Transmit Antenna Selection with Microdiversity and Macrodiversity in CDMA Networks*

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Abstract — We consider rapid selection of the transmit antenna(s) through joint power control when the same information signal is transmitted from one or more antennas at multiple base stations of a code-division multiple-access (CDMA) network. The total power transmitted to any mobile is divided among the active antennas according to channel conditions so as to optimize the signal-interference ratio (SIR) at each mobile station (MS). MSs use one receive antenna or two antennas and maximal ratio combining (MRC). We compare selecting different numbers of active transmit antennas and show that two of six is the best practical choice.

I. INTRODUCTION

Transmit diversity can be exploited to provide diversity benefits at a receiver when multiple transmit antennas are available. Many recent publications report on the performance of transmit diversity [1]-[3]. The performance of a number of transmit diversity schemes was examined and compared in [1, 2], showing that if feedback from MS is permitted, selection transmit diversity (STD) can provide better performance than others such as time switched transmit diversity (TSTD) and space time transmit diversity (STTD). Winters [3] showed the diversity gain of transmit diversity by dividing the total transmit power equally among multiple antennas. Joint power control of the selected antennas can provide additional benefits. Power control reduces the effects of interference in neighboring cells in CDMA cellular systems [4, 5]. Heikkinen el al. [6] proposed an optimum power allocation scheme on the forward link, which improves performance as opposed to equal power transmission. However, when the number of MSs is increased, the system proposed there becomes excessively complex.

In this paper, we consider forward link transmission in CDMA networks where the information signal is transmitted on a subset of available antennas at three base stations (BSs). The respective information signals are power controlled to best meet the SIR requirements of MRC reception at the MSs. The propagation channels from each antenna are continuously estimated to counteract multipath and Rayleigh fading with fast Doppler spread. Transmit antenna selection is introduced to reduce the received interference, particularly on the weak signal components. The goal of this work is to distribute the total transmitted power directed to each MS more efficiently so as to reduce the probability of SIR outage when signal reception is available from the nearest three BSs.

We assume that a distinct pilot signal is transmitted on each antenna of each BS to allow rapid channel estimation. The relative strengths of the received pilots at any MS are used to select periodically the antennas on which information signals are to be transmitted to that MS. These information signals are power controlled so as to satisfy the SIR requirements and permit maximum system capacity.

II. SYSTEM MODEL

We assume that the entire network consists of seven hexagonal cells with maximum BS-MS distance R, and BSs are located at three corners of each cell. Each BS employs M antennas whose transmitted signals are assumed to be uncorrelated. Here, we consider a sectorized model as in IS-95 (i.e., 120° sectorization). Thus each directional BS antenna covers its own sector and transmits data and pilot signals to each MS on the forward link. Also, we assume that there are L antennas installed on each MS on which the received signals are uncorrelated. Each receive antenna receives P independent equal power multipath components from each transmit antenna.

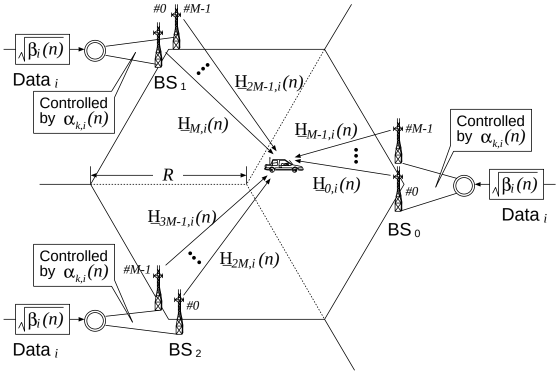

Figure 1: The model of multiple active antenna transmission with joint power control on the forward link.

We further assume that each MS controls the transmit antenna selection at the nearest three BSs based on the channel conditions as determined by the received pilot signals. The signal with controlled power is

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transmitted to each MS by K active antennas simultaneously, with different PN sequences, where $K \leq 3M$, as illustrated in Fig. 1. The active antennas are located either at a single BS or at multiple BSs. Here, we assume that the channel response is characterized by three independent phenomena; path loss variation with distance, slow log-normal shadowing and fast multipath fading [7]. Antennas at the same BS exploit micro-diversity by dividing the data signal between transmissions over multiple independent short-term Rayleigh fading channels. Antennas at the different BS exploit macro-diversity by dividing the data signal among transmissions over multiple independent long-term lognormal fading channels.

Through this paper, for the sake of simplicity, we do not take into account the additive white Gaussian noise (AWGN). We assume that the noise only results from the multiple access interference due to co-channel transmissions from other MSs.

III. TRANSMIT ANTENNA SELECTION WITH JOINT POWER CONTROL

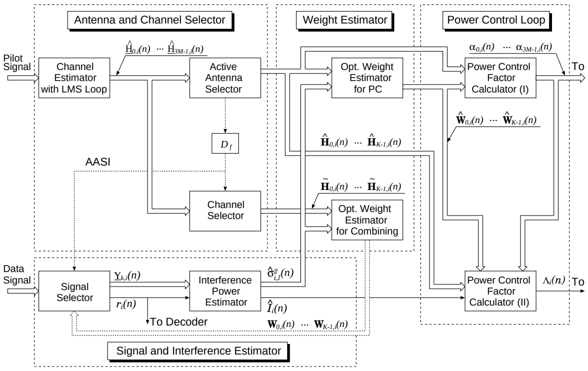

Figure 2: The block diagram for transmit antenna selection and joint power control at each MS.

The structure concerning the transmit antenna selection with joint power control is illustrated in Fig. 2. This structure is composed of four blocks; antenna and channel selector, weight estimator, signal and interference estimator, and power control loop.

In the antenna and channel selector, the channel estimator estimates the vectors of channel responses between the mth transmit antenna at the jth BS and the ith MS, say $\underline{\hat{\mathbf{H}}}_{Mj+m,i}(n) \in \mathbb{C}^{PL\times 1}$, by an LMS loop, based on the received pilot. The resulting estimate vectors are then fed into both the active antenna selector and the channel selector to generate two channel estimate vectors $\hat{\mathbf{H}}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$ and $\tilde{\mathbf{H}}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$. The former is used to calculate MRC weight vectors relative to the joint power control factors predicted for the next power control frame, and the latter to calculate the MRC weight vectors to be used by the combiner for the current desired signal.

The signal selector and the interference power estimator comprise the signal and interference estimator. The signal selector determines the selected signal vector $\underline{\Upsilon}_{k,i}(n)$ and the combining signal $r_i(n)$. The interference power estimator requires $\underline{\Upsilon}_{k,i}(n)$ and $r_i(n)$ to obtain estimates of the interference power on each receive antenna, $\hat{\sigma}^2_{i,l}(n)$, and the total interference power, $\hat{I}_i(n)$. The interference power, $\hat{\sigma}^2_{i,l}(n)$, received on the lth antenna at the ith MS, is used to calculate the optimum power-control weights. The total interference power, $\hat{I}_i(n)$, received by the ith MS and weighted by the optimum weights is used to derive the power control factors $\Lambda_i(n)$ for MSs sharing the same BS.

The weight estimator generates two optimum weights: $\hat{\mathbf{W}}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$ for the power control and $\mathbf{W}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$ for the combiner.

Finally, in the power control loop, two power control factor calculators are used, (I) to determine the power control factors $\alpha_{k,i}(n)$ and (II) to determine the power control factor $\Lambda_i(n)$. Those factors are transmitted to the nearest three BSs for joint power control.

A. *Active Antenna Selection*

The active antenna selector uses channel estimates made more robust by averaging. We average the channel response vectors, $\underline{\hat{\mathbf{H}}}_{Mj+m,i}(n)$, over n_{as} symbols to obtain the short-term fading estimate vectors and over n_{al} symbols to obtain the long-term fading estimate vectors, where $n_{as} \ll n_{al}$. The resulting short-term fading estimate vectors $\hat{\mathbf{H}}_{k,i}(n)$ are reordered according to the *norm* values of the long-term fading vectors, where

$$\hat{\mathbf{H}}_{k,i}(n) = \left[\hat{\mathbf{H}}^T_{k,i,0}(n), \hat{\mathbf{H}}^T_{k,i,1}(n), \cdots, \hat{\mathbf{H}}^T_{k,i,L-1}(n)\right]^T. \quad (1)$$

Here, $\hat{\mathbf{H}}_{k,i,l}(n) \in \mathbb{C}^{P\times 1}$ is expressed in terms of inphase and quadrature components and its elements represent the estimates of channel response for the pth multipath between the kth active transmit antenna and the lth receive antenna at the ith MS. The selector retains the first K vectors, $\hat{\mathbf{H}}_{0,i}(n), \cdots, \hat{\mathbf{H}}_{K-1,i}(n)$, to determine the K active transmit antennas among $3M$. This active antenna selection is up-dated frame by frame.

The channel selector determines the short-term channel response vectors for the selected tranmit antennas, $\tilde{\mathbf{H}}_{0,i}(n), \cdots, \tilde{\mathbf{H}}_{K-1,i}(n)$. The seletion is made according to the active antenna selection information (AASI) pertinent to the current selection interval as previously decided above. Since the combiner implementation requires the channel response vectors in the presence of Rayleigh fading, it uses the instantaneous short-term fading estimate vectors for $\tilde{\mathbf{H}}_{k,i}(n)$, obtained from $\underline{\hat{\mathbf{H}}}_{Mj+m,i}(n)$ directly.

B. *Received Signal Formation*

The signal selector determines the selected despread signal vector received on the multiple receive antennas, based on the AASI. The selected signal vector, defined as $\underline{\Upsilon}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$ for the kth active transmit antenna and the ith MS, is given by

$$\begin{aligned}\underline{\Upsilon}_{k,i}(n) \;&=\; \sqrt{\mathcal{E}\rho \cdot \beta_i(n-n_d)} \cdot b_i(n) \cdot \mathbf{H}_{k,i}(n) \\ &\quad \cdot \alpha_{k,i}(n-n_d) + \mathbf{N}_{k,i}(n) \qquad (2)\end{aligned}$$

where $\mathcal{E}$ is the total transmission power allocated to all MSs by three BSs, ρ is the fraction of total cell site power devoted to MSs ($1-\rho$ is devoted to the pilots), $b_i(n)$ is the BPSK data signal of the ith MS, and $\mathbf{N}_{k,i}(n) \in \mathbb{C}^{PL\times 1}$ is the received interference vector. Finally, $\alpha_{k,i}(n-n_d)$ and $\beta_i(n-n_d)$ are the power control factors which are determined by the power control factor calculators, where n_d is the number of data symbols corresponding to the time delay due to the power control intervals, the propagation and processing time. The factor $\alpha^2_{k,i}(n-n_d)$ controls the ratio of transmission power on the kth active antenna to the total transmission power allocated for the ith MS. The factor $\beta_i(n-n_d)$ represents the ratio of the total transmission power assigned to the ith MS to the total transmission power assigned to all the MS. The joint power control is carried out by exploiting both factors. Thus the fraction of the total transmission power $\mathcal{E}$ transmitted from the kth active antenna to the ith MS is equal to $\alpha^2_{k,i}(n)\cdot\beta_i(n)$. Note that

$$\sum_{i=0}^{N-1}\sum_{k=0}^{K-1}\alpha^2_{k,i}(n)\cdot\beta_i(n)=1 \tag{3}$$

where N is the number of MSs per cell.

By weighting the selected signal, the despread and combined signal for the ith MS can be represented as

$$\begin{aligned} r_i(n) = \Re\mathrm{e}\Bigg(& \sqrt{\mathcal{E}\rho\beta_i(n-n_d)}\cdot b_i(n)\sum_{k=0}^{K-1}\mathbf{H}^T_{k,i}(n) \\ &\cdot\mathbf{W}^*_{k,i}(n)\alpha_{k,i}(n-n_d)+\sum_{k=0}^{K-1}\mathbf{N}^T_{k,i}(n)\mathbf{W}^*_{k,i}(n)\Bigg) \end{aligned} \tag{4}$$

where $\mathbf{W}_{k,i}(n)$ is the opitmum weight vector as determined by the weight estimator. Note that the $\Re\mathrm{e}(\cdot)$ function is used to extract the real signal and reduce the interference power by half [8].

C. *Calculation of Optimum Combining Weights*

Separate weight estimators are used to determine the optimum weight vectors $\hat{\mathbf{W}}_{k,i}(n)$ and $\mathbf{W}_{k,i}(n)$. One is used for joint power control, and the other for the desired signal combining. The two estimators have the same structure but use different input signals. Based on MRC method in each MS receiver, we have

$$\hat{\mathbf{W}}_{k,i,l}(n) = \hat{\mathbf{H}}_{k,i,l}(n)/\hat{\sigma}^2_{i,l}(n) \tag{5}$$

$$\mathbf{W}_{k,i,l}(n) = \tilde{\mathbf{H}}_{k,i,l}(n)/\hat{\sigma}^2_{i,l}(n) \tag{6}$$

where $\hat{\sigma}^2_{i,l}(n)$ is the estimate of interference power on the lth receive antenna at the ith MS, and $\hat{\mathbf{W}}_{k,i,l}(n)$ and $\mathbf{W}_{k,i,l}(n)$ are the elements of $\hat{\mathbf{W}}_{k,i}(n)$ and $\mathbf{W}_{k,i}(n)$, respectively.

D. *Joint Power Control*

Joint power control is exploited to achieve the optimum power allocation to multiple active transmit antennas. This power control requires $\hat{\mathbf{H}}_{k,i}(n)$, $\hat{\mathbf{W}}_{k,i}(n)$, and $\hat{I}_i(n)$. The power control achieves two objectives; one to control $\alpha^2_{k,i}(n)$, and the other to control $\beta_i(n)$, explained in section B. The first guarantees that each MS receives sufficient power, the second ensures that all MSs experience the same SIR.

1. *Optimum Power Control of Each Active Transmit Antennas to the Same MS*

The optimum power allocation is concerned with the maximization of the received power that can be derived from (4), while keeping the total transmission power constant. Here, assume that the variation in the interference power is small enough so that the power may be considered constant over the power control intervals. Thus, we have an optimization problem in restricted form

$$\max_{\substack{\alpha_{0,i}(n),\cdots,\\ \alpha_{K-1,i}(n)}}\left\{\sum_{k=0}^{K-1}\Re\mathrm{e}\left(\hat{\mathbf{H}}^T_{k,i}(n)\cdot\hat{\mathbf{W}}^*_{k,i}(n)\right)\cdot\alpha_{k,i}(n)\right\}^2,$$

$$\text{subject to }\sum_{k=0}^{K-1}\alpha^2_{k,i}(n)=1. \tag{7}$$

By the Lagrangian method of constrained optimization, we obtain the optimum power control weight for the kth active antenna and the ith MS as given by

$$\alpha_{k,i}(n)=\sqrt{\frac{\left\{\Re\mathrm{e}\left(\hat{\mathbf{H}}^T_{k,i}(n)\cdot\hat{\mathbf{W}}^*_{k,i}(n)\right)\right\}^2}{\sum_{l=0}^{K-1}\left\{\Re\mathrm{e}\left(\hat{\mathbf{H}}^T_{l,i}(n)\cdot\hat{\mathbf{W}}^*_{l,i}(n)\right)\right\}^2}} \tag{8}$$

where $k=0,1,\cdots,K-1$. Note here that the power control weights $\alpha_{k,i}(n)$, for inactive antennas where $k=K,K+1,\cdots,3M-1$, are set to zero.

2. *Optimum Power Control Across MSs*

By controlling $\beta_i(n)$, each MS is made to receive the desired signal with the same SIR. According to the optimum power allocation, we obtain the optimum power control weight for the ith MS as given by

$$\beta_i(n)=\Lambda_i(n)/\sum_{l=0}^{N-1}\Lambda_l(n) \tag{9}$$

where

$$\begin{aligned}\Lambda_i(n)=\hat{I}_i(n)& \\ \cdot&\left\{\sum_{k=0}^{K-1}\Re\mathrm{e}\left(\hat{\mathbf{H}}^T_{k,i}(n)\cdot\hat{\mathbf{W}}^*_{k,i}(n)\right)\cdot\alpha_{k,i}(n)\right\}^{-2}\end{aligned} \tag{10}$$

and $\hat{I}_i(n)$ is the estimate of interference power.

E. *Interference Analysis*

We assume that $\mathbf{N}_{k,i}(n)$ can be expressed by the sum of two interference components; in-cell and out-cell components. The interference power calculated by the auto-correlation can be written as

$$I_i(n)=E\left[\left\{\Re\mathrm{e}\left(\sum_{k=0}^{K-1}\mathbf{N}^T_{k,i}(n)\cdot\mathbf{W}^*_{k,i}(n)\right)\right\}^2\right]. \tag{11}$$

Here, we assume that the multipath signals received on different antennas are uncorrelated while the multipath signals received on the same antenna are partly correlated. Their covariance σ_η^2 is set equal to 0.13 as estimated from computer simulations.

F. *Procedure for Transmit Antenna Selection and Joint Power Control*

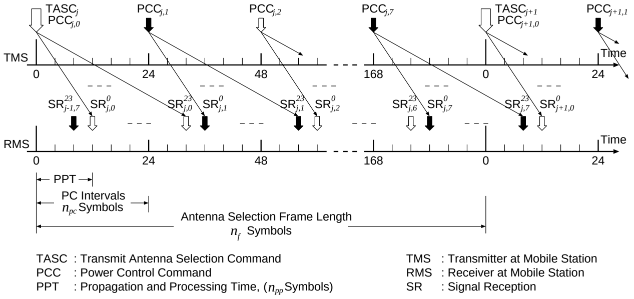

Figure 3: The procedure for the transmit antenna selection and the joint power control in the MS transmitter and receiver.

As illustrated in Fig. 3, we assume that the frame length for transmit antenna selection corresponds to n_f symbols intervals. At the beginning and the end of this frame, the transmit antenna selection commands (TASC) are transmitted by each MS. Also, we assume that the power control command (PCC) is transmitted as the same timing as TASC and updated at power control intervals (n_{pc} symbols).

If we assume that the propagation and processing time is equal to n_{pp} symbols intervals, the delay in terms of the number of symbols n_d between the power-control-command transmission and the data-signal reception is in range $[n_{pp}$ to $n_{pp} + n_{pc} - 1]$. Therefore, the active antenna selection between $\mathrm{SR}^0_{j,0}$ and $\mathrm{SR}^{23}_{j,7}$ is controlled by the TASC_j, and the transmit data signal power received at $\mathrm{SR}^0_{j,0}$ – $\mathrm{SR}^{23}_{j,0}$ is controlled by the $\mathrm{PCC}_{j,0}$, and so forth.

IV. Numerical Results

A. *Simulation Model*

The network simulated consists of seven hexagonal cells, each composed of three sectors with 120° sectorization. Each BS employs two antennas and is located at one of three corners of each cell, resulting in twelve BSs for the entire network. Each antenna transmits data signals at a transmission rate of 19.2 kbps, and a pilot with 20% total transmission power. The signals are spread by different PN sequences with a processing gain of 128. Each MS has one or two receive antennas and each receives two independent equal power multipath components. The path loss varies with distance as d^{-4} and exhibits log-normal shadowing with $\sigma =$ 8dB. A fast Doppler spread of 90Hz is assumed. To simplify our simulation, we normalize the total transmission power across the three BSs of each cell ($\mathcal{E} = 1$). To study the probability of SIR outage, we select as threshold the desired SIR of 5dB. The simulation follows the procedure as shown in Fig. 3, with the frame length of 10 msec ($n_f = 192$ symbols), power control intervals of 1.25 msec ($n_{pc} = 24$ symbols), propagation and processing time of 0.625 msec ($n_{pp} = 12$ symbols), and 12 symbols for short-term fading channel estimation ($n_{as} = 12$ symbols) and 192 symbols for long-term fading channel estimation ($n_{al} = 192$ symbols). Table I lists the numerical parameters used in the calculations.

Table I: Numerical parameters used in the calculations

Number of sectors per cell	3
Number of BSs	12
Number of antennas per BS, M	2
Number of antennas per MS, L	1 or 2
Number of multipaths per antenna, P	2
Propagation attenuation, μ	4
Standard deviation of shadowing, σ	8 dB
Processing gain, $\mathcal{G}$	128
Transmission rate	19.2 kbps
Threshold for SIR outage rate	5 dB
Doppler spread, f_D	90 Hz
Interference covariance, σ_η^2	0.13
Fraction of pilot trans. power, $1 - \rho$	20%

The simulation is performed with two sources of channel identification errors; one resulting from the time delay due to the power control, propagation and processing time, and the other resulting from the channel estimation noise. These sources of error are the major contributors to degradations in system capacity.

B. *Performance with Delayed Perfect Channel Identification*

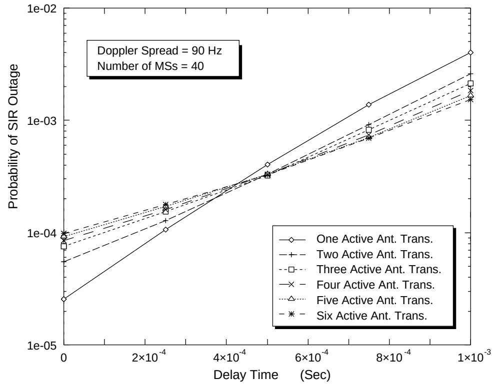

Figure 4: Probability of SIR outage for MSs = 40 as a function of delay time. One antenna reception and MRC with no channel identification errors.

To assess the benefits of transmit antenna selection with joint power control, we study the probability of SIR outage as a function of the time delay between the channel estimation and the implementation of the resulting selection and power control decisions. In this subsection, we simplify the simulation model. We take into account the identification error resulting from this time delay only. The goal in this simulation is to investigate the effects of the changing channel characteristics over the delay interval on the power control decisions. Fig. 4 shows that when the delay time is small, use of one of six active antennas shows the best performance. As the delay increases, multiple antenna selection shows much better performance. The reason for this is the relatively more rapid increase in variance for one of six as opposed to multiple antennas, as shown in Fig. 5. The reduced variance reduces the probability of SIR outage. Also, the result suggests that we cannot obtain significant gains by increasing the number of active transmit antennas beyond two. As a consequence, the choice of two of six active antenna transmission is reasonable for practical applications.

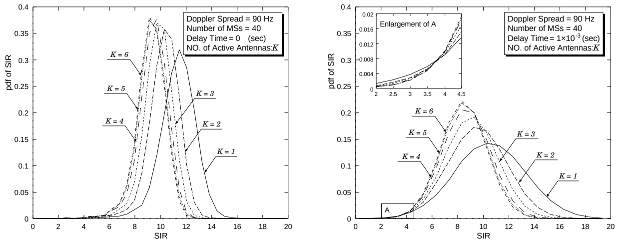

Figure 5: The pdf as a function of SIR for MSs = 40 with delay time of 0 and 1.0 msec. One antenna reception and MRC with no channel identification errors.

C. *Performance with Channel Identification Errors*

We compare the system capacity for one of six and more than one of six active transmit antennas with the optimum power control. In Fig. 6, the system capacity is expressed as the number of MSs per cell. We observe that with one or two receive antennas, multiple active transmit antenna selection achieves a much higher gain than one of six, but no more is gained by increasing active transmit antennas beyond two. With one receive antenna, a 2.3 dB gain is noted at an SIR outage rate of 3×10^{-2} for two of six active transmit antennas as opposed to one of six. This gain grows to 3.3 dB for two receive antennas and an SIR outage rate of 10^{-3}.

V. CONCLUSIONS

In this paper, we proposed a scheme concerning transmit antenna selection with a joint power control, whereby the same information signal is transmitted on multiple selected active antennas at multiple BSs of a CDMA network. At each MS, we employed MRC for data signal combining. Joint power control is used based on the estimated optimum weights.

We evaluated the probability of SIR outage as a function of the delay time as well as the system capacity, under the condition of fast Doppler spread of 90Hz. When the delay time between channel estimation and implementation of the resulting power control is small, one of six active antenna transmission shows the best performance. When the delay time becomes large, however, the use of more than one of six active antennas for transmission shows much better performance. The result shows that a choice of two of six active antenna transmission is reasonable for practical applications.

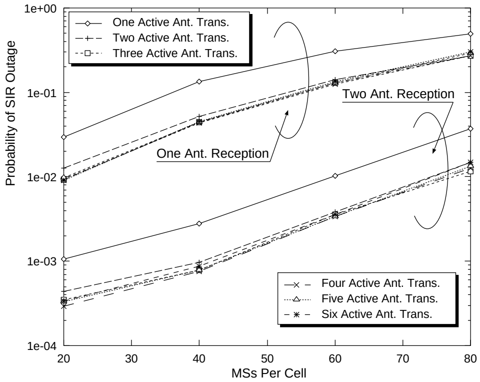

Figure 6: Comparison with one of six and more than one of six active transmit antennas with the optimum ratio power ontrol scheme, with MRC and consideration of channel identification errors.

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