

Multuser MIMO Downlink System Capacity Analysis in Wireless Communication for Time Varying Channel

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Abstract—Very few technologies have shown as much impact on the trajectory of evolution of wireless communication systems as multiple input multiple output (MIMO) systems. MIMO systems have already been employed in the existing 802.11n and 802.16e standards resulting in a huge leap in their achievable rates. A relatively recent idea of extending the benefits of MIMO systems to multi-user scenarios seems promising in the context of achieving high data rates keeping in the mind for future cellular standards after 3G. For applications such as wireless LANs and cellular telephony, MIMO systems will likely to be deployed in environments where a single base station must communicate with many users simultaneously. As a result, the study of multi-user MIMO systems has emerged recently as an important topic for research in future. Such systems have the potential to combine the high capacity that can be achieved with MIMO processing by using space-division multiple access techniques. This paper aims at giving an insight into Multuser MIMO downlink systems—its concept, capacity, and transmission techniques related issues. In this paper several approaches including linear and non-linear channel precoding are reviewed which analyze the capacity for multuser MIMO downlink channel. We conclude by describing future areas of research in multi-user MIMO communications.

Keywords— Multuser, MIMO, Sum capacity Downlink, Precoding

I. INTRODUCTION

Multiple-input multiple-output (MIMO) communication systems have attracted attention in recent years. Such multiple-antenna potentially allow higher throughput, increased diversity, and reduced interference as they communicate with multiple wireless users. The use of MIMO systems was traditionally intended for point to point communication. MIMO techniques were first investigated in single-user scenarios. The natural extension of this thought would be to consider MIMO systems in a multi-user scenario. It is well known that in a MIMO system with N_B transmit and N_M receive antennas, capacity grows linearly with $\min(N_B, N_M)$. Current interest in the multiple user case is motivated by recent results indicating that similar capacity scaling applies when an N_B antennas communicates with N_M users. The vision for next generation cellular networks includes data rates approaching 100 Mb/s for highly mobile users and up to 1Gb/s for low mobile or stationary users. This calls for efficient use of the existing spectrum. Multuser MIMO technology is expected to play a key role in this context. There are two challenges in a multi-user MIMO scenario: uplink (where multiple users transmit simultaneously to single base station) and downlink (where the base station transmits to multiple independent users). The uplink challenge is addressed using array processing and multi-user detection techniques by the base station in order to separate the signals transmitted by the users. The downlink challenge is somewhat different. MU-MIMO downlink channel is similar to that of single-user

MIMO (SU-MIMO) except that the receiver antennas are distributed among different independent users. In the multi-user case, interference must be taken into account and balanced against the need for high throughput. A transmission scheme that maximizes the capacity for one user in the network might result in unacceptably high interference for the other users, rendering their links useless. If high throughput is the goal, a better approach might be to maximize the sum capacity of the network, or the maximum sum transmission rate, where the inter-user interference is taken into consideration. This paper is organized as follows: An overview of the Multuser MIMO is presented in Section II. In Section III, capacity analysis of Multuser MIMO downlink channel is detailed. In section IV various transmission methods for multuser MIMO downlink channel are discussed. Finally conclusions are drawn with some future work in V.

II. MULTIUSER MIMO COMMUNICATION SYSTEM

In most communication systems deal with multiple users who are sharing the same radio resources. Fig.1 illustrates a typical multi-user communication environment in which the multiple mobile stations are served by a single base station in the cellular system. In Fig.1 users are selected and allocated communication resource such as time, frequency, and spatial stream. Suppose that the base station and each mobile station are equipped with N_B and N_M antennas, respectively. As K independent users form a virtual set of $K \times N_M$ antennas which communicate with a single BS with N_B antennas, the end-to-

end configuration can be considered as a $(KN_M) \times N_B$ MIMO system for downlink, or $N_B \times (KN_M)$ MIMO system for uplink. In this multi-user communication system, multiple antennas allow the independent users to transmit their own data stream in the uplink (many-to-one) at the same time or the base station to transmit the multiple user data streams to be decoded by each user in the downlink (one-to-many). This is attributed to the increase in degrees of freedom with multiple antennas as in the single-user MIMO system. In the multi-user MIMO system, downlink and uplink channels are referred to as broadcast channel (BC) and multiple access channel (MAC), respectively. Since all data streams of K independent users are available for a single receiver of the base station in the multiple access channel, the multi-user MIMO system is equivalent to a single user $(KN_M) \times N_B$ MIMO system in the uplink. Similar to the single-user MIMO system, therefore, it can be shown that the uplink capacity of multi-user MIMO system is proportional to $\min(N_B \times KN_M)$. This calls for efficient use of the existing spectrum. MU-MIMO technology is expected to play a key role in this context. This creates a challenge in decoding the received symbols since joint decoding requires each user to have the symbol received from all the receiver antennas of all the users. It is practically impossible to achieve this level of coordination between all users. Almost all of the proposed techniques ideated for addressing the MU-MIMO downlink challenge employ processing of data symbols at the transmitter itself known as precoding. Although precoding is not a new concept and has been used in SU-MIMO systems as well, it was optional and used only to improve signal to noise ratio (SNR) at the receiver. However, in MU-MIMO systems precoding is essential to eliminate or minimize inter-user interference. Precoding is per-formed with the help of downlink channel state information or channel state information (CSI). This requires the transmitter to know the downlink CSI of each user in order to model the precoding transformation variables for each user. A number of different techniques to address the issue of MIMO downlink transmission and reception have been discussed in this paper.

Capacity is an important tool for characterizing any communication channel. In a single-user channel, capacity is the maximum amount of information that can be transmitted as a function of available bandwidth given a constraint on transmitted power. For the multi-user MIMO downlink channel, the problem is somewhat more complex. Given a constraint on the total transmitted power, it is possible to allocate varying fractions of that power to different users in the network, so that a single power constraint can yield many different information rates. The result is a “capacity region” like that illustrated in Fig.2 for a two-user channel. The maximum capacity for user 1 is achieved when 100% of the power is allocated to user 1; for user 2 the maximum capacity is also obtained when it has all the power. For every possible power distribution in between, there is an achievable information rate, which results in the capacity regions depicted in the illustration. Two regions are shown in Fig.2 the bigger one for the case where both users have roughly the same maximum capacity and the other for a case where they are different (due, for example, to user 2’s channel being attenuated relative to user 1). For K users, the capacity region is characterized by a K -dimensional volume. The maximum achievable throughput of the entire system is characterized by the point on the curve that maximizes the sum of all of the users’ information rates, and is referred to as the sum capacity of the channel. This point is illustrated in Figure 1.1 by asterisks. Achieving the sum capacity point may not necessarily be the goal of a system designer. One example where this may be the case is when the “near-far” problem occurs, where one user has a strongly attenuated channel compared to other users. As depicted in Figure 1.1, obtaining the sum capacity in such a situation would come at the expense of the user with the attenuated channel. The sum capacity for a system described by (1.1) has been formulated using the dirty paper coding (DPC) framework (see, for example for the case of Gaussian noise). The capacity is defined in terms of the achievable rate for each user given the set of covariance matrices for each transmitted data vector $S_k = \xi\{s_k s_k^*\}$:

$$R_k = \frac{\text{Log} |I + H_k (\sum_{j=1}^k S_j) H_k^*|}{\text{Log} |I + H_k (\sum_{j=1}^k S_j) H_k^*|}$$

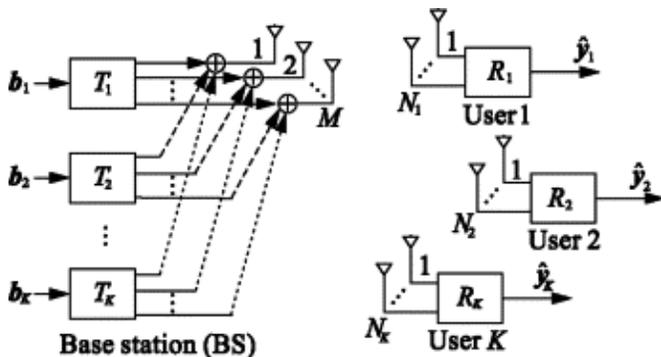
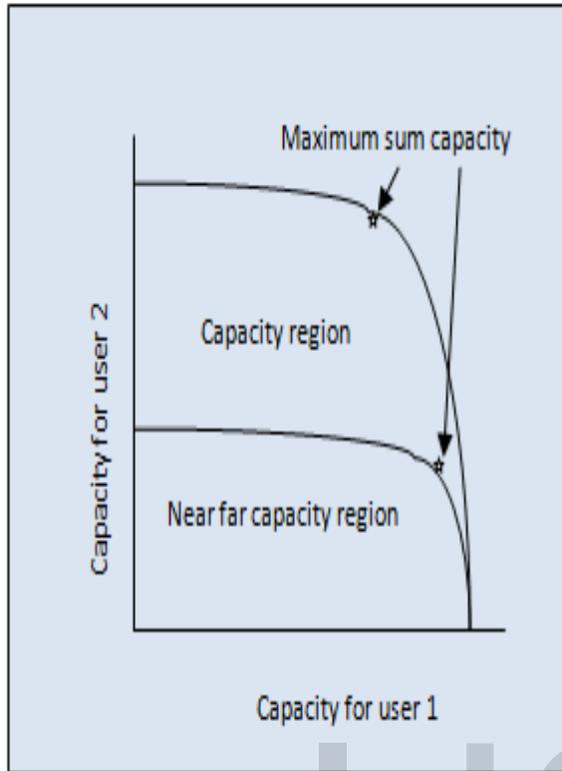


Fig.1 Multi-user MIMO communication systems
 Model for downlink with BD method

III. CHANNEL CAPACITY OF MULTIUSER MIMO DOWNLINK CHANNELS

Fig.2 An illustration of a Multi-user capacity region



IV. TRANSMISSION TECHNIQUES IN MULTIUSER MIMO DOWNLINK CHANNELS

The main difficulty in data transmission in BC is that the coordinated signal detection on the receiver side is not straightforward, and thus, interference cancellation at BS is required. There are various linear precoding and non linear precoding techniques for multiuser MIMO downlink transmission.

A. LINEAR PRECODING TECHNIQUES

A simple way of dealing with inter user interference is by imposing the constraint that all interference terms be zero. Assuming that $N_M \leq N_B$, this can be accomplished at the transmitter by precoding D which is the transmit data vector with the pseudo inverse of the channel matrix: $x = H^\dagger D = H^* (HH^*)^{-1} D$. At the receivers, this approach results in $y = D + w$. This technique is referred to as channel inversion, for the case where H is square. The columns of H^\dagger can be weighted to yield different SNRs for each user, depending on their given rate requirement. *Channel inversion* is a good solution for low-noise or high-power situations. But it does not result in the linear capacity growth with $\min(N_M, N_B)$ that should be achievable in the multi-user channel. This is because with a power constraint, an ill-conditioned channel matrix when inverted will require a large normalization factor that will dramatically reduce the SNR at the receivers. Ultimately, the drawbacks of channel inversion are due to the stringent requirement that the interference at the receivers be identically zero. Allowing a limited amount of interference at each receiver allows one to consider a larger set of potential

solutions that can potentially provide higher capacity for a given transmit power level, or a lower transmit power for a given rate point. This behaviour is seen in the solutions that maximize sum capacity; they allow some level of MAI at each receiver. One simple approach with this idea in mind derives from linear minimum mean squared error (MMSE) receivers used in the uplink. If we assume white noise and power constraint P , the MMSE uplink receiver is given by $(HU^*HU + K/PI)^{-1} HUy$, where HU is the uplink channel. For the downlink, it is possible to assume a similar MMSE-like structure, using $x = H^* (HH^* + \alpha I)^{-1} D$. This type of "regularized" channel inversion shows that the loading factor $\alpha = K/P$ maximizes the signal-to-interference-plus-noise ratio (SINR) at the receiver when this scheme is used. This simple procedure results in a solution that does achieve linear growth in throughput with $\min(N_M, N_B)$, but at a rate that is somewhat slower than that for capacity. Both types of channel inversion we have described are designed to achieve some SINR that is identical for each user. It is expected that in next generation communication systems there will be an increasing need to support heterogeneous wireless services, which implies that each user may have different bandwidth and/or SINR requirements. One way to achieve this is to adjust the amount of power transmitted to each user. This is straightforward with direct channel inversion because the sub channels created to each user are independent, but with regularized inversion, changing the power transmitted to one user changes the interference for all other users. This necessitates a *beam forming* solution where the beam forming vectors and power weights are jointly optimized user may have different bandwidth and/or SINR requirements. One way to achieve this is to adjust the amount of power transmitted to each user. This is straightforward with direct channel inversion because the sub channels created to each user are independent, but with regularized inversion, changing the power transmitted to one user changes the interference for all other users. This necessitates a beam forming solution where the beam forming vectors and power weights are jointly optimized. A natural extension of this problem is to consider cases where the users also have arrays, a scenario of interest for next-generation systems. Adding multiple antennas at each receiver makes it possible to consider the transmission of parallel data streams to multiple users, as accomplished, for example, by BLAST in a single-user system. Channel inversion could still be employed in this case, but is not a particularly efficient solution, since forcing two closely spaced antennas belonging to a single user to receive different signals would require extra power when the channels for these antennas are highly correlated. It also ignores the possibility of the receiver employing beam forming of its own. One solution to this problem is to use block channel inversion or *block diagonalization*. This approach is essentially a generalization of channel inversion that optimizes the power transfer to a group of antennas rather than a single antenna. Like channel inversion for single antennas, this approach requires that the number of transmit antennas be larger than the total number of receive antennas (except in some special cases), and does not achieve capacity, but also offers relatively low computational cost.

B. NON LINEAR PRECODING TECHNIQUES

We now turn to a nonlinear technique based on the concept of "writing on dirty paper" introduced by Costa in which the traditional additive Gaussian noise channel is modified to include an additive interference term that is known at the transmitter: received signal = transmitted signal + interference + noise. The simplest thing to do in such a scenario would be to set the transmitted signal equal to the desired data minus the interference, but such an approach requires increased power. Costa proved the surprising result that the capacity of this channel is the same as if the interference was not present; no more power is needed to cancel the interference than is used in a nominal additive Gaussian noise channel. To use Costa's analogy, writing on dirty paper is information i.e theoretically equivalent to writing on clean paper when one knows in advance where the dirt is. Costa's approach is theoretical, however, and does not provide a practical technique for approaching capacity. As the transmitter has channel state information, it knows what interference user 1's signal will produce at user 2, and hence can design a signal for user 2 that avoids the known interference. This concept has been used to characterize the sum-capacity and capacity region of the multi-antenna multi-user channel. The most well-known dirty paper technique for the MIMO downlink uses a QR decomposition of the channel, which can be written as the product of a lower triangular matrix L with a unitary matrix $H = LQ$. The signal to be transmitted is precoded with the Hermitian transpose of Q, resulting in the effective channel L. The first user of this system sees no interference from other users; its signal may be chosen without regard for the other users. The second user sees interference only from the first user; this interference is known and thus may be overcome using dirty paper coding. Subsequent users are dealt with in a similar manner. Another approach applies dirty paper techniques directly, rather than for individual users. An important difference between the multi-user MIMO channel and the interference channels for which dirty paper techniques are designed is that the interference depends on the signal being designed. In the previous section this problem is solved using a QR-type decomposition, so the interference for any particular user depends only on the interference generated by previous users. Dirty paper coding is then applied to cancel this interference. An alternate technique is to design all the signals jointly; this is the approach taken in, where matrix algebra is used to solve for the signal to be transmitted. The simple dirt paper technique of applying a modulo operation to the transmitted and received data is shown to operate close to the sum capacity vector precoding. It can be seen as a modification of channel inversion, where the desired signal D is offset by a vector l of integer values chosen to minimize the power in the transmitted signal, $x = H^{-1}(D + \tau l)$: where τ is chosen in the same way as for the successive algorithm described above. As with basic channel inversion, this encoding results in the kth receiver seeing an additive Gaussian channel $y_k = D_k + \tau l_k + w_k$. The integer offset l_k is removed by applying a modulo function at the receiver, resulting in a signal that looks very much like an additive noise channel: A modification of this technique uses a

regularized inverse at the encoder rather than simple channel inversion. The transmitted signal in this case is $x = H^*(HH^* + K/P)^{-1}(D + \tau l)$, where the vector l is again chosen to minimize the norm of x. Decoding occurs in the same way as for the non regularized approach. Extensions to this approach include use of the lattice techniques for dirty paper coding. The lattice used is the simple one-dimensional lattice defined by the modulo function; further gains are anticipated with the use of higher-dimensional lattices. Fast algorithms for finding the integer vector l have been proposed is based on lattice reduction and the VBLAST algorithm. These techniques have lower complexity than do the sphere-algorithm-based techniques of. Only single-antenna users are considered in; a simple extension to situations involving multiple receive antennas per user is to treat each antenna as a different user. Fig shows the uncoded probability of error performance of five modulation techniques for the multi-user downlink: simple and regularized channel inversion, successive precoding, and basic and regularized vector precoding. The simulation results are for a system with 10 transmits antennas and 10 single-antenna users. At low SNR, precoding with the regularized channel inverse surprisingly performs the best, while at high SNR the regularized precoding technique is best. The basic and regularized vector precoding techniques have a significant diversity advantage over the other techniques in this uncoded example. One possible explanation for basic regularized inversion's performing better than regularized vector precoding at low SNR is that the cubical lattice used in the latter algorithm is finite. Lattices as described in may enable the vector precoding techniques to perform as well as the basic inversion-based methods. DPC on the transmitter side is very similar to decision feedback equalization (DFE) on the receiver side. In fact, combination of DPC with symmetric modulo operation turns out to be equivalent to Tomlinson Harashima (TH) precoding. TH precoding was originally invented for reducing the peak or average power in the decision feedback equalizer (DFE), which suffers from error propagation. The original idea of TH precoding in DFE is to cancel the post-cursor ISI in the transmitter, where the past transmit symbols are known without possibility of errors. In fact, it requires a complete knowledge of the channel impulse response, which is only available by a feedback from the receiver for time-invariant or slowly time-varying channel.

V. CONCLUSION

The multi-user MIMO problem has recently started to attract the attention of the researchers. In this paper we have presented a brief overview of two classes of downlink transmission algorithms: linear processing techniques and non linear processing techniques. Linear techniques are simple and relatively cheap computationally, but they are not able to reach the sum-capacity of the channel. Techniques based on dirty paper coding perform much better and approach the theoretical limits of the channel, but require complicated coding schemes. We propose several open problems which primarily focus on linear processing or nonlinear (dirty paper coding) approaches to MIMO multi-user transmission. Higher dimensional lattices could be used to further approach the sum-capacity of the multi-user channel. Although these

lattices are difficult to implement, techniques such as trellis precoding might prove less computationally complex. The most visible unsolved problem in this field has been determining the capacity region for the MIMO multi-user channel. Though a solution was recently found to the Gaussian problem, there are many problems yet to be solved (e.g. in the non-Gaussian case). An analysis of the penalty for using imperfect or outdated feedback of channel information would be of significant benefit to system designers. The sum-capacity when only the transmitter or when no one knows the channel would also provide insight for practical coding schemes. A related area of research is analysis of a system where the transmitter and/or receiver know only the statistics of the channel coefficients.

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