Improving Coverage and Link Quality by Macroscopic Diversity

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Abstract

In this paper we examine the use of macroscopic diversity in cellular communication systems. In the downlink we evaluate the coverage gain by selection and optimal combining macrodiversity. We propose a resource management scheme taking profit of macrodiversity to increase capacity while guaranteeing link quality. The resource management scheme is based on dynamic channel allocation and admission control. Depending on the selected admission control parameter a trade off is possible between capacity and link quality.

I. Introduction

Future mobile communication systems, like UMTS (Universal Mobile Telecommunications System) or IMT-2000 (International Mobile Telecommunications system), must fulfil many requirements: They must offer narrow- and broadband services, ubiquitous coverage, and high capacity. Additionally, speech quality must be higher than in today‘s systems. In order to cope with these demands, new techniques must be implemented in future systems. Especially for the air interface techniques must be investigated which can improve coverage, link quality and capacity. One such promising technique is macroscopic diversity.

I.1 Macroscopic diversity

Macroscopic diversity (sometimes called base station diversity) is a means to improve coverage and link quality, combat shadow fading and realize seamless (soft) handover. Macrodiversity (MD) enables a mobile station to communicate with the fixed network simultaneously by more than one fixed access point (radio port).

Due to the different propagation conditions along the paths between the mobile station and the radio ports (RPs), the information received at the different RPs in the uplink is of different quality. A combination of the multiple received information therefore results in better quality information in the majority of cases. This is the macrodiversity gain.

In the downlink the information is sent to all RPs involved in the connection. Two options are possible: The information is send to the mobile 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 (simulcast). The latter option artificially increases multipath propagation, which can be used constructively in mobiles employing an equalizer (TDMA/FDMA systems) or a RAKE receiver (CDMA systems) as long as the time differences of the signals at the receiver does not exceed a certain maximum (e.g. the equalization window in GSM handsets is 18.45 µs corresponding to a theoretical maximum path length difference of 5.5 km).

For small RP distances and for perfect equalization/ combining in the mobile stations, the received power in the downlink can be approximated by the sum of all received powers from the sending RPs:

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

It was found by measurements in [3] that this idealized assumption is close to reality. In the following we refer to this idealization by the term *optimal combining macrodiversity*.

I.2 Resource management

Earlier studies of macrodiversity evaluated the potential gain in the co-channel to interference ratio (CIR) for cellular systems with fixed channel assignment (FCA) [1, 3, 8]. They found that macrodiversity reduces co-channel interference and can therefore be used to reduce cluster size, which in turn increases system capacity. CIR distribution was evaluated by assuming interferers in the next co-channel cells independent of any traffic distribution.

We think that the application of macrodiversity gives need to design new resource management strategies for cellular systems which enable an increase in coverage, capacity, and link quality. As the improvement of link quality limits capacity increase and vice versa, a flexible possibility to allow a trade off between the two aims is desirable.

In this paper we propose a resource management scheme which combines dynamic channel assignment (DCA) and admission control to take the best profit of macrodiversity. DCA is known to cope well with the highly time and space varying traffic demand in cellular systems covering densely populated areas. Due to its flexibility it is highly suitable to reveal the full benefit of macrodiversity. Together with appropriate handover strategies our proposal will result in one integral resource management strategy, promising high coverage, high capacity, adjustable link quality, and seamless (soft) handover.

The remainder of this paper is organized as follows: Section II introduces the macrodiversity system model, the propagation model and our investigation method. Section III evaluates the coverage improvement of *selection* and *optimal combining macrodiversity* in two cellular architectures. Section IV studies capacity and link quality in a cellular system with Poisson call arrival process.

Mobility and handover is not considered in this paper. Those results will be presented in future publications.

II. The Macrodiversity System Model

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

In 1987 Bernhardt [1] compared different cellular architectures with triangle, square, and hexagonal cells equipped with RPs with omnidirectional antennas. Klein et al. introduced macrodiversity by deploying additional RPs with omnidirectional antenna on concentric circles around the centre RP. Zürbes and Papen [8] used six 120 degree antennas placed at every other edge of a hexagonal cell in two overlapping clusters of hexagonal cells.

Instead of proposing new architectures we set up a macrodiversity system from the two architectures which are the basis for today‘s field installations: the conventional architecture with an RP in the centre of a hexagonal cell using an omnidirectional antenna, and the sectorized system with three RPs using 120 degree antennas at every other edge of a hexagonal cell.

II.1 Cellular architecture

In the conventional architecture macrodiversity can simply be introduced by an overlap of the coverage area of the antennas. The number of RPs to which a mobile can have simultaneous connections is determined by the overlap factor *r/R* (ratio of coverage radius to cell radius, fig. 1 left), which in turn is determined by the transmitter power [6].

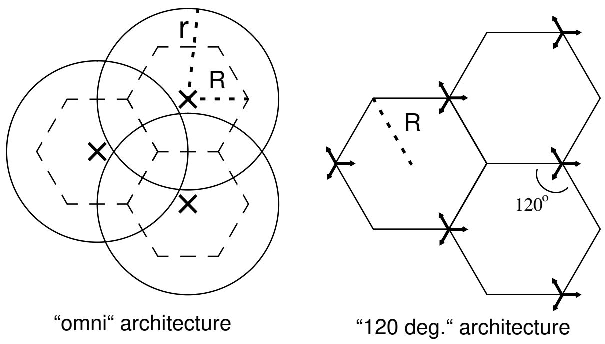

Figure 1: Cellular Architectures

Sectorized systems deploy 120 degree antennas at every other edge of the hexagonal cell (fig. 1, right). They can be converted to support macrodiversity by linking the individual RPs by a macrodiversity combining/splitting unit [2].

The macrodiversity on the air interface must be supported by the fixed network. Macrodiversity units (MDUs) must be installed in the access network. They are responsible for the combining of the different information in the uplink and for the distribution of the information to the involved RPs in the downlink. A possible macrodiversity supporting access network architecture based on the functional elements proposed for UMTS can be found in [2].

In this study the access network is assumed to be equipped in a way that macrodiversity connections are possible between all RPs in the service area (fully meshed). The following simulation results are valid for the downlink, but the general methodology can be applied to both links.

II.2 Propagation model

For all investigations we are only interested in the local mean of the received power. It can be obtained by averaging some appropriate time (e.g. 1 sec.) over the instantaneous received signal. We apply a propagation model taking into account the path loss due to the distance dependent attenuation and shadow fading due to terrain irregularities and man made obstacles [5]. The received power P_{rec} is given by

$$P_{rec} = LG_tG_rP_t \tag{2}$$

with P_t the transmit power, G_t, G_r the gain of the transmit, respectively receive antenna, and L the path loss. L in dB is modeled as a normal-distributed random variable with probability density function

$$f(L_{dB}) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(L_{dB}-\bar{L}_{dB})^2}{2\sigma^2}\right) \quad . \tag{3}$$

$\bar{L}_{dB}$ in dB is the mean path loss depending on the distance from the transmitter:

$$\bar{L}_{dB} = 10\log_{10}\left(g_0\left(\frac{d_0}{d}\right)^{\gamma}\right) \tag{4}$$

with g_0 the transmission factor in distance unit d_0, d the distance between the receiver and the transmitter and γ the attenuation factor (3...4 in a sub-urban or urban environment).

II.3 Investigation method

We used computer simulation to evaluate the performance of the macrodiversity systems. We used a rectangular service area of discrete points. On this grid we continually deployed the RPs according to fig. 1 with a cell radius of 800 meters. This lead to 27 RPs in the “omni“ architecture (fig. 1 left) and 99 RPs (i.e. 33 RP locations) in the “120 deg.“ architecture (fig. 1 right). The 120 degree directional antennas were assumed to be ideal.

The transmit power is the same for all RPs and no power control is applied. Transmission power is selected so that $P_{rec} > -105\,\mathrm{dBm}$ with probability 99.9% for a MS at the distance R from one RP. Without loss of generality g_0 in equation (4) was set to 1 and d_0 to 1 m.

For the coverage predictions we use Monte Carlo simulations with as many realizations of the log-normal distributed random variables as necessary to ensure sufficiently small 95%-confidence intervals. The difference in coverage of the studied systems is quantified with the help of cumulative distribution functions (CDFs) of the area averaged received power.

We compare three possible cases of macrodiversity. If *no macrodiversity* is applied, a MS can only access the nearest RP. The received power is then determined by the transmit power of the nearest RP and the path loss between this

RP and the MS position. If we apply *selection macrodiversity* the MS can access all RPs. At any time it will select the RP which is received with the highest power. Using *optimal combining macrodiversity* the MS combines the signals of 2, 3 or more RPs. It always selects those RPs which are received with the highest power. The combined received power is the sum of all received powers from the individual RPs (equation (1)).

For the capacity and link quality studies we use discrete event simulation. Call arrivals follow a Poisson process with parameter λ depending on the system load $A=\lambda/\varepsilon$. Call durations are assumed to be negative exponentially distributed with mean duration $1/\varepsilon$=100sec. The mobile stations are uniformly distributed in the service area at call setup. Two rings of interferers are considered. Sample simulations for 3 and 4 rings of interferes do not show remarkable difference in the simulation results.

The main quantities to evaluate the system performance in terms of coverage, capacity, and link quality are the received power P_{rec}, the blocking probability P_b, and the carrier to co-channel interference ratio *CIR* respectively.

III. Coverage Improvement

We first investigate the coverage problems of the “omni” architecture by taking qualitative snapshots of the received power. Fig. 2 depicts contour graphics of the downlink received power at one instant in time in the centre of the service area (rectangular area around the centre cell). The RP is in the centre of this snapshot. For all graphs shadow fading γ=4.0, σ=10 dB is applied. Different shading depicts different power values in dBm.

As it is expected from the propagation model, we see that the main coverage problem in the first picture are the cell borders (longest distance from the RPs). But also some points in the cell are badly covered due to the shadowing. The selection macrodiversity (2nd picture) approach tremendously alleviates the coverage problem by giving the MS the chance to always select the RP with the highest received powers. The optimal combining MD with three RPs involved (3rd picture) still increases the composite received power in some areas compared to the second picture.

Snapshots of the same area for the “120 deg.” architecture allow similar observations (fig. 3). The three RPs are located at the edges of the observed area. The biggest coverage problems appear in the cell centre, the most distant spot from the RPs in that architecture.

In order to quantify the coverage gain of macrodiversity we calculate the cumulative distribution functions (CDFs) of the received power in a rectangular area of about cell size around the central RP position. Therefore we simulated various realizations of the shadow fading. The CDF indicates the probability that the area averaged received power is less or equal to some value. We stress that the results for the macrodiversity cases are theoretical optimal values which can only be achieved if the MSs can select the best RP (or combination of RPs) at any instant of time at any position. For comparison purpose with the “omni” architecture the

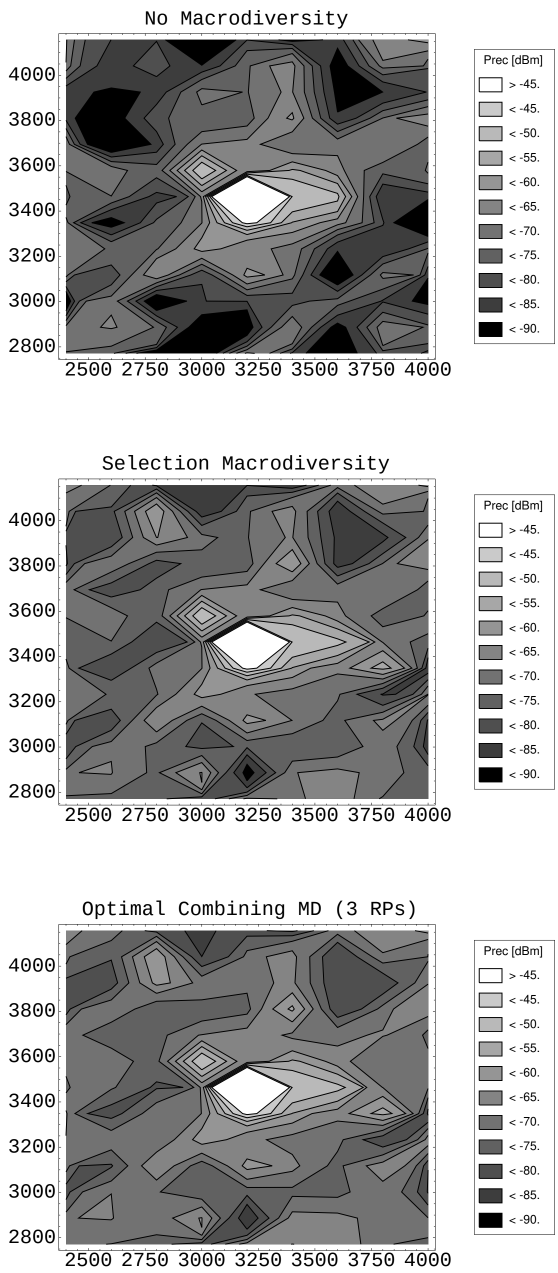

Figure 2: Coverage snapshots “omni” architecture

gain of the ideal 120 degree directional antennas was set to one inside the 120 degree angle and zero elsewhere.

Fig. 4 depicts the CDFs for the “omni” architecture. The CDFs for the “120 deg.” architecture are nearly identical. This means that there is no difference concerning coverage between the two architectures!

The graph of fig. 4 can be interpreted in two ways:

First, if a minimum of (for example) -84 dBm is necessary for good signal reception, optimal combining macrodiversity with three RPs results in 97% area coverage. Optimal combining MD with two RPs still results in a 96% area coverage, selection diversity in 92% and no macrodiversity in only 70% coverage.

Second, if we demand 90% area coverage, selection macrodiversity allows a relative gain of about 9.5 dB compared to no macrodiversity. Optimal combining MD with two RPs gives a gain of 11.3 dB and optimal combining MD with three RPs a gain of 12 dB.

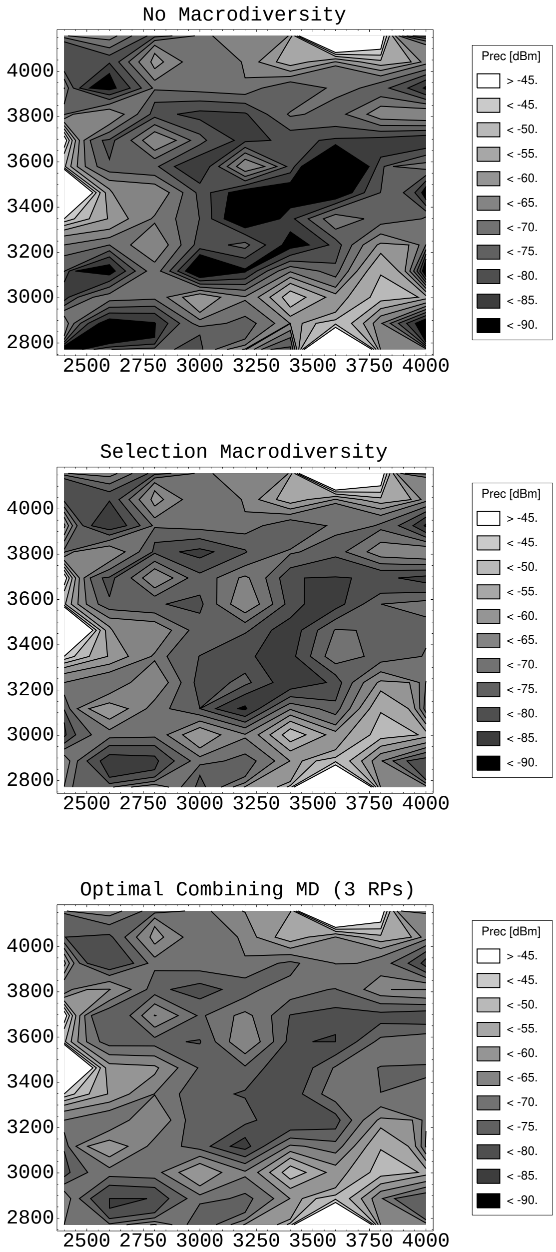

Figure 3: Coverage snapshots “120 deg.” architecture

We state that the coverage gain of macrodiversity is the higher the higher the demanded area coverage is and vice versa.

The relative coverage gain of optimal combining MD to selection MD is small compared to the relative gain of selection MD to no macrodiversity. Additionally, the relative gain of optimal combining MD decreases as the number of involved RPs increases.

We stress that the relative coverage gain is independent of the transmit power. Using different transmit power (fixed for all RPs) or a higher antenna gain only shifts the CDF curves to the left (or right), while the relative gain is the same.

The coverage gain depends on the parameters of the propagation model [1,7]. Especially, decreasing the standard deviation σ of the shadow fading decreases the relative gain of macrodiversity (and vice versa). Our studies with different σ are summarized in table 1.

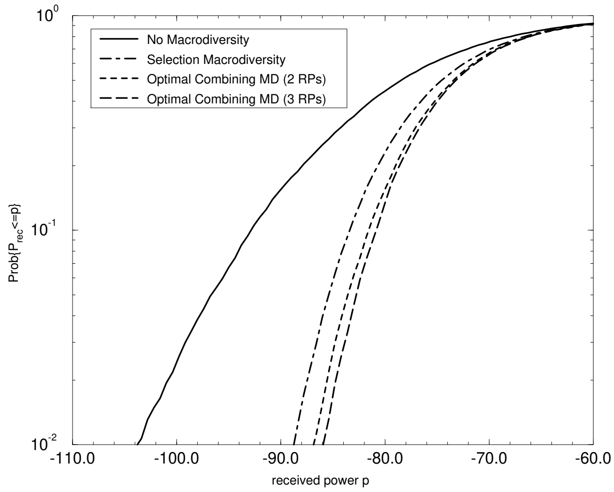

Figure 4: CDF of the received power (“omni” architecture)

We conclude that the application of macrodiversity for coverage improvement is the more useful the stronger the shadow fading (the higher σ) is. However, the gain of optimal combining macrodiversity for small σ (2 dB) is still remarkable 3.6 dB over the no macrodiversity case.

Relative gain in dB at 90% area coverage (compared to no macrodiversity)	σ [dB]		
	2	6	10
Selection MD	0.8	3.8	9.5
Optimal Combining MD (2 RPs)	2.9	5.4	11.3
Optimal Combining MD (3 RPs)	3.6	6.2	12.0

Table 1: Coverage gain depending on σ

In general, the coverage gain of macrodiversity can be turned into less transmit power of the RPs (and mobile stations in the uplink), in lower radio port density, or better reception quality.

IV. Capacity and Link Quality

In order to take maximum profit of macrodiversity and to realize high capacity with good link quality we propose a dynamic channel allocation (DCA) algorithm with appropriate admission control.

The basic algorithm for the DCA packs the resources as dense as possible to allow a tight re-use distance. The criterion which must be fulfilled while trying to achieve a most dense packing is twofold: First of all, a MS must receive at least one of the selected RPs with a minimum received power ($P_{rec,min}$). Second, a minimum CIR (*CIRmin*) must be achieved for every call.

The CIR is determined for every MS by dividing the received power from the serving RP by the sum of the received power from interfering RPs. Interfering RPs are those which use the same resource with another MS. Every MS sets up one call and needs one resource to satisfy the call. At the end of a call the MS leaves the system.

Admission control guarantees that no new call can decrease link quality (i.e. the instantaneous CIR) for the ongoing calls by more than the acceptable minimum. Hence, a new call is accepted only, if a resource can be used without decreasing the CIR of any MS to a value lower than *CIRmin.* Otherwise the call is blocked. Resource re-arrangement of ongoing connections is not applied.

Moving MS must be continuously watched and any time the criteria $P_{rec,min}$ or *CIRmin* are no longer fulfilled, a new resource assignment is necessary. However, in the remainder of this paper we do not consider mobility. All MS are fixed to their location which is calculated to realize a uniform distribution of MS in the service area.

Fig. 5 depicts the blocking probability for the "omni" and the "120 deg." architectures in the case of *no macrodiversity* and *selection macrodiversity*. The vertical bars at the

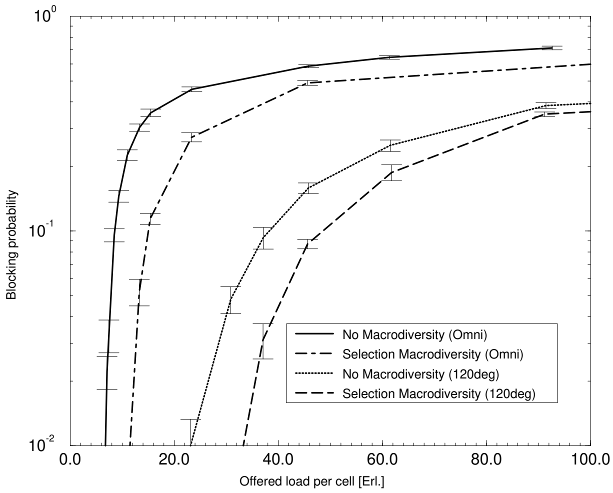

Figure 5: Blocking Probability

simulation points represent the 95%-confidence intervals. We used 36 resources in the whole service area. Any RP can access the full set of resources. Statistics were only taken in the centre cell to avoid border effects. The demanded *CIRmin* is set to 9 dB, the demanded $P_{rec,min}$ to -105 dBm. Transmitter power was again selected so that the probability of receiving less than -105 dBm at the distance R (cell radius) from a RP is 0.1%.

We define system capacity as the carried load per cell at a given blocking probability (e.g. 10%). We see that in general the "120 deg." architecture realizes higher capacity than the "omni" architecture. This is due to the effect of interference suppression by the ideal directional antennas. We further note application of selection macrodiversity in both architectures increases capacity. In the "omni" architecture it increases capacity at the 10% blocking level from 8.5 to 15.0 Erlang (factor of 1.76), and in the "120 deg." architecture from 38.0 to 48.8 Erlang (factor of 1.28). The capacity increase from selection macrodiversity in both cases is high. The absolute capacity is higher in the "120 deg." architecture while the relative gain of selection macrodiversity is higher in the "omni" architecture.

In all cases we must be assured that the link quality for all connections is guaranteed. Therefore we look on the distribution of CIR in the centre cell. Fig. 6 depicts the time weighted area averaged CDF of the CIR of all MS in the centre cell. The CDF were measured at the capacity limit of about 10% blocking. We see that the probability of having a CIR lower than 9 dB is zero. This is assured by the value of *CIRmin* selected for the admission control. We further state that there is no much differences between the CDFs of the "omni" and "120 deg." architectures.

In the mean the CIR values in the selection macrodiversity cases are slightly lower than in the cases with no

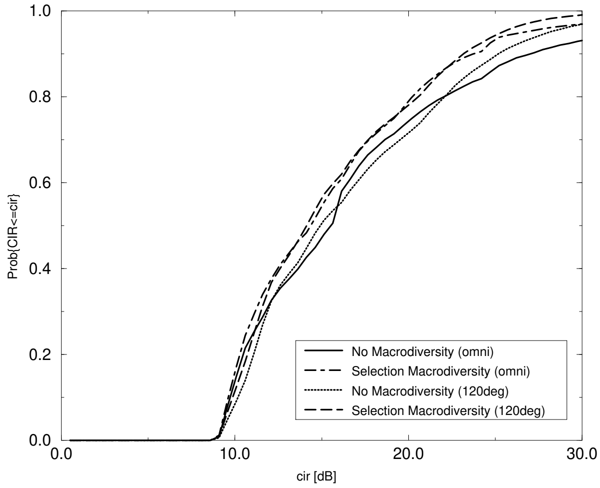

Figure 6: CIR CDFs at blocking probability of 10%

macrodiversity. Always selecting the RP with the highest received power, creates - in the mean - more interference to other users.

From fig. 6 we conclude that the higher capacity realized by selection macrodiversity is paid by only a small decrease in the mean CIR.

The minimum CIR of the MS can be adjusted by the admission control parameter *CIRmin* (selected to 9 dB in fig. 6). If this parameter is increased, the CDF curves of fig. 6 are shifted to the right. Then, the CIR seen by the MS is increased and hence link quality is increased. In turn, the system capacity is reduced, as more calls are blocked due to the interference restriction criterion. By simply adjusting the *CIRmin* parameter a trade off is possible between system capacity and link quality.

V. Conclusions

In this paper we investigated the influence of macrodiversity on cellular systems.

We illustrated the coverage problems of two different architectures ("omni" and "120 deg.") by qualitative snapshots. We quantified the relative coverage gain of selection and optimal combining macrodiversity for different values of the standard deviation σ of the shadow fading. We found that for the two cellular architectures the coverage gain of macrodiversity is the same. We showed that there is a high relative coverage gain of selection macrodiversity to no macrodiversity. Optimal combining macrodiversity can realize an additional gain, while the relative gain to selection macrodiversity is smaller than that of selection macrodiversity compared to no macrodiversity. For low σ optimal combining macrodiversity still realizes a remarkable coverage gain.

We further proposed a resource management scheme consisting of DCA and admission control algorithms aiming to realize high capacity while guaranteeing an adjustable link quality. Applying this algorithm we showed that there is a high capacity gain of selection macrodiversity. Link quality is always kept above the selected minimum. The higher capacity of selection macrodiversity is paid by only a small decrease of the mean CIR. Adjusting the admission control parameter makes it possible to trade off system capacity against link quality.

Further studies including mobility and handover algorithms shall reveal other benefits and costs of the proposed resource management scheme in macrodiversity systems.

VI. Acknowledgments

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