

1. Introduction:

Capacity of cellular systems is of major concern to designers due to its economic value. For any multiuser communication system, the measure of its economic usefulness is not the maximum number of users which can be serviced at one time, but rather the peak load that can be supported with a given quality and with availability of service [1].

In CDMA cellular systems with interference based admission control, the interference level resulting from the connected users in the cell affects the capacity and coverage of the cell and any reduction in interference converts directly into an increase in capacity. Also, It is well-known for CDMA systems with nonorthogonal users and single-user detection that the coverage of a cell has an inverse relationship with the user capacity of the cell [2]. Since all users share the same spectrum, power control is exercised in the reverse and forward links.

In this report, the capacity analysis of cellular CDMA systems and the coverage-capacity tradeoff inherent in such systems will be explored along with some methods to increase the capacity and coverage of such systems. Also, the coverage-capacity tradeoff of mixed traffic UMTS CDMA systems will be explored to touch on the differences between second generation (2G) and third generation (3G) cellular systems in terms of coverage and capacity.

2. Reverse and forward link capacity analysis of CDMA systems [3]

The capacity of CDMA systems is considered separately for forward and reverse links due to the difference in the interference characteristics. For cellular systems, interference is divided into inter-cell and intra-cell interference. The following assumptions are made throughout the analysis:

- Users are power controlled by the base station (BS).
- All base stations require the same SNR for adequate performance.
- Power control is exercised by the BS corresponding to pilot with maximum power seen at the user.
- The admission policy is based on the interference level (SIR based admission policy) where users are admitted to the cell until a predetermined level of interference is reached.
- Users are uniformly distributed in each cell and the number of users in each cell are equal.

2-1. Reverse link capacity analysis

In the reverse link, several users connect to a Base Station (BS) and the power received from all the users is equal due to power control which is accomplished by sending a pilot signal to each user with known power and phase. Therefore, the inter-cell interference in the reverse link depends only on the number of users.

For a single cell case with single user detection and deterministic number of users, the capacity analysis is straight forward as will be illustrated below. The SIR seen at BS receiver is:

$$SIR = \frac{S}{(N-1)S + \eta} \quad (1)$$

where, S: power of the received signal from each user,

N: number of users in the cell,

η : Background noise.

The SIR could be increased (interference reduced) by controlling the terms in the denominator of (1).

There are two ways to reduce the interference seen by the BS in the single cell case. First, using sectorization where directional antennas are used at the BS for receiving and transmitting. The most common case is using three antennas which divides the cell into three sectors and so the number of users seen by the sector antenna is reduced by a factor of 3. Secondly, voice activity monitoring where the transmission from the user is suppressed when no voice is present. Extensive studies showed that either speaker is active only 35% to 40%.

From (1), the SNR (Energy-per-bit to Noise density ratio) could be expressed by:

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)S/W + \eta/W} \quad (2)$$

where, E_b : Energy per bit seen at the receiver,

W: spreading bandwidth,

R: information bit rate,

N_0 : noise power spectral density.

Following from (2), the maximum number of users in the cell (capacity) could be expressed as:

$$N = 1 + \frac{W/R}{E_b/N_0} - \frac{\eta}{S} \quad (3)$$

which shows that the number of users depends on the SNR required by the BS for adequate performance. The SNR requirement could be translated into an interference level threshold for an SIR admission policy.

For a multi-cell system, the BS suffers from inter-cell interference in addition to the intra-cell interference. The effect of this interference on the SNR seen at the BS under consideration (BS_0) could be observed by simply adding an inter-cell interference term to (2)

$$\frac{E_b}{N_0} = \frac{S/R}{(N-1)S/W + I/W + \eta/W} \quad (4)$$

where, I: the total inter-cell interference seen by BS_0 receiver from users in neighboring cells who are not controlled by BS_0 .

However, the capacity couldn't be computed straightforwardly as we did in (3) because the inter-cell interference (I) is not a deterministic term. The inter-cell interference depends on the large scale variations seen by the signal of the other cell users when propagating towards BS_0 . The generally accepted model for the gain due to large scale variations is:

$$G = 10^{(\xi/10)} r^{-4} \quad (5)$$

where, $\xi: N(0, \sigma^2)$ with σ usually equal to 8 dB, r is the distance traveled by the signal.

So, for a user at distance r_m from his BS and r_0 from BS_0 , the interference seen by BS_0 can be expressed as

$$I(r_0, r_m) = \frac{10^{(\xi_0/10)}}{r_0^4} \cdot \frac{r_m^4}{10^{(\xi_m/10)}} \cdot S \quad (6)$$

where the first term represents the path loss and the second term is due to power control exercised by BS_m on the interferer (reciprocal of the path loss). To calculate the overall interference seen at the BS, we need to integrate (6) over the area seen by the BS which requires finding r₀ and r_m for each point in the region. Having the cell divided into three sectors as discussed above, the area of interest is shown in Fig .1.

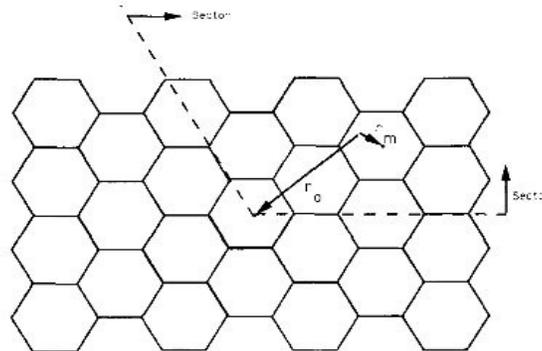


Fig. 1. Reverse link capacity calculation geometry [3]

After integrating (6) over the area shown above, the upper bounds on the statistics of I/S are found and the SNR seen at the BS can be expressed as:

$$\frac{E_b}{N_0} = \frac{W/R}{\sum_{i=1}^{N_s-1} \nu_i + I/S + \eta/S} \quad (7)$$

where, N_s: number of users per sector,

ν_i : voice activity random variable ~ Bernoulli (ρ), where ρ is usually chosen around 3/8.

In (7), we have two random variable: I and ν . Therefore, the capacity is calculated such that a certain BER required for adequate performance is achieved with a certain probability which translates to a requirement on the SNR. With an efficient modem and a powerful convolutional code and two-antenna diversity, adequate performance corresponds to BER < 10⁻³ which is achievable on the reverse link when SNR > 7 dB. Consequently, the required performance is achieved with probability P = Pr(BER < 10⁻³). Since we have upper bounds on the statistics of I/S, we can upper bound the complement of P which gives a lower bound on P (the probability of achieving the required performance). The figure below shows the reverse link capacity/sector for an upper bound on 1-P.

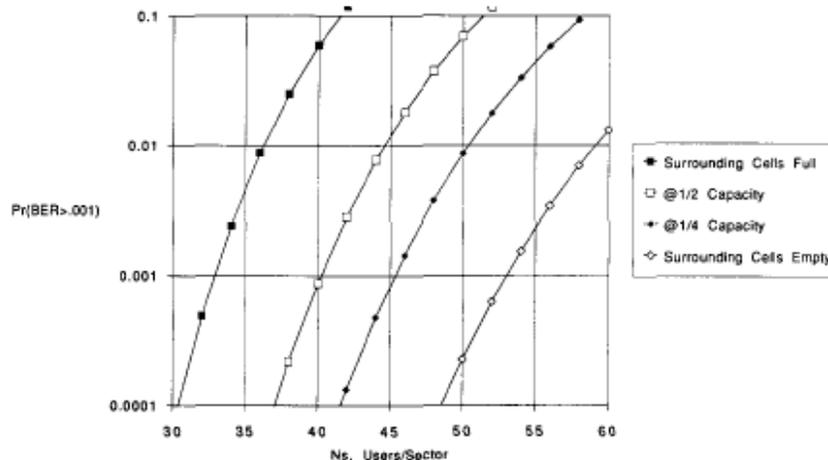


Fig. 2. Reverse link capacity/sector (W=1.25 Mhz, R= 8 kb/s, $\rho = 3/8$) [3]

Fig. 2 shows that as we relax the performance requirements, a higher capacity/sector could be achieved which shows that CDMA systems has a soft limit on the capacity compared to the hard limit in TDMA and FDMA systems. Also, as the number of users in neighboring cells increases, the capacity/sector decreases.

2-2. Forward link capacity analysis

In CDMA systems, the reverse link has less capacity than the forward link due to the limited power available at the user. For cellular systems, power control in the forward link is required due to the high interference experienced near the boundaries of the cell due to the interference from base stations of neighboring cells. Power control in the forward link takes the form of power allocation at the BS according to the needs of the users. To enable the BS to allocate power, the user sends information about the power received from its BS, which is determined based on the pilot power, and the total power received from all other BSs to its BS at the beginning of transmission. Now, the BS has reasonable accurate estimates of S_{T_1} and $\sum_{i=1}^K S_{T_i}$ where $S_{T_1} > S_{T_2} > \dots > S_{T_K} > 0$ are the powers received by the user under consideration from the sector facing it, assuming all but K received powers are negligible. The received SNR at the i^{th} user can be lower bounded by:

$$\left(\frac{E_b}{N_0}\right)_i \geq \beta \phi_i \frac{S_{(T_1)}/R}{[(\sum_{j=1}^k S_{(T_j)})_i + \eta]/W} \quad (8)$$

where, β : the fraction of the total site power devoted to users (excluding pilot),

Φ_i : the fraction of power devoted to the i^{th} user which could be viewed as the power allocation variable,

S_{T_1} : the total power transmitted by the BS controlling the user under consideration.

In (8), we have one random variable (S_{T_j}) which is a lognormal random variable since the power received from the j^{th} BS is affected by the large scale variations. Now, using the same methodology used in the reverse link capacity analysis with more complicated calculations and approximations, the following figure is obtained:

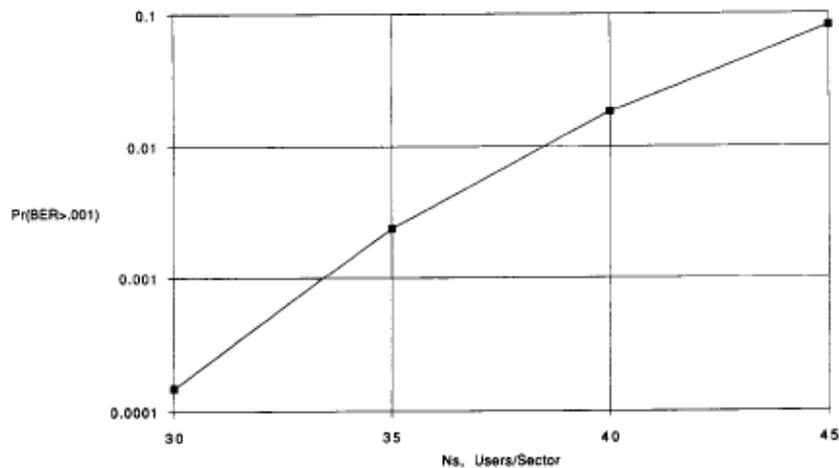


Fig. 3. Forward link capacity/sector ($W=1.25$ Mhz, $R= 8$ kb/s, $\rho = 3/8$, $\beta=0.8$) [3]

3. Reverse link Erlang capacity analysis[1]

The Erlang capacity arises in the analysis of the capacity of cellular systems as it computes the available resources for the users. Erlang capacity refers to the average traffic load in terms of average number of users requesting service resulting in a certain blocking probability. Blocking probability refers to the probability that a new user will find all channels busy and hence be denied service. In CDMA systems with SIR admission policy, this corresponds to the case when the overall interference in the system is above a certain threshold. Throughout the following analysis, the interference level isn't allowed to exceed the background noise by more than 10dB to guarantee adequate performance and the blocking probability should be less than 1% which translates to $Pr(I_0/N_0 > 10) \leq 0.01$.

First, the reverse link Erlang capacity analysis will be carried out to a simple case with the following assumptions:

- 1) Constant number of users N_u in every sector,
- 2) each user transmits continuously ($\rho=1$),
- 3) each BS receiver requires the same SNR for adequate performance.

So, there is no blocking as long as the following inequality is true:

$$N_u E_b R (1+f) + N_0 W \leq I_0 W \quad (9)$$

where, f : the ratio of the inter-cell to the intra-cell interference at BS_0 .

This translates to the following condition on the number of users in the cell:

$$N_u \leq \frac{(W/R)}{(E_b/I_0)} \cdot \frac{(1-\eta)}{(1+f)} \quad (10)$$

where, $\eta = N_0/I_0 = 0.1$.

This agrees with the analysis carried out in the previous section where the number of users is inversely proportional to the SNR requirement and the interference.

In the analysis so far, we have assumed the number of users in the cell to be deterministic. Also, we assumed that the power control is perfect. To account for the randomness of number of users and power control inaccuracies, the following assumptions are made:

- 1) Number of active calls in the sector is a Poisson random variable with mean λ/μ ,
- 2) each user is gated on with probability ρ and off with probability $1-\rho$,
- 3) each user's required energy-to-interference ratio is varied according to propagation conditions.

With the above assumptions, the no blocking condition corresponds to the following inequality:

$$\sum_{i=1}^k v_i * E_{bi} * R + \sum_j^{other\ cells} \sum_{i=1}^k v_{i(j)} * E_{bi(j)} * R + N_0 * W \leq I_0 * W \quad (11)$$

The blocking probability can then be written as:

$$P_{blocking} = P \left\{ Z = \sum_{i=1}^k v_i * \epsilon_i + \sum_j^{other\ cells} \sum_{i=1}^k v_i^{(j)} * \epsilon_i^{(j)} > \frac{W/R}{1-\eta} \right\} \quad (12)$$

where, k : number of users/sector is a Poisson random variable with mean λ/μ ,

ϵ_i : SNR required from the i^{th} user (E_{bi}/I_0).

To evaluate the expression in (12), we need to know that statistics of k , v , ϵ which are as follows:

ν : Bernoulli(ρ).

k : Poisson (λ/μ).

ϵ : depends on power control mechanism. It has been demonstrated that the inaccuracy in power control loops are approximately log-normal with a standard deviation between 1 and 2. However, for excessive multi-path, we'll get a bigger standard deviation. From field trials, with all cells fully loaded, ϵ maybe modeled as a log-normal random variable $10^{X/10}$ with $X \sim N(7, 2.5)$ dB.

For a single cell case, we get the following capacity curve:

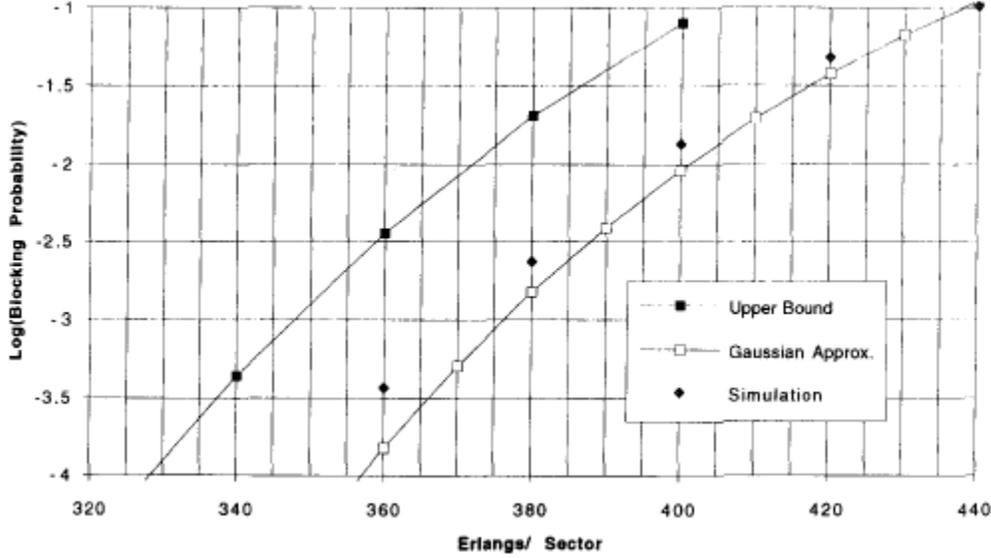


Fig. 4. Blocking probability for a single cell interference ($W/R = 1280$, $\rho = 3/8$) [1]

The capacity values obtained in this case are about 10 times larger than those obtained in the previous analysis which is because of the difference in the W/R value used in the simulation. Also, the results shown in Fig. 4 suggest that the Gaussian approximation of the random variable Z is close to the values obtained from the simulation using numerical integration. This suggests using Gaussian approximation for the multi-cell case to ease the calculations. Using the central limit theorem on Z , we get

$$P_{\text{blocking}} \approx Q\left[\frac{A - E(Z)}{\sqrt{\text{Var}(Z)}}\right] \quad (13)$$

where, $E(Z) = (1+f) E(k) E(\nu \epsilon) = (1+f)(\lambda/\mu) \exp[(\beta \sigma)^2/2] \exp[\beta m]$,

$$\text{Var}(Z) = (1+f) E(Z) \text{Var}(\nu \epsilon) + \text{Var}(k) [E(\nu \epsilon)]^2 = (1+f)(\lambda/\mu) \rho \exp[2(\beta \sigma)^2] \exp[2\beta m] .$$

From (13), we get the following expression for the Erlang capacity of the reverse link (Erlangs/sector):

$$\frac{\lambda}{\mu} = \frac{(1-\eta)(W/R) F(B, \sigma)}{\rho(1+f) \exp(\beta m)} \quad (14)$$

where, $F(B, \sigma) = \exp[-(\beta \sigma)^2/2] [1 + (\beta/2) \exp[3(\beta \sigma)^2/2] (1 - \sqrt{1 + 4 \exp[-3(\beta \sigma)^2/2] / B})]$,

$$B = \frac{Q^{-1}(P_{\text{blocking}})^2}{A} ,$$

$$A = \frac{(W/R)(1-\eta)}{\exp(\beta m)} .$$

Using (14), the Erlang capacity vs blocking probability for different cases of inaccuracies in power control where sig is the standard deviation of the SNR is shown in Fig. 5. As shown, a standard deviation of 2.5 dB in power control causes a reduction of 1 dB in capacity. Also, the curves were obtained for different value of W/R than those used in [1] which makes them closer to the values obtained in [3].

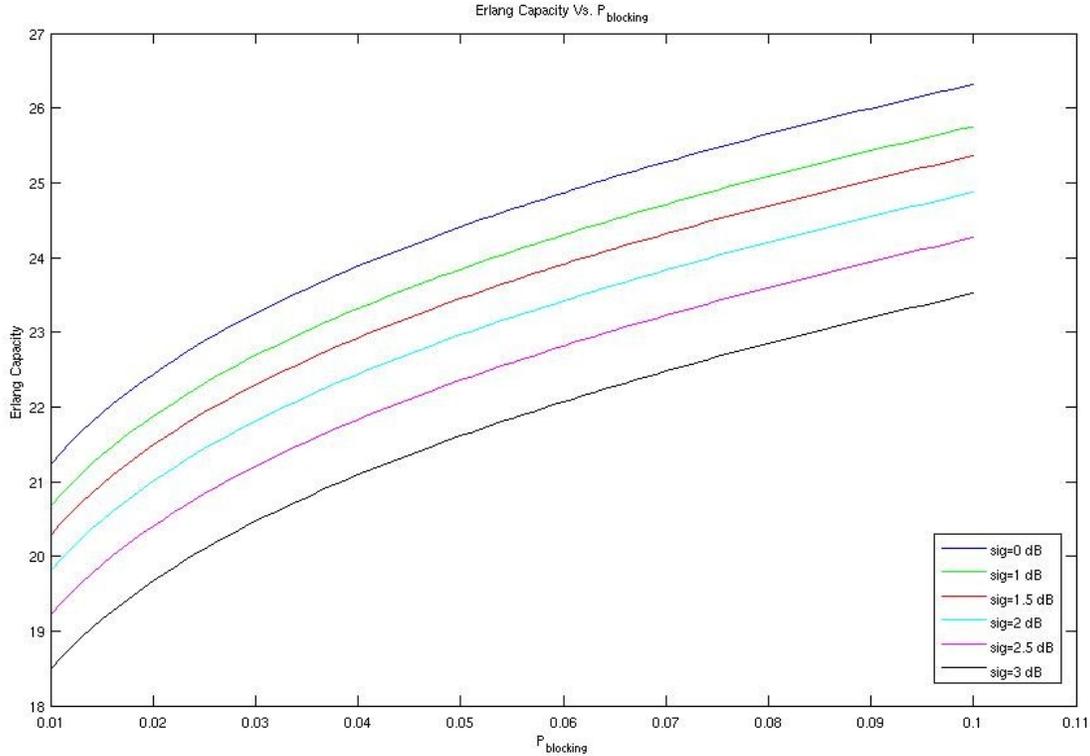


Fig. 5. Erlang capacity vs blocking probability for different values of standard deviations for X
(Parameters: W = 1.25 Mhz, R = 14.4 Kbps, $\rho = 0.45$, $m_e = 7\text{dB}$, $\eta = 0.1$)

Since cellular systems in the reverse link are power limited, it is important to determine the Erlang capacity as a function of the minimum SNR values required for each user which corresponds to the minimum transmitted power per user. This could be achieved by fixing the blocking probability and finding η for each user loading λ/μ given the link attenuation, receiver sensitivity, antenna gains. The total interference per cell can be expressed in terms of the background noise and the other user interference as:

$$I_0 W = \rho(\lambda/\mu) S + N_0 W \quad (15)$$

which is equivalent to:

$$\frac{S}{N_0 W} = \frac{1}{\rho(\lambda/\mu)} \left(\frac{I_0}{N_0} - 1 \right) = \frac{(1/\eta) - 1}{\rho(\lambda/\mu)} \quad (16)$$

Using (16) and the procedure described above, we get the minimum SNR versus Erlang capacity/sector curve shown in Fig. 6.

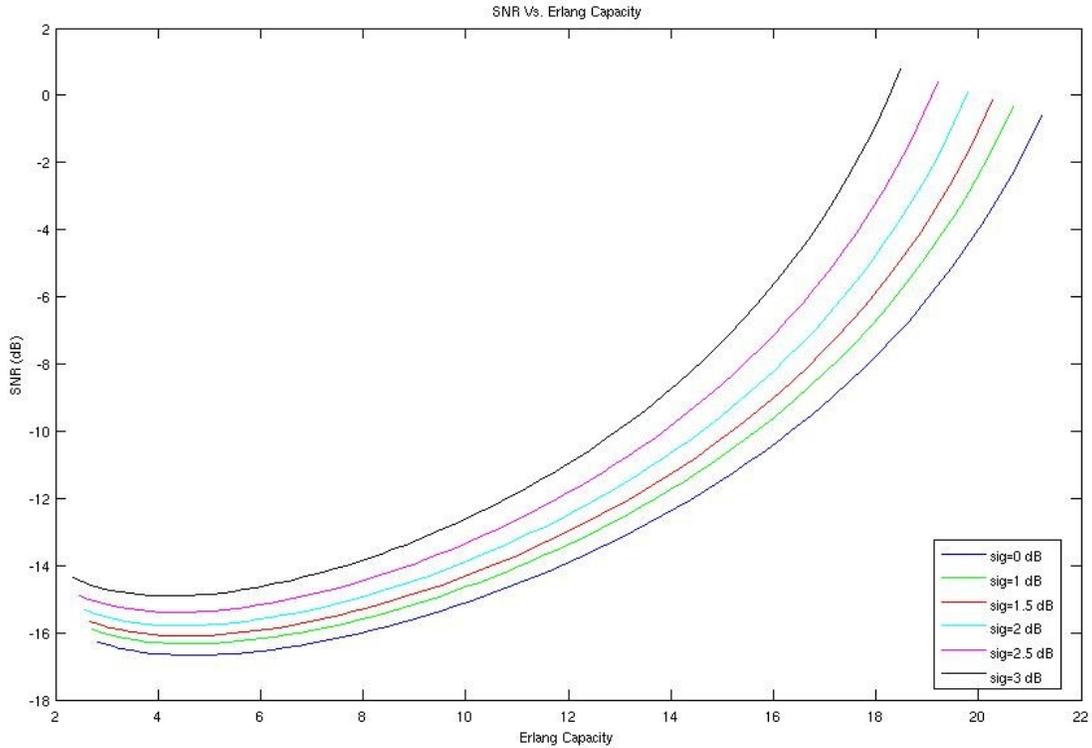


Fig. 6. Minimum SNR vs Erlang capacity/sector (Parameters: $W = 1.25$ Mhz, $R = 14.4$ Kbps, $\rho = 0.45$, $m_e = 7$ dB, $\eta = 0.1$ to 0.8)

So far, the effect of interference on the capacity of a CDMA system has been investigated along with the capacity as a function of: BER, blocking probability, and SNR. In CDMA systems, there is an inherent tradeoff between coverage and capacity. An accurate prediction of cell coverage as a function of user capacity is essential in CDMA network design and deployment. Therefore, the coverage-capacity tradeoff in cellular CDMA systems will be considered next.

4. Capacity-Coverage Tradeoff in CDMA systems [2]

In cellular CDMA systems with single-user detectors, intra-cell interference limits the coverage of the cell. Cell coverage could be defined as the maximum distance that a given user of interest can be from the base station and still have a reliable received signal strength at the base station. Since the intra-cell interference increases as the number of users increase, for a given upper limit on transmit power, the coverage of a cell is inversely proportional to the number of users in it.

To derive an analytical relationship between coverage and capacity, we need to derive an equation that relates the cell radius to the number of users in the cell which could be used to set hard limits on the maximum number of users admitted into a cell such that the coverage requirements are met. In the previous analysis, we only considered the capacity of a CDMA system which is related to the outage probability due to the overall interference exceeding a predetermined level. To analyze the coverage, we must take into consideration the probability that the user doesn't have enough power to meet the SNR requirements of the BS. Now, we define the outage as the event when the user couldn't get a reliable

communication with the BS for a certain period of time as a result of not being able to meet the SNR requirement of the BS which results in service degradation and call drop. The probability of instantaneous outage could be expressed as:

$$P_{\text{outage}} = P_{\text{blocking}} + P(\text{required power} > S_{\text{max}} \mid \text{no blocking})$$

The coverage-capacity tradeoff will be considered for two cases: the simple case of deterministic number of users and the practical case of random number of users. The coverage-capacity tradeoff analysis will be independent of the admission policy and call blocking probability.

4-1. Coverage-Capacity Tradeoff with deterministic number of users

To get an expression for the outage probability, the blocking probability will be analyzed first then a limit will be set on the maximum power. The SIR for the a user at the BS varies with time due to multipath and imperfection in power control as was shown in section 2. The inaccuracy in power control algorithm can be modeled as a log-normal random variable. So, the SIR demanded from the j^{th} user due to the power control algorithm can be modeled as a log-normal random variable and can be expressed as:

$$\hat{\epsilon}_j^x = \epsilon_j^{\text{target}} \delta_j^{\hat{\epsilon}}$$

where, $\delta_j^{\hat{\epsilon}}$: the error in the power control algorithm,

$\epsilon_j^{\text{target}}$: the target SNR required by the BS for adequate performance.

At anytime, the SIR maybe modeled as iid log-normal random variable as suggested in section 2. In order to meet the SIR requirements, the required received powers $\{\hat{S}_j^x\}$ must satisfy the power control equations

$$\hat{\epsilon}_j^x = \frac{\hat{S}_j^x / R}{\sum_{i:i \neq j} v_i \hat{S}_i^x / W + N_0 + I} \quad (17)$$

It can be easily shown that (17) has a feasible solution if, and only if, the following inequality is true:

$$\sum_{i=1}^k \frac{R \hat{\epsilon}_i^x v_i}{W + R \hat{\epsilon}_i^x v_i} < 1 \quad (18)$$

and the required received power is:

$$\hat{S}_j^x(k) = \frac{(N_0 + I) W R \hat{\epsilon}_j^x}{W + R \hat{\epsilon}_j^x v_j} \quad (19)$$

$$1 - \sum_{i=1}^k \frac{R \hat{\epsilon}_i^x v_i}{W + R \hat{\epsilon}_i^x v_i}$$

Let A_{out} be the event that (17) doesn't have a feasible solution, the blocking probability can now be

expressed as: $P\{A_{\text{out}}\} = P\left\{ \sum_{k=1}^K \frac{1}{\delta_k + 1} \geq 1 \right\}$ where $\delta_k = \frac{W}{R \epsilon_k^x}$ and $\epsilon_k^x(\text{dB}) \sim N(m_\epsilon, \sigma_\epsilon^2)$

Let $X_k = \frac{1}{\delta_k + 1}$

Then $p_{X_k}(x) = \frac{10}{\ln 10} \frac{1}{\sigma_\epsilon \sqrt{2\pi} (1-x)} \exp\left(-\frac{[10 \log_{10}\left(\frac{R}{W} \frac{1-x}{x}\right) + m_\epsilon]^2}{2\sigma_\epsilon^2}\right) \quad (20)$

Using numerical convolution it can be shown that as the number of users in the cell increases, the outage probability increases exponentially when no limit is set on the maximum transmitted power which agrees with what we have in Fig. 4. Therefore, this analysis is equivalent to the Erlang capacity analysis. After analyzing the blocking probability, we now consider the case when a limit on the maximum transmitted power is set. Let B_{out} be the event that (17) has a feasible solution but the power required is greater than the maximum available from the user. Then, $P(B_{out})=P(S_{trans}>S_{max})$ where, $S_{trans}=S_1+PL(d)+Z_1$ and $PL(d)+Z_1$ are the large scale variations in dB.

So, the outage probability can be expressed as:

$$P_{out}=P(A_{out})+[1-P(A_{out})]P(S_1^x+PL(d)+Z_1>S_{max}|A_{out}^c)$$

Now, let R_{cell} be the distance from the BS at which $P_{out} = p_m$ (maximum outage probability) for a user of interest. Then,

$$P(A_{out}) + [1 - P(A_{out})]P(S_1 + K_1 + K_2 \log R_{cell} + Z_1 > S_{max} | A_{out}^c) = p_m \quad (21)$$

In (21), there are two terms that depend on k : A_{out} and S_1^x . A_{out} could be expressed as a function of k as shown above ($P_A(k)$). After determining the distribution of S_1 conditioned on A_{out}^c as a function k we get:

$$\log R_{cell} = \frac{1}{K_2} [S_{max} - K_1 - m_S(k) - \sqrt{\sigma_S^2(k) + \sigma_Z^2} Q^{-1}(\frac{p_m - P_A(k)}{1 - P_A(k)})] \quad (22)$$

where, $PL(d) = K_1 + K_2 \log(d)$.

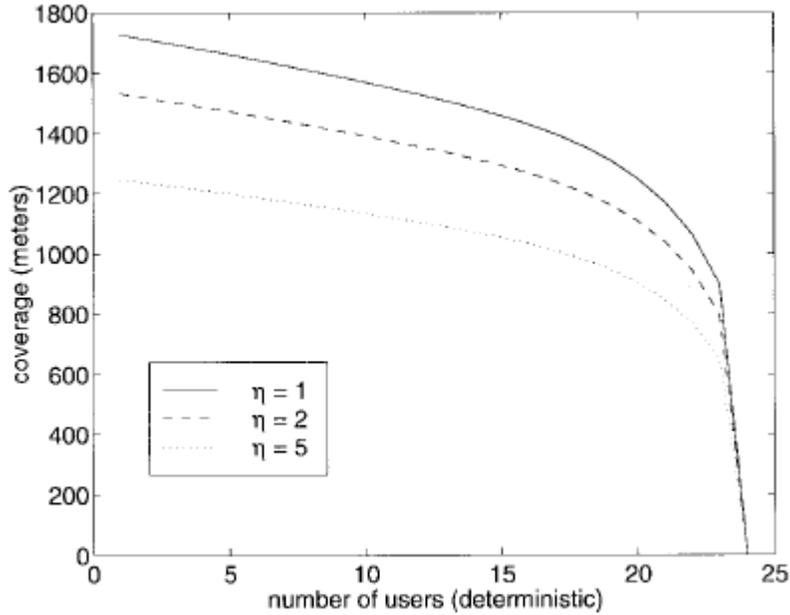


Fig. 7. Coverage versus number of users ($W = 1.25$ Mhz, $R = 14.4$ Kbps, $\rho = 0.45$, $m_e = 7$ dB, $\sigma_e = 2.5$ dB, $K_1 = 17.3$ dB, $K_2 = 33.8$ dB, $S_{max} = 23$ dBm, $N_0 = -169$ dBm/Hz, $p_m = 0.05$, $\sigma_z = 8$ dB) [2]

A point of interest in Fig. 7 is where the curve intersect the x-axis (number of users as the coverage shrinks to zero) which is defined as the pole capacity (k_{pole}). This represents the Erlang capacity of the CDMA system. Clearly, the pole capacity is independent of the maximum allowable interference because there is no limitation on the transmitted power and the total interference to background noise ratio does not affect the SIR demanded by the power control algorithm.

4-2. Coverage-Capacity Tradeoff with random number of users

To design cell coverages and capacities to match projected traffic densities in the network, it is appropriate to model the number of users in a cell as a random variable κ . The statistics will be a function of the admission policy and the offered traffic. The average outage probability at distance d can be calculated as:

$$P_{out}^-(d) = \frac{1}{1 - p_{\kappa}(0)} \sum_{k=1}^{k_{pole}} p_{\kappa}(k) [P_A(k) + [1 - P_A(k)] P(S_1^x + PL(d) + Z_j > S_{max} I A_{out}^c)] \quad (23)$$

As before, $P_{out}^-(R_{cell}) = p_m$. If κ has as Poisson with parameter ζ truncated at k_{pole} , the average number of users (c) could be expressed as

$$c = E[\kappa] = \sum_{k=0}^{k_{pole}} k p_{\kappa}(k) = \sum_{k=0}^{k_{pole}} k \frac{\zeta^k e^{-\zeta} / k!}{\sum_{j=0}^{k_{pole}} \zeta^j e^{-\zeta} / j!} = \zeta \left[1 - \frac{\zeta^{k_{pole}} e^{-\zeta} / k_{pole}!}{\sum_{j=0}^{k_{pole}} \zeta^j e^{-\zeta} / j!} \right] \quad (24)$$

By solving (23) and (24) for various values of ζ , the following tradeoff curve is obtained:

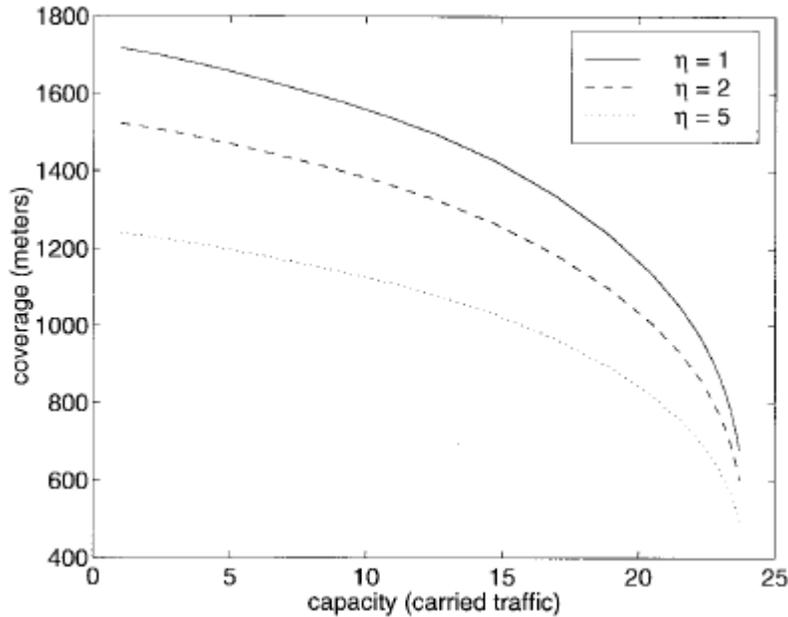


Fig. 8. Coverage versus capacity for a truncated Poisson user distribution ($W = 1.25$ Mhz, $R = 14.4$ Kbps, $\rho = 0.45$, $m_e = 7$ dB, $\sigma_e = 2.5$ dB, $K_1 = 17.3$ dB, $K_2 = 33.8$ dB, $S_{max} = 23$ dBm, $N_0 = -169$ dBm/Hz, $p_m = 0.05$, $\sigma_z = 8$ dB)[2]

The pole capacity in Fig. 8 agrees with the values shown in Fig. 5 since the same admission policy is assumed. The beauty of coverage-capacity tradeoff analysis is that it is independent of the admission policy and probability of outage. By plugging-in the values of p_m and deciding the appropriate user arrival model, the capacity-coverage tradeoff analysis is obtained for any desired case.

5. Effect of soft handoff

Soft Handoff is a technique whereby mobile units in transition between one cell and one of its neighbors transmit to and receive the same signal from all base stations simultaneously. In the following analysis, it will be shown that soft handoff increases cell coverage and reverse link capacity when compared to hard handoff.

5.1 Effect of soft handoff on cell coverage and reverse link capacity [4]

To consider the effect of soft handoff on the cell coverage, we must resort to the event B_{out} . In hard handoff where the user could only connect to one BS at any given time:

$$P(B_{out} | A_{out}^c) = P(10^{\zeta_0/10} r_0^{-4} > S_{trans} - S_0) .$$
 However, for soft handoff:

$P(B_{out} | A_{out}^c) = P(\min(10^{\zeta_0/10} r_0^{-4}, 10^{\zeta_1/10} r_1^{-4}) > \min(S_{trans1}, S_{trans0}) - S_0) .$ This shows that the coverage with soft handoff (with two BSs in this example) is better compared to hard handoff for distances from the BS greater than the cell radius. The following table compares the required margin for soft and hard handoff where γ is the power required from the user to overcome the effect of large scale variations (PL + Z). The required margin is 6 to 8 dB less for soft handoff than hard handoff. This corresponds to an increase in the distance a user can move of 1.5 to 2 dB or an increase in the area by 3 to 4dB (2 to 2.5).

Relative Distance Beyond Cell Boundary r_0	Hard Handoff Required Margin γ_{Hard} dB	Relative Margin $\gamma_{Hard} - \gamma_{soft}$ dB	Relative Coverage Area
1	10.3	4.1	1.6
1.05	11.1	4.9	1.8
1.1	12.0	5.8	2.0
1.15	12.7	6.5	2.1
1.2	13.5	7.3	2.3
1.25	14.2	8.0	2.5

Table I Relative coverage area for soft handoff compared to hard handoff [4]

Clearly, soft handoff increases the cell coverage compared to hard handoff.

The effect of soft handoff on the capacity could be analyzed by considering the intra-cell to inter-cell interference ratio (f). This is justified because all other factors that affect capacity are the same for soft and hard handoff cases. For hard handoff, assuming that handoff occurs at cell boundaries, “ f ” could be found by dividing the integral of (6) over the area containing the interferer users by the intra-cell interference which is equal to the number of in-cell users in the normalized power case. For soft handoff, the area of integration depends on the number of base stations involved in the handoff. The following table shows the value of “ f ” for hard and soft handoff. Where,

μ : the exponent of the path loss,

σ : is the standard deviation of the shadow fading,

N_c : the number of base stations taking part in the handoff.

σ	$\mu = 3$		$\mu = 4$					$\mu = 5$	
	Hard	Soft $N_c=2$	Hard	Soft $N_c=1$	Soft $N_c=2$	Soft $N_c=3$	Soft $N_c=4$	Hard	Soft $N_c=2$
0	0.77	0.77	0.44	0.44	0.44	0.44	0.44	0.30	0.30
2	0.86	0.78	0.48	0.48	0.43	0.43	0.43	0.33	0.30
4	1.18	0.87	0.67	0.67	0.47	0.45	0.45	0.46	0.31
6	2.01	1.09	1.13	1.13	0.56	0.49	0.49	0.78	0.36
8	4.21	1.60	2.38	2.38	0.77	0.57	0.55	1.64	0.47
10	10.9	2.80	6.17	6.17	1.28	0.75	0.66	4.27	0.73
12	35.1	5.93	19.8	19.8	2.62	1.17	0.91	13.7	1.42

Table II Values of “f” for hard handoff and soft handoff with different number of BSs involved [4]

Clearly, as the number of base stations in the soft handoff increases, the ratio f decreases which amounts to the BS under consideration seeing less interference and thus increasing the capacity.

5.2 Effect of soft handoff on the coverage-capacity tradeoff

Soft handoff increases the capacity and coverage of a CDMA system as shown in section 5.1. The effect of soft handoff on the capacity-coverage tradeoff curve will now be considered. To enable the comparison with the capacity-coverage tradeoff with no handoff, the cells will be partitioned as shown below.

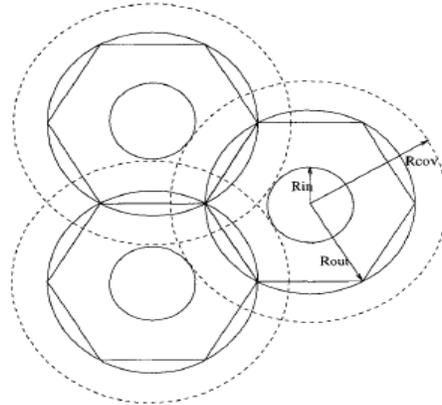


Fig. 9. Cell radii and soft handoff region ($W = 1.25$ Mhz, $R = 14.4$ Kbps, $\rho = 0.45$, $m_e = 7$ dB, $\sigma_e = 2.5$ dB, $K_1 = 17.3$ dB, $K_2 = 33.8$ dB, $S_{max} = 23$ dBm, $N_0 = -169$ dBm/Hz, $p_m = 0.05$, $\sigma_z = 8$ dB) [5]

R_{in} is designed such that the outage probability at a distance R_{in} from the cell is P_{out} (outage probability requirement) when the mobile is communicating only with the BS. So, the inner circle is the no-soft-handoff region. R_{out} is such that it allows soft handoff with other BS and R_{cov} represents the coverage of the pilot. The analysis carried out is the same as in no handoff case but with A_{out} and B_{out} replaced with their equivalent expressions for soft handoff. A_{out} will be the event that all BSs connected to the user under consideration don't have a feasible solution and B_{out} will be the event that all BSs require power from the user greater than the maximum possible.

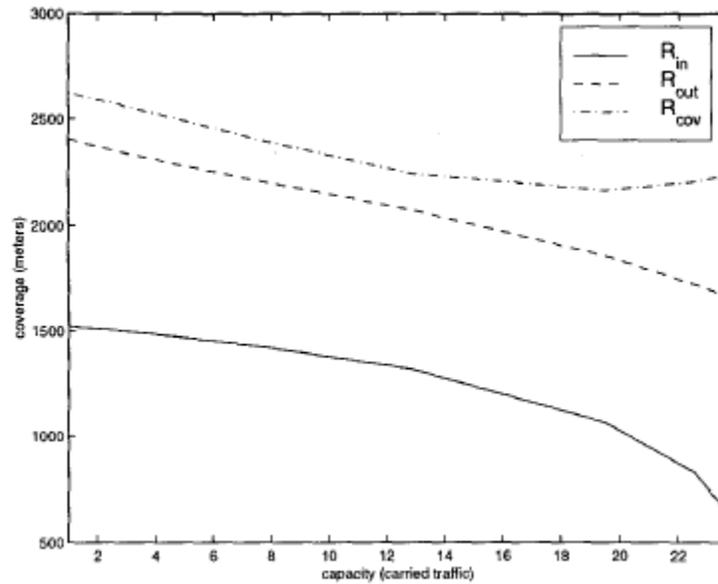


Fig. 10. Cell radii versus capacity [5]

Since R_{in} represents the distance from the BS with no soft handoff, the coverage-capacity tradeoff is the same as that shown in the section 4.2. R_{out} represents the coverage with soft handoff which is better than that with no soft handoff. R_{cov} increases near k_{pole} because R_{in} goes to zero and the pilot has to extend further to be able to cover the soft handoff region which is bigger because R_{in} is getting smaller.

6. Coverage and capacity in 3G cellular systems

6.1 Introduction to UMTS [6]

Third generation (3G) cellular systems are viewed as the enablers for high-speed data for wireless mobility market. 3G and all it is meant to be are defined in the International Telecommunications Union (ITU) specification International Mobile Telecommunications 2000 (IMT-2000). IMT-2000 is a radio network access specification defining several methods or technology platforms that meet the overall goals of the specification.

A number of technologies were proposed to meet the requirements laid down for IMT-2000. In Japan and Europe, WCDMA with FDD (and TDD for Japan) are used to meet the IMT-2000 standards. In the US, CDMA2000 is used. Since a number of groups were working on very similar technologies, two groups were created by ITU to pool resources: The third Generation Partnership Project (3GPP) and 3GPP2. 3GPP works on UMTS (Universal Mobile Telecommunication System) which is based on WCDMA, and 3GPP2 works on CDMA2000.

The radio access for UMTS is known as Universal Terrestrial Radio Access (UTRA) which is WCDMA based. The UMTS core network is based on an evolution of the GSM core network. For detailed description of UMTS, refer to [6] (pp 197 – 254).

6.2 Capacity and Coverage in mixed traffic UMTS CDMA systems [7]

In third generation systems, many applications such as Web browsing are expected to generate asymmetric traffic demand in favor of the downlink, and therefore the downlink direction is likely to be the capacity bottleneck in the WCDMA radio interface[8]. The asymmetric traffic will generate considerably more interference in the forward link than the reverse link.

In UMTS, there is a DCH transport channel (Dedicated Channel) which is mapped to two physical channels: DPDCH (Dedicated Physical Data Channel) and DPCCH (Dedicated Physical Control Channel). The DPDCH carries the actual user data and can have a variable spreading factor depending on the type of data. Spreading factor used for data is less than that for voice to keep the same processing gain ($R_{data} > R_{voice}$). Also, the voice and data SNR requirements for adequate performance are different.

The analysis of capacity-coverage tradeoff in mixed traffic UMTS differs from that of CDMA IS-95 because in UMTS the forward link is considered in the analysis. The outage event is now the event when the SNR seen by the user doesn't meet the requirements of its receiver (depending on whether data or voice is transmitted) or the event when the power required by all the users is higher than the maximum available power at the BS. Having determined the outage event, procedures with similar concepts to those in section 4 could be followed to obtain the tradeoff curves.

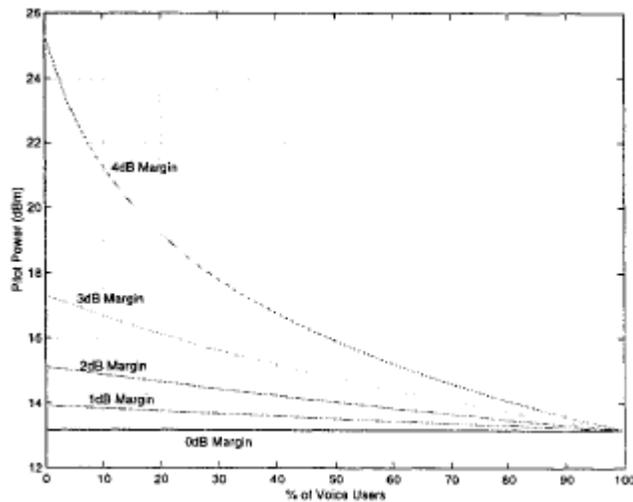


Fig. 11. Required pilot power for mix of voice and data users in an urban urban environment with $\rho=1$ [8]

Fig. 11 shows the pilot power which indicates the coverage versus the percentage of voice users. The number of voice and data users is as follows: 100% corresponds to 100 voice users and 0 data users, whereas 0% corresponds to 25 data users and 0 voice users. The rest of the points are a mix of users with the same proportion. For a 0dB interference margin (reference to the required SIR), switching between voice and data users doesn't affect the coverage. However, as the the interference increases, more power is required for data users than for voice users. Therefore, if user A (voice) and user B (data) are both in the same point in the cell, user B may notice an outage whereas user A has reliable communication with the BS. Also the interference increases, the pilot power required for data increases rapidly.

7. Conclusions

In this report, several methods to analyze the capacity of CDMA systems in literature were presented and they all showed that such systems are interference limited and any reduction in interference results in an increase in capacity. Therefore, methods such as voice monitoring, sectorization, and soft handoff increase the capacity by reducing the amount of interference seen by the BS.

Also, capacity analysis for a CDMA system is considered separately for forward and reverse links due to the difference in the interference. In the reverse link, the BS receives interference signals from in-cell and other-cell users because R-CDMA is used. However, in the forward link, orthogonal codes are used and the user receives interference signals from other BSs. In second generation cellular systems, the traffic is symmetric (voice in the forward and reverse link) and the capacity bottleneck is the reverse link because the user has much less power than the BS. Also, the forward link has better performance because coherent demodulation (with the pilot signal) and Rake receiver are used. In third generation systems however, the forward link is the capacity bottleneck because the traffic is asymmetric and the forward link (user download) is more demanding which amounts to an increase in interference.

Finally, in CDMA systems, there is a tradeoff between coverage and capacity due to the limited power available for the user. So, as the interference increases, the user has to increase his signal's power to keep the SNR at the desired value and since the power is limited, the user will experience degradation in service unless he gets closer to his BS. The coverage-capacity tradeoff curve is useful for planning cell coverage based on the expected traffic and it can be used to study the Erlang capacity. In 3G cellular systems (UMTS in our case), the coverage and capacity tradeoff is different from that of 2G. As the interference requirements are relaxed, the number of data users that the 3G system can support decreases drastically.

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