♦ Performance of 1xEV-DO Third-Generation Wireless High-Speed Data Systems

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Wireless high-speed data systems based on 1xEV-DO have recently been deployed commercially and in field trials. In this paper, the emphasis is placed on the validation of the simulated forward link system-level performance through comparison with field data. High spectrum efficiency observed both in simulations and in the field is explained by the salient features of 1xEV-DO that make it suitable for data communications in a cellular mobile environment. These features include, among others, the long-range channel estimation and rate prediction, incremental redundancy hybrid automatic request control (ARQ), turbo coding, and scheduling that exploits multi-user diversity in a fast fading environment. The paper also addresses the reverse link performance and the practical system constraints imposed by the signaling overhead necessary to support high throughput on the forward link. © 2003 Lucent Technologies Inc.

Introduction

CDMA2000* 1xEV-DO is a third-generation wireless data technology standard accepted by the Third Generation Partnership Project 2 (3GPP2) as a solution to provide data services in the wide area mobile and fixed networks [1]. It is based on the high data rate (HDR) concept introduced in [2]. The 1xEV-DO system achieves high spectral efficiency due to a number of techniques that make it uniquely suited for data transmission. These techniques include the long-range channel estimation and rate prediction, incremental redundancy hybrid automatic request control (ARQ), turbo coding, and scheduling that exploits multi-user diversity in a fast fading environment. The impact of these techniques on the forward link performance of 1xEV-DO is investigated in [3, 7]. It has been shown that in the fading environment, the aggregate forward link throughput in the sector varies significantly as a function of number of users, their channel conditions, and speed. In the 1xEV-DO system this dependence is complicated by interactions between scheduling algorithm at the serving base station and the rate prediction algorithm at the mobile. Therefore, the validation of the simulation results through comparison with the field data becomes very important. It facilitates a more accurate estimation of the expected aggregate sector throughput achievable in the 1xEV-DO system in different morphologies. In this paper, we provide such estimates for urban, suburban, and rural environments.

An important practical aspect of the 1xEV-DO system deployment is the reverse link signaling overhead necessary for the data optimized forward link operation. This overhead includes the data rate control (DRC) channel used to request the forward link data

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rate and indicate the preferred serving sector. It also includes the acknowledgment (ACK) channel, which is used to terminate the incremental redundancy hybrid ARQ packet transmission early when it is decoded successfully. These channels consume the reverse link capacity and may limit the achievable reverse link throughput. It is essential for the system to be able to satisfy the traffic demand on both the forward link and the reverse link. In this paper, we provide methodology for evaluation of reverse link throughput in the presence of signaling overhead.

Forward Link Performance

To achieve data and high spectral efficiency in the mobile wireless environment, the techniques described below are applied on the forward link of the 1xEV-DO system.

Overview of Forward Link Data Optimization Techniques

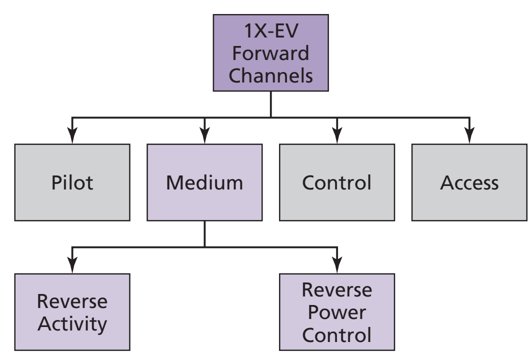
In this section, we discuss techniques employed by the 1xEV-DO system on the forward link to achieve optimal transmission of data and high spectrum efficiency in mobile cellular environments. These techniques include:

- Channel structure that uses combination of time and code division multiplexing,
- Scheduling algorithm that exploits multi-user diversity,
- Hybrid ARQ with incremental redundancy, and
- Long-range channel and rate prediction.

We start with the overview of forward link channel structure shown in **Figure 1**. The pilot, traffic, medium access, and control channels are time division multiplex (TDM) channels, while the medium access channel consists of two code division multiplex (CDM) channels, reverse activity and reverse power control channels. The control channel is used for system acquisition, system parameter broadcast, and service negotiations during call setup. The pilot channel is used to aid coherent reception, soft handoff, channel estimation, and long-range prediction and rate selection. The reverse activity channel is used for reverse link overload and rate control to indicate the reverse link interference loading of the sector. The reverse power control channel is used for the fast power control of the existing reverse link connections. The traffic channel is used to transmit data to the multiple users in a TDM fashion. The time slots have the duration of 1.67 ms and could be assigned to

Panel 1. Abbreviations, Acronyms, and Terms

3G—third generation
3GPP2—3rd Generation Partnership Project 2
1xEV-DO—CDMA evolution–data only
ACK—acknowledgment
AWGN—additive white Gaussian noise
ARQ—automatic request control
CDM—code division multiplex
CDMA—code division multiple access
CDMA2000*—3G evolution of IS-95 standard
C/I—carrier signal-to-interference
DRC—data rate control
DTX—discontinued
FER—frame error rate
HDR—high data rate
IIR—infinite impulse response
IP—Internet protocol
IR—incremental redundancy
IS-856—3GPP2 CDMA interim standard
PPP—point-to-point protocol
RF—radio frequency
RLP—radio link protocol
RRI—reverse rate indicator
TDM—time division multiplex



1xEV-DO - CDMA2000* evolution-data only

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Figure 1.
Forward link channel structure of third-generation 1xEV-DO.

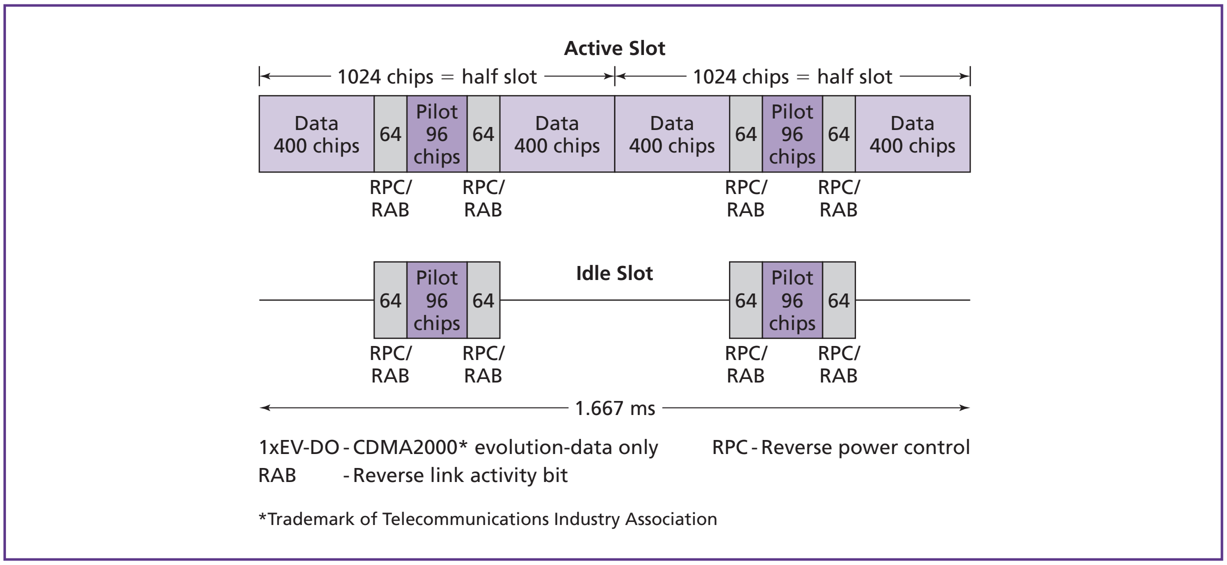


Figure 2.
The structure of third-generation 1xEV-DO forward link active and idle time slots.

Table I. Forward link rate configurations.

	Data Rates (kb/s)											
	38.4	76.8	153.6	307.2	614.4	307.2	614.4	1228.8	921.6	1843.2	1228.8	2457.6
Code Rate	1/5	1/5	1/5	1/5	1/5	1/3	1/3	1/3	1/3	1/3	1/3	1/3
Modulation Type	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	8PSK	8PSK	16 QAM	16 QAM
PN Chips/Bits	32	16	8	4	2	4	2	1	1.33	0.67	1	0.5
Encoder Packet Duration (ms)	26.67	13.33	6.66	3.33	1.67	6.66	3.33	1.67	3.33	1.67	3.33	1.67

PN—Pseudonoise

any user as determined by the scheduling algorithm. The structure of a third-generation 1xEV-DO active and idle (no data to transmit) time slot is shown in **Figure 2.**

The data on the traffic channel can be transmitted at 38.4, 76.8, 153.6, 307.2, 614.4, 921.6, 1228.8, 1843.2, and 2457.6 kb/s. The high data rates are achieved through a combination of high order modulation (QPSK, 8PSK, and 16-QAM), forward error correction coding (coding rate r = 1/5 and 1/3), and spreading. Transmission of one encoder packet can occupy from 1 to 16 time slots. The coding rate, modulation, and packet duration determines one of 12 rate configurations summarized in **Table I.**

The combination of time and code division techniques used for multiplexing forward link channels provides great flexibility of scheduling transmissions to multiple data users at different data rates based on very recent estimates of the radio frequency (RF) environment. This structure enables reliable estimation and rate prediction through sampling of the pilot channel transmitted at constant power. It also accommodates the fast power control of a sufficiently large number of users on the reverse link by the reverse power control channel.

Another important feature of the 1xEV-DO forward link is that it enables the use of scheduling algorithms that exploit multi-user diversity and fading to increase data throughput. Although the standard does not mandate the use of a specific scheduling algorithm, in [7] it is suggested that the proportional fair scheduling is an appropriate compromise between maximizing system capacity and achieving fairness among users. This algorithm prioritizes user transmissions according to the value of the ratio DRC/R, where DRC is the current value of the rate requested by the mobile on the DRC channel, and R is the infinite impulse response (IIR)-filtered user throughput achieved by the mobile in the previous filter window (e.g., set to 1024 slots).

Under the static channel conditions in the presence of the additive white Gaussian noise (AWGN) only, the proportional fair algorithm provides users with equal transmission time by maintaining their throughputs proportional to the static DRC they request. Because the ratio between the largest and the smallest DRC that mobiles can request depending on their location in the sector is 64, the maximum and minimum achievable user throughputs also differ by a factor of 64. In the fading environment, the proportional fair algorithm also allows the scheduler to prefer a user whose channel becomes favorable for a short period of time during an "up-fade" indicated by the high DRC value, while delaying data transmission to the user who is temporarily in a "down-fade" relative to its average condition. Such mechanisms are a natural way to exploit multi-user diversity [9] and to further increase achievable sector throughput [3, 7]. However, when proportional fair scheduling algorithm operates in the fast fading environment, it no longer achieves the equal transmission time distribution among users due to the interaction between the scheduler, rate predictor, and the hybrid ARQ [3].

Long-range rate prediction of fading channel is based on the current and past estimates of the pilot received by the mobile. The prediction algorithm and its critical role in achieving optimal performance are discussed in more detail in [3].

The hybrid ARQ with incremental redundancy is accomplished by transmitting the encoded packets using multiple slots interlaced by four slots and allowing early termination based on partial reception of the encoded packet signaled through the ACK channel. This approach is possible because the packets are encoded with enough redundancy to make successful reception of one slot sufficient for decoding the whole packet. Moreover, the reception of each successive slot improves the likelihood of successful decoding after combining. The four-slot interlacing provides the time necessary for the mobile to attempt decoding and to signal the status back to the base station. The incremental redundancy (IR) hybrid ARQ is especially helpful in the situations where accurate channel prediction is not possible, for example, at high mobile speeds or when other cell interference is highly variable. The operation of incremental redundancy with early packet termination is illustrated in **Figure 3**.

Simulation Validation with Field Data

Simulations of the 1xEV-DO forward link in [3, 7] showed that the sector throughput strongly depends on the RF channel assumptions and on the ability of the algorithms in the mobile and the base station to achieve theoretically optimal performance levels. Therefore, validation of predicted simulation results through comparison with field data is very critical.

In this section, we use the measurements collected from Lucent Technologies' 1xEV-DO commercial trial system. In **Figure 4**, the distribution of carrier signal-to-interference (C/I) ratios measured by the mobile in multiple locations in the test cluster of cells is presented. This distribution is based on the samples taken by the mobile every time it received the forward link pilot (twice per slot). The predictor algorithm uses these measurements to generate the rate request sent to the base station using the DRC. The ability of the rate predictor to accurately generate the rate request depends on the quality of channel estimation and the robustness of the algorithm operation over the wide range of speeds, multipath fading profiles, and in non-stationary channel conditions. It is theoretically expected that the same C/I distributions would result in different distributions of requested data rate. This is not only due to the sensitivity of the predictor algorithm itself to different channel conditions, but also because of its different interaction with the incremental redundancy hybrid ARQ scheme under these conditions. For example, it is shown in [3, 7] that

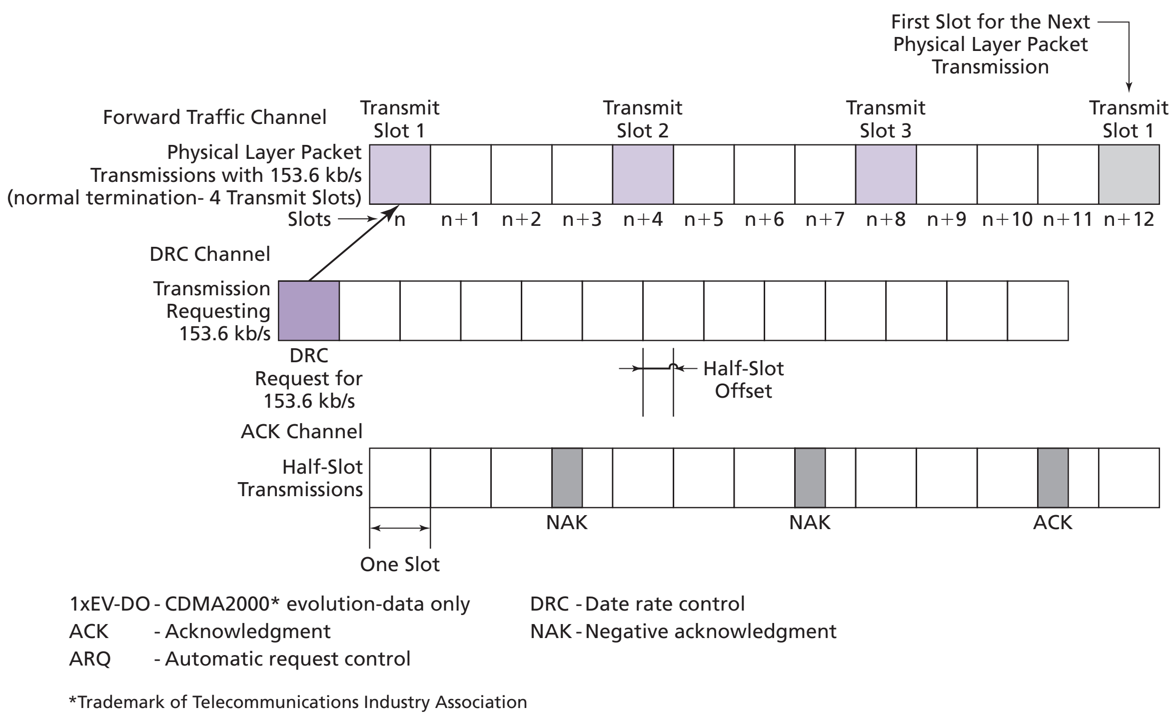


Figure 3.
Incremental redundancy hybrid ARQ with early termination of encoder packet transmission on the forward link of third-generation 1xEV-DO.

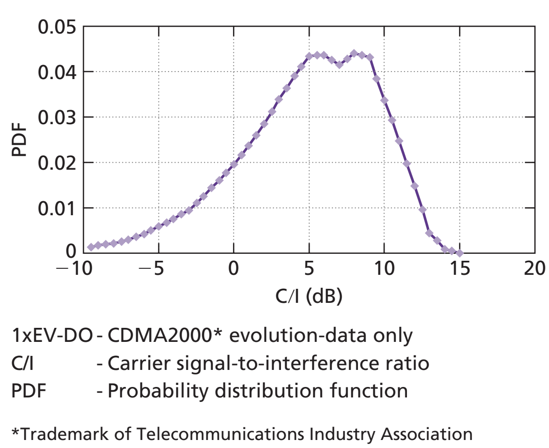


Figure 4.
Carrier signal-to-interference ratio C/I distribution measured in the 1xEV-DO commercial field trial.

while the prediction is more accurate at low mobile speeds, the effectiveness of the early termination mechanism of the hybrid ARQ at these speeds is relatively low. At high speeds, the accurate prediction becomes challenging, but the hybrid ARQ compensates this loss by achieving a larger number of early successful terminations.

In **Figure 5**, we compare the distribution of data rates requested by the mobile device that measured the C/I distribution shown in Figure 4 with the rate distributions obtained from simulation. The distribution in Figure 4 potentially includes the effects of both slow and fast fading. If we assume that the mobile environment is dominated by the signals with strong line-of-site components, we can use the distribution in Figure 4 directly in conjunction with the AWGN conditions. From the figure, we observe that the simulated rate request distribution matches (reasonably

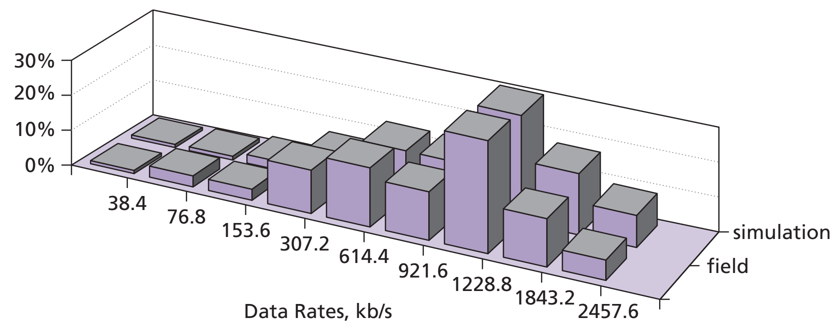


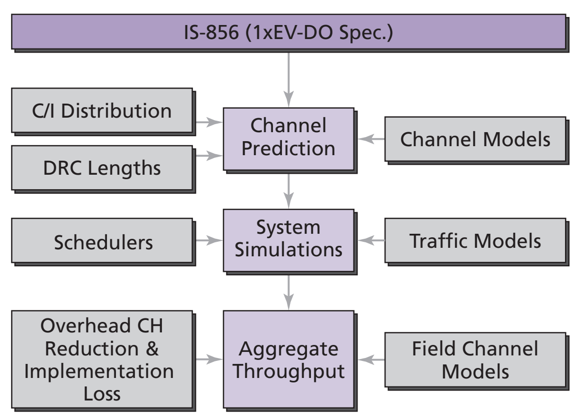
Figure 5.
Comparison of the forward link rate request distributions measured in the field and obtained using simulation.

well) the distribution collected in the field under the same signal-to-interference ratios. Field data validation is used to improve the confidence level in the simulation model. In the next section, we use the same simulation to estimate the aggregate sector throughput of the forward link of the 1xEV-DO system.

Forward Link Aggregate Sector Throughput

The simulation methodology for the forward link aggregate sector throughput consists of three major steps, as depicted in **Figure 6**. The first step involves obtaining the time sequences or traces of data rate requests under different channel conditions. This step assumes continuous data transmission to a single mobile, which locations are uniformly distributed over the coverage area of the sector embedded in the fully loaded system. The second step uses the rate request traces obtained above as an input into the scheduler algorithm. The impact of data arrival process may also be included through the traffic model. The result of the second step has to be adjusted in the final step to account for the upper layer protocol and signaling overhead, throughput losses due to data retransmissions and implementation margins. The results obtained for each channel condition are combined according to the speed and multipath profile typical for different morphologies.

The simulation model assumes that the frequency at which the mobile changes its rate request is 300 Hz. This corresponds to the repetition by the mobile of the same DRC value twice in a row, and is allowed by the 3GPP2 IS-856 standard [1] as means of reducing reverse link activity. The redundancy achieved through the DRC repetition allows transmitting this channel at a lower power. This leads to some degradation on the forward link. However, it has been found in [4] that the two-slot DRC length achieves a good balance



1xEV-DO - CDMA2000* evolution-data only
3GPP2 - 3rd Generation Partnership Project 2
CDMA - Code division multiple access
C/I - Carrier signal-to-interference ratio
CH - Channel
DRC - Data rate control
IS-856 - 3GPP2 CDMA interim standard

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Figure 6.
Forward link 1xEV-DO aggregate sector throughput simulation flow.

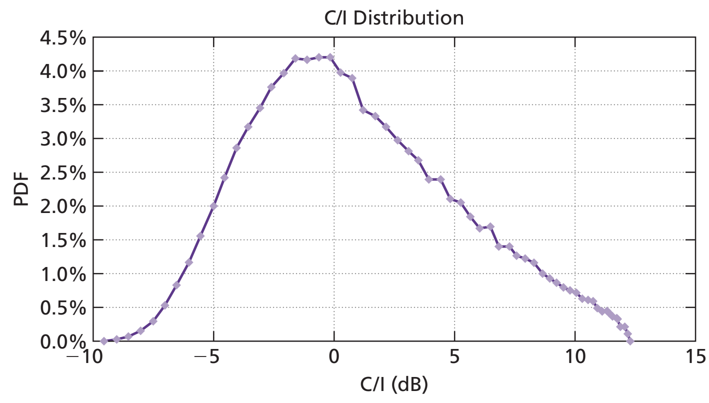

Figure 7.
Distribution of the carrier signal-to-interference ratio C/I in the sector embedded in the fully loaded system used in the simulations of the forward link aggregate throughput.

between minimizing reverse link activity and maximizing forward link throughput.

The C/I distribution used in the simulation is shown in **Figure 7** and is obtained by sampling signal-to-interference ratios at the uniformly distributed locations of the centrally embedded sector in the network of 19 three-sector cells that are fully loaded. The lognormal distribution of shadow fading with standard deviation of 8 dB is assumed. The propagation path loss model is based on the path loss exponent of 3.5. The lognormal shadowing between the mobile and different base stations is 50% correlated. The interference limited scenario is considered such that the contribution of the thermal noise is neglected. The contribution of self-interference in the transmit and receive chains due to imperfect filtering and quantization errors is assumed to limit the maximum achievable signal-to-interference ratio to 13 dB.

The characterization of the aggregate forward link sector throughput is based on the mobile speed and multipath profile distributions shown in **Figure 8**. The one-path and two-path in the figure refer to the Rayleigh fading, while the AWGN reflects the presence of the line-of-site or Ricean component. These distributions are based on the independent field measurements performed in typical urban, suburban, and rural environments and used in this paper to analyze the performance of the 1xEV-DO forward link in the corresponding network morphologies. In this analysis, we also assume that the base station uses the proportional fair algorithm to schedule transmissions to 20 data users in the sector and that the transmit buffers at the base station are always full with the data to be sent.

The simulated aggregate forward link sector throughput for different network morphologies is summarized in **Table II**. These results account for the 3.1% control channel overhead, 4.7% radio link protocol (RLP) overhead, and 10% implementation margin.

Reverse Link Performance

In this section, we extend the approach first presented in [6] and also used in [8] in the context of IS-95 systems to evaluate the reverse link capacity and throughput of 1xEV-DO. Besides the traffic channel, the reverse link of 1xEV-DO includes a number of channels used for signaling. These are the pilot, reverse rate indicator (RRI), ACK, and DRC channels. All active mobiles transmit these channels continuously, with the exception of ACK. Therefore, the impact of these channels on the reverse link capacity has to be included in the analysis. The reverse link traffic channel may be sent at one of the following data rates: 9.6, 19.2, 38.4,

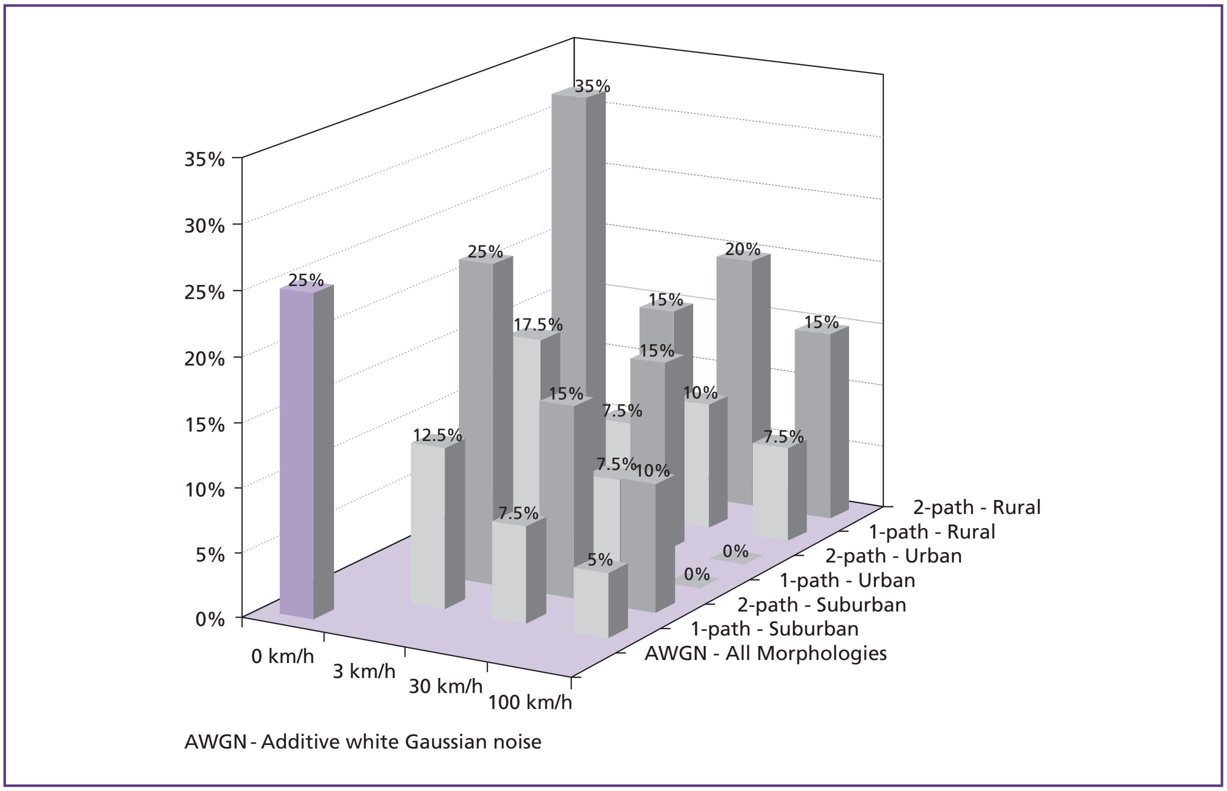

Figure 8.
Distributions of mobile speed and multi-path fading profile used in simulations of forward link aggregate sector throughput for different network.

Table II. Aggregate sector throughput for different network morphologies.

Network Morphology	Aggregate Sector Throughput (kb/s)
Urban	650
Suburban	570
Rural	500

76.8, or 153.6 kb/s, or may be discontinued (DTX) when there is no data to send. Consideration of the user's transmission rate has to be included in the reverse link sector throughput analysis as well.

Reverse link power control maintains a constant minimal ratio of the pilot chip energy to the total noise and interference power spectral density E_c/N_t at the base station receiver for each user's reverse link signal. The total noise and interference power spectral density N_t consists of the background noise power spectral density N_o and the spectral density of the broadband interference I_o received from all other users. The former must be adjusted by the base station noise figure F to account for the internally generated noise in the receive chain. The latter is composed of contributions from the users both within the same sector and in other sectors. In general, the users in different channel conditions need a different required pilot E_c/N_t to maintain a certain frame error rate (FER) on the traffic channel [5]. In the throughput analysis, the required pilot E_c/N_t for a minimum of two paths is assumed since the diversity-receive antennas employed at the cell site guarantee the presence of at least two paths. The narrow range of E_c/N_t values [5] permits the use of a single worst case value for all mobiles without being overly conservative. For the traffic channel rate of 9.6 to 76.8 kb/s, we use the required pilot channel

E_c/N_t per antenna of −23 dB, and for the traffic channel rate of 153.6 kb/s, we use the pilot channel E_c/N_t of −22 dB, since the 153.6-kb/s traffic channel uses a weaker turbo coding than the other traffic channel rates (1/2 rate versus 1/4 rate). An implementation margin of 10% is added to these values for the final reverse link throughput evaluation.

The equal pilot channel E_c/N_t requirement for all calls within the sector implies that all pilot signal strengths received at the cell site are equal to a common term denoted as p_p. The total power S received from a mobile is the sum of the pilot channel power p_p, the DRC channel power p_D, the traffic channel power p_T, and the ACK channel power p_A. To simplify the analysis, we neglect the contribution of the ACK channel, because only one mobile at most transmits the ACK channel at a time. The ratio of the total received power from the mobile to the received pilot power can be expressed as:

$$\frac{S}{p_p} = 1 + 10^{G_D/10} + \nu 10^{G_T/10}, \tag{1}$$

where G_D is the DRC channel gain in decibels, G_T is the traffic channel gain in decibels relative to the pilot channel, and ν is the traffic channel activity factor.

The required ratio of the pilot chip energy to the total noise and interference power spectral density E_c/N_t can be written as follows [6, 8]:

$$\frac{E_c}{N_t} = \frac{\dfrac{p_p}{W}}{FN_o + \dfrac{(1+\beta)(N-1)S}{W}} \equiv d, \tag{2}$$

where β is the average ratio of the interference from the sources outside the sector to the interference from the in-sector sources, N is the number of users in the sector, and W is the system bandwidth. The value of β has been determined from system simulations to be equal to 0.85 for a standard three-sector configuration [8]. Expression (2) can be rewritten to explicitly find the number of users in the sector N:

$$N = \frac{p_p}{d(1+\beta)S} + 1 - \frac{FN_oW}{(1+\beta)S} \tag{3}$$

$$\Rightarrow N_{\max} = 1 + \frac{p_p}{d(1+\beta)S}, \tag{4}$$

where $N_{\max}$ is the finite limit on capacity (pole capacity) that is reached by letting the signal-to-noise ratio go to infinity (i.e., by letting the received signal power become unbounded with respect to the cell site noise). Substituting expression (1) into (4), the pole capacity can be written as:

$$N_{\max} = \left(\frac{1}{1 + 10^{G_D/10} + \nu 10^{G_T/10}}\right)\left(\frac{1}{d(1+\beta)}\right) + 1. \tag{5}$$

The loading in the sector can be conveniently ex-pressed as a fraction of the pole point $N_{\max}$. The reverse link of the 1xEV-DO system supports similar loading levels as the reverse link of CDMA2000 1X, which is typically designed for approximately 70% of the pole. The dependency of the traffic channel gain G_T on the data rate is summarized in **Table III** and is based on the recommendation in [1]. The traffic channel activity ν for the continually transmitting users is assumed to be one. The DRC channel gain G_D is a function of the number of slots in which the same value of DRC is repeated. As discussed in the previous section, the DRC length of two slots provides an acceptable tradeoff between reverse and forward link performance [4]. The recommended value of the DRC channel gain in this case is −1.5 dB.

In **Table IV**, some examples of the reverse link operating scenarios are illustrated using expression (5). In these examples, the traffic channel is assumed to have an activity $\nu = 1$. In the second scenario, 17 primary users can be supported in an embedded sector and each of them could transmit 9.6 kb/s on the traffic channel, which results in a physical layer data throughput of

Table III. Traffic channel gains relative to pilot.

Traffic Channel Rate (kb/s)	Traffic Channel Gain (dB Relative to Pilot)
9.6	3.75
19.2	6.75
38.4	9.75
76.8	13.25
153.6	18.5

Table IV. Reverse link throughput versus the number of active users.

Operating Scenario	Number of Active Users at 70% Loading	Reverse Link Traffic Throughput (kb/s)
1	14	187
2	17	165
3	20	146

165 kb/s. A larger number of users can be traded off for a smaller data throughput (scenario 3), or vice versa (scenario 1). The same throughputs could also be achieved with many other combinations or data rates and channel activities. Suppose that only half the users have data to transmit and they transmit it at 19.2 kb/s, or even a quarter of the users at 38.4 kb/s or other such combinations of busty traffic. The throughputs presented in Table IV represent an estimate of the upper bound achievable under assumption of full link utilization. These throughputs may be reduced when the data traffic arrival pattern does not allow maximizing the link utilization efficiency.

The pole point analysis helps to estimate the number of active users that can be supported on the reverse link. In addition to these users, the system supports a number of additional dormant user sessions. In the dormant state, the user releases the RF resources (pilot channel, DRC channel, and Walsh codes) but maintains the point-to-point protocol (PPP) session and the Internet protocol (IP) address. When the dormant user has new data to send, it has to reestablish its RF connection but does not have to log in (reestablish its PPP session or obtain a new IP address). The dormant state allows for many more users in the system than the RF limit. The dormancy timer controlling the transition from active to dormant state must be carefully chosen to maximize the number of users while not significantly impacting user perceived delay due to the increased number of channel setups.

Conclusion

In this paper, the simulated forward link performance has been validated through comparison with the field data from the commercial 1xEV-DO trial system. We used the same simulation model to evaluate the forward link aggregate sector throughput for different network morphologies. The aggregate throughput has been shown to vary between 500 to 650 kb/s. To support the forward link throughput at 4:1 forward-reverse traffic demand ratio, we have identified analytically that the reverse link capacity of 146 kb/s (based on 20 active users) is sufficient to support the high spectral efficiency on the forward link.

***Trademark**

CDMA2000 is a trademark of Telecommunications Industry Association.

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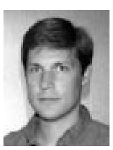

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