Power Control in Simulcast Digital Cellular Radio Networks

Stefan Zürbes

Institute of Communication Systems and Data Processing (IND),
Aachen University of Technology

IND, RWTH Aachen, Templergraben 55, D-52056 Aachen, Germany
E-mail: zuerbes@ind.rwth-aachen.de, URL: www.ind.rwth-aachen.de

ABSTRACT

A recently published novel simulcast cellular architecture for mobile radio implements corner illumination of a cell by two or three base stations and overlapping cells [3, 5, 6, 7]. Due to the macroscopic diversity, the transmission impairments caused by fading are reduced significantly. In this contribution we demonstrate the pronounced positive effect of adaptive power control on the co-channel carrier-to-interference ratio for simulcast architectures, especially in comparison to conventional structures with a single base station per cell.

INTRODUCTION

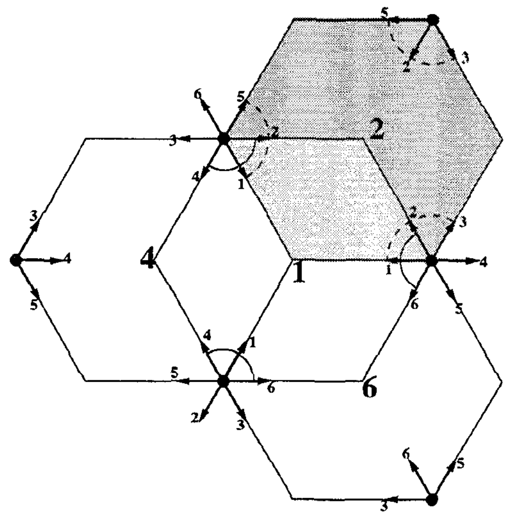
Due to the enormous increase of the number of digital mobile radio subscribers, the network operators are already running into capacity problems in urban areas, especially in so-called *hot spots*. Additionally, a large part of this traffic is generated within buildings, so that good indoor coverage must be provided. To fulfill these demands, an optimization of the cellular structure can be introduced as an alternative to the enlargement of the occupied frequency spectrum, an increase of the base station site density, or a reduction of the transmitted data rates.

The proposed simulcast approaches improve the traffic capacity and transmission quality substantially without an increase of the base station site density, thus offering a promising alternative to micro-cells [3, 5, 6, 7]. The propagation channel is modeled with a distance dependency and lognormal shadowing [4], such that the link gain factors $g = P_r/P_t$, being the ratio between received and transmitted powers, are calculated as $g \sim \zeta \cdot d^{-\gamma}$. Here d denotes the distance between transmitter and receiver, $\gamma = 3.5$ is the propagation coefficient, and ζ is a lognormally distributed random variable.

SIMULCAST CELLULAR STRUCTURES

The two basic properties of the considered simulcast radio cell architectures are *multiple supply* of each cell by simulcast and *cell overlapping* of neighboring cells [3]. Both properties are shown in Figure 1 for simulcast with three or two base stations per cell [5, 6].

a) Threefold simulcast supply:



b) Twofold simulcast supply:

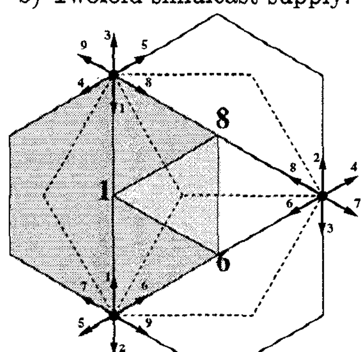


Figure 1: Simulcast architectures with cell overlapping. The numbers denote the employed frequency groups.

In both cases, each base station site carries six sector antennas with e.g. 120° horizontal opening angle, which are directed towards the center of the respective cells. While for threefold supply the base stations are located at every other corner of the hexagonal cell, they are posi-

0-7803-3871-5/97/$10.00 © 1997 IEEE

tioned at opposite corners for twofold supply simulcast.

POWER CONTROL IN CONVENTIONAL NETWORKS

Adaptive power control is used in TDMA or FDMA systems mainly to reduce the transmitted radio power and to increase operation time of mobile stations. However, the influence of conventional power control on co-channel carrier-to-interference ratios is rather small for architectures with a single base station per cell, as the following simplified consideration shows. Using the transmission and reception powers $P_{t,j}$ and $P_{r,ij}$ as well as the link gains g_{ij} from Figure 2, the carrier-to-interference ratio

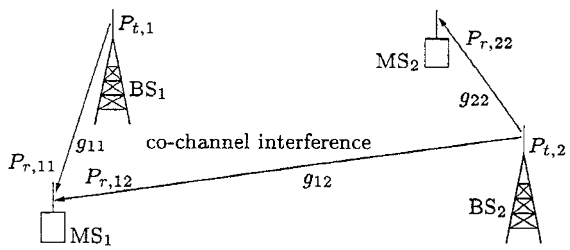


Figure 2: Power control influence on co-channel carrier-to-interference ratio

$P_{r,11}/P_{r,12}$ at mobile station MS$_1$ is given by

$$\frac{P_{r,11}}{P_{r,12}} = \frac{g_{11}P_{t,1}}{g_{12}P_{t,2}} = \frac{g_{11}}{g_{12}}, \quad (1)$$

if no power control is provided and $P_{t,1} = P_{t,2}$. If, on the other hand, power control is used and the reception powers are kept constant ($P_{r,11} = P_{r,22}$), the C/I ratio yields

$$\frac{P_{r,11}}{P_{r,12}} = \frac{P_{r,11}}{g_{12}P_{t,2}} = \frac{P_{r,11}}{g_{12}P_{r,22}/g_{22}} = \frac{g_{22}}{g_{12}}. \quad (2)$$

In the case that the cells 1 and 2 have equal sizes, g_{11} and g_{22} have identical distributions and therefore the carrier-to-interference ratio distributions are the same, independent from power control being applied or not. For networks with multiple co-channel cells, the effects are more interdependent, but the general characteristics are comparable.

POWER CONTROL IN SIMULCAST NETWORKS

Downlink Power Control

Due to the path diversity in simulcast cells, adaptive power control has a positive effect even on the co-channel carrier-to-interference ratios. In the downlink, the transmission powers $P_{t,k}$ of the b base stations of a regarded cell have to be controlled, but only one reception power

$$P_r = \sum_{k=1}^{b} g_k P_{t,k} \quad (3)$$

is obtained at the mobile station. Here g_k denotes the link gain factor between base station k and the mobile station of the considered cell. Hence, power control in simulcast structures provides additional degrees of freedom, even if the reception power P_r is controlled to be constant. A promising approach in this context is to minimize the sum

$$P_{t,sum} = \sum_{k=1}^{b} P_{t,k} \quad (4)$$

of the transmitted powers in the cell, since this figure is on average proportional to the interference introduced to other cells. Together with a constant reception power from eq. (3), this leads to a linear programming problem. Its solution yields that only one base station per cell should transmit at a given time, namely the one that currently corresponds to the largest link gain g_k. This can be achieved by setting the transmission powers $P_{t,k}$ to

$$P_{t,k} = \frac{g_k^{\alpha} P_r}{\sum_{l=1}^{b} g_l^{\alpha+1}} \quad (5)$$

with parameter $\alpha \to \infty$.

Figure 3 shows the outage probabilities of the regarded simulcast architectures and conventional structures as a function of the frequency re-use factor, both without power control [1, 2] and with power control according to eq. (5), $\alpha = \infty$. All co-channel cells within a range of 10 cell radii are considered, each of them interfering with an activity of 100 %. The mobile stations are considered to be uniformly distributed within the cell. The results are obtained by Monte Carlo simulations.

Even for the case without power control the simulcast structures show remarkable improvements in capacity (smaller re-use factors) and quality (smaller outage probabilities). If power control is implemented, further substantial improvements are achieved for simulcast, whereas the conventional structures yield even *worse* outage probabilities for operation with power control. In the case of power control, the capacity of the threefold supply simulcast is more than 2.5 times the capacity of conventional sectorization and approximately 5 times the capacity of an omnidirectional architecture, given the same outage probability.

Uplink Power Control

Unlike conventional architectures, the power control situation in simulcast structures is completely different for uplink and downlink. In the downlink, the request for constant reception powers leads to an underdetermined equation system for the transmission powers. For the uplink, however, the opposite is true, since b reception powers exist in a cell with b base stations but only one transmission power of the mobile station. Therefore, it is in general not possible to keep all reception powers

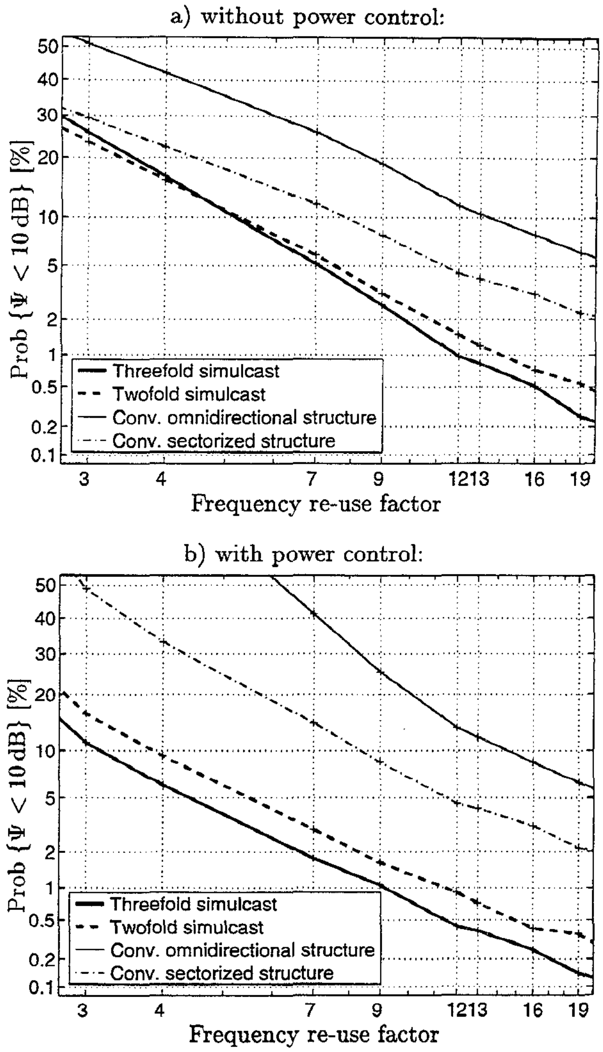


Figure 3: Downlink outage probabilities for protection ratio $\Psi_0 = 10\,\text{dB}$. Lognormal fading with $\sigma = 8\,\text{dB}$, $\gamma = 3.5$.

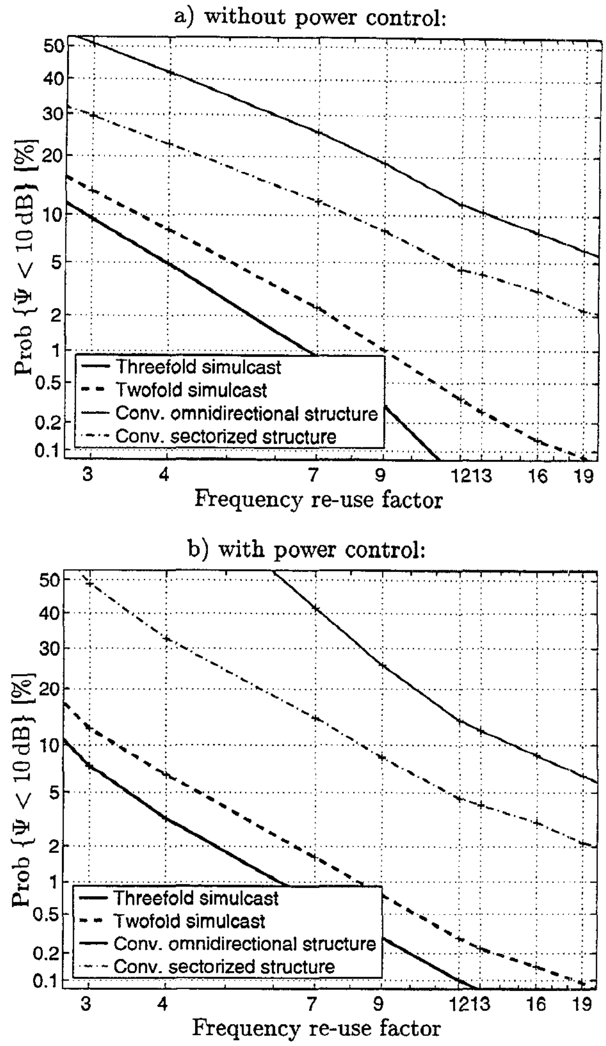


Figure 4: Uplink outage probabilities for protection ratio $\Psi_0 = 10\,dB$. Selection combining, lognormal fading with $\sigma = 8\,\text{dB}$, $\gamma = 3.5$.

of a cell constant, such that a *representative* reception power $\tilde{P}_\mathrm{r}$

$$\tilde{P}_\mathrm{r} = \left(\sum_{k=1}^{b} P_{\mathrm{r},k}^{\alpha} \right)^{1/\alpha}, \quad \alpha > 0 \tag{6}$$

is kept constant instead, which (in this case) is the α-norm of the vector of reception powers. Hence the transmission power of the mobile station is set to

$$P_\mathrm{t} = \frac{\tilde{P}_\mathrm{r}}{\left(\sum\limits_{k=1}^{b} g_k^{\alpha} \right)^{1/\alpha}}, \quad \alpha > 0\,. \tag{7}$$

E.g. with $\alpha \to \infty$ the *greatest* received power is kept constant, and with $\alpha = 1$ this is performed for the *sum* of the received powers.

Figure 4 depicts the uplink outage probabilities analogous to the downlink values in Figure 3. While the conventional structures show only negligible differences between downlink and uplink, the simulcast performance is generally better for the uplink, such that the limiting case for simulcast is the downlink.

Furthermore, the outage probabilities of the simulcast structures are nearly the same for Figure 4a and Figure 4b. Hence the effect of power control on the uplink C/I ratios is much smaller than for the downlink. This is due to the fact that, in the uplink, the selection of the best propagation path between mobile station and base stations is implicitly performed by the uplink combining scheme, while the respective task in the downlink has to be carried out by the power control algorithm.

In Figure 5 the downlink outage probabilities of threefold simulcast supply are depicted *as functions of the mobile station position.* As it can be seen from Figure 5a, the outage probability is strongly location dependent for operation without power control. Outage is very unlikely in the vicinity of the base stations, but in the major parts of the cell values in the range of 20 % to 30 % are obtained. The outage probabilities are much smaller in the case of power control, as Figure 5b shows. Furthermore, the outage is only slightly location dependent. This is due to the constant received carrier power and an interference power that is roughly uniformly distributed within the cell.

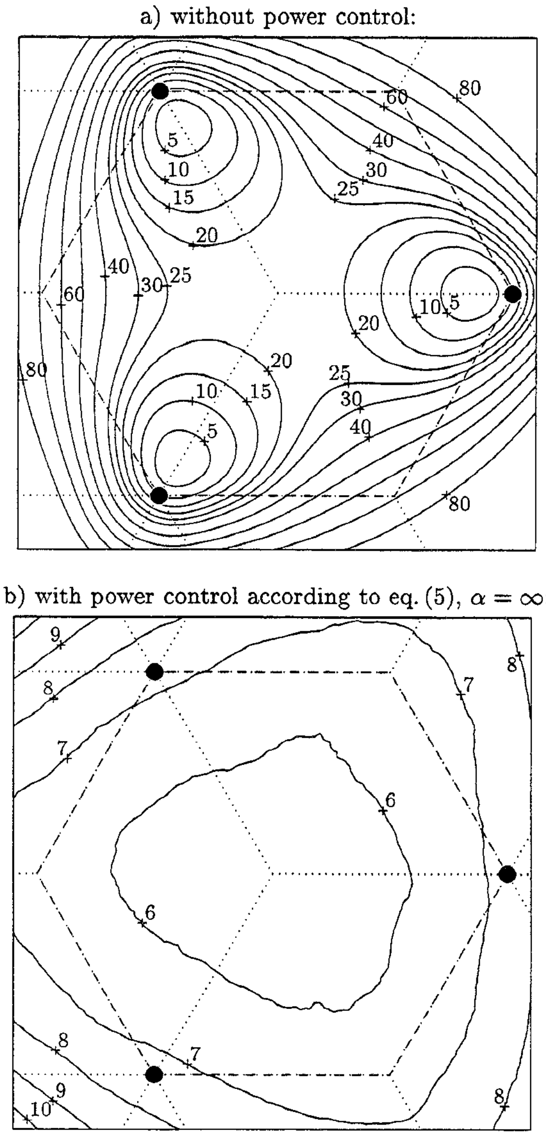


Figure 5: Downlink outage probabilities [%] for receiver protection ratio $\Psi_0 = 10\,\text{dB}$. Threefold supply simulcast with frequency re-use factors 4. Lognormal Fading with $\sigma = 8\,\text{dB}$, $\gamma = 3.5$.

GENERALIZED POWER CONTROL ALGORITHMS

As Figure 5b illustrates, the outage probability is essentially independent of the mobile station position, if power control according to eq. (5) is performed. Even in the vicinity of the base stations, the outage probability is about 7 %, since the transmission power of the base station is reduced respectively.

We propose a generalized power control algorithm which also reduces the transmission powers if the link attenuations are small, but the reduction is not such large that constant reception power would be achieved. This increases the reception power for mobile stations in the vicinity of the base stations. The interference to other cells is increased also by this measure, but only to a small extent, since the transmission powers are still small due to the close distance between base and mobile station.

To be more specific, the downlink power control algorithm eq. (5) is extended to

$$P_{t,k} = P_c \cdot \left(\frac{g_k^{\alpha}}{\sum_{k=1}^{b} g_k^{\alpha+1}} \right)^{\beta} . \qquad (8)$$

The additional parameter β indicates the degree of adaptation of the power control algorithm. The constant P_c is arbitrary from the C/I ratio point of view. However, the choice of P_c is limited in dependence of β, such that the interference limited operation property is fulfilled.

The characteristic of the power control is controlled by the parameter β. For $\beta = 1$ the algorithm eq. (5) with constant reception power is obtained, and $\beta = 0$ means no power control at all. The relevant algorithm parameters are in the range between these two values.

For the uplink, an analogous characteristic is obtained by

$$P_t = \frac{P_c}{\left(\sum_{k=1}^{b} g_k^{\alpha} \right)^{\beta/\alpha}} , \quad \alpha > 0 \qquad (9)$$

as an extension to eq. (7). P_c and β have the same significance as in eq. (8).

Figure 6 on the next page shows the results in terms of the carrier-to-interference ratio for an outage probability of 5 % for a threefold supply simulcast architecture with frequency re-use factor 4. The results are given as functions of the algorithm parameters α and β.

For the downlink, the parameter value $\alpha = \infty$ yields the best C/I ratios, as already discussed in section for the case $\beta = 1$. The optimum values for β are in the range $\beta = 0.5 \ldots 0.6$. They yield an additional improvement of 2 dB compared to the power control scheme considered in section ($\beta = 1$) and a total improvement of approx. 6 dB with respect to the operation without power control ($\beta = 0$).

For the uplink, the improvements for the best parameter values ($\alpha \approx 1$, $\beta = 0.5 \ldots 0.8$) are smaller, but the absolute C/I ratios are greater since the results for operation without power control are already much better than for the downlink. Hence, the optimum representative uplink reception power $\tilde{P}_r$ is given (approximately) by the sum of the received powers ($\alpha = 1$).

Figure 7 illustrates the downlink carrier-to-interference ratio distributions for the parameter values discussed before, both for threefold supply simulcast and a conventional sectorized structure. This shows the essential effects of the different power control variants for simulcast architectures. For the conventional sectorization, the extended power control algorithm eq. (8) also yields some improvement (for $\beta = 0.5$ and arbitrary α, due to $b = 1$ base station per cell).

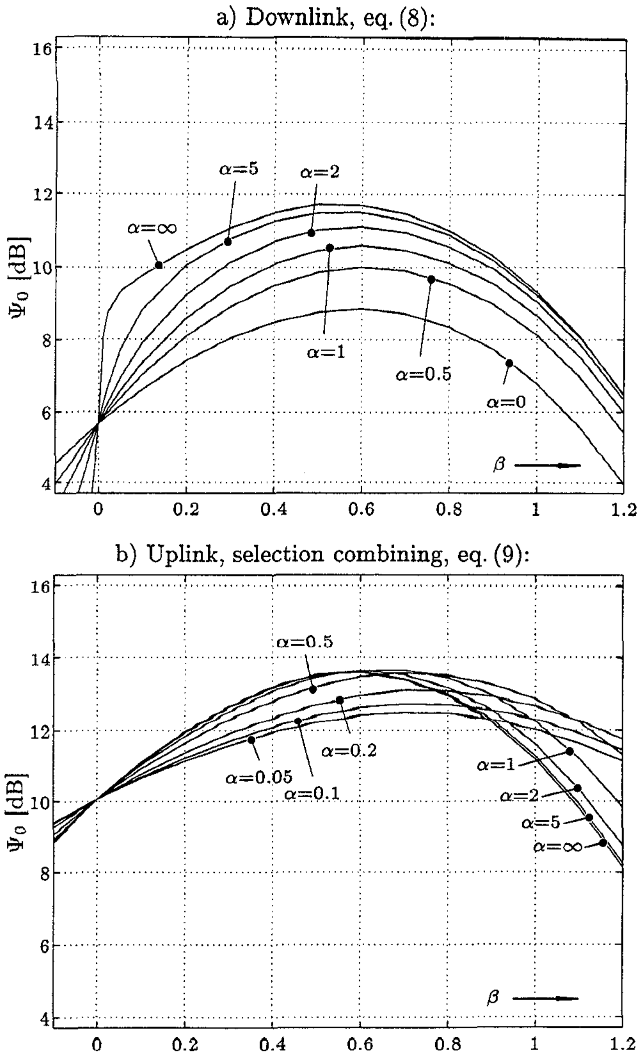


Figure 6: Carrier-to-interference ratios Ψ_0 for 5 % outage as functions of the power control algorithm parameters. Threefold supply simulcast with frequency re-use factor 4.

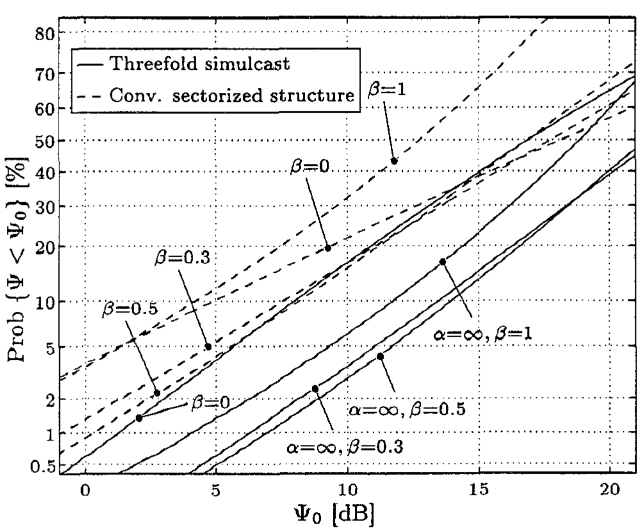


Figure 7: Downlink carrier-to-interference ratio distributions for various parameter settings of the power control algorithm eq. (8). Threefold supply simulcast and conventional sectorized architecture with frequency re-use factors 4.

CONCLUSIONS

This contribution points out that adaptive power control has an essential positive effect on the co-channel carrier-to-interference ratios in simulcast cellular architectures. In contrast to conventional cellular structures with a single base station per cell, adaptive power control reduces the outage probabilities of simulcast networks substantially, if compared with the operation without power control. Therefore, the capacity benefits of simulcast are further increased by the means of appropriate power control algorithms.

Further improvements can be obtained if the restriction to a constant received carrier power is dropped. For the downlink, the optimum operation is in general that only a single base station transmits at a certain time in each simulcast cell. From the carrier-to-interference ratio point of view, the best representative uplink reception power in a simulcast cell is approximately the sum of the received powers in the cell.

Capacity improvements larger than a factor of 2.5 with respect to conventional sectorization are gained by threefold supply simulcast employing power control.

REFERENCES

[1] B. Bornkamp, A. Kegel, and R. Prasad. Uplink and downlink performance analysis of a cellular radio system using corner base stations and directional antennas. In *Proceedings 45th IEEE Vehicular Technology Conference*, pp. 375–379, Chicago, July 1995.

[2] D. C. Cox. Cochannel interference considerations in frequency reuse small-coverage-area radio systems. *IEEE Transactions on Communications*, vol. 30(1), pp. 135–142, January 1982.

[3] German Patent DE 41 41 398 A1. *A method to improve cell illumination for a cellular mobile radio system and equipment to apply the method.* DETECON, Bonn, June 1993.

[4] G. C. Hess. *Land-Mobile Radio System Engineering.* Boston: Artech House, 1993.

[5] S. Zürbes. Outage probabilities and handover characteristics of simulcast cellular mobile radio systems. In *Proceedings 46th IEEE Vehicular Technology Conference*, pp. 522–526, Atlanta, GA, April 1996.

[6] S. Zürbes. *Analysis and Optimization of Digital Mobile Radio Networks with Simulcast.* PhD thesis, RWTH Aachen, Aachen, 1997 (in German).

[7] S. Zürbes, W. Papen, and W. Schmidt. A new architecture for mobile radio with macroscopic diversity and overlapping cells. In *Proceedings 5th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'94)*, pp. 640–644, Den Haag, September 1994.