A MAC Protocol with RCPT Coded Hybrid ARQ-II for CDMA Networks

Wenhua Jiao, Shu Li
{wjiao, shuli}@lucent.com
Bell Labs Research China, Lucent Technologies
Beijing, P.R.China, 100080

Abstract- **In this paper, a new multiple access protocol that combines the characteristics of hybrid ARQ error controlling and Turbo coding is proposed and investigated. If hybrid ARQ-II with code combining is applied, retransmissions are reduced and frame error rate is lowered when channel experiences heavy traffic. It is an adaptive optimization of the balance between the CDMA processing gain and FEC coding gain. Simulation shows that using hybrid ARQ-II with code combing in PMCAP/CDMA can improve delay performance in AWGN channels. Code limitation strategies can decrease the MAI level and frame error rate, which in turn improves the system performance when the background noise is very high.**

I. INTRODUCTION

CDMA has become an attractive technique for medium access control in cellular network and personal communication systems. But Multiple Access Interference (MAI) is a challenge to improve its capacity. Due to PN code number limitation and receiver complexity, how to assign codes for different users is also a big problem. Preamble Minislot Channel Access Protocol (PMCAP/CDMA) is receiver-oriented protocol, which has considered both interference control and QoS guarantee[1]. This protocol sends preamble before message part and requires that acknowledgement of its preamble should be received at the end of the preamble. Only upon receiving a preamble acknowledgement, will a mobile host (MH) continue its packet transmission using the same code as its successful received preamble. Fig.1 shows PMCAP/CDMA work procedure. It has a limitation of maximum simultaneous transmissions to control MAI. In our previous work[2], we have improved PMCAP/CDMA in many aspects to solve the problem of code assignment and interference limitation. In [2], if the erroneous data frame can not be corrected by BCH code, ARQ will be used to retransmit the packet. According to [3], that strategy is called hybrid type-I ARQ. In this paper, we apply hybrid type-II ARQ to PMCAP/CDMA. Type-II ARQ with code combing and conventional type-II ARQ (no code combing) are studied and compared. Rate-compatible punctured Turbo (RCPT) codes are used to provide adaptive channel coding in the hybrid ARQ-II schemes.

Hybrid type-II ARQ schemes in DS-CDMA packet networks have been studied in some papers[4], but few of them have considered MAI control and code contention problems. This paper is organized as follows: section II describes improved PMCAP/CDMA using hybrid type-II ARQ. In section Ⅲ, performance analysis is conducted. In section Ⅳ, simulation results and comparisons with type-I ARQ, conventional type-II ARQ, and ARQ-II with code combing are shown. Conclusion is given in section Ⅴ.

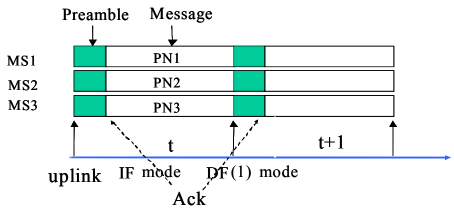


Fig. 1 PMCAP/CDMA protocol

II. IMPROVED PMCAP/CDMA USING HYBRID TYPE-II ARQ

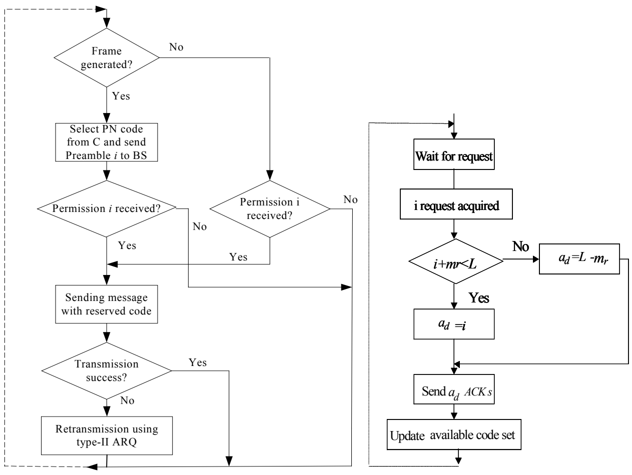
A. System description

In this paper, we focus on a single cell, in which a certain number of MHs communicate with Base Station (BS) using CDMA. The number of codes within a cell by a BS is fixed. The MH can be in one of the three states: SL (Silence), AC (Acquirement) and TX (Transmission). When there is no data coming, a MH occupies no PN code (SL state). As data packets are generated, the MH randomly selects one PN code from code pool (totally C codes, see Ref.[1] to determine C) and sends its preamble part by this code to contend PN code for its Message packet transmission (AC state). If the preamble is correctly received, the BS randomly assigns one of the available PN codes in code pool and sends ACK to the MH. The system is based on Immediately Feedback (IF) model if ACK is received by MH immediately after preamble, and on Delay Feedback (DF(1)) model if ACK is received after one slot. The MH will transmit its message packets with PN code obtained from ACK until the current Message data packet is received correctly (TX state). In this paper, IF model and error free feedback channel are assumed. Some parameters are shown in table 1.

Table 1. Some parameters of the systems

P_0	Probability that a MH is in SL state
p_r	Probability that a MH is in TX state
p_d	Preamble transmit permission probability
σ_d	Data packet generation rate each slot
$p_{c\ succ}$	Contention success probability
$p_{t\ succ}$	Transmission success probability
L	Limitation of Maximum simultaneous uses
C	Total codes in code pool
M	Total MHs in the system

The MH and base station flowchart is shown in Fig.2.



(a) Mobile host (b) Base station

Fig.2. Mobile host and base station flowchart

B. RCPT code and its application in hybrid type-II ARQ

In [2], BCH code is used to protect data packets, and the failed data packet will be retransmitted again using the same code as the last failed transmission. On the other hand, Turbo code, introduced by Berrou[5], performs very close to Shannon limits on AWGN channel. Turbo encoder, shown in Figure 3, is composed of two parallel concatenated RSC (Recursive Systematic Convolutional) encoders which are connected with an interleaver. The input for the second RSC encoder is an interleaved version of that for the first RSC encoder. Turbo codes can be decoded iteratively.

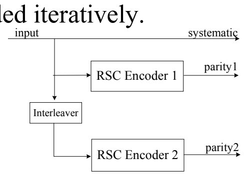


Fig.3 An example of Turbo code encoder

In this paper, rate-compatible punctured Turbo (RCPT) codes are used to adaptively correct channel errors. RCPT [6, 7] code is a combination of Turbo code and the methods of rate-compatible punctured (RCPC) codes[8].

RCPT codes are a family of codes constructed from a single rate 1/*N* Turbo code called parent code. The higher rate codes are obtained by puncturing successively greater number of coded bits. The puncturing rules require that all the coded bits in a higher rate code be contained in the lower rate code. If higher rate codes cannot correct channel errors, lower rate codes will be used in the manner that only additional coded bits previously punctured will be transmitted.

The RCPT code family used here has three rates: 1/3,1/2 and 1. The rate 1/3 parent code is the same as the Turbo code in 3GPP[9]. The two RSCs have the same generator polynomials:$G(D)=(1,1+D+D^3/1+D^2+D^3)$. The interleaver is also the same as 3GPP[9]. The rate 1/2 code is obtained by the following puncturing pattern:

$$P = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Namely, the rate 1/2 code is composed of the systematic output, parity1 at odd positions and parity2 at even positions. The rate 1 code is just the systematic output. 8 iterations are conducted for each decoding of RCPT codes in our simulation.

First, rate 1 systematic code is used for transmission. If no ACK is received, rate 1/2 code is used by transmitting bits in parity1 at odd positions and those in parity2 at even positions. The receiver will decode by combining these two transmissions. If still no ACK is received, rate 1/3 code is used by sending bits in parity1 at even positions and those in parity2 at odd positions . The decoder at the receiver will combine these three frames. If still no ACK is received, two schemes are studied, that is, *conventional ARQ-II* and *ARQ-II with simple code combing*. In the first scheme, the previous three transmissions are dropped and another turn of ARQ-II transmission is started. In the second scheme, we keep the last two transmissions, which will be combined with the newly received frame to form decoding information. Complete code combining is not adopted here because decoding is too complicated.

RCPT codes with other rates such as 2/5 and 4/11 are studied in [7]. If we only consider physical layer, these codes can utilize channels more economically, but using them will lead to variable slot duration in different transmissions and cause significant complexity in the design of MAC layer. So they are not considered in this paper.

For the failed transmission, the MH will retransmit it using the same PN code until the ACK is received. If a new packet is generated and it is the first one waiting in the buffer, it will contend the PN code as previous packet. The block diagram of the system is shown in Fig.3.

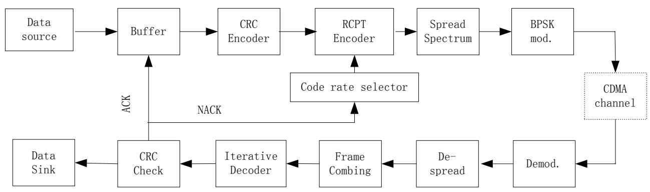


Fig.4. Diagram of ARQ-II schemes in CDMA

C. Frame structure

The MH sends message part after preamble part. For message part, frame format used in this paper is taken from 3GPP[9] with a slight modification on tailing so that all the slot duration has identical lengths. Each frame has 5098 information bits. First, 16 CRC parity check bits are calculated and added. Then the 5114=5098+16 bits will enter the RCPT encoder. To enforce that the RSC encoders end in zero state, 6 tail bits will be appended.

III. PERFORMANCE ANALYSIS

Markov chain analysis and equilibrium point analysis (EPA) are two dominated methods for MAC protocol analysis. The former can provide exact system analysis, but it is too complicated in most cases. EPA is much simpler since it does not calculate the system state transition probabilities. However, EPA is not an efficient analysis method for queuing systems. Tagged user approach (TUA) is proposed in [10]. It is rather simple and efficient. This paper combines TUA and EPA to analyze this protocol.

Suppose there are M MHs, the number of MHs in {SL, AC, TX} state is $\{m_s, m_c, m_r\}$. Packets arrive in the buffer of data user following Bernoulli process with a probability σ_d. The queue in each data user is FCFS (First Come First Served). A new packet ready for service will start to transmit its preamble to contend PN code with probability p_d. The retransmission packet is treated in a manner similar to the new packet. With the assumption that the channel is symmetric and the statistical behaviors of all users are identical, we focus on the behavior of an arbitrarily chosen user among all users and the influence of other users on it through the shared channel. The behavior of the tagged user is then used to find the system performance.

According to section II, state flow graph of the tagged data user for three hybrid ARQ schemes can be obtained in Fig.5. TX_i means the ith transmission in one turn of TX state and $p_{t\_succ}^{(i)}$ means the frame success probability of the ith transmission. We suppose this probability is fixed in steady state. In hybrid type-II ARQ with simple code combing, FER of the ith (i>3) retransmission would be the same as the third transmission in steady state. Simulation will validate our assumption. In this paper, we only analyze hybrid type-I ARQ with PMCAP/CDMA. Using similar method, we can obtain stead probability of each state for hybrid type-II ARQ.

The state flow graph of the tagged data user for ARQ-I with PMCAP/CDMA is shown in Fig.5a. When data packet comes, the MH transmits its preamble with probability of p_d. After successfully obtaining an available PN code with probability of p_{c_succ}, it transmits its data packet until packet has been successfully received. p_{t_succ} is transmission successful probability.

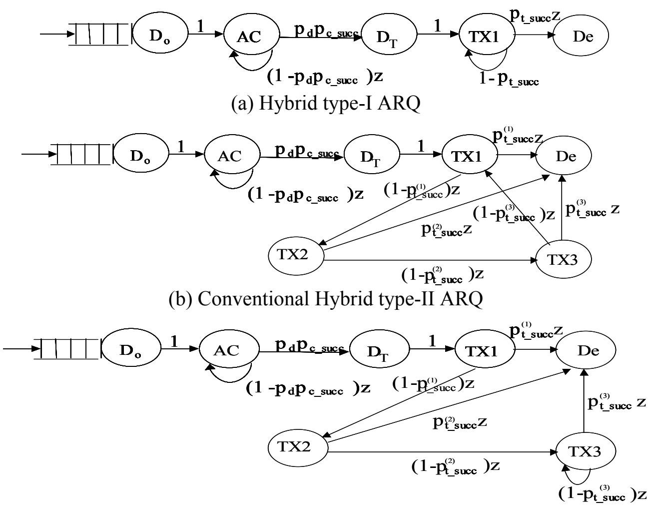


Fig.5. State flow graph of tagged user in hybrid ARQ schemes

From Fig.5a, the PGF of $C(z)$ of the duration of the MH at AC is given by

$$C(z) = \frac{D_T}{D_o} = \frac{p_d \cdot p_{c\_succ}}{1-(1-p_d \cdot p_{c\_succ})z} \tag{1}$$

And the PGF of $R(z)$ of duration of the MH at TX is given by:

$$R(z) = \frac{p_{t\_succ} z}{1-(1-p_{t\_succ})z} \tag{2}$$

Let T_1 and T_2 be the average time that a MH spends in SL, AC and TX respectively during each message service time, then

$$\begin{cases} T_1 = C'(1) = (1-p_d p_{c\_succ}) / (p_d p_{c\_succ}) \\ T_2 = R'(1) = 1/p_{t\_succ} \end{cases} \tag{3}$$

The activity of the tagged user consists of cycles of alternating idles and busy periods. The message arrivals follow a Bernoulli process with rate σ_d, therefore the mean length of SL period is

$$T_{SL} = 1/\sigma_d \tag{4}$$

If each departing message leaves the buffer empty with probability π_0, the number of messages served in each busy period is geometrically distributed with the mean $1/\pi_0$.

Hence similar to [11], in each cycle, the mean period length of a busy user spending at AC and TX states is given by:

$$\begin{cases} T_{AC} = \dfrac{1-p_d p_{c\_succ}}{p_d p_{c\_succ}} \cdot \dfrac{1}{\pi_0} \\ T_{TX} = \dfrac{1}{p_{t\_succ}} \cdot \dfrac{1}{\pi_0} \end{cases} \tag{5}$$

Next we try to obtain π_0. The probability flowchart of the queue for a tagged user is shown in Fig. 6.

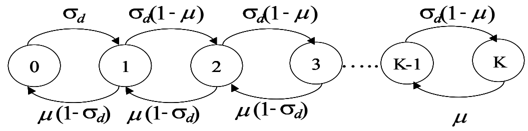


Fig.6 The probability flowchart of the queue for a tagged user

Here μ is message serve rate which can be estimated by $p_d p_{c\_succ} p_{t\_succ}$ according to Fig.5(a) if nearly all packets can be transmitted correctly ($p_{t\_succ} \approx 1$). Based on classic queue analysis (M/M/1/K model), if K is large enough and μ is larger than σ_d, π_0 can be expressed as

$$\pi_0 = (\mu - \sigma_d)/\mu \tag{6}$$

Then p_r and p_0 can be expressed by p_{c_succ} and p_{t_succ}:

$$p_r = f_1(p_{c\_succ}, p_{t\_succ}) = T_{TX}/(T_{SL} + T_{AC} + T_{TX}) \tag{7}$$

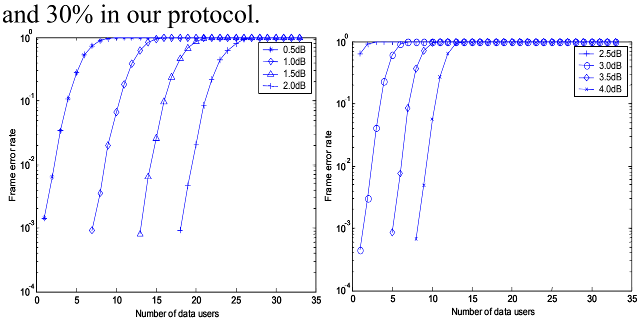
$$p_0 = f_2(p_{c\_succ}, p_{t\_succ}) = T_{SL}/(T_{SL} + T_{AC} + T_{TX}) \tag{8}$$

Transmission success probability of p_{t_succ} is determined by the influence of other users on the tagged user. Due to the channel symmetry, the busy probability of the tagged user would be the same as the other users, that is p_r. When the tagged user transmits a packet in a slot, each of other M-1 users would transmit a packet in the same slot with probability p_r. Hence p_{t_succ} is given by

$$p_{t\_succ} = \sum_{i=0}^{M-1} \binom{M-1}{i} (p_r)^i (1-p_r)^{M-1-i} Q_e(i+1) \quad (9)$$

where $Q_e(k)$ is the probability of successfully sending a frame given k simultaneous transmission. Because there is still no close form for $Q_e(k)$ of Turbo code, we obtain RCPT coded hybrid ARQ-I and hybrid ARQ-II by simulation.

Frame Error Rates (FER) of RCPT codes in AWGN channel with MAI and different E_b/N_o[1] is shown in Fig.7. The frame format and PCPT pattern have been described in Section II. From Fig.7, we can see that with the increasing channel noise, FER of the RCPT code also rises. For a given E_b/N_0, rate 1/3 RCPT code has much better FER performance than that of rate 1/2. For example, when E_b/N_o is 0.5dB, suppose there are 8 users transmitting their packets simultaneously using rate 1/3 RCPT code, nearly all the transmitted packets can't be correctly received. So there should be a code threshold L to limit correctly received access requests. If threshold L is too large, more access requests would succeed in contending PN code, but too much transmission would increase MAI. So in this case, p_{c_succ} increases while p_{t_succ} deceases. If threshold L is too small, p_{t_succ} will increase while p_{c_succ} deceases. So there should be some tradeoff to improve delay performance. Simulation shows that good performance will be obtained if we determine L that makes FER between 20% and 30% in our protocol.



(a) Rate 1/3 (b) Rate 1/2

Fig.7. FER of the RCPT codes in AWGN channel with MAI

When the steady state comes, the probability of the tagged MH into or out each state would be the same. Also, in this paper, we assume that new packet is generated no matter the MH is in SL, AC or TX state. Because the probability that a MH goes into AC state is equal to the probability that the MH leaves this state, the following equations must hold according to EPA analysis:

$$\sigma_d = (1 - p_0 - p_r) p_d p_{c\_succ} \quad (10)$$

From equation (7-10) above, we obtain the system with four equations in four unknown terms, namely p_0, p_r, p_{c_succ}, p_{t_succ}.

[1] Usually E_b/N_o is defined as SNR-10log$_{10}$(code rate).However, in this paper, we define E_b/N_o as SNR-10log$_{10}$(1/3) for both rate 1/3 and 1/2 code.

So these equations can be solved. But due to the complexity of (9), the results are not easy to be solved. Throughout this paper, when traffic load is not so heavy and stability of the system is hold, equations (7-10) are used to validate our simulation results. If our simulation results well fit these four equations, the correctness of simulations will be proved.

The average data throughput is:

$$\theta = M p_r p_{t\_succ} \quad (11)$$

Let τ denote slot duration, average data delay (second) can be expressed as:

$$D = \frac{M - m_r}{\theta} \cdot \tau \quad (12)$$

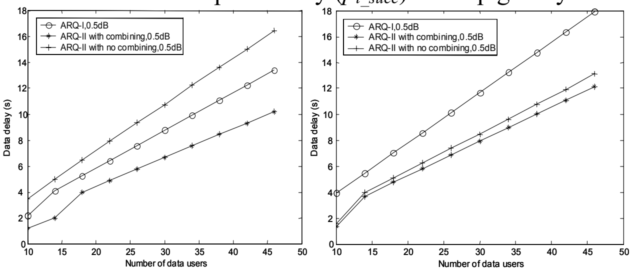
IV. COMPARISONS AND SIMULATION RESULTS

We simulated three ARQ strategies in PMCAP/CDMA, namely ARQ-I, conventional ARQ-II and simple code combing ARQ-II in AWGN channel with fixed parameters shown in Table 2. Since slot duration of ARQ-I and ARQ-II is different, the packet generate rate each slot of these two strategies is also different accordingly to ensure the same average traffic each second. RCPT codes are used to correct errors in data packets. We assume preamble is highly protected and transmission of preamble is error free. Our simulation results are verified by equation (7-10) when traffic is not so heavy and steady state can be obtained.

Table 2. Some fixed parameters in simulation

Variable	ARQ-I	ARQ-II
Processing gain (G)	31	31
Total codes in code pool (C)	33	33
Channel rate (R)	16 Kbps	16 Kbps
Frame length (F)	15360 bits	5120 bits
Slot duration (τ)	960 ms	320 ms
Packet generate rate each slot (σ_d)	0.3	0.1
Preamble transmission permission probability (p_d)	0.9	0.9

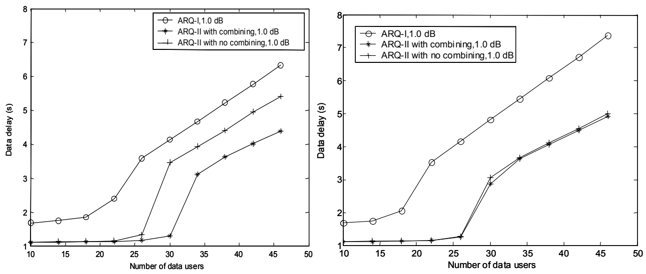
Fig.8 is the simulation result of three strategies with code limitation L=7 (see Fig.8a) and L=5 (see Fig.8b) when E_b/N_o=0.5dB. From Fig.8, when the number of MHs increases, the performance of each ARQ strategy will drop. The reason is that when the number of MHs increases, MAI is higher and p_{t_succ} decreases. Thus retransmissions will enlarge packet delay. We can also see the trends that packet delay of ARQ-II with code combining is much lower than that of ARQ-I and ARQ-II without code combining. The reason is that compared with ARQ-I, less coding redundancy is transmitted, which is enough to correct the errors when channel noise and MAI are not high. The performance of ARQ-II with coding combining superior to that of ARQ-II without coding combining is because the latter does not use previous transmitted information. From Fig.8, we also can see that conventional ARQ-II is more sensitive to code limitation L. Improper choice of L can cause the performance of conventional ARQ-II even worse than ARQ-I. The reason is that if L becomes larger, there will be more users permitted to transmit simultaneously, which leads to high MAI. Also there are more retransmissions in conventional ARQ-II, which add too much MAI in the CDMA system and cause the transmission success probability (p_{t_succ}) to drop greatly.



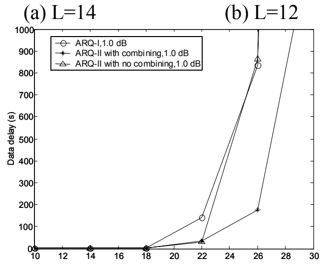
(a) L=7 (b) L=5

Fig.8. Comparison of three ARQ strategies with E_b/N_o =0.5 dB

Fig.9 is the simulation result of three ARQ strategies with code limitation L=14 (see Fig.9a), L=12 (see Fig.9b) and no code limitation used (L=33, see Fig.9c) when E_b/N_o=1.0 dB. For Fig.9a, there are maximum 14 simultaneous users permitted to transmit their data packet. So the contention success probability (p_{c_succ}) would drop and the transmission success probability (p_{t_succ}) would increase compared to Fig.9b, in which code threshold is only equal to 12. From Fig.9b, we can see that when the channel noise is not very high, too tight code threshold would decrease performance compared to Fig.9a. Meanwhile, too loose threshold can also decrease system performance. For example, if we do not apply code limitation strategies, with the number of MHs in the systems increasing, packet delay will be extremely high (see Fig.9c). So it is very important to choose the proper value of L.



(a) L=14 (b) L=12



(c) No code limitation (*L=C=33)*

Fig.9. Comparison of three ARQ strategies with E_b/N_o =1.0 dB

In general, Fig.8 and Fig.9 show delay performance of hybrid ARQ-II in PMCAP/CDMA outperforms that of ARQ-I in good channel conditions. And in good channel conditions (background noise and MAI are all considered), sometimes there is no significant difference in performance no matter whether code combing is used or not (See Fig.8b or Fig.9b). However, in bad channel conditions, delay performance of hybrid ARQ-II with code combining is superior to the ARQ-I and ARQ-II without coding combining (See Fig.8a or Fig.9a). Performance of conventional hybrid ARQ-II (without code combining) is very sensitive to code threshold L, so proper choice of L is very important.

V. CONCLUSION

In this paper, two ARQ-II strategies are applied in PMCAP/CDMA. We use both TUA and EPA method to analyze the performance of the protocol. Simulation shows that using hybrid ARQ-II with code combing in PMCAP/CDMA can significantly improve the delay performance in AWGN. Code limitation strategy can decrease the MAI level and frame error rate, which in turn improves the system performance when the background noise is very high.

REFERENCES

[1] Y. Yang, J. He, and M. Liu, "A medium access control protocol for voice and data integration in receiver-oriented DS-CDMA PCNs," IEEE ICUPC, 1997, vol.1, pp. 38-42.

[2] Wenhua Jiao, Zhimin Liu, Qinglin Liang, "Performance analysis and application of PMCAP/CDMA in voice/data integration networks", IEEE VTC2001fall, Vol.II. Page(s): 1020 –1024;

[3] L.K.Rasmussen and S.B.Wicker, "The performance of Type-I Trellis Coded Hybrid-ARQ Protocols over AWGN and Slowly Fading Channels," IEEE Trans. On Information Theory, vol.40, no.2, pp.418-428, Mar.1994.

[4] Qian Zhang, Tan F.Wong and James S.Lehnert, "Performance of a Type-II Hybrid ARQ Protocol in Slotted DS-SSMA Packet Radio Systems", IEEE Trans. On Communications, vol.47, no. 2, pp.281-290, February, 1999

[5] C.Berrou et al., "Near Shannon limit error-correcting coding and decoding: Turbo codes(1)", IEEE ICC 1993, Geneva, Switzerland, pp.1064-1070, May 1993.

[6] W.C.Chan et al., "An adaptive hybrid FEC/ARQ protocol using turbo codes", IEEE ICUPC 1997, pp.541-545.

[7] D. N. Rowitch et al., "Rate compatible punctured Turbo (RCPT) codes in a hybrid FEC/ARQ system", IEEE Globecomm 1997, Nov.1997, pp.55-59.

[8] J. Hagenauer, "Rate Compatible Punctured Convolutional Codes (RCPC Codes) and their applications," IEEE Trans. On Communications, vol. 36, pp. 389-400, Apr. 1988.

[9] 3GPP TS 25.212, Technical specification group radio access network: multiplexing and channel coding (FDD). June, 2001.

[10] Tao Wan and Asrar U. Sheikh, "Performance and Stability Analysis of Buffered Slotted ALOHA Protocols Using Tagged User Approach", IEEE Trans. On Vehiular Technology, Vol.49, No.2, pp. 582-593, March, 2000.

[11] Tao Wan et al., "Performance and Stability Analysis of Buffered R-ALOHA Systems Using Tagged User Approach (TUA)", IEEE VTC2000, May 15-18, 2000, pp.1405-1409, Tokyo, JAPAN.