CDMA
Capacity and Coverage
Abstract
The performance of a CDMA system can be difficult to assess. Link budget calculations can be used to verify performance margins for a particular set of parameters, but fail to tell the “whole” story in an easy to understand, visual way. In this paper, a graphical depiction of CDMA coverage vs. capacity is shown to be a useful tool in evaluating the performance of a CDMA system. The graphical results are used to show scenarios in which CDMA can be both uplink and downlink limited. In particular, it is shown that in either case, the addition of a low noise tower mounted amplifier (TMA) can benefit both the coverage and the capacity of the CDMA system. The analysis is then extended to demonstrate how a TMA can be used to benefit the uplink performance of a 1xEV-DO data system.

Unanswered Questions
Is CDMA uplink or downlink limited?
Is CDMA capacity or coverage limited?
Is CDMA noise or interference limited?
Are tower mounted low-noise amplifiers of any benefit in CDMA voice or data applications?

Literature surveys and conversations with “experts” will reveal contradictory answers to each of these questions. Often, the answers are based on assumptions which are not always stated or even understood. Sometimes the answers are based on equipment limitations, rather than on any inherent limitations of CDMA[1]. In other cases, the answers are buried so deeply within the mathematics that they are unintelligible to the reader.

In reality, the answer to each of these questions is “it depends…” The goal of this paper is to take existing mathematical analyses of CDMA performance and present the results in a way that allows the system designers to understand how various system parameters affect the answers to the above questions.
CDMA Basics

The performance of any digital modulation technique can be described in terms of a normalized ratio of energy per bit (Eb) to noise density (No) required to achieve the minimum desired bit error ratio (BER)\[8\]. The relationship between this normalized value and the signal-to-noise ratio over the entire occupied bandwidth (S/N) is given by:

\[
\frac{S}{N} = \frac{E_b}{N_o} \times \frac{R}{W}
\]

Solving for Eb/No, we have:

\[
\frac{E_b}{N_o} = \left( \frac{S}{N} \right) \times \left( \frac{W}{R} \right)
\]

CDMA is a spread spectrum technique, which means that the occupied bandwidth (W) is much greater than the information bit rate (R). The ratio W/R then becomes a factor by which the E_b/N_o is improved over the full bandwidth S/N. The ratio W/R is known as the “processing gain”. For a given modulation technique, there is a minimum or threshold value of E_b/N_o (defined as \( \gamma \)) which is required to achieve acceptable performance.

Given a set of system design parameters, and knowing the required E_b/N_o, the allowable path loss can be calculated. In order to perform this analysis, the following parameters need to be defined:

- \( \gamma \): Required E_b/N_o. This is defined by the modulation technique and the detection method. A value of 9 dB is typical for EIA/TIA-95 \[12\], or 7 dB for EIA/TIA-95 with receive dual-diversity \[4\].
- R: User (traffic channel) data rate. For EIA/TIA-95 voice, this can be either 9600 or 14400 bps.
- W: Occupied bandwidth after spreading. For EIA/TIA-95, this is 1.2288 MHz.
- P_{bs}: Composite base station transmit power per RF channel. This is the combined total of all traffic, paging and synch channels at the antenna input, including the effects of cable loss on the tower.
- \( \chi \): Percentage of base station power allocated to traffic channels; typically about 0.8 (80%).
- P_{mob}: Maximum mobile unit transmit power. This is the mobile transmit power when the power control parameter is set to maximum power.
- NF_{bs}: Base station noise figure, including effects of cable loss.
- NF_{mob}: Mobile unit noise figure, including the effects of receiver noise figure and environmental noise.

\( \nu \): Voice activity factor. CDMA systems can reduce self-interference by muting transmission during pauses in speech. This factor is the percentage of time the voice is active. Qualcomm uses 0.375 \[4\]; other more conservative treatments use 0.4 \[9\] to 0.67 \[5\]. The effective value is slightly higher on the downlink due to the need to send occasional power control bits, even during pauses in speech.

\( \eta \): Loading factor. This is the ratio of “other cell” interference to “own cell” interference. It is 0 in the case of no mutual interference (isolated cells), and increases as cells overlap, and as mutual interference thereby increases. \( \eta = 0.65 \) is used as a typical value. \[4\]

\( F_r \): Frequency reuse factor. This is calculated from the loading factor as follows:

\[
1/(1+\eta), \text{ or } \eta = (1/F_r) - 1.
\]

The value is 1 for no interference (isolated cells), and decreases as interference increases. \( F_r = 0.6 \) is used as a typical value \[12\].

\( \theta \): Orthogonality factor. Downlink channels are transmitted with codes that are orthogonal to one another; that is, they are encoded for minimal mutual interference. Multipath propagation causes the downlink signal to be “smeared” in time, destroying some of this orthogonality. The orthogonality factor is the percentage of downlink orthogonality remaining at the mobile receiver. The value will be 1 for a perfect signal (no multipath) and near zero for a pure Rayleigh fading environment. Typical values used range from 0.4 to 0.9 \[7\].

\( G_{sho} \): Soft-handoff gain. This is the downlink improvement achieved by maximal ratio combining in the mobile unit of signals from multiple base stations. Typical values 0.4 to 1.5 dB \[2\].

\( C_{sho} \): Soft handoff capacity overhead. This is the percentage increase in the number of base station channels which is required to support subscribers in either two-way or three-way soft handoff. Typical designs allow for approximately 30% of calls to be in soft handoff \[1\]; that is, 30% of the calls in process require channels from two, or in some cases three, base stations. \( C_{sho} \) will be 0 if there is no soft handoff (isolated cells), and approximately 0.18 if 30% of calls are in soft handoff.

1 Some authors define “frequency reuse” inversely to the way it is defined here, i.e. as \( F = 1+\eta \), or \( \eta = (1/F_r) - 1 \). This parallels the general ambiguity in defining “frequency reuse factor”. Some authors would define a seven cell reuse pattern as having a frequency reuse factor of 7, while others would define it as 1/7. When comparing various treatments, one must be sure to understand which definition is being used. This paper assumes a sense in which the reuse factor decreases as interference increases.
Knowing these parameters, one can calculate, for a given number of users (M), the maximum allowable path loss between base station and mobile in both the uplink and downlink paths. Then, for a given set of antenna gains, propagation models and desired fading margins, this path loss can be equated to a radius of coverage. In real world situations however, particularly in urban areas, the desired results may be evident more in the elimination of coverage holes and reduction in mobile unit power, than by an increase in coverage radius. For this reason, the results will be generalized to the relationship between capacity and allowed path loss, rather than coverage radius.

Details of the calculations are provided in Appendices A and B.

“Uplink Limited” Scenario

The first scenario assumes a relatively “clean” propagation path, with little multipath, and therefore a high orthogonality factor (0.9). Results for one typical set of parameters are shown in Fig. 1.

Coverage vs. capacity is plotted for both the uplink and downlink. The combinations of coverage and capacity for which the system can operate are those below and to the left of the lower of the two curves. In this case, an 8 dB base station noise figure (5 dB receiver noise figure, plus 3 dB cable loss) results in a system in which both capacity and coverage are strictly uplink limited (that is, the dark blue curve is the limiting factor).

Reducing the effective base station noise figure to 3 dB through the use of a tower top amplifier improves the uplink performance to the level described by the light blue curve. Now, the system is limited by the lower of the red and light blue curves. Because these curves intersect, the system is no longer strictly uplink or downlink limited.

The arrows show the amount of improvement achieved. This improvement can be viewed either as an increase in allowed path loss (and therefore, coverage) for a fixed capacity, an increase in capacity for a fixed coverage area, or a reduction in mobile transmit power for a given capacity/coverage combination.

“Downlink Limited” Scenario

The next example assumes a less benign environment, with considerable multipath propagation, resulting in a low orthogonality factor of 0.3. Results for one typical set of parameters are shown in Fig. 2.

Unlike the previous example, this scenario shows a system in which the coverage is uplink limited, but the capacity is downlink limited. Such a capacity limit is what leads some system designers to call CDMA a “downlink” limited system. However, even in this situation, tower-mounted low noise amplifiers (TMAs) can still improve coverage and capacity.

Although the downlink limits the maximum, or “pole” capacity of the system, the graph shows that at a typical operating point, a TMA will still provide a significant coverage improvement for a given number of users.

The amount of coverage improvement is greatest when the typical usage is less than about half the theoretical maximum capacity. The improvement, therefore, will be greatest in more lightly loaded cells.

In addition to increasing the coverage possible at maximum mobile transmit power, this improvement also means that mobiles not at the edge of the cell will be able to maintain communication with less transmit power. This translates not only into longer battery life for all users, but a potential increase in uplink coverage and capacity for adjacent cells, because of the reduction of intercell interference that occurs when mobile powers are reduced [15].

Similarly, for a fixed coverage area, the addition of a TMA can provide an increase in capacity. The increase is likely to be somewhat less than was predicted in the “uplink limited” scenario. However, the increase can still be significant, again depending on the design parameters of the system.
Additional Factors

Not included in these calculations are the effects of sectorization, imperfect power control, or such techniques as smart antennas or multi-user detection. A spreadsheet tool with graphical output makes a useful tool for assessing system performance based on a customized set of system parameters and/or technology specific equations.

1xEV-DO Systems

We will now turn our attention to CDMA-based high speed data systems, specifically to 1xEV-DO, including 1xEV-DO Rev. A.

Up to this point we have assumed voice-only systems, in which capacity requirements are defined by the number of users, which will be inherently the same for uplink and downlink. In data systems, uplink and downlink capacity requirements are not necessarily the same and, in fact, may be highly asymmetric. Plotting uplink and downlink performance on the same graph is therefore of limited value. Not only is the uplink to downlink capacity ratio an unknown, but the nature of data services allows a soft degradation of service by limiting the data rate available to each user.

For this reason, it is sufficient to treat uplink and downlink performance independently. In this discussion, we will focus on the uplink path only.

Total data throughput for a 1xEV-DO Rev. A sector is given by [1]:

\[ C_{\text{sector}} = R_c \left( \frac{E_b}{N_t} \right)_{\text{avg}} \left[ 1 - \frac{1}{RoT} \right] - K \left( \frac{E_{cp}}{N_t} \right)_{\text{avg}} \cdot E[\text{ovhd}] \]

where

- \( C_{\text{sector}} \) total sector uplink throughput
- \( R_c \) chip rate (1.2288 Mcps for 1xEV-DO)
- \( K \) number of active users per sector
- \( E_{cp}/N_t \) pilot energy (per chip) to noise density ratio seen at BTS
- \( E_d/N_t \) data energy (per bit) to noise density ratio seen at BTS
- \( E[] \) expected value
- \( f \) other-cell interference factor (typical value 0.68 [3])
- \( G_{\text{ovhd}} = 1+G_{\text{dc}} + G_{\text{rr}} + G_{\text{sc}} \) (Data Rate Control, Reverse Rate Indicator and Data Source Control channel gains relative to pilot)

and \( RoT \) is “Rise over Thermal”, which is the ratio of total power (uplink signals, interferers and noise) to thermal noise as seen at the base station front end [13]:

\[ RoT = \frac{(1 + f)K(E_{\text{avg}})}{N_o} \]

1xEV-DO power control algorithms work to keep \( E_{cp}/N_t \) and \( E_d/N_t \) at the minimum necessary for successful demodulation, resulting in a fixed RoT for a targeted coverage area and sector throughput.

Effect of Noise Figure Reduction on 1xEV-DO Uplink Performance

Case 1

For a system set up to operate at a fixed RoT and sector throughput, a reduction in base station noise figure (through the use of a tower-mounted amplifier) benefits system performance in two ways:

First of all, a lower value of \( N_o \) means that the targeted \( E_d/N_t \) and RoT values can be achieved with a proportionally lower value of received energy. Therefore, in the original coverage area, all access terminals can operate with a proportionally lower uplink transmit power.

If the noise figure reduction is implemented at all adjacent sites as well (so that the adjacent cell interference factor drops proportionally), the relationship is direct: a 5 dB reduction in noise figure will allow all access terminals in the original coverage area to operate at 5 dB lower transmit power.

As a corollary to this, the same operating point can be achieved by access terminals operating up to their maximum uplink power, but with a proportionally higher path loss. The result is an increased coverage area. Again, if the noise figure reduction is implemented at adjacent sites, the improvement is directly proportional: a 5 dB reduction in noise figure increases the path loss budget by 5 dB.

Case 2

If the system operator is satisfied with the coverage area, but needs to increase uplink data throughput, a tower-mounted amplifier can help here as well.

Typically, 1xEV-DO systems operate at an RoT of 3-5 dB, depending on loading factor and intercell interference levels. This results in a fixed relationship between the number of users and total sector throughput [3].

In order to increase sector throughput, operation at a higher level of RoT is required. This can lead to instabilities in uplink power control loops; however, 1xEV-DO Revision A includes improvements to stabilize these algorithms, making operation at higher RoT more practical.
Typically, increased RoT would imply increased access terminal transmit power and reduced coverage. However, if the base station noise figure can be reduced through the use of a TMA, then the increased RoT and increase sector throughput can be achieved without any increase in uplink transmit power or sacrifice of coverage.

The following graph shows sector throughput as a function of number of users and RoT, for a fixed set of assumptions regarding $E_b/N_0$ requirements and intercell interference levels. If the RoT is allowed to rise proportionally to the reduction of noise figure, the graph shows the resulting increase in uplink throughput that can be expected.

**Summary**

It is overly simplistic to try to define CDMA as being limited by either uplink or downlink, by either capacity or coverage, or by either noise or interference. A graphical representation of coverage vs. capacity for both uplink and downlink helps the system designer understand system behavior, and the amount of capacity and coverage improvement that can be achieved by the addition of a tower mounted amplifier.

The theoretical analysis confirms what has been observed in “real world” testing of live systems – that the use of TMAs can result in significant coverage and capacity improvement, and reduction in mobile power, even in systems which are commonly referred to as “downlink limited”.

Additionally, in data systems, such as 1xEV-DO, the analysis shows that the use of TMAs can result in either increased uplink throughput, or in reduced uplink transmit power and increased coverage.

### Appendix A: Uplink Coverage Calculation

In the uplink, the full bandwidth $S/N$ ratio is the received power of the desired signal ($P_r$) divided by the sum of the noise over the full bandwidth ($N_oW$) plus uplink interference from other users ($I_{ul}$):

$$\frac{S}{N} = \frac{P_r}{I_{ul} + N_oW} \quad (1)$$

In a CDMA cell with $M$ users per channel all occupying the same spectrum, the “same cell” interference is equal to the total power of the other ($M-1$) users.

Uplink power control is used to keep all received signals balanced; i.e. all signals are received at the same level, $P_r$. Therefore, the “same cell” interference power is:

$$I_{uls} = (M - 1) \times P_r \quad (2)$$

“Adjacent cell” interference is proportional to the “same cell” interference, according to the loading factor ($\eta$):

$$I_{ula} = \eta I_{uls} = \left(\frac{1}{F_r} - 1\right) I_{uls} \quad (3)$$

where the loading factor has been expressed as a function of the frequency reuse factor ($F_r$).

Summing the self and adjacent cell terms, and scaling each by the voice activity factor ($v$) to account for interference reduction achieved by muting transmission during pauses in speech, results in the following expression for total uplink interference:

$$I_{ul} = v\left[I_{uls} + \left(\frac{1}{F_r} - 1\right) I_{uls}\right] = \frac{v(M - 1)P_r}{F_r} \quad (4)$$

$S/N$ then can be expressed as:

$$\frac{S}{N} = \frac{P_r}{v(M - 1)P_r + N_oW} \quad (5)$$
Converting this to $E_b/N_o$ (multiplying by the processing gain) results in

$$\frac{E_b}{N_o} = \frac{P_r}{\left[ \nu \left( M - 1 \right) + N_o \right] R} \times \frac{W}{R} \quad (6)$$

which must be $> \gamma_t$.

Solving for $P_r$ gives:

$$P_r > \frac{\gamma_r N_o W}{W - \nu \left( \frac{M - 1}{F_r} \right)} \quad (7)$$

On a dB scale, received power is transmit power - path loss:

$$P_r(dBm) = P_{mob(dBm)} - PL(dB) \quad (8)$$

So maximum path loss for a given number of users is:

$$PL_{UL_{max}(dB)} = P_{mob(dBm)} - 10 \log \left( \frac{\gamma_r N_o W}{W - \nu \left( \frac{M - 1}{F_r} \right)} \right) \quad (9)$$

The maximum theoretical capacity, or “pole capacity”, is defined by the point at which the denominator of the logarithm argument goes to zero. This is the maximum capacity possible as receive power goes to infinity and/or cell coverage shrinks to zero.

$$M_{UL_{pole}} = \frac{F_r (W / R)}{\gamma_r \nu} + 1 \quad (10)$$

### Appendix B: Downlink Coverage Calculation

The downlink calculation is similar to that of the uplink, with several exceptions.

First of all, the interference term in equation (9) is scaled by a factor of $(1-\theta)$ in the downlink path, where $\theta$ is the “orthogonality factor”. Signals leave the base station with an orthogonality factor close to 1 in order to minimize channel to channel interference. The orthogonality factor used in the downlink coverage calculation reflects the proportion of orthogonality remaining by the time the signal completes its multipath propagation to the mobile unit.

A second difference between the two paths is that in the downlink, the per channel power is dependent on the number of users. All traffic channels share a total available power, which is divided evenly among the active users. If $\chi$ is the proportion of total power at the base station antenna connector which is allocated to voice channels [6], then the transmit power per channel is

$$P_{tx} = \frac{\chi \times P_{tot}}{M} \quad (10)$$

Third, the capacity value (M) is scaled by the soft handoff overhead factor ($C_{sho}$), which accounts for the extra base station channels needed to support mobiles in either two or three-way soft handoff. The effect is to replace $M$ with $M(1+C_{sho})$.

Finally, the soft handoff gain ($G_{sho}$) becomes a simple additive factor in the dB path loss calculation.

Starting with equation (9), and incorporating these downlink specific changes, results in the following expression for maximum downlink path loss:

$$PL_{DL_{max}(dB)} = 10 \log \left( \frac{\chi \times P_{tot}}{\left[ 0 + C_{sho} \right] M} \right) - 10 \log \left( \frac{\gamma_r N_o W}{W - \nu \left( \frac{M + C_{sho} - 1}{F_r} \right)} \right) + G_{sho} \quad (11)$$

Downlink pole capacity is determined by the point at which the denominator of the logarithm argument goes to zero:

$$M_{DL_{pole}} = \frac{F_r (W / R)}{\gamma_r \nu (1-\theta) (1 + C_{sho})} + 1 \quad (12)$$
References


