

Traffic management of high-speed CDMA systems based on load prediction

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Abstract: The cdma2000 1xEV-DO system has a probabilistic rate control on the reverse link, but a simple up/down command from the base station may make the reverse link unstable. In this paper, we propose and analyze an enhanced rate control that minimizes the traffic overload on the reverse link by predicting the noise rise and defining a new command for stable operation. It is shown that the proposed rate control has a much higher reverse-link throughput than the conventional schemes.

Keywords: CDMA, traffic management, noise rise, load prediction

Classification: Wireless circuits and devices

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1 Introduction

The cdma2000 1xEV-DO (1x EVolution and Data Only) system is a member of the IMT-2000 family and provides a much higher data capacity than cdma2000 1x networks [1]. The system is optimized for mobile Internet services, and operates with a separate, dedicated RF bandwidth of 1.25 MHz. Thanks to the advanced techniques including hybrid ARQ and adaptive modulation/coding, the system can achieve a maximum data rate of 2.4 Mbps on the forward link and 153.6 kbps on the reverse link.

A reverse traffic channel is assigned to each access terminal, whereas a forward traffic channel is shared by all access terminals in a cell. The reverse channel consists of a pilot channel, a data channel, a reverse rate indicator (RRI) channel, a data rate control (DRC) channel and an acknowledgement (ACK) channel. The pilot channel is used for coherent detection. The data channel carries user data packets and five data rates are available: $R_i = 9.6 \cdot 2^{i-1}$ kbps, $i = 1, \dots, 5$. The RRI channel is used to indicate the data rate of the associated data channel. The DRC and ACK channels are related to the forward-link operation. A time slot of 1.666 ms is a basic transmission unit, and a group of 16 time slots is referred to as a frame.

The 1xEV-DO system has a probabilistic rate control model that determines the data rates of access terminals [1]. A base station broadcasts a reverse activity bit (RAB), which indicates whether or not the reverse traffic load exceeds a certain threshold. A typical example of the traffic load is the noise rise over thermal noise, which is defined as the ratio of the total received power to the thermal noise power at the base station. If the noise rise η exceeds a certain threshold η_{th} , the RAB is set to 1; otherwise, it is set to 0. Each terminal determines its data rate for the next frame according to the latest RAB value and the rate-transition probabilities (p_i and q_i). If an access terminal with a data rate of R_i receives an RAB of 0, it increases the data rate to R_{i+1} with probability p_i and remains at the current rate with probability $1 - p_i$. Similarly, if the terminal receives an RAB of 1, it decreases the data rate to R_{i-1} with probability q_i and maintains the current rate with probability $1 - q_i$.

The resulting traffic load heavily depends on the RAB from the base station. Since the RAB has a binary value (i.e., up/down), the noise rise fluctuates around η_{th} [2] and this fluctuation may make the reverse link unstable. In [3], it was shown that the load prediction can prevent traffic overload effectively. However, the base station may broadcast a ‘down’ command even though the current traffic load does not exceed η_{th} . This operation can induce the access terminals to decrease the data rates unnecessarily. In addition, the system parameters and assumptions seem rather unrealistic. The traffic load was simply measured by the total data rate, not the noise rise, and the maximum allowable traffic load was chosen arbitrarily. In this paper, we propose and analyze an enhanced rate control that significantly improves upon the conventional schemes by predicting the noise rise of the next frame and defining a new value of RAB to minimize the traffic overload.

2 Proposed scheme

The base station can predict the data rate of the next frame with the help of the extended rate indicator (ERI) in [3]. ERI=1 means that the corresponding terminal wants to increase the data rate at the next frame, whereas ERI=0 means that the terminal wants to maintain the current data rate. Therefore, the data rate at the next frame can be inferred by combining the ERI and RRI values. Since the RRI value is a 3-bit symbol and repeated 37 times during a frame [1], the ERI symbol can be easily inserted to the RRI transmission by reducing the number of repetitions of RRI symbols. The ERI is determined by rate-transition probability p_i . An access terminal with a data rate of R_i sets the ERI to 1 with probability p_i , and to 0 with probability $1 - p_i$. Access terminals with ERI=1 are called candidate terminals, and those with ERI=0 are called non-candidate terminals.

Since the traffic load is measured by the noise rise in the proposed scheme, the base station has to estimate the noise rise of the next frame. In the 1xEV-DO system, the power allocated to data, DRC and ACK channels is adjusted by a fixed gain relative to the pilot channel. The data channel gain depends on the data rate R_i and its value is denoted by $G_{data}(R_i)$. The default data channel gain is defined in [1]. The DRC channel gain G_{DRC} is a function of $DRCLength$, a repetition period of the DRC value [4]. The effect of the ACK channel on the total received power is negligible. If the fast power control on the pilot channel is assumed in a single-cell environment, the noise rise is related to the data rate distribution of access terminals [5]. Letting x_i be the number of terminals having a data rate of R_i . The noise rise for $\mathbf{x} = (x_1, x_2, x_3, x_4, x_5)$, $\eta(\mathbf{x})$, can be expressed as

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

where $\tau(R_i)$ is the target value of E_c/N_0 (ratio of chip energy to noise power spectral density) for the pilot channel supporting a data rate of R_i , and $c(R_i) \triangleq 1 + 10^{G_{data}(R_i)/10} + 10^{G_{DRC}/10}$. In (1), if $\sum_{i=1}^5 x_i c(R_i) / (c(R_i) + 1/\tau(R_i)) > 1$, the value of $\eta(\mathbf{x})$ is regarded as ∞ because the noise rise does not have a negative value.

Now, the base station can estimate the noise rise at the current and next frames from (1). The proposed scheme tries to minimize the traffic overload based on the current and predicted noise rises. If the current and predicted noise rises are compared with η_{th} , there are three possible combinations of the noise rises because the predicted noise rise is always equal to or greater than the current value: 1) If the current and predicted noise rises are lower than η_{th} , the base station broadcasts the RAB of 0 and only the candidate terminals increase their data rates; 2) If the current and predicted noise rises are greater than η_{th} , the base station broadcasts the RAB of 1 and the non-candidate terminals reduce their data rates with probability q_i ; 3) If the current noise rise is lower than η_{th} and the predicted noise rise is greater than η_{th} , the base station commands all access terminals to maintain the

current data rates, by not transmitting any RAB symbol (i.e., RAB=NoTx). RAB=NoTx can be easily realized without modifying the current RA channel and it helps the access terminals not to reduce the data rates unnecessarily. Assuming an ideal situation, the resulting noise rise never exceeds η_{th} in the proposed scheme.

3 Performance analysis

We assume that there are T access terminals in a single-cell environment and all access terminals always have data to transmit. Since there are three RAB values (RAB=0, 1, NoTx), we assume that each RAB value can be decoded as other values with the following error probabilities:

- z_1 : probability that RAB=0 or 1 is decoded as the opposite value.
- z_2 : probability that RAB=0 or 1 is decoded as NoTx.
- z_3 : probability that RAB=NoTx is decoded as 0 or 1.

In this analysis, a system state of the proposed scheme is defined as a vector $\mathbf{S}(k) = (S_1(k), S_2(k), S_3(k), S_4(k))$, where $S_i(k)$ is the number of access terminals having a data rate of R_i at the k -th frame [3]. Notice that $S_5(k)$ can be easily deduced from $S_5(k) = T - \sum_{i=1}^4 S_i(k)$ and thus it is not required in the definition of $\mathbf{S}(k)$. This system model can be considered as a Markov process because the RAB is determined by combinations of the current and predicted noise rises, which are based on the current state.

Let U_i and D_i be the number of access terminals that increase and decrease the data rates, respectively, from the data rate of R_i at the beginning of the $(k+1)$ -th frame. Let $\mathbf{x} = (x_1, x_2, x_3, x_4)$ and $\mathbf{y} = (y_1, y_2, y_3, y_4)$ be the samples of $\mathbf{S}(k)$ and $\mathbf{S}(k+1)$, respectively. The state transition probability $p_{\mathbf{xy}} \triangleq \Pr(\mathbf{S}(k+1) = \mathbf{y} | \mathbf{S}(k) = \mathbf{x})$ can be transformed to $p_{\mathbf{xy}} = \Pr(\mathbf{D} - \mathbf{U} = \mathbf{e} | \mathbf{S}(k) = \mathbf{x})$, where $\mathbf{D} = (D_1, D_2, D_3, D_4)$, $\mathbf{U} = (U_1, U_2, U_3, U_4)$, $\mathbf{e} = (e_1, e_2, e_3, e_4)$ and $e_i \triangleq \sum_{k=1}^i (y_k - x_k)$.

$p_{\mathbf{xy}}$ can be obtained by conditioning on the number of candidate terminals (C_i), the number of candidate terminals that decode the RAB as 0 (M_i), and the number of non-candidate terminals that decode the RAB as 1 (N_i) at each data rate. Then, by conditioning on C_i , M_i and N_i , $p_{\mathbf{xy}}$ is expressed as

$$p_{\mathbf{xy}} = \sum_{\mathbf{c}} \sum_{\mathbf{m}} \sum_{\mathbf{n}} \Pr(\mathbf{D} = \mathbf{m} + \mathbf{e} | \mathbf{n}, \mathbf{m}, \mathbf{c}, \mathbf{x}) \times \Pr(\mathbf{N} = \mathbf{n} | \mathbf{m}, \mathbf{c}, \mathbf{x}) \cdot \Pr(\mathbf{M} = \mathbf{m} | \mathbf{c}, \mathbf{x}) \cdot \Pr(\mathbf{C} = \mathbf{c} | \mathbf{x}) \quad (2)$$

where $\mathbf{C} = (C_1, C_2, C_3, C_4)$, $\mathbf{M} = (M_1, M_2, M_3, M_4)$ and $\mathbf{N} = (N_1, N_2, N_3, N_4)$. Notice that $U_i = M_i$ ($i = 1, \dots, 4$) in the proposed scheme. Because each probability in (2) is described by the binomial distribution, it is given by

$$\Pr(\mathbf{D} = \mathbf{m} + \mathbf{e} | \mathbf{n}, \mathbf{m}, \mathbf{c}, \mathbf{x}) \cdot \Pr(\mathbf{C} = \mathbf{c} | \mathbf{x}) = \prod_{i=1}^4 f_{q_{i+1}}(n_{i+1}, m_i + e_i) f_{p_i}(x_i, c_i). \quad (3)$$

$$\Pr(\mathbf{N} = \mathbf{n} | \mathbf{m}, \mathbf{c}, \mathbf{x}) \cdot \Pr(\mathbf{M} = \mathbf{m} | \mathbf{c}, \mathbf{x})$$

$$= \begin{cases} \prod_{i=1}^4 f_{z_1}(x_{i+1} - c_{i+1}, n_{i+1}) f_{1-z_1-z_2}(c_i, m_i), & \text{RAB}(\mathbf{x}, \mathbf{c}) = 0, \\ \prod_{i=1}^4 f_{1-z_1-z_2}(x_{i+1} - c_{i+1}, n_{i+1}) f_{z_1}(c_i, m_i), & \text{RAB}(\mathbf{x}, \mathbf{c}) = 1, \\ \prod_{i=1}^4 f_{z_3}(x_{i+1} - c_{i+1}, n_{i+1}) f_{z_3}(c_i, m_i), & \text{RAB}(\mathbf{x}, \mathbf{c}) = \text{NoTx}, \end{cases} \quad (4)$$

where $f_\gamma(\alpha, \beta) \triangleq {}_\alpha C_\beta \gamma^\beta (1 - \gamma)^{\alpha - \beta}$ and $c_5 = 0$ for compact expression. The ranges of \mathbf{c} , \mathbf{n} and \mathbf{m} are $\{\mathbf{c} | 0 \leq c_i \leq x_i, i = 1, \dots, 4\}$, $\{\mathbf{n} | 0 \leq n_i \leq x_i - c_i, i = 2, \dots, 5\}$ and $\{\mathbf{m} | \max(0, -e_i) \leq m_i \leq \min(c_i, n_{i+1} - e_i), i = 1, \dots, 4\}$, respectively. A steady-state probability $\pi_{\mathbf{x}}$ for a state \mathbf{x} can be obtained by solving a set of linear equations $\pi_{\mathbf{y}} = \sum_{\mathbf{x}} p_{\mathbf{xy}} \pi_{\mathbf{x}}$ and $\sum_{\mathbf{x}} \pi_{\mathbf{x}} = 1$. A similar procedure can be used to obtain the steady-state probability for the conventional schemes.

4 Results and conclusions

In the CDMA system, a high noise rise may cause a high packet error rate even though it is required for high-speed transmission. In [6], the overload probability that the noise rise exceeds 7 dB is considered as a reference for the performance evaluation in a realistic situation. If the overload probability is less than 1%, most transmissions can be considered successful. Thus, the maximum reverse-link throughput satisfying the overload probability of less than 1% is selected as a performance metric for comparison. In this analysis, the reverse-link throughput ζ is given by $\zeta = \sum_{\mathbf{x} \in \{\mathbf{x}_u\}} \left(\sum_{i=1}^5 x_i R_i \right) \pi_{\mathbf{x}}$, where $\{\mathbf{x}_u\}$ is a set of \mathbf{x} that satisfies $\eta(\mathbf{x}) < 7$ dB from (1). ζ does not include the system states having a noise rise higher than 7 dB because most transmissions are unsuccessful in the overloaded conditions.

The rate-transition probabilities are set to $(p_1, p_2, p_3, p_4) = (0.2, 0.1, 0.05, 0.025)$ and $(q_2, q_3, q_4, q_5) = (0.1, 0.3, 0.6, 0.9)$ for all access terminals. The RAB decoding error probabilities are assumed to be $z_1 = z_2 = z_3 = 1\%$ (the RAB value is repeated over multiple slots [1]). G_{DRC} is set to -1.5 dB assuming $DRCLength$ of 2 slots [4]. The value of $\tau(R_i)$ can be determined by a link level simulation [7], and is set to -22 dB for all data rates. The same parameters are applied to the conventional schemes, except the RAB decoding error probability. Because the conventional schemes permit only two values of RAB (0 and 1), the RAB decoding error occurs when the transmitted RAB is decoded as the opposite value. This error probability z is set to $z = z_1 + z_2/2$ from the definitions of z_1 and z_2 .

Figure 1 illustrates the maximum throughput ζ_{max} in the proposed and conventional schemes. ζ_{max} in the proposed scheme is much higher than those in the conventional schemes, regardless of the number of access terminals. The proposed scheme achieves up to 45% improvement over the original scheme in [1], whereas the enhanced scheme in [3] does up to 20% improvement. The primary reason for the improvement is that the proposed scheme

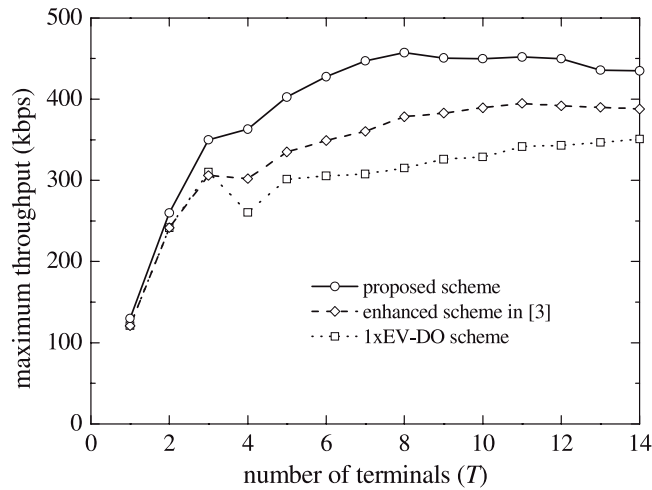


Fig. 1. Comparison of maximum reverse-link throughput.

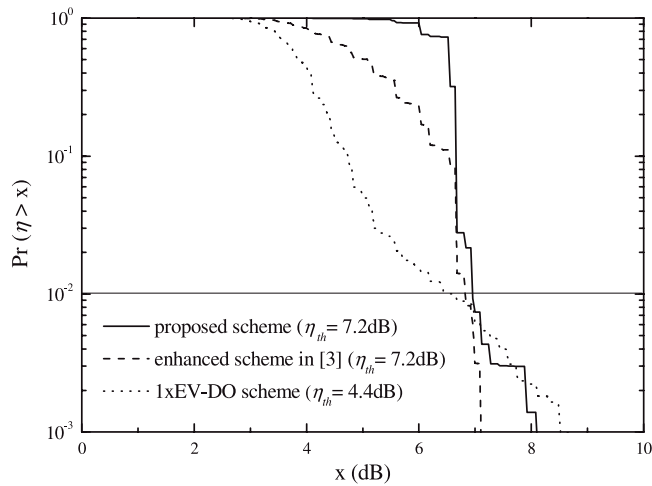


Fig. 2. Complementary cumulative density function of noise rise ($T = 10$).

suppresses the traffic overload effectively. The performance improvement can be explained by the distribution of noise rise. Figure 2 plots the complementary cumulative density function of η at $T = 10$. In each scheme, η_{th} has been adjusted so that the overload probability $\Pr(\eta > 7 \text{ dB})$ is close to 1%. We can see that the noise rise is concentrated just below 7.0 dB in the proposed scheme, whereas the noise rise in other schemes is distributed over the entire region. Because the variance of noise rise is related with the stability and performance of the 1xEV-DO system, the lower variance of noise rise in the proposed scheme is the preferred one for the efficient reverse-link transmission.