An Analytical Model for Reverse Link Rate Control in cdma2000 1xEV-DO Systems

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***Abstract*— The cdma2000 1xEV-DO standard has a distributed rate control on the reverse link. If a mobile has data to transmit, it determines the data rate of the next frame in response to a reverse activity bit broadcast by the base station. This letter proposes an analytical framework for the 1xEV-DO rate control by adopting the noise rise as the reverse traffic load, and by modeling the rate control as a discrete Markov process. We validate the proposed model through a simulation, in which 1xEV-DO reverse power control is applied to a Rayleigh fading channel. In addition, we illustrate the operation principle of the 1xEV-DO rate control based on the data rate distribution of mobiles.**

***Index Terms*— 1xEV-DO, medium access control, rate control.**

I. INTRODUCTION

THE cdma2000 1xEV-DO standard [1], also known as IS-856, provides bandwidth-efficient and high-speed wireless internet services to mobile subscribers based on CDMA technology. In the standard, a forward traffic channel is shared by all mobiles in a cell, and supports data rates up to 2.4 Mb/s depending on channel conditions. A reverse traffic channel is assigned to each mobile, and supports data rates up to 153.6 kb/s. The reverse traffic channel consists of a pilot channel, a reverse rate indicator (RRI) channel, a data rate control (DRC) channel, an acknowledgment (ACK) channel, and a data channel. The pilot channel is used for channel estimation and coherent detection. The RRI channel indicates the data rate of the associated data channel, and is time-multiplexed with the pilot channel. The DRC and ACK channels are related to the forward link operation. The DRC channel informs the access network of the best serving cell and the supportable data rate on the forward traffic channel. A DRC message is repeated over *DRCLength* (1, 2, 4, or 8 slots). The ACK channel informs the access network whether a packet transmitted on the forward traffic channel has been received successfully. Each channel in the reverse traffic channel is spread by an appropriate orthogonal Walsh function. A slot is a basic transmission unit, and is 1.666 ... ms long (2048 chips). A group of 16 slots is referred to as a frame.

If a mobile has no data to transmit (i.e., inactive mobile), it does not use the reverse data channel and its data rate is denoted by R_0 (= 0 kb/s). However, other reverse channels are still used to maintain the connection. If a mobile has data to transmit (i.e., active mobile), five data rates are available on the data channel: $R_i = 9.6 \cdot 2^{i-1}$ kb/s, $i = 1, \cdots, 5$. The active mobile has an initial data rate of R_1, and determines the data rate of the next frame according to a distributed rate control. Fig. 1 illustrates the basic concept of the rate control assuming a single cell environment. A base station broadcasts a reverse activity bit (RAB) to all mobiles. The RAB indicates whether or not the reverse traffic load exceeds a certain threshold. If the traffic load exceeds the threshold, the RAB is set to 1. Otherwise, it is set to 0. A typical example of the traffic load is the noise rise, which represents the amount of interference at the base station. An active mobile utilizes the latest RAB value and persistence probabilities (p_i and q_i) for the rate control. If the mobile with a data rate of R_i receives an RAB of 0 (or 1), it increases (or decreases) the data rate to R_{i+1} (or R_{i-1}) with probability p_i (or q_i), and stays at the current rate with probability $1-p_i$ (or $1-q_i$). The data rate cannot exceed the *RateLimit*, which is given by the base station.

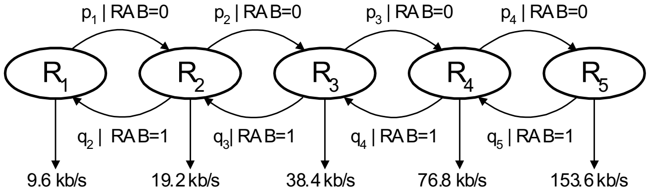

Fig. 1. Reverse link rate control for active mobiles (Self-loops are not shown)

The capacity of the 1xEV-DO reverse link has been discussed intensively in the literature [2], [3]. However, there has been insufficient research on the reverse link rate control itself, and most results were obtained only through numerical simulations [4], [5]. Recently, an enhanced rate control scheme has been proposed to prevent traffic overload on the reverse link [6]. The system model in [6], however, did not take into account the transmission characteristics of 1xEV-DO reverse channels since the traffic load was measured simply by the aggregate data rate on the reverse link. In this letter, we adopt the noise rise as the reverse traffic load, and propose an analytical framework for the 1xEV-DO rate control. We first derive an expression for the noise rise assuming perfect power control, and the rate control is modeled as a Markov process. The proposed analysis model is compared with a simulation, which has imperfect power control on the reverse link. In addition, the data rate distribution of mobiles is shown to explain the operation principle of the rate control.

II. NOISE RISE CALCULATION

In 1xEV-DO, reverse power control (RPC) is applied to the pilot channel only. The power allocated to data, DRC, and ACK channels is adjusted by a fixed gain relative to

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TABLE I
DEFAULT DATA CHANNEL GAINS

Data Rate (kb/s)	Symbol	Data Channel Gain (dB)
0	R_0	$-\infty$
9.6	R_1	3.75
19.2	R_2	6.75
38.4	R_3	9.75
76.8	R_4	13.25
153.6	R_5	18.50

the pilot channel to guarantee the desired performance. The data channel gain relative to the pilot channel has a value determined by the data rate. The default data channel gain is defined in [1] and reproduced in Table I. We denote the data rate of mobile j by r_j and the corresponding data channel gain by $G_{Data}(r_j)$, $r_j \in \{R_i,\ i = 0, \cdots, 5\}$. Similarly, we denote the DRC channel gain relative to the pilot channel by G_{DRC}. The recommended value of G_{DRC} is a function of *DRCLength* [3]. The effect of the ACK channel on the total received power is negligible because only one mobile, at most, occupies the ACK channel at a time. Therefore, the received power of mobile j at the base station, P_j, is expressed as

$$P_j = c(r_j) \cdot \overline{P}_j \tag{1}$$

where $c(r_j) \triangleq 1 + 10^{G_{Data}(r_j)/10} + 10^{G_{DRC}/10}$, and $\overline{P}_j$ is the received pilot channel power of mobile j.

The noise rise η is defined as the ratio of the total received power P_T to the thermal noise power P_N (i.e., $\eta \triangleq P_T/P_N$). In this analysis, we assume perfect power control where the transmission power of each mobile immediately converges to an optimal value after mobiles change their rates. In addition, a single cell environment is assumed. The RPC of 1xEV-DO maintains the signal quality of the pilot channel at a certain target level. The signal quality is usually measured by $\overline{E}_c/N_0$ (ratio of pilot energy per chip to noise power spectral density), which is closely related to the packet error rate [2]. The $\overline{E}_c/N_0$ of mobile j, $(\overline{E}_c/N_0)_j$, is expressed as $(\overline{E}_c/N_0)_j = \overline{P}_j/(P_T - P_j)$ using the orthogonal property of Walsh functions. Since the target value of $(\overline{E}_c/N_0)_j$ depends on r_j [2], we denote the target value by $\tau(r_j)$. Then, $\overline{P}_j$ can be expressed as

$$\overline{P}_j = \frac{1}{c(r_j) + 1/\tau(r_j)} P_T. \tag{2}$$

Let Γ be the number of mobiles in a cell. From $P_T = \sum_{j=1}^{\Gamma} P_j + P_N$, the noise rise is given by

$$\eta = \left(1 - \sum_{j=1}^{\Gamma} \frac{c(r_j)}{c(r_j) + 1/\tau(r_j)}\right)^{-1}. \tag{3}$$

In (3), η can take a negative value depending on the data rate distribution of mobiles. This case means that, even at the maximum power of a mobile, it is difficult to satisfy the required $\overline{E}_c/N_0$. Therefore, if $\sum_{j=1}^{\Gamma} c(r_j)/(c(r_j) + 1/\tau(r_j)) > 1$, the value of η is regarded as ∞.

III. SYSTEM MODEL

We assume that all mobiles change their data rates simultaneously at the beginning of a new frame. Since the base station assigns the frame offset (in slots) of each mobile during the traffic channel assignment procedure [1], the frame synchronization can be achieved by setting the offset to the same value for all mobiles. The RAB updating period is assumed to be short enough for mobiles to utilize the latest RAB value. There are N active mobiles in a cell. *RateLimit* is set to R_5 for all active mobiles. Each mobile has an RAB decoding error probability z that the received RAB is decoded as the opposite value. For example, if the base station transmits an RAB of 0, the mobile decodes the value as 1 with probability z, and as 0 with probability $1 - z$. Throughout the analysis, random variables and their samples are represented by capital letters and the corresponding lowercase letters, respectively. Vectors are denoted by boldface letters, and each subscript indicates the corresponding data rate.

Let $S_i(t)$ denote the number of mobiles with a data rate of R_i at the t-th frame. We define a state as a vector $\mathbf{S}(t) = (S_1(t), S_2(t), S_3(t), S_4(t))$. Because $S_0(t)$ is a constant and $S_5(t)$ can be deduced from $S_5(t) = N - \sum_{i=1}^{4} S_i(t)$, they are not required in the definition of $\mathbf{S}(t)$. In this model, the number of valid states that satisfy $\sum_{i=0}^{5} S_i(t) = \Gamma$ is $\binom{N+4}{N}$. Notice that noise rise calculated by (3) is related to the data rate distribution of mobiles. Therefore, the noise rise for a state $\mathbf{x} = (x_1, x_2, x_3, x_4)$, $\eta(\mathbf{x})$, can be expressed as

$$\eta(\mathbf{x}) = \left(1 - \sum_{i=0}^{5} \frac{x_i c(R_i)}{c(R_i) + 1/\tau(R_i)}\right)^{-1} \tag{4}$$

where $x_0 = \Gamma - N$ and $x_5 = N - \sum_{i=1}^{4} x_i$. Let η_{TH} be the noise rise threshold of the rate control. If $\eta(\mathbf{x}) \geq \eta_{TH}$, the RAB is set to 1. Otherwise, it is set to 0. Because the $\eta(\mathbf{x})$ in (4) and the resulting RAB depend only on the current state, this system model can be considered as a first-order discrete Markov process.

The interesting characteristic of the rate control is that the rate transition is restricted to neighboring data rates. Let $\mathbf{x}$ and $\mathbf{y} = (y_1, y_2, y_3, y_4)$ be the samples of $\mathbf{S}(t)$ and $\mathbf{S}(t+1)$, respectively. Then, the valid range of $\mathbf{y}$ is $\{\mathbf{y} | 0 \leq y_1 \leq x_1 + x_2, \sum_{k=1}^{i-1} x_k \leq \sum_{k=1}^{i} y_k \leq \sum_{k=1}^{i+1} x_k, i = 2, 3, 4\}$. If $\mathbf{y}$ is not in the valid range, the state transition probability $p_{\mathbf{xy}} \triangleq \mathtt{Pr}(\mathbf{S}(t+1) = \mathbf{y} | \mathbf{S}(t) = \mathbf{x})$ will be 0. To obtain the $p_{\mathbf{xy}}$ for $\mathbf{y}$ in the valid range, we assume that U_i and D_i mobiles increase and decrease their rates from the data rate of R_i, respectively, at the beginning of the $(t+1)$-th frame. If we define $e_i \triangleq \sum_{k=1}^{i} (y_k - x_k)$, the $p_{\mathbf{xy}}$ can be expressed as

$$p_{\mathbf{xy}} = \mathtt{Pr}(\mathbf{D} - \mathbf{U} = \mathbf{e} | \mathbf{S}(t) = \mathbf{x}) \tag{5}$$

where $\mathbf{D} = (D_2, D_3, D_4, D_5)$, $\mathbf{U} = (U_1, U_2, U_3, U_4)$, and $\mathbf{e} = (e_1, e_2, e_3, e_4)$ [6].

Let M_i be the number of mobiles that decode the RAB as 0 at the data rate of R_i. By conditioning on M_i and U_i, the $p_{\mathbf{xy}}$ in (5) is rewritten as

$$\begin{aligned} p_{\mathbf{xy}} &= \sum_{\mathbf{m}} \sum_{\mathbf{u}} \mathtt{Pr}(\mathbf{D} = \mathbf{u} + \mathbf{e} | \mathbf{u}, \mathbf{m}, \mathbf{x}) \\ &\quad \times \mathtt{Pr}(\mathbf{U} = \mathbf{u} | \mathbf{m}, \mathbf{x}) \mathtt{Pr}(\mathbf{M} = \mathbf{m} | \mathbf{x}) \end{aligned} \tag{6}$$

where $\mathbf{M} = (M_1, M_2, M_3, M_4, M_5)$. Each probability in (6) is given as follows.

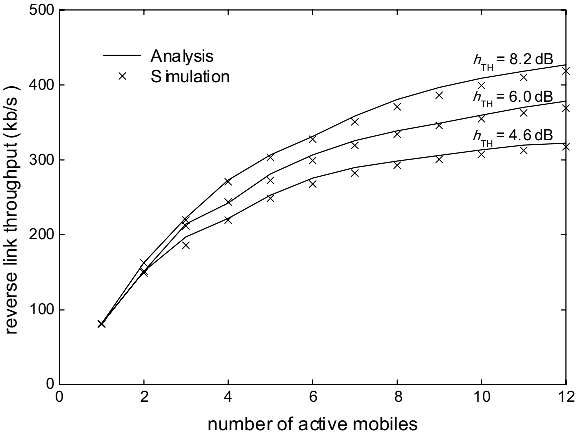

Fig. 2. Reverse link throughput for various values of η_{TH} ($\Gamma = 15$).

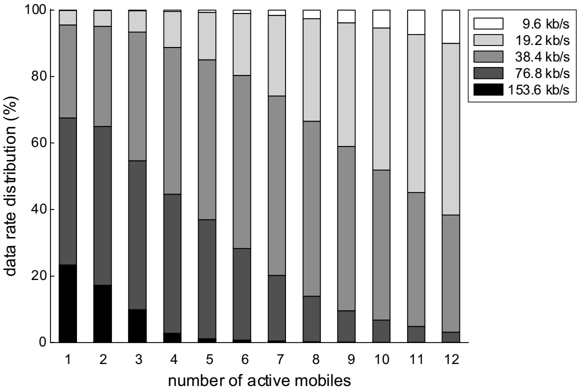

Fig. 3. Data rate distribution with $\eta_{TH} = 4.6$ dB.

$$\mathtt{Pr}(\mathbf{D} = \mathbf{u} + \mathbf{e}|\mathbf{u}, \mathbf{m}, \mathbf{x}) = \prod_{i=1}^{4} \binom{x_{i+1} - m_{i+1}}{u_i + e_i} {q_{i+1}}^{u_i + e_i} \times (1 - q_{i+1})^{x_{i+1} - m_{i+1} - u_i - e_i} \quad (7)$$

$$\mathtt{Pr}(\mathbf{U} = \mathbf{u}|\mathbf{m}, \mathbf{x}) = \prod_{i=1}^{4} \binom{m_i}{u_i} {p_i}^{u_i} (1 - p_i)^{m_i - u_i} \quad (8)$$

$$\mathtt{Pr}(\mathbf{M} = \mathbf{m}|\mathbf{x}) = \begin{cases} \prod_{i=1}^{5} \binom{x_i}{m_i} (1 - z)^{m_i} z^{x_i - m_i}, & \mathbf{x} \in \{\mathbf{x}_u\} \\ \prod_{i=1}^{5} \binom{x_i}{m_i} z^{m_i} (1 - z)^{x_i - m_i}, & \mathbf{x} \in \{\mathbf{x}_o\} \end{cases} \quad (9)$$

In (9), $\{\mathbf{x}_u\}$ is a set of $\mathbf{x}$ that satisfies $\eta(\mathbf{x}) < \eta_{TH}$, and $\{\mathbf{x}_o\}$ is a set of $\mathbf{x}$ that satisfies $\eta(\mathbf{x}) \geq \eta_{TH}$. The ranges of $\mathbf{m}$ and $\mathbf{u}$ are $\{\mathbf{m}|0 \leq m_i \leq x_i, i = 1, 2, 3, 4, 5\}$ and $\{\mathbf{u}|\max(0, -e_i) \leq u_i \leq \min(m_i,\ x_{i+1} - m_{i+1} - e_i), i = 1, 2, 3, 4\}$, respectively.

Because the Markov model is irreducible, aperiodic, and positive recurrent, there will be a unique steady-state probability $\pi_{\mathbf{x}}$ for a state $\mathbf{x}$. $\{\pi_{\mathbf{x}}\}$ can be obtained by solving a set of linear equations $\pi_{\mathbf{y}} = \sum_{\forall \mathbf{x}} p_{\mathbf{xy}} \pi_{\mathbf{x}}$ and $\sum_{\forall \mathbf{x}} \pi_{\mathbf{x}} = 1$. Then, the reverse link throughput (i.e., average data rate on the reverse link) is expressed as $\sum_{\forall \mathbf{x}} (\sum_{i=0}^{5} x_i R_i) \pi_{\mathbf{x}}$.

IV. RESULTS

In this section, the proposed rate control model is compared with a simulation that has imperfect power control on the reverse link. In the simulation, the 1xEV-DO RPC mechanism is applied to a flat Rayleigh fading channel. The carrier frequency is 800 MHz, which is one of the candidate carrier frequencies of 1xEV-DO. The RPC update rate is 600 Hz and the RPC step size is set to 1 dB [1]. RPC bits are immediately delivered to mobiles without error. We assume a pedestrian fading model in which each mobile is moving at a velocity of 3 km/h. The RAB value is generated by comparing the noise rise threshold (η_{TH}) to the averaged noise rise over the previous frame. In both analysis and simulation, $(p_1, p_2, p_3, p_4) = (0.2, 0.1, 0.05, 0.025)$, $(q_2, q_3, q_4, q_5) = (0.1, 0.3, 0.6, 0.9)$, and $z = 5\%$ are assumed for all mobiles. There are 15 mobiles in a cell. G_{DRC} is set to -1.5 dB assuming *DRCLength* of two slots [3]. The value of $\tau(\cdot)$ can be determined by a link level simulation that considers various channel conditions [2]. We set $\tau(\cdot)$ to -22 dB for all data rates.

Fig. 2 illustrates the reverse link throughput for various values of η_{TH} (4.6, 6.0, and 8.2 dB). We can see that the analysis results are almost coincident with those of the simulation. The reason is that, in the simulation, the 1xEV-DO RPC mechanism almost compensates for the path loss of the fading channel. Fig. 3 shows the data rate distribution of mobiles based on the analysis model ($\eta_{TH} = 4.6$ dB). Inactive mobiles are excluded in the figure since the rate control is applied only to active mobiles. The figure explains the operation principle of the 1xEV-DO rate control. As the number of mobiles increases, the proportion having a low data rate (e.g., 9.6 or 19.2 kb/s) increases, whereas the proportion having a high data rate (e.g., 76.8 or 153.6 kb/s) decreases according to the 1xEV-DO rate control.

V. CONCLUSIONS

In this letter, the 1xEV-DO rate control on the reverse link has been analyzed by adopting the noise rise as the reverse traffic load and modeling the rate control as a discrete Markov process. The proposed system model was compared with a simulation, in which 1xEV-DO reverse power control is applied to a Rayleigh fading channel. The results showed that the proposed model provides a good analytical framework for modeling the 1xEV-DO rate control.

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