CODE DIVISION MULTIPLE ACCESS WIRELESS NETWORK PLANNING CONSIDERING CLUSTERED SPATIAL CUSTOMER TRAFFIC

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In this paper we have modelled the behavior of the CDMA cell using clustered Poisson process. We have found that when the RF dynamics of the cell is modelled using this two dimensional description of the user arrival process, the size and the capacity of the cell are completely determined by the spatial traffic density and stability arguments. This is much like provisioning a server in a queueing system. This paper is an extension of the work presented in [8] by incorporating the idea of a clustered nature of customers in a cell.

1 INTRODUCTION

CDMA networks have recently seen a rapid growth all over the world. The reason for this lies in its technological advantages over second generation systems. However, since the newly rolled-out networks have often not yet reached their normal operation conditions, the effects of varying traffic load on coverage and capacity still need to be investigated. Additionally, *soft capacity* leads to a description of the term *coverage* that differs from its conventional usage. Unlike conventional systems like FDMA or TDMA, where coverage is purely determined by radio frequency (RF) aspects, the cell coverage in CDMA is extremely sensitive to the customers that are supplied in the cell.

Due to the soft-capacity nature of CDMA networks, the coverage of a cell depends on several factors: i) the transmission characteristics of the terrain, ii) the dynamics of the power control procedure, iii) the desired quality of service in term of sustainable interference level, and iv) the spatial customer distribution and corresponding time-dependent customer traffic intensity.

From previous studies it is known that the coverage area of a CDMA cell is of an *elastic* nature, cf. [8]: as the number of customers in the cell increases, the area of coverage may shrink. This effect indicates that the customer population and its *spatial distribution* has to be taken into account carefully in the context of CDMA network planning, especially in the design of connection admission control (CAC) and overload control algorithms. Looking e.g. at the CAC, the impact of accepting new calls is that those at the fringe of the cell would face a deteriorating service. Therefore both, coverage and capacity of a cell need to be planned in such a way that all calls are sufficiently supplied, i.e. power-controlled according to the defined quality of service.

This paper is intended to provide the infrastructure to analyze a CDMA cell. We define an outage condition metric that can be used in the network design process. When analyzing a CDMA cell, its complexity is determined by the stochastic property of the customer population and the probabilistic nature of the radio transmission. Due to these issues, the cell capacity and the cell radius become probabilistic quantities. It is therefore also necessary to define the coverage and the capacity in a probabilistic fashion.

As the analysis of the capacity and coverage of a CDMA cell are crucial issues for network dimensioning, numerous work on this topic already exists. A first approach to analyze the capacity of a cell by modeling it as $M/M/\infty$ queue is performed in [9], where equally loaded cells are assumed. An extension to that paper is presented in [2], which also includes a good overview on further traffic models. Another study that also assumes a non-uniform loading of cells is given in [3]. Here, the number of customers is modeled as Poisson random variables and focus is laid on the capacity of a hot cell in the center with two tiers with less traffic surrounding it. We used results from [8] as starting point in this study. In [8] an equation for outage probability is developed that is conditioned on the number of currently supported customers and their location. The approach in this paper differs from the previously mentioned studies in that the population of customers in the cell is considered as a number governed by a two dimensional Poisson process, cf. [1]. Recent publications, such as [7], indicate the growing importance of modeling traffic with spatial cluster processes.

This paper is organized as follows. Section 2 describes the CDMA network model that is examined. A short derivation of the term for outage probability is given. In Section 3, the relation between cluster processes and traffic modeling is shown and included in the network model. Numerical results are presented in Section 4, conclusions and an outlook are given in Section 5.

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[1]Dr. Jain was working with NORTEL Wireless Networks, Richardson, TX, while this work was completed.

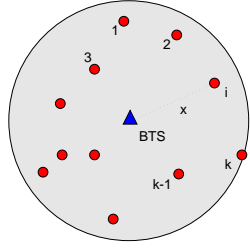## 2 NETWORK PARAMETER MODELING ASSUMPTIONS

Figure 1: CDMA cell with k supported calls

We consider a cell in a CDMA network with a Base Transceiver Station (BTS) supporting a number of calls (Fig. 1). At the observation instant there are k calls to be supported and power-controlled in the cell.
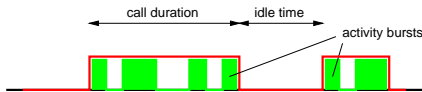

Figure 2: CDMA customer and call process

We observe in particular a customer i in conversation phase. This is the period of time, when a customer transmits an activity burst during his call. These bursts are separated by idle phases, like illustrated in Fig. 2. The probability that the customer gets an acceptable link quality is a function of the distance x to the base station (BS) and the current interference characteristics. The interference characteristic is however not only depending on x, but is also a function of the distribution of calls currently supported in the cell. In the general modeling context we consider the number of connections in cell to be a random variable denoted by K, which is governed by a cluster process described in the next section. At the observation instant K takes an instantaneous value denoted by $k(K = k)$.

We use as performance metric of the network an expression for the *signal outage probability*, i.e. the probability that a customer at distance x from the base station will require more than maximum power to maintain a desired signal–to–interference ratio (SIR or E_b/I_0). In the following, we will be using the terms outage and signal outage equivalently. In the North American IS–95 system [6] this maximum transmit power is 200mW. In line with [8] let this outage probability be defined as $P_{\text{out}}(x, k)$. Our aim in this paper is to uncondition $P_{\text{out}}(x, k)$ by utilizing the properties of the spatial process, i.e. we want to obtain values $P_{\text{out}}(x)$ and $P_{\text{out}}(k)$.

A term for outage probability just depending on the location of the customer is useful for network planning purposes, where the objective is to maintain a $P_{\text{out}}(x)$ below a given threshold for all customers within a coverage circle of radius x in the cell. The function $P_{\text{out}}(k)$ on the other hand can be used for determining the maximum number of customers that can be admitted to the network without exceeding a maximum outage probability.

To ease the further reading of the paper we will in the following summarize the derivation of $P_{\text{out}}(x, k)$.

2.1 Outage Model for a Fixed Number of Customers

Consider a case where the number of customers, hence the interference characteristics of the cell that is being analyzed, is a constant. The objective of this section is to estimate the probability of outage for a fixed number of customers k. The model presented here is along the lines presented in [8].

2.1.1 Outage Condition

If we look at the customer at a point in the cell, let the distance of this customer from the transmitter be x. The transmit power (in dB-W) of the customer is given in terms of his received power S at the BS by

$$S_{\text{trans}} = S + \text{PL}(x) + Z,$$

where $\text{PL}(x)$ is the path loss at distance x from the BS (including antenna gains) and Z is a random variable representing shadow fading. The path loss is usually well modeled using Hata's model, [5]:

$$\text{PL}(x) = K_1 + K_2 \log x.$$

The shadow fading variable Z is well modeled as a zero-mean Gaussian random variable with variance σ_Z^2, see [5]. As discussed in [8] the probability of outage is the probability that S_{trans} exceeds S_{max}.

Thus, the probability of outage at a distance x from the BTS is given by

$$P(\text{``outage''}) = P\left(S + \text{PL}(x) + Z > S_{\text{max}}\right). \quad (1)$$

The only quantity in Eqn. (1) that depends on the number of customers in the cell is S. Thus, a relationship between coverage and number of customers k may be derived if we find the distribution of S as a function of k.

2.1.2 Outage Probability

After giving the definition for the outage event, its probability can be computed. All variables and notation are used in analogy to [8], especially the notation

that for any power or signal–to–interference ratio χ in dB, its transformation to linear space is denoted by $\hat{\chi} = 10^{\frac{\chi}{10}}$.

The SIR $\hat{\varepsilon}_j$ for the j-th customer at the BS may be expressed in terms of the received powers $\hat{S}_j$ of the various customers as:

$$\hat{\varepsilon}_j = \frac{\frac{\hat{S}_j}{R}}{\sum\limits_{i \neq j} \frac{\nu_i \hat{S}_i}{W} + N_0 + I}$$

Here, ν_j is the voice activity factor of the j-th call, as described above, cf. (Fig. 2). The variables $\{\nu_j\}$ are modeled as independent Bernoulli random variables that take the value 1 with probability ρ. R denotes the information bit rate in bits per second and W is the system bandwidth in Hz. The total interference in the denominator is added by the background noise power spectral density N_0 and the other-cell interference density I.

The random variables $\hat{S}$, $\hat{S}_1$, $\hat{S}_2, \ldots, \hat{S}_{k-1}$ are modeled as i.i.d. log-normal distributed random variables. Since the required SIR $\hat{\varepsilon}$ is also log-normal, $\varepsilon = 10 \log \hat{\varepsilon}$ is Gaussian with typical values for the mean and standard deviation of $m_\varepsilon = 7$ dB and $\sigma_\varepsilon = 2.5$ dB, cf. [9]. The mean $m_{\hat{\varepsilon}}$ and second moment $\delta_{\hat{\varepsilon}}$ of the random variable $\hat{\varepsilon}$ are:

$$m_{\hat{\varepsilon}} = \exp\left(\frac{(\beta\sigma_\varepsilon)^2}{2}\right) \exp(\beta m_\varepsilon)$$

$$\delta_{\hat{\varepsilon}} = \exp\left(2(\beta\sigma_\varepsilon)^2\right) \exp(2\beta m_\varepsilon)$$

where $\beta = \frac{\ln 10}{10}$.

The mean and the second moment of $\hat{S}$ are then derived as:

$$m_{\hat{S}}(k) = \frac{(N_0 + I)W m_{\hat{\varepsilon}}}{\frac{W}{R} - \rho(k-1)m_{\hat{\varepsilon}}} \tag{2}$$

$$\delta_{\hat{S}}(k) = \frac{\left(\left((N_0+I)W + \rho(k-1)m_{\hat{S}}\right)^2 - \rho^2 m_{\hat{S}}^2\right) \delta_{\hat{\varepsilon}}}{\left(\frac{W}{R}\right)^2 - \rho(k-1)\delta_{\hat{\varepsilon}}}$$

Examination of Eqn. (2) shows that k cannot exceed the value for which the denominator is zero. This value is defined as the *pole capacity*

$$k_{\text{pole}} = \frac{W}{R m_{\hat{\varepsilon}} \rho} + 1.$$

and can be interpreted as the limit on the number of customers a cell can support when the coverage shrinks to zero.

Since $\hat{S}$ is log-normal, S is Gaussian. The mean and variance of S can easily be calculated in terms of $m_{\hat{S}}$ and $\delta_{\hat{S}}$ as given below:

$$m_S(k) = 20 \log_{10} m_{\hat{S}}(k) - 5 \log_{10} \delta_{\hat{S}}(k)$$

and

$$\sigma_S^2(k) = \frac{1}{\beta}\left(10 \log_{10} \delta_{\hat{S}}(k) - 20 \log_{10} m_{q\hat{S}}(k)\right) \tag{3}$$

Assuming that S and Z are uncorrelated, we can hence rewrite Eqn. (1) as:

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

Eqn. (4) yields the probability of an outage as function of the distance of the customer from the base station and the number of customers that are supplied in this cell. However, it is desired to have a term that is unconditional of the second parameter, i.e. making $P_{\text{out}}(\cdot)$ a function of only x or k. Considering the outage perceived by the customer at distance x from the BTS, we can formulate $P_{\text{out}}(x)$ as:

$$P_{\text{out}}(x) = \sum_k P_{\text{out}}(x, k) \cdot P\left(\begin{array}{c} k \text{ calls in cell} \\ \text{with radius } x \end{array}\right) \tag{5}$$

The derivation of the probability to have k customers in a cell based on a certain traffic behavior is done with a spatial Poisson process and is described in Section 3. In a similar fashion we will later describe:

$$P_{\text{out}}(k) = \int_0^\infty P_{\text{out}}(x, k) \cdot P\left(\begin{array}{c} \text{radius of cell} \\ \text{with } k \text{ users} \\ \text{is } x \end{array}\right) dx \tag{6}$$

3 CDMA COVERAGE IN A CLUSTERED ENVIRONMENT

So far the randomness was only taken into account for the modeling of the transmission channel. The equation for the probability of outage requires as parameters the number of customers in the cell and the distance of the customer. Our aim is to uncondition the outage probability of one of the parameters. By modeling the location of the customers with a spatial process, we can obtain a mathematical description of the customer distribution within the cell. We can then use the point process to characterize the relationship between number and location of the customers. In this paper we will deal with the most general case of spatial point processes, the homogeneous Poisson process, cf. [1].

3.1 Spatial Traffic and Basic Relations

To estimate the coverage of CDMA cells in a network planning context, we consider in the following the customer population on a two-dimensional surface to constitute a spatial homogeneous Poisson process. Thus, the distribution of the random variable K_A of calls on a surface with area A is Poisson distributed as:

$$P(K_A = k) = \frac{(\lambda A)^k}{k!} \cdot e^{-\lambda A} \tag{7}$$

where λ (in calls per km^2) denotes the spatial traffic intensity. The distribution of K_A given above is valid at any arbitrary observation instant.

Based on this Poisson process assumption we now consider a cell modeled by a circle with radius R_C. One active call is assumed to be on the circle and $k-1$ connections are inside the circle, see also Fig. 1. The corresponding coverage area is $A = \pi R_C^2$, where both A and R_C are random variables. To give a precise mathematical description, we can define the random variable A as the surface of the smallest circle containing k points. Due to the property of the spatial Poisson process, the size of the surface A is distributed according to an Erlang-distribution of order k:

$$A(y) = P(A \le y) = 1 - \sum_{i=0}^{k-1} \frac{(\lambda y)^i}{i!} \cdot e^{-\lambda y}$$

with the probability density function:

$$a(y) = \frac{d}{dy} A(y) = \frac{\lambda (\lambda y)^{k-1}}{(k-1)!} \cdot e^{-\lambda y}$$

It is more useful, however, to consider the radius of the cell rather than its surface, as this can translate directly to the distance between customer and base station. The distribution of the radius R_C can be derived as

$$R_C(x) = 1 - \sum_{i=0}^{k-1} \frac{(\lambda \pi x^2)^i}{i!} \cdot e^{-\lambda \pi x^2}$$

with the probability density function

$$r_C(x) = \frac{\lambda (\lambda \pi x^2)^{k-1}}{(k-1)!} \cdot e^{-\lambda \pi x^2} (2\pi x) \tag{8}$$

With (8) we can now calculate the probability that we have a cell radius of x for a cell currently supporting k calls assuming an intensity of λ.

The following figures illustrate the shape of the curve of $r_C(x)$. Fig. 3 depicts the sensitivity of $r_C(x)$ on variations of k. It shows that to support fewer calls, the mean cell radius is in general smaller than for larger values of k, for a fixed traffic intensity of $\lambda = 50$. The shape and variance of the curves stay the same.

In Fig. 4 the curve for $r_C(x)$ is plotted with a fixed value of $k = 20$ and varying traffic intensities λ. It indicates that for areas with high values of λ, e.g. urban or dense urban regions, the cell radius is more clearly defined than for areas with lower intensity, like the curve for $\lambda = 10$. The range of the radius is here more than double the size compared to $\lambda = 100$.
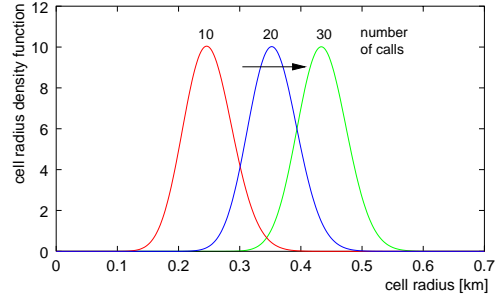

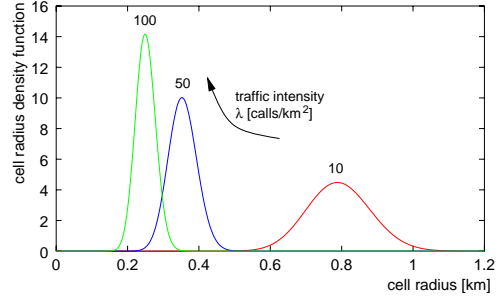Figure 3: Density function of the cell radius for different number of calls

Figure 4: Density function of the cell radius for different spatial traffic intensity

3.2 CDMA Cell Coverage

Considering the two-dimensional customer traffic process as discussed above, the coverage area of a cell in a CDMA network will be estimated, where the outage probability given in Eqn. (4) will be taken as the criterion to define the boundary of a cell.

We can now get back to Eqn. (5) and Eqn. (6). With the Poisson process we now have a mechanism to describe the probability to have k calls in the cell with radius x and the probability that the radius of the cell with k calls is x.

First we look at a cell with radius $R_C = x$. The probability to have k connections in the cell with radius x is simply Poisson distributed, as shown in (7). The overall unconditioned outage probability for this cell can then be derived as:[2]

$$P_{\text{out}}(x) = \sum_{k=1}^{\infty} P_{out}(x,k) \cdot \frac{(\lambda \pi x^2)^k}{k!} \cdot e^{-\lambda \pi x^2} \tag{9}$$

The resulting outage probability in (9) is now no longer dependent on the number of calls in the cell like Eqn. (4), but only on the distance from the base station and the intensity of the cluster process. This translates to an assumed traffic value for the area of the cell. Therefore, it is enough to know the environment of the cell, such as urban or suburban, and map

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[2]For the summation over k, values for $P_{out}(x,k) = 1$ were assumed, when k exceeded k_{pole}.

this value to a certain value of λ.

We now focus on the question, how large the coverage area of a CDMA cell is if we want to cover a given number of k active calls. From network design viewpoint the coverage corresponds to a chosen outage probability, which can be derived by combining Eqn. (4) and Eqn. (8).

$$P_{out}(k) = \int_0^\infty P_{\mathrm{out}}(x,k) \cdot r_C(x) \, dx \qquad (10)$$

Eqn. (10) gives us a relationship between probability of outage and number of calls. Here, it is no longer necessary to know the distances of the individual customers as these are being implicitly represented by the Poisson process.

4 RESULTS

The results analyzed by this paper suggest that the CDMA cell has to be provisioned like a processor in a queuing system. This implies that like queueing systems we can construct load service curves and use stability arguments to determine how heavily they should be loaded up. These curves are presented in this section. Like average delay, the GOS for CDMA cell would be the outage probability P_{out}.

The choice of P_{out} would depend on the area over which the coverage of a CDMA cell is desired. In this analysis, P_{out} is maintained along the edge of the cell, the area over which the outage will be maintained will extend from the base station to the edge of the cell. In general, the target of about 90-95% edge coverage is desired. In otherwords we would like P_{out} to be between 5-10 %. In the following section we discuss this issue in more details with some numerical examples.

4.1 Coverage Capacity Dynamics

Given a value of $P_{\mathrm{out}}(x,k)$ and a number of calls currently being supported by the cell, the radius of the cell is fixed. Similarly, given a value of $P_{\mathrm{out}}(x,k)$ and the radius of a cell, the number of calls supported by the cell is fixed. These ideas are summarized in Fig. 5, where we plot $P_{\mathrm{out}}(x,k)$ from Eqn. (4) versus calls and Fig. 6 with $P_{\mathrm{out}}(x,k)$ versus distance.

Some interesting observations about the behavior of these relationships can be made. Both curves have a slowly increasing part and a very fast increasing part. In general, we would like to operate in the slowly changing part of the curve as far as possible to ensure stability of the GOS for the customers.
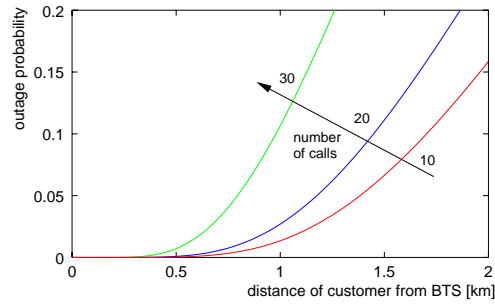

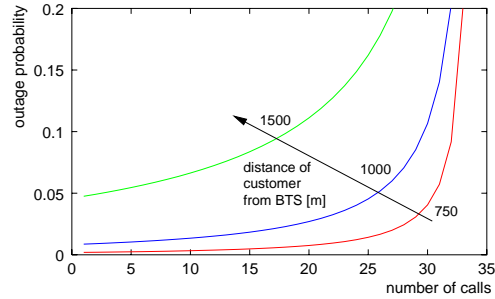Figure 5: Impact of customer-BTS distance on outage probability

Figure 6: Impact of number of calls on outage probability

4.2 Interaction of Capacity and Customer Dynamics

The interaction between customer dynamics and the capacity dynamics leads to the new definitions of the coverage and the capacity of the cell as given by Eqn. (9) and Eqn. (10). In particular, consider Fig. 7 and 8.
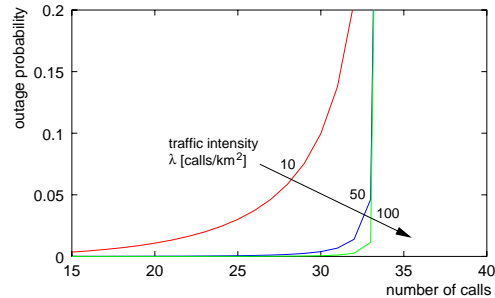

Figure 7: Relationship between capacity and outage probability

It is clear that the rate of change of $P_{out}(x)$ as a function of distance is small until it reaches a certain point where it extends exponentially (much like the delay curves of the queuing system). Similarly, if you look at the capacity part of the curve, the rate of change of $P_{out}(k)$ is initially small but extends exponentially as the number of calls increase. Both curves approach a step function for a limit of $\lambda \to \infty$.

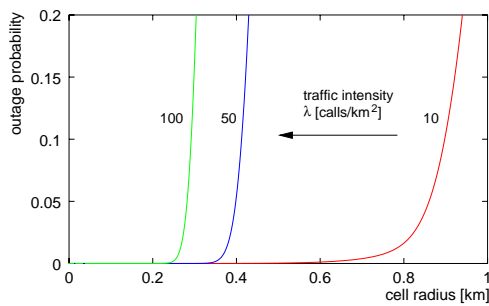Thus, for a CDMA cell the capacity and coverage

Figure 8: Relationship between radius and outage probability

are both provisionable quantities and will be dominated by stability issues more than actual resource constraints. In general given a spatial traffic intensity λ and P_{out}, the capacity and the coverage of the cell can both be determine by stability arguments.

5 CONCLUSIONS AND OUTLOOK

In this paper we have modelled the behavior of the CDMA cell using clustered Poisson process. We have found that when the RF dynamics of the cell is modelled using this two dimensional description of the user arrival process, the size and the capacity of the cell are completely determined by the spatial traffic density and stability arguments. This is much like provisioning a server in a queueing system.

The above conclusion has some very interesting ramifications. For example, during CDMA cellular network design it will be important to consider the spatial traffic intensity. This is a new finding because in our opinion this was not a requirement for network planning of TDMA and FDMA cellular system.

The definition of cell capacity has to be revisited. In the classical cellular systems the capacity of the cell was defined as the number of radio channels or time division channels that the cell could support. This number was independent of the spatial traffic intensity. In CDMA the capacity of a cell will be dependent on the spatial traffic intensity.

So far we examined only a single cell, assuming a given value for interference from other cells. Our next step will be to take a look at a cluster of two or more cells and the shape of the outage probability at the common cell boundaries. This is especially interesting, since through CDMA's *soft handoff* a mobile station is contacting to 3 base stations with the best signal–to–interference ratios at a time. Soft handoff will take place at the cell boundary regions and further reduce the probability of outage there. We can therefore consider the present work as a worst case approximation.

Another improvement can be done by enhancing the model of the spatial point process, e.g. using a phase–type process [4]. Here, we hope to be able to also consider areas with an inhomogeneous traffic distribution or the situation where a cell with high intensity is next to a cell with lower intensity. A further topic of research is the examination of different activity patterns of the customers to model different types of traffic like voice and data.

Acknowledgement

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