Designing Macroscopic Diversity Cellular Systems

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Abstract - With regard to the requirements of high capacity and high quality speech and data transmission of future communication systems, we study the application of macroscopic diversity in cellular systems. Macrodiversity is applied during the entire call in order to improve coverage and link quality. The influence on system capacity is studied by the means of discrete event simulation. We propose an access network architecture and cellular layouts which can support macrodiversity. For resource management we apply dynamic channel assignment with an appropriate admission control to guarantee a minimum link quality for all users.

I. INTRODUCTION

Macrodiversity is a powerful technique to improve coverage, link quality and capacity in cellular systems. Though macrodiversity technology is already known for years, it has not been fully exploited yet. Today it is deployed in CDMA cellular systems to enable soft handover [10]. There, macrodiversity is only used during the short period of time when a mobile moves from one cell to another. It reduces handover failure (i.e. dropping of calls) and data loss during the handover procedure.

In this paper we introduce macrodiversity in a wider sense. Macrodiversity is applied for the full duration of a call. We investigate the potential in combating fading, increasing coverage, and link quality. We also study the influence of macrodiversity on the capacity of cellular systems.

Macroscopic Diversity

The weakest link in mobile communications is the radio link between the mobile station and the fixed network. Badly covered zones and shadow fading cause the loss of data or speech and sometimes force the interruption of a call. In some situations a mobile may not even be admitted to the network because of a temporally unavailable radio link. To circumvent these problems macroscopic diversity may be applied in a cellular system.

The basic idea of macrodiversity is to enable a mobile station to communicate with the fixed network by more than one radio link. For a voice or data communication, the system sets up radio connections to several base stations (fig. 1).

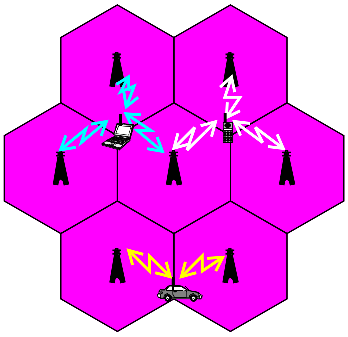


Figure 1: Macrodiversity connections

The base stations are spatially separated by some hundred meters (pico-cells) up to some kilometers (micro-cells or short-macro-cells). As the propagation conditions between the mobile station and the base stations are different at the same instance of time, a combination of the received signals is (in most cases) better than each individual signal. If one radio link totally fails due to shadow fading, the communication will continue without interruption through the remaining radio links.

In a macrodiversity supporting cellular system the base stations may have the same functionality as in today‘s second generation cellular systems or may be realized as remote antennas [3][4]. Remote antennas are small devices containing antennas and electric-optic converters which relay the radio signal to a control unit in the access network. Then, demodulation and data recuperation is done in the control unit. Both base station types are possible options for a macrodiversity system. Hence, we use the generic term *radio ports* (RPs) in the following.

II. ACCESS NETWORK

An access network architecture supporting macrodiversity is depicted in figure 2. It is the general view on an UMTS access network already presented in [2].

The main component for macrodiversity is the *macrodiversity unit* (MDU). It is responsible for combining the information received from different RPs in the uplink

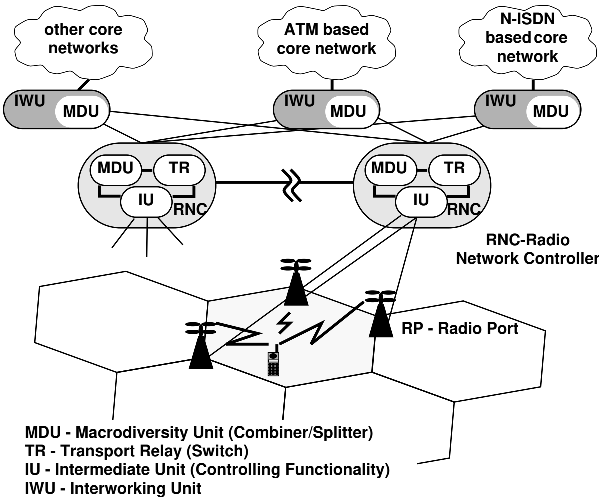


Figure 2: Macrodiversity supporting access network

and for distributing the information towards the RPs in the downlink. The MDU normally is located in the Radio Network Controller. If macrodiversity is applied between RPs connected to different RNCs, the MDU of one RNC must act as master. If additional MDUs are placed in the Interworking Units, hierarchical operation can be used.

Information Combination and Distribution

In the uplink, the signal from the mobile station is received at several (e.g. three) RPs. Depending on the type of the RP (remote antenna or full base station) either the signal or the detected data unit is then forwarded to the MDU in the access network. The MDU combines the signals or data units which belong to one connection. Depending on the capacity which can be spent for the links between the RPs and the MDU, the analog signal, the detected bits including soft-decision information, or hard-detected bits with quality information per data unit are forwarded to the MDU [7]. By applying a well adapted combining algorithm (e.g. maximum ratio combining, equal gain combining, selection combining, etc.) the MDU constructs one resulting data unit. This data unit generally is of better quality than each individual data unit before the combining process.

In the downlink the information is sent to all RPs involved in the connection. Two options are possible: The information is sent to the mobile station by only one RP at a time, always selecting the RP which has the best propagation conditions towards the mobile station (*selection macrodiversity*), or all RPs send the information simultaneously (*simulcasting*). The latter option artificially increases multipath propagation, which can be constructively used in mobiles employing an equalizer (TDMA/FDMA systems) or a RAKE receiver (CDMA systems). For TDMA/FDMA systems this is possible as long as the time differences of the signals at the receiver do not exceed a certain maximum. The equalization window in GSM handsets for example is 18.45 μs corresponding to a theoretical maximum path length difference of 5.5 km.

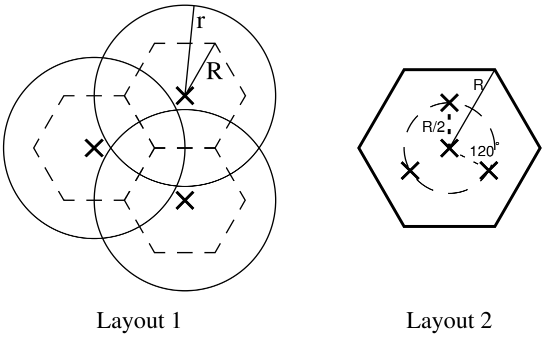
The receiver in the mobile station combines the signals from the different RPs so that the resulting power is the sum of the power of the individual signals:

$$P_{rec} = \sum_{i=1}^{n} P_{rec_i} \qquad (1)$$

Measurements in [3] report that equation (1) is applicable to a real-world GSM system.

III. CELLULAR ARCHITECTURES

A macrodiversity cellular system must be designed in a way that the mobile stations in principle can have connections to more than one RP at all spatial positions.



Layout 1 Layout 2

Figure 3: Possible cellular layouts (omnidirectional antennas)

Fig. 3 and 4 depict some possible cellular layouts for macrodiversity cellular systems. Derived from existing cellular systems with omnidirectional antennas in the cell center, layout 1 introduces macrodiversity by an overlap of the coverage areas. The number of RPs, which a mobile can have simultaneous connections to, is determined by the overlap factor *r/R*, which in turn is determined by the transmission power [8].

Deploying additional RPs on one (or more) concentric circles around the cell centre can also introduce macrodiversity into a conventional cellular system (layout 2) [5].

Sectorized systems deploy 120 degree antennas at every other edge of the hexagonal cell (layout 3). They can be converted to support macrodiversity by linking the antennas (RPs) by a macrodiversity unit [6].

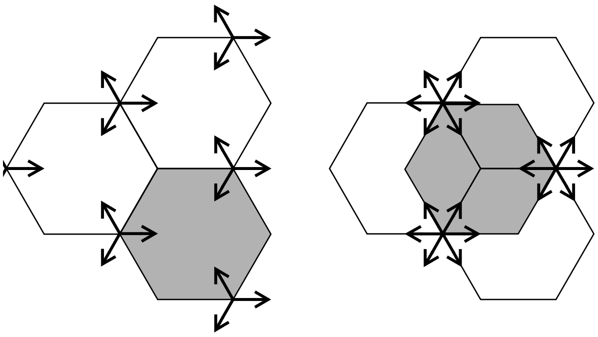

Layout 3 Layout 4

Figure 4: Possible cellular layouts (directional antennas)

Another layout using 120 degree antennas deploys two overlapping clusters of hexagonal cells [9]. Six antennas are placed at every other edge of the hexagonal cell (layout 4). The angle difference between the antennas is 60 degrees.

In [1] Bernhardt evaluates cellular layouts with radio ports distributed in triangle, rectangle, and hexagonal scheme over the service area. All RPs use omnidirectional antennas.

The advantage of layouts 1 (fig. 3) and 3 (fig. 4) is that they are already used in today‘s cellular systems. The search for new RP locations and the installation of new antennas is not necessary when realizing a macrodiversity cellular system with these layouts. It suffices to adapt the access network to support macrodiversity.

IV. SYSTEM SIMULATION

In order to investigate the performance of *simulcasting* in a cellular system we use computer simulations. We apply a cellular system according to layout 1 and 3 of figure 3 and 4 respectively. We study the coverage improvement of macrodiversity, which is a measure of the ability to combat shadow fading. The influence of macrodiversity on system capacity and link quality is investigated thereafter.

For the simulations we focus on the downlink (RP to mobile station) direction only. For the propagation model we apply path loss and shadow fading (log-normal fading) [6]. The path loss coefficient γ was set to 4 and the standard deviation σ to 10 dB. Fast fading is supposed to be averaged out, as we are only interested in the local mean powers.

For *simulcasting* operation we calculate the received power by applying equation (1). For the capacity studies we calculate the carrier to co-channel interference ratio *CIR* as the sum of all received useful carrier powers to the sum of all interfering powers:

$$CIR = \frac{\sum_{i=1}^{N} C_{rec_i}}{\sum_{k=1}^{S} I_{rec_k}} \qquad (2)$$

N is the number of useful radio links and S the number of co-channel interferers.

For comparison purpose with *simulcasting* we investigate the *no macrodiversity* and the *selection macrodiversity* scheme. In the latter the downlink information is always transmitted from the RP which attains the highest received power at the mobile station. Then, only one downlink is active at a time. In the *no macrodiversity* case always the geographically nearest RP to the mobile station transmits.

Coverage Improvement

The coverage improvement of a macrodiversity cellular system can be quantified by the area averaged cumulative distribution functions (CDFs) of the received power (figure 5).

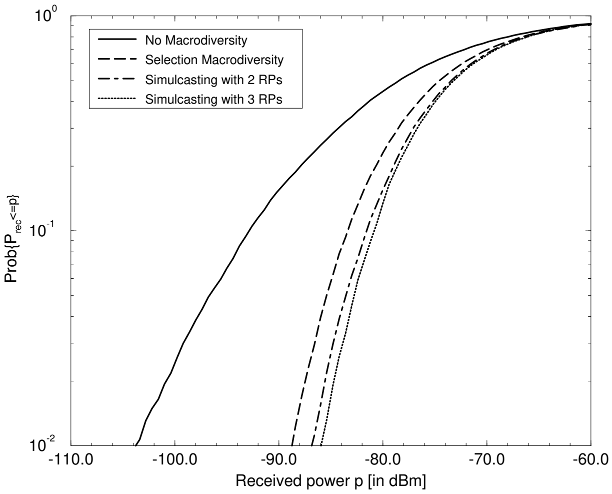


Figure 5: Area averaged CDFs of the received power

The CDFs are calculated by Monte Carlo simulations taking as many realizations of the random shadow fading as necessary to ensure sufficiently small 95%-confidence intervals. The area in which we averaged the received power is the rectangle of about cell size around the central RP of the cellular system. All RPs use the same fixed transmit power. Varying the transmit power moves the curves of figure 5 to the left or right. The relative gain between the curves will stay the same.

We see for example, that at the 90% area coverage level *selection macrodiversity* realizes a relative gain of about 9.5 dB compared to *no macrodiversity*. *Simulcasting* with two RPs gives a gain of 11.3 dB and with three RPs a gain of 12 dB.

From the curves of figure 5 we conclude that *selection macrodiversity* realizes high gain over the *no macrodiversity* case. *Simulcasting* still provides higher gain than *selection macrodiversity*. The relative gain of *simulcasting* becomes smaller and smaller as more and more RPs are involved (2 and 3 RPs in figure 5). Additional results for the coverage improvement for different values of the standard deviation σ of the shadow fading can be found in [11].

The CDFs of figure 5 are exactly the same for layout 1 and 3, if the gain of the ideal 120 degree directional antennas is the same as for the omnidirectional antennas. The normally higher antenna gain of a directional antenna can be used to reduce transmit power, but it does not change the relative gain between the macrodiversity schemes.

Capacity and Link Quality

In order to study the influence of downlink macrodiversity on capacity and link quality, we use discrete event simulations in a cellular grid according to layout 1 (figure 3). Capacity is evaluated in terms of blocking probability for a given offered load. Link quality is measured by the average CIR of all connections.

Our resource management strategy is a combination of dynamic channel assignment (DCA) and admission control. For the DCA algorithm all system resources are available at every RP. A resource can be used at any RP which can realize sufficient received power (P_{rec}>-105dBm) at the mobile station‘s position. If a resource is used at one RP, it can be re-used at another RP, as long as the achievable CIR is higher or equal to a threshold $\mathrm{CIR}_{\mathrm{min}}$.

The admission control cares for protecting active connections from being disturbed by new users. A new call is only admitted, if a resource is available the use of which does not disturb any active connection. Hence, it is guaranteed that an active connection has a $\mathrm{CIR} \geq \mathrm{CIR}_{\mathrm{min}}$.

The advantage of this resource management scheme is that it can make a trade of between system capacity and link quality. Reducing $\mathrm{CIR}_{\mathrm{min}}$ results in a higher system capacity at the expense of lower link quality (and vice versa) [11]. In the following studies however, we set $\mathrm{CIR}_{\mathrm{min}}$ to a fixed value of 9 dB for all mobile stations.

In the simulation, new calls arise uniformly distributed in a rectangular service area of about 25 hexagonal cells. The arrivals follow a Poisson process with inter-arrival times depending on the offered load. Call durations are negative exponentially distributed with a mean of 100s. Mobility is not considered at this point of the study. The system has got 36 downlink resources (independent channels) available in the whole service area. Statistics are collected in the center cell only to avoid border effects. RP transmit power is fixed for all RPs so that received power at the cell border is at least -105dBm in 97% of the cases.

We again compare three scenarios: in the *no macrodiversity* case a resource can only be allocated at the geographically nearest RP. In the *selection macrodiversity* case a resource is allocated at the RP which is received with the highest power and still has a resource available. In the *simulcasting* case a resource is allocated at maximal three RPs. If it is not possible to find a resource which can be used with three RPs, a resource is selected which can be used with two RPs or at least with one RP. This scheme tries to maximize the number of radio links up to the hard limit of three. At all times the constraint of not disturbing any active connection is fulfilled.

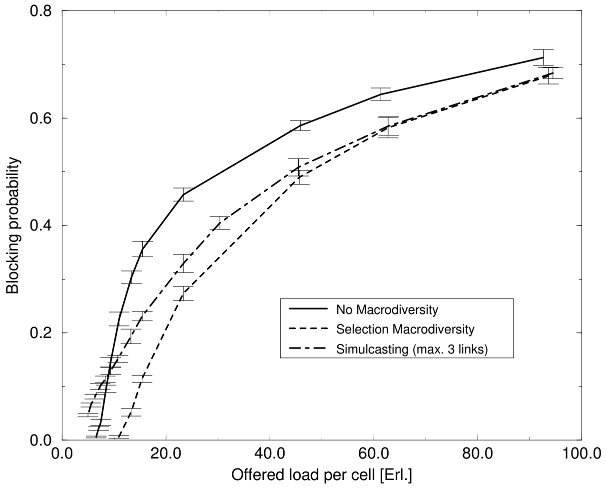


Figure 6: Blocking probability

Figure 6 depicts the blocking probability over the offered load for the three different schemes. We notice that *selection macrodiversity* realizes a high capacity gain over the *no macrodiversity* case. At the 10% blocking margin the gain is about 6.4 Erlangs per cell.

The curve for *simulcasting* approaches the *selection macrodiversity* curve for high offered loads, but for low loads the blocking probability of *simulcasting* is higher than in the *no macrodiversity* case. At low loads the scheme reserves a resource (in the mean) at three RPs, so that the re-use distance increases. For high loads a resource is in the mean allocated at only one RP, so that the scheme becomes the same as *selection macrodiversity*.

In order to evaluate the link quality in the system, we record the average CIR of all active connections during a simulation run. For comparison of the three macrodiversity schemes we choose an operation point of a fixed carried load. The carried load $L_{carried}$ can be calculated from figure 6 by applying $L_{\text{carried}} = (1 - P_{\text{blockking}})L_{\text{offered}}$. For the same carried load, the same number of mobile stations is active in the mean.

Figure 7 depicts the cumulative distribution functions of the CIR at a carried load of 10 Erlangs. The distribution curves are time weighted means of the CIR of all active mobile stations.

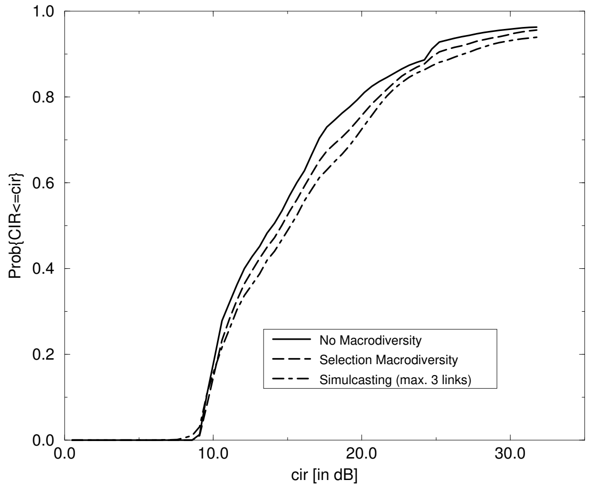


Figure 7: CIR-CDFs averaged over all active connections

Even if the differences in the average CIR are small, we notice that the probability having a high CIR is higher for *simulcasting* than for *selection macrodiversity* and higher than for *no macrodiversity*.

Using always the RP which can realize the highest received power improves the average CIR slightly. Another slight improvement in average CIR is possible with *simulcasting*.

V. CONCLUSIONS

In this paper we studied the use of macrodiversity in a cellular system.

Macrodiversity is understood in the sense that multiple radio links can be maintained during the entire call. We proposed an access network architecture which can support macrodiversity in this sense. We further presented different cellular architectures which allow macrodiversity operation at all spatial positions.

Simulation studies of the downlink show that high coverage improvement is realized by *selection macrodiversity* and still higher gain is realizable by *simulcasting*.

We proposed a resource management scheme based on dynamic channel allocation and admission control guaranteeing link quality for all active connections. The highest capacity is achieved by *selection macrodiversity*, whereas *simulcasting* can realize a slightly higher average CIR.

REFERENCES

[1] Bernhardt, R. C. „Macroscopic Diversity in Frequency Reuse Radio Systems“, IEEE Journal on Selected Areas in Communications, vol. SAC-5, no. 5, June 1987, pp. 862-870

[2] Boldt, M.; Weiss, U.; Sigle, R.; Dropmann, U. „Modeling an ATM-Based Access Network for 3rd Generation Mobile Communication Networks“, Proc. of VTC`98 - 47th IEEE Vehicular Technology Conference, Ottawa, Canada, 18.-21.5.1998

[3] Graf, F.; Fischer, P.; Humburg, E.; Lueders, C. „Technical Potential and Economic Efficiency of Macro Diversity in a GSM Mobile Radio Network“, Proc. of EPMCC`97 - 2nd European Personal Mobile Communications Conference, Bonn, Germany, 30.9.-2.10.1997, pp. 127-134

[4] Heidemann, R.; Hofstetter, R.; Schmuck, H.; Lane, P. „Remoting of UMTS- and MBS- antennae by fibre optic technology“, Proc. of RACE 94 - RACE Mobile Telecommunications Workshop, Amsterdam, Netherlands, May 17-19, 1994, pp. 103-110

[5] Klein, Anja; Steiner, Bernd; Steil, Andreas „Known and novel diversity approaches as a powerful means to enhance the performance of cellular mobile radio systems“, IEEE Journal on Selected Areas in Communications, vol. 14, no. 9, December 1996, pp. 1784-1795

[6] Lee, William C.Y. „Mobile communications design fundamentals“, 1993, Editor(s): John Wiley & Sons, Inc., New York, ISBN 0-471-57446-5

[7] Papen, Wolfgang, „Improved soft handoff and macrodiversity for mobile radio“, Proc. of ICC‘95 - the 1995 IEEE Internat. Conf. on Communications, Seattle, USA, June 18-22, 1995, pp. 1828-1833

[8] Weiss, Ulrich; Dropmann, Ulrich; Godlewski, Philippe „Admission Control Guranteeing Quality of Service in Packet Access based Pico-Cellular Networks“, Proc. of the 1996 ACTS Mobile Telecommunications Summit (ACTS 96), Granada, Spain, November 27-29, 1996, pp. 204-210

[9] Zürbes, Stefan; Papen, Wolfgang; Schmidt, Werner „A New Architecture for Mobile Radio with Macroscopic Diversity And Overlapping Cells“, Proc. of PIMRC 94 Personal, Indoor and Mobile Radio Communications, Den Haag, Holland, September 18-22, 1994, pp. 640-644

[10] Viterbi, Andrew J.; Viterbi, Audrey M.; Gilhousen, Klein S.; Zehavi, Ephraim „Soft handoff extends CDMA cell coverage and increases reverse link capacity“, IEEE Journal on Selected Areas in Communications, vol. 12, no. 8, October 1994, pp. 1281-1288

[11] Weiss, Ulrich, „Improving Coverage and Link Quality by Macroscopic Diversity“, Proc. of EPMCC 99 - the 3rd European Personal Mobile Communications Conference, Paris, France, March 9-11, 1999