On the Performance of Hybrid Macro/Microdiversity in the Reverse-Link Microcellular Networks

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***Abstract*— We investigate hybrid macro/microdiversity employed in the reverse-link microcellular wireless networks where low power, small and cost-effective radio access ports are linked to a central unit. We propose a new macro-selection strategy to improve the conventional macrodiversity selection technique. Furthermore, the issue of macrodiversity maximal ratio combining in non-CDMA microcellular networks is investigated as a natural extension of the soft handover of the already established CDMA cellular systems. The proposed schemes have performance advantage over the conventional macrodiversity method at a modest extra processing.**

I. Introduction

The conventional macrodiversity method (used to combat against shadowing) involves of serving a wireless unit with several base stations simultaneously, and of choosing the one with the best signal quality; this technique is known as selection combining. Macrodiversity selection has been the choice of implementation despite its inferior performance compared against other combining techniques (such as maximal ratio combining (MRC)) because of the difficulties in having access to all signals received at different base stations with the correct phase information. Given this limitation, a number of post-detection techniques have been proposed to improve the performance of conventional scheme [1], [2]. An example is the multiply detected macrodiversity (MDM). In MDM all the received signals are detected in parallel at different base stations and an algorithm is employed at the central unit to maximize the probability of correct decision. Algorithms that have been considered for post detection combining include maximum-likelihood [1], and optimal fusion [2].

In recent years, some new visions are emerging, providing novel ways of handling signals received at widely separated antennas, such as the sectorized distributed antennas (SDA) [3] and the radio-on-fiber (RoF) architectures [4], [5], [6]. Such architectures are particularly suitable for the microcellular systems where fiber links can conveniently connect these distributed antennas, henceforth referred to as ports or access points, to a central unit.

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Within the framework of this new vision, more advanced combining schemes which also incorporate microdiversity are being proposed. For instance, microdiversity antennas have been incorporated within the macrodiversity structure [7], [8]. The combined performance of this hybrid scheme has been evaluated and is found to yield excellent improvement in system outage probability [7] and bit error probability [8]. The scheme studied in [8] involves putting M microdiversity antennas on each of K macrodiversity ports deployed in a wireless network. MRC is implemented on all of the M branches of the selected port, or on a subset (say, m) of the M branches. Selecting m out of M branches of a particular port has been referred to as hybrid macrodiversity/GSC(generalized selection combining). This approach is very appealing when there is a heavy constraint on electronic and RF units that preclude the use of all branches for processing. The conventional macrodiversity combining which uses the local mean SNR as the basis of port selection has been employed in [8]. We shall refer to such an approach as Scheme I.

With microcellular networks in mind, and the perspective described above, we dispense with the conventional cellular concept by eliminating the need for expensive base station resources. Instead, we consider a wireless network with cost-efficient radio access ports which are linked to a central unit (CU). In this architecture, we introduce a novel way of implementing the macro-selection (Scheme II) and also demonstrate its superiority over the conventional method. Furthermore, we explore macrodiversity MRC in microcellular systems referred to as Scheme III, which can be viewed as a natural extension of the CDMA cellular soft handover. Although, the analysis presented here is for a non-CDMA system, it can easily be extended to a CDMA system, if a rake-type receiver is employed to collect energy from multiple ports.

The rest of the paper is organized as follows. The system and channel descriptions are given, then the proposed schemes are discussed, followed by the numerical performance evaluation. Having illuminated the potential gains in the proposed architecture and algorithms, we draw attention to some practical considerations, complexity and implementation issues, towards realizing these gains. Finally, some conclusions are drawn.

II. System and Channel Description

In microcell systems, low power, small and cost-effective radio access ports can easily be deployed and connected to a central unit using broadband transmission techniques. For example, in the reverse-link of a microcellular networks, the signals can be collected by these access ports and sent to the central unit through an optical fiber link. Since the small cell architecture is the focus of this paper, the important issue of port correlations is also investigated.

In the wireless network considered, a region is equipped with K strategically and widely separated access ports (K-microcells), each of these ports carries M microdiversity antennas as shown in Fig. 1. We consider the case where a separate feeder exists between each branch (microdiversity antenna) and the central unit, where processing is performed. Hence, a total of $M \times K$ distinct signals are received at the central unit, which enables the separation of the received signals. We have considered a realistic wireless channel model with both small scale (Rayleigh) and large scale (lognormal shadowing) fading effects which can be described as Rayleigh-lognormal.

III. The Novel Macrodiversity Schemes

Let x represent the complex transmitted signal at a certain time, and $\mathbf{a}_k = \{a_{k,1}, a_{k,2}, \cdots, a_{k,M}\}$, $1 \leq k \leq K$, represent the Rayleigh-lognormally shadowed channel gain experienced by the signal reaching the k-th port. The lognormally distributed shadowing has an area mean of μ_k dB and a standard deviation of σ_k dB.

For the port's M microdiversity antennas the received signal at the l-th branch can be represented in the following form

$$y_{k,l} = a_{k,l} x + n_{k,l}, \qquad 1 \leq l \leq M, \tag{1}$$

where $\mathbf{y}_k = \{y_{k,1}, y_{k,2}, \cdots, y_{k,M}\}$ is the received signal and $\mathbf{n}_k = \{n_{k,1}, n_{k,2}, \cdots, n_{k,M}\}$ is the zero mean complex Gaussian random variable each component with variance $N_0/2$ per dimension.

Let us define $\Gamma_{k,l}$ as the instantaneous SNR at each branch. The following strategies are used to take advantage of all the distinct $M \times K$ signals at the central unit.

1) **Scheme I** (Traditional Method):
The local mean SNR is the basis of port selection.
  - Obtain the local means, $\Omega_k = E[a_{k,l}^2]$, $1 \leq k \leq K$. Note that shadowing is same for all branches in a port.
  - Identify the port k^* with the largest local mean; i.e., $k^* = \underbrace{\text{argmax}}_{1 \leq k \leq K} \{\Omega_k\}$.
  - At this port select $m \leq M$ branches with the largest $\Gamma_{k^*,l}$.

2) **Scheme II**:
The results of Scheme I using the local mean SNR as the basis of port selection puts most of the gain on the macrodiversity. If we consider that at each branch of a port SNR depends on both the macroscopic and microscopic fading, we can exploit this fact in making port selection decision.
  - Choose the port k^* that has the largest overall aggregate SNR; i.e., $k^* = \underbrace{\text{argmax}}_{1 \leq k \leq K} \{\sum_{l=1}^{M} \Gamma_{k,l}\}$.
  - At this port select $m \leq M$ branches with the largest $\Gamma_{k^*,l}$.

In a suboptimal implementation of Scheme II, the port selection can be performed on the highest branch SNR;
  - Identify $k^* = \underbrace{\text{argmax}}_{1 \leq k \leq K, 1 \leq l \leq M} \{\Gamma_{k,l}\}$.
  - At this port select $m \leq M$ branches with the largest $\Gamma_{k^*,l}$.

3) **Scheme III:**
Since the CU has access to all the $M \times K$ separable signals, it can process across all the ports; Hence,
  - Arrange all the $M \times K$ signals in order of their SNR, $\Gamma_{k,l}$, across all ports.
  - Select the largest m out of the $M \times K$ branches.

In all cases, MRC technique is used to process the m selected branches, where $1 \leq m \leq M$.

IV. Correlated Branches

Due to small cell size which results in insufficient spacing of ports in the microcell systems, significant correlation may exist among macrodiversity branches. Hence, the results obtained with zero correlation assumptions are biased due to over-estimation of the diversity gains. The zero correlation assumption is made in most of the existing literature on the analysis of the effect of macrodiversity on system performance; this is largely due to analytical convenience. In practical wireless systems however, the ports are likely to be shadowed by the same obstacles which, unfortunately, results in port correlations. The few studies addressing the effect of branch correlations [9], [10] stress that its impact should not be ignored in claiming diversity gains when macrodiversity is deployed in small cell systems. Hence, some illustrative results are presented below.

V. Discussion of Results

The algorithms described above have been used to evaluate the probability of error for different combinations of K, M, and m, which are the number of port sites, microdiversity branches, and order of GSC, respectively, for BPSK modulation. The variance of the lognormal shadowing, σ, is treated as a variable. The mean of the lognormal fading is assumed to be zero dB, which in effect, removes the distance-dependent received power variations. In other words, the performance is evaluated at locations equidistant from the macrodiversity ports. Fig. 2 shows three set of curves for the following

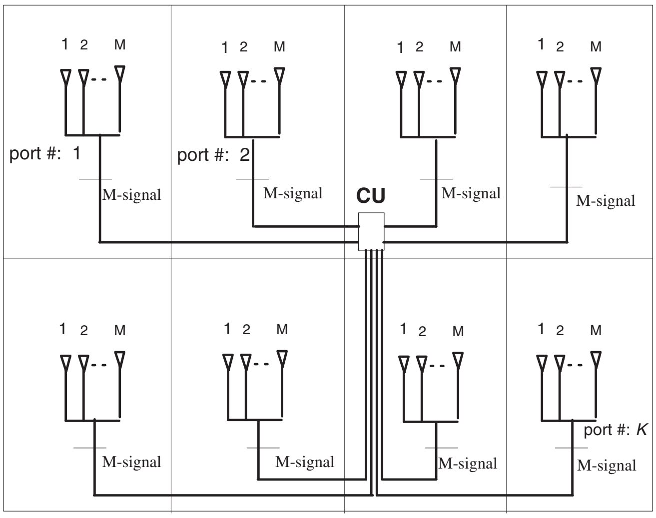

Fig. 1. Antenna layout for the macro- and microdiversity in a microcellular network.

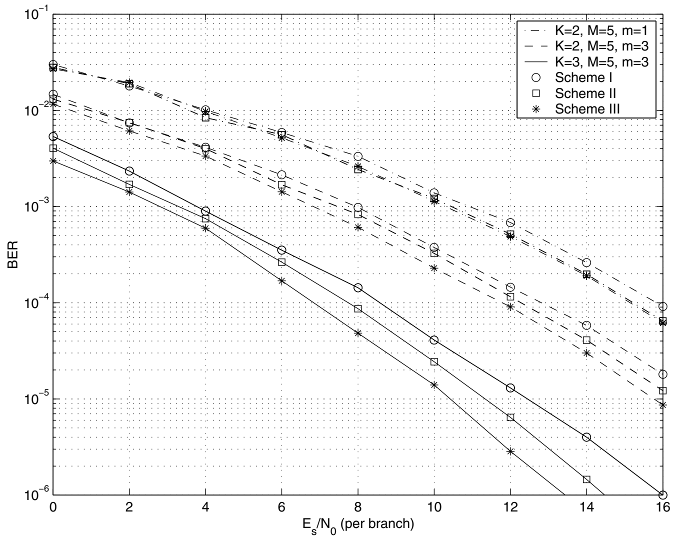

Fig. 2. Performance comparison of the schemes ($\sigma = 8$ dB).

values of diversity parameters ($K = 2, M = 5, m = 1$), ($K = 2, M = 5, m = 2$), and ($K = 3, M = 5, m = 3$), for $\sigma = 8$ dB. Fig. 3 shows performance curves for the same parameters but with σ set to 4 dB. For each set of diversity parameters, bit error probability (BER) versus average SNR per branch is plotted for Schemes I-III, the suboptimal metric of Scheme II has been used in the simulations. From Fig. 2, it is observed that for $K = 3, M = 5, m = 3$, Scheme III has about 1.5 dB advantage over the conventional Scheme I at an error rate of 10^{-4}; the corresponding gain from Scheme II is about 1 dB. These gains are respectively about 2 dB and 1.25 dB over the conventional scheme for $\sigma = 4$ dB (Fig. 3). However, when we consider $K = 2, M = 5, m = 3$, the proposed schemes (Schemes II and III) still outperform the conventional Scheme I but with reduced gain margins. At lower error rates, the proposed schemes enjoy more marginal

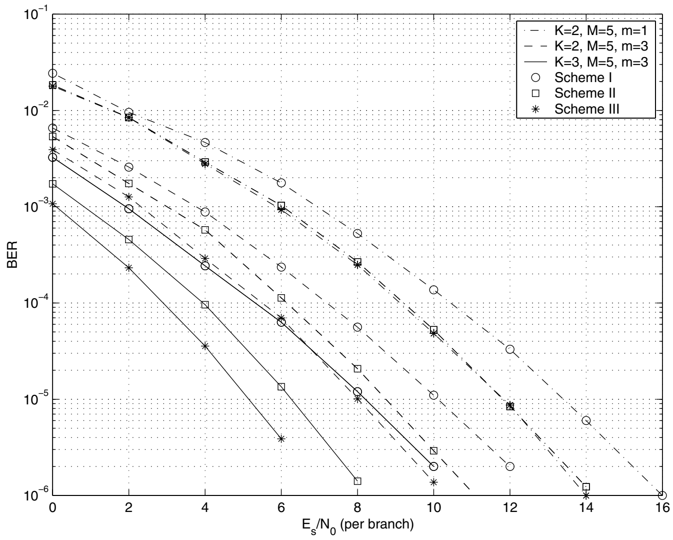

Fig. 3. Performance comparison of the schemes ($\sigma = 4$ dB).

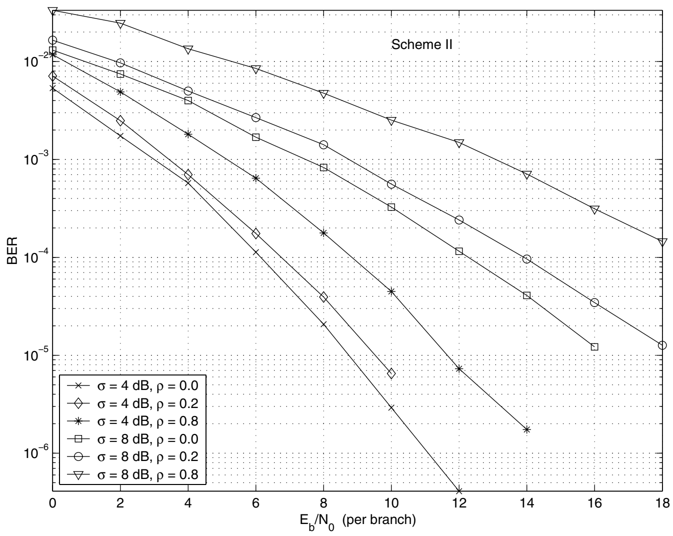

Fig. 4. Effect of branch correlation on Scheme II for different σ, and $K = 2, M = 5, m = 3$.

gains over the conventional scheme. For instance, for Scheme III these gains are close to 3 dB and 2 dB at BER $= 10^{-5}$ for $K = 3, M = 5, m = 3$ as can be observed in Fig.s 2 (for $\sigma = 8$) and 3 (for $\sigma = 4$ dB), respectively.

The benefit of using more ports is evident comparing the cases $K = 3, M = 5, m = 3$ and $K = 2, M = 5, m = 3$. A 5 dB advantage is obtained when $\sigma = 8$ dB as seen in Fig. 2 when Scheme III is implemented. This gain reduces to about 2.5 dB for $\sigma = 4$ dB. These results also show the importance of macrodiversity (more access ports) in combating shadowing. Furthermore, from Fig.s 2 and 3, it can be observed that the case for a microscopic selection ($m = 1$) yields almost the same performance for Schemes II and III which is in agreement with expectation.

The results obtained can be explained in the following

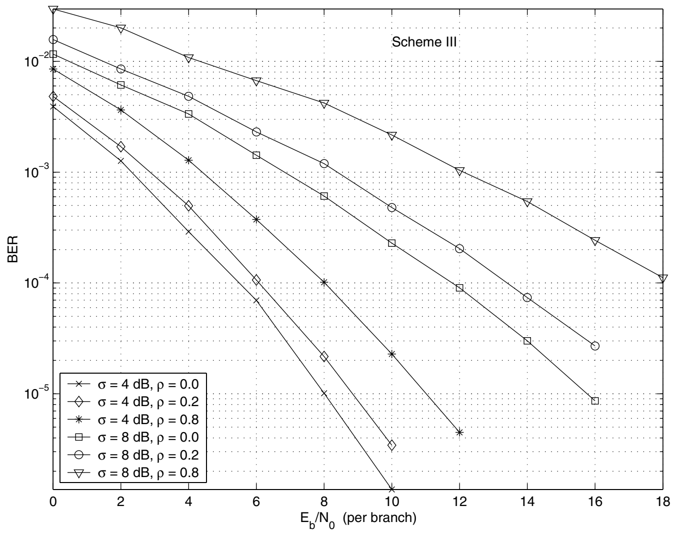

Fig. 5. Effect of branch correlation on Scheme III for different σ, and $K = 2, M = 5, m = 3$.

way. The Scheme III outperforms Scheme II which, in turns, performs better than Scheme I. Scheme III can be seen as a benchmark (or performance upper bound) of the hybrid schemes. If at the moment, we put aside shadowing, Scheme III degenerates to classical Rayleigh fading GSC, as the best m branches will always be selected. However, in Scheme II, it can not always be guaranteed that this will be the case, hence, the inferior performance of Scheme II compared to that of Scheme III.

The performance improvement of Scheme II over Scheme I comes from just the way the received signals are treated without the need for extra-ordinary signal processing, demonstrating that with modest extra processing efforts (discussed in sec. 6), a gain as high as 3 dB can be obtained using the proposed Scheme II rather than the conventional macrodiversity selection.

The results above are for zero port correlation. The impact of moderate and significant correlation is shown next. The correlation is measured through the correlation coefficient, ρ.

Fig.s 4 and 5 show the impact of $\rho = 0.2$ and $\rho = 0.8$ cases, moderate and significant correlation, respectively, on the proposed Schemes II and III. Two macrodiversity ports ($K = 2$) are considered with $M = 5$ assuming that the available radio resources allow three ($m = 3$) branches to be selected and combined. In the following, we make the performance comparison for a BER of 10^{-4}. In Fig. 4 we observe that for Scheme II, the correlation results in about 3 dB SNR loss for $\sigma = 4$ dB; this loss is about 7 dB for $\sigma = 8$ dB and $\rho = 0.8$. SNR loss is defined as the additional required SNR to maintain the same BER. Subjecting Scheme III to the same operating conditions, we observe that for $\rho = 0.8$, correlation inflicts about 2.3 dB loss when $\sigma = 4$ dB, but this loss increases to about 6 dB for $\sigma = 8$ dB. Although, correlation affects the performance of both schemes significantly, Scheme III is more robust than Scheme II to the tune of about 1 dB for the cases considered. This is due to the fact that Scheme III selects m branches across the ports, as compared to Scheme II that concentrates on a single port. For moderate correlations ($\rho = 0.2$), the performance advantage of Scheme III over Scheme II diminishes as depicted in Fig.s 4 and 5.

VI. Practical and Complexity Issues

The aim of the illustrative results presented is to stir some interest into the potentials of the proposed hybrid macro/microdiversity scheme. Therefore, we have considered a slotted system in the frequency-time domain with orthogonal slots to each user, which takes care of the co-channel interference. In the following we will discuss issues of practical interest that facilitate some of the assumptions made in this work and close the discussion with some comments on the expected system complexity.

- **Equal Distances and Average SNR:** We have assumed that the user is equidistant from all the ports for analytical convenience. This also ensures equal average port SNR suitable for the optimal operation of MRC. There are many practical scenarios where the equidistant assumption can hold reasonably. One typical situation is when the macro/microdiversity architecture is used in environments with dense deployment of access ports, such as campuses (industrial, university, etc.) and indoors (airports, malls, etc.) [11]. Some of these examples are typical scenarios fitting into the indoor microcellular systems, see for example [12, pp. 104-105]. In such environments the number of deployed access ports will be large; and it is reasonable to assume that a small number of ports can be found that are at, more or less, the same distances from the user. For this scenario, such ports may form a "macrodiversity group" which will ensure even local mean SNR distributions thereby deriving the full benefit of MRC.

  The whole picture in itself may open other ways of research, which may be referred to as generalized selection macrodiversity (GSM), where a subset of macrodiversity ports may be selected from the total number of ports deployed. For this reason, results have been shown for small values of macrodiversity group ($K = 2, 3$) where the geometry allows equal distance assumption in certain scenarios. In an extreme case however, when a user is very close to a port and relatively far from the rest the need for extra benefit from diversity is remotely small anyway.

  Another scenario is when the access ports are deployed on the opposite sides of streets and highways, which can represent a typical scenario fitting into the definition of (outdoor) microcellular system [12, pp. 100-102]. In this case, a user's trajectory will be the locus of points equidistant between two ports located on the opposite sides of the road. Apart from all these scenarios, empirical studies have shown that as the amount of macrodiversity in the network increases, the system uplink becomes less sensitive to user location [13].

- **Complexity:** The complexities of the proposed schemes (Schemes II and III) can be estimated by comparing them with that of the conventional method. For example, the feasibility of the assumed scanning receiver has already been discussed for the classical generalized selection microdiversity [14]. Scheme II requires an additional summer circuitry; but the associated processing cost will be just negligible. Therefore, proposed Scheme II has comparable complexity with the conventional Scheme I. Although the way we exploit the macrodiversity in scheme III can be viewed as a natural extension of CDMA soft handover technique to the non-CDMA framework considered in this paper, the associated receiver complexity requires a more careful analysis. If the symbol rate is high and the relative distances of the ports in a "macrodiversity group" to the CU is large, then this situation will necessitate the use of some sort of equalization. In a CDMA system a relatively simple rake-type receiver can be used to coherently combine the signals in such a scenario. In a non-CDMA system, however, a more complex equalizer may be required. Intuitively the equalization may require new formulations different than those being used for single path channels. On the other hand, since the ports are fixed entities and their positions are known, synthetic link delays may be inserted in the cable connecting the ports to the CU to help reduce the perceived delay spread at the CU and thus simplifying the required equalizer since the equalizer will need less number of taps. This strategy is borne out of the fact that in the proposed architecture signals are delivered separately to the CU unlike the natural delay spread where the signals are entangled in the air.

VII. Conclusion

We investigate the use of hybrid macro/microdiversity in the reverse-link of microcellular networks. These schemes involve K radio access ports carrying M microdiversity antennas deployed in a wireless network region where expensive base stations would have been used in an attempt to improve system capacity or coverage. This architecture favours low power, small and cost-effective radio access ports which can easily be linked to a central unit by using broadband transmission techniques. In the light of this, we propose a new algorithm which is an improvement over conventional macrodiversity selection technique. Macrodiversity MRC was also investigated. The proposed schemes have performance advantage over the conventional method at reasonable signal processing efforts. The power savings of the proposed schemes could help in coverage extension or capacity boosting of wireless systems without the need for expensive base stations deployment. Finally, the impact of port correlation on the proposed schemes was also investigated.

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