論文 96-1-1-15

기지국이 있는 주파수 도약 대역확산 통신 시스템에서의 채널 입력 트래픽 제어

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Channel Input-Traffic Control of FH/SSMA Systems with a Centralized Controller

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要 約

주파수 도약 대역확산 통신망에서 최적 입력 트래픽 제어 방식을 고려했다. 먼저, 채널 입력 패킷 수가 최적일 때 조건부 처리량을 분석하였다. 그리고, 상태 천이 확률을 얻었고, 정상 상태 성능을 분석하였으며, 평균 패킷 지연 시간을 얻었다. 특히, 재전송 모드의 사용자들에게 전송 우선권을 주면 평균 패킷 지연 시간을 줄일 수 있음을 보였다. 한편, 주파수 슬롯 수가 작을수록 여러 제어 방식들 사이의 성능 차이가 많았다.

ABSTRACT

An optimal channel input-traffic control (OCIC) policy is proposed for slotted frequency-hopped spread-spectrum multiple access communication systems. When the number of channel input packets is set to the optimal number, the conditional throughput for the OCIC policy is analyzed. The state transition probability is derived, the steady state performance is analyzed, and the mean packet delay is obtained. It is shown that the mean packet delay decreases considerably when the priority of transmission is given to backlogged users. The smaller is the number of frequency slots, the larger are the differences between the performance of the OCIC policy and that of the other policies.

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論文番號 : 95085-0227
接受日字 : 1995年 2月 7日

Ⅰ. Introduction

Multiple access techniques for communication have been topics for many researches and implementation challenges. In recent years, random access packet switching has been developed as a useful multiple access technique for systems with high peak-to-average traffic ratios [1]. In a slotted system, the channel time is divided into slots whose duration is equal to the transmission time of a packet. Each user is allowed to start transmission of his packet only at the beginning of a slot [2], [3], [4], [5].

More recently, we have seen the introduction of spread-spectrum as a modulation and access tool in the multiple access systems [6] to improve the multiple access capability, motivated mainly by military applications. Spread-spectrum uses the spectrum efficiently by allowing the users to use the same frequency band: channel coding permits the simultaneous transmission of two or more user's packet in code division multiple access (CDMA) systems [7]. This suggests the possibility of using spread-spectrum systems in a multiple access mode of operation. Consequently when we apply the appropriate traffic control policy to random access system in conjunction with spread-spectrum, we can expect that the multiple access capability will be improved efficiently [3].

In this paper, when the access system is assumed to be the slotted frequency-hopped spread spectrum multiple access (FH/SSMA) system with a centralized controller (base station), the optimal channel input-traffic control (OCIC) policy is proposed. In practical systems, the centralized controller must exist to connect each user by assigning the unique frequency hopping pattern (code). Each user requests the centralized controller to allow transmission, and the centralized controller, having the information on the users requesting channel, can control the users through the forward link channel. In this case, the state estimation problem need not be considered any longer.

This paper is structured as follows. In Chapter Ⅱ, a slotted FH/SSMA system description is given, and the FH/SSMA channel and packet flow model of the system are explained. In Chapter Ⅲ, we find the optimal number of channel input packets maximizing the channel throughput according to various code rates and various number of frequency slots. We apply the OCIC policy to the system and analyze the steady state performance using the Markov chain [8], in which the mean packet delay is derived. Conclusions are given in Chapter Ⅳ.

Ⅱ. System Definition

We consider a slotted FH/SSMA packet broadcast system which has centralized controller (base station) with N subscribers (transmitter-receiver pairs). Each user of a transmitter can communicate with any user of a receiver under the control of the base station. The scheme is assumed to use the CDMA in which transmitting nodes use different spreading codes in a frequency hopped systems. The base station assigns a unique frequency hopping pattern (code) to each user to communicate each other. The system model is shown in Fig. 1.

The N users transmit over a common wide frequency band that is divided into q possible frequency bins. Each frequency bin can support narrow band communication. A packet consists of n symbols on a frequency bin that

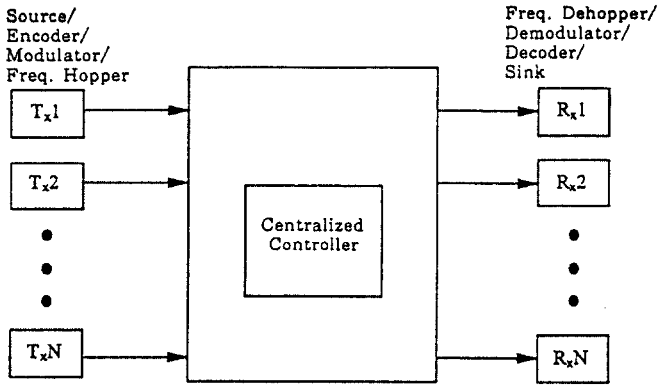

Fig. 1. Frequency-hopped spread-spectrum multiple access system model which has centralized controller with N subscribers.

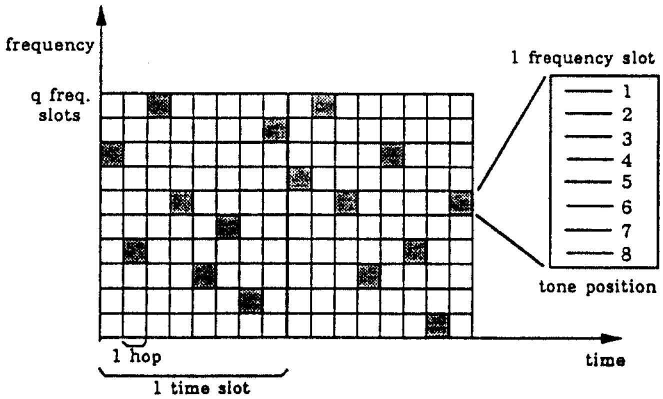

Fig. 2. Frequency-hopping channel with M-ary FSK symbol transmitted per hop and one packet (code word) transmitted during each time slot.

is chosen according to some patterns modeled as a memoryless sequence with each frequency chosen uniformly among the q possible bins with probability $1/q$ as shown in Fig. 2.

Each transmission must begin on a network synchronization boundary, where the slot time is enough to transmit a packet. A single packet (code word) can be transmitted during each time slot. Network synchronization is not feasible at the symbol level and a single M-ary FSK symbol can be transmitted per hop.

There is no conflict due to multiple transmitters simultaneously sending data to the same receiver or due to a half-duplex operation. The background noise in the FH/SSMA channel is ignored and the receiver input SNR is assumed to be sufficiently high so that the correct reception can be assumed when the symbol is not hit.

If two or more active transmitters choose the same frequency bin during overlapping symbol transmissions, then a "hit" occurs. Since the hit symbol cannot be demodulated correctly, the hit symbol is erased under the assumption of the receivers having the perfect side information.

The network is asynchronous at the symbol level due to the synchronization feasibility, and memoryless hopping patterns are used. The probability p_h of a symbol being hit by another transmitter is, as shown in [9],

$$p_h = \frac{2}{q} - \frac{1}{q^2}, \qquad (1)$$

where q is the number of possible frequency bins, and q/N generally lies between 0.5 and 2. The probability $p_{h,m}$ of a particular symbol being hit (i.e., probability of symbol erasure) given m simultaneous transmissions is given by

$$p_{h,m} = 1 - (1-p_h)^{m-1}. \qquad (2)$$

Data is transmitted in packets, and each packet consists of an (n,k) Reed - Solomon (RS) codeword with the erasure only decoding. Since the (n,k) RS code can correct up to $e=n-k$ erasures, a packet containing more than $(n-k)$ symbol erasures will be unsuccessfully corrected. In this event, the packet must be retransmitted [10]. The probability $P_s(m)$ of a packet being correctly decoded (i.e., the probability of successful transmissions) given m simultaneous transmissions is given by

$$P_s(m) = \sum_{l=0}^{n-k} \binom{n}{l} p_{h,m}^{l} (1 - p_{h,m})^{n-l}. \qquad (3)$$

The unspread case of the FH/SSMA systems without error correction coding corresponds to the conventional S-ALOHA system.

The packet flow in the system is shown in Fig. 3. Each user is in one of two modes: the thinking (T) and backlogged (B) modes. Users who have a packet to be retransmitted are in the B mode, and other users are in the T mode. A new packet can be generated with probability p_n by each user in the T mode. A user whose packet is not correctly decoded is sent to the B mode and the user retransmits the packet in the next time slot with probability p_r. A user in the B mode cannot generate a new packet.

The channel input consists of m_n new packets generated from the T mode and m_r backlogged packets from the B mode. The channel does not distinguish between the new and retransmitted packets.

In this paper, we consider a channel input traffic control scheme using a centralized controller roled by the base station. The number of channel input packets is con-

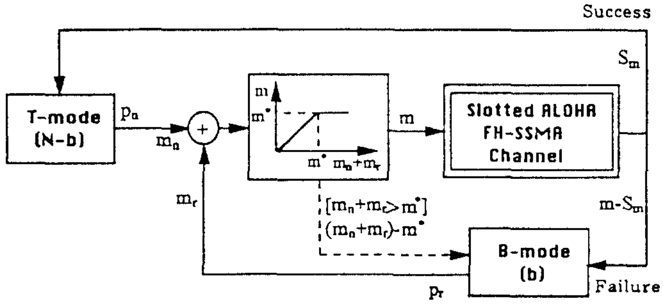

Fig. 3. Packet flow description of slotted FH/SSHA system with centralized controller (base station)

strained to the optimal number of channel input packets m^* as shown in the block diagram of Fig. 3. Therefore, if the number of channel input packets m_n+m_r is less than the threshold level m^*, all m_n+m_r packets are transmitted during that slot; when m_n+m_r is larger than m^*, only m^* channel input packets will be transmitted, and the other packets are sent to the B mode.

Ⅲ. Optimal Channel Input-Traffic Control

1. Conditional throughput

In many multiple access systems, two important measures of performance are the throughput and packet delay. The channel throughput is the average number of successful transmissions per time slot. When m packets are transmitted simultaneously, the conditional channel throughput is defined as

$$S(m) = mP_s(m), \tag{4}$$

where $P_s(m)$ is the probability of successful transmission given m packets being simultaneously transmitted.

Therefore, the channel throughput S with a population of N users is given by

$$S = \sum_{m=1}^{N} S(m)f(m) \tag{5}$$

$$= \sum_{m=1}^{N} mP_s(m)f(m), \tag{6}$$

where $f(m)$ is the steady state packet arrival distribution. The value m^* maximizing $S(m)$ in (4) can be determined, and it can easily be shown that m^* depends on the code rate r and number of frequency slots q. Table 1 shows the values of m^* for several code rates and Table 2 shows m^* and $S(m^*)$ for several number of frequency slots q. Since the code rate is related to the error correction capability, as the code rate is reduced, the value of m^* increases and vice versa. In addition, as the value of q becomes larger, the values of m^* and $S(m^*)$ increase naturally due to lower hit probability.

Given that the system state is b and the threshold value is set to the optimal number of channel input packets m^*, the conditional throughput S^b is given by

$$S^b = E[S \mid b] = \sum_{\substack{m_n=0 \\ m_n+m_r \le m^*}}^{N-b} \sum_{m_r=0}^{b} (m_n+m_r)P_s(m_n+m_r) f_{M_n}(m_n \mid b) f_{M_r}(m_r \mid b)$$

Table 1. Optimun number of users (m^*) for several code rates when n=32, 256, ∞, N=50, and q=50.

Code Rate	Optimum number of users (m^*)		
r (=k/n)	n=32	n=256	n=∞
0.3	26.0	27.0	30.2
0.4	20.0	21.0	23.2
0.5	14.0	16.0	17.8
0.6	11.0	12.0	13.4
0.7	8.0	8.0	9.6
0.8	6.0	5.0	6.4
0.9	4.0	3.0	3.6

Table 2. Optimun number of users (m^*) and maximal conditional throughput for sevral frequency slots when N=50, r=0.7, and k=10.

Freq. slot q	Optimum number of users m^*	Maximal conditional throughput $S(m^*)$
30	5.0	3.89
40	7.0	4.94
50	8.0	6.02
60	10.0	7.08
70	11.0	8.15
80	13.0	9.23
90	14.0	10.29
100	16.0	11.37

$$+ \sum_{\substack{m_n=0 \\ m_n+m_r>m^*}}^{N-b} \sum_{m_r=0}^{b} m^* P_s(m^*) f_{M_n}(m_n \mid b) f_{M_r}(m_r \mid b), \quad (7)$$

where

$$f_{M_n}(m_n \mid b) = \binom{N-b}{m_n} p_n^{m_n}(1-p_n)^{N-b-m_n}, \quad m_n = 0, 1, \cdots, N-b, \quad (8)$$

and

$$f_{M_r}(m_r \mid b) = \binom{b}{m_r} p_r^{m_r}(1-p_r)^{b-m_r}, \quad m_r = 0, 1, \cdots, b. \quad (9)$$

Equation (7) makes use of the fact that new transmission and retransmission events are independent of each other.

Fig. 4 illustrates the conditional throughput versus the system state b for various control methods. The proposed OCIC policy is superior to any other policy including the adaptive retransmission probability control (ARPC) [11], combined OCIC and ARPC, and fixed retransmission probability control (FRPC) policies. In the ARPC, we can adjust p_r depending on the state b so that the average number of packets transmitted to channel equals to the optimum value m^*. Since the ARPC implies that the mean of the channel input packets traces the optimal value m^*, while the OCIC implies that the maximum number of input packets is limited to the optimal value m^*, the performance of the OCIC is better than that of the ARPC. In the OCIC policy, we fixed the retransmission probability as $p_r = 1$ in order to retransmit all the users in the B mode as soon as possible.

2. Steady state throughput

In order to analyze the steady state performance, we use the Markov chain model to describe the system state transition probability in the slotted FH/SSMA system. If we let the number of users in the B mode be B_t, B_t will be one of the $N+1$, possible values of the backlog states {0,1,2 ⋯ , ,N}, and is consid-

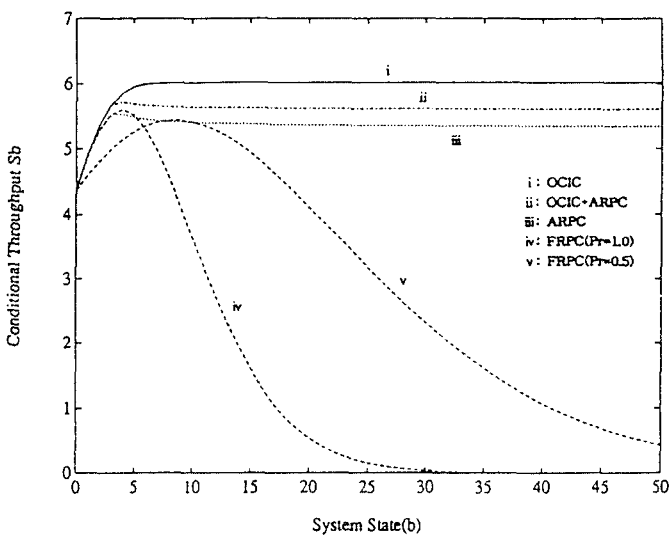

Fig. 4. Conditional throught vs. system state : N=50, p_n=0.1, k=10, r=0.7, q=50.

ered as the state variable of the system. Due to the memoryless assumption, the sequence of states $B(t)$, $B(t+1)$, $B(t+2)$, $\cdots$, can be described as a discrete - time Markov chain on $\{0, 1, \cdots, N\}$. The state transition matrix $P = [p_{ij}]_{(N+1)\times(N+1)}$, where the element $p_{ij} = \Pr[B(t+1) = j \mid B(t) = i]$, denotes the probability that the system moves from the state i to the state j, and i and j are the number of backlogged users in the successive slots t and $t+1$, respectively.

In the OCIC policy, the number of packets j in the B mode at time slot $t+1$ can be obtained to be

$$j = \begin{cases} (i-m_r)+F(m_n+m_r) & , m_n+m_r \le m^* \\ (i-m_r)+(m_n+m_r-m^*)+F(m^*) & , m_n+m_r > m^*, \end{cases} \quad (10)$$

where $F(m)$ is the number of unsuccessful transmissions when m packets are transmitted at time slot t. Thus the number of successful transmissions N_s can easily be obtained as

$$N_s = \begin{cases} m_n+m_r-F(m_n+m_r) & , m_n+m_r \le m^*, \\ m^*-F(m^*) & , m_n+m_r > m^*. \end{cases}$$
$$= i+m_n-j. \quad (11)$$

That is, for both cases ($m_n+m_r \le m^*$, $m_n+m_r > m^*$), the number of successful transmissions is $i+m_n-j$. Thus, the element p_{ij} of the state transition probability matrix P with the OCIC is given by

$$\begin{aligned} p_{ij} = & \sum_{\substack{m_n = max(0, j-i) \\ m_n+m_r \le m^*}}^{N-i} \sum_{m_r=max(0,i-j)}^{i} \binom{N-i}{m_n} p_n^{m_n}(1-p_n)^{N-i-m_n} \\ & \cdot \binom{i}{m_r} p_r^{m_r}(1-p_r)^{i-m_r} \cdot P_{i+m_n-j|m_n+m_r} \\ & + \sum_{\substack{m_n = max(0, j-i) \\ m_n+m_r > m^*}}^{N-i} \sum_{m_r=max(0,i-j)}^{i} \binom{N-i}{m_n} p_n^{m_n} (1-p_n)^{N-i-m_n} \\ & \cdot \binom{i}{m_r} p_r^{m_r}(1-p_r)^{i-m_r} \cdot P_{i+m_n-j|m^*}, \end{aligned} \quad (12)$$

where

$$P_{k|m} = \binom{m}{k} P_s^k(m)(1-P_s(m))^{m-k} \quad (13)$$

is the probability that k packets out of the m packets transmitted in the slot t are successfully transmitted, and it is assumed that the successful transmission is identically and independently distributed for each of the m packets. Hence, the number of successfully transmitted packets is binomially distributed with parameters m and $P_s(m)$.

Then the steady state occupancy probability vector can be represented as Π_B $[\pi_B(0), \pi_B(1), \cdots\pi_B(N)]$. Note that π_B and $\Pi_b(n)$ satisfy

$$\Pi_B = \Pi_B \cdot P \quad (14)$$

and

$$\sum_{b=0}^{N} \pi_B(b) = 1, \quad (15)$$

respectively [8], [12]. When the values of $\pi_B(b)$, are obtained, the steady state throughput S can be computed by

$$S = \sum_{b=0}^{N} S^b \cdot \pi_B(b), \quad (16)$$

where S^b is the conditional throughput given in (7).

3. Mean packet delay analysis

The mean packet delay $E[D]$ represents the average time (slots) required for the successful transmission of a packet, where D denotes the random variable that represents the number of time slots spent until the successful transmission of a packet. The mean packet delay can be rewritten as

$$E[D] = \sum_{k=1}^{\infty} kPr\{D=k\}, \quad (17)$$

Also, let D_B be the random variable that represents the number of time slots spent until the successful transmission of a backlogged packet. Then the expected value of D_B becomes

$$E[D_B]=\sum_{k=1}^{\infty}kPr\{D_B=k\} \tag{18}$$

and from Little's law [13], $E[D_B]$ can be rewritten as

$$E[D_B]=\frac{\bar{b}}{S_B} \tag{19}$$

where S_B is the throughput due to the backlogged packets and $\bar{b}$ is the expected backlog evaluated by

$$\bar{b}=\sum_{b=0}^{N}b\cdot\pi_B(b). \tag{20}$$

Using (19) and that $Pr\{D=k\} = Pr\{D_B=k-1\}$, $E[D]$ can be rewritten as

$$\begin{aligned}E[D] &= \sum_{k=1}^{\infty}Pr\{D=k\}+\sum_{k=1}^{\infty}(k-1)Pr\{D=k\}\\ &= 1+\sum_{k=0}^{\infty}kPr\{D_B=k\}\\ &= 1+\frac{\bar{b}}{S_B}.\end{aligned} \tag{21}$$

Note that S_B can be obtained by $S_B=\sum_{b=0}^{N}S_B^b\cdot\pi_B(b)$, where S_B^b denotes the conditional throughput due to the backlogged packets.

In the OCIC policy, we have two choices of choosing m^* packets among the m_n+m_r packets, when $m_n+m_r>m^*$. One is to choose the packets randomly, and the other is to choose the packets with the priority to the backlogged users. For the two methods, S_B^b is given by

$$\begin{aligned}S_B^b &= E[S_B\mid b]\\ &= \sum_{\substack{m_n=0\\ m_n+m_r\le m^*}}^{N-b}\sum_{m_r=0}^{b}m_rP_s(m_n+m_r)f_{M_n}(m_n\mid b)\, f_{M_r}(m_r\mid b)\\ &+\sum_{\substack{m_n=0\\ m_n+m_r>m^*}}^{N-b}\sum_{m_r=0}^{b}c(m_r)\cdot P_s(m^*)f_{M_n}(m_n\mid b)\, f_{M_r}(m_r\mid b),\end{aligned} \tag{22}$$

where

$$c(m_r)=\begin{cases}m_r, & m_r\le m^*,\\ m^*, & m_r>m^*,\end{cases} \tag{23}$$

when the priority is given to the backlogged users, and

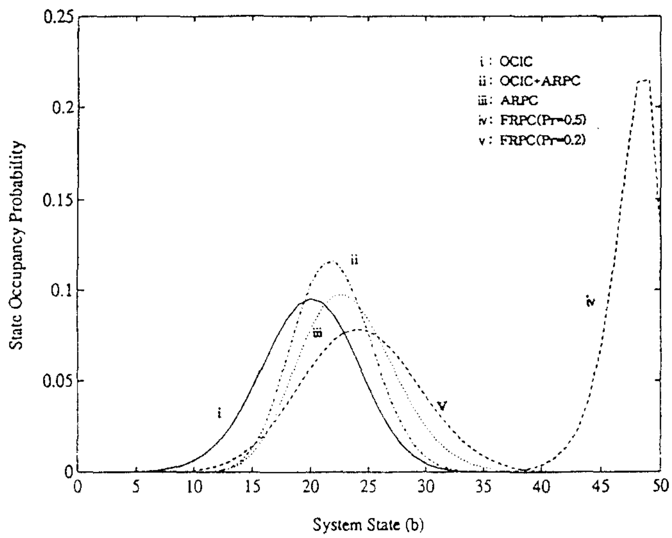

Fig. 5. State occupancy probability vs. system state : N=50, p_n=0.2 k=10, r=0.7, q=50.

$$c(m_r) = m^* \cdot \frac{m_r}{m_n + m_r}, \tag{24}$$

in the case of randomly choosing.

From the above equations (21)-(24), the mean packet delay can be computed.

Now, we compare the performance of various control policies in the steady state. The following parameters are assumed for the performance evaluations : the number of users N = 50, the code rate r = 0.7, and the number of information symbols k = 10.

Fig. 5 illustrates the state occupancy probability $\pi_B(b)$ in several control policies. It is assumed that the new packet generation probability in the T mode is p_n = 0.2 so that the difference can be clearly shown, and the number of frequency slots q = 50. It is also

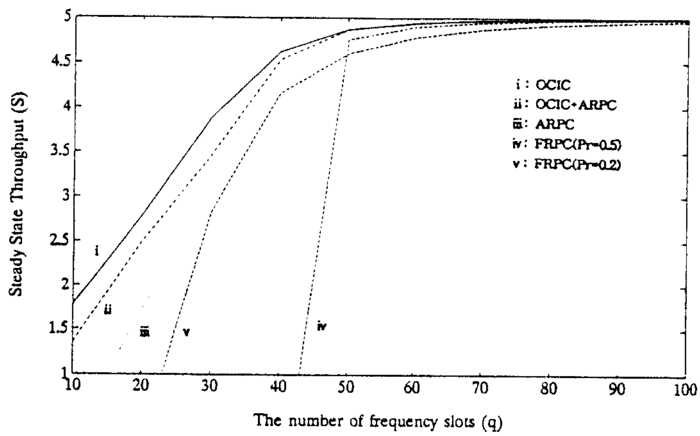

Fig. 6. Steady state throughput vs. frequency slots (q) : N=50, k=10, r=0.7, p_n=0.1.

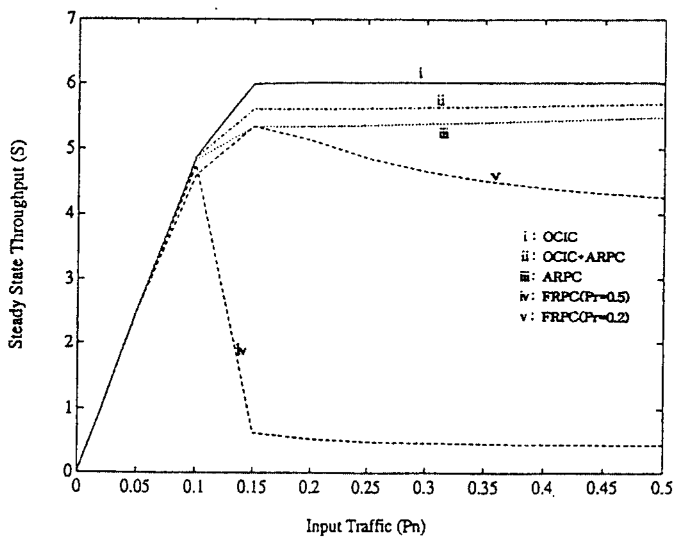

Fig. 7. Steady state throughput vs. input traffic (varying p_n) : N=50, k=10, r=0.7, q=50.

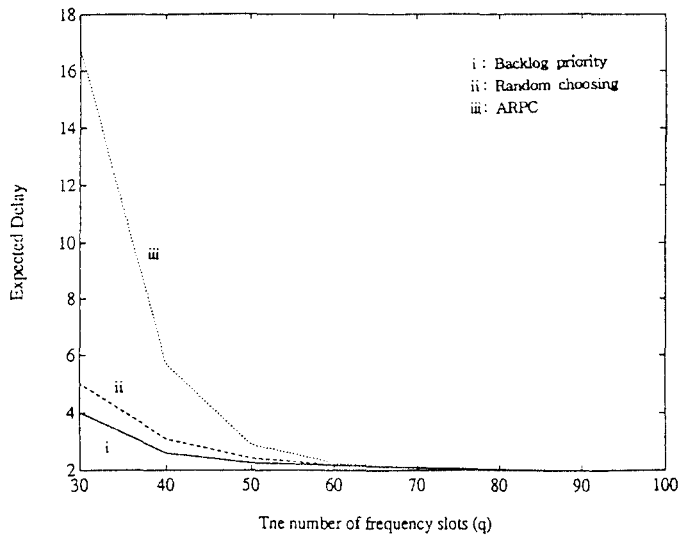

Fig. 8. Steady packet delay vs. frequency slots (q): N=50, k=10, r=0.7, p_n=0.1.

assumed that, for the OCIC scheme, p_r = 1 and m^* = 8. In the FRPC policies, the retransmission probability is assumed to be p_r=0.5 and 0.2. When p_r is more than 0.5, the state occupancy probability mass will be concentrated near state 50. In such a case, the system will become very unstable and an even worse performance is expected; thus, the case p_r>0.5 is excluded in the comparisons. We can see that the OCIC policy allows the system to stay longer at low states than any other policy. Although we do not show explicitly, it turns out that, as the value of q becomes smaller, the state occupancy probability for all of the policies is more widely spread.

Fig. 6 shows the steady state throughput for a number of frequency slots with several control policies. It can be noticed that the smaller is the number q, the larger is the difference of performances among several polices and the superiority of the OCIC becomes clearer. In short, the OCIC policy results in the best throughput. Fig. 7 shows the steady state throughput as a function of the input traffic (new packet generation probability p_n). This figure also shows that the OCIC policy has better throughput than the others.

Fig. 8 shows the mean packet delay for various number of frequency slots. The OCIC results in smaller mean packet delay than the ARPC. In addition, when the priority is given to the backlogged users, the mean packet delay decreases when compared with the random selection case.

Ⅳ. Conclusion

A new traffic control policy, called the OCIC, was proposed. In the OCIC, the number of channel input packets was set to the optimal number of channel input packets maximizing the channel throughput. Evaluation of the conditional throughput for the proposed policy has been done and comparison with other control policies was presented. It has been shown that the steady state performance could be obtained using the Markov chain and that the proposed OCIC policy achieved higher throughput than other policies. The mean packet delay has also been obtained. It was shown that the mean packet delay for the OCIC decreases considerably when the priority of transmission was given to the backlogged users. The smaller is the number of frequency slots, the better is the performance of the OCIC policy compared with other policies.

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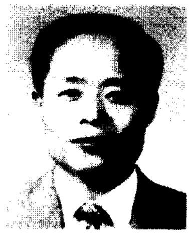

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