# A Forward Link Performance Study of the 1xEV-DO Rev. 0 System Using Field Measurements and Simulations

## Summary

Based on extensive measurements and simulations, the physical layer sector aggregate throughput of the 1xEV-DO system is estimated to be about 1225 kbps.

Using the 3GPP2 traffic models, the numbers of supportable users per sector per carrier are estimated to be between 30 and 60 for the HTTP application and between 10 and 12 for the FTP application, under the assumption that the user perceived data rates are between 435 and 250 kbps.

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## Abstract

Following the unprecedented growth of voice applications in wireless mobile communication, high-speed wireless data applications have started to proliferate. One system that has attracted considerable attention is the third generation one-carrier evolution–data only (1xEV-DO) high-speed data system. Extensive analyses indicate that the spectral efficiency of a wireless data application can be increased significantly compared to that of a wireless voice application by means of a number innovative techniques, including turbo coding, rate adaptation, early completion, packet scheduling, and receive diversity. In this paper, we offer extensive field measurements to quantify the gains provided by these techniques. We also provide estimates of the throughput and capacity of the 1xEV-DO system that are validated by both field measurements and simulations. 

## Introduction

Because of the popularity of the cellular phone, wireless mobile voice applications have become commonplace. While the number of voice subscribers worldwide is still increasing at a healthy rate, the focus of the wireless mobile industry has shifted to wireless data applications, which are viewed as a source of potential growth. With the deployment of the one-carrier evolution–data only (1xEV-DO) system in the United States and in other regions of the world, there has been increasing interest in its performance and capabilities. The 1xEV-DO system is a third-generation wireless data technology standard proposed by the 3rd Generation Partnership Project 2 (3GPP2) as a solution that can be used to provide data services to wide area mobile and fixed networks [1]. It is based on the high data rate (HDR) concept introduced in [3]. Previous studies of the performance of the 1xEV-DO system can be found in [5–11 and 16]. These studies are based primarily on theoretical predictions and computer simulations that are sensitive to many aspects of the radio frequency (RF) environment, including the layout of the cells (e.g., cellular or clover-leaf), the antenna characteristics, the propagation models, the channel types (e.g., additive white Gausian noise [AWGN], Ricean, and Rayleigh), the number of paths, the handoff status, the nature of the time correlation of the RF channel, and the details of the implementations of the terminal and the base station. Because of this long list of dependencies, predictions based on theoretical analysis and computer simulation tend to forecast results that vary widely—from unacceptably low to excitingly high—depending on the assumptions that are used in the study. Consequently, theoretical predictions of system performance contain, in addition to objective analysis, an element of art. Considerable practical experience is required to choose assumptions that are close enough to the conditions in the field to make an accurate prediction of system performance possible. Although performance validation by means of field measurements is, therefore, both necessary and desirable, very few studies are available in the literature due to the high cost of making the measurements and the difficulty of analyzing and interpreting the results.

The purpose of this paper is to provide a detailed performance analysis of the 1xEV-DO Rev. 0 system based on extensive field measurements. Based on the measurements and the analysis, we also discuss various simulation assumptions that appear to provide performance results consistent with the field measurements.

The organization of this paper is as follows. In the first section, we provide brief descriptions of the key design features of the 1xEV-DO system that have resulted in high system throughput. In the second section, we discuss simulations that were carried out before field measurements were available. In the third section, after a short discussion of data collection methodology, we analyze the field measurements together with the simulation results. Our analysis focuses on the key performance features, i.e., those that are of greatest interest to the technical community. In the fourth section, we provide further analysis to estimate sector throughput and capacity, taking the randomness of call arrivals and packet lengths into consideration. Finally, in the fifth section, we summarize the results of the preceding sections and draw conclusions.

# I. Key Performance Features of the 1xEV-DO System

The 1xEV-DO system can achieve higher spectral efficiency than other data systems, including CDMA2000* third generation one-carrier (3G1X) data, General Packet Radio Service (GPRS), and enhanced data for Global System for Mobile Communications* (GSM*) evolution (EDGE), because it employs many techniques that are optimized for data transmission. The following subsections describe some of the techniques that we will investigate, by means of simulations and field measurements, in detail.

## Combination of TDMA and CDMA

In the 1xEV-DO system, time is divided into many time slots and each user uses one or more time slots to transmit their payload. Further, each time slot can only accommodate one user. Multiple users are accommodated using the time division multiple access technique (TDMA) As a result, each user can use the maximum power of the entire base station. Now, each second is divided into 600 timeslots, and the system decides which user should transmit at the timeslot boundary. In revision 0 of the 1xEV-DO standard, thirteen data rates are supported. The number of bits transmitted in a packet and the number of timeslots needed for a packet depend on the data rate and are summarized in **Table I**. (The channel coding rates and the corresponding modulations are also included in the table.)

**Table I. Date rates, frame, slot sizes, and DRC index as defined in the DOr0 standard.**

| DRC index | Data rate (kb/s) | Slots needed | Bits per packet | Code rate | Modulation |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | - | - |
| 1 | 38.4 | 16 | 1024 | 1/5 | QPSK |
| 2 | 76.8 | 8 | 1024 | 1/5 | QPSK |
| 3 | 153.6 | 4 | 1024 | 1/5 | QPSK |
| 4 | 307.2 | 2 | 1024 | 1/5 | QPSK |
| 5 | 307.2L | 4 | 2048 | 1/5 | QPSK |
| 6 | 614.4 | 1 | 1024 | 1/3 | QPSK |
| 7 | 614.4L | 2 | 2048 | 1/3 | QPSK |
| 8 | 921.6 | 2 | 3072 | 1/3 | QPSK |
| 9 | 1228.8 | 1 | 2048 | 1/3 | 8-PSK |
| 10 | 1228.8L | 2 | 4096 | 1/3 | 8-PSK |
| 11 | 1843.2 | 1 | 3072 | 1/3 | 16-QAM |
| 12 | 2457.6 | 1 | 4096 | 1/3 | 16-QAM |

1xEV-DO—First generation evolution–data only
DRC—Data rate control
PSK—Phase shift keying
QAM—Quadrature amplitude modulation
QPSK—Quaternary phase shift keying

Note: Some frequently used data rates are defined with long (L) and short versions.

While the TDMA technique may be well suited to the bursty nature of packet data, the code division multiple access (CDMA) technique has the advantage of being able to have frequency reuse in every sector, which is also highly desirable. To combine the advantages of both techniques, the 1xEV-DO system scrambles data from each timeslot and spreads it using a computer generated pseudo-random -sequence unique to the sector.

## Adaptation of Modulation, Coding, and Data Rate

In the wireless mobile environment, the RF condition changes significantly with time. When the RF condition is good, little coding protection is needed and modulation with high constellation can be used, making it possible to transmit at a high data rate in a given timeslot. To take advantage of this possibility, the RF condition is constantly monitored by the handset in the 1xEV-DO system. Based on the RF measurement, the handset determines the proper modulation, coding, and supportable data rate in each timeslot (see Table I). Using the data rate control (DRC) channel, this information is then transmitted on the reverse link to the base station. The DRC channel is a 4-bit channel that allows 16 data rates to be defined.

The structure of the reverse link traffic channel is shown in **Figure 1**. The pilot channel aids coherent demodulation and tracking. The reverse rate indicator (RRI) channel is used to inform the base station about the data rate being transmitted on the reverse link. The acknowledgement channel is used to support early completion of forward link packets, as will be discussed in the next subsection. If the base station decides to transmit a packet for a given handset, it is required to transmit it at the data rate specified by the DRC request from that handset. Clearly, it would be of great interest to determine the possible data rate distribution by means of field measurements of data rate adaptation.

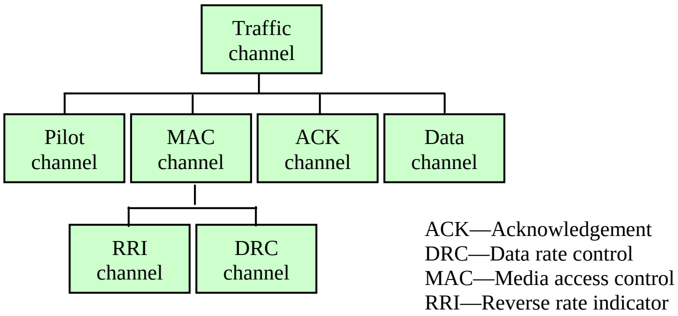


**Figure 1. Reverse link traffic channel structure.**

## Early Completion Using Incremental Redundancy

While the data rate adaptation discussed above significantly improves spectral efficiency, further gain can be obtained by dividing the total packet energy in each packet into several portions and incrementally transmitting the packet with a port of the energy using multiple subpackets in separate timeslots. and terminating the transmission as soon as the packet is decoded correctly at the other end. This gain exists because the estimation of the RF environment at the handset is not perfect. Consequently, the data rate requested by handset via DRC channel for the base station to transmit is usually conservative. This mismatch between the data rate that should be transmitted and the data rate that is requested by the handset is effectively mitigated by early completion. In the 1x-EVDO system, the repetition of the packet bits in the subpacket is accomplished by means of channel coding to obtain further coding gain. To allow time for the handset to process each subpacket and feed back the information to the base station, each subpacket is transmitted disjointly in time, with three timeslots between subpackets. This is known as 4-slot packet interlacing. Based on simulations, the early completion gain should be small if the channel is close to AWGN and large if the channel suffers unpredictable fading. It would be of great interest to measure the gain that can actually be obtained in the field due to early completion.

### Packet Scheduling

When data from multiple users is waiting to be transmitted, the RF conditions of the users may differ. In the 1xEV-DO system, the base station can schedule data from users with more favorable RF conditions for transmission first; meanwhile, the RF conditions of other users may improve before their data is scheduled. This method of packet scheduling provides a gain known as multi-user diversity gain. In the 1xEV-DO system, the proportional fair [12, 14] scheduler is the default method used for packet scheduling, although other schedulers have also been implemented to provide options with different definitions of fairness.

### Handset Receive Diversity

Most commercial handsets provided by service providers for the 1xEV-DO system have two-antenna receive diversity capability. The gain achievable from receive diversity is usually difficult to predict. In theory, a 3 dB gain should be expected for an AWGN channel, assuming that noise and interference received by the two antennas is statistically independent. In reality, due to the limitation on the size of a handset, there may be a noticeable correlation between the interference received by the two antennas, which may result in a reduction in gain. On the other hand, two-antenna receive diversity has the potential to provide a gain of more than 3 dB if the signal received on the two antennas suffers strong fading. Because of this complexity, simulations usually result in gains ranging from very small to very large, depending on the assumptions concerning channel type and RF conditions. Thus, it would be useful if the achievable receive diversity gain could be verified by field measurements.

## II. Performance Predictions Using Simulations

Before the availability of field measurements, computer simulations were carried out to predict the performance of the 1xEV-DO system and to guide system deployment planning. Even when field measurements are available, computer simulations are still useful for understanding and interpreting them. For example, the assessment of the capacity of a fully loaded system is made using both measurements and simulation. It is usually not possible to obtain field measurements from a fully loaded network, because measurements are from the actual load on the network at the time they are made. In order to assess the capacity of the fully loaded system, computer simulation modeling is usually first carried out based on the network conditions under which the measurements were made. Then, the measurements are used to fine-tune and validate the computer simulation model. Finally, after validation, the simulation model is used to predict the capacity of the fully loaded system.

For computational efficiency, our simulation is divided into two stages. In the first stage, the physical layer link-level simulation is carried out. In **Figure 2**, the physical layer link-level simulation block diagram of the 1xEV-DO system is shown in detail. The $E_b/N_0$ performance from the link-level simulation is obtained using AWGN, Rayleigh fading, and other channels. The detailed $E_b/N_0$ performance curves for AWGN and other channels are available in the literature [15] and will not be discussed here.

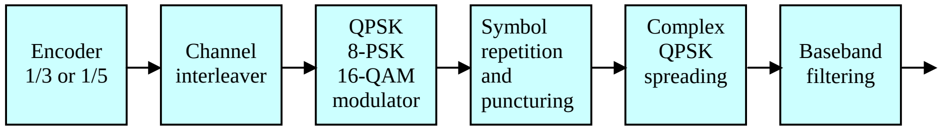


**Figure 2. Physical layer link-level simulation block diagram.**

PSK—Phase shift keying
QAM—Quadrature amplitude modulation
QPSK—Quaternary phase shift keying

While the link-level simulation is straightforward and can easily be verified by other technical groups, the use of the link-level simulation to predict system throughput is a complex problem and the results critically depend on the channel assumptions. It is well known that the use of different channel models (e.g., AWGN channel and Rayleigh fading channel) will produce throughput predictions ranging from pessimistic to optimistic. For this reason, a mix of different channel types, including AWGN, Rayleigh, and Ricean channels, is usually adopted. Many mixes of channel types have been standardized by the International Telecommunication Union (ITU) and other standards organizations. These standardized mixes were generated primarily to facilitate performance benchmarking of proposed systems from different research and industrial organizations. Little attempt was made to determine whether these standardized mixes could produce performance predictions that match field measurements. Indeed, some of the standardized channel mixes are known to provide voice capacity predictions that are overly pessimistic when compared with field measurements. In this paper, we use the channel mix shown in **Table II**, which is based on extensive field measurements from several large cities in the U.S. and abroad. One of the reasons for using this particular model is that it has been calibrated based on simulation results from many existing CDMA voice and data systems. This channel mix has been found to produce capacity predictions that match the field measurements for both voice and data applications in many systems, including IS-95 and 3G1X [7]. It also produces capacity predictions that match the field measurements for the 1xEV-DO system, as will be shown later in this paper.

**Table II. Channel mix used in this paper.**

| | 3 km/h | 30 km/h | 100 km/h |
|---|---|---|---|
| AWGN | 25% | – | – |
| 1-path Rayleigh | 12.5% | 7.5% | 5% |
| 2-path Rayleigh | 25% | 15% | 10% |

AWGN—additive white Gaussian noise

In the second stage of our simulation, the system-level simulation is carried out. To simplify the computation, we used a center cell surrounded by two layers of cells for our simulation of the 1xEV-DO system. Only the performance of the center cell is considered in our results. **Table III** provides a list of the system assumptions for the system-level simulation.

**Table III. Simulation parameters.**

| RF parameters | Values |
|---|---|
| Number of 3-sector cells | 19 |
| Path loss model | Cost 231 |
| Cell radius | 3 km |
| Log-normal shadowing | 8 dB |
| Shadow correlation | 0.5 |
| Carrier frequency | 1.9 GHz |
| BS antenna gain | 17 dB |
| Cable loss | 2 dB |
| MS noise figure | 10 dB |
| Fast fading model | Jakes |
| Handoff add thresholds | $T_{add}$= –7 dB |
| Handoff drop thresholds | $T_{drop}$ = –9 dB |

BS—Base station
MS—Mobile station
RF—Radio frequency

## III. Field Measurements and Simulation Results

To verify the system performance of 1xEV-DO systems, extensive measurements were made on commercial 1xEV-DO systems. To carry out the measurements, a 1xEV-DO Personal Computer Memory Card International Association (PCMCIA) card was used as a terminal; it was connected to the laptop used for data logging. The drive routes used for the measurements included city streets, local roads, and highways. The signal to noise and interference ratio (*C/I*) from the measurements and the computer simulation were plotted together, as shown in **Figure 3**. The *C/I* measurements are from the pilot channel in a loaded system with many cells. As Figure 3 shows, the drive routes selected were reasonable and were representative of an embedded cell environment, because the measurements matched the simulations to within 1 dB around the median. The measurements showed a slightly longer tail at low values of *C/I*, because the drive routes included areas that did not have good coverage. Most of the difference between the measurements and the simulations results from the fact that the simulations were carried out under interference-limited condition in order to investigate the capacity under a fully loaded condition, whereas the measurements also included noise-limited areas.

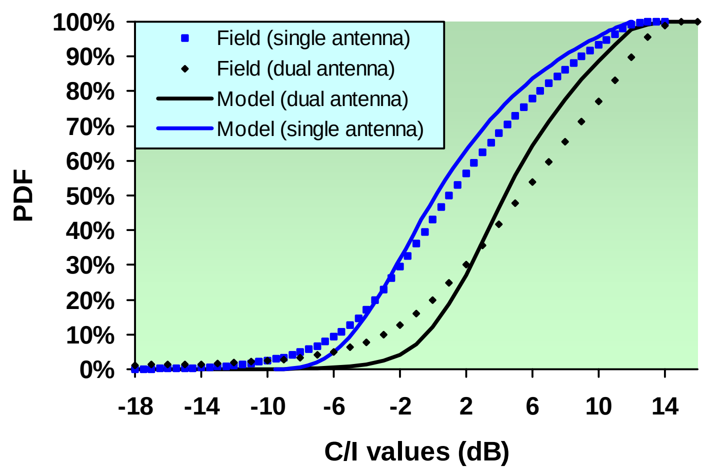


**Figure 3. The C/I probability distribution function from simulations and measurements.**

C/I—Signal to noise and interference ratio
PDF—Probability distribution function

As Figure 3 shows, the two-antenna multiple-paths curve shows a large improvement in *C/I* distributions over the single-antenna single-path curve. The logged RF signal profile indicated that noticeable gains were obtained through multiple paths as well. To demonstrate this, **Figure 4** shows the number of locked paths at the terminal. (An RF path is locked if its strength is larger than a predetermined threshold.) Only locked paths are used for the signal detection process. The demodulator for the 1xEV-DO card has six fingers that are capable of locking to six paths simultaneously from the signals of the two antennas.

Next, we investigate the performance of the data rate adaptation as shown by the field measurements. **Figure 5** shows the distributions of the data rate on the DRC channel obtained from measurements and from simulation using the channel mix shown in Table II. Recall that the data rate on the DRC channel is the data rate that is requested by the terminal and is sent back to the base station through the reverse link DRC channel. The mean data rate from the measurements is about 850 kb/s; that from the simulation is about 880 kb/s. As Figure 5 illustrates, the match of the two distributions is remarkably good.

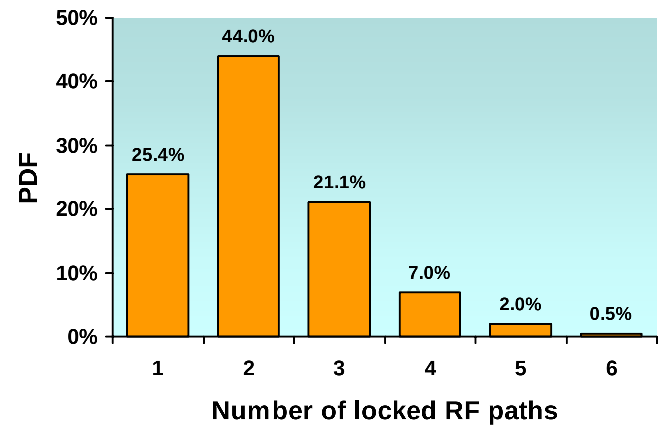


**Figure 4. Number of locked RF paths for the demodulator.**
PDF—Probability distribution function
RF—Radio frequency

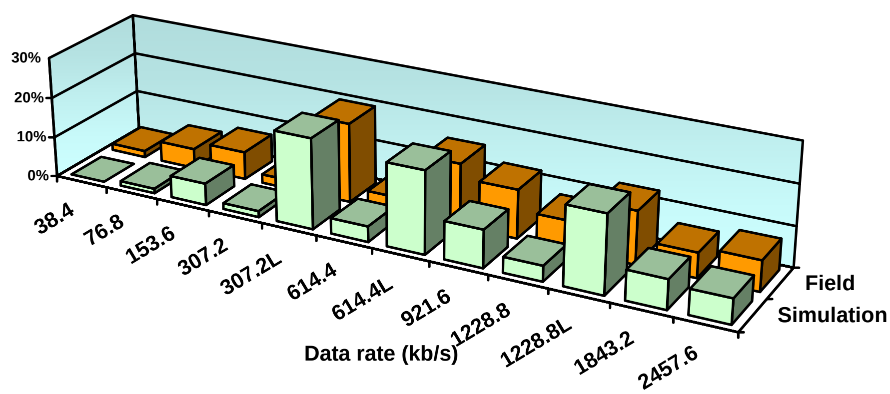


**Figure 5. Distribution of the data rate on the DRC channel.**

Simulations have long predicted that the data rate reported on the DRC channel will be higher when the mobile is moving at low speeds than when it is moving at high speeds, because the mobile estimator can track the RF condition much better at low speeds. To verify this assertion, the measurements were also plotted against the mobile speed and fitted into a solid curve for clarity. As shown in **Figure 6**, the data rates reported on the DRC channel increase linearly when the speed of the mobile decreases below 10 miles per hour. When the speed of the mobile is from 10 to 50 mph, the data rates reported on the DRC channel appear to be stable and are not a clear function of the speed of the mobile.

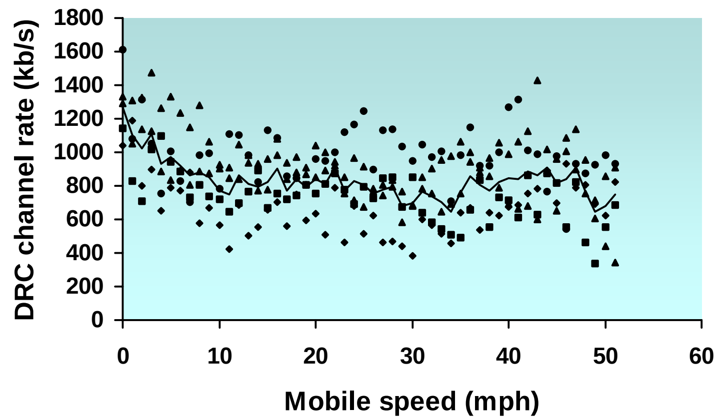


**Figure 6. Data rate measured on the DRC channel as a function of speed.**

DRC—Data rate control

At this point, it is also interesting to compare the required *C/I* derived from the simulation with that derived from the measurements. **Figure 7** shows the required *C/I* of a dual antenna terminal derived from field measurements and from a computer simulation with a mix of channels. Clearly, the simulation predicted the required *C/I* very well for most data rates, the exception being low data rates, for which the simulation was more conservative than the measurements.

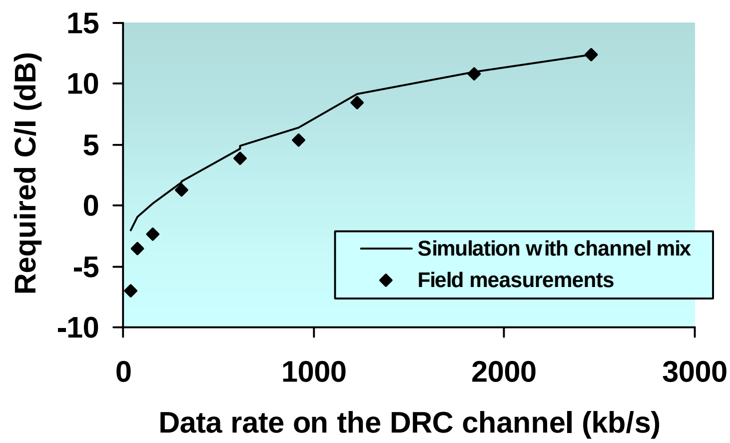


**Figure 7. The required C/I derived from measurements and simulation.**

C/I—Signal to noise and interference ratio
DRC—Data rate control

One of the key goals of the measurements is to study the early completion technique, which is expected to provide gains in addition to the throughput gains measured by the DRC data rate. **Figure 8** shows the early completion gain as a function of data rate as given by the simulation and the measurements. It is apparent that the early completion gain indicated by the measurements is about double that predicted by the simulation.

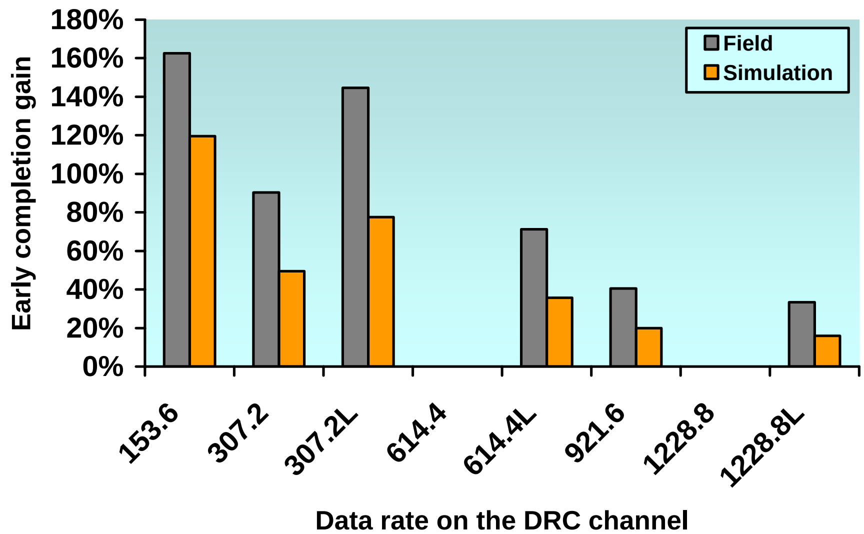


**Figure 8. Early termination gain as a function of data rate.**

At first glance, one might be tempted to conclude that the gain indicated by the measurements is more accurate than that indicated by the simulation, but a closer look reveals that this is not the case. In the 1xEV-DO system, the forward link pilot signals are time multiplexed along with the user traffic data in each time frame. Because global positioning system (GPS) synchronization is used for the whole network, pilot signals from all base stations are time synchronized. Since terminals use the strength of the pilot signal to estimate the *C/I* values, and since all pilots are transmitted at full base station power, the *C/I* value of the pilot channel often does not match that of the traffic channel if the surrounding cells are not fully loaded. Because the data rate of the DRC channel is based on the *C/I* of the pilot channel, its value will be conservative when traffic channels from the adjacent cells are not fully occupied; this will produce a larger early completion gain.

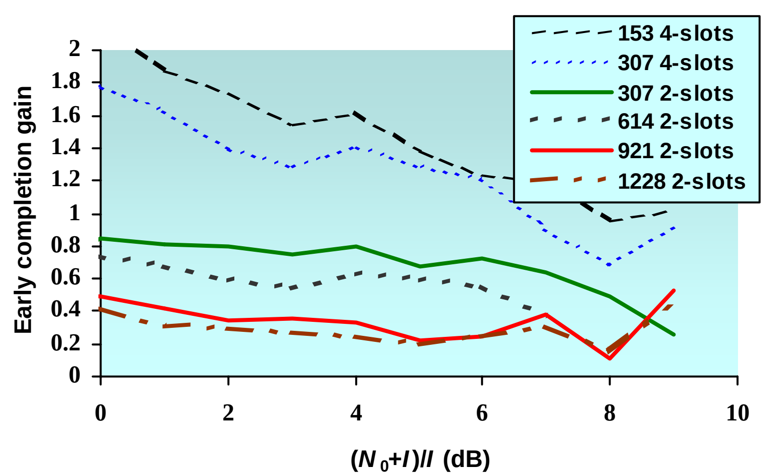


**Figure 9. Early completion gain as a function of ($N_0$+I)/I.**

$N_0$—Noise density
I—Interference density

As the observations above indicate, the early completion gain will be large in a live network, because there will always be a mismatch between the *C/I* of the pilot channel and that of the traffic channel. But we are also interested in determining the early completion gain when the network is fully loaded in every base station. Under fully loaded conditions, the traffic channel will be fully occupied and the *C/I* mismatch between the pilot and the traffic channel will disappear. To determine the early completion gain when there is no *C/I* mismatch, we plotted the early completion gain as a function of $(N_0+I)/I$ in, where $N_0$ represents the noise density and $I$ represents the interference density from the surrounding cells (see **Figure 9**).

When the value of $(N_0+I)/I$ increases, the effect of $N_0$ begins to dominate and the mismatch between the *C/I* of the pilot channel and that of the traffic channel diminishes. In the region in which $(N_0+I)/I$ is about 10 dB, the early completion gain shown by the measurements is reduced by about one half and matches that indicated by the simulation very well. The early completion gains derived from the measurements of a live network and those predicted by the simulation for a fully loaded network are summarized in **Table IV**. In that table, the early completion gain is defined as the difference between the achieved data rate and the target data rate, normalized by the target data rate. The rate distribution provides the probability of the occurrence of a particular rate. The average gain is obtained by weighting the gain of each data rate with its corresponding probability.

**Table IV. Early completion gain summary for the 1xEV-DO system.**

| | Field measurements | | | Simulation predictions | | |
|---|---|---|---|---|---|---|
| Target data rate | EC gains | Achieved data rate | Rate distribution | EC gains | Achieved data rate | Rate distribution |
| 38.4 | 344.4% | 170.7 | 1.6% | 308.0% | 156.7 | 0.0% |
| 76.8 | 263.6% | 279.3 | 4.9% | 221.3% | 246.7 | 1.2% |
| 153.6 | 162.6% | 403.4 | 6.9% | 119.5% | 337.1 | 5.5% |
| 307.2 | 90.4% | 584.9 | 2.2% | 49.5% | 459.1 | 1.5% |
| 307.2L | 144.6% | 753.5 | 19.6% | 77.4% | 546.3 | 21.5% |
| 614 | 0.0% | 614.4 | 3.8% | 0.0% | 614.4 | 3.7% |
| 614L | 71.2% | 1053.1 | 15.4% | 36.0% | 836.6 | 20.1% |
| 921.6 | 40.5% | 1295.2 | 12.0% | 20.0% | 1105.9 | 9.4% |
| 1228.8 | 0.0% | 1228.8 | 7.1% | 0.0% | 1228.8 | 3.8% |
| 1228.8L | 33.3% | 1638.7 | 12.9% | 15.8% | 1423.8 | 19.8% |
| 1843.2 | 0.0% | 1843.2 | 6.1% | 0 | 1843.2 | 7.3% |
| 2457.6 | 0.0% | 2457.6 | 7.5% | 0 | 2457.6 | 6.1% |
| Weighted average | 35% | | | 20% | | |

1xEV-DO—One-carrier evolution–data only
EC—Early completion

It is interesting to note that, as shown in Table IV, the achieved minimum average data rate from the field measurements is about 170 kb/s after the early completion gain is taken into account, although the packets are sent through a 38.4 kb/s channel.

In the 1xEV-DO system, packets are scheduled using the proportional fair algorithm. To investigate the possible gains from scheduling, simulations were carried out before the measurements. When the number of transmitting users in the simulation is increased, sector throughput showed a clearly increasing trend. The simulation using the proposed channel mix and that using the field measurement trace are shown in **Figure 10**. From Figure 10, it appears that the simulations match well and that the scheduling gain is about 20% to 30% when the number of transmitting users is between 5 and 15.

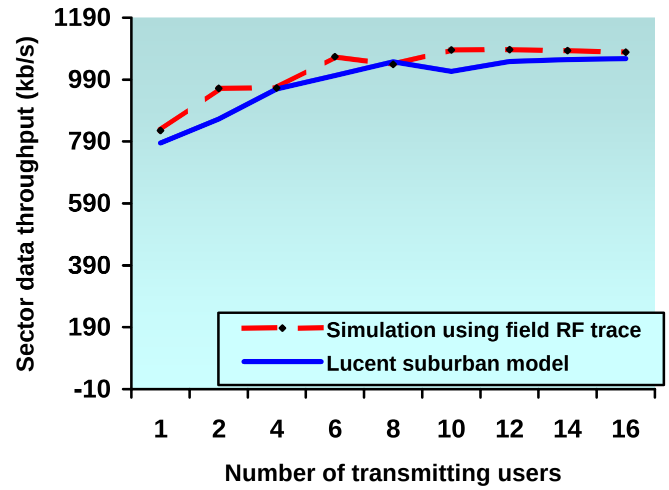


**Figure 10. Proportional fair packet scheduler gain.**

RF—Radio frequency

The power transmitted by the mobile and the power received by the base stations were also collected from the field measurements. This made it possible to determine the path loss between the mobile and the base station. Furthermore, by using the Hata model, the distance between the mobile and the base stations could be determined. **Figure 11** shows the achieved data rate reported on the DRC channel as a function of the distance between the mobile and the base stations. As Figure 11 shows, cell radii of 3 km and 6.5 km can be supported when the required data rate from the DRC channel is about 200 kb/s. When reading Figure 11, it is important to note that the gains from early completion and packet scheduling must be added to the DRC channel data rate when assessing the physical layer data rate of the handset. This matter will be discussed in the next section.

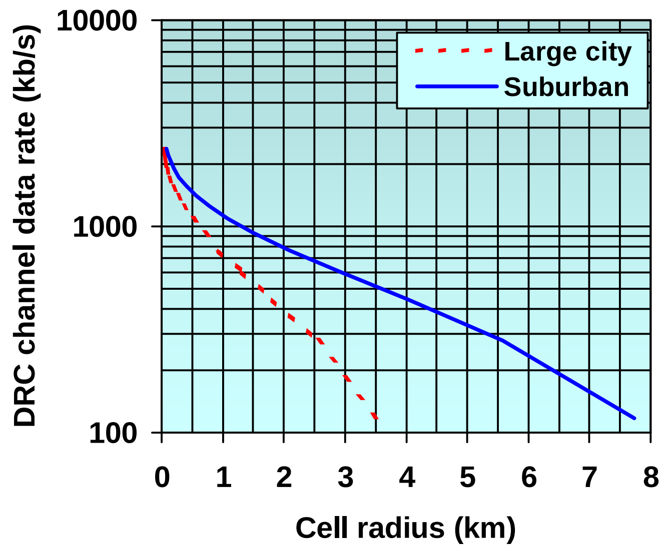


**Figure 11. DRC channel data rate as a function of cell radius.**

## IV. Analysis of System Capacity

In the previous section, we obtained measurements of the 1xEV-DO system and investigated possible gains from some of its key features. In this section, we obtain estimates of the aggregate throughput and user capacity of the sector, two important metrics for measuring the spectral efficiency or capacity of a data application.

For voice applications, the voice Erlang—rather than the number of supportable users—has been used extensively by the technical and business communities as a key metric for measuring spectral efficiency and capacity. The difference between the two metrics (i.e., the Erlang and the number of supportable users) is that the Erlang takes the randomness of call arrival and call length into consideration. Consequently, the Erlang can be considered a more accurate metric than the number of supportable users, assuming that call arrival and call duration conform to the random processes specified. However, in data applications, the random arrival of packets may or may not be significant, depending on the packet buffer size and the delay time constraint, because the existence of the buffer queue can change the random characteristics of packet arrival. Therefore, the data Erlang may not be as useful for data applications as the voice Erlang is for voice applications. Nevertheless, it is still instructive to calculate the data Erlang for delay-sensitive applications. For such applications, the data Erlang can be understood as the average number of users for a given average user data rate, taking into consideration the random characteristics of packet arrival and waiting time.

To calculate the aggregate throughput of the sector, we proceed as follows. Let $R_a$ be the aggregate throughput of a sector, $R_{DRC}$ be the data rate reported on the DRC channel by the handset, $g_{EC}$ be the early completion gain, $g_S$ be the packet scheduler gain, and $R_e$ be the percentage of packets in error. Then, using these factors, we can approximate the aggregate throughput of the sector as:

$$R_a = R_{DRC}(1+g_{ET})(1+g_S)(1-R_e). \qquad (1)$$

In the 1xEV-DO system, the packet error rate is usually controlled to be less than 1%; therefore, we will ignore its effect on the aggregate throughput. From the previous section, we have $g_{EC}$ = 0.2, $g_S$ = 0.2, and $R_{DRC}$ = 850 kb/s. Substituting these values into equation (1) gives an aggregate throughput on the physical layer of approximately 1.225 Mb/s.

Apart from the sector aggregate throughput, the throughput perceived by the individual user is also of great interest. The throughput perceived by the user is usually defined as the number of bits transmitted by the user divided by the time needed for queuing and transmission. (The user reading time is excluded from the calculation.) Clearly the queuing time is a random process that depends on the amount of data traffic, the time of arrival, and the length of the packets.

To obtain the data Erlang, we assume that the data streams from the users follow Poisson processes and that the aggregated data streams arrive at rate $\lambda$. Further, we assume that the service time (i.e., $1/\mu$) for all packets from different users is statistically independent. (The service time is defined as the time needed to transmit the packet by the air interface; it does not include queuing delay or other delays.) We consider two cases. In the first case, we assume that the service time can be approximated by an exponential process. Because the 1xEV-DO system serves one user at a time, we can model this process as an $m/m/1$ queue. In the second case, we assume that the service time follows a general random process with mean $1/\mu$ and variance $\sigma^2$. In this case, we model the process as an $m/G/1$ queue. To improve the air interface efficiency, users who having nothing to transmit for a period of time will be pushed from the active state to the dormant state and all RF resources associated with them will be released. Therefore, the average time, $T_s$, needed to transmit a packet from the base station to the handset can be obtained from [4]:

$$T_s = \frac{1}{\mu} + \frac{\lambda(\sigma^2 + 1/\mu^2)}{2(1-\rho)} + T_d P_d, \tag{2}$$

where $T_d$ is the average time needed to bring the user from the dormant to the active state, $\rho = \lambda/\mu$, and $P_d$ is the probability of being in the dormant state. Specifically,

$$P_d = \begin{cases} 1 & T_r - T_{dormancy} > 0 \\ 0 & T_r - T_{dormancy} < 0 \end{cases} \tag{3}$$

where $T_{dormancy}$ is the dormancy timer and $T_r$ is the reading time after each transmission. In general, the data rate perceived by the user (i.e., $n/T_s$, where $n$ is the packet size in bits) is a parameter that is set by service providers.

When modeled as an $m/m/1$ queue, $(\sigma^2+1/\mu^2) = 2/\mu^2$ and equation (2) simplifies to:

$$T_s = \frac{1}{\mu} + \frac{\rho}{\mu(1-\rho)} + T_d P_d. \tag{4}$$

Rearranging equations (2) and (4), we have

$$\rho = 1 - \frac{(T_s - T_d P_d - 1/\mu^2)}{\left(T_s - T_d P_d - 1/\mu + \mu(\sigma^2 + 1/\mu^2)/2\right)}, \tag{5}$$

which is based on the $m/G/1$ queuing model, and

$$\rho = \frac{(T_s - T_d P_d) - 1/\mu}{(T_s - T_d P_d)}, \tag{6}$$

which is based on the $m/m/1$ queuing model.

Now consider the simplified Hypertext Transport Protocol (HTTP) traffic model proposed by the 3GPP2 [2], in which the reading time $T_r$ is 30 seconds after the arrival of 55 Kbytes. Suppose that $T_d$ is 0.5 seconds and that the dormancy timer $T_{dormancy}$ is set to 10 seconds. First, let us consider $\rho$ from equation (6). The value $\rho = \lambda/\mu$ is, in general, a function of the target user-perceived data rate $r = n/T_s$. **Figure 12** illustrates the relationship between $r$ and $\rho$ when $1/\mu = n/R_a = 0.36$ seconds, where $R_a = 1225$ and $n = 55\times8$.

Next, let us consider the $m/G/1$ model. In this case, we need the second-order statistics of the service time. **Table V** contains the rate distribution from the simulation using the proposed channel model mix when both the early completion and the scheduler gain are included.

**Table V. Rate distribution of the 1xEV-DO system, including scheduler and early completion gains.**

| | Simulation results | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Data rate** | [illegible] | 246.7 | 337.1 | 459.1 | 546.3 | 614.4 | 836.6 | 1105. | 1228. | 1423. | 1843. | 2457. |
| **Probability** | [illegible] | 0.0% | 2.3% | 0.1% | 18.3 | 2.1% | 12.7 | 10.3 | 13.1 | 20.8 | 11.8 | 8.5% |

1xEV-DO—One-carrier evolution–data only
Note: This table is based on simulation results using the channel mix given in Table II.

Using the rate distribution from Table V, the last term in the denominator of equation (5) becomes $\mu(\sigma^2+1/\mu^2) = 0.268$. Substituting this value into equation (5) provides the results shown in Figure 12. As can be seen, the results from the $m/m/1$ model are very close to those predicted by the $m/G/1$ model and they have the advantage of not requiring a detailed data rate distribution for the data Erlang calculation. Therefore, when a detailed data rate distribution is not available, results from the *m/m*/1 model can be used to estimate the data Erlangs for the HTTP case with good accuracy.

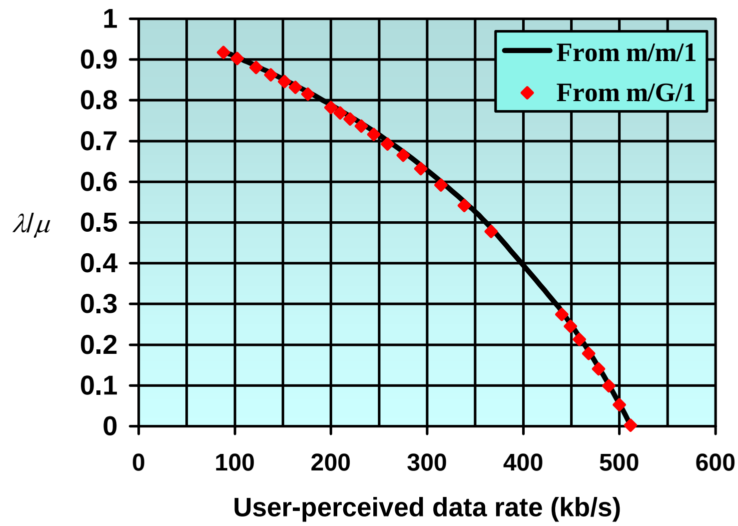


**Figure 12. λ/μ based on the 3GPP2 HTTP traffic model.**

Based on the results illustrated in Figure 12, the system can support one arrival per second (i.e., $\lambda$ = 1, $\rho$ = 0.36) when $r$, the data rate perceived by the user, is about 415 kb/s and two arrivals per second when $r$ is about 245 kb/s. Using the 3GPP2 HTTP traffic model, and taking into account the 30-second reading time, this results in 30 or 60 data Erlangs per sector per carrier when the data rate perceived by the user is 415 kb/s or 245 kb/s, respectively.

Now consider the 3GPP2 File Transfer Protocol (FTP) model, in which the reading time is 180 seconds after the arrival of 2 Mbytes. In this case, $n$ = 2000×8 and $1/\mu = n/R_a$ = 16000/1225 = 13.1. The possible data rates perceived by the user using the two queuing models are illustrated in **Figure 13**.

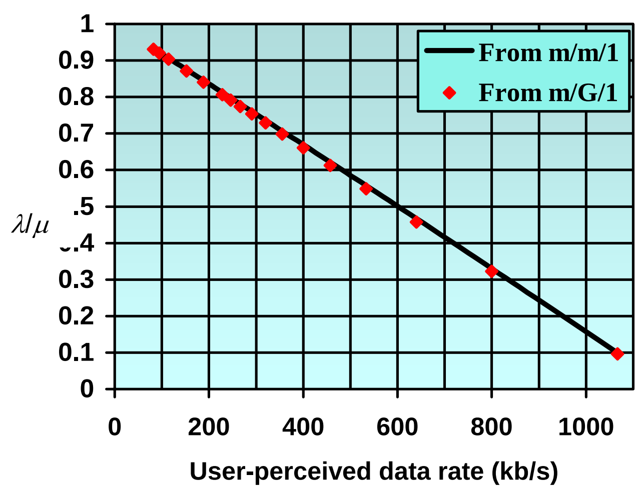


**Figure 13. λ/μ based on the 3GPP2 FTP traffic model.**

Assume that the service provider wants to target a user-perceived throughput of 240 kb/s. In this case, as shown in Figure 13, the system can support $\lambda = \rho\mu = 0.8/13.1 = 0.061$ arrivals per second. Using the 3GPP2 FTP traffic model, and taking into account the 180 second reading time given in [2], this results in eleven data Erlangs per sector per carrier when the data rate perceived by the user is 240 kb/s. Again, the result from the *m/m/*1 model is an excellent approximation to that from the *m/G/*1 model for an FTP application.

Based on the above discussion, **Figure 14** shows data Erlangs as a function of the data rate perceived by the user. As shown in the figure, the 1xEV-DO system can support 1 to 12 FTP users or 1 to 80 HTTP users, depending on the target user-perceived data rate. Furthermore, the HTTP user-perceived data rate is limited to about 512 kb/s rather than the 1225 kb/s available from the 1xEV-DO system, because the amount of time needed to transmit 55 Kbytes of HTTP packets includes 0.5 seconds wake-up time from the dormant state. Reducing or eliminating this wake-up time would result in a corresponding improvement in the perceived data rate.

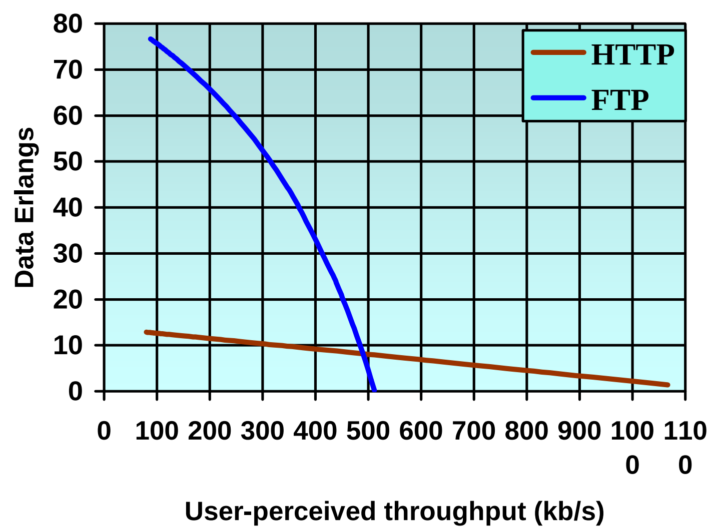


**Figure 14. Data Erlangs for HTTP and FTP applications.**

## V. Conclusions

In this paper, we have provided extensive field measurements that have characterized the performance of commercial 1xEV-DO systems. We have also provided computer simulation results that match the measurements exceptionally well using a proposed channel mix. Based on the results from the measurements and simulations, the following observations can be made regarding a two-antenna receive-diversity-enabled terminal in commercial 1xEV-DO systems.

- The data rate reported on the DRC channel by the dual-antenna mobile averaged over the entire sector under fully loaded network conditions is about 850 kb/s in a mobile environment. The data rate is about 20% higher when mobile speeds are less than 10 miles per hour.

- The early completion technique appears to provide about a 20% gain over the data rate reported on the DRC channel when the system is fully loaded. In a live network, in which the surrounding cells are typically not fully loaded, the early completion gain averages 35%, based on field measurements.

- The scheduling gain of the proportional fair scheduler is estimated on the basis of simulations to be between 20% and 30% when the number of transmitting users is between 5 and 15.
- To achieve at least 200 kb/s on the border of the base station, the supportable cell radius is estimated on the basis of measurements from the field and the Hata model to be about 3 km for large cities and 6.5 km for suburban environments.
- Based on the traffic models proposed by the 3GPP2, the *m/G*/1 model shows that about 60 data Erlangs can be supported for HTTP applications and about 11 for FTP applications when the target user-perceived data rate is about 240 kb/s. Furthermore, the *m/m*/1 model seems to be a good approximation for determining data Erlangs when the simplified 3GPP2 traffic models are used.
- The channel mix proposed in Table II appears to produce simulation results that match the field measurements of both the 1xEV-DO system and the voice and data applications of IS-95 and 3G1X as reported in [7] very well.

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## *Trademarks

CDMA2000 is a trademark of the Telecommunications Industry Association.

Global System for Mobile Communications and GSM are registered trademarks of GSM Association.

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## Abbreviations, Acronyms, and Terms

1xEV-DO—One-carrier evolution–data only
2G—Second generation
3G—Third generation
3G1X—CDMA2000* The third generation one-carrier
3GPP2—3rd Generation Partnership Project 2
AWGN—additive white Gaussian noise
CDMA—Code division multiple access
CDMA2000—3G evolution of IS-95 standard
C/I—Signal to noise and interference ratio
DRC—Data rate control
EDGE—Enhanced data rates for GSM* evolution
FTP—File Transfer Protocol
GPRS—General Packet Radio Service
GPS—Global positioning system
GSM—Global System for Mobile Communications*
HDR—High data rate
HTTP—Hypertext Transfer Protocol
IS-95—2G CDMA standard
ITU—International Telecommunication Union
PCMCIA—Personal Computer Memory Card International Association
PN—Pseudo-Random
RF—Radio frequency
RRI—Reverse rate indicator
TDMA—Time division multiple access