Throughput Analysis of 1x EV-DO System with Multi Cells

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Abstract: *In this paper, the average sector throughput of 1x EV-DO system is analyzed. The analysis is based on a mathematical approach rather than a field test or a computer simulation. By this analysis, the average sector throughput can be easily estimated under various conditions without complex simulations. In the typical urban environment, the estimated average throughput is 683 Kbps.*

I. Introduction

The demand for wireless data service has been dramatically growing and CDMA cellular service providers have accommodated the demand with evolved cellular systems such as IS-95B and cdma2000 1x (IS-2000). However, now, those evolved cellular systems cannot fully support the demand of subscribers who are familiar with high-speed wired network. Some new wireless data services that need high data rate and high spectral efficiency, particularly, in the forward link also make the systems no longer efficient in addressing new data applications. The limitation of the systems such as IS-95B/1x result from the fact that they were originally designed focusing on the voice service rather than the data service. The characteristics of data applications differ fundamentally from those of speech in traffic asymmetry, tolerance to latency, and so on. To efficiently address data applications and demands of people anticipating high rate, a new system supporting traffic asymmetry and utilizing tolerance to latency for improving throughput performance has been required.

The 1x EV-DO system (IS-856, also known as HDR) [1], which has been recently implemented in KOREA for the first time in the world, is the newly evolved system optimized to data applications and can provide good performance and economical benefits.

There have been many researches focusing on the data throughput performance of the IS-95B and cdma2000 1x since the systems provide not only a voice service but also data services [2]-[5]. Although the 1x EV-DO is highly interoperable with the precedent CDMA systems, it fundamentally differs from them in the design: 1) The 1x EV-DO employs a shared forward link and 2) the shared forward link is operated based on time-multiplexed manner. 3) The SNR level at each user dynamically determines the forward link data rate. These factors make the 1x EV-DO an optimized system to data applications. Therefore, the results and the methods of the works on the precedent CDMA system cannot be directly applied to the throughput analysis of the 1x EV-DO. An analysis reflecting key characteristics of the 1x EV-DO is required.

From this point of view, the paper of [6] is timely and helpful in understanding the 1x EV-DO system. It gives a good description of 1x EV-DO system and shows the overall performance of the 1x EV-DO system. However, the throughput estimation in [6] is obtained based on the computer simulation rather than a mathematical analysis. In [6], the probability distribution for the forward link data rate, necessary to estimate throughput, is obtained by computer simulation. Although a simulation is very useful and necessary, simulation results can vary according to simulation parameters and assumptions and the impact by such parameters and assumptions on the results cannot be clearly analyzed. In addition, the inter-cell interference that cannot be avoided in multi-cell cellular systems is not taken into account in the result of [6].

In this paper, the sector throughput of the 1x EV-DO system with multi cells is estimated in a fading channel by mathematical analysis. The Rayleigh fading is taken into account in the analysis since the data rate for a user is instantly and adaptively determined by the received SNR and Rayleigh fading affects the instant SNR.

The rest of this paper is organized as follows: In section II, key characteristics of the 1x EV-DO and system model to analyze in this paper are presented. The throughput of the 1x EV-DO system with multi cells is analyzed in section III. We show some numerical results in section IV and finally, we draw some conclusive remarks in section V.

II. Analysis Environments

It is necessary to know the key characteristics of the 1x EV-DO system for analysis. In this section, we firstly present key characteristics of the 1x EV-DO system and then describe system model and assumptions used in the analysis. The details on the 1x EV-DO can be referred to [1] and [6].

A. Characteristics of the 1x EV-DO [1],[6]

The 1x EV-DO system is optimized to data services.

One of the key premises of 1x EV-DO is that voice and data have very different requirements and there will be inefficiencies in case that the two services are combined. Therefore, the 1x EV-DO requires a separate CDMA carrier operation.

In the IS-95B/1x forward link, a multitude of low-data-rate channels are code-multiplexed together and share the available base station transmitted power with some form of power control. This is an optimal choice for many row-rate channels sharing a common bandwidth. The situation becomes less optimal when a low number of high-rate users share the bandwidth. With that reason, the 1x EV-DO employs a shared forward link instead of a code-multiplexed forward link. The shared forward link spread by PN sequence can serve a user at any instant in time-multiplexed manner. When being served, a mobile calculates its Signal-to-Noise Ratio (SNR) and continually updates the home base station with the SNR or equivalently supportable data rate value through each user's reverse link channel as fast as 1.67ms (= every slot). With this information the system can serve a single user with the data rate that is determined by the received SNR of the mobile at any instant. This adaptive rate control feature enables the base station to operate at full power achieving highest data rate for users. That is, the mobile station and the base station jointly determine each user's forward link data rate. The mobile station measures the pilot strength, and continuously requests an appropriate data rate based on the channel conditions. The mobile station also select only the best station in terms of SNR to reduce the interference to users of other base station.

The 1x EV-DO adopts a burst pilot and the burst pilot is not transmitted on a separate code channel as in IS-95/1x but is punctured into the forward link waveform at pre-determined intervals. The 1x EV-DO burst pilot is transmitted at the maximum power. Using the full power of the cell for the pilot provides the highest possible pilot SNR so that an accurate estimate can be obtained quickly, even during dynamic channel conditions. The burst pilot is received only in the presence of pilots from other base stations and is not affected by other transmissions of data.

B. Analysis Environments

The throughput of an air interface depends on various factors such as physical layer protocol, ARQ protocol, framing method, and resource allocation algorithm. In this paper, we only focused on the throughput of physical layer so that we don't consider ARQ protocol and framing method. The slot allocation algorithm considered in this paper, a kind of resource allocation algorithm, is a basic slot allocation scheme that slots are assigned one at a time successively to each user. With this scheme, of course, the lower data rate user may suffer higher latency. However, overall throughput performance of the 1x EV-DO system can be shown with that scheme.

In the analysis, some assumptions are made as follows: 1) We assume a multiple hexagonal cell structure and 2) users in each cell are uniformly distributed. 3) The short term fading is slow enough not to vary during chip duration. 4) Averaged path loss values are considered in the inter-cell interference derivation. That is, the lognormal shadowing is not considered in the propagation path loss.

The path-loss model used in this paper is a basic model that the path loss is proportional to propagation distance and given by

$$L_i(r,\theta) = d_i^{-l}(r,\theta) \qquad (1)$$

where $d_i(r,\theta)$ is the distance from the the i th base station to the mobile station at (r,θ) and l is the path loss exponent.

III. Throughput Analysis

In the 1x EV-DO system, the received SNR at a mobile station determines the forward link data rate for the mobile station among 11 data rate classes (refer to table 1). The selected data rate for a mobile station is higher as the received SNR of the mobile station is higher. Under the slot allocation scheme that slots are assigned one at a time successively to each user, the slot throughput equals to the expected data rate for each user during a slot. And the average sector throughput can be obtained by averaging the slot throughput over the predetermined number of slots. Thus, the average sector throughput can be given by

$$C = \frac{1}{N}\sum_{i=1}^{N} E\left[R_{slot,i}\right] = \frac{1}{N}\sum_{i=1}^{N}\left(\sum_{n=1}^{11} R_n P_n\right) \qquad (2)$$

where N is the number of slots considered in the averaging and P_n is the probability that the estimated SNR is in such range that R_n is the highest supportable data rate. In (2), since we assume the uniformly distributed mobile stations, the slot throughputs for each slot are all the same from probabilistic point of view and the average sector throughput can be given by

$$C = \sum_{n=1}^{11} R_n P_n \qquad (3)$$

From (3), the sector throughput can be estimated by finding the probabilities, P_n's, and those probabilities can be found from the distribution of the received SNR of mobile stations. And a received signal power and a total interference power at a mobile should be firstly estimated in order to estimate the SNR.

The total received signal power of a mobile station at (r,θ) from home base station is given by

$$P(r,\theta) = \alpha^2 \cdot S \cdot L_0(r,\theta) \qquad (4)$$

where α, S, and $L_0(r,\theta)$ are a Rayleigh distributed random variable representing the short term fading, the transmitted power from a base station, and the path loss from the home base station, respectively.

The inter-cell interference from adjacent K base stations is given by

$$I_{oc}(r,\theta) = \sum_{i=1}^{K} S \cdot L_i(r,\theta) \qquad (5)$$

The received SNR at the mobile station is equal to E_c / N_t because the forward link is spread by PN sequence with spreading bandwidth *W*. From (4), (5), and the fact that mobile stations don't experience intra-cell interference as in IS-95/1x since the forward link of 1x EV-DO is shared in time-multiplexed manner, the E_c / N_t can be derived as

$$\frac{E_c}{N_t} = \frac{|\alpha|^2 \cdot S \cdot L_0(r,\theta)/W}{N_o + \sum_{i=1}^{K} S \cdot L_i(r,\theta)/W} \tag{6}$$

where E_c, N_t and N_o denote a received signal energy in a chip, a total interference power spectral density, and a thermal noise density, respectively.

The thermal noise level is comparably small enough to be neglected in the denominator of (6). Therefore, the E_c / N_t can be approximated as

$$\frac{E_c}{N_t} = \gamma(\varsigma, r, \theta) = \varsigma \cdot \Psi(r,\theta) \tag{7}$$

where $\varsigma = |\alpha|^2$ and $\Psi(r,\theta)$ are given by

$$\Psi(r,\theta) = \frac{L_0(r,\theta)}{\sum_{i=1}^{K} L_i(r,\theta)} = \frac{1}{\sum_{i=1}^{K}\left(1 + \left(\frac{r_i}{r}\right)^2 + \frac{2r_i}{r}\cos|\theta - \theta_i|\right)^{-\frac{l}{2}}} \tag{8}$$

where (r_i, θ_i) is the location of the i th adjacent base station in the $r-\theta$ coordination.

In (7), the ς is an exponentially distributed random variable with *p.d.f.* $f_\varsigma(\varsigma) = e^{-\varsigma}$ since α is a Rayleigh distributed random varialbe and is independent on $\Psi(r,\theta)$. Therefore, for given (r,θ), $\gamma(\varsigma, r, \theta | r, \theta)$ is an exponetially distributed random variable and the conditional probability that the data rate is determined as the class 1 (=38.4 Kbps) at (r,θ) can be given by

$$\begin{aligned} P_1\big|_{r,\theta} &= P\left[-10.5dB \le \gamma(\varsigma, r, \theta | r, \theta) < -7.5dB\right] \\ &= P\left[\frac{10^{-1.05}}{\Psi(r,\theta)} \le \varsigma < \frac{10^{-0.75}}{\Psi(r,\theta)}\right] \\ &= e^{-\frac{10^{-1.05}}{\Psi(r,\theta)}} - e^{-\frac{10^{-0.75}}{\Psi(r,\theta)}} \end{aligned} \tag{9}$$

Similarly, the conditional probabilities for class 2, calss3, $\cdots$, and class 11 data rate are given as follows

$$\begin{aligned} P_2\big|_{r,\theta} &= P\left[-7.5dB \le \gamma(\varsigma, r, \theta | r, \theta) < -6.5dB\right] \\ &= e^{-\frac{10^{-0.75}}{\Psi(r,\theta)}} - e^{-\frac{10^{-0.65}}{\Psi(r,\theta)}} \end{aligned} \tag{10}$$

$$\vdots \qquad\qquad \vdots$$

$$P_{11}\big|_{r,\theta} = P\left[11.5dB \le \gamma(\varsigma, r, \theta | r, \theta)\right] = e^{-\frac{10^{1.15}}{\Psi(r,\theta)}} \tag{11}$$

Since the mobile stations are uniformly distributed in a cell the probability that class 1 data rate is selected for a mobile station is given by

$$\begin{aligned} P_1 &= \int_0^D \int_0^{\theta_s} P_1\big|_{r,\theta} \cdot r \cdot \frac{2}{D^2\theta_s} drd\theta \\ &= \int_0^{D} \int_0^{\theta_s} \{e^{-\frac{10^{-1.25}}{\Psi(r,\theta)}} - e^{-\frac{10^{-0.95}}{\Psi(r,\theta)}}\} \cdot r \cdot \frac{2}{D^2\theta_s} d\theta\, dr \end{aligned} \tag{12}$$

where D is radius of a cell and θ_s is the sectorization angle in radian vaule. In the square integration, the hexagonal shaped cell is approximated as a circular shaped cell with radius *D*. The $P_2, P_3, \cdots$, and P_{11} can be derived in the same way as (12). The probabilities given in the form of (12) can be easily computed with a numerial integration method.

Then, the average sector throughput can be completely estimated with the derived probabilities and the equation in (3). The computed probabilities and the average throughput are given in the section IV.

If we assume the worst case that all mobile staions are at the cell egde, the lower bound of the average sector throughput can be obtained. In that case, it is known that the other cell inteference power ratio to the selfcell power ratio, $1/\Psi(r,\theta)$, is about 2.5 dB [7] and then,

$$P_1 = e^{-\frac{10^{-1.05}}{10^{-0.25}}} - e^{-\frac{10^{-0.75}}{10^{-0.25}}} = 0.12454 \tag{13}$$

$$P_2 = e^{-\frac{10^{-0.75}}{10^{-0.25}}} - e^{-\frac{10^{-0.65}}{10^{-0.25}}} = 0.0573 \tag{14}$$

$$\vdots \qquad\qquad \vdots$$

$$P_{11} = 1 - e^{-\frac{10^{1.15}}{10^{-0.25}}} = 1.22 \cdot 10^{-11} \tag{15}$$

The lower bound of average sector throughput can be estimated using (3) and (13) to (15) to 203.26 Kbps

IV. Numerical Results

Some numerical results are presented in this section. In the multicell structure, 2 tiers, that is 18 adjacent base stations, are considered. The omni cells are considered so that the sectoriztion angle is 2π. The mapping rule between the received SNR and the selection of data rate is given in table 1, which includes an additional 2dB of margin and is identical to that of [6].

In figure 1, the probabilities for 11 possible data rates are shown. The probabilities are obtained by a simple numerical integration method based on the (12). The path loss exponent in the propagation path loss model is assumed as 3, which is a typical value for urban cellular environment.

In the typical urban environment, i.e., the value of the path loss exponent is 3, the average sector throughput is estimated at 683 Kbps from the computed probabilities in figure 1 and (3).

Figure 2 shows the average sector throughputs of the 1x EV-DO physical layer with various values of the path loss exponent. As the value of the path loss exponent increase, the propagation loss becomes larger and the inter cell interference problem is relatively mitigated. The inter cell interference problem in the 1x EV-DO system has a more serious effect on the throughput performance than that in the IS-95B/1x system since the base stations of the 1x EV-DO system always transmit their forward link at full power. Therefore, the average sector throughput performance is considerably improved as the value of the path loss exponent become large.

V. Conclusions

In this paper, we analyzed the average sector throughput of the 1x EV-DO system focused on the physical layer. The analysis was based on the mathematical approach rather than a field test or a computer simulation. By this analysis, the average sector throughput can be easily estimated in various conditions without complex simulations.

In the typical urban environment, i.e., the value of the path loss exponent is 3, the average throughput was estimated at 683 Kbps according to the analysis introduced in this paper. If some other slot allocation algorithm is applied, the average sector throughput performance of the 1x EV-DO can somewhat differ from that of this paper. The study on throughput and latency of the 1x EV-DO when various slot allocation algorithms are adopted remain as our further research area.

The results of this paper can be applied to a cell planning and a system design.

References

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Table 1. Various data rate and required Ec/Nt (2dB margin is included) [6]

Class	Data rate (kbps)	Modulation	Required Ec/Nt for 1% PER
1	38.4	QPSK	-10.5 dB
2	76.8	QPSK	-7.5 dB
3	102.6	QPSK	-6.5 dB
4	153.6	QPSK	-4.5 dB
5	204.8	QPSK	-3.7 dB
6	307.2	QPSK	-2.0 dB
7	614.4	QPSK	1.0 dB
8	921.6	8PSK	3.3 dB
9	1228.8	8PSK	5.0 dB
10	1843.2	8PSK	9.2 dB
11	2457.6	16QAM	11.5 dB

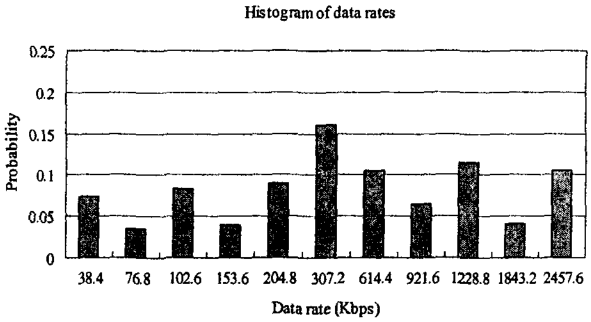

Figure 1. Probabilities for 11 possible data rates.

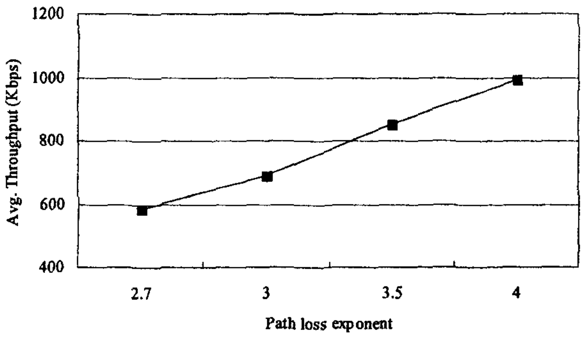

Figure 2. Average throughput with various values of path loss exponent.