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Distributions in CDMA Radio Network
Planning**

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Abstract

In this paper we investigate the impact of a clustered traffic distribution on the coverage and capacity of a CDMA cell and its implications on network planning. We assume the users to be distributed according to a spatial Poisson process and derive expressions for outage probability as quality-of-service (QoS) measure. This allows the derivation of a tradeoff between coverage and capacity in a single and multi-cell environment. We will also show how this tradeoff can be used in an algorithmic approach to demand oriented CDMA network planning.

1 INTRODUCTION

Code division multiple access (CDMA) is the potential upcoming RF technology for future mobile communication systems. Beside the success of the North American networks based on the IS-95 standard by Qualcomm Inc. (CDMAOne), CDMA has become a global issue especially after the efforts of the ETSI in agreeing on the standard of the air interface of the third generation system UMTS (Universal Mobile Telecommunication System) to be a wide-band CDMA system. However, the effects of varying traffic load on coverage and capacity still need to be investigated, especially since most of the newly rolled-out networks are experiencing capacity problems.

In cellular systems employing CDMA, there is a well known relationship between coverage of the cell and the user capacity. In contrast to conventional FDMA or TDMA systems, CDMA has a *soft capacity* which is not a fixed term, but can be increased at the slight cost of worse quality of service (QoS). In the same way, the coverage area of a cell can be considered as

being of an *elastic* nature: as the number of users in the cell increases, the area of coverage may shrink. The cell coverage is therefore dependent on the location and the density of the users in the cell.

Several factors influence this elastic coverage: the propagation characteristics of the terrain, the power control dynamics, the desired level of QoS, and the spatial customer distribution and the corresponding time-dependent traffic intensity. The last item requires special attention in the planning of a CDMA network or in the design of connection admission control (CAC) and overload algorithms. Especially, users at the fringe of the cell would face a deteriorating service due to propagation loss. Therefore, both, coverage and capacity of a cell need to be planned in such a way that all calls are sufficiently supplied.

The analysis of coverage and capacity has been investigated in numerous papers. In [1] the capacity of equally loaded cells was analyzed by modeling them as $M/M/\infty$ queues. An extension to that paper is presented in [2]. In [3] an equation for outage probability for a single cell is developed that gives a relationship between coverage and capacity that is conditioned on the number of users currently supported in the cell and their location. This paper is extended in [4] by considering the population of customers in the cell as a number governed by a two-dimensional Poisson process. In this paper we continue the work in [4] to extend the expression for outage probability from a single cell to a multiple cell environment. We measure the performance indicating the desired QoS in terms of outage probability, which is also used to obtain explicit curves indicating the tradeoff between cell coverage and user capacity. We will also show how this tradeoff can be applied in a network planning algorithm.

This paper is organized as follows. Section 2 describes the CDMA network model and the computation of outage probability for a single cell. In Section 3 the model is extended to a system with 3 cells including soft-handoff. The coverage and capacity tradeoff that is obtained there is then used in Section 4 for an algorithmic planning approach. Results obtained from a network planning tool also show the feasibility of this new approach.

2 COVERAGE AND OUTAGE FOR A SINGLE CDMA CELL

In this first section we will consider a single CDMA cell with a *base transceiver station* (BTS) supporting a number of k users. As performance metric of the system we will use the term *outage probability*. This value describes the probability of the bit-energy-to-noise ratio $\hat{\epsilon}_j$ not

fulfilling the requirements for a particular user j , who is located at a distance x from the BTS

$$\hat{\epsilon}_j = \frac{\frac{\hat{S}_j}{R}}{\sum_{i \neq j} \frac{\nu_i \hat{S}_i}{W} + N_0 + I}. \quad (1)$$

Note that $\hat{\chi}$ indicates that the value is in linear space; the corresponding level in dB is χ . In Eqn. (1), \hat{S}_i is the received signal strength from user i , W and R are the frequency bandwidth and data bitrate, N_0 denotes the thermal noise power and I is the other-cell interference. The variables ν_i are the voice activity factor which we will model as Bernoulli random variables that take the value 1 with probability $\rho = 0.4$. Outage probability for user j can then given as:

$$P_{\text{out}} = P(\hat{\epsilon}_j < \hat{\epsilon}_{j,\text{required}}). \quad (2)$$

In [3], it is shown that the probability of outage for user j can be computed from the probability of this user exceeding his maximum transmit power level S_{max}

$$P_{\text{out}} = P(S_j + L(x) + Z > S_{\text{max}}). \quad (3)$$

where $L(x)$ is the path loss at distance x (including antenna gains) and Z is a log-normal random variable representing shadow fading. Since S_j is a random term, which depends on the number of users k , a relationship between coverage and capacity is derived in [3] using the knowledge that the bit-energy-to-noise ratios $\hat{\epsilon}_i$ are log-normal distributed [1]. Hence, using the Gaussian Q-function Eqn. (3) can be rewritten as:

$$P_{\text{out}}(k, x) = Q \left(\frac{S_{\text{max}} - L(x) - m_S(k)}{\sqrt{\sigma_S(k)^2 + \sigma_Z^2}} \right). \quad (4)$$

In Eqn. (4), m_S and σ_S are the mean and standard deviation of the *mobile station* (MS) received power S and σ_Z is the standard deviation of the log-normal shadowing.

So far the randomness was only taken into account for the modeling of the transmission channel. In [4], a spatial homogeneous Poisson process is used to characterize the relationship between the number and location of the users in the cell. Thus, the r.v. for the number of users distributed in a cell with area A is Poisson distributed with density λ :

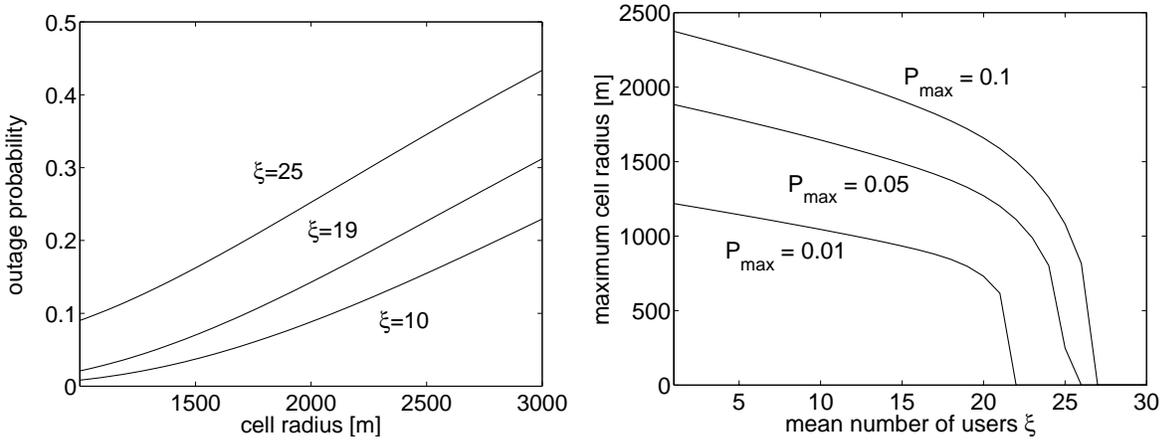
$$P(K = k) = \frac{(\lambda A)^k}{k!} \exp(-\lambda A). \quad (5)$$

With Eqn. (5) it is now possible to give an outage probability unconditioned of the number of users k . The probability to have k connections in a cell with radius x is Poisson distributed

and this leads to:

$$P_{\text{out}}(x) = \sum_{k=1}^{\infty} P_{\text{out}}(k, x) P(K = k). \quad (6)$$

The term in Eqn. (6) is no longer dependent on the number of users in the cell, but now only has as parameters the distance x from the BTS and the density of the spatial process λ , which translates to an expected number of users in the cell $\xi = \lambda A$. Fig. 1(a) shows that P_{out} increases with the distance from the BTS. When the mean number of users ξ increases, the probability for outage gets worse.



(a) Outage probability depending on mean number of users

(b) Coverage-capacity tradeoff

Figure 1: Outage probability and coverage-capacity tradeoff for spatial Poisson traffic

We are now interested in the tradeoff between cell radius and capacity in terms of served number of users. For this we assume a fixed maximum outage probability P_{max} defining our quality of service and which we do not wish to exceed. In solving Eqn. (6) for x we can derive the maximum cell radius for which P_{max} is still maintained. The curves for the coverage-capacity tradeoff are given in Fig. 1(b). Note that the stricter we get with our outage requirements, i.e., P_{max} becoming smaller, we also reduce the maximum cell radius for the same mean number of users.

3 COVERAGE-CAPACITY TRADEOFF IN A MULTI-CELL ENVIRONMENT

In this section, we extend the above characterization of coverage and capacity from a single to a multi-cell environment. We assume a standard hexagonal layout of BTS as shown in Fig. 2(a). In such an environment it is very important to account for soft-handoff because many studies, such as [5] and [6], have revealed that this feature of CDMA systems increases the performance in terms of both coverage and capacity. A mobile is in N -way soft-handoff if it is in simultaneous communication with N BTS. If one of the N links suffers deep fading, another one may still be acceptable. Thereby, outage probability is reduced because the mobile transmit power does not have to be increased.

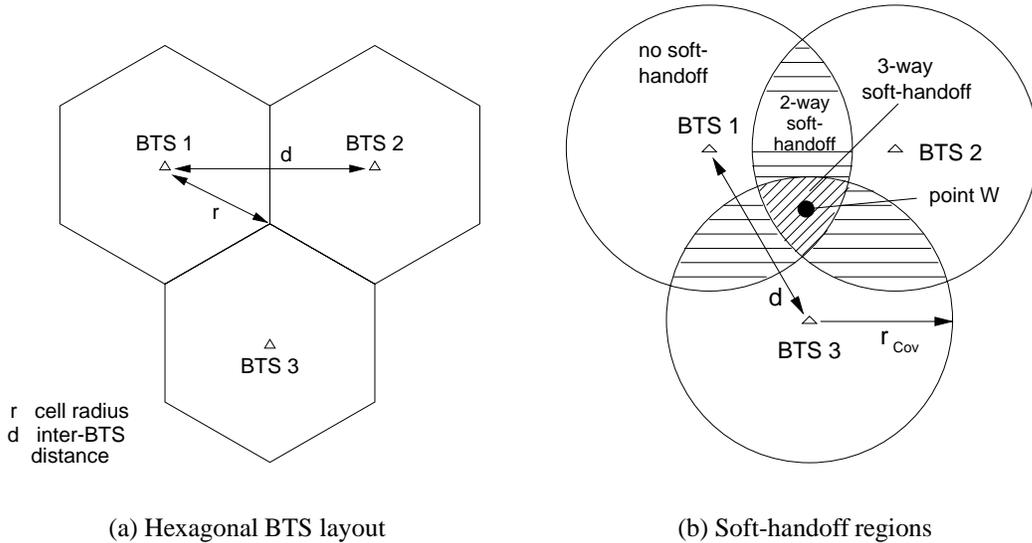


Figure 2: CDMA cell layout models

3.1 Soft-Handoff Probabilities

Whether a mobile is in soft-handoff or not depends on the forward path pilot signal-to-interference ratio received from the surrounding BTS. Since our primary interest is studying the long term system behavior, we do not consider mobility of the users and only need to focus on one of the soft-handoff parameters, T_{Drop} . A mobile is in at least N -way soft-handoff if N

pilot-to-interference values are received above the drop threshold. Although higher degrees of soft-handoff are possible, they are extremely unlikely under our assumption of a hexagonal layout of BTS. We therefore will only consider the case for $N = 2$ and $N = 3$.

Fig. 2(b) shows three BTS and the mean coverage areas of their pilot signals. As we can see, 3-way soft-handoff is confined to the region in the middle between all three BTS. No soft-handoff occurs in areas close to the cell sites and the 2-way soft-handoff regions cover the remaining area. Since the pilot signals are affected by shadow fading and their coverage is therefore varying, the soft-handoff regions are not as clearly defined as suggested by the figure. At any location there is a certain probability for 1-, 2-, and 3-way soft-handoff.

In the remainder of this subsection, we summarize and extend the characterization of the soft-handoff probabilities found in [7]. Let x_1, \dots, x_K be the distances from the investigated mobile location to the K closest cell sites in ascending order, i.e., x_1 is the distance to the closest BTS, x_2 the distance to the second closest BTS, and so on. Further, denote Ec_i the pilot signal-to-interference-and-noise ratio from cell i , then Ec_i is given as

$$Ec_i = \frac{p_i E_i \hat{L}(x_i) \hat{Z}_i}{\sum_{k=1}^K E_k \hat{L}(x_k) \hat{Z}_k + N_0 W}, \quad (7)$$

where Z_k is the random variable for shadow fading with $Z_k = a\zeta + \sqrt{1 - a^2}\zeta_k$. The variables ζ and ζ_n are i.i.d. distributed according to $N(0, \sigma_Z^2)$ with a determining the degree of fading correlation. The fraction of cell power allocated to the pilot signal is p_i and E_i is the total effectively radiated power (ERP) of cell i . $L(x_i)$ denotes the path loss from cell site i to a mobile at distance x_i .

Neglecting the term for background noise $N_0 W$, Eqn. (7) can be rewritten as

$$Ec_i = \frac{p_i}{1 + 10 \frac{Y_i}{10}}$$

with Y_i being the normally distributed ratio of interference received from cell sites $k \neq i$ to the signal power received from BTS i . The mean and standard deviation m_{Y_i} and σ_{Y_i} of Y_i are functions dependent on x_k , σ_Z , and a . Assuming independence of Y_i and Y_j ($i \neq j$), the

desired soft-handoff probabilities are given as

$$P_{3\text{-sh}}(\{x_K\}) = \prod_{i=1}^3 \left(1 - Q \left(\frac{10 \log_{10} \left(\left(\frac{p_i}{T_{drop}} \right) - 1 \right) - m_{Y_i}}{\sigma_{Y_i}} \right) \right) \quad (8)$$

$$P_{2\text{-sh}}(\{x_K\}) = \prod_{i=1}^2 \left(1 - Q \left(\frac{10 \log_{10} \left(\left(\frac{p_i}{T_{drop}} \right) - 1 \right) - m_{Y_i}}{\sigma_{Y_i}} \right) \right) - P_{3\text{-sh}}(\{x_K\}). \quad (9)$$

A user is accordingly in 1-way soft-handoff with probability $P_{1\text{-sh}} = 1 - P_{2\text{-sh}} - P_{3\text{-sh}}$.

Fig. 3 shows the 2- and 3-way soft-handoff probabilities encountered by a user moving from BTS 1 in the direction to point W in Fig. 2(b). The 3-way soft-handoff probability is greatest at point W at the distance of about 1000 m. We also see that the 2-way soft-handoff probability is greatest in the region labeled “2-way soft-handoff” at distances above 1300 m.

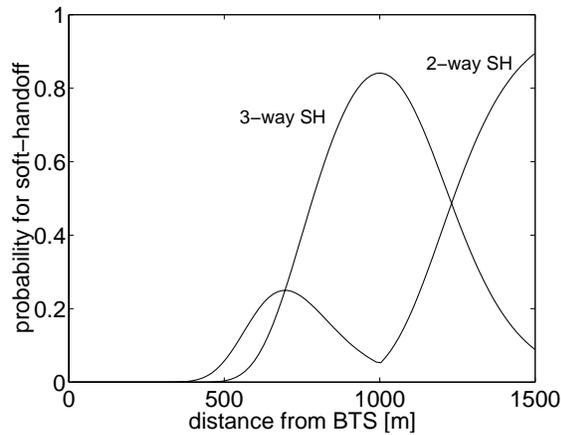


Figure 3: Probability for 2- and 3-way soft-handoff

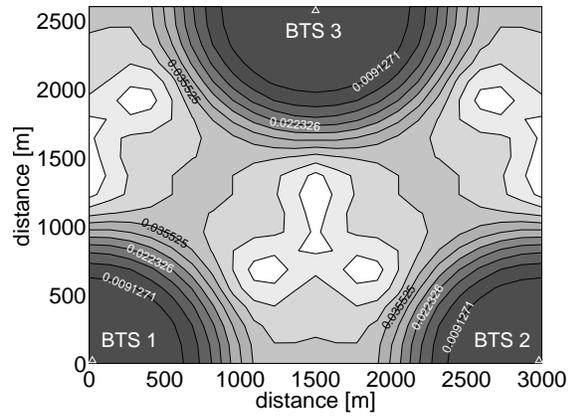


Figure 4: Unconditioned outage probability with $\xi = 20$ users

3.2 Outage Probability under Soft-Handoff

If a mobile is in N -way soft-handoff, it has links to the N closest BTS. Therefore, outage only occurs if the transmit power required for all these links exceeds the maximum transmit power S_{\max} . Thus, under soft-handoff Eqn. (3) becomes

$$P_{\text{out}} = P \left(\bigcap_{n=1}^N \{S^{(n)} + L(x_n) + Z_n > S_{\max}\} \right)$$

where $S^{(n)}$ is the received power from our observed user at BTS n . Like in the previous section, Z_n is a random variable representing shadow fading for the link to BTS n .

Sendonaris et al. [6] show that the probability of outage for a customer at distance x_n to the n -th closest BTS that is serving k_n active users is

$$P_{\text{out}}(N, \{k_n\}, \{x_n\}) = \int_{-\infty}^{\infty} \left[\prod_{n=1}^N Q \left(\frac{S_{\text{max}} - L(x_n) - m_S(k_n) - a\sigma_Z x}{\sqrt{(1-a^2)\sigma_Z^2 + \sigma_S^2(k_n)}} \right) \right] \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx$$

where $m_S(k_n)$ and $\sigma_S^2(k_n)$ are the mean and the variance of the required received power for a cell site with k_n mobiles.

Since from the previous section we know the probabilities for being in soft-handoff, Eqns. (8) and (9), we can give an expression for the outage probability not depending on the degree of soft-handoff N :

$$P_{\text{uncond}}(\{k_n\}, \{x_K\}) = \sum_{n=1}^3 P_{\text{out}}(n, \{k_n\}, \{x_n\}) P_{n\text{-sh}}(\{x_K\}). \quad (10)$$

As in Section 2, we assume that the customers are distributed according to a spatial Poisson process. Therefore, the number of customers per cell is Poisson distributed with mean $\xi = \frac{3\sqrt{3}}{2} r^2 \lambda$. Here, r is the cell radius as introduced in Fig.2(a) and λ the traffic intensity of the Poisson process. Using the customer distribution, Eqn. (10) becomes

$$P_{\text{pois}}(\{x_K\}) = \sum_{k_1=1}^{\infty} \cdots \sum_{k_3=1}^{\infty} \left(\prod_{n=1}^3 \frac{\xi^{k_n} e^{-\xi}}{k_n!} \right) P_{\text{uncond}}(\{k_n\}, \{x_K\}). \quad (11)$$

Fig. 4 shows the contour plot of P_{pois} . Base stations are located in the lower left and lower right corner and in the top center. It can be clearly seen that outage probability increases with the distances to the BTS. However, due to soft-handoff the area between the cells sees smaller outage probabilities than in the case without soft-handoff.

3.3 Determining the Coverage-Capacity Tradeoff

Like in Section 2 the greatest outage probability value within a cell P_{worst} is only a function of r and λ . The multi-cell counterpart to Fig. 1(a) is Fig. 5. It shows the same behavior: the greater the cell radius and the mean number of users, the worse P_{worst} becomes. The curves lie below the ones in Fig. 1(a), indicating the gain from soft-handoff.

From this we can derive the multi-cell coverage-capacity tradeoff that is relating the mean number of users per cell with the maximum cell radius. This tradeoff is derived exactly like in Section 2. For varying mean number of users per cell ξ , we determine the maximum cell radius, for which P_{worst} equals the maximum allowed outage probability P_{max} . Fig. 6 depicts the resulting tradeoff together with the single cell tradeoff both for $P_{\text{max}} = 0.05$. We see that soft-handoff leads to a gain in coverage as well as capacity. For a fixed ξ , the maximum cell radii are greater for the soft-handoff curve and vice versa a certain cell radius corresponds to a greater ξ . The tradeoff will be used for an algorithmic approach to network planning in the following section.

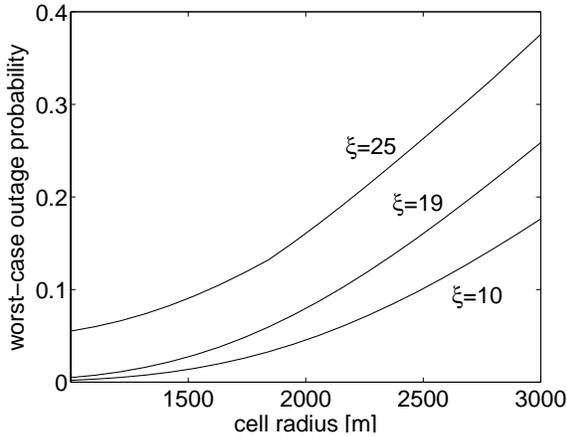


Figure 5: P_{worst} as function of cell radius

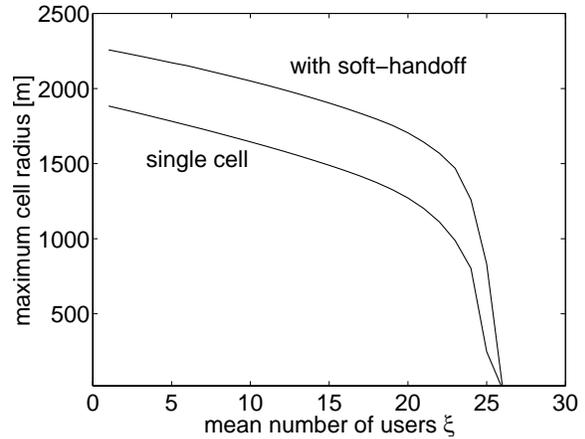


Figure 6: Coverage-capacity tradeoff

4 ALGORITHMIC APPROACH TO NETWORK PLANNING

In this section we consider arbitrary realisations of cluster processes as user distributions and show how the above results can be used to perform network planning. A cluster process can be viewed as a snapshot of the user distribution in the planning region at a certain time instant. Alternatively, the spatial distribution of demand for mobile services can be represented by discrete points, called demand nodes, as described in [8]. Those demand nodes also form a realization of a cluster process.

4.1 Algorithm

We have developed an algorithm that takes the coverage-capacity tradeoff, an arbitrary user distribution and planning parameters, such as the dimensions of the planning region and the minimum percentage of users to be covered, as input and yields BTS positions and coverage. The algorithm consists of the following steps:

1. Generate the candidate set of BTS. Instead of considering an infinite number of possible locations, we place a limited number of candidate BTS on a grid with uniform distances between two BTS. We are using the coverage-capacity tradeoff to determine the greatest possible radii of the BTS. Since now the number of users in a certain area is fixed and not Poisson distributed, we have to assume a fixed number of users per cell when computing the coverage-capacity tradeoff, i.e., we are using Eqn. (10) instead of Eqn. (11).
2. Perform planning by selecting out of the candidate set as few BTS as possible that suffice to supply the required percentage of customers. Since this problem is NP-complete [9], we apply a Greedy heuristic for solving it in polynomial time. Basically, in each step the BTS covering most new customers is selected.
3. Employ a location optimization step to improve the solution. The goal is to increase the total coverage and to reduce the overlap of cells. In a first phase, for each BTS the desirability of moving the BTS is computed and the most desirable is selected. In the next phase, the selected BTS is moved towards uncovered mobiles and away from multiple covered customers.

4.2 Results

The described algorithm has been implemented in a simple planning tool. We will now use this tool to analyze the influence of user clustering on teletraffic engineering of CDMA networks. Using the tool, planning was performed for a region of 10 by 5 km containing 100 customers, with a requirement of covering 90% of the customers. Figure 7 shows the result for an unclustered and Fig. 8 for a heavily clustered user distribution. The small points represent the users and the circles the cell coverage areas. As we can see, considerably less BTS are needed in Fig. 8 than in the unclustered case .

To provide more evidence for this result, we made 100 experiments for each user distribution. We also investigated the deterministic user distribution, where mobiles are placed on a regular grid with constant and equal distance from one another. The following table gives the results for the numbers of required BTS. We also calculated the corresponding 90% Student-t confidence intervals.

user distribution	mean	variance	90% confidence interval
deterministic	10	0	[10; 10]
Poisson process	8.45	0.6075	[8.317; 8.583]
clustered	6.41	1.6619	[6.189; 6.631]

As mentioned, the mean number of BTS is lower for more clustered customers. The variance is 0 for the deterministic case since there is no source of randomness. We also see that the less uniform the user distribution, the greater the variances and, consequently, the wider the confidence intervals.

The explanation for the result that less BTS are needed for more clustered traffic is easy. Due to the Greedy heuristic, areas with high user density are selected first as BTS locations. In the presence of clusters, we therefore have more users per BTS compared to a more uniform user distribution. Thus, if it is only the goal to cover customers and not also area, less BTS are needed to supply a certain number of users.

Since in the real world the demand for mobile services is very high in some areas like cities or highways and very low in other areas such as woods and farmland, demand oriented network planning can lead to a substantial decrease of the required number of BTS. Thereby, setup and operating costs can be significantly reduced because cell sites are among the most important cost factors in cellular communication systems.

In addition to performing the planning steps as described above, the planning tool can visualize soft-handoff and outage probabilities. Like for determining the coverage-capacity tradeoff, these probabilities can be computed using Eqns. (8), (9) and (10). This time the distances d_K to the closest BTS are not given by the hexagonal layout of BTS, but by the actual BTS locations after planning. These are depicted in Fig. 9 and Fig. 10 for the planning result of Fig. 7.

The areas in Fig. 9 which are colored light gray are areas with low outage probabilities. In Fig. 10, the dark gray areas represent low probabilities of soft-handoff, whereas lighter shading

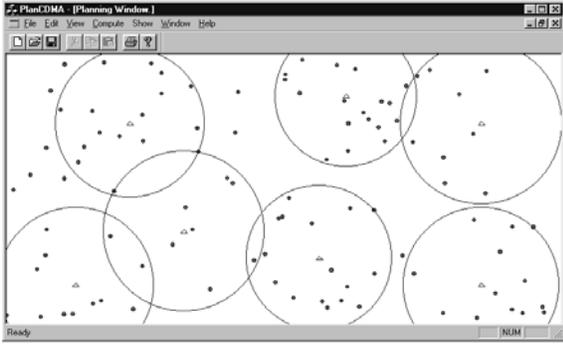


Figure 7: Planning result for unclustered customer distribution

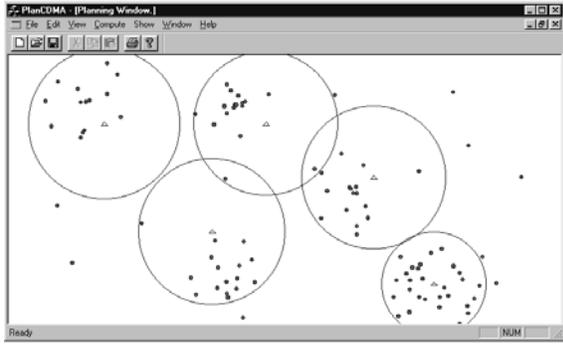


Figure 8: Planning result for clustered customer distribution

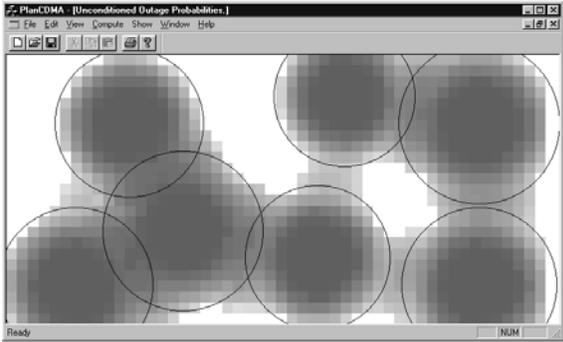


Figure 9: Unconditioned outage probabilities

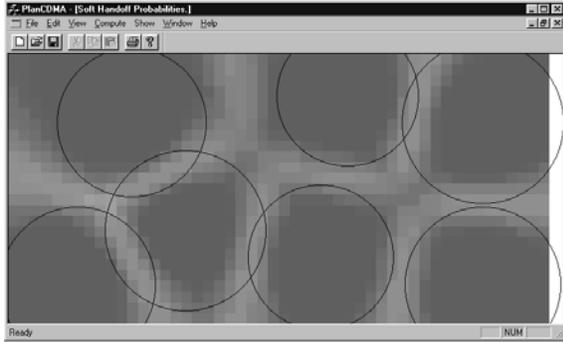


Figure 10: Soft-handoff probabilities

indicates a high degree of soft-handoff.

5 CONCLUSION

We have presented a convenient way to determine the tradeoff between coverage and capacity in CDMA networks under the assumption that users are distributed according to a spatial Poisson process. To this end, outage probability was used as a QoS measure. The tradeoff was first derived for a single and for a multi-cell environment, where soft-handoff has to be taken into account. We saw that, as expected, soft-handoff leads to a gain in both coverage and capacity. We then described how the tradeoff is used as input to a network planning algorithm that is implemented in a simple planning tool. The algorithm is demand oriented in the sense

that it tries to cover a projected percentage of arbitrarily distributed users with base stations. The results from the planning tool show the importance of demand oriented planning for cost efficient cellular service provision.

Further research is required for a more realistic and time independent characterization of demand, for example by using the demand node concept presented in [8]. A demand node represents the center of an area containing a quantum of demand from teletraffic viewpoint, accounted in a fixed number of call requests per time unit. The planning tool can also be enhanced by including a more realistic propagation model relying on morphological and geographical data of the planning region. Currently, a flat earth model with uniform propagation conditions is used.

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