이기종망간의 핸드오프에 대한 TCP 적응성능 분석연구

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Adaptation Latency and Throughput of TCP Congestion Control Schemes on Vertical Handoff

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요약

이기종망간의 핸드오프 시, TCP는 새로운 망 환경에서 최적의 전송 CWND 값을 갖기까지 비효율적인 전송을 하게 된다. 본 논문에서는 이러한 전송상태에서의 SACK TCP와 BIC TCP의 성능과 이에 영향을 미치는 요소들을 분석하였다. 수치적 분석과 시뮬레이션 분석을 통하여, BIC TCP가 SACK TCP보다 훨씬 좋은 성능을 보여 주었으며, RTT와 전송대역의 변화에 대해서도 좋은 성능을 보여 주었음을 알 수 있었다.

Key Words : vertical handoff, TCP, performance evaluation

ABSTRACT

Where a wireless LAN and a cellular network coexist, a mobile node has to experience vertical handoffs to move between them. Immediately after the vertical handoffs, TCP must need adaptation latency to adjust its congestion window to the proper size at a newly arrived network to use full of a new end-to-end available bandwidth. Even though SACK TCP has the best performance among other regular TCPs in the previous studies, it still cannot use full of the new available bandwidth quickly due to its inefficient increasing way of congestion window. BIC TCP, that becomes a popular TCP in long fat networks, has great feature working well against vertical handoffs by increasing congestion window exponentially with TCP connection sustained. In this paper, we derive adaptation latency of SACK TCP and BIC TCP numerically, and verify them by simulations. We also find that the shorter adaptation latency of BIC TCP produces higher throughput than SACK TCP on vertical handoffs. Consequently, to get higher performance on vertical handoff situations, we propose to use BIC TCP.

Ⅰ. Introduction

When a mobile node moves over heterogeneous wireless networks, it meets a new type of handoff, and we call it a vertical handoff. Especially, we call it a downward vertical handoff when a mobile node moves from a cellular network, a low quality network, to a wireless LAN, a high quality network, and an upward vertical handoff, vice versa. In the vertical handoff situation, the network conditions that can affect TCP performance are dramatic changes of bandwidth, latency, and buffer size[1],[2],[3]. At the vertical handoff situations, the following three types of latencies

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have to be considered as done for a regular handoff[4].

- Detection Period : The time taken by a mobile node to discover that it is under the coverage of a new wireless access network to the instant it receives a router advertisement from the new access router.
- Address Configuration Interval : The interval from the time a mobile node receives a router advertisement, to the time it takes to update its routing table, and assign its interface with a new care-of address.
- Network Registration Time : The time taken to send a binding update to the home agent as well as the correspondent node, to the time it takes to receive the first packet from the correspondent node.

In addition of the three regular handoff latencies done at IP layer or below, we need to consider the latency of TCP to find a new proper CWND(Congestion Window) in a newly arrived network for a downward vertical handoff. For an upward vertical handoff, most of TCP should go into slow-start phase because retransmission timeout must expire due to the suddenly prolonged link latency. We focus on the downward vertical handoff situations in this paper because it heavily depends on the feature of the different behaviors of TCP congestion control. We define this additional latency as T_{cwnd}.

TCP Adaptation Latency, T_{cwnd} *: The time to need to find a new and proper CWND in a newly arrived network.*

$$T_{cwnd} = T_1 - T_2$$

T1 is the time when TCP gets to the proper CWND, so TCP can use full of the end-to-end available bandwidth as it can. T2 is the time when a downward vertical handoff occurs.

SACK TCP shows better performance than Tahoe TCP or Reno TCP to a vertical handoff due to its great feature against multiple packet losses that can be produced by lots of packet reordering[5]. But SACK TCP still has a long T_{cwnd} after it moves into a wireless LAN from a cellular network because the bandwidth gap between them is large but SACK TCP can increase just one CWND for one RTT due to the behavior of its congestion avoidance mode.

Among TCPs proposed to improve the performance against linearly increasing property, BIC TCP has great behavior to vertical handoffs since it can increase CWND with exponential in the middle of a TCP connection. If CWND grows past the last CWND that caused a segment loss before, a new and proper CWND must be larger than the last one. Then, BIC TCP enters a new phase called max probing, and the growth function is exponential[6]. The aggressive way to find the proper CWND in the max probing mode can reduce T_{cwnd} in vertical handoff situations. That is why we select BIC TCP to compare it with SACK TCP against a vertical handoff. Even though BIC TCP has an aggressive behavior to find a new proper CWND, it is friendly with the other TCPs in normal behavior since it responses quickly to network congestions[6].

The behaviors of SACK TCP and BIC TCP to upward vertical handoffs are exactly the same. They all enter slow-start mode due to the expiration of RTO (Retransmission Timeout) because suddenly changed latency definitely makes RTO to be expired. So the comparisons to upward vertical handoffs are not considered in this paper.

When a mobile node enters into a wireless LAN, we need to consider the effects of RTT and available bandwidth on both T_{cwnd} and throughput because RTT and available bandwidth are not consistent whenever a mobile node moves into a wireless LAN. The details are specified as follows.

- RTT : It depends on the distance between AP(Access Point) and a mobile node and how many other nodes are trying to send data. A wireless LAN has a shared link using CSMA/CA(Carrier Sense Multiple Access /Collision Avoidance) channel access method, so the contentions by mobile nodes produce latency due to the backoff mechanism of CSMA/CA[7].

- The available bandwidth : It depends on the version of 802.11, the antennas on each device, the distance between AP and a mobile node and how many other nodes are requesting bandwidth[7],[8].

In this paper, we will analyze T_{cwnd} and throughput of SACK TCP and BIC TCP, and the effects of RTT and available bandwidth on them.

Ⅱ. TCP Adaptation Latency : Tcwnd

In this section, we derive T_{cwnd} of SACK TCP and BIC TCP numerically, and verify the results by simulations. The handoff is a downward and soft handoff.

2.1 Tcwnd of SACK TCP

After a downward vertical handoff, SACK TCP needs to increase one CWND for one RTT. T_{cwnd} is required to increase CWND linearly to the proper one in a newly arrived wireless LAN. From this property, we can derive T_{cwnd} as follows.

$$T_{cwnd} = \sum_{j=1}^{Q} \left(RTT + \frac{S}{R}\right)$$

S is segment size, and R is transmission rate, so $\frac{S}{R}$ is the time to send a segment. RTT + $\frac{S}{R}$ is the elapsed time between the instant of sending segments and the instant of sending the next segments. T_{cwnd} can be derived by multiplying RTT + $\frac{S}{R}$ by Q that is the number of stops the sender has to wait for ACKs. After Q, the end-to-end link is used optimally, and SACK TCP is said to be adapted.

W is the half of the last highest CWND of SACK TCP. The reason to use the half is that 3 duplicate packets must come immediately after the downward vertical handoff due to the packet reordering problem issued in [5] and [9]. 2-W is a small constant since W is the CWND used in cellular network that is relative small due to the less bandwidth than that of wireless LAN. So, we ignore it to simplify the equations.

$$\begin{aligned} Q &= \max\left(j \mid RTT + \frac{S}{R} - (W + j - 1) \times \frac{S}{R} \geq 0\right) \\ &= 2 - W + RTT \times \frac{R}{S} \\ &\approx RTT \times \frac{R}{S} \end{aligned}$$

Therefore,

$$\begin{aligned} Tcwnd &= \left(RTT + \frac{S}{R}\right)\left(RTT \times \frac{R}{S}\right) \\ &= RTT^2 \times \frac{R}{S} + RTT \qquad (1) \end{aligned}$$

2.2 Tcwnd of BIC TCP

After a downward vertical handoff, BIC TCP needs to increase CWND by binary searching and exponential way. T_{cwnd} is required to increase CWND to the proper one. T_{cwnd} is separated by two periods of T_{phase1} and T_{phase2}.

$$T_{cwnd} = T_{phase1} + T_{phase2}$$

T_{phase1} is the time to increase CWND to the last highest one immediately after the downward vertical handoff. Binary searching way is used in this period.

$$T_{phase1} = \sum_{j=1}^{P} \left(RTT + \frac{S}{R}\right)$$

P is the number of stops that the sender has to wait for ACKs in T_{phase1}, and it can be derived as follows. Let f_k be the function of CWND, where k is the subscript to represent the order of stops during T_{phase1}. f_k is a similar function of binary search due to the feature of BIC TCP. It takes the middle value between current CWND and the last highest CWND repeatedly. C is the last highest CWND, and f_1 should be 0.875 times C because BIC TCP shrinks its CWND to 0.875 times of the last status. $S_{\min}$ is a small constant for finishing the binary search used to find a new proper CWND, then,

$$
\begin{aligned}
P &= \min(j \mid f_j \geq C - S_{\min}) \\
&= \min(j \mid \frac{C}{2} + \frac{C}{2^2} + \ldots + \frac{C}{2^j} + \frac{f_1}{2^j} \geq C - S_{\min}) \\
&= \min(j \mid j \geq \log(\frac{0.125 \times C}{S_{\min}})) \\
&= \log(\frac{0.125 \times C}{S_{\min}})
\end{aligned}
$$

f_k increases like binary search, so

$$
\begin{aligned}
f_1 &= 0.875 \times C \\
f_j &= f_{j-1} + \frac{C - f_{j-1}}{2}
\end{aligned}
$$

until

$$C - f_{j-1} > S_{\min}$$

where $S_{\min}$ is set in BIC TCP as a constant.

Therefore,

$$T_{phase1} = (RTT + \frac{S}{R})\log(\frac{0.125 \times C}{S_{\min}})$$

T_{phase2} is the time to increase CWND exponentially to find a proper CWND after T_{phase1}.

$$T_{phase2} = \sum_{j=1}^{Q}(RTT + \frac{S}{R})$$

Q is the number of stops that the sender has to wait for ACKs in T_{phase2}, and BIC TCP increases its CWND exponentially to the next threshold in this period. The threshold is updated by adding $C + C \times \frac{1}{l-1}$ to the last threshold, where C is the last threshold and l is an integer scale.

To make the derivation simple, we assume BIC TCP sets the next threshold by linearly increasing way rather than by exponentially increasing way, and then the gradient is $\frac{C}{\log C}$. This means that BIC TCP updates the next threshold by adding just C to the threshold rather than by adding $C + C \times \frac{1}{l-1}$. This makes sense in overall performance because BIC TCP does not have many chances to update the threshold in the bandwidth of a wireless LAN, and $C \times \frac{1}{l-1}$, that is added to the last threshold, is not a large value. For example in Fig. 1 case, BIC TCP has 2 chances to update the threshold, and l is 4 that is a default value primarily set in the distributed simulation code of BIC TCP. With this assumption, Q can be derived as follows.

$$
\begin{aligned}
Q &= \max(j \mid RTT + \frac{S}{R} - j \times \frac{C}{\log C} \times \frac{S}{R} \geq 0) \\
&= (\frac{\log C}{C} \times \frac{R}{S})(RTT + \frac{S}{R})
\end{aligned}
$$

So,

$$T_{phase2} = (\frac{\log C}{C} \times \frac{R}{S})(RTT + \frac{S}{R})^2$$

Therefore,

$$
\begin{aligned}
T_{cwnd} &= (RTT + \frac{S}{R})\log(\frac{0.125 \times C}{S}) \\
&\quad + (\frac{\log C}{C} \times \frac{R}{S})(RTT + \frac{S}{R})^2 \\
&= K_2 \times \frac{R}{S} \times RTT^2 + (K_1 + 2K_2) \times RTT \\
&\quad + (K_1 + K_2) \times \frac{S}{R} \qquad (2)
\end{aligned}
$$

where

$$K_1 = \log(\frac{0.125 \times C}{S}) \text{ and } K_2 = \frac{\log C}{C}$$

2.3 Simulations and Discussions

In simulations, we have two nodes where one node sends segments with FTP over a TCP connection, and the other node receives or discards the segments depending on the buffer status. To simulate the vertical handoff scenario that one node moves from a cellular network to a wireless LAN in the middle of transferring a file by FTP, we change the bandwidth and the latency between two nodes suddenly.

We assume the bandwidths between the two nodes are 150Kbps for the cellular network and 10Mbps for the wireless LAN. We also assume that the segment size is 536 bytes and object to transfer is infinitely large. The cellular network has 600ms RTT, and the wireless LAN has 120ms RTT. The handoff is a downward and soft handoff. A downward vertical handoff is issued on 100 second, and SACK TCP and BIC TCP have to adjust each CWND to a newly arrived wireless LAN immediately after 100 second. SACK TCP increases CWND linearly, while BIC TCP increases it exponentially.

As shown in Fig. 1, BIC TCP has its CWND to the proper peak on 106.8 second, where it can use full of the end-to-end available bandwidth, so T_{cwnd} is 6.8 seconds. SACK TCP, however, has its CWND to the proper peak on 135.0 second, so T_{cwnd} is 35.0 seconds. This results tell us that BIC TCP has less T_{cwnd}, so it has great advantage to be used over vertical handoff situations. Detail analysis about T_{cwnd} are discussed in next two sub-sections.

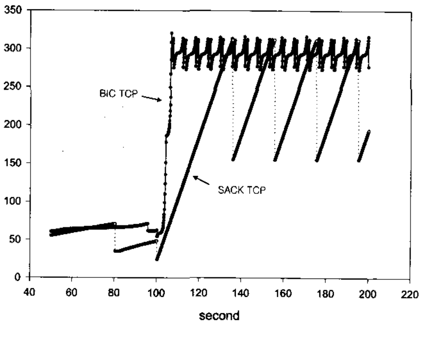

Fig. 1. CWND of SACK TCP and BIC TCP

2.4 The Effect of RTT

From equation (1) and equation (2), we can expect that T_{cwnd} of SACK TCP and BIC TCP increases by the square function of RTT. The coefficient of the square of RTT of SACK TCP is R/S while that of BIC TCP is $\frac{\log C}{C}\times\frac{R}{S}$. $\frac{\log C}{C}$ is very small, so T_{cwnd} of BIC TCP is expected to be much less than that of SACK TCP.

To verify it, we have simulations with 8 different RTT cases of 40ms, 80ms, 120ms, 160ms, 200ms, 300ms, 400ms, and 500ms. The conditions of the simulations are exactly same with those used in Fig.1. As shown in the upper figure of Fig. 2, as RTT increases, T_{cwnd} of SACK TCP increases very rapid while T_{cwnd} of BIC TCP increases very slow. The difference between T_{cwnd} of SACK TCP and BIC TCP gets larger as RTT increases, and this is expected by the fact that BIC TCP has less coefficient of the square of RTT than SACK TCP. With less T_{cwnd}, BIC TCP will have better performance

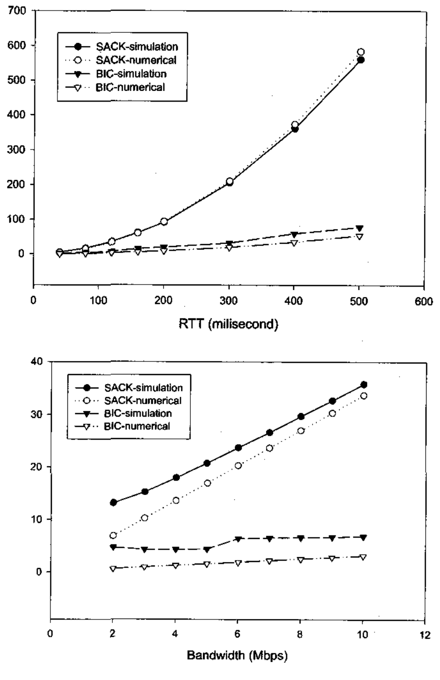

Fig. 2. Effect of RTT(upper) and Available Bandwidth(lower) on Tcwnd

than SACK TCP for RTT changes, the throughput gained by BIC TCP will be shown in the section 3.

2.5 The Effect of Available Bandwidth

From equation (1) and equation (2), the coefficient of bandwidth, R, of BIC TCP is $\frac{\log C}{C}\times\frac{RTT^2}{S}$ and that of SACK TCP is $\frac{RTT^2}{S}$. $\frac{\log C}{C}$ is very small, so T_{cwnd} of BIC TCP is expected to be much less than that of SACK TCP.

To verify it, we have simulations with 8 different available bandwidth cases. The conditions of the simulations are exactly same with those used in Fig.1. As shown in the lower figure of Fig. 2, T_{cwnd} of SACK TCP and BIC TCP increases linearly, but BIC TCP has less gradient, so T_{cwnd} of BIC TCP gets less than SACK TCP as the available bandwidth increases.

The simulation result of BIC TCP has a jump in the curve. In the curve at 6Mbps, the first 4 lower bandwidth cases have one threshold, but the next 5 higher bandwidth cases have two thresholds. So, immediately after updating the second threshold, BIC TCP has to begin slow-starting again from initial status, and this produces the jump. With less T_{cwnd}, BIC TCP will have better performance than SACK TCP for available bandwidth changes, the throughput gained by BIC TCP will be shown in the section 3.

Ⅲ. Tcwnd and Throughput

In this section, we compare the throughput of SACK TCP and BIC TCP and analyze the effect of T_{cwnd} on the throughput. The conditions of the simulation unspecified in this section are the same with those used in Fig. 1.

In the simulations to generate the results of Table 1, the handoff occurs at 100 second, and the simulation runs during 100 seconds after a vertical handoff. T_{cwnd} of BIC TCP is 6.8 second and T_{cwnd} of SACK TCP is 35 second.

Table 1. Throughput of SACK TCP and BIC TCP: Gain means throughput gain earned more by BIC TCP than SACK TCP.

	100-106.8 sec	106.8-135 sec	135-200 sec
SACK TCP (Mbps)	1.76	6.68	7.89
BIC TCP (Mbps)	4.34	9.30	9.30
Gain (Mbps)	2.58	2.62	1.41

After 135 second, the difference between BIC TCP and SACK TCP just depends on their own and normal feature of their congestion control, and that is not our consideration in this paper. In addition of 1.41 Mbps more earned by BIC TCP than SACK TCP after 135 second, BIC TCP has performance gain by 1.17 Mbps (2.58-1.41) after a downward vertical handoff until T_{cwnd} of BIC TCP, and 1.21 Mbps (2.62-1.41) after then until T_{cwnd} of SACK TCP. These performance gains are achieved from the great feature of BIC TCP to vertical handoff.

This result tells us that CWND of BIC TCP gets to the peak earlier than SACK TCP, and this gives BIC TCP big performance gains. The throughput TCP can earn over the vertical handoff situations can be derived as follows.

$$Throughput = \frac{f_{cwnd} + f_{\max}}{T} \qquad (3)$$

f_{cwnd} and $f_{\max}$ are CWND during T_{cwnd} and $T - T_{cwnd}$, respectively. f_{cwnd} is CWND after a downward vertical handoff, and $f_{\max}$ is the average CWND on staying at peak. f_{cwnd} of SACK TCP increases linearly, and f_{cwnd} of BIC TCP increases exponentially. T is the total duration. Therefore, to have higher Throughput, we must reduce T_{cwnd} because $f_{\max}$ is always larger than f_{cwnd}.

We verify the effect of T_{cwnd} by RTT and available bandwidth on the throughput by simulations. Additionally, we also verify the effect of duration stayed at a wireless LAN. That is, the throughput of a fast moving mobile node that stays very short in a wireless LAN is expected to have a negative impact from relatively long T_{cwnd}. Detains are discussed in next sub-sections.

1. The Effects of RTT and Available Bandwidth

In the upper figure of Fig. 3, as RTT increases, the throughput of SACK TCP decreases more rapid than BIC TCP. Especially, BIC TCP with a vertical handoff can achieve closer throughput of BIC without the vertical handoff than SACK TCP. In the lower figure of Fig. 3, as available bandwidth gets larger, BIC TCP can achieve better throughput than SACK TCP. Especially, BIC TCP with a vertical handoff can achieve closer throughput of BIC TCP without the vertical handoff than SACK TCP.

The fact, that BIC TCP with a vertical handoff can produce closer throughput of BIC TCP without the vertical handoff than SACK TCP, means that BIC TCP can sustain performance better against vertical handoffs than SACK TCP. And this great property of BIC TCP comes from less T_{cwnd} than SACK TCP. When a mobile node enters into a wireless LAN, where the degree of contentions gets higher, or the distance of a mobile node from AP gets farther, or the achievable available bandwidth is higher, BIC TCP can achieve better performance than SACK TCP.

3.1 The Effect of Fast Moves

In addition of the two parameters, RTT and available bandwidth, that can affect TCP performance, a mobile node will have seriously negative effect on performance when it stays very short in a wireless LAN in case that it moves fast or frequently over a cellular network and a wireless LAN. From equation (3), the fast or frequent moves will cause $f_{\max}$ to be small because it will cause $T-T_{cwnd}$ short. So reducing T_{cwnd} in this scenario is also very important to performance.

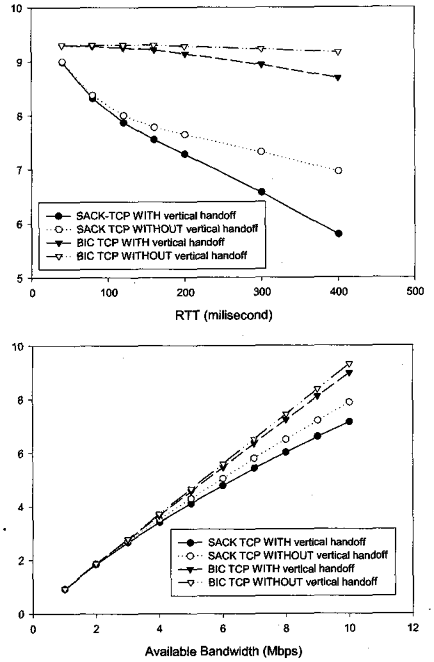

Fig. 3. Effect of RTT(upper) and Available Bandwidth(lower) on Throughput

Table 2. Performance Gain By BIC TCP : Throughput(Mbps)(% means the rate of the case with handoff to the case without handoff.)

Second	240	180	150	120	90	60
SACK with handoff	7.64	7.52	7.45	7.28	7.06	6.55
SACK without handoff	7.96	7.95	7.96	7.90	7.89	7.67
%	95.9	94.6	93.5	92.0	89.4	85.4
BIC with handoff	9.16	9.11	9.08	9.02	8.93	8.74
BIC without handoff	9.30	9.30	9.30	9.30	9.30	9.30
%	98.4	97.9	97.5	96.9	95.9	93.9

We have 6 cases of total durations as shown in Table 2, and less duration means faster move. The conditions of simulations are the same with done in Fig. 1. SACK TCP with a vertical handoff achieves 95.9% of the throughput of SACK TCP without the vertical handoff for 240 second duration, and 85.4% for 60 second duration. On the other hand, BIC TCP achieves 98.4% for 240 second, and 93.9% for 60 second. In this scenario, where a mobile node moves fast or frequently, BIC TCP can achieve much better performance than SACK TCP. And this can be explained by the fact that BIC TCP has much less T_{cwnd} than SACK TCP, and this can make $T-T_{cwnd}$ longer, so BIC TCP can sends many segments as $f_{\max}$ for longer duration.

Ⅳ. Conclusions

We compared the performance of SACK TCP and BIC TCP to a downward vertical handoff. BIC TCP can open its CWND more quick than SACK TCP can, so it can adapt itself to a newly arrived wireless LAN with less T_{cwnd}. This behavior for T_{cwnd} gives BIC TCP great performance to the vertical handoff.

With numerical analysis, we derived Tcwnd of SACK TCP and BIC TCP. BIC TCP had less T_{cwnd} than SACK TCP due to less coefficient. T_{cwnd} of BIC TCP got less as RTT or available bandwidth increased, and less T_{cwnd} gave higher throughput to BIC TCP than SACK TCP. The numerical results were verified by simulations. From both numerical analysis and simulations, we concluded to propose to use BIC TCP rather than SACK TCP in the vertical handoff situations. Especially, it had much bigger performance gain than SACK TCP when RTT gets longer, available bandwidth gets higher, and a mobile node moves more frequent or faster so it stays shorter in a wireless LAN.

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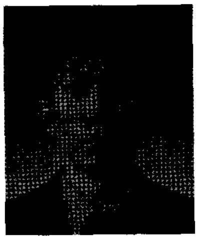

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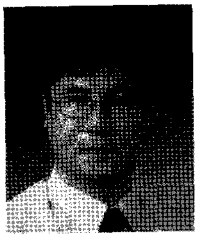

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