

ESG

Engineering Services Group

Capacity Enhancement Solutions for CDMA2000 1X Networks

80-W0861-1 Rev B





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80-W0861-1 Rev B**

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1 Introduction

Packet switched data services are emerging as market differentiators and important new sources of revenue, yet voice service continues to be the key driver of revenue for most CDMA2000 operators. In order to compete with other wireless operators in the same market, CDMA2000 operators must offer their customers more attractive pricing plans and better services. In response to this demand, most CDMA2000 operators face the challenge of utilizing network capacity more efficiently, without overspending on spectrum and network infrastructure.

As we all know, spectrum is a valuable and limited resource. Therefore, for an operator, cost effective improvement in capacity is always an important goal. Capacity gain, both for voice and new data services, is critical for an operator's competitiveness. It is possible to achieve significant capacity improvements in existing networks without deploying additional carriers and base stations or drafting new standards.

By following proper RF network planning and optimization techniques, CDMA operators would see immediate benefits on their network capacity. During peak daily load periods in a CDMA network, it is possible to further increase capacity by compromising the quality of service (voice quality) through dynamic network parameter adjustments. The long term voice capacity enhancements can be achieved extensively in the forward link by using dual receive antenna diversity and Quasi-Linear Interference Cancellation (QLIC) schemes in the mobiles; and transmit diversity, 4GV vocoders, and other interference cancellation techniques in the base station. Techniques such as 1/8th rate gating on the reverse fundamental channel, 4-way receive diversity in the base station, and 4GV vocoders in the mobiles can enhance reverse link voice capacity.

This white paper discusses capacity improvement techniques that can be implemented immediately. It also discusses long term capacity enhancement solutions that illustrate how operators can effectively enhance the voice capacity of their CDMA2000 networks.

2 Capacity Improvements with Optimization

Network optimization is an integral part of the operation and maintenance of CDMA2000 systems. It should be performed frequently, whenever there is a change in the network. Proper optimization techniques enable an operator to fine tune the network for maximum attainable capacities. This section covers the important steps that need to be followed in the network optimization process to achieve improvements in network capacity.

2.1 RF Network Planning and Optimization

Most CDMA2000 networks that suffer from RF capacity degradation are the result of poor RF network planning and optimization. An optimized RF environment is vital for operators seeking to maximize capacity. Figure 1 illustrates the relationship between BTS Tx power reduction and combined forward link pilot E_c/I_o under different forward link loading scenarios. The figure shows that for higher combined E_c/I_o , lower traffic channel E_c/I_o is required and more BTS HPA power is conserved to accommodate more users in the same sector. Typically, a 1 dB BTS Tx power reduction for each voice channel increases RF capacity by approximately 15% for any given BTS sector.

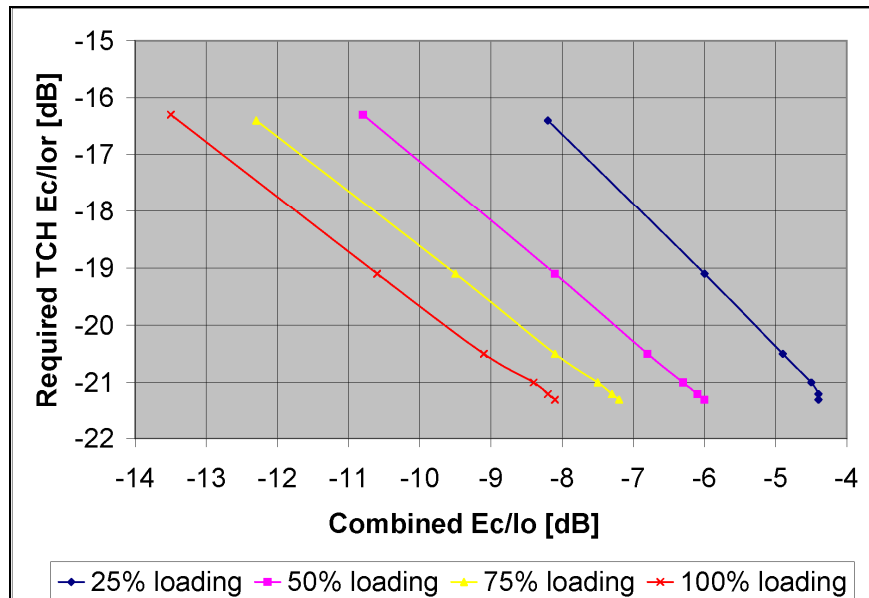


Figure 1– BTS Tx Power Reduction Vs. Combined E_c/I_o

2.2 Capacity Improvement Areas

The following problems are common in a sub-optimal CDMA network that might have RF capacity issues:

- Forward / reverse link imbalance – RF coverage on the forward link is much larger than that on reverse link; excessive BTS Tx power is allocated for the remote user.
- Excessive soft handoff area – Caused by improper cell site layout, misuse of base station antennas.
- Improper RF parameter settings – RF parameter settings should be fine-tuned according to the traffic loading distribution to improve the overall network performance.

Solutions to resolve the problems above are presented in the subsequent sections.

2.2.1 Avoid Forward / Reverse Link Imbalance

This problem is normally caused by boomer sites with elevated antenna radiation centers. The BTS forward link covers distant areas or deep inside buildings where the reverse link of a mobile cannot reach back to the base station. In this case, excessive forward link traffic channel power is always allocated to compensate for the path loss. Link imbalance areas typically can be identified if the forward link coverage is sufficient (good pilot E_c/I_o) but call setup failure is high due to exhausted mobile transmit power on the reverse link. Link imbalance can be identified by drive testing into problematic areas or analyzing the network performance data for problematic clusters / sectors.

The following possible solutions should be considered to address this imbalance:

- Reduce the base station antenna height, if practical
- Apply correct down-tilts (both mechanical and electrical) to the relevant antennas
- Select lower gain antennas, where applicable
- Add a tower mounted amplifier (TMA) to enhance the reverse link coverage
- Apply attenuation loss to the BTS antenna (by using pads or parameter settings such as TxPowerLimitOffset)

Before implementing any adjustments, they should be simulated with planning tools, such as Atoll or cdmaPlanner. After the changes are implemented, they should be validated by drive testing.

2.2.2 Reduce Excessive Soft Handoff Areas

In a well-optimized, lightly-loaded CDMA network, the typical soft handoff reduction factor is between 1.6 and 1.8; this range is reduced to 1.4 to 1.6 for a loaded network. If a higher value is seen in some areas of the network, this could indicate that those areas have more soft handoff than necessary. Soft handoff increases the reliability of the radio link, but the base station requires more power to maintain the soft handoff, which reduces the forward link capacity.

The following methods are typically considered to reduce unnecessary soft handoff areas:

- Enable the Dynamic Soft Handoff Thresholds by setting proper values for SOFT_SLOPE (2 dB to 3 dB), ADD_INTERCEPT (0 dB to 3 dB), and DROP_INTERCEPT (0 dB to 3 dB).
- If Dynamic Soft Handoff Thresholds are not enabled, set higher values for T_ADD, T_DROP, and T_COMP; and set a lower value for T_TDROF for highly loaded sectors. For example, set -12 dB for T_ADD and -14 dB for T_DROP, and set T_TDROF to 2 seconds for the highly loaded sectors in an embedded network.
- Keep a single dominant server in highly loaded areas.
- Adjust the base station antenna to reduce RF coverage overlap from different sectors/sites.

2.2.3 Fine-tune RF Parameter Settings

RF parameter adjustments could be considered after the RF environment has been optimized and the network has reached a stable stage. Some RF parameter settings are dependent upon the vendor's implementation and various settings always result in trade-offs. It is best to consult with the vendor prior to changing any parameter settings. There are no fixed rules on parameter changes. When voice capacity enhancement is the objective, some channel power management and power control parameters can be considered for fine-tuning.

Instead of discussing specific parameter settings, this white paper presents the parameter options and the results you can expect from the changed settings. All parameter setting changes should conform to vendor guidelines, and validation testing is needed after every change to verify the objective is achieved without causing other side-effects.

Channel Power Management Parameter Tuning

Forward link capacity is limited by base station's transmitter HPA power. The HPA power is shared by forward overhead channels and traffic channels. Depending on the individual base station products, infrastructure vendors may recommend

different parameter settings for forward overhead channels. Figure 2 shows an example of parameters related to forward link channel power management. The key parameter is **MinPilotToTotalPowerRatio**, which indicates the power level allocated to Pilot channel and other overhead channels (Paging and Sync channels) referenced to the Pilot channel power level. **PagingToPilotPowerRatio** relates to the Paging channel parameter, and **SyncToPilotPowerRatio** relates to the Sync channel parameter.

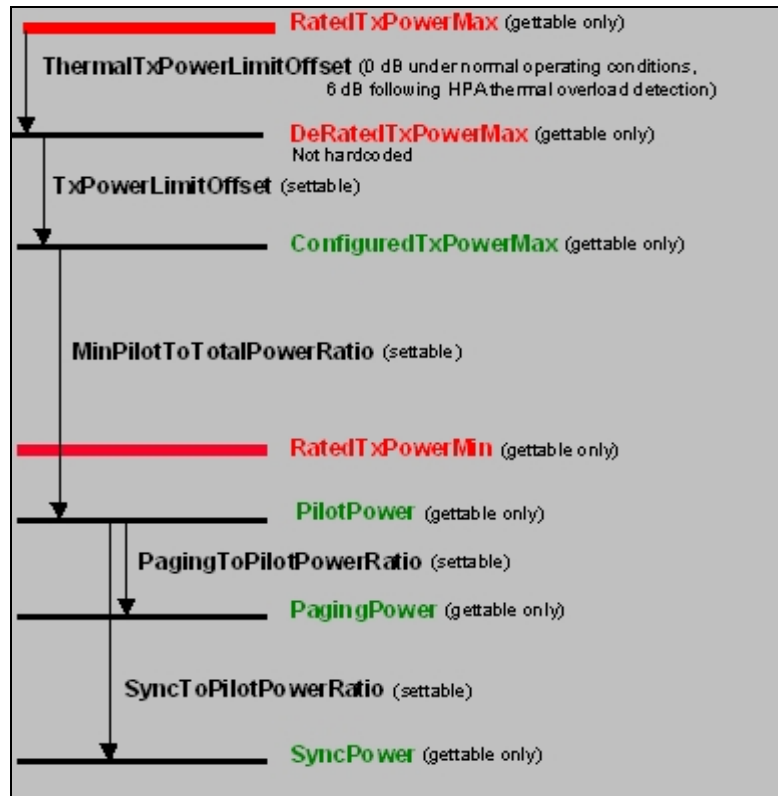


Figure 2 – Parameters on Forward Link Power Management

The typical setting for **MinPilotToTotalPowerRatio** is -7.5 dB. If a base station sector lacks HPA power on traffic channels but RF coverage is sufficient, one can consider reducing **MinPilotToTotalPowerRatio** between 0.5 dB to 1 dB; the power allocation to all overhead channels will be reduced accordingly. The trade-offs for this change include possible diminished RF coverage, especially in marginal areas such as inside buildings, and less effective soft handoffs in certain areas.

Increase the setting of FPC FCH FER

Most CDMA operators set this parameter at 1% to achieve good voice quality. A setting higher than 1% may affect forward link voice quality but will increase

forward link capacity. A setting of 1.5% to 2% is recommended if the network is running out of forward link capacity and no other options are available.

As shown in Figure 3, the forward FER is not convergent to the target value of 1%; as a result, the forward link capacity cannot be fully utilized.

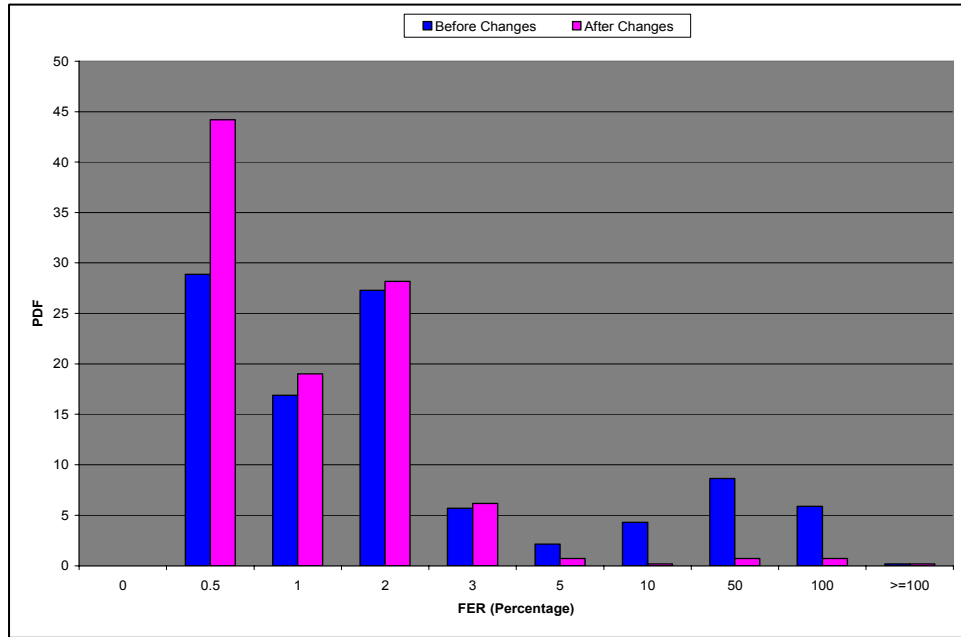


Figure 3 – Example of Forward FER

Lower the settings of FPC FCH {INIT, MIN, MAX} SETPT

Setting this value close to the minimum value usually lowers the power transmission from the base station to the mobile, which increases forward link capacity. The trade-off is that the forward link power control might be too slow to overcome fast fading for those lower settings. An optimum value should be based on field validation testing. For example, for sectors running out of forward link capacity, one can consider lowering the FPC_FCH_{INIT, MIN, MAX}_SETPT settings to {2 dB, 3 dB, 7 dB}, respectively. Setting the FPC_FCH_MIN_SETPT too low (1 dB) is not recommended because it increases recovery time if a mobile moves out of good RF coverage too quickly and unnecessary dropped calls might occur.

3 Enhancements through Antenna Diversity

In CDMA2000 systems, both forward and reverse link capacity enhancements can be achieved using space diversity techniques with multiple antennas. Forward link capacity can be expanded through dual receive antennas in the mobile terminals and/or transmit diversity implemented in the base station. After mobile receive diversity is fully implemented and the stipulated gains have been achieved, the CDMA2000 operator cannot realize additional significant gains with later implementations of transmit diversity. Reverse link capacity can be enhanced through 4-way receive diversity in the base station.

3.1 Capacity Enhancement to Forward Link

CDMA2000 operators can choose either dual receive antennas at the mobile or dual transmit antennas at the base station, or both, to increase the forward link capacity.

3.1.1 Receive Diversity in Mobile Terminals

Receive diversity with dual receive antennas in mobiles offer a cost effective way to add more capacity without using extra spectrum (additional CDMA carriers) and/or deploying additional base stations. In this case, the mobile terminals are modified to include an additional antenna and receiver. The primary antenna can be an extendable Whip antenna used for both transmit and receive. The secondary antenna can be a Wire Inverted-F Antenna (WIFA) used only for the receive function. Receive diversity lowers base station power for a given user, which, in turn, increases the forward link capacity. When receive diversity is fully implemented in all mobiles, it is possible to realize a forward link voice capacity gain of nearly 2.5 dB.

A cellular-band antenna must be about twice the length of a PCS-band antenna. Often a Meander Line Antenna (MLA) is used to fold a long antenna into the small mobile encasement. The MLA is printed on flexible film so it can conform to the contours of the inside back plastic cover of the mobile. The MLA offers flexibility for handset designers. How to achieve higher forward link capacity is explained as follows:

- Terminal receiver diversity improves C/I.
- Better C/I results in lower base station power allocation to each user.
- More base station power is then available to additional users, increasing network capacity.

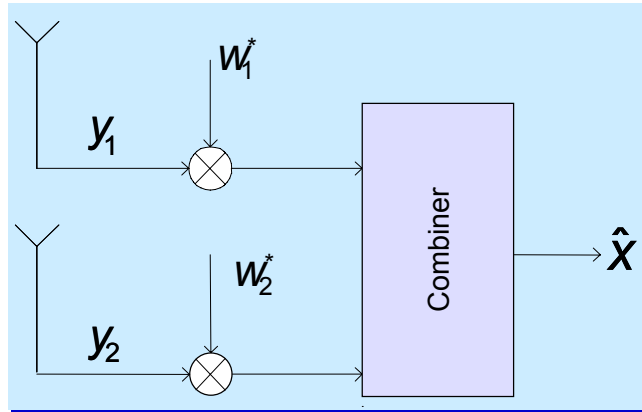


Figure 4 – Receive Diversity in Mobiles with Dual receive antennas

The efficiency of the dual receive diversity technique also depends on how the signals from the two different antennas are combined (as shown in Figure 4). In the Minimal Mean Square Error (MMSE) combining scheme, the weights for each path are chosen to minimize the mean square error between the combined voltage stream and the signal. In the Maximal Ratio Combining (MRC) scheme, received signals are combined proportionally to the SNR for each path on each antenna. When the noise and interference for a path are uncorrelated between the two antennas, MRC is equivalent to MMSE. The graph shown in Figure 5 illustrates the base station transmit power savings with the MMSE and MRC combining techniques compared to using only the factory-installed retractable Whip antenna (without any receive diversity).

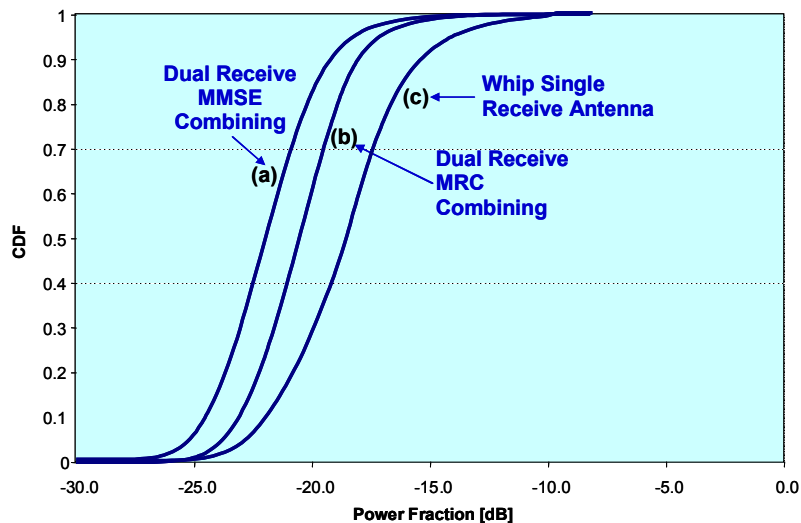


Figure 5 – Base Station power utilization with Dual Receive Diversity

3.1.2 Transmit Diversity in the Base Station

Using transmit diversity in the base station would yield some capacity gains, but at the cost of additional transmit chain requirements. A CDMA operator with CDMA2000 1X Release 0 equipment can use the Orthogonal Transmit Diversity (OTD) scheme; whereas with the Release A (and above) capable equipment, operators can choose either the OTD or STS (Space Time Spreading) scheme. Most of the time, the mobiles are in a stationary or low speed (pedestrian) environment. The transmit diversity schemes would provide better gains in a stationary or pedestrian environment. Also, there is an advantage with STS compared to OTD; STS would require more constant E_c/I_{or} in all mobility environments. Also, QUALCOMM simulations have shown that at 100 km/hour speeds, OTD provides about 1 dB gain and STS provides about 1.6 dB gain in the required E_c/I_{or} values. Whereas at pedestrian speeds, the OTD scheme provides a 1.5 dB gain and STS provides about 3 dB maximum gain to the average required E_c/I_{or} .

Using a transmit diversity scheme is optional for the CDMA operator. The main difference between implementing OTD or STS is: OTD uses two antennas with each antenna transmitting half the data, whereas STS uses two antennas with each antenna transmitting all data. The STS scheme appears to have superior performance, but that comes with higher complexity and cost. Other problems with the STS scheme are that the operator achieves transmit diversity gains only after at least one-third of the mobiles in the network are transmit diversity enabled. Also, when transmit diversity is initially implemented, it degrades the performance of the non-transmit diversity mobiles.

3.2 Capacity Enhancement to Reverse Link

Currently, dual receive diversity is the most commonly used scheme in CDMA2000 base stations. Additional increases in reverse link capacity of 60% to 70% (around 2 dB capacity gain) can be achieved using 4-branch/way receive diversity in the base station. Cross polarization antennas are recommended to eliminate or reduce the need for additional space on the antenna tower/mast. A 4-branch cross-polarization (x-pol) diversity scheme would improve the pilot signal-to-noise ratio (SNR) by an average of 2.2 dB.

Spatial/x-pol diversity reduces the requirement on the average antenna SNR needed to achieve a specific frame error rate. This reduction in required SNR increases capacity. Spatial/x-pol diversity also reduces the average terminal transmit power requirement. Lower transmit power expands the coverage range

and extends battery life. Hence, this additional diversity offers a cost effective way to add capacity and improve performance. Figure 6 illustrates the configuration of 4-branch receive diversity in the base station.

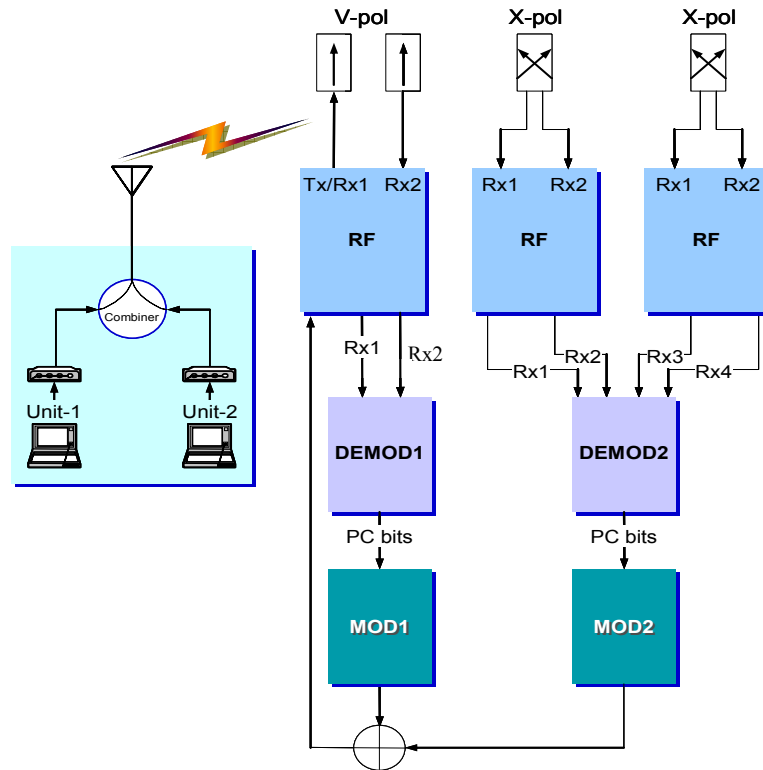


Figure 6 – Four-branch Receive Diversity Configuration in Base Station

As Figure 1 shows, two pairs of cross-polarized antennas spatially separated would effectively provide 4-branch receive diversity in the reverse link. For comparison, this example uses two vertically polarized spatially separated antennas and two test terminals sharing the same antenna. The signal from Terminal1 is demodulated by the two vertically polarized antennas, and the signal from Terminal2 is demodulated by the two pairs of X-pol antennas. The forward link is served by the V-pol antenna to both terminals. This setup accurately determines the difference in transmit power because open loop power control variations are eliminated.

Figure 7 shows that a four-way X-pol diversity antenna scheme implementation improves the required E_c/N_o values from 2 dB to 2.5 dB. This improvement in the average signal-to-noise ratio per antenna increases capacity.

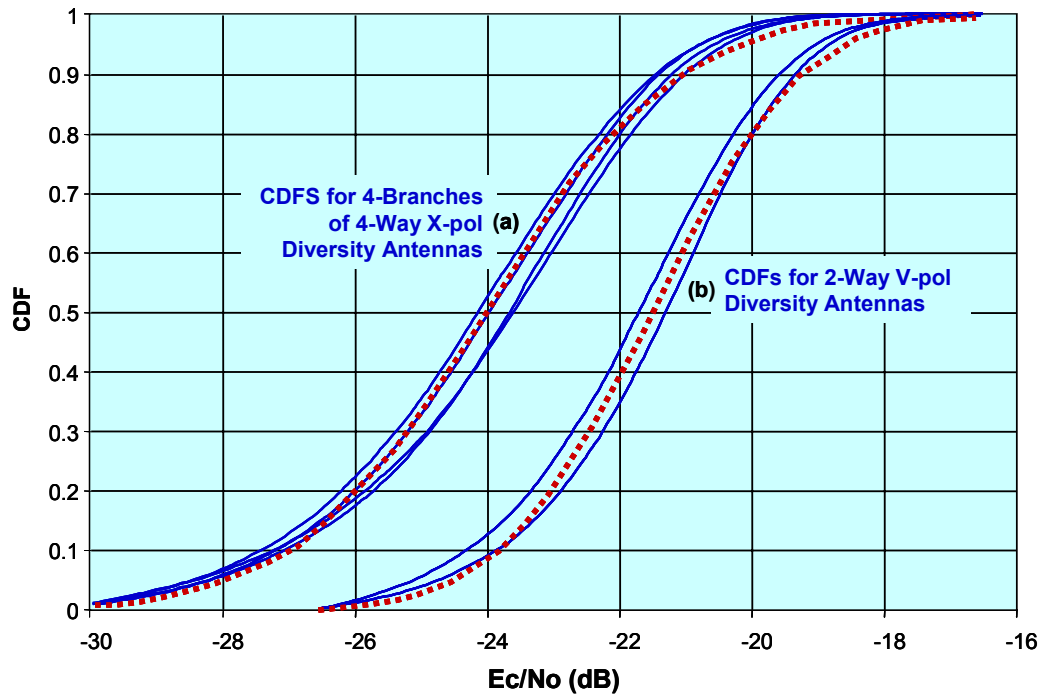


Figure 7 – Improvement in E_c/N_o requirement with 4-way X-pol diversity

For best performance, the QUALCOMM CSM6800 (and above) chipset supports 4-way receive diversity in the infrastructure. The QUALCOMM CSM5000 chipset also supports this feature, but with sub-optimal performance.

4 Enhancements through 4GV Vocoders

Capacity demand of a cell/sector varies according to many factors such as time of day, morphology, and demography. It would be difficult for an operator with fixed resources to meet such variable demand. CDMA operators soon will have 4th Generation Vocoders (4GV, commercially available by end of 2006) that can select the best average vocoder rate at a given time of the day, to address varying demands with optimal quality of service. This enables CDMA operators to control capacity and voice quality, based on the time of the day (variable) demand.

The 4th Generation Vocoder resulted from QUALCOMM's development of a new speech codec with enhanced voice quality and greater flexibility over existing voice coding service options such as Enhanced Variable Rate Codec (EVRC). To support both dynamic and static tradeoff between voice quality and system capacity, 4GV includes several operating modes that voice code audio at different average bit-rates. The highest-rate mode, 4GV COP-0 (Capacity Operating Point-0), exhibits average data rates similar to those of EVRC. Meanwhile, COP-1 through COP-6 successively trade off voice quality for lower average data rate and increased system capacity.

As Figure 8 shows, an intelligent radio resource management entity that monitors system loading can determine the optimal average rate of operation for 4GV and configure the network to provide the optimal voice quality while monitoring other Quality of Service (QoS) parameters such as blocking factor and Frame Error Rate (FER).

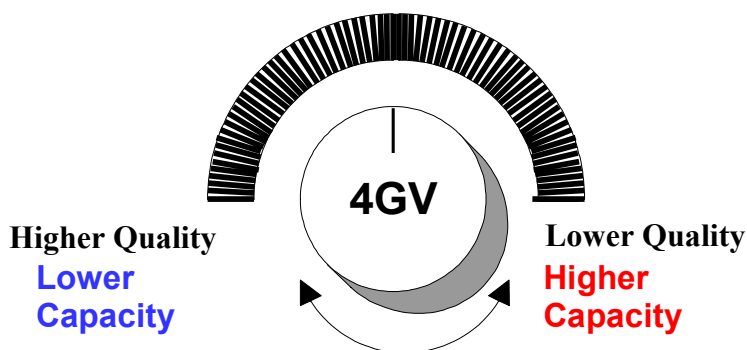


Figure 8 – Arbitrary range of Capacity Operating Point (COP) in 4GV

The rate-decision algorithm within 4GV dynamically and optimally determines the point at which the encoder output average rate is close to the target active speech average rate. The number of voice calls in a sector with 4GV is equal to the number of voice calls in a sector with EVRC times the Power Margin increase due to rate reduction.

The frame distribution of 4GV COP-0 is similar to that of EVRC, while the other modes of 4GV have lower average data rates by vocoding fewer full-rate frames and more quarter- and eighth-rate frames. Table 1 shows average bit rates seen with different modes of 4GV.

	Full	Half	Quarter	Eighth	Average Rate (bps)
EVRC	71.37%	3.83%	0.00%	24.80%	7407.4
4GV COP-0	70.38%	3.94%	0.00%	25.68%	7330.8
4GV COP-4	41.29%	2.62%	29.35%	26.74%	5283.2
4GV COP-6	32.58%	2.79%	36.98%	27.66%	4675.0

Table 1 – Average Data rate comparison of EVRC and 4GV

An experiment conducted in QUALCOMM labs observed that by using a speech sample with approximately 50% voice activity rate, the highest rate 4GV mode (COP-0) results in 4% to 7% increase in forward link capacity and approximately 4% to 5% improvement in reverse link capacity. The medium average rate 4GV (COP-4) results in a capacity gain between 31% to 38% on the forward link, and 23% to 24% on the reverse link. The lowest average rate 4GV mode (COP-6) results in 45% to 51% gain in forward link capacity, and 29% to 32% increase in reverse link capacity. Because lower rate 4GV modes voice code more 1/8th rate frames, enabling reverse link 1/8th rate R-FCH gating (see Section 5.2 for more details) can produce greater reverse link capacity gains. It was assumed that the base station was only power limited and not Walsh code limited. Actual forward link voice capacity may be less than the results found in this study due to the Walsh code limitation. An RC4 configuration would solve the Walsh code limitation problem, but would require more forward link power for each voice channel.

QUALCOMM chipsets MSM 6100 and above, except for the QUALCOMM Single Chip (QSC), support 4GV. It is expected that by the end of 2006, very low end (VLE) CDMA2000 mobiles with QSC (MSM6010, MSM6020, and MSM6030) would support the 4GV vocoder. From a network infrastructure perspective, the BSC needs only a software upgrade to support 4GV.

5 Other Capacity Enhancement Techniques

Additional important capacity enhancement techniques worth discussing are: 1) Interference cancellation technique in mobiles; and 2) 1/8th-rate gating on the reverse fundamental channel.

5.1 Quasi-Linear Interference Cancellation

In CDMA networks, the pilot consumes a sizeable fraction (15% to 20%) of the total transmit power, and it is fairly easy to learn the pilot symbols pattern. Understanding the spreading codes of signals coming from different sectors on the forward link can be used for interference cancellation. Hence, the Pilot Interference Cancellation (PIC) technique is fairly easy to apply. Moreover, forward link interference cancellation on all channels would enhance the interference-limited capacity of the forward link. Thus, it is advantageous to implement interference cancellation on all channels. Quasi-Linear Interference Cancellation (QLIC) is a proprietary scheme used for of both pilot interference cancellation and traffic interference cancellation. This QLIC feature is expected to be available in future releases of the QSC chipset product line.

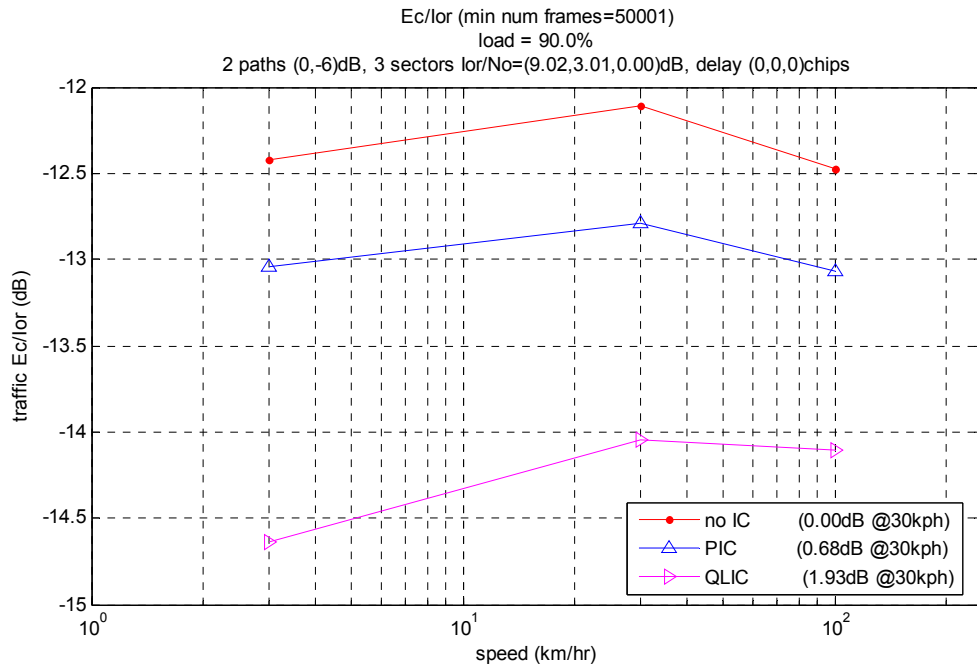


Figure 9 – QLIC benefits - Lower E_c/I_{or} requirement

Figure 9 plots link simulations from tests done by QUALCOMM. The results show that, at 30 km/hr speeds with an RC4 configuration and network load under 90%, the PIC gain is 0.68 dB; whereas the QLIC gain is 1.93 dB. The network simulations show that QLIC can increase voice capacity by approximately 30%, and increase the number of users per sector from 35 users (for EVRC) to 45 users.

5.2 One-eighth rate Gating on R-FCH

If the CDMA operator observes a capacity imbalance through reverse link capacity limitations in their network, the immediate solution is to implement 1/8th-rate gating on the reverse link traffic channels. Even CDMA2000 Release 0 systems support this feature. 1/8th-rate gating can be applied to reverse traffic channels, either on RC3 or RC4 configurations. Gating can be enabled or disabled on an MSC-wide basis. During inter-MSC handoffs with an MSC area that does not support reverse link gating, the mobile would be instructed to disable gating through a general handoff direction message (GHDM).

During gating, the mobile's transmit duty cycle is 50% and both reverse pilot and fundamental channels (R-PICH and R-FCH) are gated. Gating is not allowed during reverse supplemental channel assignment. 1/8th-rate gating provides reverse link capacity gains and increases the talk time of the mobile (by reducing power consumption during talk mode). The only drawback of this feature is some loss in the forward link system capacity due to the reduced forward power control (FPC) update rate. When gating is enabled, the power control rate is reduced by one-half, which yields a slight increase in the BTS power allocation per traffic channel.

Gating increases handset talk time by approximately 10%. Assuming 40% voice activity, 1/8th-rate gating would provide about 0.8 dB of improvement (up to 15% capacity gain) to the reverse link E_c/N_t values. However, there is a disadvantage: depending on channel conditions and mobility (speeds), the forward link E_c/I_{or} values could degrade up to 0.4 dB (up to 10% capacity loss).

6 Conclusions

The CDMA operators have various solutions, both short term and long term, to enhance their system capacity. Anomalies such as forward/reverse link imbalance, excessive soft handoff areas, and improper RF parameter settings could lead to under utilization of system capacity. With proper network planning and network optimization of the installed CDMA network, operators can quickly and efficiently utilize their network resources to achieve optimum system capacity.

In addition to network optimization, the following techniques can be implemented throughout the network to achieve further capacity enhancements over the long term.

Forward link capacity enhancement techniques:

1. Usage of 4GV vocoders (up to 40% increase).
2. Mobile Receive Diversity (up to 80% increase upon full penetration).
3. Transmit Diversity in the BTS (not popular due to cost and complexity).
4. Quasi-Linear Interference Cancellation in mobiles (up to 30% increase).

The reverse link capacity enhancement techniques:

1. Usage of 4GV vocoders (up to 23% increase).
2. 4-way receive diversity in the base station (up to 100% increase).
3. 1/8th-rate gating to R-FCH (up to 15% increase).

Important points to keep in mind while implementing these capacity enhancement techniques include:

1. 4GV vocoder implementation would increase both forward and reverse link capacity gains.
2. CDMA operators would get more forward link capacity gains if both Mobile Receive Diversity and QLIC techniques are implemented. However, in order to achieve overall capacity gain, other reverse link capacity enhancement techniques could be implemented simultaneously.
3. Combination of 4GV, QLIC, and 1/8th-rate gating would be a good choice for initial phase capacity gains, which may provide nearly balanced links.

4. For second phase capacity gains, the Mobile Receive Diversity would be an excellent choice if performed in conjunction with 4-way receive diversity in the BTS.

Depending on factors such as implementation/expansion plan, present network status, short term and long term requirements, and other cost related aspects, CDMA2000 operators can choose any of the system capacity enhancement techniques discussed in this document. It is relatively easier to incorporate capacity enhancement techniques such as 4GV and 4-way receive diversity in the infrastructure. However, implementing enhancement techniques such as 4GV, QLIC, and mobile receive diversity in all the mobiles is a tough task.

In general, it is advantageous to implement such techniques in heavily used mobiles. In a typical mobile wireless network, approximately 10% of users consume 33% of system capacity (or 20% of users utilize 50% of capacity). For immediate capacity enhancements, the operator should initially target those higher-usage subscribers and replace their mobiles with new ones that support any of the discussed capacity enhancement solutions.

7 References

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Appendix A: Voice Capacity Analysis

The voice capacity of a CDMA2000 system is measured by the average number of users receiving service or the average traffic load with a given physical layer quality metric (typically measured by FER) and availability (typically measured by blocking probability).

Forward Link Capacity Analysis

In a CDMA2000 system, one of the major factors influencing the forward link capacity is the availability of base station (BS) transmit power. Assuming enough Walsh codes are available, blocking occurs when the BS does not have sufficient transmit power to support any additional users at their specified target FER. For voice calls, the instantaneous transmit power is proportional to the transmitted data rate. Transmitting data symbols of one half-rate frame (4800 bps) requires approximately 3 dB less power than transmission of one full-rate frame (9600 bps). Similarly, transmit power decreases by 3 dB for every reduction by half in rate. Thus, the average transmit power required to support a voice call is proportional to the average vocoded rate of the speech.

Because the total available BS transmit power is limited, a reduction in transmit power required for one user translates to more available power for supporting other users. Thus, forward link capacity is inversely proportional to the BS transmit power needed for each user. To determine the percentage of change in BS transmit power for mobile B relative to mobile A, we may use the following equation:

$$\% \Delta Power_{B,A} = \frac{Power_B - Power_A}{Power_A} \quad \text{Equation 1}$$

Since

$$Capacity \propto \frac{1}{Power} \quad \text{Equation 2}$$

Resulting differences in forward link capacity due to this difference in channel power can be determined by

$$\% \Delta Capacity = \frac{\frac{1}{Power_B} - \frac{1}{Power_A}}{\frac{1}{Power_A}} = \frac{Power_A}{Power_B} - 1. \quad \text{Equation 3}$$

For example, using this equation, a 50% decrease in channel power translates to a 100% increase in forward link capacity. These calculated forward link capacity increases assume the system is power-limited and not limited by other necessary forward link resources such as Walsh codes. A Walsh code-limited system may not be able to fully achieve the capacity increases calculated from the reduction of required forward transmit power.

Reverse Link Capacity Analysis

The reverse link of a CDMA2000 system is limited by the level of multiple access interference. Because all users share a common frequency spectrum, each user's signal interferes with the signals of other users. Blocking occurs when the noise plus interference level caused by users exceeds the background thermal noise level by a specified level. Above this blocking interference-to-noise level, known as outage rise-over-thermal, the addition of only one user produces a significant increase in interference. This occurs when, in response to the interference increase of one user, other users raise their transmit power, thereby increasing their interference to others. Such an occurrence potentially results in system instability. To guarantee stability, the outage rise-over-thermal level is typically limited to 6 dB to 10 dB [1].

To calculate reverse link capacity, we use the method presented in [1, 2] and assume an isolated cell with k_u statistically identical users being independently power controlled. Signals from all users in the cell arrive at the BS with equal strength, so the average noise and interference power I_oW at the BS is

$$I_oW = \sum_{i=1}^{k_u} E_b R + N_o W \quad \text{Equation 4}$$

Where, I_o is interference density, N_o is thermal noise density, W is the spread-spectrum bandwidth, R is the data rate, and E_b is bit energy.

To maintain system stability, we limit the rise-over-thermal ratio $\frac{I_oW}{N_oW}$ to a particular outage level ρ :

$$\frac{I_o}{N_o} < \rho . \quad \text{Equation 5}$$

Combining Equations 4 and 5, we obtain

$$\sum_{i=1}^{k_u} E_b R = (I_o - N_o)W < I_oW(1 - \frac{1}{\rho}) . \quad \text{Equation 6}$$

Since $E_b = E_c \cdot \frac{W}{R}$ where E_c represents chip energy, we have

$$\sum_{i=1}^{k_u} \frac{E_c}{I_o} < 1 - \frac{1}{\rho} \equiv K_o' \quad \text{Equation 7}$$

When the condition in Equation 7 is not satisfied, the system is considered to be in outage. Therefore, the probability of outage, P_{out} , is

$$P_{out} = \Pr \left\{ \sum_{i=1}^{k_u} E_c / I_o > K_o' \right\} \quad \text{Equation 8}$$

As explained in [3], a Poisson process is a good model for the aggregate traffic of a large number of similar and independent users. Thus, we assume that calls from the entire population in the cell arrive according to a Poisson process with a total average arrival rate of λ calls/second. Call service-times are exponentially distributed with average call duration of $1/\mu$ seconds. To determine the occupancy distribution and the probability of blocked calls, we use the “lost call held” (LCH) model, which assumes that unserved users repeat their call attempts immediately and remain in the system unserved, as typical for mobile communication systems. From [1], under this model, the number of active calls in a cell k_u is a Poisson random variable with distribution

$$P_{k_u} = \frac{(\lambda/\mu)^{k_u}}{k_u!} e^{-\lambda/\mu} \quad k_u = 0, 1, 2, \dots \quad \text{Equation 9}$$

However, the level of interference power at a given base station is caused not only by users in the cell, but also by users in surrounding cells controlled by other base stations. Assuming uniform loading of all cells, interference from users of surrounding cells increases the interference at the base station under analysis by a fraction f of the interference from the desired cell’s users [1]. If users of surrounding cells are also power controlled and thus have similarly distributed (E_c/I_o) , the average interference power due to users of surrounding cells can be modeled as $f \cdot k_u$ additional users, where k_u is the average number of active users per cell. Modifying the results of Equation 8 to include the effects of other-cell interference, we have:

$$P_{out} = \Pr \left\{ \sum_{i=1}^{k_u(1+f)} E_c / I_o > K_o' \right\} = \Pr \left\{ \sum_{i=1}^{k_u'} E_c / I_o > K_o' \right\} \quad \text{Equation 10}$$

Where,

$$k_u' = k_u(1+f) \quad \text{Equation 11}$$

Continuing with the probability of outage, we may define the random variable of interest Z' as the sum of the signals of users in the cell (including the effects of other-cell users),

$$Z' \equiv \sum_{i=1}^{k_u'} E_c / I_o . \quad \text{Equation 12}$$

The outage probability can now be expressed as

$$P_{out} = \Pr\{Z' > K_o'\} . \quad \text{Equation 13}$$

Due to inaccuracies in power control loops, the received (E_c / I_o) of the R-PICH of a particular user is log-normally distributed with a standard deviation of 1. dB to 2.5 dB [1]. Since the strength of the R-FCH is specified as an offset from the R-PICH, the total received (E_c / I_o) from a user varies as a function of the data rate. Assuming users exhibit similar data rate characteristics, the received (E_c / I_o) from different users in the sector may be modeled as independent and identically distributed (IID) random variables. Unfortunately, it is not easy to obtain the exact analytical derivation of the sum of these IID random variables, the desired random variable Z' . Thus, for ease of computation, we can invoke the Central Limit Theorem to approximate Z' as a Gaussian random variable. While a stricter upper limit can be obtained by numerically computing the Chernoff bound, simulations run in [2] show that the Gaussian approximation underestimates this limit by at most 1%, so it is used here for convenience.

Since Z' is the sum of k_u' random variables, where k_u' is itself a random variable, as shown in [1] the mean and variance are given by

$$E\{Z'\} = E\{k_u'\} E\{E_c / I_o\} = (\lambda / \mu)(1 + f) \cdot E\{E_c / I_o\} \quad \text{Equation 14}$$

$$\text{Var}\{Z'\} = E\{k_u'\} \text{Var}\{E_c / I_o\} + \text{Var}\{k_u'\} [E\{E_c / I_o\}]^2 \quad \text{Equation 15}$$

Furthermore, since k_u' is a Poisson random variable,

$$E\{k_u'\} = \text{Var}\{k_u'\} = (\lambda / \mu) \cdot (1 + f), \text{ so that}$$

$$\text{Var}\{Z'\} = (\lambda / \mu) \cdot (1 + f) \cdot E\{(E_c / I_o)^2\} . \quad \text{Equation 16}$$

Thus, the normal approximation for probability of outage can be written

$$P_{out} \approx Q \left[\frac{K_o' - E\{Z'\}}{\sqrt{\text{Var}\{Z'\}}} \right] \quad \text{Equation 17}$$

Where, $E\{Z'\}$ is given by Equation 14 and $\text{Var}\{Z'\}$ is given by Equation 16.

The Erlang capacity of the system is measured by the average traffic load corresponding to the number of active users causing blocking with the designated blocking probability, which in the above analysis, corresponds to the value of λ / μ .