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CDMA Unslotted ALOHA Systems with Packet Retransmission Control

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SUMMARY In this paper, we analyze the throughput and delay performances of the CDMA unslotted ALOHA system considering packet retransmission. We also clarify the stability of the system. Based on these results, we propose the optimal retransmission control (ORC) to improve the performances. The ORC is the scheme to prevent the system from drifting to an undesirable operating point by controlling the birth rate of retransmitted packets. As a result, it is shown that the throughput and delay performances of the system with the ORC are better than without the ORC and the system does not drift to an undesirable operating point.
key words: CDMA unslotted ALOHA, throughput, delay, system stability, retransmission control

1. Introduction

The packet radio systems combined with the code-division multiple-access (CDMA), which we call CDMA ALOHA systems, have attractive features, such as random access capability, potentiality for high throughput performance, low peak power in the transmitters and flexible transmission of multi-media signals. Great deal of works, therefore, have been made on these systems so far. Many of them were on the slotted ALOHA with CDMA (CDMA S-ALOHA) [1]–[3] and several on the unslotted ALOHA with CDMA (CDMA U-ALOHA) [4]–[7]. The CDMA U-ALOHA would be preferable to the CDMA S-ALOHA from the view point of easier asynchronous random access.

In the CDMA ALOHA system, the probability of unsuccessful packet transmission will become higher with increase in the number of simultaneous packet access because of interference from other packets, thereby increasing in the number of packet retransmission. We will have to take the effect of packet retransmission into account in order to evaluate the system performance precisely. In connection with the packet retransmission in the CDMA ALOHA, the system would have a bistable behavior, similarly to the pure ALOHA systems [8]–[10]. This behavior implies that the system may drift to an undesirable operating point where the throughput drops to almost zero.

In the past, the performance of a CDMA U-ALOHA system was analyzed in consideration of the effect of packet retransmission under the assumption that when the number of packet access exceeds a threshold, the bit error rate is one, and otherwise zero [7]. But in this assumption, it is not considered that an advantage of the CDMA ALOHA system that the bit error probability tends to decrease gracefully as the number of transmitted packets increases. The analysis was made for the exponentially distributed packet length. Any schemes to avoid drifting to the undesirable operating point have not been presented so far.

In this paper, we analyze the throughput and delay performances of the CDMA U-ALOHA system taking the effect of packet retransmission into account and assuming a more practical model. In this model, each packet length is fixed, the bit error rate is gracefully increased with the number of multiple-access interfering signals, and the packet success probability is determined by the gracefully altering bit error rates. We also clarify the stability of the system, and propose a scheme to prevent the system from drifting to the undesirable operating point. This scheme is called Optimal Retransmission Control (ORC). The ORC is proposed in [10] for pure ALOHA system, but has never been proposed for the CDMA U-ALOHA system. Since the CDMA U-ALOHA system has advantages of simultaneous packet transmissions and graceful degradation of packet success probability, we clarify the system stability in consideration of these advantages. By doing this, it becomes possible to apply the ORC to the CDMA U-ALOHA system. In the ORC, the packet retransmission birth rate is controlled in accordance with the fraction of users in the retransmission mode.

2. System Model

A single hop spread spectrum network model is assumed. Consider a large number of independent users sharing random signature. We assume that every packet is received with equal power and all data bit errors are caused by the effect of multiple access interference and additive white Gaussian noise. With Gaussian approximation [11], the bit error probability is given as,

$$P_b(k) = Q\left[\left(\frac{k}{3N} + \frac{N_0}{2E_b}\right)^{-\frac{1}{2}}\right], \tag{1}$$

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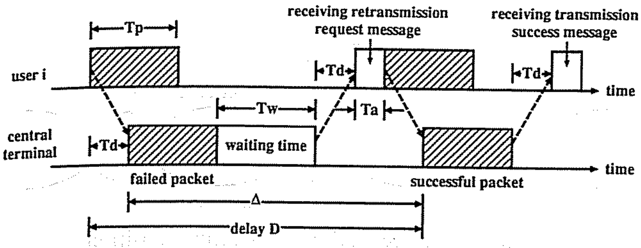

Fig. 1 Elapsed time between packets when the retransmission is required.

where N is the number of chips per bit, k is the number of interfering packets, E_b is the bit energy of the signal, N_0 is two-sided spectral density of Gaussian noise and,

$$Q[x] = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-u^2/2)\, du. \tag{2}$$

In the CDMA U-ALOHA system the time to receive a message when there is no collision, is merely the propagation delay time T_d, which is obtained as,

$$T_d = \frac{d}{c}, \tag{3}$$

where d is the distance traveled and c is the speed of light. Figure 1 illustrates the case where a collision occurs and retransmission is required. Note that packet is transmitted and then received after a time T_d. After examining the entire message, if an error is detected, a retransmission request message of duration T_a will return to each user after waiting for exponentially distribution average time intervals T_w, so that, hopefully, the users who collided before will not do so again. Otherwise, a transmission success message will return.

We assume as the following. All users belong to either the originating mode or the retransmission mode. Figure 2 shows the state transition of a user between the originating mode and the retransmission mode. Users in the originating mode generate new packets, and users in the retransmission mode manage backlogged packets. If a user is in the originating mode and fails to transmit the new packet, he will move into the retransmission mode. If a user is in the retransmission mode and succeeds in a packet retransmission, he will move into the originating mode. When the number of users K is large, we can use Poisson approximation [8] as the approximation becomes of quit insensitive to the exact distribution of individual user packet generation. Let Λ_o be the birth rate of packet generation when all users are in the originating mode. Let Λ_r be the birth rate of packet generation when all users are in the retransmission mode. We define the system state r as the fraction of users in the retransmission mode. Because of large number of users, the fluctuation of the system state is very slow. We assume fixed packet length and the generation of a packet in the system as Poisson process with the birth rate obtained as,

$$\lambda = (1-r)\Lambda_o + r\Lambda_r. \tag{4}$$

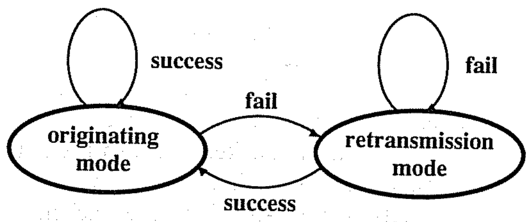

Fig. 2 Transition of users between the originating mode and the retransmission mode.

The offered load is defined as the mean number of generating packets in a packet time $T_p(= L/R)$, where R [bit/second] is a data rate, L [bit] is the length of a packet. The offered load G is expressed as,

$$G = \lambda T_p = \{(1-r)\Lambda_o + r\Lambda_r\}T_p. \tag{5}$$

By setting $G_o = \Lambda_o T_p$ and $G_r = \Lambda_r T_p$, G is deduced as the following.

$$G = (1-r)G_o + rG_r \tag{6}$$

3. Packet Success Probability

We can transmit a packet successfully only when all bits in a packet are transmitted successfully. Because of Poisson generation of packets and fixed packet length, CDMA U-ALOHA system can be thought as an M/D/∞ queue with the birth rate λ and the death rate $\mu(k_1)$. The birth rate is as the following.

$$\lambda = \frac{G}{T_p} \tag{7}$$

For a fixed packet length, the death rate is derived as [6],

$$\mu(k_1) = \frac{k_1}{T_p}, \tag{8}$$

where k_1 is the number of interfering packets at first bit in a packet.

Consider the situation that at certain i-th bit in a packet the number of interfering packets is k. As we assume the Poisson packet generation, two or more packets can be hardly generated simultaneously. The increase of the number of interfering packets is one in a short duration Δt, and since the packet length is constant, the decrease of the number of interfering packets is also one. The probability that both increase and decrease of packet occurs in Δt is negligible. Therefore, after Δt seconds, the interference level k of the i-th bit of the packet will increase to $k+1$, decrease to $k-1$, or remain to k. Using the birth rate λ and the death rate $\mu(k_1)$, it is gained the state equation for the number of interfering packets as,

$$\begin{aligned} P_k(t+\Delta t) = {} & P_k(t)\cdot(1-\mu(k_1)\Delta t - \lambda\Delta t) \\ & + P_{k-1}(t)\cdot\lambda\Delta t \\ & + P_{k+1}(t)\cdot\mu(k_1)\Delta t, \end{aligned} \tag{9}$$

where $P_k(t)$ is the probability that $k+1$ of packets exist on a server at certain time t.

We define the probability $P_S(k,i,k_1)$ as the following. When the number of interfering packets is k_1 at first bit in a packet, the packet is transmitted successfully from first bit to $i-1$-th bit, and the number of interfering packets is k at i-th bit in the packet.

Case $i=1$; (*the number of interfering packets is* k_1 *at first bit.*)

Using the steady state probability of an M/D/∞ queue, we obtain as the following.

$$P_S(k,i=1,k_1) = \begin{cases} \dfrac{(\lambda T_p)^k}{k!}\exp(-\lambda T_p) = \dfrac{G^k}{k!}\exp(-G); & \text{if } k=k_1 \\ 0; & \text{otherwise} \end{cases} \tag{10}$$

Case $i>1$; (*the number of interfering packets is* k *at* i*-th bit.*)

As the transition of the number of interfering packets may occur every Δt seconds, and hence the $P_k(t)$ is conditioned on the bit error probability $P_b(k)$, we get,

$$\begin{aligned} P_S(k,i,k_1) = {} & P_S(k,i-1,k_1) \\ & \cdot\{1-\mu(k_1)\Delta t-\lambda\Delta t\}\cdot\{1-P_b(k)\} \\ & +P_S(k+1,i-1,k_1)\cdot\mu(k_1)\Delta t \\ & \cdot\{1-P_b(k+1)\} \\ & +P_S(k-1,i-1,k_1)\cdot\lambda\Delta t \\ & \cdot\{1-P_b(k-1)\}. \end{aligned} \tag{11}$$

Using $P_S(k,i,k_1)$ and the packet length L, the packet success probability is calculated by setting $i=L$ and multiplication of the probability that L-th bit is succeed. Averaging over all possible value of k and k_1, we get the packet success probability $Q_S(G)$ as the following.

$$Q_S(G)=\sum_{k=0}^{\infty}\sum_{k_1=0}^{\infty}P_S(k,L,k_1)\cdot(1-P_b(k)) \tag{12}$$

4. Throughput and Delay Analysis

From (12), the throughput $S(r)$ and the delay $D(r)$ are obtained as the function of the system state r.

$$S(r)=G\cdot Q_S(G) \tag{13}$$

$$\begin{aligned} D(r) = {} & \frac{1}{T_p}\{T_dQ_S(G) \\ & +(T_d+\Delta)(1-Q_S(G))Q_S(G) \\ & +(T_d+2\Delta)(1-Q_S(G))^2Q_S(G)+\cdots \\ & +(T_d+q\Delta)(1-Q_S(G))^qQ_S(G)+\cdots\} \\ = {} & \frac{1}{T_p}\cdot\left\{T_d+\frac{\Delta}{Q_S(G)}(1-Q_S(G))\right\}, \end{aligned} \tag{14}$$

where G is obtained by (6) and the time between the second reception and the first reception of packet $\Delta = T_p+T_a+T_w+2T_d$. Average waiting time $T_w=K\cdot T_p/G_r$.

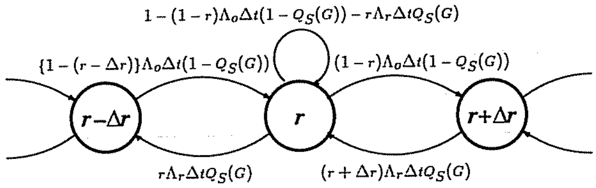

Fig. 3 State occupation probability transition.

To calculate the throughput and delay of the system, we clarify the state occupation probability, which is the probability distribution function of the system state r. Because of Poisson packet generation, we assume that in an interval Δt, the system state r increases by Δr, decreases by Δr, or remains to r. The above leads to the system state transition shown in Fig. 3. In an interval Δt, if a user in the originating mode generates a packet and the packet fails, the system state r will increase by Δr, and if a user in the retransmission mode generates a packet and the packet succeeds, the system state r will decrease by Δr. Thus, the state occupation probability $\pi(r)$ is obtained as follows,

$$\begin{aligned} \pi(r) = {} & \{1-(r-\Delta r)\}\Lambda_o\Delta t\cdot(1-Q_S(G)) \\ & \cdot\pi(r-\Delta r) \\ & +\{1-(1-r)\Lambda_o\Delta t\cdot(1-Q_S(G)) \\ & -r\Lambda_r\Delta t\cdot Q_S(G)\}\cdot\pi(r) \\ & +(r+\Delta r)\Lambda_r\Delta t\cdot Q_S(G)\cdot\pi(r+\Delta r). \end{aligned} \tag{15}$$

Accordingly, the throughput and delay performances are the following.

$$S=\int_0^1 G\cdot Q_S(G)\cdot\pi(r)\,dr \tag{16}$$

$$D=\frac{1}{T_p}\int_0^1\left\{T_d+\frac{\Delta}{Q_S(G)}(1-Q_S(G))\right\}\cdot\pi(r)\,dr \tag{17}$$

5. Expected Drift

In this section, we clarify a stability of the system. It is interesting to compute the expected drift, an indicator of system dynamics, which denotes the time rate of change of the system state r. The rate at which users move from the originating mode into the retransmission mode is $(1-r)G_o(1-Q_S(G))$, since $(1-r)G_o$ is the rate of generation of new transmissions and $(1-Q_S(G))$ is the probability that a transmission is not successful. Similarly, the rate at which terminals leave the retransmission mode is $rG_rQ_S(G)$. The net rate of increase of users in the retransmission mode is the difference between these two quantities and is also equal to the expected drift $d(r)$. It is obtained as the following.

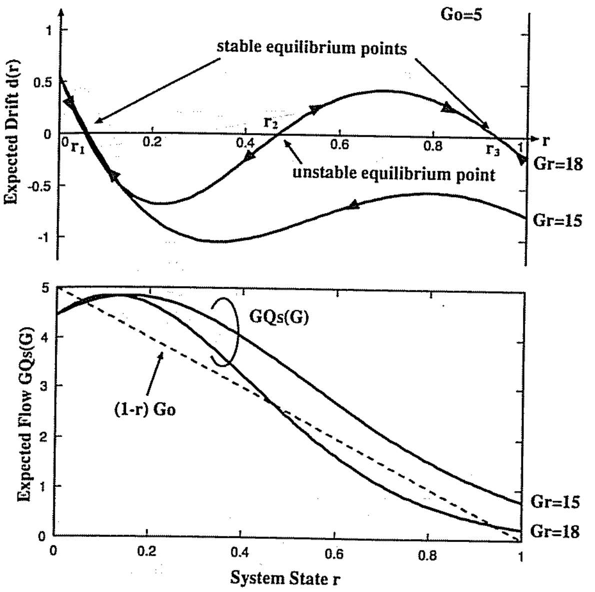

Fig. 4 Expected drift and expected flow and a bistable behavior.

$$d(r) = (1-r)G_o - GQ_S(G) \tag{18}$$

The first term shows the offered load of new packet generation. The second term is the throughput in the system state r, which we call the expected flow. If the offered load of new packet generation is equal to the expected flow, r will remain to the same state. We can observe that the system is in an equilibrium condition. Figure 4 shows the expected drift and the expected flow of the system. There are some properties between the offered load of new packet generation and the expected flow.

1) if $r = 0$, then $(1-r)G_o \geqq GQ_S(G)$.

2) if $r = 1$, then $(1-r)G_o \leqq GQ_S(G)$.

Because of these properties, we see that $d(0)$ is greater than 0 and $d(1)$ is less than 0; hence, the number of equilibrium points must be odd. Furthermore, odd equilibrium points are stable and even ones are unstable. Generally, the throughput curve is increasing linearly for small offered load, reaches a maximum after this initial linear region, and then is decreasing. Accordingly, $GQ_S(G)$ is convex cap, and either gradually becomes convex cup or remains convex cap. We also observe that $(1-r)G_o$ is linearly decreasing. This fact restricts the number of equilibrium points to be no more than three. With these observations, we therefore conclude that the system can only have either: one stable equilibrium point or three equilibrium points with the first one and the third one stable and the second one unstable.

Accordingly the system exhibits a bistable behavior. One possible stable condition (with short delays and reasonable good throughput) has most terminals in the originating mode. The other stable condition has most terminals in the retransmission mode, obstructing the channel with prevailing interference. Transitions from one condition to the other should occasionally take place, due to statistical fluctuations.

6. Optimal Retransmission Control

From the previous section, we recognize that there exists a bistable behavior. This behavior implies that the system may, due to statistical fluctuations in the rate of attempts to transmit, drift to an undesirable operating point where the system throughput drops to almost zero and the delay increases to an unacceptable level. In this section, we apply the optimal retransmission control (ORC) [10] to prevent the system from drifting to an undesirable operation point.

6.1 Control Method

The ORC policy is a rule for choosing the retransmission birth rate Λ_r as the system evolves. Intuitively, when the system is in the high system state (the system state r is large, that is, there exist many users in retransmission mode.), we choose a smaller Λ_r to avoid the undesirable stable equilibrium point. On the other hand, when the system is in the low system state (the system state r is small, that is, there exist a few users in retransmission mode.), we choose a larger Λ_r to decrease the delay for backlogged packets. The function of the retransmission birth rate chosen by the policy may depend on the past history of the process. The policy is stationary if the selection of Λ_r at time t depends only on the state of the process at time t. Hence, a stationary retransmission policy is the retransmission birth rate function $\Lambda_r(r)$ $(= G_r(r) \cdot R/L)$, where $\Lambda_r(r)$ is used when the system is in the state r.

We now define $\Lambda_r(r)$ from the viewpoint of the system's expected drift $d(r)$. The more negative the value of $d(r)$, the more likely it is that the system will drift to smaller r and, hence, the higher the probability that the system stays at a low state (small r). Therefore, the best policy should make $d(r)$ as negative as possible for all r except $r = 0$. From (18) and the above observation, we thus reach the conclusion that the optimal retransmission policy is the one which makes $GQ_S(G)$ as large as possible for all $r \neq 0$. Now, we assume that $GQ_S(G)$ is maximum at $G = G_{\max}$, which can be obtained from (13). From (6), we have the following equation.

$$G_{\max} = (1-r)G_o + rG_r(r) \tag{19}$$

After simple algebraic manipulations, we have the following.

$$G_r(r) = \begin{cases} \dfrac{G_{\max} - (1-r)G_o}{r}; & \text{if } r \geqq 1 - \dfrac{G_{\max}}{G_o} \\ 0; & \text{otherwise} \end{cases} \tag{20}$$

If $G_r(r)$ is negative, we define that $G_r(r) = 0$, that is, we do not generate retransmission packets.

In practice, we have the problem how to estimate the system state r. To solve the problem, each packet has an information of the originating mode or the retransmission mode, and a hub-station evaluates the change from the originating mode to the retransmission mode or from the retransmission mode to the originating mode. However, we suspect that the ORC is not sensitive to estimation error of the system state r because the derivative of the expected flow $GQ_S(G)$ at the maximum point is almost zero and the throughput performance does not vary greatly at this point. It is also explained from the fact that a slight change in k affects little in the performance since the system is based on CDMA ALOHA.

6.2 Performance

From Sect. 4, we can similarly calculate properties of the system. By replacing G_r with $G_r(r)$, the state occupation probability $\pi(r)$, the throughput S, the delay D, and the expected drift $d(r)$ with the ORC are obtained, respectively, as the following.

$$\begin{aligned}\pi(r) = &\{1-(r-\Delta r)\}\Lambda_o\Delta t\cdot(1-Q_S(G))\\ &\cdot\pi(r-\Delta r)\\ &+\{1-(1-r)\Lambda_o\Delta t\cdot(1-Q_S(G))\\ &-r\Lambda_r(r)\Delta t\cdot Q_S(G)\}\cdot\pi(r)\\ &+(r+\Delta r)\Lambda_r(r+\Delta r)\Delta t\cdot Q_S(G)\\ &\cdot\pi(r+\Delta r)\end{aligned} \tag{21}$$

$$S = \int_0^1 G\cdot Q_S(G)\cdot\pi(r)\,dr \tag{22}$$

$$\begin{aligned}D = &\frac{1}{T_p}\int_0^1\left\{T_d+\frac{\Delta}{Q_S(G)}(1-Q_S(G))\right\}\\ &\cdot\pi(r)\,dr\end{aligned} \tag{23}$$

$$d(r) = (1-r)G_o - GQ_S(G) \tag{24}$$

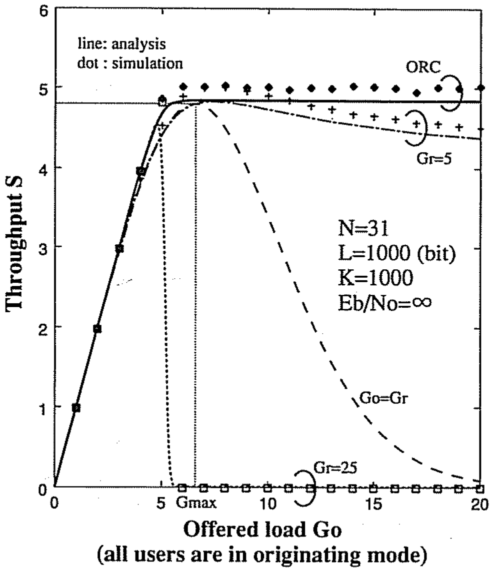

Fig. 5 Throughput performance as a function of the offered load.

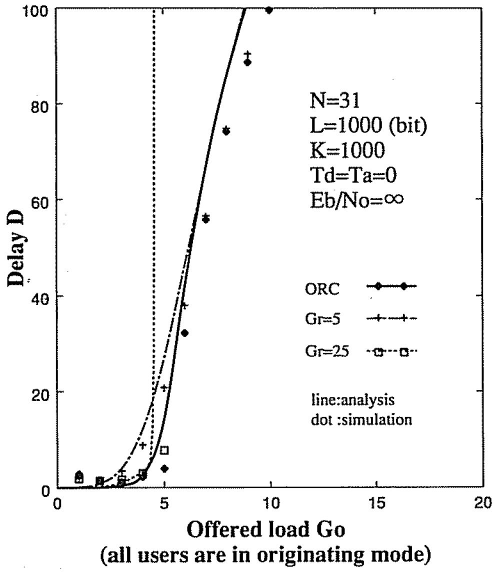

Fig. 6 Delay performance as a function of the offered load.

7. Numerical Example

The throughput and delay performances of CDMA U-ALOHA system are shown in Fig. 5 and Fig. 6 for the case of $G_r = 5$ and 25 respectively, where we set $N = 31$ and $E_b/N_0 = \infty$. The simulated results are also plotted in the figures. We observe that the analytical results come close to the simulated results. At first, we observe the performance without the ORC policy. In small G_o, the throughput performance for the case of $G_r = 25$ is slightly better than that of $G_r = 5$. On the other hand, the throughput performance for the case of $G_r = 25$ drops to zero for G_o more than 6, while the throughput for the case of $G_r = 5$ tends to stay near the maximum value of the throughput. As the throughput is the function of the packet success probability $Q_S(G)$ and it depends not only on G_o and G_r but also on the system state r, we evaluate the system state r as the function of G_o and G_r.

Figure 7 shows the expected drift and the state occupation probability. For the case of $G_o = 5$ and $G_r = 5$, as shown in Fig. 7 (a), we observe that $d(r)$ occupies the negative region for $r > 0.2$ and $\pi(r)$ has a peak value near the stable equilibrium point. On the other hand, we observe that there are three equilibrium points for $G_o = 5$ and $G_r = 25$ and $d(r)$ almost al-

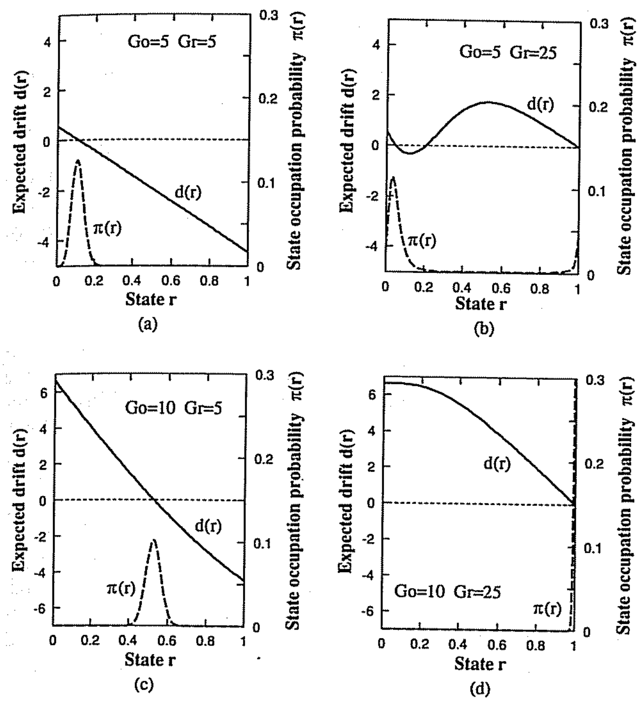

Fig. 7 Expected drift and state occupation probability.

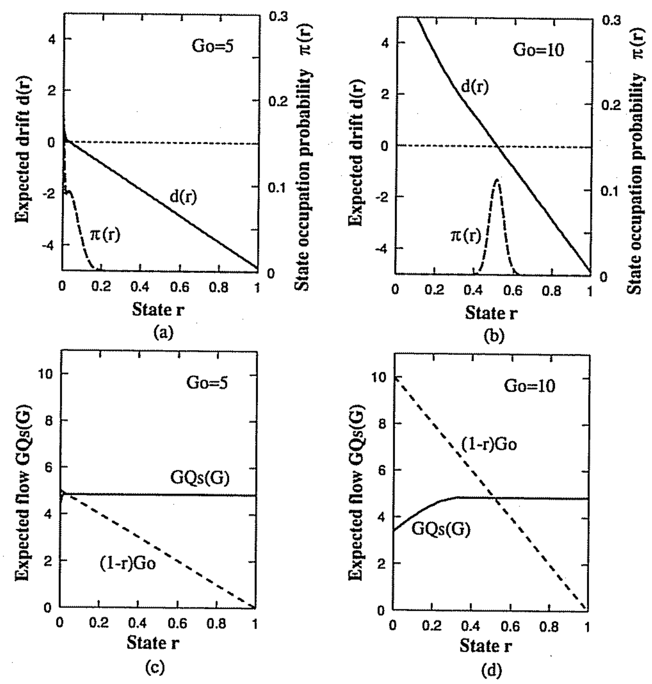

Fig. 8 Expected drift, state occupation probability and expected flow under ORC policy.

ways has positive value expect in the range of first stable equilibrium point and the unstable equilibrium point. Since these are the case of small G_o, we can expect the good packet success probability regardless of G_r and the throughputs are almost same for both $G_r = 5$ and 25, respectively, as shown in Fig. 5. For $G_o = 10$, $d(r)$ and $\pi(r)$ are depicted in Fig. 7 (c) and (d) for $G_r = 5$ and 25, respectively. From the figures, we observe that for $G_r = 5$, $\pi(r)$ has a peak value at $r = 0.5$, while a peak is found at $r = 1$ for $G_r = 25$. As all users are in the retransmission mode for $r = 1$, this is the case of the undesirable condition. For a large G_o, the users tend to move into the retransmission mode, therefore, $\pi(r)$ has a peak at rather large r. The throughput performance is determined by the system offered load G, which is given in (6). A large r decreases the value of the first term of (6), $(1-r)G_o$, while it increases the value of the second term, rG_r. Therefore, when G_r is small, we can expect that in contrast with G_o, G gradually changes its value and so does the throughput performance. This can be recognized from the curve of $G_r = 5$ in Fig. 5.

The expected drift, the state occupation probability and the expected flow performances with the ORC policy are shown in Fig. 8. We observe that the expected flow is monotonously increasing on the system state r, takes a maximum value and keeps constant value after this maximum point. Because of large system state r, the retransmission control is more effective. Accordingly the system has only one stable point, and an undesirable operating point does not exist. The throughput is maintained at the maximum value for $G_o > 6$, as the ORC controls the system offered load G so as to stay in $G_{\max}$ and the throughput performance depends on G (shown in Eq. (22)). Accordingly, the best throughput is kept constant for $G_o > 6$, as shown in Fig. 5.

If G_o, which is the birth rate of new packets, was kept at about $G_{\max}$, we would not have to use the ORC, as we get good throughput performance. But, it is not possible to keep G_o at a certain value, because G_o varies with time and may become very large. With the ORC, we can control the system offered load G to stay in $G_{\max}$ regardless of G_o. Accordingly, the ORC is very effective.

8. Conclusions

The throughput and delay performances of the CDMA U-ALOHA system have been analyzed in consideration of packet retransmission. We have derived the state occupation probability and the expected drift of the system as the function of the packet success probability. As a result, we found that when the offered load G was large, the state occupation probability $\pi(r)$ had a peak value at a large system state r, which was the fraction of users in the retransmission mode. Therefore, by controlling the packet retransmission birth rate under the ORC policy, the best throughput performance was found as it stayed in the maximum value regardless of G. As a result, it was shown that the throughput and delay performances of the system with the ORC were better than without the ORC and the system did not drift to an undesirable operating point.

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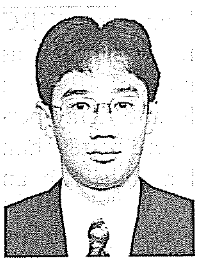

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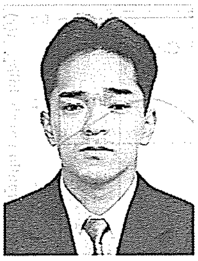

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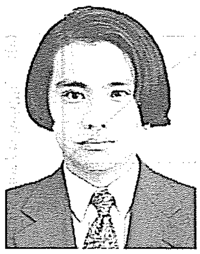

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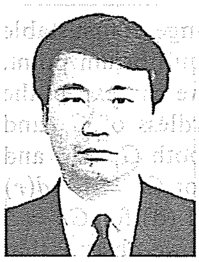

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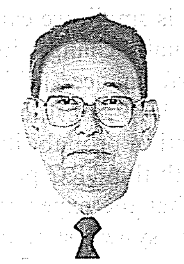

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