JOINT ADAPTIVE POWER AND MODULATION MANAGEMENT IN WIRELESS NETWORKS WITH ANTENNA DIVERSITY

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ABSTRACT

In multi-access wireless communication systems,power control and adaptive modulation are two important means to increase spectral efficiency, combat with time varying fading environment, and reduce co-channel interference. In this paper, the overall uplink transmitting power is optimized while the overall network throughput is fixed. Each link can select a range of targeted Signal-to-Interference-Noise-Ratio (SINR) according to its current channel condition and each link's time average SINR is maintained as a constant to ensure fairness. Adaptive M-QAM or M-PSK modulation with antenna diversity is applied to increase spectral efficiency. The scheme can be interpreted as "water filling" each link's SINR in time domain and allocating network throughput to different links at each time. From the simulation results, our scheme reduces about 40% of overall transmitting power and increases average spectral efficiency by about 0.9 bit/s/Hz.

Keywords: Power Control, Adaptive Modulation, Antenna Diversity, Co-channel Interference, Spectral Efficiency.

1. INTRODUCTION

The radio spectrum available for wireless communication is extremely limited, while the demand for the services is growing rapidly. Spectral efficiency is therefore of primary concern in the design of future wireless communication systems. Two of the important detrimental effects to decrease spectral efficiency are the time varying nature of the channel and co-channel interference. Due to these effects, the Signal-to-Interference-Noise-Ratio (SINR) at the output of the receiver can fluctuate in the order of tens of dBs. A general strategy to combat these detrimental effects is by the dynamic allocation of resources such as transmitting power and modulation methods based on the current channel conditions. In power control, the transmitting powers are constantly adjusted. Such process improves the quality of weak links. But at the same time, it increases the co-channel interferences during the deep fading. In adaptive modulation, the system assigns the modulation methods with different spectral efficiency to different links according to their current channel conditions. There are tradeoff and practical constraints to allocate these resources. So how to optimally manage these resources becomes a hot topic in nowadays wireless research.

Many works [1] [2] [5] have been done for power control and adaptive modulation in multi-access wireless channels. In traditional power control, each link's transmitting power is selected so that its SINR is larger than or equal to a fixed and predefined targeted SINR threshold required to maintain its link quality, while minimizing the overall transmitting power of all the links. However a link with bad channel response requires too much transmitting power and therefore causes unnecessary co-channel interference to other links. This is a major issue that we will address here. We concentrate on uplink situation. The downlink case can be developed in a similar way. We introduce joint adaptive power and modulation allocation scheme using M-QAM or M-PSK modulation with antenna diversity. The goal of this paper is to minimize overall transmitting power while the overall network throughput is fixed. Instead of having fixed and predefined targeted SINR threshold to each link, each link can select a range of targeted SINR according to its current channel fading condition. The time average SINR of each link is maintained as a constant. The overall network throughput is kept as a constant at each time. The scheme can be interpreted as "water filling" each link's SINR in time domain and allocating network throughput to different links at each time. From the simulation results, our scheme reduces about 40% of overall transmitting power and increases average spectral efficiency by about 0.9 bit/s/Hz.

2. SYSTEM MODELS AND PROBLEM FORMULATION

Consider K co-channel links that may exist in distinct cell such as in TDMA or FDMA networks. Each link consists of a mobile and its assigned base station. Assume coherent detection is possible so that it is sufficient to model this multiuser system by an equivalent baseband model. Antenna arrays with P elements are used only at base station. We assume that each link is affected by the multipath slow Rayleigh fading. The multipath delay is far less than one

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symbol duration. The maximum path number is L. For uplink case, the signal at the p^{th} antenna array of the i^{th} base station can be expressed as:

$$x_i^p(t) = \sum_{k=1}^{K}\sum_{l=1}^{L}\sqrt{\rho_{ki}G_{ki}\alpha_{ki}^{pl}P_k g_k(t)s_k(t)} + n_i^p(t) \quad (1)$$

where α_{ki}^{pl} is the Rayleigh fading loss, P_k is the k^{th} link's transmitting power, $g_k(t)$ is the shaping function, $s_k(t)$ is the message symbol, $n_i^p(t)$ is the thermal noise, ρ_{ki} is log normal shadow fading and G_{ki} is the path loss[3].

We assume that channels are stable within a frame of hundreds of symbols. Define the impulse response from the k^{th} mobile to the p^{th} element of the i^{th} base station as: $h_{ki}^p = \sum_{l=1}^{L}\sqrt{\alpha_{ki}^{pl} r_{ki}^{pl}}$, where r_{ki}^{pl} includes the effect of the transmitter, receiver filter and shaping function $g_k(t)$. Then the p^{th} antenna's sampled received signal is:

$$x_i^p(j) = \sum_{k=1}^{K} h_{ki}^p\sqrt{P_k\rho_{ki}G_{ki}}s_k(j) + n_i^p(j) \quad (2)$$

where $n_i^p(j)$ is the sampled thermal noise.

The antenna outputs are combined by Maximal Ratio Combining (MRC) or Selective Combining (SC) [4] shown in Fig. 1. MRC diversity requires that the individual signals from each branch be weighted by their SINR then summed coherently. We assume perfect knowledge of the branch amplitudes and phases. MRC is the optimal diversity combining scheme and therefore provides the maximum capacity improvement relative to all combining techniques. The disadvantages of MRC is that it requires all knowledge of the branch parameters. Selective Combining (SC) diversity only processes one of the diversity branches. Specifically, the combiner chooses the branch with the highest SINR. SC is simpler than MRC, but also yields suboptimal performance. Since the output of the SC combiner is equal to the signal on one of the branches, the coherent sum of the individual branch signals is not necessary. Therefore, SC can be used in conjunction with differential modulation techniques, which is much simpler than coherent modulations. By using the antenna diversity, the i^{th} base station's combiner output can be written as $\mathbf{w}_i^H\mathbf{x}_i$, where $\mathbf{x}_i = [x_i^1 \dots x_i^P]^T$ and $\mathbf{w}_i$ is the $P \times 1$ combiner weight vector. The i^{th} base station's combiner output SINR is

$$\Gamma_i = \frac{P_i\rho_{ii}G_{ii}\|\mathbf{w}_i^H\mathbf{h}_{ii}\|^2}{\sum_{k\neq i}P_k\rho_{ki}G_{ki}\|\mathbf{w}_i^H\mathbf{h}_{ki}\|^2 + \mathbf{w}_i^H N_i\mathbf{w}_i} \quad (3)$$

where $N_i = E\{\mathbf{n}_i\mathbf{n}_i^H\}$ and $\mathbf{n}_i = [n_i^1 \dots n_i^P]^T$.

Now we show the relation between SINR and throughput. In the i^{th} cell, the i^{th} link between the mobile and its assigned base station uses the modulation with constellation size M_i. We assume M_i is continuous in this paper. The i^{th} link has throughput $T_i = log_2(M_i)$. In [1], the BER using different modulation can be approximated as:

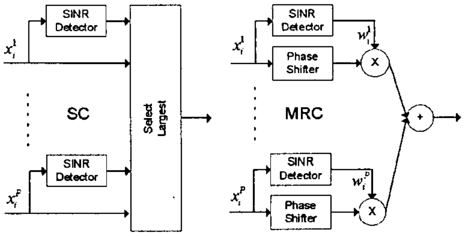

Fig. 1. Selective Combine and Maximum Ratio Combine

$$BER_i \approx c_1 e^{-c_2\frac{\Gamma_i}{2^{c_3T_i}-1}} \quad (4)$$

where $c_1 \approx 0.2$, $c_2 \approx 1.5$, and $c_3 \approx 1$ for MQAM. $c_1 \approx 0.05$, $c_2 \approx 6$, and $c_3 \approx 1.9$ for MPSK. For differential MPSK, 2dB to 3dB more SINR is needed to get desired BER than for MPSK with the same constellation size. Rearrange Equ. 4. For specific BER, the i^{th} link's throughput is:

$$T_i = c_4^i log_2\left(1 + c_5^i\Gamma_i\right) \quad (5)$$

where $c_4^i = 1/c_3^i$ and $c_5^i = -c_2^i/ln(BER_i/c_1^i)$. Without loss of generosity, assume each user has the unit bandwidth. Define the overall network throughput as: $T = \sum_{i=1}^{K} T_i$.

We assume all the links can accept instantaneous SINR thresholds γ_i $(\Gamma_i \geq \gamma_i)$ within a range $[\gamma_i^{min}, \gamma_i^{max}]$, according to their current channel conditions, while the overall network throughput is maintained as a constant. At each time, the links with bad channel conditions sacrifice their SINR, i.e. they transmit less throughput, which reduces the unnecessary co-channel interference. The links with good channel conditions get better SINR, i.e. more bits per symbol is selected, which increase the network throughput. For each link, the time average SINR is a constant to ensure the fairness and the SINR is "water filled" in different time. For the whole system at any specific time, the overall network throughput is allocated in different links according to their current channel conditions. The matrix version of this problem can be expressed as:

$$\min_{\gamma_i}\sum_{i=1}^{K} P_i \quad (6)$$

$$\text{subject to}\begin{cases}\text{Feasible: } (I - DF)\mathbf{P} \geq \mathbf{u}, \\ \text{Network Performance: } T = \text{const.}, \\ \text{SINR Range: } \gamma_{min} \leq \gamma_i \leq \gamma_{max}, \\ \text{Fairness: } \lim_{N\to\infty}\frac{\sum_{n=1}^{N}\gamma_i(n)}{N} = const.\end{cases}$$

$\mathbf{u} = [u_1 \dots u_K]^T$, $u_i = \gamma_i\mathbf{w}_i^H N_i\mathbf{w}_i/(\rho_{ii}G_{ii}\|\mathbf{w}_i^H\mathbf{h}_{ii}\|^2)$, $\mathbf{P} = [P_1, \dots, P_K]^T$, $D = diag\{\gamma_1, \dots, \gamma_K\}$, and $[F_{ij}] = 0$, if $j = i$, $\rho_{ji}G_{ji}\|\mathbf{w}_i^H\mathbf{h}_{ji}\|^2/\rho_{ii}G_{ii}\|\mathbf{w}_i^H\mathbf{h}_{ii}\|^2$, if $j \neq i$

3. POWER AND MODULATION MANAGEMENT

In [2], the author proves that $P_{sum} = \sum_{i=1}^{K} P_i$ is a convex and increasing function of γ_i, when γ_j, $j = 1 \dots K$, $j \neq i$ is fixed. Because of the convexity, we can find adaptive algorithm to adjust each link's targeted SINR threshold to reduce the overall transmitting power. Since the links with bad channel conditions need larger transmitting power from the assigned base station, if these links sacrifice their SINR requirement, the total transmitting power is reduced greatly. On the other hand, the links with good channel conditions can have better targeted SINR threshold so that the network throughput can be improved. P_{sum} can be written as:

$$P_{sum} = \mathbf{1}^T (I - DF)^{-1} \mathbf{u}$$

where $\mathbf{1} = [1 \dots 1]^T$. Take derivatives of γ_i at both sides, then we have the i^{th} element of gradient $\mathbf{g} = [g_1 \dots g_K]^T$ of the overall uplink transmitting power P_{sum} as:

$$\begin{aligned} g_i &= \frac{\partial P_{sum}}{\partial \gamma_i} = \mathbf{1}^T (I - DF)^{-1} [\hat{D}_i F \mathbf{P} + \hat{\mathbf{u}}_i] \\ &= \frac{c_i \left(\mathbf{w}_i^H N_i \mathbf{w}_i + \sum_{j \neq i} P_j \rho_{ji} G_{ji} \|\mathbf{w}_i^H \mathbf{h}_{ji}\|^2 \right)}{\rho_{ii} G_{ii} \|\mathbf{w}_i^H \mathbf{h}_{ii}\|^2} = \frac{c_i P_i}{SINR_i} \end{aligned} \tag{7}$$

where $SINR_i$ is SINR detected at the i^{th} base station's antenna diversity output, $c_i = \mathbf{1}^T (I - DF)^{-1} \mathbf{v}_i$, and $[\hat{\mathbf{v}}_i]_j = 1\,, if\ j = i; 0\,, otherwise.$ The value of c_i reflects how severe the co-channel interferences are. When the co-channel interferences are large, c_i tells which user causes more co-channel interferences to other users. When the co-channel interferences are small, $c_i \approx c_j\ \forall i, j$. Since we only care the direction of the gradient and do not care the amplitude, we can ignore the value of c_i when the co-channel interferences are small. Equ. 7 is very significant in that it provides very simple way to find the gradient. In this case, we can measure SINR at each base station's antenna diversity output and use the feedback channel to get the mobile transmitted power value to calculate the direction of gradient. Consequently the system complexity is reduced greatly. By using the gradient, we know how to optimally reduce the overall transmitted power.

We assume that each link can select targeted SINR threshold in a range from γ_{min} to γ_{max}. Unfortunately, if we don't have any constraint, because of the convexity, every link will select γ_{min} as their targeted SINR threshold, consequently the network throughput is reduced. So we assume the overall network throughput is a constant at each time. The problem becomes how to allocate throughput to different users at each time. In order to develop the adaptive algorithm to find the optimal solution, we need to modify the gradient such that $T = const.$ holds. First, we find out the plane that is tangent to the curve $T = const.$ at point $[\gamma_1, \dots, \gamma_K]$. Without loss of generosity, we can move this plane to original. The plane can be expressed as: $\sum_{i=1}^{K} k_i x_i = 0$, where $k_i = c_4^i c_5^i / log_2(1 + c_5^i \gamma_i)$. The modified gradient is given by $\mathbf{q} = [q_1 \dots q_K]^T$. By the definition of projection, vector $\mathbf{q}$ satisfies equation $\|\mathbf{g} - \mathbf{q}\|^2 = \min_{\forall \mathbf{x} \in plane} \|\mathbf{g} - \mathbf{x}\|^2$. We only need to minimize the right hand side to get the optimal vector, i.e. the projection $\mathbf{q}$.

In practice, each link's targeted SINR is bounded by some practical constraints and the time average SINR threshold is a constant so that the system is fair for each user. The link adjusts its SINR threshold according to its current channel condition. The scheme can be interpreted as "water filling" each user's SINR in time domain. In order to implement such a scheme, we develop the following algorithm. Instead of having fixed SINR range $[\gamma_{min}, \gamma_{max}]$ for each link, we can adaptively change the SINR range, which takes into account of the links' SINR history. Suppose the i^{th} link can select SINR level $\gamma_i^{min}(n) \leq \gamma_i(n) \leq \gamma_i^{max}(n)$ at time n and the targeted average SINR for the i^{th} link is γ_i^{ave}. Each time $\gamma_i^{min}(n)$ and $\gamma_i^{max}(n)$ are modified by the current $\gamma_i(n)$. When $\gamma_i(n)$ is smaller than γ_i^{ave}, $\gamma_i^{min}(n+1)$ and $\gamma_i^{max}(n+1)$ are increased so that there is higher probability that $\gamma_i(n+1)$ is larger than γ_i^{ave}. When $\gamma_i(n)$ is larger than γ_i^{ave}, $\gamma_i^{min}(n+1)$ and $\gamma_i^{max}(n+1)$ are decreased so that there is higher probability that $\gamma_i(n+1)$ is smaller than γ_i^{ave}. $\gamma_i^{min}(n+1)$ and $\gamma_i^{max}(n+1)$ are bounded by $\hat{\gamma}_i^{min}$ and $\hat{\gamma}_i^{max}$, which are the minimum and maximum SINR respectively that the i^{th} link can select. The values are fixed and predefined by the system. In order to track the history of γ_i, we define $\gamma_i^{mid}(n) = \gamma_i^{mid}(n-1) + (\gamma_i(n) - \gamma_i^{ave}) * \beta$, $0 < \beta < 1$, where β is a constant that is depended on how fast the channel changes. If the channel changes fast, β should select a relatively larger number, so that the SINR range can keep track of the channel changes. If the channel changes slowly, β should select a relatively smaller number to have smooth effect. In each iteration, $\gamma_i^{min}(n)$, $\gamma_i^{max}(n)$ and $\gamma_i^{mid}(n)$ are updated by the algorithm in Table 1.

Table 1. *Adaptive Algorithm for SINR Range*

`Initial:` $\gamma_i^{min}(0) = \hat{\gamma}_i^{min}, \gamma_i^{max}(0) = \hat{\gamma}_i^{max}, \gamma_i^{mid}(0) = \gamma_i^{ave}$
`Iteration:` $\gamma_i^{mid}(n) = \gamma_i^{mid}(n-1) + \beta(\gamma_i(n) - \gamma_i^{ave})$ $\gamma_i^{min}(n+1)$ $= \min(\max(\gamma_i^{ave} - \gamma_i^{mid}(n) + \hat{\gamma}_i^{min}, \hat{\gamma}_i^{min}), \hat{\gamma}_i^{max})$ $\gamma_i^{max}(n+1)$ $= \max(\min(\hat{\gamma}_i^{max} - \gamma_i^{mid}(n) + \gamma_i^{ave}, \hat{\gamma}_i^{max}), \hat{\gamma}_i^{min})$

When $\gamma_i(n)$ is continuously less than γ_i^{ave} for some time, the $\gamma_i^{min}(n)$ is increased to γ_i^{ave}. Then the next $\gamma_i(n+1)$ have to select SINR threshold equal to or greater than γ_i^{ave}, consequently $\gamma_i^{mid}(n)$ stops increasing. The same analysis can be applied to $\gamma_i^{max}(n)$. Since $\gamma_i^{min}(n)$ and $\gamma_i^{max}(n)$ are bounded and they are linearly modified by

$\gamma_i^{mid}(n)$, the $\gamma_i^{mid}(n)$ is also bounded. Rearrange $\gamma_i^{mid}(n)$ and sum with the different time. We have

$$\frac{\sum_{n=1}^{N}\gamma_i(n)}{N} = \gamma_i^{ave} + \frac{(\gamma_i^{mid}(N) - \gamma_i^{ave})}{\beta N} \tag{8}$$

Since $\gamma_i^{mid}(N)$ is bounded, the second term in the right hand side decreases to zero as $N \to \infty$. So we prove that $\lim_{N\to\infty}\frac{\sum_{n=1}^{N}\gamma_i(n)}{N} = \gamma_i^{ave}$.

Now we can construct the adaptive iterative algorithm to find the best power and modulation allocation. The initial and n^{th} step are shown in Table 2.

Table 2. *Adaptive Algorithm for Resource Management*

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Initial:
  $\gamma_1 = \gamma_1^{ave}, \ldots, \gamma_K = \gamma_K^{ave}$
  $P_1, P_2 \ldots P_K = any\ \ feasible\ \ positive\ \ const.$
Iteration:
  Antenna Diversity:   MRC or SC
  Power Allocation Update:
    $D[n] = \mathrm{diag}(\gamma_1, \gamma_2 \ldots \gamma_K)$;
    $\mathbf{p} = DF\mathbf{p} + \mathbf{u}$.
  Adaptive Threshold Allocation
    $\mathbf{g} = \nabla P_{sum}$;   $\mathbf{q} = \mathrm{projection}(\mathbf{g})$;
    do {
      $\gamma_i = \gamma_i - \mu.\mathbf{q}_i \ \forall \ i$;
      if $(\gamma_i > \gamma_i^{max})$   $\gamma_i = \gamma_i^{max}$; .
      if $(\gamma_i < \gamma_i^{min})$   $\gamma_i = \gamma_i^{min}$}
    while $(\gamma_i \ not \ stable)$
Adaptive Modulation:
  $Select \ \ M_i = (1 + c_5^i \gamma_i)^{c_4^i}$
SINR Range Update:
  $Update \ \ \gamma_i^{mid}(n), \gamma_i^{min}(n), \gamma_i^{max}(n)$.
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where μ is a small constant, whose value decides the rate of convergence and the variance of final result. Whether or not γ_i is stable is decided by comparing the maximum difference of γ_i in two consecutive steps. Following the same proof in [5] , it can be shown that the algorithm is convergent.

4. SIMULATION RESULTS

In order to evaluate the performance of our algorithms, a network with hexagonal cells is simulated as shown in Fig. 2. The radius of each cell is 1000m. Two adjacent cells do not share the same channel. The number in each cell represents the assigned channel number. One base station is placed at the center of the each cell. In each cell, one user is placed randomly with a uniform distribution. We assume the mobile antenna height is 2m and the base station antenna height is 50m. The carrier frequency is 900-MHz. For each link, 3dB log normal shadow fading is considered. In the simulation, we consider three multipaths with equal power Rayleigh fading. The delay spread between the different paths is far less than one symbol duration.

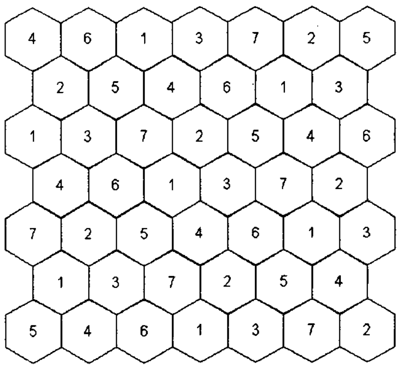

Fig. 2. Simulation Setup

It is well known that antenna diversity can increase SINR of each link, consequently increase maximum achievable network throughput. In Fig. 3, we compare the normalized overall transmitting power saving with antenna number for M-QAM with $BER = 10^{-2}$ and $BER = 10^{-5}$ respectively. We can see that the overall transmitting power is greatly reduced even with $P = 2$, which in turn reduces co-channel interference and increases spectral efficiency a lot. SC is strictly worse than MRC. Since SC doesn't need coherent modulation, it reduces complexity of communication network a lot. The overall power is improved more and SC performs more similar to MRC in $BER = 10^{-5}$ case than in $BER = 10^{-2}$ case. With the antenna number P increasing, the decreasing speed of overall transmitting power is reduced. Because the number of antenna is the key factor of communication system cost, we conclude that the scheme of four antennas is the most cost effective.

In Fig. 4 and Fig. 5, we compare the MQAM performances of MRC and SC at $BER = 10^{-2}$ and $BER = 10^{-5}$ respectively. The antenna number $P = 4$. We assume $window\ size$=$10log_{10}(\gamma_i^{max}/\gamma_i^{ave}) = 10log_{10}(\gamma_i^{ave}/\gamma_i^{min})$ = $3dB$, $\forall i$. The fixed scheme is that every links select the same constellation size. From the results, we can see MRC scheme has better performance than SC scheme. However this improvement is decreasing as BER going small. The adaptive algorithm can improve the average spectral efficiency by 0.9 bit/s/Hz and decrease the overall transmitting power by 40% than the fixed schemes. If we further increase the window size, the performance gain stop increasing. The reason is that some links with good channel condition are too greedy and demand too many targeted SINR at one time, they have to pay back with lower SINR allocation later be-

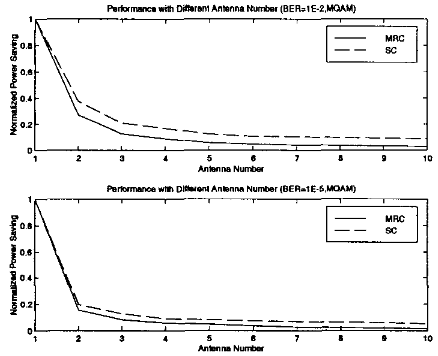

Fig. 3. Performance with Different Antenna Number

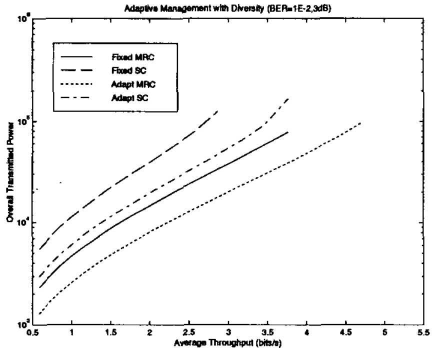

Fig. 4. MQAM Performance at BER=10E-2

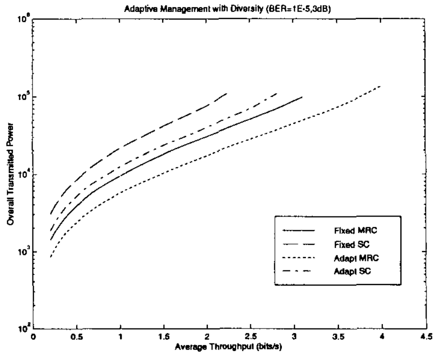

Fig. 5. MQAM Performance at BER=10E-5

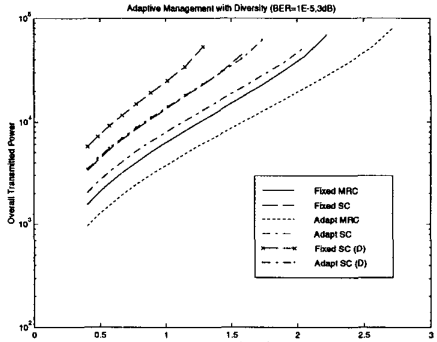

Fig. 6. MPSK and DMPSK at BER=10E-5

cause of the constraint that each link has the fixed time average SINR.

In Fig. 6, we compare the MPSK and DMPSK performances of MRC and SC with $BER = 10^{-5}$. We assume DMPSK needs 2.3 dB more SINR than MPSK [4]. It is shown that the performances of MPSK are about 0.9 bit/s/Hz worse than those of MQAM and the performance DMPSK are about 0.4 bit/s/Hz even worse. However in the channel with amplitude distortion, MPSK is very useful. For the noncoherent receiver, differential MPSK with SC combining is quite valuable.

5. CONCLUSIONS

In this paper, we use joint adaptive power and modulation management with antenna diversity to increase the spectral efficiency, combat with time varying nature of wireless channel and reduce co-channel interference. Our scheme can be interpreted as "water filling" each link's SINR in time domain and allocating the network throughput to different links at each time. The algorithm reduces 40% of the total transmitting power of mobile users, which is very critical in terms of battery life. The spectral efficiency is increased about 0.9bit/s/Hz, which in turn increases the whole network throughput.

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