Title
Interference Management: A New Paradigm for Wireless Cellular Networks

Author
Garcia-Luna-Aceves, J.J.

Publication Date
2009-10-18

Peer reviewed

Interference Management: A New Paradigm for Wireless Cellular Networks

Zheng Wang[†], Mingyue Ji[†], Hamid R. Sadjadpour[†], J.J. Garcia-Luna-Aceves[‡]

Department of Electrical Engineering[†] and Computer Engineering[‡]
University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
[‡] Palo Alto Research Center (PARC), 3333 Coyote Hill Road, Palo Alto, CA 94304, USA
Email:{wzgold, davidjmy, hamid, jj}@soe.ucsc.edu

***Abstract*— We introduce a new interference management technique for wireless cellular networks when the base station (BS) has K antennas and there are M mobile stations (MS), each with a single antenna. Our interference management scheme takes advantage of multiuser diversity to transmit K independent data streams to K out of M mobile stations. The new approach achieves the dirty paper coding (DPC) capacity of $K \log\log(M)$ as M tends to infinity. Surprisingly, the new scheme does not require full channel state information (CSI) and needs only close to K integers related to CSI are fed back to the transmitter. Moreover, the encoding and decoding of the new scheme is significantly simpler than existing MIMO schemes and is similar to point-to-point communications.**

I. Introduction

Information theorists have pursued computing the capacity of wireless networks in the presence of interference for several decades. The main observation in such networks is the fact that the capacity of such networks is limited by interference. Based on the strength of the interference, there are three remedies to solve this problem. If the interference is very strong, then the receiver can decode the interfering signal and then subtract it using successive interference cancelation [1]. In some cases, the interference signal is weak compared to the desired signal and it is treated as noise. The third and most common case is when the interference is comparable with the desired signal. The solution for this case is to avoid the interference by orthogonalizing it with the signal using such techniques as time division multiple access (TDMA) or frequency division multiple access (FDMA).

In wireless cellular networks, base stations (BS) can have large numbers of antennas, while most mobile stations (MS) have only a single antenna. In order to achieve the maximum multiplexing gain in these systems, a BS requires to transmit independent packets from its antennas, but all of these packets do arrive at the MSs. One remedy to solve this problem is to use a distributed MIMO at the receiver side, which requires the MSs to exchange significant information in order to be able to decode the packets. Although there are many papers related to distributed MIMO decoding, they are not very practical due to the significant feedback requirement between MSs.

The multiuser diversity scheme [2] was introduced as an alternative to increase the capacity of wireless networks. The main idea behind this approach is that the BS selects an MS that has the best channel condition by taking advantage of time varying nature of fading channels, thus maximizing the signal-to-noise ratio (SNR). This idea was later extended to mobile wireless ad hoc [3] and MIMO cellular [4] networks. Sharif and Hassibi [5] proposed to construct K random beams and transmit information to the users with the highest signal-to-noise plus interference ratio (SINR).

This paper introduces a new multiuser diversity scheme that utilizes fading in channels to mitigate interference. Unlike all existing techniques that are trying to fight fading and interference in wireless channels individually, our scheme actually takes advantage of one of them (fading channel) to reduce the negative effects of the other one (interference). By taking advantage of multiuser diversity, we attempt to maximize the SNR beyond a threshold while minimizing the interference-to-noise ratio (INR) below another threshold such that the interference signal strength is no longer significant. The result is very effective, and constitutes a powerful technique that achieves the dirty paper coding (DPC) capacity asymptotically and yet requires minimum feedback and simple point-to-point encoding and decoding techniques.

The remaining of this paper is organized as follows. Section II presents an overview of related work. Section III introduces the model used in our analysis. Section IV presents the new interference management approach. Simulation results are presented in Section V and we conclude the paper in Section VI.

II. Related Work

Our work is mainly motivated by the multiuser diversity concept. Knopp and Humblet [2] derived the optimum capacity for the uplink of a wireless cellular network taking advantage of multi-user diversity. They proved that if the "best" channel (i.e., the channel with the highest SNR in the network) is selected, then all of the power should be allocated to this specific user with good "channel," instead of water-filling power control technique. Furthermore, Viswanath et al in [4] used similar idea for the downlink channel using the so called "dumb antennas" by taking advantage of opportunistic beamforming. Grossglauser et al [3] extended this multi-user diversity concept to mobile ad hoc networks and took advantage of node mobility to scale the capacity.

Interference alignment [6], [7] is another technique to manage interference. The main idea in this approach is to use part of the degrees of freedom to transmit the signal and the remaining part to transmit the interference. For example, the approach in [7] considers $K \times M$ interference channel and demonstrate that achievable degrees of freedom is $\frac{KM}{K+M-1}$. The drawback of interference alignment is that it requires global knowledge of the channel state information (CSI), which is very difficult to attain in practice, and the feedback of the CSI is MK complex numbers in $K \times M$ interference channels.

In this paper, we present an interference management technique for the downlink of wireless cellular networks such that the BS can transmit D independent data streams when the BS has K antennas and there are M MSs in the network. Furthermore, we demonstrate that D can be any number with probability one up to the maximum value of K, as long as M satisfies certain conditions. Therefore, interference management is capable of achieving the maximum multiplexing gain as long as there is a minimum number of MSs in the network. Surprisingly, by fully taking advantage of fading channels in multiuser environments, the feedback requirement to achieve maximum multiplexing gain is close to K, while the encoding and decoding schemes needed are very simple and similar to the point-to-point communications. The original multiuser diversity concept was based on looking for the best channels, while our approach shows that searching simultaneously for the best and worst channels is important and can lead to significant capacity gains. This technique can asymptotically achieve the DPC capacity when $M \rightarrow \infty$.

Sharif and Hassibi introduced a new approach [5], [8] to search for the best SINR in the network. Their approach requires M complex numbers for feedback instead of full CSI knowledge while achieves the same capacity of $K \log \log M$ similar to DPC. There are major differences between our approach and the design by Sharif and Hassibi [5]. First, our approach does not require beamforming, while the proposed techniques in [5], [8] take advantage of beamforming. Second, the cooperation requirement in our technique is significantly lower than that of [5], [8]. Third, the feedback requirement in our scheme is proportional to K integers, while this value is proportional to M complex numbers in [5], [8]. When M grows, the feedback requirement for [5], [8] approaches a linear growth, while in our scheme, this complexity is close to the number of antennas at the BS. Finally, we can achieve the same capacity of $K \log \log M$.

III. Network Model

The BS has K antennas and there are M MSs, each having a single antenna. In this paper, we assume that $M \gg K$. The channel between the BS and MS users $\mathbf{H}$ is a $M \times K$ matrix with elements h_{ij} where $i \in [1, 2, \ldots, K]$ is the antenna index of the BS and $j \in [1, 2, \ldots, M]$ is the mobile station index. We consider block fading model, where the channel coefficients are constant during coherence interval of T. Then the received signal $\mathbf{Y}^{M \times 1}$ can be expressed as

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{x}$ is the transmit $K \times 1$ signal vector and $\mathbf{n}$ is the $M \times 1$ noise vector. The noise at each of the receive antennas is i.i.d. with $\mathcal{CN}(0, \sigma_n^2)$ distribution.

IV. Interference Management

A. The scheduling protocol

During the first phase of communication, the antennas of the BS sequentially transmit a pilot signal, which requires K time slots. In this period, all the MSs listen to these known messages. After the last pilot signal is transmitted, MS users evaluate the SNR for each antenna. If the SNR for only one transmit antenna is greater than a pre-determined threshold SNR_{tr} and below another pre-determined threshold of INR_{tr} for the remaining $K - 1$ antennas, that particular MS user selects that particular antenna at the BS. In practice, some MS users have this property for the same or different antennas of the BS. The number of MS users with this property can be smaller, greater or equal to K. For this reason, in the second phase of communications, these MS users notify the BS about their corresponding BS antenna. Clearly, many MS users will be silent during this time, because they do not have the above conditions. We will prove later that the number of MS users with interference management capability can be close to K by selecting the appropriate network parameters with probability arbitrarily close to 1. We will not discuss the MAC protocol required for these MS users to contact the BS. Once the BS receives all information related to qualifying MS users, it selects and notifies those MS users in one time slot, because the BS can transmit their individual messages from their corresponding antennas without any significant interference between the messages. Note that, if we choose appropriate values for SNR_{tr} and INR_{tr} such that $\text{SNR}_{tr} \gg \text{INR}_{tr}$, then the BS can simultaneously transmit different packets from its antennas to different MS users. The MS users only receive their corresponding packets with strong signal and can treat the rest of packets as noise. The value of SNR_{tr} (or INR_{tr}) can be selected as high (or low) as required for a given system as long as M is large enough. We will show their relationship in detail later. Figure 1 illustrates the system that is used here. Without loss of generality, we assume that the MS user i for $i \in [1, 2, \ldots, K]$ is assigned to antenna i in the BS. In this figure, solid and dotted lines represent strong and weak channels respectively.

B. Capacity Computation

Define SNR_{ij} as the signal-to-noise ratio when antenna i at the BS is transmitting packet to MS user j in the downlink. The objective of interference management is to find K MS users out of M choices to satisfy the following criterion.

$$\begin{aligned} &\text{SNR}_{ij} \geq \text{SNR}_{tr}, \forall i, j \in 1, 2, \cdots, K, i = j \\ &\text{INR}_{ij} \leq \text{INR}_{tr}, \forall i, j \in 1, 2, \cdots, K, i \neq j \end{aligned} \tag{2}$$

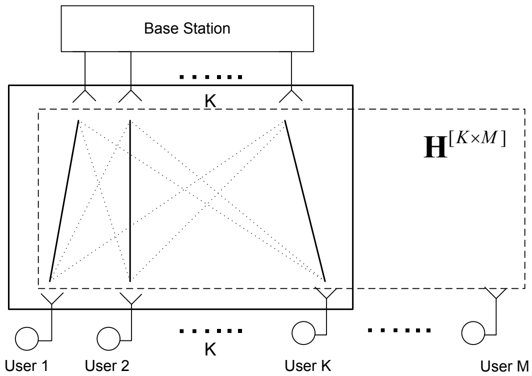

Fig. 1. Wireless cellular network model

This condition basically states that for each MS user $j, 1 \leq j \leq K$, each one of them has a very good channel with only a single antenna in the BS and strong fading channel with all other BS antennas. It also implies that different MS users have good channel condition with different BS antennas. It is important to note that the number of MS users that have the interference management condition is a random variable X. This value can change at each epoch when the channel state information in the network changes. The parameter D is actually the average value of X, i.e., $D = E(X)$. We will later compute the probability distribution function of X.

Further, we define SINR_{ii} as

$$\text{SINR}_{ii} = \frac{\text{SNR}_{ii}}{\sum_{j=1, j\neq i}^{D-1} \text{INR}_{ij} + 1} \tag{3}$$

and SINR_{tr} as

$$\text{SINR}_{tr} = \frac{\text{SNR}_{tr}}{(D-1)\text{INR}_{tr} + 1}. \tag{4}$$

Hence, the average sum rate capacity can be written as

$$\begin{aligned} C_{\text{proposed}} &= E\left(\sum_{i=1}^{X} \log\left(1 + \text{SINR}_{ii}\right)\right), \\ &= E\left(\sum_{i=1}^{X} \log\left(1 + \frac{\text{SNR}_{ii}}{\sum_{j=1, j\neq i}^{D-1} \text{INR}_{ij} + 1}\right)\right), \\ &\geq D \log\left(1 + \frac{\text{SNR}_{tr}}{(D-1)\text{INR}_{tr} + 1}\right), \\ &= D \log(1 + \text{SINR}_{tr}). \end{aligned} \tag{5}$$

The third line is derived based on the fact that $\text{SINR}_{ii} \geq \text{SNR}_{tr}$, $\text{INR}_{ij} \leq \text{INR}_{tr}$, and $D = E(X)$.

In the following, we first prove that for any value of SINR_{tr}, there exists a minimum value of M that will satisfy Eq. (5). We will then demonstrate that this scheme achieves the optimum capacity of DPC. To prove the validity of this algorithm, we need to prove that there are K MS users that satisfy (2) with probability one.

To prove the condition in Eq. (5), we assume that the channel distribution is Rayleigh fading channel. However, any time-varying channel model can be utilized for the following derivations. Note that for a Rayleigh fading channel $\mathbf{H}$ distribution, the probability distribution of SNR is given by

$$p(\text{x}) = \begin{cases} \frac{1}{\sigma}\exp\left(-\frac{x}{\sigma}\right), & x > 0 \\ 0, & x \leq 0 \end{cases} \tag{6}$$

where x is the SNR value and $\sigma = E_{\mathbf{H}}(x)$.

Assume that event A is for any mobile station that satisfies condition in (2). This probability can be derived as

$$\begin{aligned} P(A) &= \int_{\text{SNR}_{tr}}^{\infty} p(x)dx \left(\int_{0}^{\text{INR}_{tr}} p(x)dx\right)^{K-1}. \\ &= e^{-\frac{\text{SNR}_{tr}}{\sigma}}\left(1 - e^{-\frac{\text{INR}_{tr}}{\sigma}}\right)^{K-1}. \end{aligned} \tag{7}$$

Note that $P(A)$ is the probability of a MS user satisfying the condition in Eq. (2) for any of the K antennas at the BS. Therefore, the probability that any MS user satisfy at least one of the BS antennas is $K \times P(A)$. Also, we assume that the channels between different MS users and BS antennas are i.i.d. which means all of them have the same probability of satisfying condition in (2). If there are only a total of D MS users that satisfy condition in (2), then we have [1]

$$M \times (K \times P(A)) \cong D. \tag{8}$$

From Eq. (8), the relationship between M and $P(A)$ can be derived. Note that M is a function of network parameters such as $K, D, \text{SNR}_{tr}, \text{INR}_{tr}$, and σ. The parameters K, D and σ are really related to the physical properties of the network and are not design parameters. Furthermore, the parameters SNR_{tr} and INR_{tr} can be replaced with a single parameter SINR_{tr} using (4).

$$M(K, D, \text{SNR}_{tr}, \text{INR}_{tr}, \sigma) \cong \frac{D}{K}(P(A))^{-1} \tag{9}$$

In order to compute a lower bound for M, the minimum value for $(P(A))^{-1}$ must be derived such that the SINR_{tr} condition in (4) is satisfied.

$$\text{minimize} \qquad \frac{D}{K}(P(A))^{-1} \tag{10}$$

$$\text{subject to} \qquad \text{SINR}_{tr} = \frac{\text{SNR}_{tr}}{(D-1)\text{INR}_{tr} + 1} \tag{11}$$

This optimization problem can be rewritten as

$$\begin{aligned} &\min_{Eq.(11)} \left(\frac{D}{K}(P(A))^{-1}\right) \\ &= \frac{D}{K} \min_{Eq.(11)} \left(\frac{e^{\frac{\text{SNR}_{tr}}{\sigma}}}{\left(1 - e^{-\frac{\text{INR}_{tr}}{\sigma}}\right)^{K-1}}\right) \\ &\overset{(a)}{=} \frac{De^{\frac{\text{SINR}_{tr}}{\sigma}}}{K} \min_{\text{INR}_{tr}} \left(\frac{e^{(D-1)\frac{\text{SINR}_{tr}\text{INR}_{tr}}{\sigma}}}{\left(1 - e^{-\frac{\text{INR}_{tr}}{\sigma}}\right)^{K-1}}\right) \\ &\overset{(b)}{\cong} \frac{De^{\frac{\text{SINR}_{tr}}{\sigma}}\sigma^{K-1}}{K} \min_{\text{INR}_{tr}} \left(\frac{e^{(D-1)\frac{\text{SINR}_{tr}\text{INR}_{tr}}{\sigma}}}{(\text{INR}_{tr})^{K-1}}\right) \end{aligned} \tag{12}$$

[1] The probability that two MS users satisfy (2) for the same antenna in BS is ignored in this analysis. Hence the above analysis is approximation.

We derive the second equality (a) above by replacing SNR_{tr} with INR_{tr} and SINR_{tr} using Eq. (4). The approximation in (b) is derived by assuming $\frac{\text{INR}_{tr}}{\sigma}$ is a value much smaller than 1 and the fact that $\lim_{x\to 0}(1-\exp(-x)) = x$. Note that the unique characteristic of this new scheme is to take advantage of fading and clearly, under this circumstance the value of $\frac{\text{INR}_{tr}}{\sigma}$ is small.

The minimum value of $\left(\frac{e^{\frac{(D-1)\text{SINR}_{tr}}{\sigma}\text{INR}_{tr}}}{\text{INR}_{tr}^{K-1}}\right)$ is derived by taking its first derivative with respect to INR_{tr} and making it equal to zero.

$$e^{\frac{(D-1)\text{SINR}_{tr}}{\sigma}\text{INR}_{tr}} \times \left(\frac{(D-1)\text{SINR}_{tr}}{\sigma}\text{INR}_{tr}^{K-1} - (K-1)\text{INR}_{tr}^{K-2}\right) = 0 \quad (13)$$

The solution for INR^*_{tr} is

$$\text{INR}^*_{tr} = \frac{K-1}{D-1}\frac{\sigma}{\text{SINR}_{tr}}. \quad (14)$$

Then the optimum value for M is given by[2]

$$M^* = \lceil \frac{D}{K} e^{\frac{\text{SINR}_{tr}}{\sigma}} \left(\frac{D-1}{K-1}\text{SINR}_{tr} e\right)^{K-1} \rceil. \quad (15)$$

This value is derived by replacing the optimum value of INR^*_{tr} into (12) and using the approximation of (b) in this equation. σ represents the strength of fading channel and as this parameter increases or equivalently the channel experiences more severe fade, then this technique can work at lower values of SNR_{tr} when SINR_{tr} is constant. The main reason is the fact that fading environment helps to combat interference. Furthermore, the optimum value for M demonstrates that by increasing the SINR_{tr}, the minimum number of MS users increases exponentially.

For constant values of SINR_{tr} and when $\sigma \to \infty$, then the minimum M^* is

$$\lim_{\sigma\to\infty} M^* = \lceil \frac{D}{K} \left(\frac{D-1}{K-1}\text{SINR}_{tr} e\right)^{K-1} \rceil. \quad (16)$$

This results implies that there exists a minimum value of MS users to implement this technique, even for very strong fading channels.

Now we investigate the asymptotic behavior of the network (i.e., $M \to \infty$) and try to compute the maximum achievable capacity and scaling laws for this scheme. Clearly, when M tends to infinity, the SINR_{tr} increases because we can select a higher value for SNR_{tr} and a smaller value for INR_{tr}. Under such conditions, the minimum value of M is given by

$$M^* \cong \lceil \frac{D}{K} \left(e\frac{D-1}{K-1}\right)^{K-1} e^{\frac{\text{SINR}_{tr}}{\sigma}} \rceil. \quad (17)$$

Then SINR_{tr} is

$$\text{SINR}^{\max}_{tr} \cong \sigma \log\left(\frac{K}{D}\left(\frac{1}{e}\frac{K-1}{D-1}\right)^{K-1} M\right). \quad (18)$$

[2]Note that M has to be an integer and consequently, we need to use the ceil function in this equation.

When $D = K$, then the $\text{SINR}^{\max}_{tr}$ scales as $\log M$, so that by utilizing (5), the scaling laws of this network is

$$C = \Theta(K \log\log M). \quad (19)$$

This is exactly the same scaling laws as in [5], [8], which is equivalent to the DPC capacity. However, our scheme requires a finite number close to K feedback information, which is much smaller than M or $2KM$ for [5], [8] or DPC, respectively. Furthermore when $K = D > \log(M)$, we can see from Eq. (18) that the $\text{SINR}^{\max}_{tr}$ tends to zero. This result implies that the number of antennas at the BS should not grow faster than $\log(M)$ in order to assure that we can achieve the maximum capacity. This result was also reported in [5], [8].

It is worth pointing out that this technique cannot achieve the optimum value of K multiplexing gain in the downlink if σ is small or, equivalently, if the channel fading is not strong. In a multiuser environment, fading actually is very helpful. Our proposed multi-user diversity scheme is different from the original scheme that requires the transmitter to search for the node with the best channel condition. As we showed in this paper, searching for both strong and weak channels is important in combating the multiuser interference.

When $K = 1$, then our approach is similar to that of [2]. Moreover, if $M \to \infty$ and $D = K$, then our scheme has the same asymptotic scaling laws capacity result as that of [5], [8]. The cost of the proposed scheme is the need for a minimum number of MS users, M. In most practical cellular systems, in any given frequency and time inside a cell, there is only one assigned MS, while this technique suggests that we can have up to the number of BS antennas utilizing the same spectrum at the same time with no bandwidth expansion. Clearly, this approach can increase the capacity of wireless cellular networks significantly. This gain is achieved with a modest feedback requirement that is proportional to the number of transmitter antennas at the BS. We conclude our results in the following theorem.

Theorem 4.1: In wireless cellular networks with M mobile stations, each one having a single antenna and the base station with K antennas, we can achieve D multiplexing gain in the downlink when M satisfies Eq. (15). This scheme only requires D integers as feedback CSI where $D = \Theta(K)$.

C. Feedback requirements

A natural question regarding our interference management scheme is what the number of MS users is that satisfies the interference management criterion. Clearly, this number is a random variable, which we denote by X. We will prove that this value is at most K with probability arbitrarily close to one if the network parameters are appropriately selected. More specifically, the probability that $X \leq K$ MS users satisfy the interference management criteria denoted as η can be arbitrarily close to 1 if we select proper SINR_{tr} based on network parameters such as fading the parameter σ and M.

For any MS, the probability that it satisfies the interference management condition is $K \times P(A)$, i.e., the MS has a very strong channel with a single BS antenna and a very weak channel (deep fade) with all other BS antennas. The number of the MSs satisfying the interference management criteria is a random variable X satisfying binomial distribution whose probability density function (pdf) is given by

$$Pr(X=x) = \binom{M}{x}\left(\binom{K}{1}P(A)\right)^{x}\left(1-\binom{K}{1}P(A)\right)^{M-x}. \quad (20)$$

Therefore, the cumulative distribution function can be expressed as

$$\begin{aligned} Pr(X \leq K) &= \sum_{i=0}^{K}\binom{M}{i}(KP(A))^{i}(1-KP(A))^{M-i} \\ &\geq \eta, \end{aligned} \quad (21)$$

where $0 < \eta < 1$ can be arbitrarily close to 1 , i.e., $\eta = 99\%$.

Note that, for any value of K, M and σ, the designer can select the appropriate value for SINR_{tr} such that with probability close to 1 the value of random variable X is less than K as numerically shown in Fig. 2. Given that the number of active MSs in a cell is known to the BS, the BS can adjust the SINR_{tr} value such that the number of MS users qualifying the interference management condition does not increase significantly. This is a significant improvement compared to the dirty paper coding or techniques introduced in [5], [8], which require $K \times M$ and M CSI feedback information respectively. When M increases, the feedback information also increases accordingly. However, interference management requires $\Theta(K)$ CSI feedback regardless of the number of mobile stations with probability arbitrarily close to 1 as long as the SINR_{tr} is adjusted appropriately.

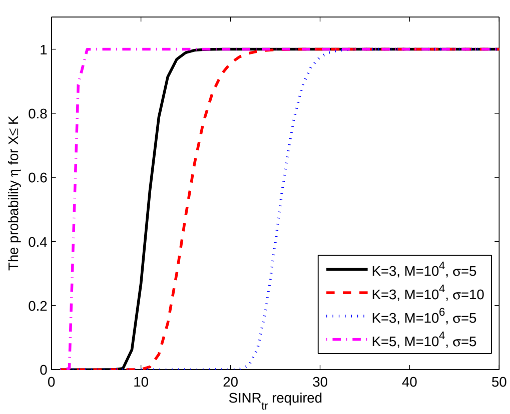

Fig. 2. The feedback is at most K with almost sure

D. Signaling requirement

One of the main advantages of this technique is the fact that, by taking advantage of multiuser diversity, we reduce a distributed MIMO system in the downlink of wireless cellular networks into a group of parallel single-input single output (SISO) systems. For this reason, all challenges and complexities related to space-time signal processing design can be replaced by simple point-to-point communications while achieving maximum capacity as long as the number of mobile stations is adequate. This significant simplification of the signalling in the wireless systems is an additional advantage of our interference management scheme.

V. Simulation Results

Fig. 3 shows the theoretical values of M for different values of K (dotted lines in this figure) when the fading channel is very strong, i.e., $\sigma = 100$. We have also plotted the simulation results obtained by simulating the fading channel and counting the number of MS users that satisfy the interference management condition (solid line in this figure). The result demonstrates that our theoretical analysis matches the simulation results well. As we can see from this simulation results, when the SINR_{tr} requirement increases, the number of MS users required to implement this technique increases significantly. Therefore, using such capacity-approaching techniques as Turbo code or LDPC that requires very low SINR_{tr} will help to implement this technique with modest number of MS users. We also notice that, when SINR_{tr} decreases, the simulation results deviate slightly from the theoretical values, which can be easily explained by simplification technique used in Eq. (12,(b)).

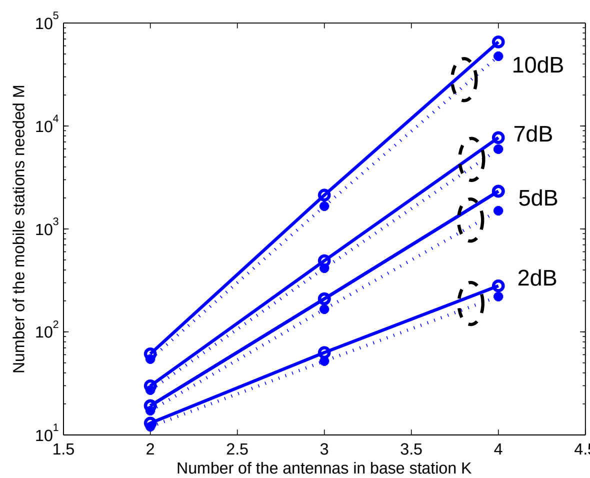

Fig. 3. Simulation results for different values of SINR

The next figure shows the theoretical requirement for the number of MS users when the channel fading strength varies, $2 \leq \sigma \leq 100$. As we can see from this result, as long as the fading channel is strong or modestly strong, the number of MS users are reasonable, but when fading is weak, then this number increases significantly. One remedy to solve this problem is to only choose D out of K antennas in the base station when we do not have too many MS users.

VI. Conclusion

In this paper, we proposed an interference management technique to mitigate interference so that the desired signal, i.e. SNR, is "strong" while the interference to others INR is "weak". By doing so, the system achieves the optimum K

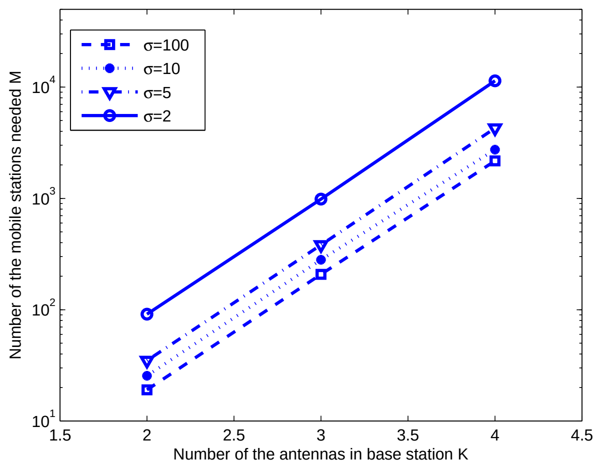

Fig. 4. Simulation results for different fading channel environments when SINR=5dB

multiplexing gain in the downlink of cellular networks when the number of mobile stations M is large enough. Moreover, this technique requires only K integers for feedback, compared with MK complex numbers in [5], [8]. This technique reduces the encoding and decoding complexity for the downlink of wireless cellular networks to simple point-to-point communications which is much simpler than proposed MIMO systems in literature. The ramifications of this technique can be significant for wireless cellular networks, where multiple communications in the downlink broadcast channel can be conducted with minimum complexity requirements. It also appears that the extension of this technique to wireless ad hoc networks is possible, which is the topic of future studies.

VII. Acknowledgments

This work was partially sponsored by the U.S. Army Research Office under grant W911NF-05-1-0246, by the National Science Foundation under grant CCF-0729230, and by the Baskin Chair of Computer Engineering. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government.

References

[1] H. Sato, "The capacity of the gaussian interference channel under strong interference," *IEEE Transactions on Information Theory*, vol. 27, no. 6, pp. 786– 788, November 1981.

[2] R. Knopp and P. Humblet, "Information capacity and power control in single-cell multiuser communications," in *Proc. of IEEE ICC 1995*, Seattle, Washington, USA, June 18-22 1995.

[3] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad hoc wireless networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 4, pp. 477–486, August 2002.

[4] P. Viswanath, D. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Transactions on Information Theory*, vol. 48, no. 6, pp. 1277–1294, June 2002.

[5] M. Sharif and B. Hassibi, "On the capacity of MIMO broadcast channels with partial side information," *IEEE Transactions on Information Theory*, vol. 51, no. 2, pp. 506–522, February 2005.

[6] V. Cadambe and S. Jafar, "Interference alignment and degrees of freedom of the K-user interference channel," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3425–3439, August 2008.

[7] ——, "Degrees of freedom for wireless X networks," *Submitted*, 2007.

[8] M. Sharif and B. Hassibi, "A comparison of time-sharing, DPC, and beamforming for MIMO broadcast channels with many users," *IEEE Transactions on Communications*, vol. 55, no. 1, pp. 11–15, January 2007.