The Multiply-Detected Macrodiversity Scheme for Wireless Cellular Systems

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***Abstract*—In this paper, the multiply-detected macrodiversity (MDM) scheme is proposed for wireless cellular systems. As opposed to the traditional macrodiversity schemes, in which at any time a signal from only one base station is selected, in the MDM scheme there is no selection, but all the received signals are detected, and a maximum-likelihood decision algorithm is employed to maximize the probability of correct decision. We study the performance of the MDM scheme and compare it with the performance of the traditional selection-based macrodiversity schemes. Depending on the propagation parameters, our results show that through the use of the MDM scheme, significant improvement in the bit-error rate (BER) can be achieved. For instance, if the outage probability is defined as BER above 10^{-4}, the outage is eliminated at least 45% of the time as compared with signal-to-interference (S/I) diversity, for a propagation attenuation exponent of 4.0 and shadowing standard deviation of 4.0 dB. Furthermore, as compared with the (S/I) diversity, the MDM scheme reduces, on the average, the BER at least two orders of magnitude throughout more than 60% of the cell area for a propagation attenuation exponent of 3.5, shadowing standard deviation of 4.0 dB, and system loading of less than 50%.**

***Index Terms*—Cellular systems, diversity techniques, macrodiversity, macroscopic diversity, maximum likelihood.**

I. Introduction

THE PRINCIPLE of diversity reception is based on the fact that independent signals have a low probability of experiencing deep fading at the same time instant. Therefore, if certain information is independently available on two or more branches (known as *diversity branches*), the probability that all of the branches suffer from deep fading simultaneously is rather low. Thus, by taking into the account the information extracted from multiple different branches, more of the original signal can be recovered, as compared with the case in which a single branch is used alone ([8], [9], [23]–[25]).

Macrodiversity, also known as *base-station diversity*, is a form of large-scale space diversity and can be used to combat the effects of shadowing in cellular mobile communication networks. The conventional macrodiversity schemes reduce the effect of shadowing by selecting the diversity branches that avoid the obstructions, i.e., the schemes consist of receiving a mobile's transmission by several base stations simultaneously in time and selecting *the one* with the best signal quality. The best signal quality can be defined as ([21]):

1) the signal[1] with the strongest received power—the (S) diversity;
2) the signal with the largest signal-to-interference ratio (SIR)—the signal-to-interference (S/I) diversity;
3) the signal with the largest signal plus interference power—the (S + I) diversity.

Of course, as the SIR directly determines the bit-error rate (BER), the (S/I) diversity corresponds to the best performing system. Thus, we adopt the (S/I) diversity as the comparison basis for the MDM scheme. However, practically, the (S/I) diversity is also the most difficult scheme to implement.

Various studies have analyzed network architectures employing selection-based macroscopic diversity. We discuss here some representative examples. In [4], Bernhardt simulated the performances of different macroscopic diversity configurations in frequency reuse radio systems: in [16], a network architecture with overlapping cells and macrodiversity is proposed to enhance the signal transmission quality or to solve capacity problems at the so-called "hot spots" by increasing the realizable channel reuse factor. In [15], two-branch site diversity is considered and applied to the ALOHA-based cellular networks. [21] compares the various selection-based macrodiversity schemes and concludes that the performance of the (S/I) macrodiversity is significantly better than the (S) and the (S + I) diversity schemes, while the difference between (S) and (S + I) diversity is relatively small. In [22], an exact analysis is provided for the cochannel interference of an (S) diversity system for the lognormally shadowed Rayleigh fading channel. A closed-form analytical solution for the probability of error of M-branch macroscopic selection diversity can be found in [20]. Link quality is used as a selection criterion in most of these studies. In a different approach, [6] and [7] proposed the use of coding information as an indication of link quality. This indication is then used for selection of one of the links. Macrodiversity using antenna sectorization is presented in [5], where the performance of two variations of capture-division packetized access is investigated, and in [28], where the SIR statistics for mobile telephony system with hexagonal coverage areas, multiple interferers, and three-corner base stations are obtained. Finally, combined performance of macro and microdiversity schemes has been analytically examined in [1] for shadowed Nakagami fading channels.

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[1] In this paper, we refer to "the signal" as the "desired signal," which should be distinguished from the signals that produce cochannel interference.

II. The Multiply-Detected Macrodiversity Scheme

In the traditional macrodiversity techniques, only one of the received signals is selected at any time. Therefore, these techniques do not take advantage of the signals received by the other base stations, which, even though possibly of inferior quality, may still be useful to improve the overall BER performance. In contrast, in the scheme considered here [13] and termed multiply-detected macrodiversity (MDM), there is no selection, but all the received signals are detected in parallel at the different base stations and an algorithm—*the MDM decision algorithm*—is employed to maximize the probability of correct decision. Our results presented here demonstrate that a considerable improvement can be obtained with this scheme, as compared with the selection-based macrodiversity, especially when the mobile is located close to the boundary between the cells. As boundary between the cells is exactly the region where the mobile station is expected to suffer the most degradation in the received signal, the MDM scheme tends to equalize the network performance throughout the coverage area. In this paper, we investigate the performance of the MDM scheme and compare it with the performance of the traditional, selection-based macrodiversity schemes.

We assume the common cellular network model in which base stations are connected to a mobile switching center (MSC) through fixed-network connectivity. We refer to the set of the base stations serving a mobile at a particular point in time as its base-station covering set (BCS). Furthermore, we term the base station that would normally serve a mobile[2] as its *primary base station*, while the other base stations that detect the mobile's signal are termed *secondary base stations*. The number of the secondary base stations depends on several factors, chief of which are the propagation conditions.

The operation of the MDM scheme is as follows. As a mobile station roams throughout the coverage area, its signal is continuously received and detected by the base stations that belong to its BCS. The detected signals are then transmitted as digital data over the terrestrial network to one central point, which can be the MSC, for instance. Additionally, "every so often"[3] each BCS base station evaluates the quality of its link with the mobile station. The evaluation can consist of measurement of the quality criterion, such as SIR, for example, or estimation of the link's BER, for example. Whatever the procedure for link evaluation is, the quality of links is conveyed to the central point as well.

At that central point, a decision-making algorithm is executed that makes an "optimum" bit-by-bit decision of what was transmitted by the mobile station. The decision-making algorithm is based on the *maximum-likelihood* criterion [17] and incorporates the quality of links as "weighting" factors in its decision. The output of the decision algorithm is then sent to the destination.

Thus, the MDM scheme is based on *postdetection combining technique* [26], which is usually less complex as compared with the *predetection combining* techniques [2], [3], [11], [12], [18], [23], [24].[4] In postdetection combining, the detected signals in digital form are "combined" rather than the analog signals. Although, in general, predetection combining yields more improvement, its implementation on the macroscale imposes a prohibitively large penalty on the traffic in the terrestrial network and requires complex synchronization.

As described here, the proposed scheme is based on communicating hard-detection decisions to the central point. At the expense of somewhat increased terrestrial traffic, conveying soft detection decisions would improve the performance. We consider soft-decision MDM scheme as future research.

Our claim in this paper is that, due to the additional information (i.e., the detected signals from the secondary base stations), the error-rate of the decision-making algorithm will be lower, sometimes much lower, than in the traditional macrodiversity schemes. For example, as compared with (S) diversity, the improvement of the MDM scheme results from several factors.

1) The configuration or the locations of the interferers can be such that the secondary base stations experience a lower amount of interference than the primary one, even though the primary base station receives the strongest signal.
2) The slow fading phenomenon can reduce the interfering signal (or increase the signal itself) at the secondary base stations more than the reduction of the interfering signal (or increase in the signal itself) at the primary base station.
3) If a mobile is close to the boundary between two or three cells, the quality of the signal at the secondary base stations may be comparable to the quality of the signal at the primary base station.
4) Some combination of the above factors.

Note that when qualities of the received signals at the secondary base stations are considerably poorer than that of the primary base station, practically the decision-making algorithm relies on the detection of the primary base station only. Thus, the MDM scheme always yields at least as good results as the traditional macrodiversity scheme that is based on the same link quality criterion.

The MDM scheme addresses the uplink[5] direction only, which is more problematic, since the mobile's transmitting power is considerably lower than the base-station emitted power. The attribute of mobiles being power limited is expected to persist in the future as the miniaturization of the wireless devices continues.

The purpose of the study presented here is to estimate the amount of improvement in BER that can be achieved through the general concept of hard decision—postdetection combining using the maximum-likelihood criterion. (We do not intend to study here a particular implementation of any wireless communication standard.)

[2] For example, the base station that would be selected when the specified macrodiversity scheme is implemented.

[3] The determination of the frequency with which the quality of the links are evaluated depend on the mobility patterns and propagation conditions and is outside the scope of this paper.

[4] An implementation of predetection-based macrodiversity would involve the received signals themselves, rather than the detected signals, to be transmitted in analog form to the central point. The central point then adds the signals using some weighting algorithm.

[5] The direction from mobile to base stations.

The following are a number of assumptions used throughout the rest of the paper that are related to the operation and performance evaluation of the MDM scheme.

1) Link quality is determined by SIR measurements.
2) The transmission is based on time-division multiple-access scheme (TDMA).
3) At the base stations, the mobile's transmission is received, detected, and decoded. As we would like to study the MDM scheme in the general case, independent of the actual coding scheme used, we evaluate the improvement due to the MDM scheme as related to a raw channel, without specifying an encoding scheme. The reader is referred to [14] for the performance of the MDM scheme with the IS-136 standard.
4) In the same vein, we study here the improvement in BER and not in word-error rate (WER), which is a more practical quantity. However, expressing our results in WER would require us to fix the word length and, thus, lose generality of our study.
5) A synchronization scheme is implemented that allows to match on the slot-by-slot (i.e., burst-by-burst) basis the data streams from the BCS base stations at the central point. Such a scheme may include periodic transmission of markers (e.g., code violations), possibly with some limited sequencing information by the mobile stations. This sequencing information is then forwarded to the central point. A sufficient amount of sequencing information would ensure very low probability of synchronization loss, and, thus, we neglect such effects.
6) There are a number of networking issues that we do not address in this paper. For example, TDMA slot synchronization at the BCS base stations, "handoffs" between the BCS base stations,[6] and the effect of power control and its associated issues. These issues are left for a future study.

The following example in Fig. 1 further illustrates the operation of the scheme. In this figure, a mobile station is located within the triangular area formed by three BCS base stations: BS1, BS2, and BS3. For the purpose of explanation, assume first that there is no shadow fading and that the cochannel interference sources are fixed at their locations, determined based on the regular fixed channel allocation (FCA) reuse patterns. When a mobile station is very close to BS0, the signal received by BS0 is of the best quality. Thus, the information provided by BS1 and BS2 is of no potential use in improving the decision made by BS0. However, when the mobile station is getting farther away from the BS0, the signal power received by the BS0 decreases. At the same time, the signal powers received by BS1 and BS2 increase. As the amount of cochannel interference at the BCS base stations is independent of the mobile's position, the resulting SIR at BS0 decreases, while the SIR's at BS1 and BS2 increase. Thus, as the mobile is getting closer to the boundary between the three cells, the signals received at BS1 and BS2 carry more and more information. When the mobile station crosses some "critical line" toward the cell boundary, the quality of the signals at BS1 and at BS2 is so good that it can be used to improve the detection of the BS0. The area defined by these critical lines in the neighboring cells is referred to as the gain area (to be precisely defined later)—the performance of the MDM scheme in the gain area is better than the performance of the corresponding selection-based macrodiversity schemes.

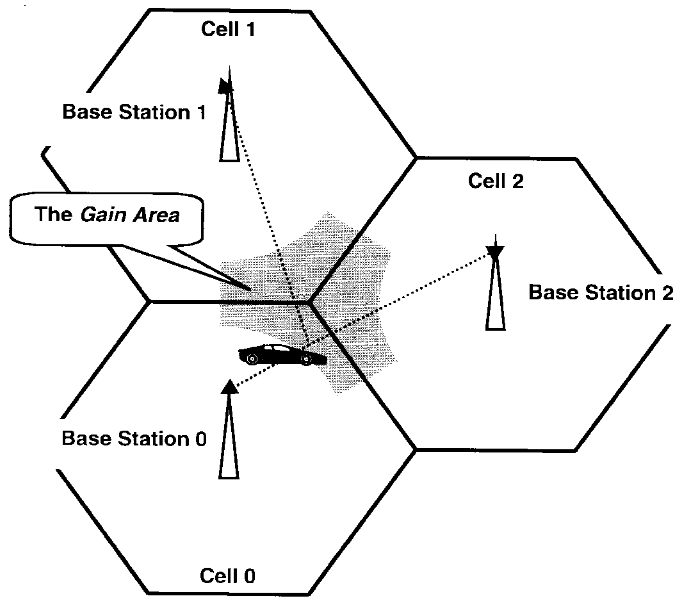

Fig. 1. An example of a three-base-station BCS.

Consider now the case in which the link qualities between the mobile and the three base stations are approximately equal.[7] Thus, the BER's of the individual links are also approximately equal. A simple majority voting will improve the probability of error by nearly squaring the individual probability of error of each link. (If the individual probability of error is p, then the majority voting with equal-quality signals results in a probability of error equal to $3p^2 - 2p^3 \approx O(p^2)$ for $p \ll 1$.)

A comment about the practicality of SIR measurements follows. A possible scheme to estimate the SIR can be to measure the amount of interference (I) during the TDMA slot guard times[8] and the signal + interference (S + I) during the actual burst transmission. Another possibility is to periodically skip slots during which the (I) could be measured in analogy to the "idle" slots in the global system for mobile communication (GSM). Of course, as the propagation and interference conditions change continuously, these measurements need to be averaged over many slots. Averaged measurements of $(\bar{\mathrm{I}})$ and of $(\overline{\mathrm{S}+\mathrm{I}})$ are then used to calculate the estimate of the SIR

$$\mathrm{SIR}_{\mathrm{estimated}} = \left[\frac{(\overline{\mathrm{S}+\mathrm{I}})_{\mathrm{measured}}}{(\bar{\mathrm{I}})_{\mathrm{measured}}}\right] - 1. \tag{1}$$

[6] Note that the "handoff" in the MDM scheme consists of addition and removal of base stations from BCS. Thus, the procedure that determines when to add or remove a base station is outside the scope of this paper.

[7] The probability of this situation to occur is large when the mobile is on the boundary between the three base stations.

[8] Just before/after the burst's beginning/ending is detected.

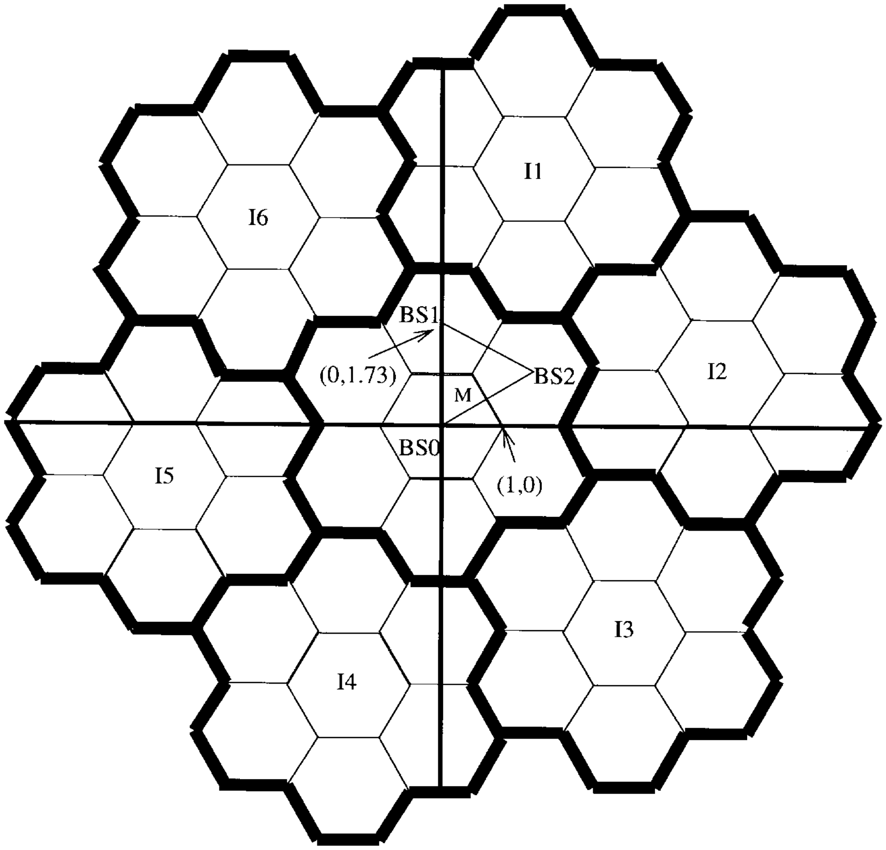

Fig. 2. Location of interferers in the reuse of seven case.

The above approach is based on measurements of the desired signals' and interferers' power. There are other possible approaches to estimate the quality of a channel. For example, one can directly measure the channel's BER, for example, with the assistance of a channel coding scheme (e.g., [4], [6], [7]). Yet another scheme is to use the soft-decoding information from a convolutional decoder to get an indication on the channel quality. Comparison of the way that the quality of channel information is obtained is outside the scope of this paper. We assume here that signal and interference measurements are used to determine the channels' quality.

Of course, the improvement in BER due to the MDM scheme does not come for free. In addition to potential increase in equipment at the secondary base stations (i.e., each base station needs now to be able to receive channels of its neighboring cells), there is also an increase in the processing load due to the implementation of the centralized decision algorithm. Finally, an additional bandwidth is required in the fixed wireline network to communicate the extra data and some additional control information. The scheme, however, does not consume any additional wireless bandwidth. Also, as the dynamic channel allocation (DCA) schemes require installing at the base station more than the minimum number of radio channel cards, one may argue that the increase in the equipment at the base stations is not really thatj substantial.

A. The Models

The following are the models used in our MDM study presented here. We refer to the selection-based macrodiversity schemes, with which we compare the performance of the MDM scheme, as "traditional schemes."

1) The Network and Traffic Models:

1) A representative mobile M is associated with a set of three base stations BS0, BS1, and BS2, i.e., BCS $=$ $\{$BS0, BS1, BS2$\}$. Larger BCS would further improve the performance. However, larger BCS results in more system overhead, such as extra traffic in the fixed network.
2) Channel reuse is based on FCA with reuse factor of seven, as shown in Fig. 2.
3) In the traditional schemes, the channel assignment is based on the mobile's location.
4) Each cell has a fixed radius (R), which is set at 1 km.
5) We label by $\rho(i)$ the probability that the channel assigned to mobile M (in cell j) is used in the cell i ($i \neq j$). We further assume that $\rho(i)$ is constant for all cochannel cells. Thus, in particular, $\rho(i_1) = \rho(i_2) = \cdots = \rho(i_6) = \rho$, where $\{i_1, i_2, \cdots, i_6\}$ is a set of cochannel cells. We assume that all the channels are equally loaded (i.e., choice of channel is made randomly), and we refer to ρ as the *channel occupancy*.[9]

[9] ρ is an indication of the system load.

2) The Radio Propagation Model, Interference Model, and Signal Modulation:

1) Wireless signals are modulated using the quadrature phase-shift keying (QPSK) modulation scheme.
2) We evaluate our results for the following discrete values of the signal attenuation exponent r: 2.0, 2.5, 3.0, 3.5, and 4.0.
3) In modeling the shadow fading environment, we assume that the power (in decibels) of the signal, as well as each of the six possible interferences, follow the lognormal distribution with some value of standard deviation. We compute the results for standard deviation of 4 and 8 dB.
4) For a particular signal or interference source, the amounts of shadow fading at different base stations are independent of each other. In addition, we assume that, for any particular base station, the shadow fading effects of all the signals and interference sources are all independent of each other.
5) We assume that there is no power control at the mobile station, i.e., all the mobile stations transmit their signals with the same power, P_M.
6) P_M is determined so that due to the propagation attenuation and the shadow fading, the transmitted power is such that 90% of the time the closest base station receives signal power level of at least −105 dBm under the worst condition (i.e., when the mobile is on the cell fringe).
7) We neglect the signal's fast-fading problem, assuming that a microscopic diversity scheme is implemented.
8) A zero-mean stationary white Gaussian noise is added to any received signal. The power of this additive white Gaussian noise (AWGN) is assumed to be at the constant value of $V = 10^{-15}$ [W].
9) We consider the cochannel interference resulting from interferers in cochannel cells $i_1, i_2, \cdots, i_6$ only (see Fig. 2). Of course, in principle, there are many other cochannel interfering mobile stations. However, because these mobile stations reside in cells considerably further away from the primary base station, we neglect this "second-" and "third-tier" interference.
10) The interfering mobile stations in $i_1, i_2, \cdots, i_6$ are fixed at their locations and contribute the maximum possible interference, i.e., in each case considered, the interferers are positioned in their cells in the "worst" location—on the circumference of the cell and as close as possible to the base station under question.
11) We assume that the cochannel interference sources add in power. Furthermore, we assume that for QPSK, the BER of the resulting total interference subject to fast fading can be approximated by the BER resulting from Gaussian noise, with power equal to the power of the total interference. This approximation is good when the number of interferers is sufficiently large. However, even when the number of interferers is not large, the error introduced by this approximation is not too substantial (see [10]).
12) We neglect the adjacent channel interference (of the intercell and the intracell types).
13) We assume that, due to other practical limitations, such as bit synchronization, there is a floor (Pe^{floor}) on the achievable BER for any wireless link. Here, we study the cases when $P_e^{\text{floor}} = 10^{-6}$, 10^{-8}, and 10^{-10}.
14) The error rate of the terrestrial network is significantly lower than the error rate of the wireless links. Thus, we neglect the effect of the fixed network impairments.

B. The Decision-Making Algorithm

The MDM decision algorithm is based on maximum-likelihood decision, i.e., for each bit, and calculates the probability that "zero" was transmitted and the probability that "one" was transmitted given the detections at the BCS base stations and the probability of erroneous detections at each one of the base stations. The decision algorithm then chooses the case which gives the larger transmission probability. The probabilities of erroneous detections at the BCS base stations are determined based on the respective link qualities (i.e., SIR estimations).

We adopt the notation, in which $Pc(0)$, $Pc(1)$, and $Pc(2)$ stand for the probabilities of correct bit reception at BS0, BS1, and BS2, respectively, and $Pe(0)$, $Pe(1)$, and $Pe(2)$ stand for the probabilities of erroneous bit reception at BS0, BS1, and BS2, respectively.

Thus, for example, assume that the BCS detections are [0,1,0]. The decision algorithm calculates

$$\begin{aligned} P_t(0) &= \text{probability of "zero" transmission} \\ &= \Pr(\text{correct reception at BS0}) \\ &\quad \cdot \Pr(\text{erroneous reception at BS1}) \\ &\quad \cdot \Pr(\text{correct reception at BS2}) \\ &= Pc(0) \cdot Pe(1) \cdot Pc(2) \end{aligned} \tag{2}$$

and

$$\begin{aligned} P_t(1) &= \text{probability of "one" transmission} \\ &= \Pr(\text{erroneous reception at BS0}) \\ &\quad \cdot \Pr(\text{correct reception at BS1}) \\ &\quad \cdot \Pr(\text{erroneous reception at BS2}) \\ &= Pe(0) \cdot Pc(1) \cdot Pe(2). \end{aligned} \tag{3}$$

If $P_t(0) < P_t(1)$, the algorithm concludes that "one" was transmitted; otherwise it decides that "zero" was transmitted.

In particular, if all the three BCS detections are the same (i.e., [0,0,0] or [1,1,1]), the algorithm's decision is equal to the individual decisions, since the probability of all the three correct detection is $Pc(0) \cdot Pc(1) \cdot Pc(2)$, which is, under usual circumstances, greater than the probability of all the three erroneous detections [$Pe(0) \cdot Pe(1) \cdot Pe(2)$].

The above algorithm is captured in Table I. The inputs in this table are the "quality of links' reception" and "detected signals." "Quality of links' reception" is expressed as three conditions involving the $\{Pc(i), Pe(i)\}$, $i = 0, 1, 2$. The "detected signals" are triplets of binary single-bit detections of the three BCS base stations. The three possible "quality of links' reception" conditions lead to eight possible inequalities: the cases *A, B, C,…H.* These determine the appropriate column that will be used in the decision-making process (the

TABLE I
FINAL DECISIONS MADE BY THE THREE BASE STATIONS TOGETHER (THE MDM DECISION ALGORITHM)

Condition	A	B	C	D	E	F	G	H	Condition	Quality of links' reception (inputs)
$Pc(0) \cdot Pc(1) \cdot Pe(2)$	>	>	>	>	<	<	<	<	$Pe(0) \cdot Pe(1) \cdot Pc(2)$	
$Pc(0) \cdot Pe(1) \cdot Pc(2)$	>	>	<	<	>	>	<	<	$Pe(0) \cdot Pc(1) \cdot Pe(2)$	
$Pe(0) \cdot Pc(1) \cdot Pc(2)$	>	<	>	<	>	<	>	<	$Pc(0) \cdot Pe(1) \cdot Pe(2)$	

BS 0	BS 1	BS 2	Final Decision							
0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	1	1	1	1
0	1	0	0	0	1	1	0	0	1	1
1	0	0	0	1	0	1	0	1	0	1
0	1	1	1	0	1	0	1	0	1	0
1	0	1	1	1	0	0	1	1	0	0
1	1	0	1	1	1	1	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1
Detected signals (inputs)			MDM decision (outputs)							

TABLE II
CALCULATION OF THE BER OF THE MDM SCHEME

Condition	Formulas for BER of the MDM Decision Algorithm (P_e^{MDM})	Note
A	$Pc(0) \cdot Pe(1) \cdot Pe(2) + Pe(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	
B	$Pe(0) \cdot Pc(1) \cdot Pc(2) + Pe(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	$= Pe(0)$
C	$Pc(0) \cdot Pe(1) \cdot Pe(2) + Pc(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	$= Pe(1)$
D	$Pe(0) \cdot Pc(1) \cdot Pc(2) + Pc(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	
E	$Pc(0) \cdot Pe(1) \cdot Pe(2) + Pe(0) \cdot Pc(1) \cdot Pe(2) + Pc(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	$= Pe(2)$
F	$Pe(0) \cdot Pc(1) \cdot Pc(2) + Pe(0) \cdot Pc(1) \cdot Pe(2) + Pc(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	
G	$Pc(0) \cdot Pe(1) \cdot Pe(2) + Pc(0) \cdot Pe(1) \cdot Pc(2) + Pc(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	
H	$Pe(0) \cdot Pc(1) \cdot Pc(2) + Pc(0) \cdot Pe(1) \cdot Pc(2) + Pc(0) \cdot Pc(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) \cdot Pe(2)$	

"final decision" portion of the table). The intersection of this column with the row that corresponds to the "detected signals" is the algorithm's result.

Since the BER's of the individual links are less than or equal to 0.5, not all eight columns in Table I are possible—only cases A, B, C, and E are practical. It is also interesting to note that the decisions of column A are the same as those made by the majority voting.

Thus, the decision-making algorithm operates as follows. The SIR's of the links are evaluated periodically by the BCS base stations and are communicated to the central point (MSC). The SIR's are then translated to the appropriate probabilities of error, based on the particular modulation and coding schemes used. These probabilities are then used to select the appropriate column in the Table I until new SIR evaluations are received. The individual detections of the BCS base stations are continuously conveyed to the central point, which uses the table as a lookup to determine, on the bit-by-bit basis, what was most probably transmitted.

Table I can be also used to calculate the residual probability of error of the MDM scheme, which we denote by P_e^{MDM}. The formulas for P_e^{MDM} are listed in Table II. The conditions A, B, ...H correspond to those in Table I. For example, if condition A in Table I holds, the corresponding P_e^{MDM} is obtained by calculating the formula in row A of Table II. The formulas in Table II are obtained by summing the probability that the opposite bit was transmitted rather than what the decision-algorithm indicates. In arriving at these formulas, we assumed that "zero" and "one" are transmitted with equal probabilities. More specifically

$$\begin{aligned} P_e^{\mathrm{MDM}} &= \mathrm{Prob}\{\text{ "one" is decided} \cap \text{ "zero" was transmitted}\} \\ &\quad + \mathrm{Prob}\{\text{ "zero" is decided} \cap \text{ "one" was transmitted}\} \\ &= \mathrm{Prob}\{\text{ "one" is decided} | \text{ "zero" was transmitted}\} \\ &\quad \cdot \mathrm{Prob}\{\text{ "zero" was transmitted}\} \\ &\quad + \mathrm{Prob}\{\text{ "zero" is decided} | \text{ "one" was transmitted}\} \\ &\quad \cdot \mathrm{Prob}\{\text{ "one" was transmitted} \\ &= \tfrac{1}{2} \cdot \{\mathrm{Prob}\{\text{ "one" is decided} | \text{ "zero" was transmitted}\} \\ &\quad + \mathrm{Prob}\{\text{ "zero" is decided} | \text{ "one" was transmitted}\}\} \end{aligned}$$

Take column A, for example,

$$\begin{aligned} P_e^{\mathrm{MDM}} &= \tfrac{1}{2} \cdot \{\mathrm{Prob}\{\text{local decisions of } [0,1,1], [1,0,1], \\ &\quad [1,1,0] \text{ or } [1,1,1] | \text{ "zero" was transmitted}\} \\ &\quad + \mathrm{Prob}\{\text{local decisions of } [0,0,0], [0,0,1], \\ &\quad [0,1,0] \text{ or } [1,0,0] | \text{ "one" was transmitted}\}\} \\ &= \mathrm{Prob}\{\text{local decisions of } [0,1,1], [1,0,1], [1,1,0] \\ &\quad \text{or } [1,1,1] | \text{ "zero" was transmitted}\} \\ &= Pc(0) \cdot Pe(1) \cdot Pe(2) + Pe(0) \cdot Pc(1) \cdot Pe(2) \\ &\quad + Pe(0) \cdot Pe(1) \cdot Pc(2) + Pe(0) \cdot Pe(1) \cdot Pe(2). \end{aligned} \tag{4}$$

One can observe from the MDM decision algorithm that the decisions made by column B, C, and E are the same as those made by BS0, BS1, and BS2, respectively. Columns

B, C, and E correspond to the BER of $Pe(0)$, $Pe(1)$, and $Pe(2)$, respectively, (see Table II). This is so, since, for a specific column, the BER of the corresponding base station is considerably lower than the other two. Thus, the additional information of the other two poor-quality links do not contribute significantly to the final decision. Consequently, when compared with the (S/I) diversity scheme, the improvement provided by the MDM scheme comes solely from the cases corresponding to column A.[10] Furthermore, comparing the three inequalities in columns A and B (and similarly the inequalities of columns A and C and of columns A and E), one can observe that the improvement of the MDM scheme occurs when $Pe(0) \cdot Pc(1) \cdot Pc(2) > Pc(0) \cdot Pe(1) \cdot Pe(2)$ [or $Pc(0) \cdot Pe(1) \cdot Pc(2) > Pe(0) \cdot Pc(1) \cdot Pe(2)$ and $Pc(0) \cdot Pc(1) \cdot Pe(2) > Pe(0) \cdot Pe(1) \cdot Pc(2)$]. Since $Pe(0)$, $Pe(1)$, and $Pe(2)$ are very small under most circumstances and $Pc(0) \approx Pc(1) \approx Pc(2) \approx 1$, we conclude that the improvement of the MDM scheme occurs mainly when the error rate of the highest quality link is larger than the product of the error rates of the two other links, e.g., $Pe(0) > Pe(1) \cdot Pe(2)$.

We study the performance of the MDM scheme based on a number of criteria, one of those being the *gain*. The gain is defined in comparison with a traditional scheme (reference scheme) as

$$\text{Gain} = -\log_{10}\left(\frac{P_e^{\text{MDM}}}{P_e^{ref}}\right) \tag{5}$$

where P_e^{ref} is the probability of error of the reference scheme.

Assume now that BS0 has the highest quality link (i.e., $Pe(0) \leq Pe(1)$ and $Pe(0) \leq Pe(2)$). Therefore, when compared with the (S/I) diversity scheme, the gain of the MDM scheme is approximately given by

$$\begin{aligned} \text{Gain} &= -\log_{10}\left[\frac{P_e^{\text{MDM}}}{P_e^{\text{S/I}}}\right] \\ &\approx -\log_{10} \\ &\quad \cdot \left[\frac{Pe(1) \cdot Pe(2) + Pe(0) \cdot Pe(1) + Pe(0) \cdot Pe(2)}{Pe(0)}\right] \\ &= -\log_{10}\left[\frac{Pe(1) \cdot Pe(2)}{Pe(0)} + Pe(1) + Pe(2)\right]. \end{aligned} \tag{6}$$

Consequently, for a given $Pe(0)$, the largest gain is obtained when $Pe(1) \approx Pe(0)$ and $Pe(2) \approx Pe(0)$, i.e., when the error rates of the other two links are comparable to the highest quality link. We call to this feature equal link qualities (ELQ). Under ELQ, the gain is given by

$$\text{Gain} \approx -\log_{10}[3 \cdot Pe(0)]. \tag{7}$$

To save the communication and processing load and extra delay associated with the execution of the MDM scheme, one can envision a wireless cellular system which has two operational modes: a conventional mode and a MDM mode. As soon as the central point receives the quality of link estimations, it determines whether any gain is expected from the MDM scheme by calculating the expected BER (P_e^{MDM}) and comparing it with the expected BER of the reference scheme (P_e^{ref}). If $P_e^{\text{MDM}}/P_e^{Ref} < 1$, the MDM scheme is employed. Otherwise, the central point instructs all the BCS base stations other than the base station that would be selected by the reference scheme to refrain from sending their detections to the central point. The use of the MDM scheme is reevaluated by the central point each time new quality of link estimations are received.

[10] Of course, when compared with other diversity schemes, the improvement is also affected by the other column cases.

III. MDM Performance Evaluation

In this section, we describe the simulation methodology used for evaluating the MDM scheme performance based on the model defined in the previous section. First, we show how we calculate the size of the area where the MDM scheme outperforms the traditional methods (i.e., the gain area) and the amount of decrease in BER (i.e., the gain). Then, we address the calculation of the outage probability of the traditional schemes and compare it with outage probability of the MDM scheme.

The performance of the MDM scheme is affected by the presence or the absence of interferer sources. As a consequence, we evaluate each of the performance criteria for all the possible combinations of the interfering sources and then average them, subject to the probability of the interferers' presence—the interfering channel occupancy (ρ). Therefore, our results, which include the average gain area (AGA), the average gain (AG), and the average outage probability (AOP), are presented as a function of ρ. Additionally, the AG is obtained by averaging the gain over the whole cell area.

Another performance measure we use is the conditional average gain (CAG), which is the AG averaged in the gain area only, or the AG conditioned on the fact that the mobile is, indeed, in the gain area. Similarly, we calculate the conditional probability of no outage (CPNO), which is the averaged probability of no outage, given the condition that there is an outage in the traditional scheme.

The averages calculated in this paper should be interpreted as the expected values, when the quantity under question is measured and its mean is evaluated over many measurements both at different times and at different locations. Although the averages do not provide all the information about the behavior of the measured quantity, they are useful as an indication of the amount of performance improvement and for purpose of comparison with other schemes. A more comprehensive picture is provided by the corresponding distribution function, which is also presented later in the paper.

The method we use to evaluate the above performance criteria is by simulating the propagation conditions, evaluating the BER of the links between the mobile and the BCS base stations, and calculating the residual BER of the MDM scheme. The BER of a reference scheme is also computed and compared with the BER of the MDM scheme. To accomplish this, the cell area is divided into small regions, with a point in the middle of each region. Then, the above evaluation is

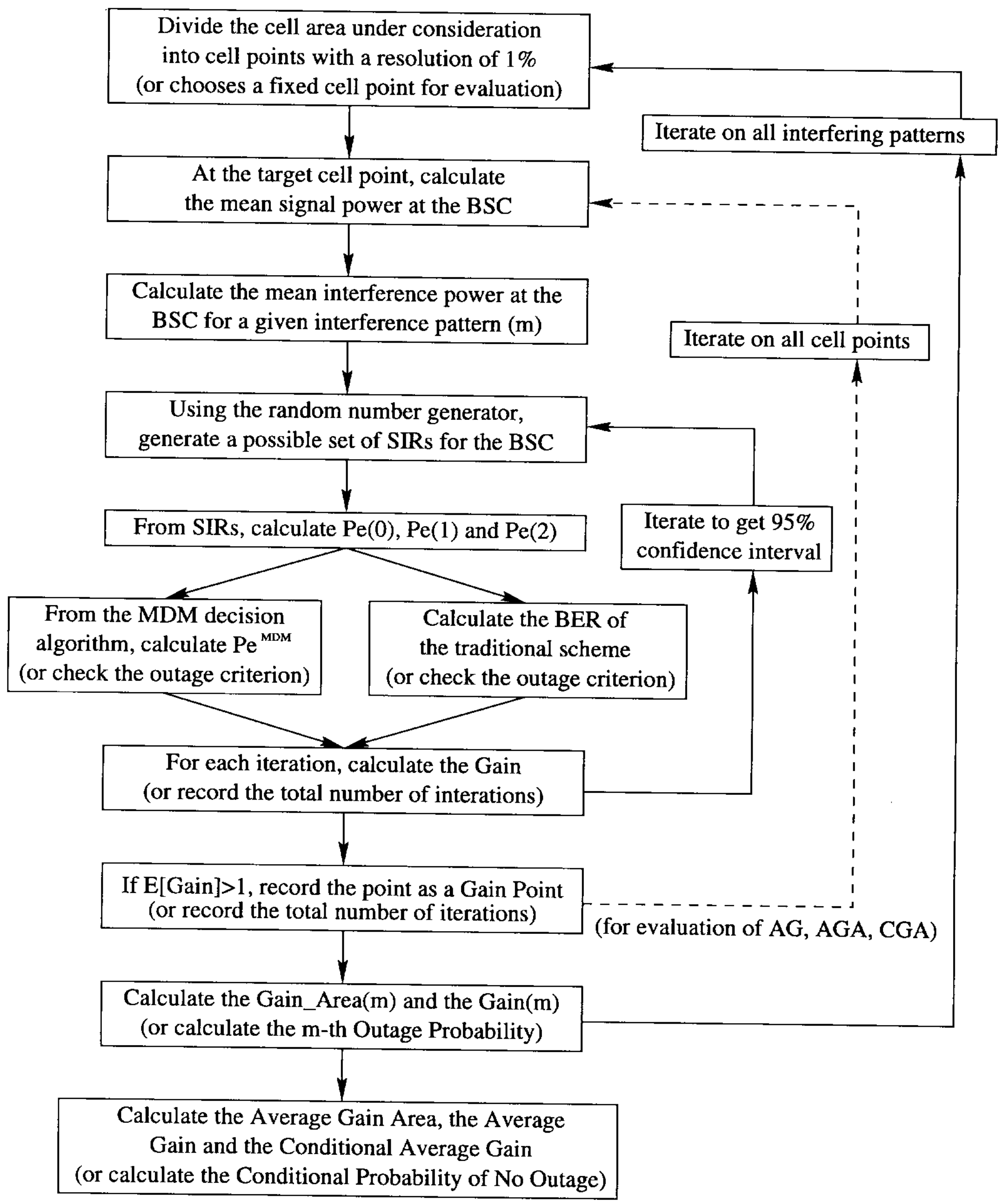

Fig. 3. Flowchart for evaluation of AG, AGA, CAG, AOP, and CPNO.

performed at each of these points.[11] In particular, the AG [as defined in (5)] is calculated at each of these points by a Monte Carlo simulation of shadow fading on a sufficiently large number of trials to yield a 95% confidence interval. This value is then used to calculate the AG throughout the cell area. Additionally, if the AG at a specific point satisfies the gain area criterion, the region that belongs to this point is counted as part of the gain area and the point is called a *gain point*. Here, we define the *gain area* criterion as gain of at least one, i.e., one order of magnitude improvement relative to the particular reference scheme. Note that a point may be counted as a gain point under certain combinations of network parameters and interfering patterns, while it might not be a gain point under some other combinations of these parameters. Of course, only one sixth of a cell area needs to be inspected because of the hexagonal symmetry. This procedure is depicted in the flow chart in Fig. 3. A similar process is used for evaluation of the AOP and the conditional probability of no outage, except that these measures are evaluated at a single point as opposed to being averaged over some cell area. In Fig. 3, paths specific to the outage evaluation are shown in parenthesis.

In this paper, we consider four reference schemes.

1) The *no macrodiversity*—the MSC always chooses the base station with the shortest distance from the mobile.[12]

[11] For practical reasons of limiting the computer run-time duration, the size of the small region is set at 1% of the cell diameter.

[12] This scheme can be approximated by the mobile's signal being measured by the neighboring base stations and *long-term* averaged. When the average of the link with the current base station falls below the average of a link with another base station for longer than some time interval, the mobile is handed off between the base stations. The assumption is that the long-term averaging averages out most of the shadowing effects and the handoff is based mostly on the propagation attenuation with distance.

2) The (S) diversity—the MSC selects the base station with the strongest signal.
3) The (S/I) diversity—the MSC picks up the base station with the largest SIR: the (S + I) diversity—the MSC chooses the base station in which the combined power of the signal and interference is the strongest.

A. Details of the Evaluation Process

At each base station, the received signal power from the mobile is modeled by the lognormal distribution, which is determined by its mean and its standard deviation (σ). The mean of the standard deviation is inversely proportional to the distance between the mobile and the base station raised to the power of the propagation exponent (r). In addition, for a given interfering pattern, the received power of each interferer at a base station is also modeled as a lognormally distributed random variable. The total interfering power, the sum of all the individual interferences, at each of the base stations is, in turn, a random variable.

In our simulation, the innermost loop consists of the generation of large numbers of random samples of the SIR's at the three BCS base stations. This is done by generating random values of shadowing for both, the signal and the interferences (see Fig. 3). Once the signal and the interference are known, the probability of a correct (P_e) and erroneous (P_c) reception on a particular link can be calculated using the modified QPSK formulas [17]

$$P_e = \frac{1}{2} \cdot \operatorname{erfc}\left(\sqrt{\frac{\text{Signal}}{V + \sum \text{Interference}}}\right) \tag{8}$$

and

$$Pc = 1 - Pe$$

where V stands for additive Gaussian noise at the level of 10^{-15} [W]. As mentioned before in Section II-A2, the BER can be quite well approximated by the modified QPSK formula, where the power of the noise equals the sum of the interferers' powers [10].

To obtain the BER of the MDM scheme for a particular sample of the SIR's at the three base stations, Table II is consulted. The BER of the reference scheme is the BER of the base station that would be selected by the reference scheme. Using (5), the gain of this sample is obtained.

The interferers $i_1, i_2, \cdots, i_6$ shown in Fig. 2 may or may not be present at any time in a cochannel cell. The probability that a particular interferer shows up at a specific time equals ρ, the interfering channel occupancy. As there are six possible interfering mobile stations, each of which is either present or not, there are $2^6 = 64$ possible combinations of the interfering mobile stations, resulting in 64 interfering patterns. The sum of the interferers' powers in (8) takes into the account only the present interferers for a particular pattern. Then, the average improvement provided by the MDM scheme is obtained by averaging all the 64 possible situations, with the probability function of the occurrence of the corresponding interferers' pattern. This is the outermost loop in Fig. 3.

B. Average Outage Probability

Outage is a condition in which the fading of the received signal is so severe that it carries, essentially, no information. Outage is usually defined as an SIR threshold, which corresponds to unacceptable BER. In this paper, we evaluate the performance of the MDM scheme for values of *threshold* that correspond to BER of $10^{-3}, 10^{-4}$, or 10^{-5}. In general, outage is the result of cochannel interference, channel noise, and fast and slow fadings.[13] The *outage probability*, denoted here by P_{outage}, is defined as the probability of the received signal falling below some SIR level. Outage probability has been extensively used as a criterion for evaluation and comparison of wireless systems [27], [28].

If the intended mobile is fixed at a cell point and if the noise if negligible, the outage probability of (S/I) diversity can be calculated as follows. Given the mobile's location, the lognormal distribution of the signal power (P^{signal}), the lognormal distribution of the sum of the interference powers ($\sum_j P_j^{\text{interference}}$), and the distribution of the resulting SIR at any base station can be easily determined:

$$\sum_j P_j^{\text{interference}} \equiv e^{\text{I}}, \qquad \text{I}\,(\text{dB}) \sim N[\eta_{\text{I}}\,(\text{dB}), \sigma_{\text{I}}\,(\text{dB})]$$

$$P^{\text{Signal}} \equiv e^{\text{S}}, \qquad \text{S}\,(\text{dB}) \sim N[\eta_{\text{S}}\,(\text{dB}), \sigma_{\text{S}}\,(\text{dB})]$$

where η_{I}, σ_{I}, η_{S}, and σ_{S} are the respective mean and standard deviation of the total interference and of the signal and can be determined from the location of the mobile and the interferer sources. Therefore, the SIR (in decibels) also follows the normal distribution

$$\frac{P^{\text{Signal}}}{\sum_j P_j^{\text{interference}}} = \frac{e^{\text{S}}}{e^{\text{I}}} = e^{\text{S}-\text{I}} \tag{9}$$

$$[\text{S}\,(\text{dB}) - \text{I}\,(\text{dB})] \sim N[\eta\,(\text{dB}), \sigma\,(\text{dB})] \tag{10}$$

where $\eta[\text{dB}] = \eta_{\text{S}}[\text{dB}] - \eta_{\text{I}}[\text{dB}]$ and $\sigma[\text{dB}] = \sigma_{\text{S}}[\text{dB}] + \sigma_{\text{I}}[\text{dB}]$. With the knowledge of the distributions of the SIR's at a base station, the outage probability can be calculated by

$$P_{\text{outage}}(0) = \int_{-\infty}^{\text{threshold}} f(\text{SIR})\, d\,\text{SIR} \tag{11}$$

where the threshold is determined by the definition of an outage event. In (S/I) diversity, since the base station with the largest SIR is always selected, an outage event occurs only if all the base stations experience outage. Therefore, for 3 BCS base stations, the outage probability can be obtained by

$$P_{\text{outage}}^{(\text{S/I})\text{diversity}} = P_{\text{outage}}^{\text{BS0}} \cdot P_{\text{outage}}^{\text{BS1}} \cdot P_{\text{outage}}^{\text{BS2}}. \tag{12}$$

In contrast with the above derivation for the (S/I) diversity, analytical derivations for the (S + I) and (S) diversities result in nonexplicit formulas.

[13] As noted before, in this paper we assume that the fast fading is taken care by microdiversity techniques.

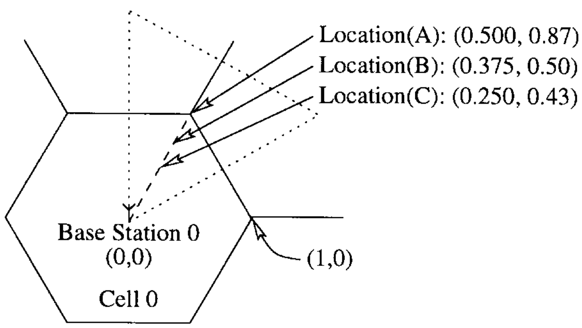

Fig. 4. Test mobile's locations for outage probability evaluation.

In the MDM scheme, some of the outage events of the (S/I) diversity are eliminated, since even though each one of the received signals at all the BCS base stations is *individually* below the threshold, the output of the MDM decision algorithm can still yield acceptable BER due to its use of all the BCS signals. These are evaluated at a number of selected points, as shown in Fig. 4.

At each mobile location, we iterate the simulation program to obtain 95% confidence interval. In each iteration, we calculate the BER of each scheme under consideration and check for an outage event. By dividing the number of outage events by the total number of iterations, we obtain the outage probability. In addition to the outage probability, we also evaluate the probability of no outage in the MDM scheme when there is an outage in the traditional scheme—we term this metric the *conditional probability of no outage* (CPNO). (See Appendix A for a precise definition of CPNO.)

C. Average Gain and Average Gain Area

For a given interfering pattern and assuming some reference scheme, the relative size of the *gain area* is determined by finding the ratio of the number of the gain points to the total number of cell points under consideration. Obviously, as the interfering pattern changes, the gain area also changes as well. For each interference pattern, the gain area is denoted by $\text{Gain\_Area}(m)$, where m is the mth cochannel interference pattern, $m = 1, 2, \cdots, 64$. Furthermore, we also define the $\text{Gain}(m)$ as the expected gain in each of the cell point under the mth interfering pattern, that is,

$$\text{Gain\_Area}(m) \stackrel{\text{def}}{=} \left.\frac{\text{Number of Gain Points}}{\text{Number of Total Cell Points}}\right|_{\text{Interf.Pattern}=m} \quad (13)$$

$$\text{Gain}(m) \stackrel{\text{def}}{=} \left.\frac{\text{Sum of } E(Gain) \text{ of All Points}}{\text{Number of Total Cell Points}}\right|_{\text{Interf.Pattern}=m}. \quad (14)$$

Finally, the AG and AGA are obtained by averaging all the 64 possible $\text{Gain}(m)$ and $\text{Gain\_Area}(m)$ with the probability of occurrence of the specific interferers' pattern. Thus, the AGA is found by

$$\text{AGA} = \sum_{m=1}^{64} \text{Gain\_Area}(m) \cdot \rho^{n(m)} \cdot (1-\rho)^{6-n(m)} \quad (15)$$

where $n(m)$ is the number of the cochannel interfering mobile stations that are present in the mth cochannel interference pattern.

The AG is calculated over the entire cell in a similar way

$$\text{AG} = \sum_{m=1}^{64} \text{Gain}(m) \cdot \rho^{n(m)} \cdot (1-\rho)^{6-n(m)}. \quad (16)$$

The CAG is obtained through the following formula (derivation is given in Appendix B):

$$\text{AG}|_{\text{inGainArea}} = \frac{\sum_{m=1}^{64} \{(\text{Sum of } E[Gain] \text{ in } m\text{th Gain Area}) \cdot \text{Prob}(m)\}}{\sum_{m=1}^{64} \text{GP}(m) \cdot \text{Prob}(m)} \quad (17)$$

where $\text{Prob}(m) \stackrel{\text{def}}{=} \rho^{n(m)} \cdot (1-\rho)^{6-n(m)}$ and $\text{GP}(m)$ represents the number of gain points under the mth interference pattern.

IV. Simulation Results and Discussions

The following performance measures are considered in this section: AOP, conditional probability of no outage (CPNO), AGA, AG, and CAG. In general, the reference schemes considered are: 1) no macrodiversity; 2) (S) diversity; 3) (S + I) diversity; and iv) (S/I) diversity. The values of standard deviation of shadow fading, σ, are 4.0 and 8.0. The values of propagation attenuation exponent, r, range from 2.0 to 4.0 with increments of 0.5. Finally, the values of BER floor (P_e^{floor}) considered are: $Pe^{\text{floor}} = 10^{-6}$, 10^{-8}, and 10^{-10}.

A. Average Outage Probability

A comparison of AOP's between different schemes is shown in Fig. 5. These results support our intuitive understanding of the schemes' behavior: the (S/I) diversity scheme has the smallest AOP since the base station with the smallest BER has been selected. In addition, the (S) diversity has a slightly smaller BER than the (S + I) diversity because there is a finite probability that the interfering power is relatively strong, compared with the signal power. Under such a circumstance, the (S + I) diversity has poor ability in selecting the best base station. The worse case of AOP always results from the no-macrodiversity scheme, since it does not consider the shadowing at all.

The AOP increases with the increase in channel occupancy. This is due to the increase in the interference power, which leads to a lower SIR and, thus, a higher probability of outage. In addition, an increase in r decreases the AOP. This is a result of the fact that the distances between the BCS base stations and the interferer sources are larger than the distances to the mobile. Thus, increasing r reduces the power of the interferers more than the power of the signal. Additionally, the AOP increases with σ due to the fact that when σ is large,

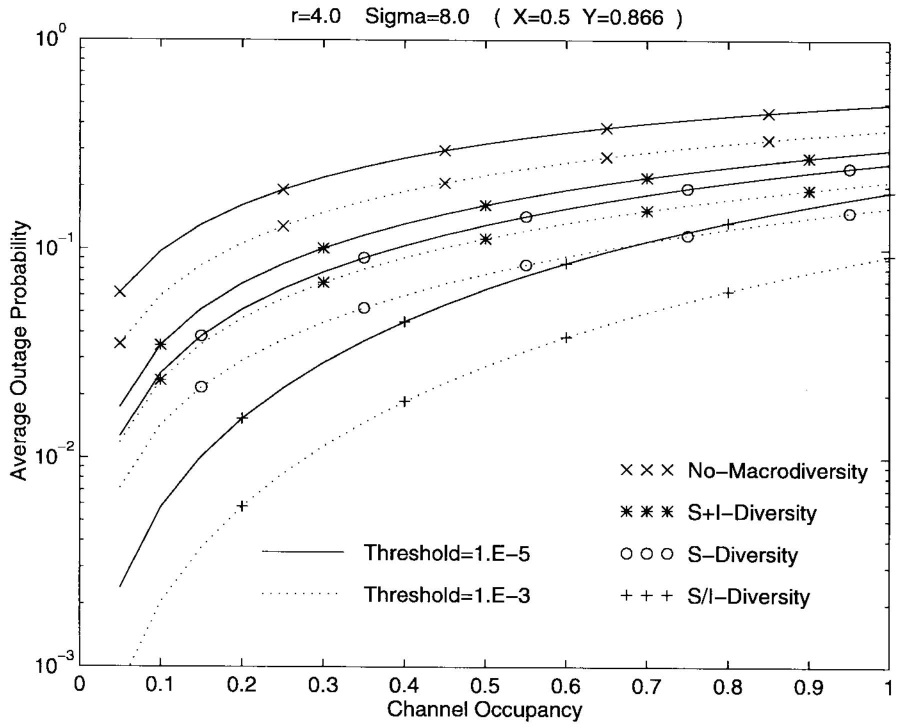

Fig. 5. Comparison of AOP of different schemes.

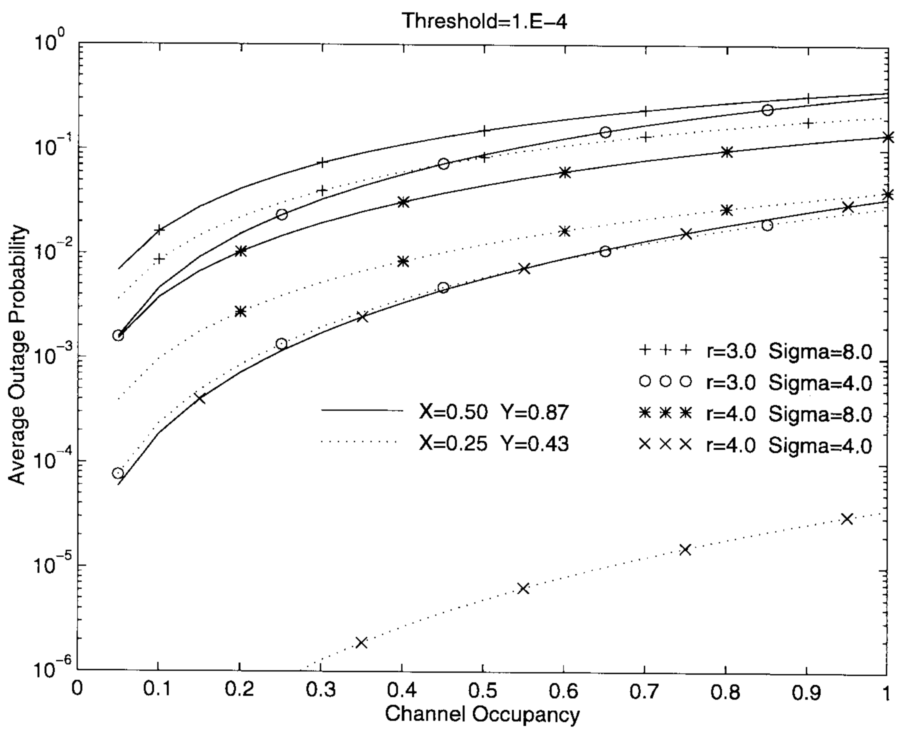

Fig. 6. The AOP: (S/I) diversity scheme.

there is high probability that one of the interfering branches has a much stronger power and results in an outage event. From these observations, we conclude that all the traditional schemes give lower AOP's when channel occupancy is small, σ is small, and r is large.

Fig. 6 depicts the AOP of the (S/I) diversity at a threshold of 10^{-4} for different combinations of r, σ, and locations. From this and other results not shown here, we learn that location (A) results in the largest AOP.

B. Comparison of AOP Between the MDM Scheme and the (S/I) Diversity Scheme

Since the (S/I) diversity has the lowest AOP (due to the fact that it always selects the base station with the largest

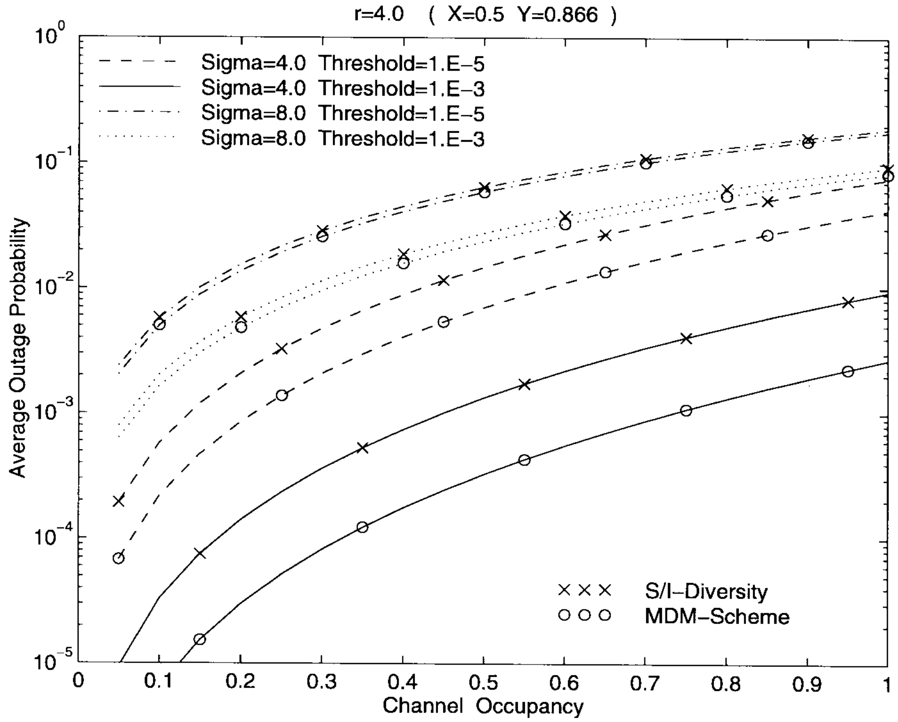

Fig. 7. The AOP: (S/I) diversity versus MDM scheme.

SIR), we chose this scheme for comparison with the MDM. An outage event in the (S/I) diversity means that the BER of all the base stations are higher than the threshold. In this situation, there is a certain probability that the MDM scheme will decrease the total BER, and, thus, the MDM scheme can eliminate the outage. This is the mechanism through which the MDM scheme improves the AOP of (S/I) diversity.

We first compare the AOP of the MDM and the (S/I) diversity schemes. Then, we calculate the probability that, given the (S/I) diversity scheme experiences an outage event, there is no outage in the MDM scheme. We term this probability *conditional probability of no outage* (CPNO).

1) Average Outage Probability: From our simulation results, we observe that substantially more improvement in the AOP is achieved at location closer to the boundary between the cells. Fig. 7 shows the AOP when $r = 4.0$ at location (A) for different combinations of σ and the outage threshold, while Fig. 8 demonstrates the combined effect of r and the outage threshold. Finally, Fig. 9 depicts the AOP for the outage threshold of 10^{-4} and for different combinations of σ and r.

All our results indicate that the AOP of the MDM scheme is lower for smaller σ. This is a result of the fact that lower σ favors the ELQ condition, which leads to a more substantial improvement in the MDM's BER. The ELQ condition is less likely to occur when σ is large. Additionally, as an increase in r results in a relatively larger reduction in the interfering power than in the signal power, increasing r improves the BER of the individual links. Moreover, it tends to keep the links' BER comparable, which, again, increases the chances of the ELQ situation. From all the above observations, we conclude that the MDM scheme improves the outage probability more when r is large, σ is small, and the mobile is close to the boundary between cells.

2) Conditional Probability of No Outage (CPNO): Fig. 10 shows the CPNO at the location A. This figure demonstrates the critical effect of σ. CPNO is always more than 12% and can be as high as 82% for $\sigma = 4.0$. However, for $\sigma = 8.0$, CPNO is at most 21%. We conclude from this and other results that σ plays a dominating role in the value of CPNO of the MDM scheme. In addition, CPNO increases with r, increases with the BER threshold, and decreases with channel occupancy (Figs. 10 and 11).

Finally, CPNO also increases as the mobile gets closer to the boundary between cells (Fig. 11).

C. Average Gain Area

1) Comparison Among the Schemes: When comparing the performances between different schemes, the MDM scheme has, in general, the largest AGA relative to the no-macrodiversity scheme (Fig. 12) since the no-macrodiversity scheme does not take the signal strength and interfering power into consideration at all. This means that the no-macrodiversity scheme less often selects the best base station, i.e., there is more improvement by the MDM scheme. In addition, because the (S/I) diversity scheme always selects the base station with the best link's quality (largest SIR), the smallest improvement in AGA is obtained when the MDM scheme is compared with the (S/I) diversity.

2) AGA as a Function of Channel Occupancy: The basic observation is that AGA always decreases with the increase of the channel occupancy (Figs. 14 and 15). The reason is that the system benefits mostly from the MDM scheme under the ELQ condition (defined in Section II-B). The ELQ condition

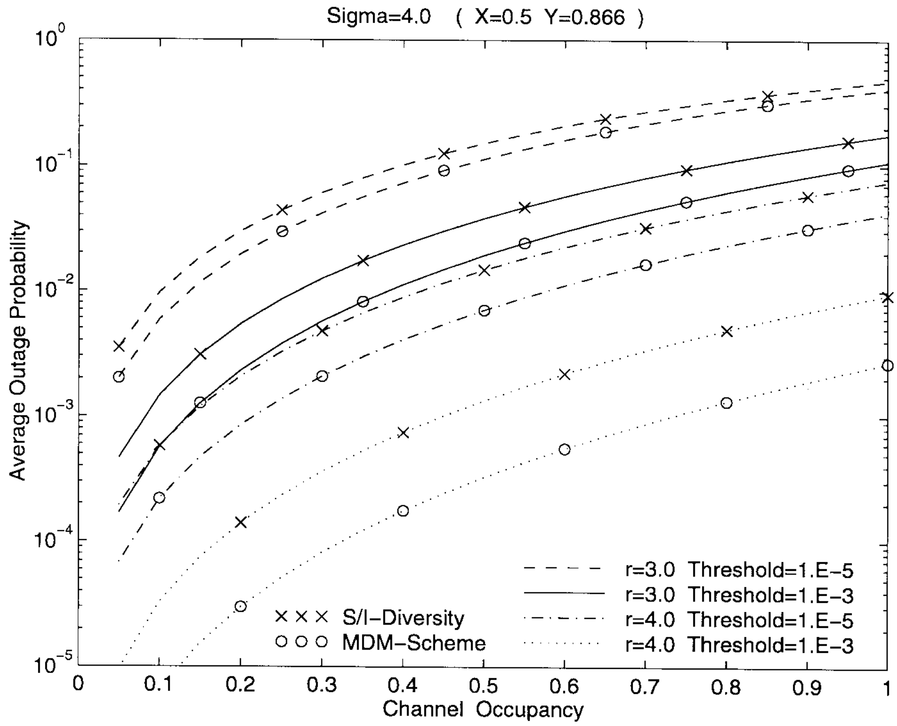

Fig. 8. The AOP: (S/I) diversity versus MDM scheme.

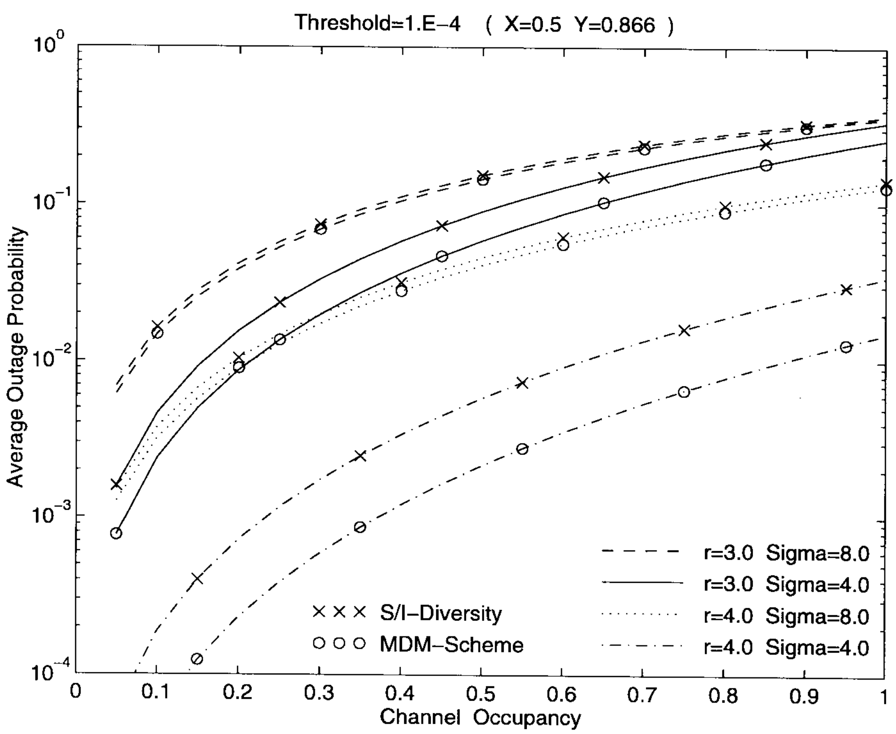

Fig. 9. The AOP: (S/I) diversity versus MDM scheme.

is more likely to happen when the number of interferers is small, which is more probable at low channel utilization. As the number of interferers increases, the lognormally distributed shadowing, which is assumed to be independent at the different base stations, leads to two possible cases: one of the base stations has a poor link quality, which results in small MDM improvement, or one of the base stations has a much better link quality than the other two, resulting in basically the same decision as made by the (S/I) diversity scheme.

3) AGA as a Function of Propagation Attenuation Exponent: The AGA increases with an increase in r (Fig. 14). As the distance between the BCS base stations and the interferers

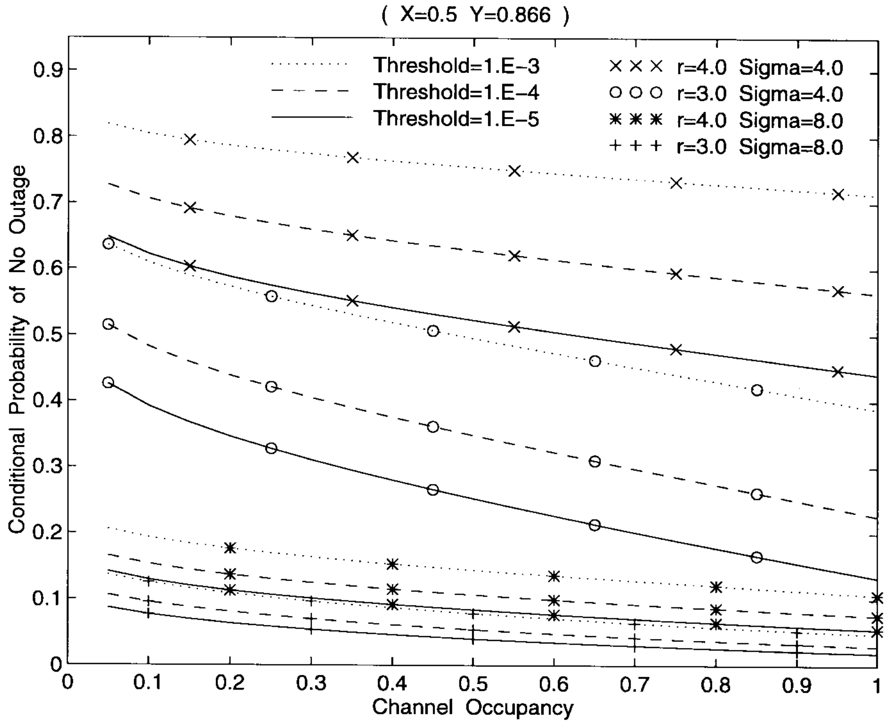

Fig. 10. Conditional probability of no outage.

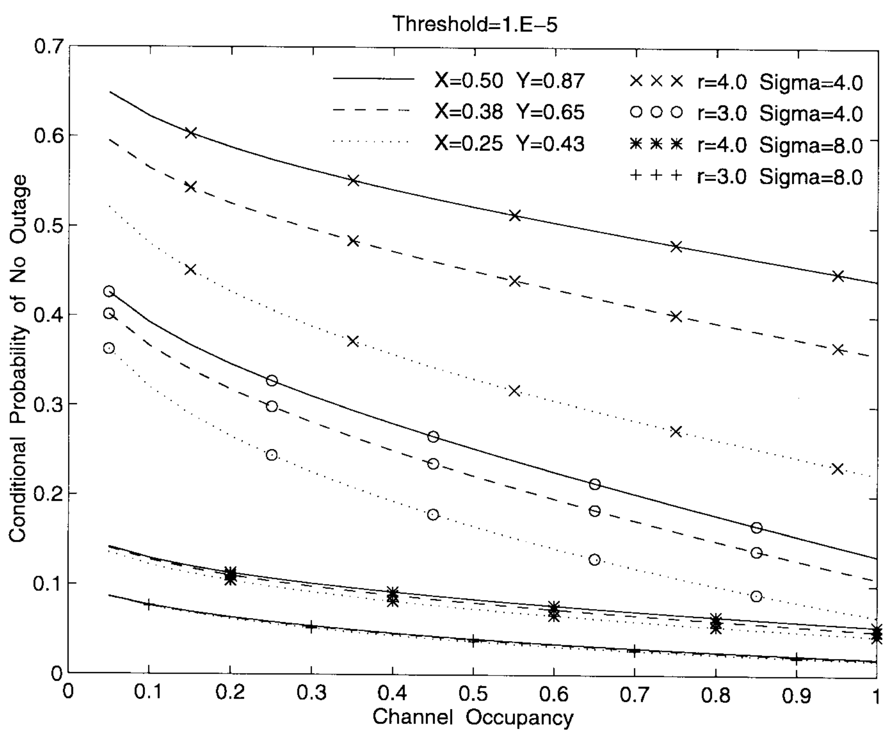

Fig. 11. The CPNO of the MDM scheme.

is larger than the distance between the base stations and the mobile, an increase in r reduces the interference power more than the signal power. Thus, the SIR improves and so does the BER. As the gain is larger at smaller BER, points which fail to satisfy the gain area criterion for small r can become gain points at larger r. Note that this is less likely to occur at high channel utilizations (as in these cases many interferers are usually present) and at very low channel utilizations (as often there are no interferers present). This is why the impact of r is most profound at some intermediate value of ρ (see Fig. 14 as a good example). Moreover, this dependency of AGA on r is diminished with an increase in σ. As for larger σ, there

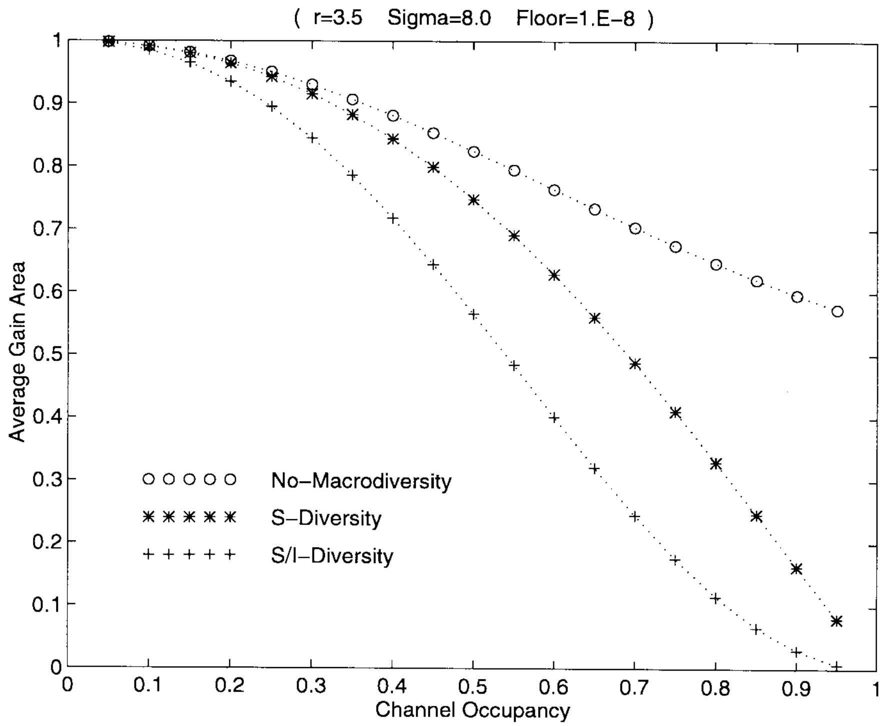

Fig. 12. Comparison of AGA for different reference schemes.

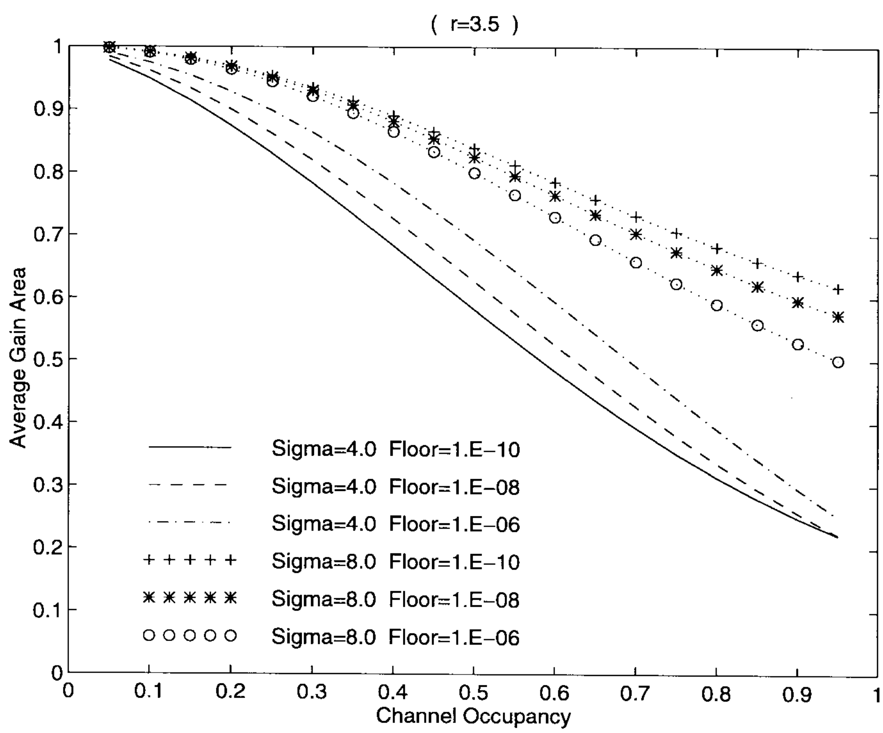

Fig. 13. The AGA: no macrodiversity versus MDM scheme.

is more randomness in both the signal and the interference strengths, and the effect of the above-described mechanism is further reduced.

In addition, the difference between the schemes gets smaller with an increase in r. The reason is that since the total interfering power decreases more than the desired signal as r increases, all the reference schemes are more likely to choose the same base station when r is large.

An additional observation is that the AGA approaches one for small ρ, for all the reference schemes (e.g., Fig. 12). The reason for this behavior is that at low channel occupancy there is little interference and the SIR is large, as it is mainly

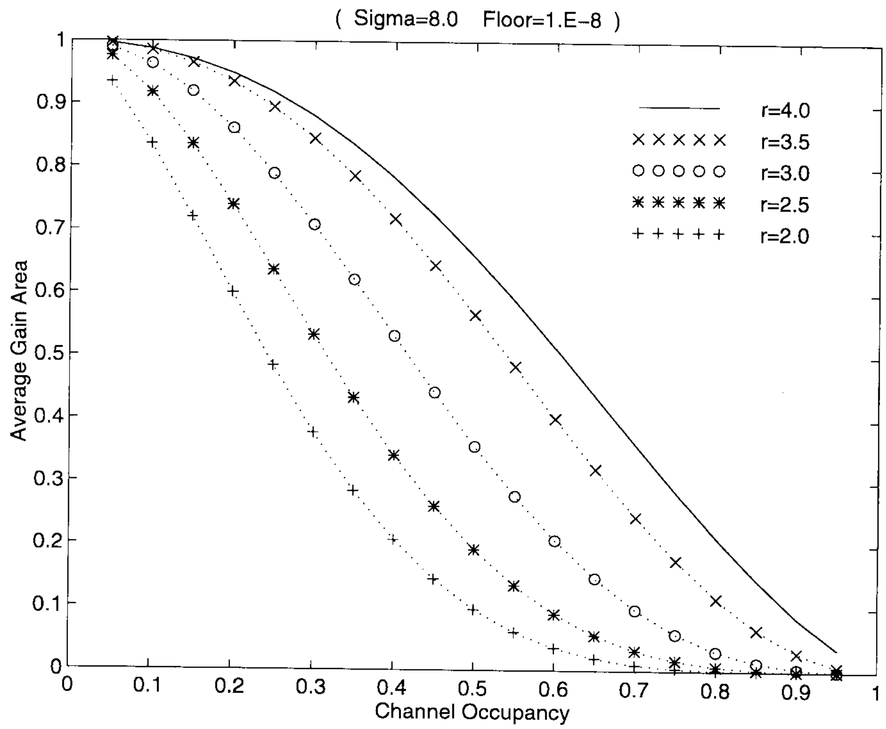

Fig. 14. The AGA: (S/I) diversity versus MDM scheme.

determined by the additive noise. In many cases, the resulting BER will be constrained by the BER floor. This produces the ELQ condition at nearly all the cell area and the possibility of large gain.

4) AGA as a Function of the Standard Deviation of Shadow Fading: In the no-macrodiversity case, the AGA increases as a function of the shadow fading deviation, since, when σ is large, the primary base station is less probable to be the base station with the best SIR (Fig. 13). Thus, at larger σ, the no-diversity scheme more often tends to err in its choice of the base station, and the AGA increases. This also holds true for the (S) diversity at small channel utilization. However, for (S) diversity at larger ρ, the AGA is actually smaller for larger σ. This has to do with the fact that at larger ρ, there are many interferers present and the ELQ condition is less probable, especially at larger σ.

For the (S/I) diversity, the reference scheme always chooses the best base station—the one with the strongest SIR (Fig. 15). Thus, the MDM scheme cannot improve in this aspect. The main improvement comes from the cases of ELQ condition. However, the effect of increased number of interferers, which reduces the probability of the ELQ condition, often drives the AGA lower for larger σ, especially at larger ρ. [Interestingly, when the number of interferers is small (small ρ), some amount of shadowing is necessary to improve the probability of achieving the ELQ condition.]

For larger σ (i.e., $\sigma = 8.0$ as compared with $\sigma = 4.0$), the differences between the AGA's of the different schemes tend to increase. This results from the fact that larger σ causes larger signal and interference deviations and, thus, poorer ability in predicting the best base station in the no macrodiversity and the (S) diversity schemes. For example, when $r = 4.0, \sigma = 4.0$, and ρ is small, the AGA's of the three different schemes are almost the same.

From the above discussion, we conclude that all the reference schemes tend to select the same base station when r is large, σ is small, and the number of interferers is small.

5) AGA as a Function of the BER Floor: In general, for small σ, AGA decreases with the decrease in P_e^{floor}, while for large σ, AGA increases with the decrease in P_e^{floor}. This can be observed in Figs. 13 and 15, which depict the results of varying P_e^{floor} for $\sigma = 4.0$ and for $\sigma = 8.0$. This phenomenon is explained by the fact that the BER floor tends to "equalize" the BER's of the base stations, effectively creating the ELQ-like condition. Thus, by increasing the floor, more points turn into gain area points. This is the behavior at small σ, i.e., increasing the floor increases the gain area. Moreover, the larger the floor is, the more cases will be picked up and converted to gain points, although with lower gain. At large σ, the individual BER's are more scattered. It is more probable then that points will cease to be gain points as the floor is increased, due to the lower gain associated with the higher floor and, thus, the higher probability that a point will not meet the gain area criterion anymore.

The more dispersion in the BER values for larger σ is also the cause for less sensitivity to P_e^{floor} changes in this case (Fig. 15). The reason being that the ELQ conditions are less likely to occur for large σ, and the actual value of the floor, unless very large, has little impact on its ability to "equalize" these BER values.

As a general reference point, for all the reference schemes, the AGA extends to about 60%–70% of the cell area at $\rho = 0.5$, $r = 3.5$ and for $P_e^{\text{floor}} = 10^{-8}$.

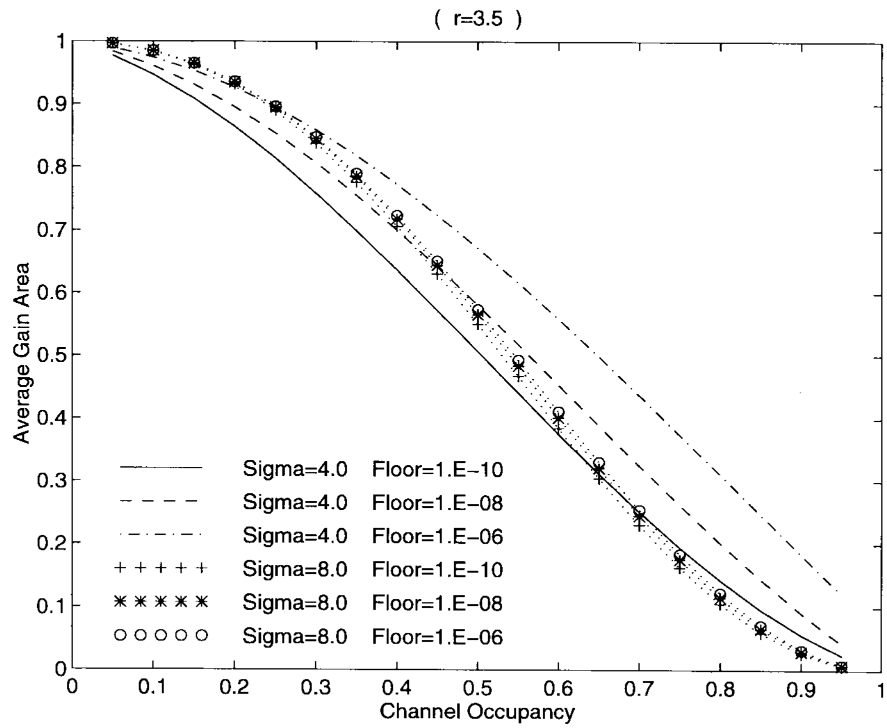

Fig. 15. The AGA: (S/I) diversity versus MDM scheme.

D. Average Gain

The behavior trends of the AG can be justified using the same lines as in the AGA case. In particular, most gain is obtained relative to the no-macrodiversity scheme, and the least gain is in the case of (S/I) diversity (Fig. 16). In general, the differences in AG's between different schemes are smaller when channel occupancy is small, σ is small, and r is large. Also, AG is a monotonically decreasing function of channel occupancy.

As a function of propagation attenuation exponent, in general, AG increases with r (Fig. 18). The exception here is the case of very large r (e.g., $r = 4.0$) at low channel utilization. In these conditions, although the gain area is marginally larger (Fig. 14), the gain at these additional gain points is small, thus reducing the total AG.

In general, in the no diversity and (S) diversity for small ρ, larger σ corresponds to smaller AG, even though the AGA is larger. (Compare Figs. 15 with 19.) The reason for this behavior is that although the reference scheme often does not select the best base stations when the σ is large, the chances of the ELQ condition are also reduced, leading to lower AG. (For very small floor and low ρ, the behavior can be reversed, as in such cases the randomness of shadowing will increase the probability of ELQ to occur.)

Finally, in the (S) diversity and (S/I) diversity cases at small channel utilization, the larger the BER floor is the smaller the gain (Figs. 17 and 19). This trend is reversed at large utilization due to the fact that as the interference increases, the BER increases and low floor is less effective in "equalizing" the BER (recall that the gain is largest in the ELQ condition). Also, for small channel occupancy, the effect of change in P_e^{floor} is more profound. On the other hand, for channel occupancy greater than 0.5, the influence of P_e^{floor} is not substantial, especially when $r \leq 3.0$.

As a point of reference, the AG over all the schemes is at least two orders of magnitude for channel utilization less than 40%, when $r = 3.5, \sigma = 8.0$, and P_e^{floor} of 10^{-8}. Under the same conditions, the AG is at least one order of magnitude for channel utilization less than 65%.

E. Conditional AG

A comparison between the schemes is shown in Fig. 20 for $r = 4.0, \sigma = 8.0$, and $P_e^{\text{floor}} = 10^{-8}$. The case of no diversity still corresponds to the largest AG. However, the CAG of the (S) diversity and the (S/I) diversity yield much closer results. For $\sigma = 4.0$ and $r \geq 3.0$, the CAG of the three reference schemes are almost identical.

F. Probability Distribution Function of Gain

Since the AG is a mean over a large number of experiments at a single location, as well as over the whole cell points, it does not reveal enough information about the distribution of the gain. For instance, are the gain samples uniformly distributed over some gain interval or are they concentrated around the AG? To answer such questions, we studied the probability distribution function (PDF) of the gain at a fixed point within the cell. As an example, Fig. 21 depicts the PDF for $\sigma = 8.0$, $r = 4.0$, and Pe^{floor} of 10^{-8} at the location A (Fig. 4).

The discontinuities of the graphs at gain of about 7.5 are due to the limiting effect of the BER floor. The impairment that

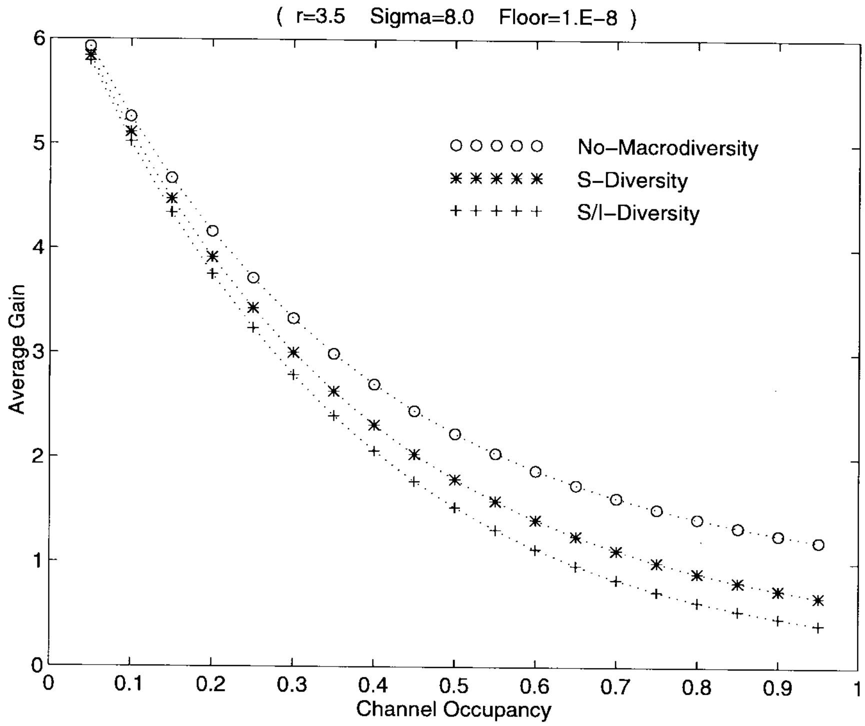

Fig. 16. Comparison of AG of different schemes.

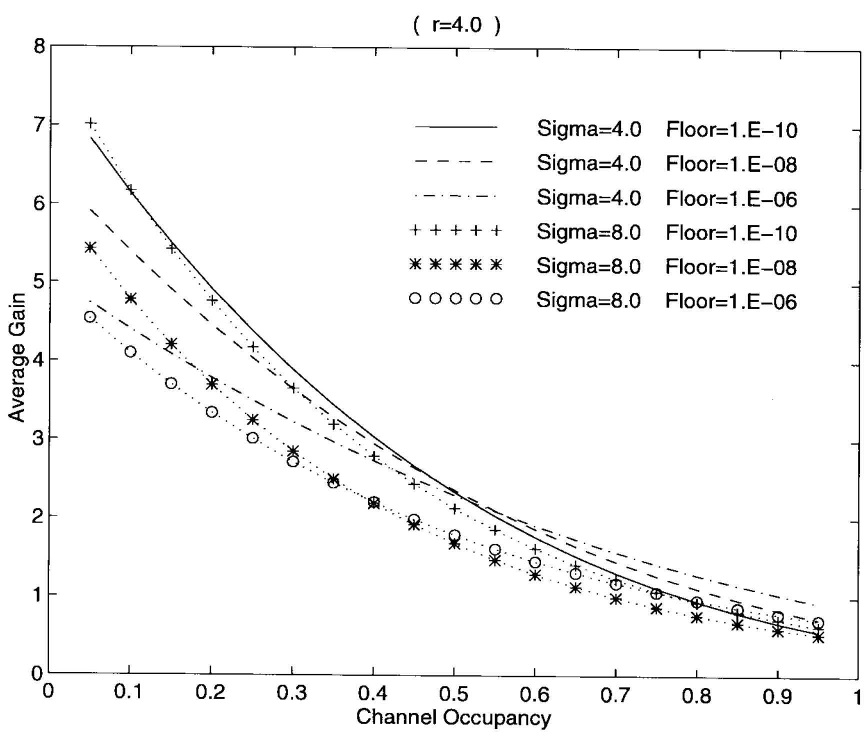

Fig. 17. The AG: (S) diversity versus MDM scheme.

would normally occur at high gain is limited by the floor at the gain of about $(P_e^{\text{floor}})^{-1}$, i.e., the size of the discontinuity is equal to the probability that, in an unlimited system, the gain would be larger than $(P_e^{\text{floor}})^{-1}$.

From Fig. 21 one can learn that more than 50% of the time, the gain is greater than one when the channel occupancy is less than 0.5. For channel occupancy equal to 0.9, about 30% of the time the gain is greater than one, and about 55% of the time there is no gain at all ($G = 0$).

In general, as the channel utilization increases, so does the probability that the improvement of the MDM scheme is small.[14] Also, for small utilization ($\rho \approx 0.1$), the gain

[14]Graphs for different parameter sets exhibit similar behavior.

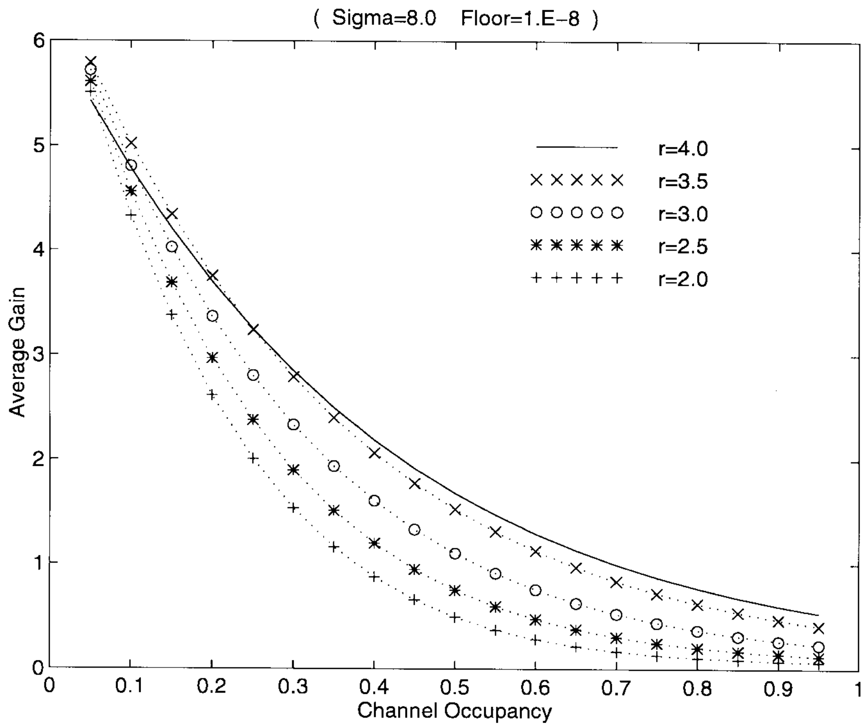

Fig. 18. The AG: (S/I) diversity versus MDM scheme.

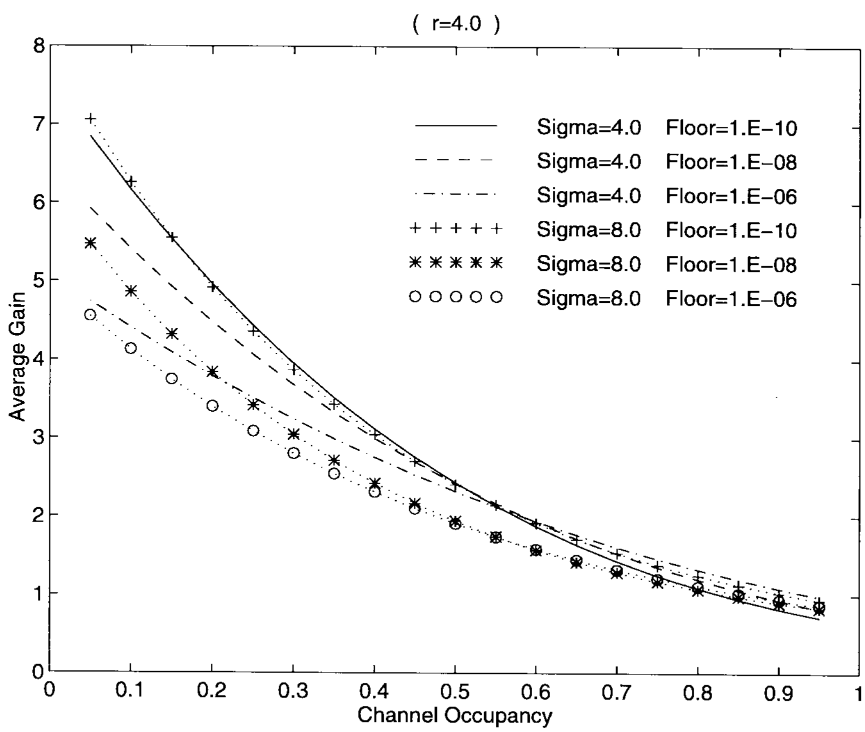

Fig. 19. The AG: (S/I) diversity versus MDM scheme.

distribution is nearly uniform between zero and the maximal value determined by the BER floor. However, at larger channel utilization, the density of the gain is shifted toward the smaller gain values. Finally, the lower the channel utilization is, the more substantial the "equalization effect" of the BER floor is.

The PDF shown in Fig. 21 does not differentiate at what point the gain is obtained, i.e., one order of magnitude improvement at BER of 10^{-2} may be more significant than one order of magnitude improvement at BER of 10^{-6}. This dependency on the link qualities is shown in Fig. 22. The

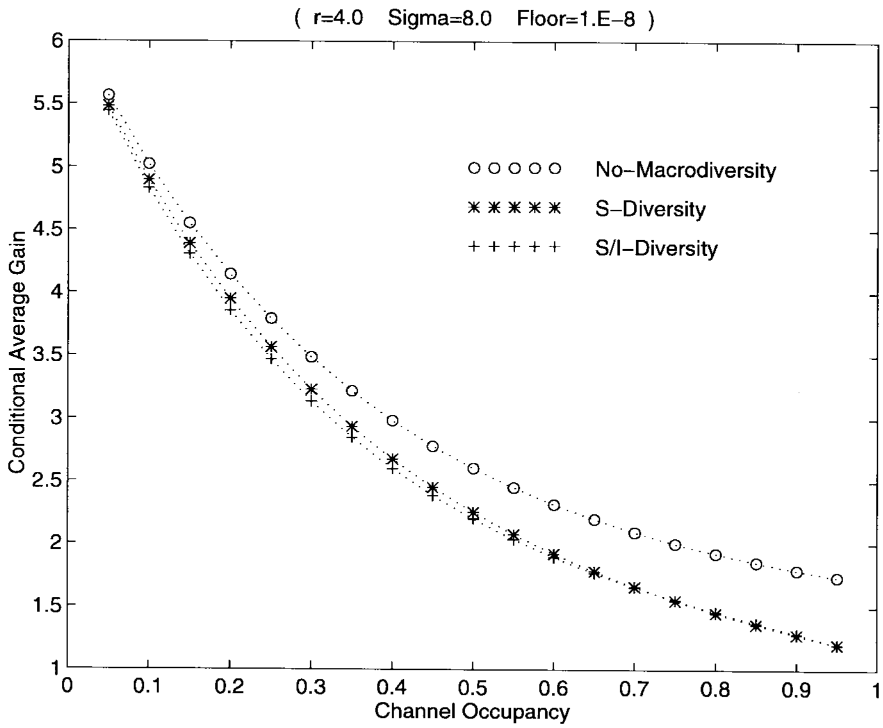

Fig. 20. Comparison of CAG of different schemes.

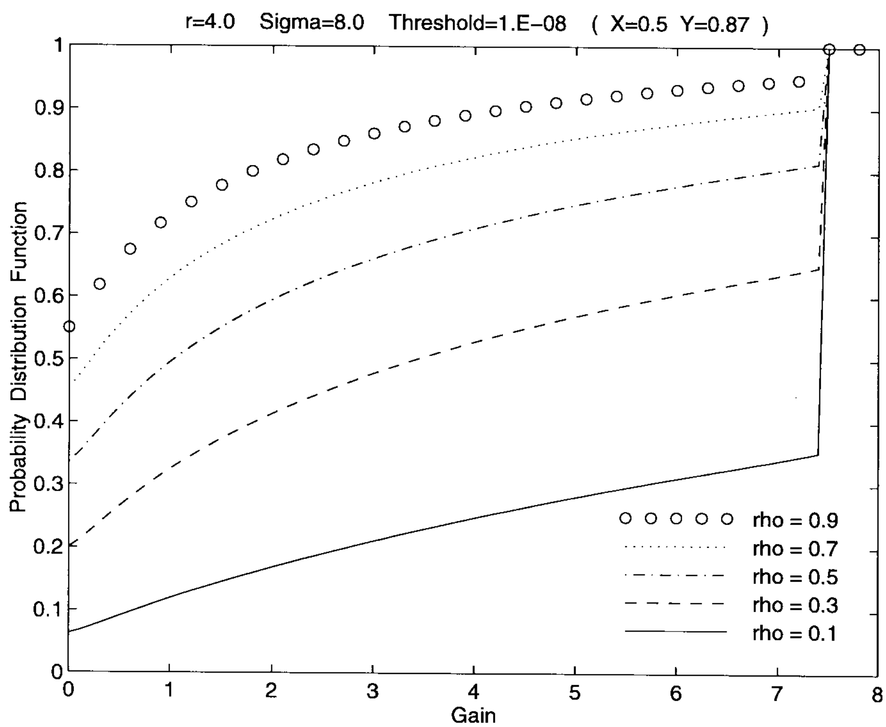

Fig. 21. Probability distribution function of the gain.

figure clearly demonstrates the ELQ phenomenon [the gain is maximal on the diagonal of $Pe(1)$ and $Pe(2)$]. The smaller the links' BER's are, the larger the gain is [i.e., compare the four cases for different values of $Pe(0)$]. The distribution of the gain (in the form of probability density function) as a function of the quality of the best link [best base station (BBS)] is presented in Fig. 23. The importance of this figure is in that it shows both, the distribution of the gain and at what point it occurs. One can conclude from this figure that the better the link qualities are, the broader the range of the gain values is. The gain is also more uniformly distributed within this range. As the conditions deteriorate, the gain range is considerable

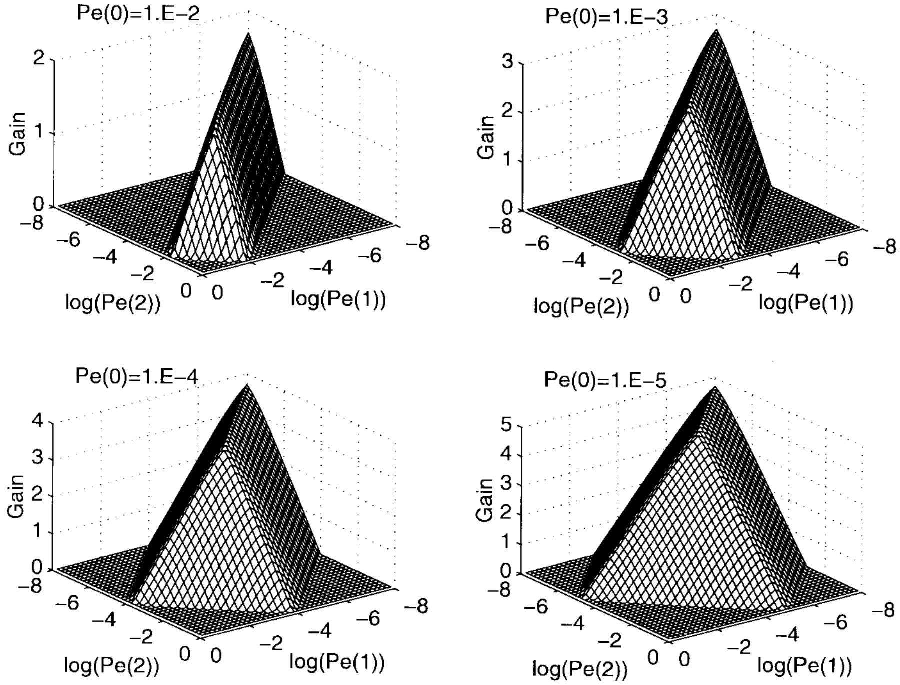

Fig. 22. Gain (relative to (S/I) diversity) of different combinations of links' BER. (Floor = 1.E-8.)

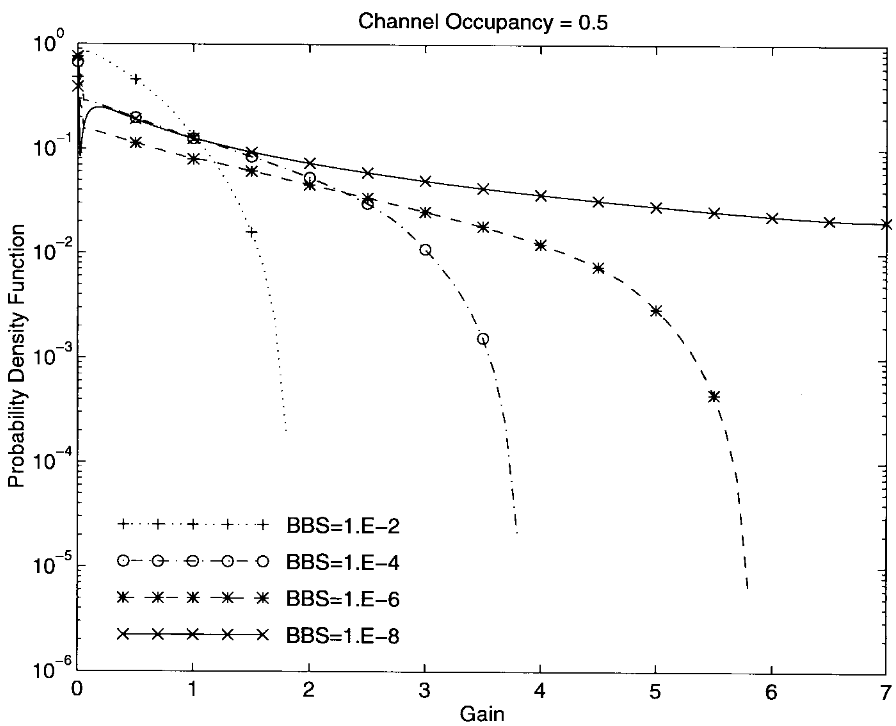

Fig. 23. Probability distribution function of gain for different conditions of BBS.

smaller and its distribution tends to be concentrated around the zero gain, i.e., there are more cases with no gain.

V. Summary and Concluding Remarks

In this paper, we analyzed the MDM scheme for wireless cellular systems. As oppose to the traditional macrodiversity scheme, in which only one signal is selected for detection, in the MDM scheme all the received signals are detected and conveyed to a central point. There, an algorithm is employed to maximize the probability of correct decision. The central point could be the MSC, one of the base stations, the destination node, or any other node in the network.

The MDM scheme is, thus, a postdetection combining scheme. Although predetection combining schemes lead to more substantial improvement, such scheme create prohibitively large load on the fixed network and require complex synchronization schemes. In contrast, assuming that the capacity of the fixed network is significantly larger than the wireless network, the MDM scheme has only minor effect on the fixed network. The synchronization requirements of the MDM scheme are readily solved by conventional frame-synchronization method, such as those used in the data-link-layer protocols.

Nevertheless, soft-decision information could be used in the decision algorithm to further improve the performance, without creating excessive traffic on the fixed network or requiring complex synchronization schemes. This is an area for future research. Similarly, using information from the decoding process to estimate the channel quality (instead of power measurements) should also be considered in the context of the MDM scheme.

The main advantage of the MDM scheme is that it improves the reception (BER) mostly in the area close to the boundary between cells. This is exactly the area in which the mobile can expect worst conditions. Thus, the MDM scheme tends to "equalize" the performance throughout the coverage of the cellular system.

Outage probability is defined as a BER (or SIR) threshold above (or below, for SIR) which the reception is declared useless. In general, our studied traditional macrodiversity schemes results in lower AOP when channel occupancy is small, σ is small, and r is large. The MDM scheme can improve the outage probability by bringing the resulting BER below the threshold, even though the BER of each one of the individual links is above the threshold. We showed that the improvement of the MDM's outage probability is more substantial when r is large, σ is small, and the mobile is located close to the boundary between cells.

Conditional outage probability is the probability of no outage, when there is an outage in the corresponding traditional macrodiversity scheme [(S/I) diversity, in our case]. The variance of the shadow fading has a crucial impact on the conditional outage probability. Furthermore, the probability increases with r, increases with the BER threshold, and decreases with channel occupancy. At $\sigma = 4.0$, the conditional outage probability at the cell boundary varies from 10% to as high as 73%, for the outage threshold of 10^{-4} and $r = 4.0$. For $r = 4.0, \sigma = 4.0$, and the outage threshold value in the range of 10^{-5} to 10^{-3}, the conditional outage probability is never less than 45%.

Average metrics, such as the AG and the AGA, provide an indication on how well the MDM scheme performs in relation to other diversity schemes. The AG, as compared with the traditional macrodiversity schemes studied here, is at least two orders of magnitude for channel utilization less than 40% when $r = 3.5$, $\sigma = 8.0$, and $P_e^{\rm floor}$ of 10^{-8}. Under the same conditions, the AG is at least one order of magnitude for channel utilization less than 65%. Furthermore, the AGA extends to about 60%–70% of the cell area at $\rho = 0.5, r = 3.5$, and for $P_e^{\rm floor} = 10^{-8}$.

At low channel utilization, the gain is nearly uniformly distributed between zero and the maximal value determined by the BER floor. At larger channel utilization, the density of the gain is shifted toward the smaller gain values. In fact, as the channel utilization increases, the MDM scheme provides less and less improvement and there is less of the "equalization effect" of the BER floor.

In summary, the MDM scheme allows overall improvement in the cellular system performance, which translates to reduced interference, increased reuse factor, or reduced spectrum requirements. In particular, since the main gain of the MDM scheme is achieved in the most vulnerable area (the boundaries between cells), the scheme results in a dramatic enhancement in the quality of service offered to the users. Furthermore, the MDM scheme can be applied to the already existing wireless networks without the need for additional wireless spectrum. As the technology progresses into higher and higher spectrum (e.g., 28 GHz) in which the radio propagation impairments are more profound, schemes like MDM will be primary candidates to alleviate some of these ill effects of operation in this high-frequency regime.

VI. Appendix A

Given that the base station selected by the (S/I) diversity scheme has an outage, we calculate the probability that there is no outage in the MDM scheme. This probability is termed the conditional probability of no outage (CPNO). The following derivation of the CPNO formula is similar to that of the CAG. We define the following notations.

m	Index of interfering patterns ($m = 1, \cdots 64$).
$\mathrm{Prob}(m)$	Occurrence probability of the mth interfering pattern.
Iterations(m)	Number of total simulation iterations for the m^{th} interfering pattern.
$N(m)$	Number of outage events of (S/I) diversity for the mth interfering pattern out of the Iterations(m) simulation iterations.
i_m	ith outage event of the (S/I) diversity for the mth interfering pattern ($i_m = 1, \cdots, N(m)$).
$No\_\mathrm{Out(m)}$	Number of events of the mth interfering pattern, when there is no outage in the MDM scheme and given that there is an outage in the (S/I)-diversity scheme.

In addition, given that there is an outage in the (S/I) diversity scheme, we define the indication function $\mathrm{I}(m, i_m)$ as

$$\mathrm{I}(m, i_m) = \begin{cases} 1, & \text{if there is no outage in the MDM scheme} \\ 0, & \text{if there is an outage in the MDM scheme.} \end{cases}$$

From the above definitions, we can obtain the CPNO formula as derived in (A.1), given at the bottom of the next page, where $n(m)$ is the number of interferers of the mth interfering pattern and ρ is the channel occupancy.

APPENDIX B

The CAG is defined as the AG in the gain area and is denoted as $\text{AG}|_{\text{GainArea}}$. We define the following terms.

m	Index of an interfering pattern ($m = 1, \cdots, 64$).
$\text{Prob}(m)$	Occurrence probability of the mth interfering pattern.
N	Number of total cell points.
GP(m)	Number of gain points for the mth interfering pattern.
i_m	ith gain point of the mth interfering pattern [$i_m = 1, \cdots, \text{GP}(m)$].
$\overline{\text{gain}}(m, i_m)$	Average gain at the ith gain point of the mth interfering pattern.

From the above definitions, the CAG, $\text{AG}|_{\text{GainArea}}$, can be obtained as derived in (A.2), given at the bottom of the next page.

The values of N, $GP(m)$, and $\overline{\text{gain}(m, i_m)}$ are obtained from the simulation. $\text{Prob}(m)$ is given by $\text{Prob}(m) = C^6_{n(m)} \cdot \rho^{n(m)} \cdot (1-\rho)^{6-n(m)}$, where $n(m)$ is the number of interferers of the m^{th} interfering pattern and ρ is the channel occupancy.

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$$
\begin{aligned}
\text{CPNO} &= E[\text{I}(m, i_m)|\text{Outage in (S/I) diversity}] \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{N(m)} \{\text{I}(m, i_m) \cdot \text{Prob}[m, i_m|\text{Outage in (S/I) diversity}]\} \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{N(m)} \left\{\text{I}(m, i_m) \cdot \frac{\text{Prob}[m, i_m, \text{Outage in (S/I) diversity}]}{\text{Prob(Outage in (S/I) diversity)}}\right\} \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{N(m)} \left\{\text{I}(m, i_m) \cdot \frac{\text{Prob}(i_m) \cdot \text{Prob}[m, \text{Outage in (S/I) diversity}]}{\sum_{m'=1}^{64} \{\text{Prob}[\text{Outage in (S/I) diversity}|m'] \cdot \text{Prob}(m')\}}\right\} \\
&= \sum_{m=1}^{64} \left\{\left[\sum_{i_m=1}^{N(m)} \text{I}(m, i_m)\right] \cdot \frac{\frac{1}{N(m)} \cdot \text{Prob}[\text{Outage in (S/I) diversity}|m] \cdot \text{Prob}(m)}{\sum_{m'=1}^{64} \{\text{Prob}[\text{Outage in (S/I) diversity}|m'] \cdot \text{Prob}(m')\}}\right\} \\
&= \sum_{m=1}^{64} \left\{\text{No\_Out}(m) \cdot \frac{\frac{1}{N(m)} \cdot \frac{N(m)}{\text{Iterations}(m)} \cdot \text{Prob}(m)}{\sum_{m'=1}^{64} \left[\frac{N(m')}{\text{Iterations}(m')} \cdot \text{Prob}(m')\right]}\right\} \\
&= \sum_{m=1}^{64} \left\{\frac{\frac{\text{No\_Out}(m)}{\text{Iterations}(m)} \cdot \text{Prob}(m)}{\sum_{m'=1}^{64} \left[\frac{N(m')}{\text{Iterations}(m')} \cdot \text{Prob}(m')\right]}\right\} \\
&= \frac{\sum_{m=1}^{64} \left[\frac{\text{No\_Out}(m)}{\text{Iterations}(m)} \cdot \text{Prob}(m)\right]}{\sum_{m=1}^{64} \left[\frac{N(m)}{\text{Iterations}(m)} \cdot \text{Prob}(m)\right]},
\end{aligned}
$$

$$
\text{where } \text{Prob}(m) \text{ is given by } \text{Prob}(m) = C^6_{n(m)} \cdot \rho^{n(m)} \cdot (1-\rho)^{6-n(m)}. \tag{A.1}
$$

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$$
\begin{aligned}
\mathrm{AG}|_{\mathrm{GainArea}} &= E(\mathrm{gain}|\mathrm{Gain\ Area}) \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{GP(m)} [\overline{\mathrm{gain}}(m, i_m) \cdot \mathrm{Prob}(m, i_m|\mathrm{Gain\ Area})] \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{GP(m)} \left[\overline{\mathrm{gain}}(m, i_m) \cdot \frac{\mathrm{Prob}(m, i_m, \mathrm{Gain\ Area})}{\mathrm{Prob}(\mathrm{Gain\ Area})}\right] \\
&= \sum_{m=1}^{64} \sum_{i_m=1}^{\mathrm{GP}(m)} \left\{\overline{\mathrm{gain}}(m, i_m) \cdot \frac{\mathrm{Prob}(i_m) \cdot \mathrm{Prob}(m, \mathrm{Gain\ Area})}{\sum_{m'=1}^{64} [\mathrm{Prob}(\mathrm{Gain\ Area}|m') \cdot \mathrm{Prob}(m')]}\right\} \\
&= * \sum_{m=1}^{64} \left\{\left[\sum_{i_m=1}^{\mathrm{GP}(m)} \overline{\mathrm{gain}}(m, i_m)\right] \cdot \frac{\frac{1}{\mathrm{GP}(m)} \cdot \mathrm{Prob}(\mathrm{Gain\ Area}|m) \cdot \mathrm{Prob}(m)}{\sum_{m'=1}^{64} [\mathrm{Prob}(\mathrm{Gain\ Area}|m') \cdot \mathrm{Prob}(m')]}\right\} \\
&= \sum_{m=1}^{64} \left\{\left[\sum_{i_m=1}^{\mathrm{GP}(m)} \overline{\mathrm{gain}}(m, i_m)\right] \cdot \frac{\frac{1}{GP(m)} \cdot \frac{GP(m)}{N} \cdot \mathrm{Prob}(m)}{\sum_{m'=1}^{64} \left[\frac{\mathrm{GP}(m')}{N} \cdot \mathrm{Prob}(m')\right]}\right\} \\
&= \sum_{m=1}^{64} \left\{\frac{\frac{\left[\sum_{i_m=1}^{\mathrm{GP}(m)} \overline{\mathrm{gain}}(m, i_m)\right]}{N} \cdot \mathrm{Prob}(m)}{\sum_{m'=1}^{64} \left[\frac{\mathrm{GP}(m')}{N} \cdot \mathrm{Prob}(m')\right]}\right\} \\
&= \frac{\sum_{m=1}^{64} \left\{\frac{\left[\sum_{i_m=1}^{\mathrm{GP}(m)} \overline{\mathrm{gain}}(m, i_m)\right]}{N} \cdot \mathrm{Prob}(m)\right\}}{\sum_{m=1}^{64} \left[\frac{\mathrm{GP}(m)}{N} \cdot \mathrm{Prob}(m)\right]} \\
&= \frac{\sum_{m=1}^{64} \left\{\left[\sum_{i_m=1}^{\mathrm{GP}(m)} \overline{\mathrm{gain}}(m, i_m)\right] \cdot \mathrm{Prob}(m)\right\}}{\sum_{m=1}^{64} [\,\mathrm{GP}(m) \cdot \mathrm{Prob}(m)].}
\end{aligned}
\tag{A.2}
$$

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