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시변 채널에서 Bit-Interleaved Coded OFDM을 위한 적응 변조 기법

(Adaptive Bit-Interleaved Coded OFDM over Time-Varying Channels)

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요 약

송신단에서 채널 상태 정보를 알고 있는 폐루프 시스템은 개방 루프 시스템에 비하여 더 효율적인 전송을 수행할 수 있다. 그러나 실제 시스템은 제한된 피드백 채널을 가지므로 송신단에서 완벽한 채널 정보를 알 수 없으며, 따라서 부분 채널 정보를 활용하는 시스템의 설계가 중요한 요소로 부각되고 있다.

특히, 모바일 환경에서는 사용자의 이동성으로 인하여 채널 상태가 유동적으로 변화하며 이는 성능의 열화를 초래한다. 본 논문에서는 비트 인터리버와 결합한 부호화된 직교 주파수 다중 분할 (BIC-OFDM; Bit-Interleaved Coded Orthogonal Frequency Division Multiplexing) 시스템을 위하여 채널 변화에 적절히 대응하는 적응 변조 코딩 기법을 제안한다. 합리적인 피드백 정보량을 통해, 제안하는 기법은 도플러 확산에 의한 채널 변화를 보상하여 향상된 성능을 제공한다. 실험 결과를 통해 제안하는 기법이 정확한 비트 에러율의 추정을 통한 성능 이득을 가짐을 확인한다.

Abstract

When adapting the transmitter to the channel state information (CSI), improved transmission is possible compared to the open loop system where no CSI is provided at the transmitter. However, since the perfect channel information is rarely available at the transmitter, the system design based on the partial CSI becomes an important factor.

Especially, in mobile environments, the consideration for the outdated CSI should be applied for mitigating the performance degradation. In this paper, we propose a robust adaptive modulation and coding scheme for bit-interleaved coded orthogonal frequency division multiplexing over time-varying channels. With reasonable feedback overhead, the proposed scheme shows the enhanced performance by compensating for the outdated CSI due to Doppler spread. Simulation results confirm that the performance gain is achieved by applying an accurate BER estimation method.

Keywords : adaptive modulation and coding (AMC), bit-interleaved coded modulation (BICM), orthogonal frequency division multiplexing (OFDM)

I. Introduction

For high speed wireless packet communication systems, we need to combat interference caused by frequency selective fading channels. Orthogonal frequency division multiplexing (OFDM) is an effective means which mitigates the inter-symbol interference (ISI) without applying equalizer. By combining with bit-interleaved coded modulation (BICM), the bit-interleaved coded OFDM (BIC-OFDM) is a good candidate for reliable wideband transmission, which has been applied to a wide range of wireless standards such as the IEEE 802.11a wireless local area network (WLAN)[1].

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When channel state information (CSI) is available at the transmitter, adaptive modulation and coding (AMC) is a powerful technique to enhance the overall link performance[2]. The adaptive transmission adjusts the transmission power level, channel coding rate and/or constellation size according to the current CSI with the specified performance constraint. Thus, the AMC can enhance the average throughput by transmitting at high data rates under favorable channel conditions, and reducing the transmission rate as the channel state degrades[3]. An adaptive BIC-OFDM system with full feedback information (FI) has been proposed in [3] by employing bit loading and power adaptations based on the water-filling algorithm, and is referred to as the water-filling AMC (WF-AMC) scheme. However, in practice, this requires intensive traffic overheads for control channels to report the CSI for all subcarriers. In contrast, an AMC scheme for the BIC-OFDM system with reduced FI has been introduced in [4], which can significantly reduce the amount of feedback payloads by employing a rate adaptation based on an individual OFDM symbol rather than each subchannel, and is called the block AMC (BL-AMC) scheme.

To employ such AMC schemes, accurate channel information is required at the transmitter. In time varying channels, however, the reported CSI may be outdated due to feedback delays, which causes performance degradation of the AMC scheme. This mismatch in CSI for the transmitter and the receiver is a crucial impairment in time-varying channels. In this paper, we propose a robust AMC scheme on time varying channels based on the BL-AMC scheme in [4]. The proposed scheme compensates for the outdated CSI by considering the channel estimation error. Simulation results show that the proposed scheme exhibits a robust performance on various time-varying channels.

The paper is organized as follows: In section II, the system structure for an adaptive BIC-OFDM is introduced. A brief review of the adaptive BIC-OFDM is presented in III. In section IV, we propose a compensation algorithm to enhance the performance of the system over time-varying channels. Finally, the simulation results and conclusion are presented in sections V and VI, respectively.

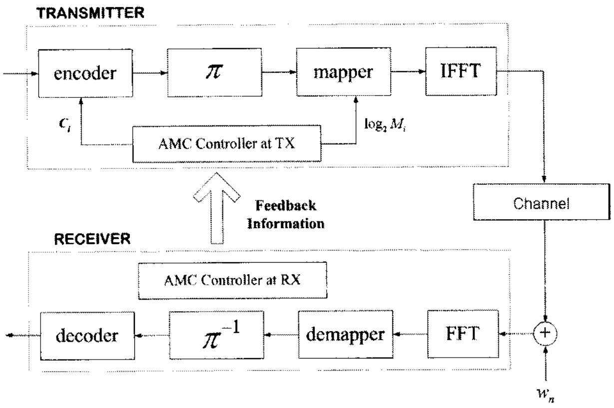

그림 1. 적응 BIC-OFDM의 시스템 구조도
Fig. 1. System structure for the adaptive BIC-OFDM.

II. System Model

When applying an AMC scheme, the estimated CSI at the receiver should be delivered to the transmitter through a feedback channel. Generally, the reliable feedback channel is established by employing lower rate channel codings and modulation levels. Therefore, error-free feedback channels are assumed for simplicity.

Consider a BIC-OFDM system with N subcarriers. As shown in Fig. 1, information bit streams are encoded using convolutional codes and are mapped into a symbol s_n in constellations after bit-level interleaving[5] where n indicates the subcarrier index. Then, symbols are serial-to-parallel converted and modulated by an inverse fast Fourier transform (IFFT) operation.

In contrast to the WF-AMC scheme which requires full FI, the BL-AMC scheme only needs to feed back the modulation and coding scheme (MCS) level index for the selected code rate and constellation size. Each MCS level i $(i=1,\cdots i_{\max})$ consists of a convolutional encoder $C_i \in \{C_1,\cdots,C_V\}$ and a M_i

-QAM constellation with $\log_2 M_i \in \{1,\cdots m_{\max}\}$. Assuming that m_n bits are loaded at the nth subcarrier, the spectral efficiency supported by the selected MCS level i can be obtained as

$$R_T = \frac{R_c(C_i)}{N}\sum_{n=1}^{N} m_n \ (bps/Hz) \tag{1}$$

After the FFT demodulation, the received signal at the nth subcarrier can be represented as

$$y_n = H_n s_n + w_n \tag{2}$$

where H_n represents the channel frequency response at the nth subcarrier and w_n denotes complex additive Gaussian noise with zero mean and variance σ_n^2 per complex dimension. In time domain, the frequency selective channel can be expressed as $h(t,\tau) = \sum_{l=1}^{L} h(l;t)\delta(\tau-\tau_l)$ where the channel coefficients $h(l;t)$ are complex Gaussian with zero mean (Rayleigh fading), $\delta(\bullet)$ represents the Dirac delta function, τ_l means the propagation delay, and the L denotes the number of channel taps. Omitting the time index t in $h(l;t)$, for simplicity, the channel frequency response at the nth subcarrier is given as

$$H_n = \sum_{l=1}^{L} h(l) e^{-j2\pi n \tau_l / NT}$$

where T denotes the sampling period.

III. Adaptive BIC-OFDM in Quasi-static Channels

In this section, we briefly review the rate adaptation algorithm which employs a simple BER estimation method in [4] in quasi-static channels. The basic concept of the adaptation scheme is that the user equipment (UE) computes the maximum achievable spectral efficiency satisfying the BER constraint and then sends back only the selected MCS level index to the transmitter.

The AMC strategy can be reformulated as finding the MCS level index i which maximizes the spectral efficiency by assigning the same constellation for all subcarriers in (1). Defining the channel vector $\boldsymbol{H}$ as $\{H_1,\cdots,H_N\}$, the AMC scheme should satisfy the BER constraint as

$$\frac{1}{p_i}\sum_{d=d_H(C_i)}^{d_H(C_i)+5} N_i(d) P(d,\boldsymbol{H}) \le P_e \tag{3}$$

where p_i represents the puncturing period for a rate-compatible punctured convolutional (RCPC) code[6], $d_H(C_i)$ indicates the minimum Hamming distance of the code C_i, $N_i(d)$ denotes the total input weight of the error events at Hamming distance d $P(d,\boldsymbol{H})$ specifies the average codeword pairwise error probability between codewords with Hamming distance d, and P_e is the target BER, respectively.

Assuming Gray mapping, $P(d,\boldsymbol{H})$ can be evaluated as

$$P(d,\boldsymbol{H}) \le B_M(\boldsymbol{H}) \equiv \left(\frac{1}{N}\sum_{n=1}^{N} B_M(\boldsymbol{H})\right)^d$$

where $B_M(\boldsymbol{H})$ can be obtained as $Q_{1,n}+Q_{2,n}$, $\frac{3}{8}(2Q_{1,n}+3Q_{2,n})$, and $\frac{1}{48}(28Q_{1,n}+49Q_{2,n})$ for QPSK, 16QAM, and 64QAM, respectively[4]. Here, $Q_{1,n}$ and $Q_{2,n}$ are computed by

$$\begin{aligned} Q_{1,n} &= Q\left(\sqrt{\frac{|H_n|^2 6\sigma_s^2}{4\sigma_s^2(M_i-1)}}\right) \\ Q_{2,n} &= Q\left(\sqrt{\frac{|H_n|^2 12\sigma_s^2}{4\sigma_s^2(M_i-1)}}\right) \end{aligned} \tag{4}$$

where $Q(x)$ is defined as $\frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-z^2/2}dz$ and σ_s^2 represents the average symbol energy.

By employing the Gaussian approximation in [7] which provides a tighter bound, the constraint in (3) can be rewritten as

$$\frac{1}{p_i}\sum_{d=d_H(C_i)}^{d_H(C_i)+5} N_i(d) Q\left(\sqrt{-2\log B_M(\boldsymbol{H})}\right) \le P_e$$

Ⅳ. A Robust AMC Scheme over Time-varying Channels

When AMC schemes are employed over time-varying channels, the channel state may not be static during the period of the CSI feedback and the downlink data transmission. This means that the CSI at the time of data transmission is different from the one at the time of channel estimation. Even a wireless system using fixed modulation and coding experiences variations in fadings due to the movement of objects in the environment. This variation in the CSI yields the outdated information at the transmitter when deciding the AMC choice. Such outdated CSI causes a crucial impairment because the AMC algorithm requires the accurate channel information. There, if the variations in the CSI are not taken into account in the AMC design, the performance of the closed-loop algorithm will degrade, and eventually may get worse than that open-loop transmission systems. In this section, we propose a robust AMC scheme in the mobile environment.

1. Channel model

When considering the effect of the outdated CSI, we adopt the mean feedback channel model[8] on each OFDM subcarrier. The transmitter obtains an estimated channel $\boldsymbol{H} = [H_1, H_2, \cdots, H_N]$ through a feedback channel and the reported channel can be modeled by adding a perturbation term to account for the channel variation during the channel feedback. Thus, the frequency channel $\overline{\boldsymbol{H}} = [\overline{H_1}, \overline{H_2}, \cdots, \overline{H_N}]$ at the transmitter at the time of the transmission can be expressed as

$$\overline{\boldsymbol{H}} = \boldsymbol{H} + \Xi$$

where $\Xi = [\Xi_1, \Xi_2, \cdots, \Xi_N]$ is a random vector which represents the uncertainty term of the CSI. Here we assume that the perfect CSI is obtained at the receiver for simplicity.

The frequency channel $\boldsymbol{H}$ can be converted to the time domain channel $\boldsymbol{h}$ by the IFFT operation. Assuming that the finite impulse responses (FIR) coefficients of channel taps are perfectly known to the receiver and are fed back to the transmitter with a certain delay through an error-free feedback channels, the minimum mean-square error (MMSE) prediction $\boldsymbol{h}$ of the current CSI can be expressed as $\boldsymbol{h} = \rho \boldsymbol{h}_M$ where $\boldsymbol{h}_M$ denotes the channel response estimated at the receiver, and ρ represents the time correlation expressed as $\rho = J_0(2\pi f_d \tau_d)$, where $J_0(\bullet)$ means a zero-order Bessel function of the first kind[9]. Here τ_d denotes the feedback time delay and f_d indicates the Doppler frequency $f_d = \frac{v}{c} f_c$ where v and c represent the velocity of the user and light, respectively, and f_c denotes the carrier frequency. The correlation coefficient ρ is determined by the Doppler frequency f_d and the time delay τ_d which is a function of the block length and the number of blocks required for the processing. Note that $\rho = 1$ accounts for the quasi-static case and the value decreases as the mobility of the user grows. For example, if 5GHz carrier frequency and 30km/h user mobility are assumed, the Doppler frequency is equal to f_d = 138.89Hz. Assuming that the number of delayed blocks is about 330 in the IEEE 802.11a environment, $f_d \tau_d$ and ρ become 0.15 and 0.8, respectively. The values of ρ according to $f_d \tau_d$ with these assumptions are listed in table 1.

Assuming all FIR channels have the same total average energy σ_h^2 in the mean feedback channel model, the current time domain channel $\overline{\boldsymbol{h}}$ can be predicted from

$$\overline{\boldsymbol{h}} = \boldsymbol{h} + \xi$$

where ξ denotes the prediction uncertainty vector which is a function of ρ and σ_h^2. By applying the discrete Fourier transform, $\overline{\boldsymbol{h}}$ and ξ can be transformed to the frequency response $\overline{\boldsymbol{H}}$ and Ξ,

표 1. $f_d\tau_d$ 값에 따른 상관 계수 ρ

Table 1. Correlation coefficients according to $f_d\tau_d$.

$f_d\tau_d$	0.00	0.15	0.24	0.30
ρ	1.0	0.8	0.5	0.3

respectively. Here, Ξ have a covariance matrix $(1-|\rho|^2)\sigma_h^2 I_N$ where I_N denotes N by N an identity matrix[8].

2. Proposed BL-AMC scheme

In the time-varying channel model described above, the received signal at the nth subcarrier in (2) is rewritten as

$$\begin{aligned} y_n &= \overline{H}_n s_n + w_n \\ &= (H_n + \Xi_n)s_n + w_n \\ &= H_n s_n + (\Xi_n s_n + w_n) \end{aligned} \tag{5}$$

where $\Xi_n s_n + w_n$ can be regarded as an additive Gaussian noise component[8]. Thus, the error variance in the above model becomes

$$\widehat{\sigma^2} = \sigma_n^2 + E\left[\Xi_n^2\right]\sigma_s^2 = \sigma_n^2 + (1-|\rho|^2)\sigma_h^2\sigma_s^2$$

where $E\left[\Xi_n^2\right]$ denotes the variance of the channel perturbation at nth subcarrier.

Then, $Q_{1,n}$ and $Q_{2,n}$ in (4) at the nth subcarrier can be rewritten as

$$\widehat{Q_{1,n}} = Q\left(\sqrt{\frac{|H_n|^2 6\sigma_s^2}{4(\sigma_n^2+(1-|\rho|^2)\sigma_h^2\sigma_s^2)(M_i-1)}}\right)$$

$$\widehat{Q_{2,n}} = Q\left(\sqrt{\frac{|H_n|^2 12\sigma_s^2}{4(\sigma_n^2+(1-|\rho|^2)\sigma_h^2\sigma_s^2)(M_i-1)}}\right)$$

By taking the channel estimation errors into account, more robust BER estimation is achieved and thus the AMC algorithm can be applied more effectively over time-varying channels.

The computational complexity of the proposed compensation scheme is at most $O((l_{\max}+1)N)$. Compared to the conventional BL-AMC scheme in [4], it is expected that the compensation process gives rise to performance gain by calculating a better BER estimation. This result indicates that the proposed compensation scheme with only N additional computation can be employed for the AMC algorithm more efficiently over time-varying channels.

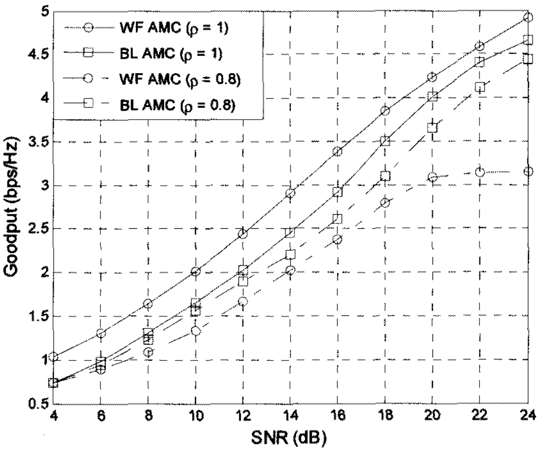

그림 2. WF-AMC와 BL-AMC의 평균 goodput 비교 성능

Fig. 2. Average goodput for the BL-AMC compared to the WF-AMC.

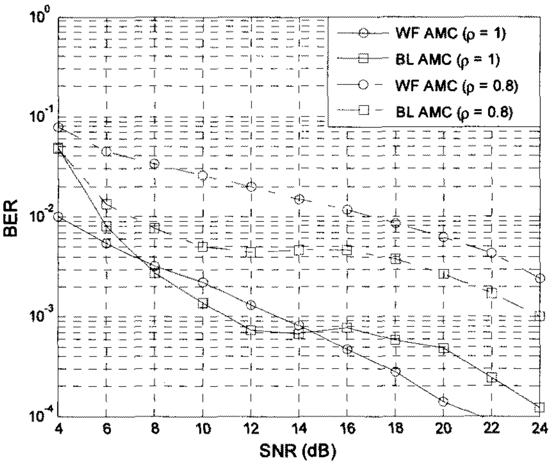

그림 3. WF-AMC와 BL-AMC의 비트 에러율 성능 비교

Fig. 3. Bit error rate of the BL-AMC compared to the WF-AMC.

V. Simulation Results

In this section, we will present the simulation results for the proposed method. For the OFDM modulation, $N=64$ subcarriers are used and the cyclic prefix length is set to 16 samples. The AMC table used for simulations is presented in Table 2.

표 2. 시뮬레이션을 위한 AMC 테이블
Table 2. AMC table for simulations.

i	$R_T\ (bps/Hz)$	R_c	Modulation
1	1	1/2	QPSK
2	2	1.2	16-QAM
3	3	3/4	16-QAM
4	4	2/3	64-QAM
5	4.5	3/4	64-QAM
6	5	5/6	64-QAM

표 3. RCPC 코드의 오류이벤트에 대한 총 input weight
Table 3. Total input weight of the error events for RCPC codes.

R_c	d_H	p	$N_i(d)\ (d=d_H,\cdots,d_H+5)$
1/2	10	3	108,0,633,4212,0
2/3	6	2	3,70,285,1276,6160,27128
3/4	5	3	42,201,1492,10469,62935,379546
5/6	4	5	92,528,8694,79453,791795,7369828

The target BER constraint is set to 10^{-3} and the average symbol energy E_s for each constellation is equal to 2. A 64-state RCPC code is employed where higher rate codes are acquired by puncturing the 1/2 mother code[6]. The total input weight of the error events $N_i(d)$ at Hamming distance d is listed in Table 3[10].

First, without compensating CSI errors, we represent the performance for the BL-AMC scheme over time-varying channels in Figures 2 and 3. In Fig. 2, we plot the average "goodput"[11] of the BL-AMC scheme[4] and the WF-AMC scheme in [3] where the channel gap Γ = 6.8dB is used for the BER constraint of 10^{-3}. In the presence of the CSI errors ($\rho=0.8$), which corresponds to $f_d\tau_d=0.15$, the performance of the BL-AMC is degraded by 20 % at a SNR of 18dB, compared to the perfect CSI case ($\rho=1$). In contrast, the performance of the WF-AMC is flattened out in a high SNR region which results in a 60% loss in the average goodput. These results indicate that the BL-AMC scheme is more robust to CSI errors than the WF-AMC, even if the WF-AMC exhibits the optimal performance in the perfect CSI case.

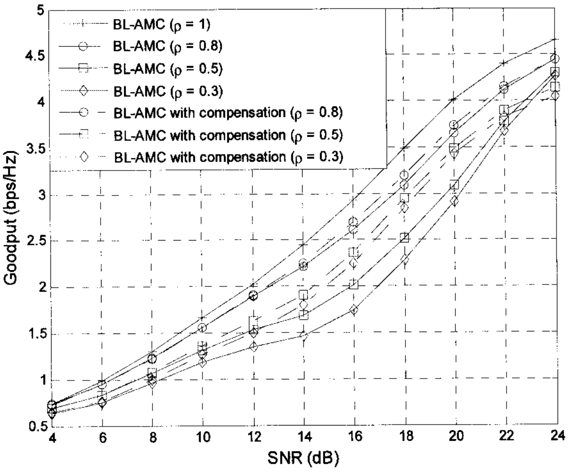

그림 4. 제안하는 기법의 평균 goodput 성능
Fig. 4. Average goodput for the proposed scheme.

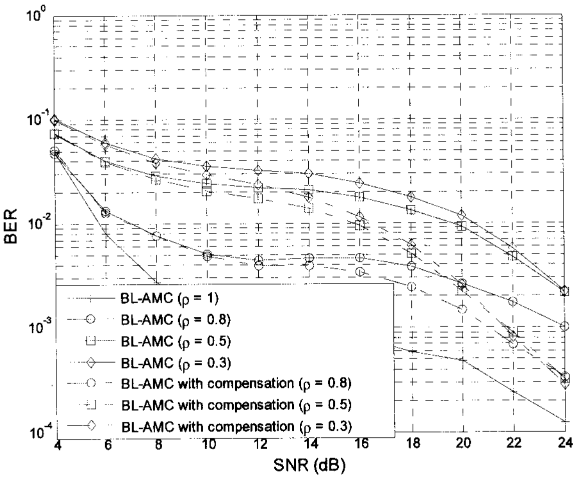

그림 5. 제안하는 기법의 비트 에러율 성능
Fig. 5. Bit error rate of the proposed scheme.

The BER performance of the BL-AMC scheme is presented in Fig. 3. In the presence of the CSI errors, the BL-AMC scheme also outperforms the WF-AMC scheme. As the mobility of the user increases, the compensation is more important to the performance and this fact will be verified in the following simulation results.

When the proposed compensation scheme is applied, the performance of the BL-AMC scheme improves substantially as the user mobility grows.

Fig. 4 shows the average goodput of the proposed scheme compared to the system without the CSI compensation. In the figure, the goodput of the proposed scheme at $\rho = 0.5$ and $\rho = 0.3$ improve up to 10% and 15%, respectively, at a SNR of 20dB. Note that the performance gain of the proposed scheme shown in Fig. 4 is related to the accuracy of the BER estimation. As shown in this plot, the performance gain is large in middle SNR region. This is attributed from a better performance in the BER estimation. In high mobile environments ($\rho = 0.5$), because a better BER estimation is also obtained, the performance gain of the proposed scheme is attained. This results indicate that the compensation scheme is available regardless of the user mobility. It is desirable from a system implementation point of view, as the proposed scheme can be applied in time-varing channels without the feedback channel knowledge much.

Also, the BER performance of the proposed scheme enhances when the CSI errors are taken into account. Compared to the conventional system without considering the channel perturbation, Fig. 5 shows that the performance of the proposed BL-AMC system improves by about 2dB in high SNR region. As shown in this figure, the performance gain from the CSI compensation maintains though the user mobility increases.

Ⅵ. Conclusion

In this paper, we propose a robust adaptive BIC-OFDM scheme over time varying channels. As shown in the simulation section, the proposed scheme exhibits an enhanced performance in terms of both the average goodput and the BER. Compared to the optimal water-filling method, it is shown that the BL-AMC system is more robust to the channel variations due to user mobility than the WF-AMC scheme which requires considerably higher feedback traffics to represent the bit loading information or channel coefficients on all subcarriers Also, the proposed compensation scheme exhibits the enhanced system performance by considering the effect of time varying channels effectively.

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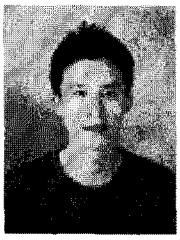
저자소개



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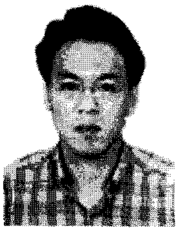

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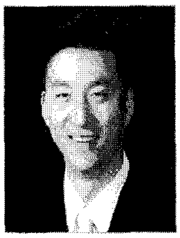

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