Abstract—cdma2000 high rate packet data standard, also known as IS-856, is a next generation solution to high-speed wireless internet access. The IS-856 air interface incorporates several advanced techniques such as adaptive modulation and coding, turbo codes and incremental redundancy, Hybrid-ARQ, fast channel feedback information and multiuser diversity just to name a few. In this paper, we present an overview of the reverse link characteristics and its performance. In particular, we evaluate the capacity of the reverse link in both a single cell and multi-cell, 3-sectored networks. Analytical expressions are derived to include the effect of practical antenna patterns on the reuse factor, f. Also, a novel approach to model sector load is considered in order to account for the effects of high data rate transmissions.

Index terms— Reverse link capacity, cdma2000 1xEV, IS-856, Wireless internet access, high-data rate cellular systems, IS-95, HDR.

I. INTRODUCTION

Third generation cellular systems are designed to provide enhanced voice capacity and the support of high data rate packet data services. These data services are typically characterized by asymmetric traffic requirements subjected to the adverse effects of the mobile channel. Such conditions require the use of advanced techniques such as fast feedback channel information, adaptive modulation and coding, incremental redundancy, multiuser diversity, receive diversity, efficient handoff algorithms, adaptive rate control, etc. Many of these features are present in the cdma2000 high rate packet data air system (a.k.a IS-856) [1], which is a spectral-efficient air interface that has been recently approved as part of IMT-2000. A detailed overview of the IS-856 basic concepts can be found in [2]. In this paper, we focus on the performance and capacity of the reverse link channel. One of the main differences from IS-95 reverse link is that IS-856 uses a pilot signal to coherently demodulate the reverse traffic channel. In addition, the reverse link of IS-856 introduces new low-rate subchannels that are used to support advanced medium access control (MAC) on both forward and reverse links. For low-rate voice systems, reverse link capacity analysis has been extensively analyzed in the literature, e.g.[3][4]. In this paper we extend such results to account for high data rate transmissions as well as the effects of practical antenna gain patterns on sectorization gains.

II. THE REVERSE LINK PHYSICAL LAYER

The IS-856 reverse channel structure, as described in Figure 1, consists of the Access channel and the Reverse Traffic channel. The Access channel, which further consists of Pilot and Data channels, is used by the access terminal (AT) when in the idle state to send signaling messages to the access network. In connected state, the AT transmits on the Reverse Traffic channel, which contains a Pilot channel, a Reverse Rate Indicator (RRI) channel, a Data Rate Control (DRC) channel, an Acknowledgement (ACK) channel, and a Data channel. The RRI Channel indicates whether or not the Data channel is being transmitted on the Reverse Traffic channel and its associated data rate. Explicit rate information allows demodulation without complex rate determination algorithms. The DRC channel indicates to the access network the supportable data rate on the Forward Traffic channel and the best serving sector for the forward link. The DRC channel provides a priori channel state information used for forward link adaptation and multiuser diversity scheduling. The ACK channel informs the access network whether a data packet transmitted on the Forward Traffic channel has been received successfully. The ACK channel provides a mechanism to perform fine link adaptation based on a posteriori channel state feedback information [2].

Figure 1 Reverse HDR Channel Structure

A. Reverse Link Waveform

Figures 2 and 3 show the Reverse Traffic channel block diagram of the IS-856 standard. There are four orthogonal code-division multiplexed channels. The Pilot/RRI channel is time multiplexed so that the RRI channel is transmitted during 256 chips at the beginning of every slot (1.66…ms). The 3-bit RRI symbol transmitted every frame (16 slots), is encoded using a 7-bit simplex codeword [1]. Each codeword is repeated 37 times over the duration of the frame, while the last 3 code symbols are not transmitted. The DRC symbols (4 bits indicating the desired data rate) are encoded using 16-ary biorthogonal code. Each code symbol is further spread by one of the 8-ary Walsh functions indicating the desired transmitting sector on the forward link. The DRC message is transmitted.
half-slot offset with respect to a slot boundary. The reason is to minimize prediction delay while providing enough time for processing at the desired sector before transmission on the forward link starts on the next slot. The ACK channel is BPSK modulated in the first half-slot (1024 chips) of an active slot. Transmissions on the ACK channel only occur if the access terminal detects a data packet directed to it on the Forward Traffic channel. For a forward data packet transmitted in slot \( n \), a ‘0’ bit is transmitted on the ACK channel in slot \( n+3 \) if a data packet has been successfully, otherwise a ‘1’ bit is transmitted. The 3 slots of delay allow the terminal to demodulate and decode the received packet before transmitting on the ACK channel.

The Data channel supports data rates from 9.6 to 153.6 kbps for a forward data packet transmitted in slot \( n \). The parameters of the reverse link encoder for different data rates are summarized in Figure 2. The code symbols are bit-reversal interleaved and block repeated achieving a fixed 307.2 ksps modulation symbol rate.

The Pilot/RRI, DRC, ACK and Data channel modulation symbols are each spread by an appropriate orthogonal Walsh function as shown in Figure 2. Before quadrature spreading (see Figure 3), the Pilot/RRI and ACK channels are scaled and combined to form the in-phase component. Similarly, the Data and DRC channels are scaled and combined to form the quadrature component of the baseband signal. Reverse link power control (both open and closed loops) is applied to the Pilot/RRI channel only. The power allocated to the DRC, ACK and Data channels are adjusted by a fixed gain relative to the Pilot/RRI channel in order to guarantee the desired performance of these channels. For example, the relative gain of the Data Channel increases with the data rate so that the received Eb/Nt is adjusted to achieve the required packet error rate (PER).

In this paper, we concentrate on the reverse Data channel performance and sector capacity estimates. For reverse link capacity purposes, the DRC and ACK channels can be considered overhead channels. While the addition of Pilot and RRI channels improve the demodulator performance at the base station, thus enhancing reverse link capacity, DRC and ACK channels mostly contribute to improve forward link throughput. Moreover, for a terminal that has an active connection, Pilot/RRI, DRC and ACK channels are transmitted on the reverse link even when the reverse Data channel is not being used. As a consequence, reverse link capacity decreases as the number of active terminals increase.

### III. DATA CHANNEL PERFORMANCE

The performance of the reverse Data channel was simulated under different channel scenarios and with power control. We consider 2 independent and equal-strength paths, each being affected by Rayleigh fading channel with a classic Doppler spectrum at vehicular speeds of 0, 3, 30 and 120 km/h (1.9GHz carrier frequency). The 0 km/h speed corresponds to a simple AWGN channel. The Data Channel gains used in these simulations were the default values provided in [1] and reproduced in Table I.

The required per path average Pilot Ec/Nt for 1% PER is shown in Figure 4 for all data rates as a function of the vehicular speed. The performance is very similar for all code rate \( \frac{1}{2} \) packets, requiring a per path Pilot Ec/Nt between –24.8 and –22.8 dB to achieve 1% PER. Also in this case, we can conclude that there is a small difference (2.0dB) in performance between stationary versus mobile users, which is a desirable feature for adjusting power control setpoint as the mobile environment changes [4].

For the code rate \( \frac{1}{2} \) packet (153.6kbps), the spread in required Pilot Ec/Nt is about 3.5dB. For 153.6 kbps data rate, the default Data Channel gain of 18.5dB was chosen in order to “equalize” the required Pilot Ec/Nt across the range of speeds. At low speeds the selected gain makes the occasional transitions to 153.6kbps to be conservative. On the other hand, such transitions will achieve a slightly higher PER at high
vehicular speeds. Of course for long periods of 153.6kbps transmissions, the outer loop power control will eventually converge to the correct setpoint [4].

Table I
Default Data Channel Gains

<table>
<thead>
<tr>
<th>Data Rate ($r_i$) (kbps)</th>
<th>Data Channel Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null</td>
<td>$-\infty$</td>
</tr>
<tr>
<td>9.6</td>
<td>3.75</td>
</tr>
<tr>
<td>19.2</td>
<td>6.75</td>
</tr>
<tr>
<td>38.4</td>
<td>9.75</td>
</tr>
<tr>
<td>76.8</td>
<td>13.25</td>
</tr>
<tr>
<td>153.6</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Required Pilot Ec/Nt per path for 1% PER - Single Cell, 2 Equal-Strength Paths

Figure 4 Required Pilot Ec/Nt for 1% PER

Required Pilot Ec/Nt per Antenna for 1% PER

Figure 5 The Effect of antenna Diversity on Required Pilot Ec/Nt

Next, we consider the effect of diversity reception at the base station. Diversity reception is a relatively simple technique to improve reverse link capacity and power consumption of mobile terminals. In Figure 5, we present a comparison between the per antenna Pilot Ec/Nt required to achieve 1% PER. We consider 9.6kbps packets only with a 1 path per antenna Rayleigh channel model. Except for very low speeds, where coherence loss due to weaker pilots is observed, the performance is improved by at least 3dB. At 10km/h the gain is in the order of 3.4dB because of the increased diversity provided by the 4-branch receiver. No attempt to optimize the default Data channel gain or the channel estimator was performed for the four-antenna case.

IV. CAPACITY ANALYSIS

Several analyses of capacity of CDMA cellular systems have appeared in the literature [3][4]. For the reverse link, capacity is derived by characterizing the statistical distribution of the total received power at the desired base station antennas. In this paper, we consider an idealized hexagonal placement of base stations, each with 3 sectors as depicted in Figure 6 (Just one tier of interference cells is shown for simplicity). For each cell, the 3 ideal 120-degree boundaries are shown with the corresponding labels $\alpha$, $\beta$ and $\gamma$. As in [4], we consider soft handoff between multiple sectors since it provides a significant reduction on the interference levels seen at the desired sector. In our model, soft handoff is allowed to occur only with the $N_c$ nearest cells ($3N_c$ sectors). In addition, we assume soft combining of the received signal across the 3 sectors within a cell and that each sector is equipped with an $N_a$ antenna diversity receiver. It is assumed that a lognormal shadowing random variable affects the link from the terminal to a cell site and that the terminal’s transmit power is determined by the cell with minimum harmonic sum of the propagation losses to all of its three sectors.

In IS-856, the power controlling base station (BS) attempts to control each terminal’s transmit power so that the pilot SINR received at each antenna of the BS is averages $\gamma$, the target pilot SINR for a particular user. If data is available at the users’ terminal (AT) for transmission, the AT sends a packet at a given rate $r_i$ determined by the reverse-link MAC algorithm. The data packet transmission causes the total transmit power to be increased with respect to the pilot power by an amount proportional to the data rate. As a result, we can define the total received power from the access terminal $i$ (AT) at a given sector as

$$S_i^T = S_i^P (\mu_i + \eta_i)$$

where $S_i^P$ is the received Pilot power from AT; and

$$\eta_i = \eta(r_i) = 10^{DataChannelGainDB(r_i)/10}$$

$$\mu_i = 1 + 10^{DRCChannelGainDB/10}$$

where $\eta_i$ and $\mu_i$ are the relative gains of the Data channel and the combined effect of Pilot and DRC channels, respectively. Note that, the Data channel gains in (2) are given in Table I. Clearly, if a data packet is not being transmitted, $\eta_i = 0$. Moreover, in (3), we have neglected the effects of the ACK channel. Given that the ACK channel is transmitted only
when a packet is received on the forward link and that transmissions on the forward link are time division multiplexed, the effect of ACK channel on the total power received at a given sector is negligible. In this paper we will assume that the nominal values for the DRC channel gain and length are adjusted as a function of the handoff state of the access terminal. The values are shown in Table II and represent a good tradeoff between forward and reverse link capacities while providing a reliable channel state feedback channel when the terminal is in soft-handoff with multiple base stations [7]. The probabilities shown represent the relative occurrence of softer (handoff between sectors of a given cell) and soft handoff and will be used to characterize the average received interference level as a function of $N_s$, the number of connected terminals per sector.

### Table II

<table>
<thead>
<tr>
<th>Handoff Scenario</th>
<th>Probability</th>
<th>DRC Length (slots)</th>
<th>DRC Gain (DB)</th>
<th>$\mu_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft-Handoff</td>
<td>$1 - p_{softer}$</td>
<td>2</td>
<td>-1.5</td>
<td>$\mu_{softer} = 1.71$</td>
</tr>
<tr>
<td>Soft-Handoff</td>
<td>$p_{softer}$</td>
<td>2</td>
<td>-1.5</td>
<td>$\mu_{softer} = 1.71$</td>
</tr>
<tr>
<td>Soft-handoff</td>
<td>$p_{soft}$</td>
<td>4</td>
<td>-3.0</td>
<td>$\mu_{soft} = 1.5$</td>
</tr>
</tbody>
</table>

![Figure 6](image) Three Sector Hexagonal Cell Model

### A. Sector Load and Rise-Over-Thermal

Using (1), the total received power at the target sector can be modeled as

$$I_oW = N_oW + (1 + f) \sum_{i=1}^{N_s} S_i^P (\mu_i + \eta_i)$$  \hspace{1cm} (4)

The per user pilot power, $S_i^P$, is controlled by the target cell such that the pilot SINR per receiving antenna is given by $\gamma_{c,i}$, which is typically assumed to be a lognormal random variable with mean $m_c$ (dB) and standard deviation given by $\sigma_c$ (dB). Moreover, due to the sector combining assumption, the target SINR at the desired sector, say $\alpha$, is reduced by an antenna combining gain factor $G_a$. This can be approximated by averaging (A.1) over the idealized hexagonal region defining the desired sector (see Figure 6). For the pattern shown in Figure 7, $G_a = 0.948$. Next we follow the approach in [2], where the rise-over-thermal, $Z = 1_{o}/N_o$, is calculated based on (4) and the target pilot SINR. Then, it can be shown that

$$Z = \frac{1}{1 - Y}$$  \hspace{1cm} (5)

where the sector load $Y$ is given by

![Figure 7](image) Typical Antenna Gain (Normalized) for a Sectorized Cell

### Table III

<table>
<thead>
<tr>
<th>LogNormal Standard Deviation, $\sigma$</th>
<th>$N_c = 4, m = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.56</td>
</tr>
<tr>
<td>8</td>
<td>0.64</td>
</tr>
<tr>
<td>10</td>
<td>0.77</td>
</tr>
</tbody>
</table>
\[ Y = (1 + f) \sum_{i=1}^{N_s} \frac{G_a Y_{c,i}(\mu_i + \eta_i)}{1 + G_a Y_{c,i}(\mu_i + \eta_i)} \tag{6} \]

The significance of the denominators in (6) is to convert each terminal’s required \( E_c / N_t \) to \( E_c / I_o \). In [3][4] this effect is neglected since for voice signals the numerator in (6) is typically much less than 1. For high data rates, however, the denominator in (6) may take on values in the order of 1.5. In this paper, each term under the summation in (6) is approximated by the first two terms of its Taylor expansion about the expected value of the numerator. That is define,

\[ X_i = G_a Y_{c,i}(\mu_i + \eta_i) \tag{7} \]

\[ m_{X_i} = E[X_i] = G_a e^{\beta m_c + \frac{(\beta \sigma_c)^2}{2}} (\bar{\mu} + \eta_i) \tag{8} \]

where \( \bar{\mu} = p_{\text{soft}} \cdot \mu_{\text{soft}} + (1 - p_{\text{soft}}) \mu_{\text{softer}} \) and \( \beta = \ln(10) / 10 \). Then, the sector load is approximated by

\[ Y = (1 + f) \sum_{i=1}^{N_s} \frac{m_{X_i} - X_i}{1 + m_{X_i}} \tag{9} \]

It can be shown that the average error in (9) is small for reasonable values of \( m_c \) and \( \sigma_c \).

**B. Capacity of a Genie-Aided MAC Algorithm**

The capacity analysis of the decentralized reverse link MAC algorithm in IS-856 is beyond the scope of this paper. In [5], a detailed description of the algorithm and network simulation results is presented. In this paper, we consider the limiting capacity scenario where a genie-aided MAC algorithm is assumed. This implies that all terminals know the data rate allocation \( \{r_1, r_2, ..., r_{N_t}\} \) maximizes total throughput and satisfies an outage criterion. The outage criterion is specified in terms of the probability that the sector’s rise over thermal (ROT), or equivalently its load, exceeds a certain level. Under these assumptions capacity is achieved by maximizing \( \sum_{i=1}^{N_s} r_i \) such that

\[ \text{Prob}(Y > L_{\text{max}}) \leq p_{\text{out}} \tag{10} \]

We use a Gaussian approximation to evaluate (10) so that only the first and second order moments of (9) are necessary\(^1\). In this case, defining

\[ \sigma_{X_i}^2 = G_a^2 e^{2\beta m_c + (\beta \sigma_c)^2} \left[ e^{(\beta \sigma_c)^2} (\eta_i^2 + 2 \bar{\mu} \eta_i + \bar{\mu}^2) \right. \]

\[ \left. - (\eta_i^2 + 2 \bar{\mu} \eta_i + \bar{\mu}^2) \right] \tag{11} \]

where \( \bar{\mu}^2 = p_{\text{soft}} \mu_{\text{soft}}^2 + (1 - p_{\text{soft}}) \mu_{\text{softer}}^2 \), it can be easily shown that,

\[ \sigma_{X_i}^2 = (1 + f) \sum_{i=1}^{N_s} \frac{\sigma_{X_i}^2}{1 + m_{X_i}} \tag{12} \]

Thus, we rewrite (10) as

\[ Q\left( \frac{L_{\text{max}} - m_Y}{\sigma_Y} \right) \leq p_{\text{out}} \tag{13} \]

The genie-aided capacity can be evaluated using non-linear constrained optimization techniques. This is carried out for the performance of a 2 antenna per sector receiver as discussed in Section III. In this case we assume, \( m_c = -22.75 \text{ dB} \), \( \sigma_c = 1.3 \text{ dB} \), \( p_{\text{soft}} = 1/3 \), \( L_{\text{max}} = 0.80 \) (\( Z < 7 \text{ dB} \)), \( p_{\text{out}} = 2\% \) and the three lognormal shadowing scenarios in Table III. The results are shown in Figure 8. The maximum capacity in the order of 240-280kbps is achieved when the number of terminals per sector is about 10. Beyond this point, the sector capacity and consequently the average user throughput decrease almost linearly with the number of terminals in the sector. Note the number of users refer to the ones that are actively moving data over the air as opposed to a much larger number of users that can be dormant due to the burtiness of data traffic. Also, note the rugged appearance of the curves is due to the discrete set of available data rates.

**C. Special Cases**

In this Section, we evaluate the impact of certain scenarios on reverse link capacity. In particular, we evaluate the capacity of a single 3-sector cell since it would be of interest wherever there is a high data demand concentrated in a small geographical area. This is obtained from the previous equations if we set \( f = 0 \) and \( p_{\text{soft}} = 0 \) (other parameters remain unchanged). In addition, we consider two special multi-cell cases with lognormal shadowing standard deviation.
of 8 dB: 1) A very slow mobility case (2 Rx antennas) with \( m_c = -24.2 \) dB, \( \sigma_c = 1.1 \) dB and \( \mu_{\text{sector}} = 1.5 \). 2) A four-antenna diversity receiver (mobile) with \( m_c = -26 \) dB, \( \sigma_c = 1.0 \) dB. The results are shown in Figure 9.

![Figure 9 Single Cell and User Throughput](image)

### V. CONCLUSIONS

In this paper we provided an overview of the IS-856 reverse link and its Data channel packet error performance. In addition, we extended the typical CDMA capacity analysis to include the effect of practical antenna pattern on sectorization gains and high data rate transmission on the sector load. A genie-aided MAC algorithm was used to establish the limiting capacity that can be achieved. It is shown that the capacity decreases as the number of connected terminals increase due to the overhead of Pilot and DRC channels. However, a much larger number of active users can be present due to the burstiness of data traffic. In addition, peak capacities in the order of 250 to 600 kbps can be achieved depending on the number of receiving antennas, interference environment and user mobility.

### APPENDIX A

The ratio of the received interference at the target sector generated by terminals power-controlled by other cells to the received signal at the desired sector (say \( \alpha \)) is proportional to

\[
\frac{r_i^m(x, y)}{r_o^m(x, y)} = \frac{10 \xi_i / 10}{10 \xi_o / 10} \frac{G_i(x, y)}{G_o(x, y)}
\]

with

\[
\Delta G_i(x, y) = \frac{G_o(\theta, \alpha(x, y))}{G_o(\theta_i, \alpha(x, y)) + G_o(\theta_i, \beta(x, y)) + G_o(\theta_i, \gamma(x, y))},
\]

(A.1)

and \( G_o = \mathbb{E}[\Delta G_o(x, y)] \) assuming a uniform distribution of terminals in the sector \( \alpha \) of cell 0. \( r_i(x, y) \) is the distance between a terminal located at the \((x,y)\) coordinates and cell \( i \), \( m \) is the path loss exponent, \( \theta_i, \alpha(x, y) \) is the incident angle from the terminal at \((x,y)\) to the \( \alpha \) sector of cell \( i \), and \( \xi_i \) log-normal shadowing process affecting the link between the terminal and cell \( i \). Following the notation in [4] but redefining \( M_i = 10 m \log(r_i(x, y)) \)

\[
-10 \log(G_o(\theta_i, \alpha(x, y)) + G_o(\theta_i, \beta(x, y)) + G_o(\theta_i, \gamma(x, y)))
\]

for \( i = 0, \ldots, N_C \).

we can write the average normalized interference factor as

\[
f = (I_{S_0} + I_{\bar{S}_0})/(N_S G_o) \quad \text{(A.2)}
\]

where \( N_S \) is the number of connected terminals per sector and

\[
I_{S_0} = e^{(b \beta \sigma)^2} \int \int_{S_0} R_j^{m} \int \int_{S} e^{-z^2/2} \left( z + b \beta \sigma + \frac{M_j - M_o}{b \sigma} \right) dz \Delta G_j(x, y) \rho dxdy
\]

and

\[
I_{\bar{S}_0} = e^{(b \beta \sigma)^2} \int \int_{\bar{S}_0} R_j^{m} \int \int_{\bar{S}} e^{-z^2/2} \left( z + b \beta \sigma + \frac{M_j - M_i}{b \sigma} \right) dz \Delta G_j(x, y) \rho dxdy
\]

with \(-b^2\) being the correlation coefficient between any pair of lognormal random variables, \( \beta = \log(10)/10 \), \( S_0 \) and \( \bar{S}_0 \) are the regions of points \((x,y)\) for which the nearest \( N_C \) cells contain and not contain the center cell (cell 0), respectively.

The normalized interference factor given in (A.2) has been numerically evaluated and the results are summarized in Table III.

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### REFERENCES


