Uplink Performance of a New Macro-Diversity Cellular Mobile Radio Architecture

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***Abstract*— This contribution analyzes the uplink performance of a new mobile radio network architecture with overlapping cells and macroscopic diversity with regard to outage probabilities. Results are obtained by computationally efficient analytical/numerical evaluation of cumulative density functions. Various combining schemes are investigated, taking into account correlated lognormally distributed carrier and interferer signals. Comparisons of the new with conventional cellular architectures show significant improvements with respect to shadow fading. Gains obtainable by the new macroscopic diversity architecture may not only be used to increase transmission quality or decrease outage probabilities, but also to considerably lower the channel re-use factor, thereby solving capacity problems for so-called "hot spots".**

I. Introduction

Signal transmission in cellular mobile radio systems suffers from major impairments. The most serious degradations are due to Rayleigh and lognormal fading. To overcome the short-term Rayleigh fading, techniques like coding in combination with interleaving and microscopic antenna diversity are most often employed, while macroscopic (multiple base station site) diversity is known to be effective against the severe long-term shadowing effects [1], usually modelled as a lognormal distribution.

Various analyses on network architectures employing macroscopic diversity have been presented in the literature, e.g. in [1], [2] and [3]. Recently, the applicability to GSM of a new network architecture with overlapping cells and macro-diversity has been demonstrated [4], see fig. 1. A detailed section of the corresponding cluster is shown in fig. 2. Each cell consists of three inward-directed sectorized antennas at alternate corners of the hexagonal cell area. In total, six different channel/frequency groups are necessary to realize a cluster, but due to cell overlapping an actual channel re-use factor of three is achieved. As shown in [4] co-channel and adjacent-channel carrier-to-interference ratios are comparable to or better than in a conventional network architecture applying omnidirectional antennas in the center of a cell and a re-use factor of seven. It should be noticed that variants of the cluster according to fig. 1 exist which achieve e.g. a re-use factor of four. This leads to even higher carrier-to-interference ratios.

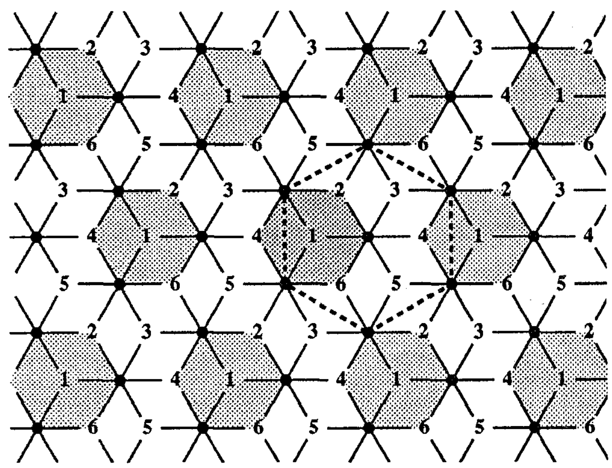

Figure 1. New network architecture with $2 \cdot 3$ channel groups

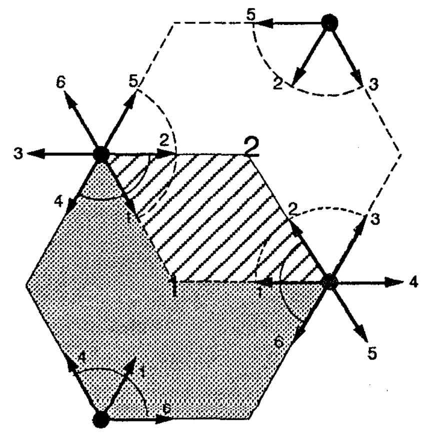

Figure 2. 2 overlapping cells of the new architecture

This paper presents numerical results on the performance of the abovementioned three base station site macroscopic diversity system in terms of the outage prob-

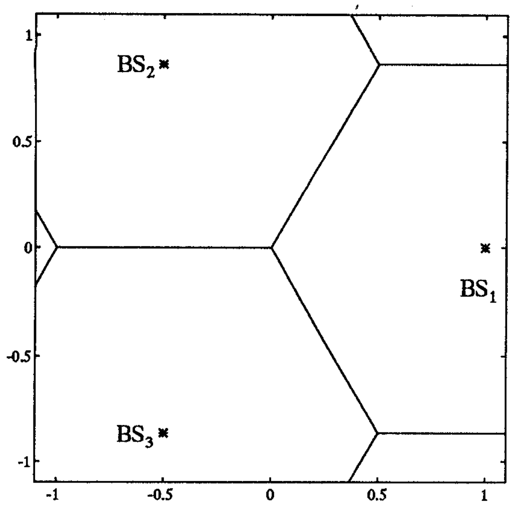

Figure 3. Considered cell area for conventional hexagonal cells

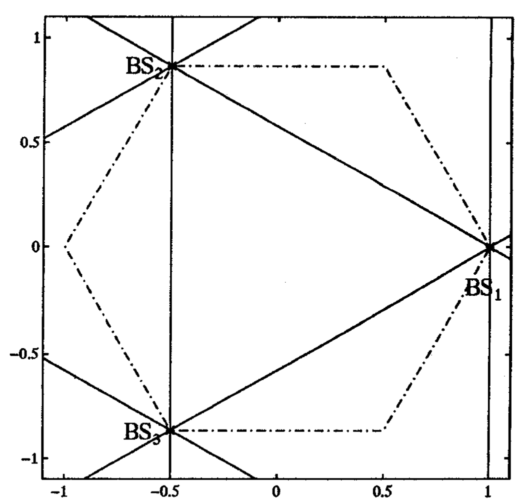

Figure 4. Considered cell area for cells with macrodiversity

ability criterion in the uplink in comparison to a system with one base station site per cell as in conventional clusters. The analysis takes various fading, combining and correlation conditions into account. Besides cumulative density functions for single locations, area averaged statistics are provided. Furthermore, it is shown that the new network architecture allows uncritical handoffs within broad regions of low outage probabilities and high transmission quality.

II. Models and System Configurations

In the following, the main assumptions and models underlying the numerical evaluations are briefly reviewed.

Cell areas

The cell areas under study are depicted in fig. 3 and 4. Fig. 3 represents a part of the well-known conventional cell architecture consisting of hexagonal cells and omnidirectional antennas with a channel re-use factor of e.g. 7, 9 or 12. Channel/frequency assignments are not shown since they are not of interest here. A part of the new network architecture with sectorized antennas [4] making use of macroscopic diversity is shown in fig. 4. Results are provided for the hexagonal cell area surrounded by the dash-dotted line. But as can be seen from fig. 2, two hexagonal cells overlap each other by one third of the hexagonal cell area (hatched rhomb). Actually, a mobile station (MS) moving e.g. from cell 1 to cell 2 will experience a handoff when the signals of cell 2 are stronger (neglecting any handoff thresholds). This handoff will ideally take place exactly on the straight lines between base stations, thus resulting in triangular cell geometries as depicted in fig. 4 (solid lines). Therefore, simulation results will also be shown for the triangular cell area, called "kernel cell" in the sequel.

Propagation

The *averaged* received logarithmic signal power $\overline{P_i}$ (in dB) at base station i can be expressed as (e.g. [1])

$$\overline{P_i} = P_t \; - \; 10\,\gamma\,\log\left(d_i/d_0\right), \quad \gamma = 3\ldots4 \quad . \qquad (1)$$

d_i is the distance between mobile station and base station i, d_0 is a reference distance, and P_t represents the transmitted signal power. The propagation coefficient γ is assumed constant all over the area; different antenna gains or heights are not considered here. For the presented results a fixed value of $\gamma = 3.5$ has been used.

Accordingly, we may define the logarithmic *local area mean* power or simply *local mean* P_i (in dB) which is the composite of the averaged power plus shadowing fading variation as

$$P_i = \overline{P_i} \; + \; X_i \qquad (2)$$

where X_i stands for the lognormal shadowing component. All equations apply to carrier powers C_i as well as interferer powers I_i.

Shadowing

Shadowing due to significant changes in the surroundings of the mobile and/or base station, respectively, is widely modeled by a lognormal distribution. Accordingly, the pdf of the fading variation X_i (in dB) is described as

$$p(X_i) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{X_i^2}{2\sigma^2}\right) \qquad (3)$$

with zero mean power and standard deviation σ. Thus, on a logarithmic scale, the carrier-to-interference ratio $CIR = 10\log(C_{\mathrm{lin},i}/I_{\mathrm{lin},i})$ [dB] becomes a normally distributed random variable $(C_i - I_i)$ with mean $(\overline{C_i} - \overline{I_i})$ and variance $\sigma^2_{C,i} + \sigma^2_{I,i}$ assuming independent random shadowing variables.

Short-term fading

Since it is assumed that Rayleigh fading caused by multipath propagation is mitigated by means of coding/interleaving and/or microscopic diversity it is not considered here.

Power control

Each MS controls its transmitted power according to eq. 1 so that the received mean carrier power $\overline{C_i}$ at the *nearest* BS is constant, i.e. the mobile's mean transmitted power $\overline{P_t}$ is simply dependent on the distance between MS and nearest BS and the propagation coefficient. This power control algorithm is only suboptimal. In fact, long-term shadow fading caused by obstacles can be compensated by power control at the transmitter, but this leads to a higher interference variance in surrounding co-channel cells. However, Monte-Carlo simulations have shown [5] that the resulting CIR probability functions are nearly equal to the ones obtained by analytical/numerical analysis of the distance-controlled power adjustment as presented here.

Handoff

For a conventional system without macro-diversity and ideal handoff procedures each MS is connected with the strongest BS. For simplicity, in this study each MS is allocated to the cell with the nearest BS, i.e. a handoff will take place as soon as a mobile crosses the ideal hexagonal cell boundaries (fig. 3). In the new architecture with macroscopic diversity the situation is slightly different. Due to overlapping cells as depicted in fig. 2 a handoff may take place at any location inside the overlap area (hatched rhomb). Since a handoff decision should be based not only on signal power measurements but also on capacity requirements, results are provided for the hexagonal and the triangular cell area, see fig. 4 (cf. subsection *Cell areas*).

Interference and traffic considerations

The performance evaluation is mainly dependent on the interferer activity in surrounding co-channel cells as well as the channel re-use factor. As pointed out in [4], the new architecture exhibits an actual re-use factor of three. However, its worst-case performance (all co-channel interferers active) is better than that of a conventional architecture with a re-use factor of seven. In order to fairly compare macro- with conventional non-macro-diversity systems, the interference conditions shall be *the same* for both architectures. We choose an interferer activity in the range of 70...80 % at randomly selected locations. Thus, for a standard deviation of $\sigma_C = \sigma = 8$ dB in each mobile to base station path, the summation of multiple lognormal interferer powers [6] results in a mean carrier-to-interference ratio of $\overline{CIR} = 15$ dB and an interference standard deviation of $\sigma_I = 5.5$ dB. For $\sigma_C = \sigma = 6$ dB, the corresponding values amount to $\overline{CIR} = 17$ dB and $\sigma_I = 4$ dB. Within the conventional architecture without macro-diversity, this mean $\overline{CIR}$ is obtained at *all* base stations: each cell has only one base station (BS) determining the mobile stations power. Within the macro-diversity system, the mean $\overline{CIR}$ is obtained at the *nearest* BS of a cell since this one determines the mobile stations power; the received average powers at the other BSs are lower due to larger distances, cf. subsection *Power Control*. Note that if different traffic activity is assumed, the actual outage probability values are different, but the relationships between the architectures are nearly the same.

All interferer powers at the three base stations are assumed to be statistically independent because the interference at base stations with sectorized antennas is caused by *different* mobiles.

Diversity combining

For maximal ratio combining (MRC), the outage probability is calculated according to [1]

$$\text{Prob}_{MRC}(CIR \le CIR_0) = \text{Prob}\left(\sum_{i=1}^{3} CIR_i \le CIR_0\right) \tag{4}$$

where CIR_0 denotes the protection ratio. For selection combining (SC) we have

$$\text{Prob}_{SC}(CIR \le CIR_0) = \prod_{i=1}^{3} \text{Prob}(CIR_i \le CIR_0) \quad . \tag{5}$$

In the case of correlated lognormally distributed carrier signals, the sum of the three random variables CIR_i (eq. 4) is calculated by the method presented in [6] which is an extension of the paper by Schwartz and Yeh [7]. Evaluation of the performance of selection combining (eq. 5) for correlated random variables is obtained by applying coordinate transformation to the multivariate correlated gaussian distributions which leads to uncorrelated random variables [8].

III. Results

Several test cases under various carrier and interferer conditions were run to validate the computations, including results of [6, 7]. Furthermore, distributions for specific locations which can be calculated analytically were proven to be correct.

Fig. 5 shows the outage probability for systems with and without macro-diversity. For the cell center (best case), macro-diversity is most effective due to nearly equal mean carrier powers $\overline{C_i}$ at each of the three base stations. In comparison to this best point statistics, macro-diversity gains are decreased when averaged over the whole cell area (solid and dashed line, respectively, for different cell geometries). Outage probabilities for the hexagonal and triangular cell area average are nearly equal. Hence it can be concluded that a handoff may occur anywhere inside the large handoff area (hatched rhomb in fig. 2) and not necessarily exactly on the triangular kernel cell bound-

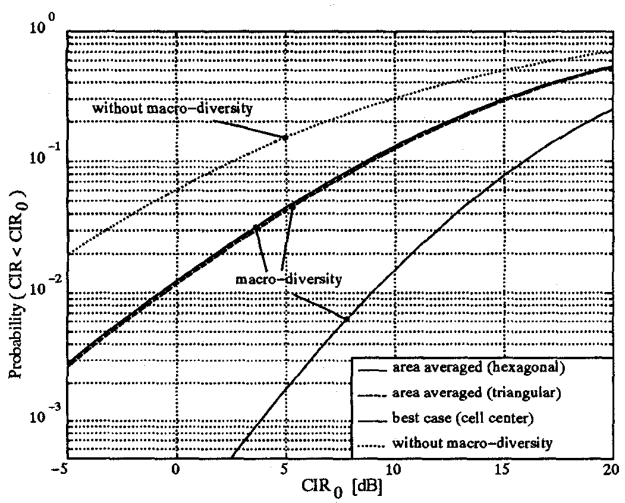

Figure 5. Outage probabilities for systems with and without macro-diversity; maximal ratio combining, standard deviation of shadowing $\sigma = 8$ dB, uncorrelated paths

aries (fig. 4). In comparison to signal transmission without macro-diversity an area averaged gain of about 6...7 dB can still be achieved for outage probabilities between $\approx 10^{-2}$ and 10^{-1}. Note that without macro-diversity the outage probability remains constant all over the cell area due to the power control and handoff assumptions.

As can be seen from fig. 6 the standard deviation σ of the lognormal shadowing process has large impact on system performance, for conventional systems as well as for systems with macro-diversity.

When comparing maximal ratio and selection combining (fig. 7) one notices only little additional gain (less than 1 dB, area averaged) achieved by the optimum scheme. This is mainly due to the different mean carrier powers $\overline{C_i}$ for each base station as can be observed from the statistics at the best-case point (cell origin) where the gain is larger.

The influence of correlated random variables X_i (eq. 2) [9] representing shadowing in the three carrier signal paths is depicted in fig. 8. It should be emphasized that actual correlation coefficients are usually quite low (< 0.2); higher coefficients may appear when a mobile moves into unfavorable locations, e.g. cellars or tunnels.

The results clearly emphasize the advantageous application of macro-diversity to mobile cellular radio systems. However, some comments on the presented simulation results should be given.

A critical point is our assumption on handoff decisions. The actual performance of the examined cellular systems will be slightly better than shown here because the nearest BS does not necessarily coincide with the strongest, and a handoff will be carried out if the received carrier power falls short of a specified threshold. Despite the simplifying assumptions, it can be stated that soft handoff which can be considered as macro-diversity performs much better than conventional handoff with regard to outage probability and capacity. This observation has also been confirmed elsewhere [10].

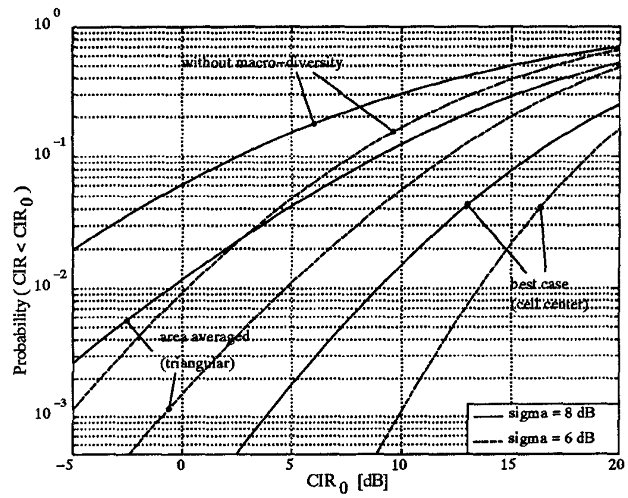

Figure 6. Impact of different σ; maximal ratio combining, uncorrelated paths

IV. Conclusions

The results clearly underline the possible improvements obtainable by employing the new architecture with macroscopic diversity and overlapping cells in mobile radio systems. Selection combining which allows a simple implementation of the macro-diversity combining process is only slightly worse in comparison to maximal ratio combining.

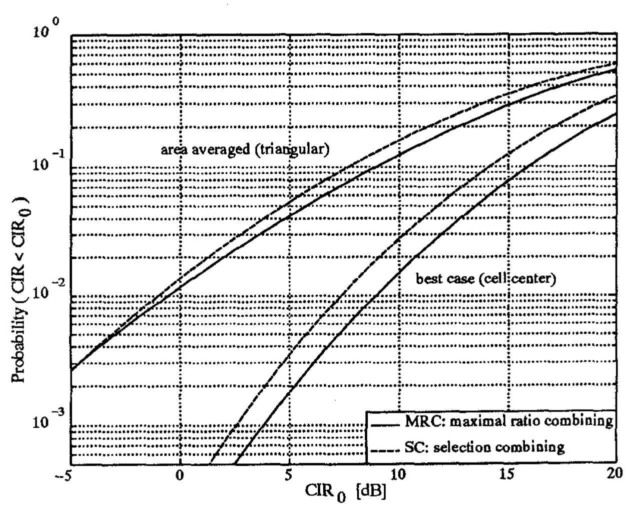

Figure 7. Comparison of maximal ratio and selection combining; $\sigma = 8$ dB, uncorrelated paths

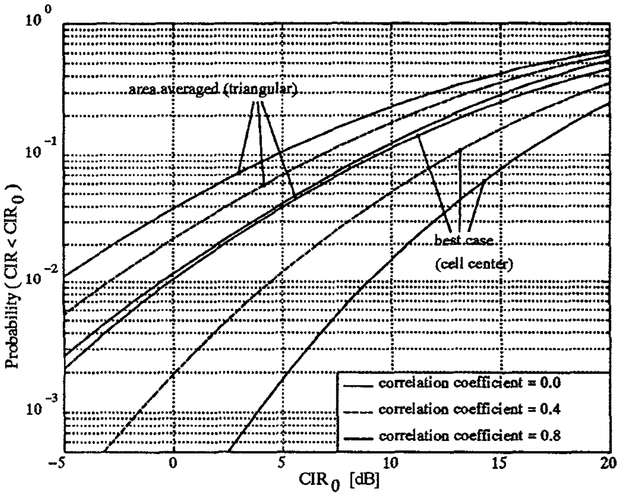

Figure 8. Comparison for different correlation coefficients; maximal ratio combining, $\sigma = 8$ dB

The new network architecture may advantageously be used in order to enhance the signal transmission quality or - as suggested for heavily traffic-loaded regions - solve capacity problems at so-called "hot spots" by increasing the actually realizable channel re-use factor.

Acknowledgments

This work was sponsored by the German Research Council (DFG). The author would like to thank M. Elsner who prepared most of the programming work during his diploma thesis and S. Zürbes and Prof. P. Vary for valuable discussions.

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