user must scale linearly with NT and also with SNR in order to extract the full multiplexing gain. Although quantized CDI is enough for recovering the full multiplexing gain, when K > NT , but it alone cannot achieve the optimal multi-user diversity gain of log log KN . In order to fully exploit the multi-user diversity benefit, the users must also feedback the channel quality indicator (CQI) like SINR which can then be used by the transmitter to select users resulting in selection diversity. Another associated issue with the limited feedback techniques is that due to the rate limited nature of the feedback channel if there are many users feedbacking their quantized CSI then the feedback channel is inundated. Hence smart user scheduling algorithms are required which can achieve the near-optimal performance but require less feedback from users. These issue on limited rate feedback will also be focused in this thesis and efficient user selection algorithms will be proposed. It will be shown that the proposed algorithms can significantly reduce the the amount of feedback from users but with minor sum rate performance penalty.

VIII. Outputs

The simplified schemes presented here for ZF have slightly higher complexity at the BS and slightly lower complexity at the user terminal compared to RBF, and can be considered to be of similar complexity overall.

For SNR=10dB, N=4

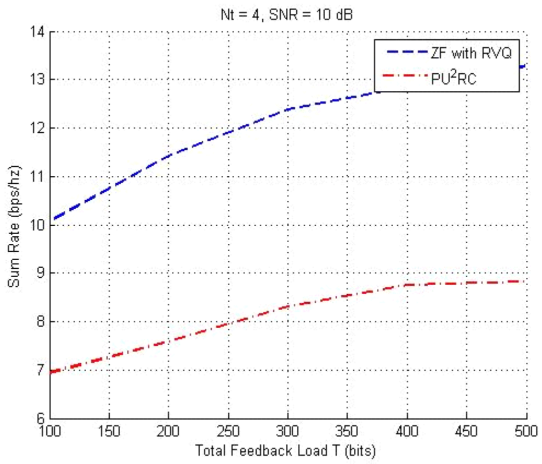

Fig 2 Sumrate vs total feedback

For SNR=10dB, N=4

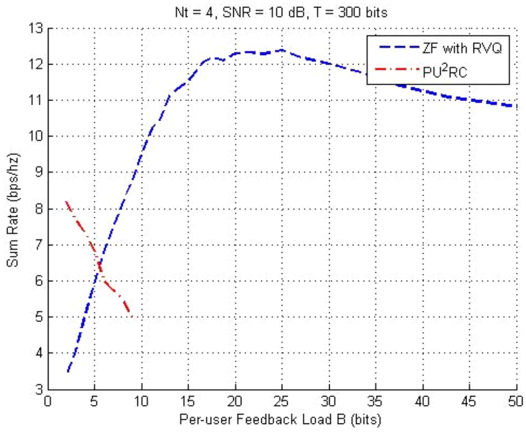

Fig 3 Sumrate vs Per User feedback

Nt = 2, SNR = 5 dB, T = 500 bits

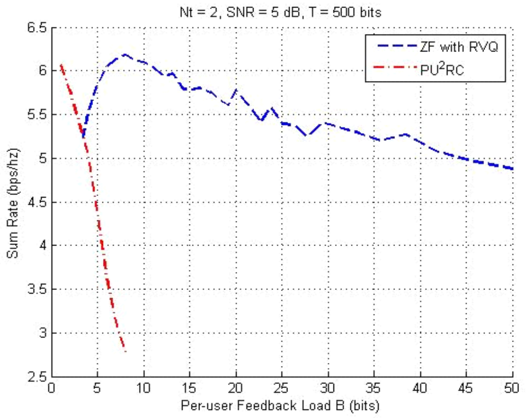

Fig 4 Sumrate vs Per User feedback

Nt = 2, SNR = 5 dB, T = 500 bits

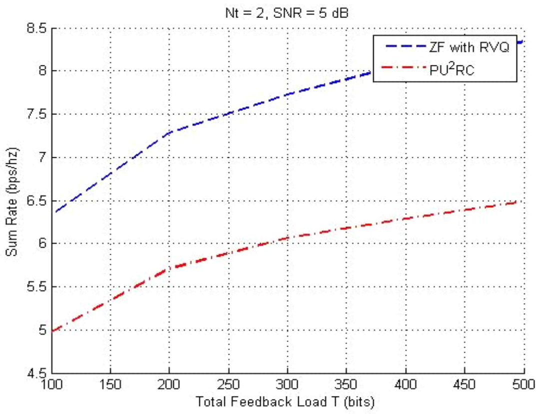

Fig 5 Sumrate vs total feedback

IX. Conclusion

In this work considers two different multiuser wireless communication systems: the MIMO broadcast channel and a networked control system. The MIMO BC with special interest in FDD systems where the transmitter receives quantized channel information from the receivers. Differently, consider NCSs where multiple sensors, controller and actuator exchange low-rate messages to monitor or control a dynamical system. In the following we summarize the main contributions of the different chapters. We assume perfect CSIT and describe a sub-optimum multiuser eigenmode transmission (MET) technique based on ZF BF where the set of active users and the set of eigenmodes per user are selected with a greedy algorithm in order to maximize the weighted throughput. MET outperforms most state-of-the-art linear precoding strategies and achieves a large fraction of DPC capacity in most channel environments.

We also assume limited uplink FB from single antenna receivers and in vestigate: i) beamformer design, ii) channel quantization and feedback signalling optimization and iii) user selection. We design a novel MMSE beamformer under incomplete CSIT that outperforms ZF BF when users are randomly selected, but provides marginal gains when user selection follows an opportunistic approach. Another way of looking at rate allocation is by scheduling users for data transfer such that the system sum rate is maximized. It turned out that the picked users result in perturbation vector which minimize the transmit power which is effectively achieved by channel determinant maximization. We also reduce the user selection algorithm complexity by performing the user shedding step based on our proposed closed form high-SNR upper bound. The simulations show that the proposed algorithm has superior performance and simplified practical implementation than other greedy algorithms in literature.Moreover we propose various LBG-based FB strategies that exploit spatial and time correlation of the MIMO channel. In particular hierarchical FB and predictive FB provide the largest gains. Finally robust and efficient greedy user selection algorithms are derived for the maximization of the system sum rate.

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