CRC-Turbo Concatenated Code for Hybrid ARQ System

Woo Tae Kim* ***Regular Member,*** Jeong Goo Kim**, Eon Kyeong Joo*** ***Lifelong Members***

ABSTRACT

The cyclic redundancy check(CRC) code used to decide retransmission request in hybrid automatic repeat request(HRAQ) system can also be used to stop iterative decoding of turbo code if it is used as an error correcting code(ECC) of HARQ system. Thus a scheme to use CRC code for both iteration stop and repeat request in the HARQ system with turbo code based on the standard of cdma 2000 system is proposed in this paper. At first, the optimum CRC code which has the minimum length without performance degradation due to undetected errors is found. And the most appropriate turbo encoder structure is also suggested. As results, it is shown that at least 32-bit CRC code should be used and a turbo code with 3 constituent encoders is considered to be the most appropriate one.

Key Words : HARQ system, CRC code, Turbo code, Undetected error, Encoder structure

Ⅰ. Introduction

Methods of controlling errors in communication systems can be classified into two categories such as automatic repeat request (ARQ) and error correcting code (ECC)[1]. Hybrid ARQ (HARQ) system has been established successfully, which exploits both the predictable performance of ECC and rate flexibility of ARQ[2]. The errors are corrected by ECC at first and then the existence of residual errors is checked by cyclic redundancy check (CRC) code in this system. The retransmission is requested if there is an error. Otherwise, the decoding is completed.

It is required to use a powerful ECC to provide a multimedia services in the future communication systems. Turbo code which was proposed by Berrou et. al.[3] in 1993 may be an appropriate ECC of HARQ system due to its good error performance. But there are some drawbacks in turbo code such as increase in the computational complexity and delay when the number of iterations is increased. So many researches on reducing the delay of turbo code have been surveyed[4-6]. The scheme of using CRC code is known to be the most efficient one among them[7]. The CRC code used with the turbo code checks the errors when every iteration is finished. The decoding is completed if there is no error. Otherwise, the iterative decoding is carried out till the predetermined maximum number of iterations.

So CRC code can be used to stop the iterative decoding as well as request retransmission in the HARQ system with turbo code. But the research on both applications of the CRC code has not been reported yet. And the results are drawn under the assumption of perfect error detection in the case of using CRC code to decide retransmission request[8]. Therefore, CRC-turbo concatenated code for HARQ system which is used for both iteration stop and retransmission request is proposed at first. And the conventional assumption of perfect error detection is investigated and its proper alternative is also suggested.

Generally, the performance of turbo code depends on the encoder types such as the number of constituent encoders and code rates[9,10]. So there may be various

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* 삼성전자 정보통신총괄 무선사업부 (wootae77.kim@samsung.com), ** 부산대학교 정보컴퓨터공학부 (kimjg@pusan.ac.kr)

*** 경북대학교 전자전기컴퓨터학부 (ekjoo@ee.knu.ac.kr)

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transmission schemes for HARQ system with turbo code according to encoder structure. Accordingly, the most appropriate encoder structure for HARQ system is also suggested in this paper by analyzing the error performance among three possible scheme.

The main focus of this paper is to find the optimum CRC code and the most appropriate encoder structure for the conventional HARQ system. So the cdma2000 system which is the standard of the current domestic mobile communication is considered in this paper.

Ⅱ. HARQ system with turbo code

The system model of HARQ system with turbo code used in this paper is depicted in Fig. 1. The information bits are passed to the CRC encoder. The turbo coded bits are classified into two groups according to the code rate of HARQ system. One group is transmitted at the first transmission and the other is stored for retransmission. The various code rates of HARQ system are obtained by puncturing. The code rate considered in this paper is varied from 1/2 to 1/5. The turbo decoding is performed by maximum *a posteriori* (MAP) decoders. And the errors are checked by CRC decoder with the hard decision values of log-likelihood ratio (LLR).

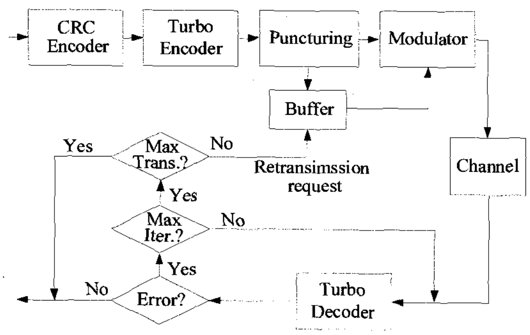


Fig. 1. System model.

The information and parity bits which are selected according to the code rate are sent at the first transmission. Iterative decoding is done by the turbo decoder at the receiver. If there is no error after each iteration, the whole decoding is completed. Otherwise, the iterative decoding is continued until the predetermined maximum number of iterations. And if there are still errors after that, retransmission is requested. Then the bits which were stored in the encoding process are transmitted. The iterative decoding is performed with the information and parity bits which were received before and stored in the buffer at the receiver as well as the transmitted bits received presently.

Ⅲ. Analysis of CRC code according to three kinds of simulation

Error detection capability is increased as the length of CRC code is increased in general. However the redundancy is also increased. We are concerned about finding the minimum length of CRC code without the performance degradation here. Accordingly, three kinds of computer simulation are carried out in additive white Gaussian noise (AWGN) channel to analyze the effect of CRC code in HARQ system with turbo code. The first simulation is performed under the assumption of perfect error detection which has been used in the conventional research and analysis. The number of iterations of turbo code is set to 7 since it is generally known that there is little performance improvement above it[3]. The CRC code is used for retransmission request only in the second simulation and the number of iterations is also set to 7. And the last simulation is carried out for the case that the CRC code is used to stop the iterative decoding as well as request retransmission. The decoding is finished if there is no error after being checked by the CRC code in this case. So the average number of iterations can be reduced. But the iterative decoding is continued if errors are detected. So the maximum number of iterations is set to 20. Three CRC codes such as LRCC-8[11], CCITT-16[12], and ETHERNET-32[13] are used. And the maximum number of transmissions is set to 4, in other words, up to 3 retransmissions are possible. Binary phase shift keying (BPSK) is used for modulation and the semi-random interleaver is used.

3.1 *Simulation 1*: Perfect error detection

The throughput and error performance are obtained under the assumption of perfect error detection in the conventional researches of CRC code in HARQ system. The throughput, T, is represented as follows. Here, F is the length of frame and C is the length of CRC code. And a is the average number of transmissions.

$$T=\frac{F-C}{F(1-a)} \qquad (1)$$

The bit error rate (BER) and frame error rate (FER) of the first simulation are shown in Fig. 2. The same result can be obtained regardless of the length of CRC code since perfect error detection is assumed. For example, about 1.0dB, -0.1dB, -0.8dB, and 1.5dB are required from the first to fourth transmission to get the BER of 10^{-6}.

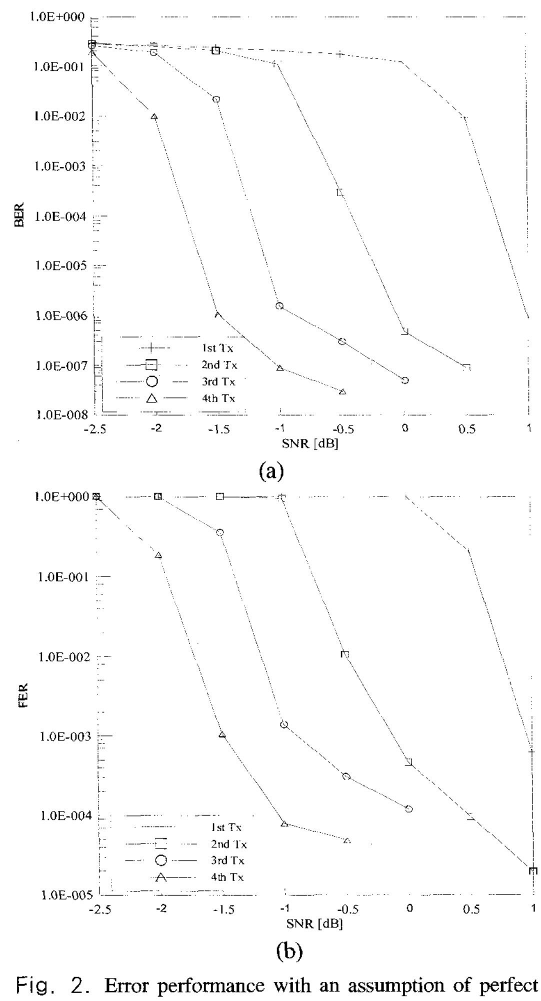


Fig. 2. Error performance with an assumption of perfect error detection. (a) BER, (b) FER

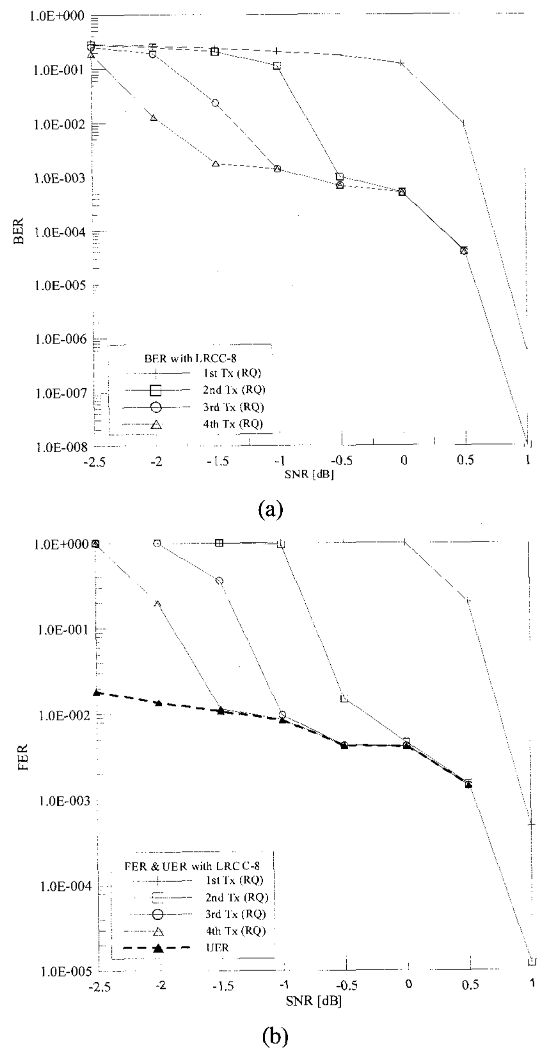


Fig. 3. Error performance of LRCC-8 when it is used for retransmission request only. (a) BER, (b) FER and UER

3.2. *Simulation 2*: Retransmission request only

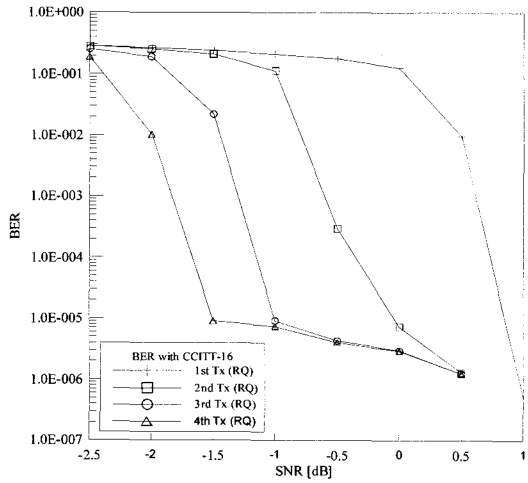
The second simulation deals with the case that CRC code is used for retransmission request only. The retransmission is requested if there remains still errors after finishing the fixed number of iterations of 7.

The BER of LRCC-8 is depicted in Fig. 3(a). FER and undetected error rate (UER) are shown in Fig. 3(b). The BER is not decreased even though signal-to-noise ratio (SNR) and number of transmissions are increased. That is, performance enhancement cannot be expected by retransmission. The FER is also not improved and has the same value as UER about 0.0dB, -1.0dB, and -1.5dB from the second to fourth transmission. This means that the observed errors are mainly the undetected errors. Thus, 8-bit CRC code is considered to be an inappropriate one to get the effect of retransmission.

The error performance of CCITT-16 is shown in Fig. 4. It is noticed that the same phenomenon is occurred like the 8-bit CRC code even though there is a little performance improvement in this case. The undetected errors are occurred at the SNR from -2.5dB to 0.5dB and it is shown that FER is almost same as UER at the fourth transmission at the SNR from -0.5dB to 0.5dB. So 16-bit CRC code is not an appropriate one to get the effect of retransmission either.

The BER and FER of ETHERNET-32 are depicted in Fig. 5. The undetected errors which were found at the 8- and 16-bit CRC code are not observed in this case. And the error performance is improved as the number of retransmissions is increased.

For example, SNR's of above 1.0dB, -0.1dB, -0.9dB, and -1.5dB are necessary to get the BER of 10^{-6} from the first to fourth transmission, respectively. This is almost the same results as the first simulation. So BER of 10^{-6} can be obtained at various channel conditions with the SNR range down to -1.5dB. Therefore, it is required that at least 32-bit CRC code should be used to get the effect of retransmission.



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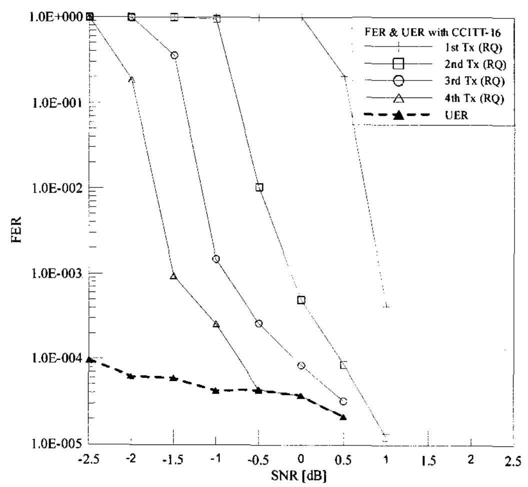

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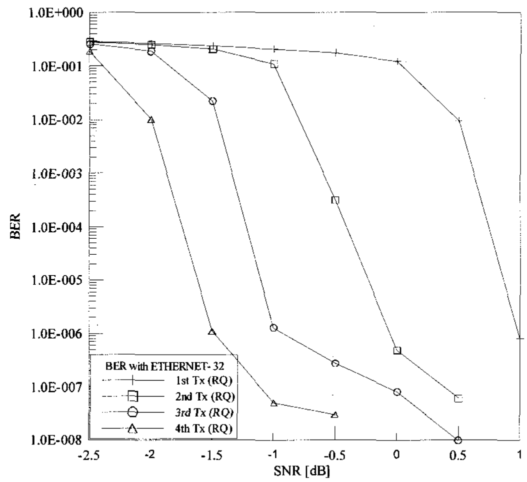
Fig. 4. Error performance of CCITT-16 when it is used for retransmission request only. (a) BER, (b) FER and UER



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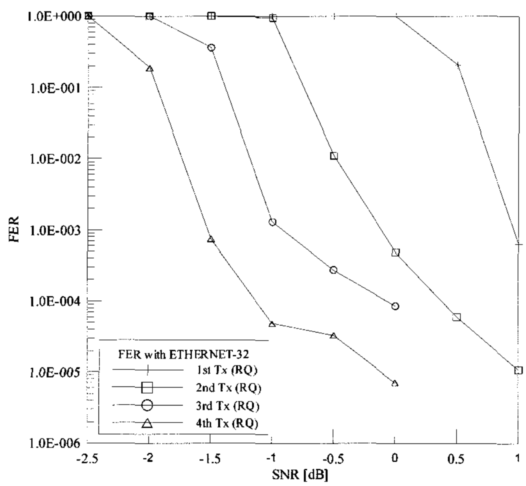

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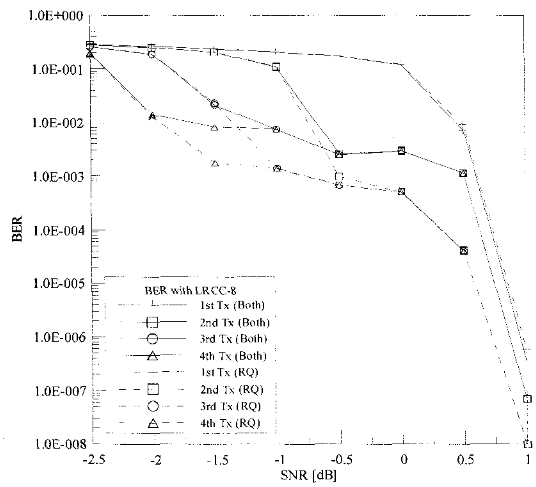
Fig. 5. Error performance of ETHERNET-32 when it is used for retransmission request only. (a) BER, (b) FER

3.3. *Simulation 3*: Both retransmission request and iteration stop

The CRC code is used to stop iterative decoding as well as request retransmission in this simulation. BER of LRCC-8 is depicted as solid line and that obtained by the second simulation is shown as dotted line in Fig. 6(a).

The performance is compared to the result of the second simulation in order to check the effect of undetected error. There is no performance improvement after the third transmission which shows almost the same result as the second simulation.

In other words, there is no effect of retransmission above -0.5dB and -1.0dB at the third and fourth transmission. This is due to the fact that the undetected errors are dominant even though the fourth transmission is completed as can be seen from the Fig. 6(b). In addition, BER is increased as compared to the case that the CRC code is used for retransmission request only. False iteration stop of turbo code by undetected error which was not considered in the second simulation may be the cause of this phenomenon. The error performance of CCITT-16 is represented in Fig. 7.



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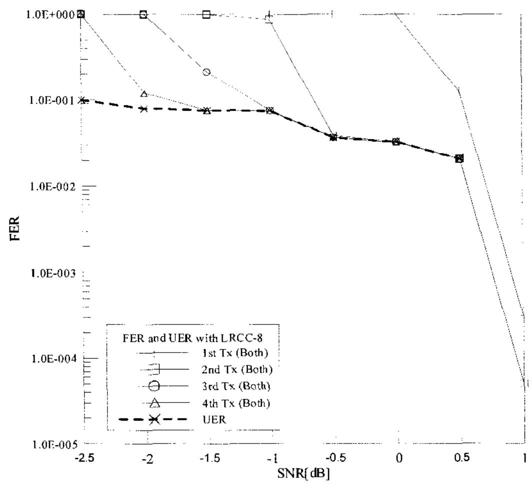

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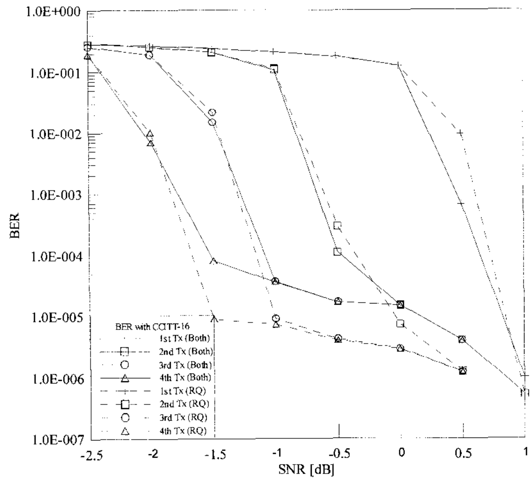
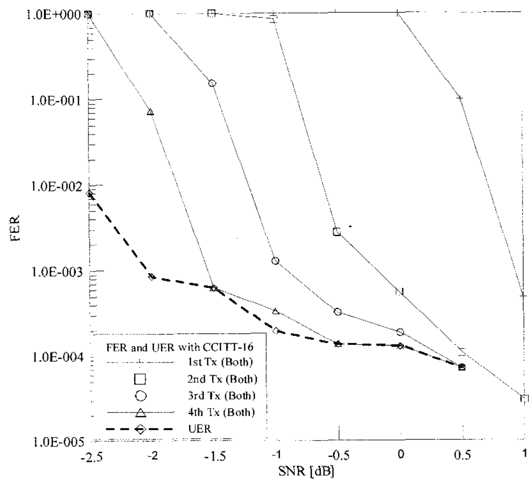
Fig. 6. Error performance of LRCC-8 when it is used for both retransmission request and iteration stop. (a) BER, (b) FER



(a)



(b)

Fig. 7. Error performance of CCITT-16 when it is used for both retransmission request and iteration stop. (a) BER, (b) FER

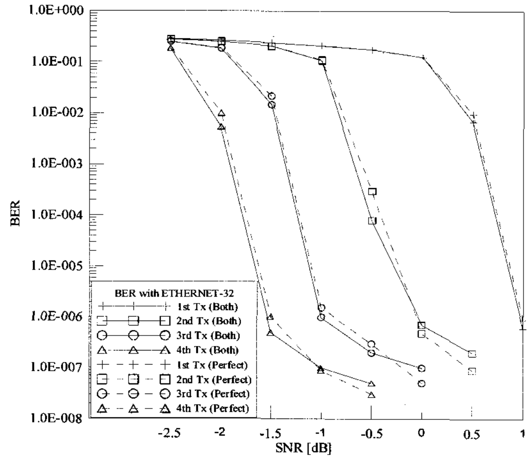
The BER of CCITT-16 is decreased as compared to that of LRCC-8, but there is also no performance improvement after the third transmission which is the same result of the second simulation. The undetected errors are still found up to 0.5dB as shown in Fig. 7(b) like LRCC-8. Thus, the assumption of perfect error detection is not valid in this case either. Error performance of ETHERNET-32 is shown in Fig. 8.

The undetected errors are not observed in this case, so the same results can be obtained from the first simulation as well as the second one. Therefore, the performance is compared to that of the first simulation in this case.

The BER and FER are decreased as the number of transmissions is increased. The error performance is similar to that of the first simulation whose performance is shown in the Fig. 2 and again by dotted lines in the Fig. 8. So the effects of retransmission and iteration can be obtained and the assumption of perfect error detection is valid in this case unlike the cases of LRCC-8 and CCITT-16.

The throughput and the average number of transmissions of three CRC codes of the third simulation are shown in Fig. 9.

The throughput of three CRC codes is almost same even though that of ETHERNET-32 is a little bit lower



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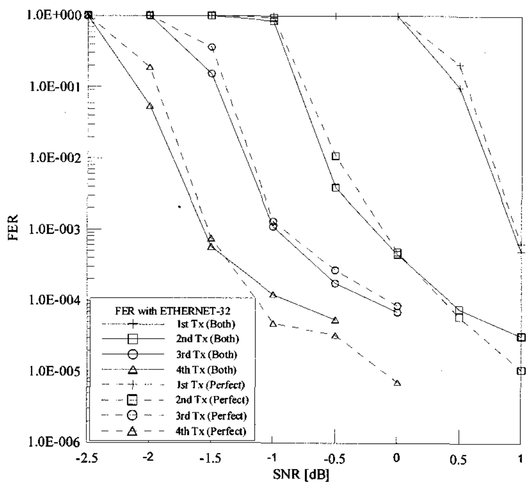

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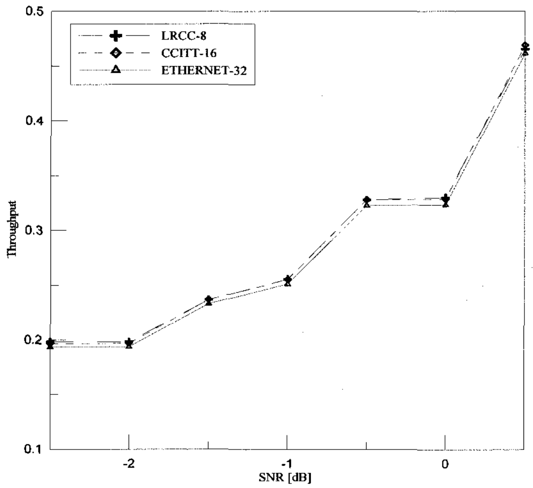
Fig. 8. Error performance of ETHERNET-32 when it is used for both retransmission request and iteration stop. (a) BER, (b) FER



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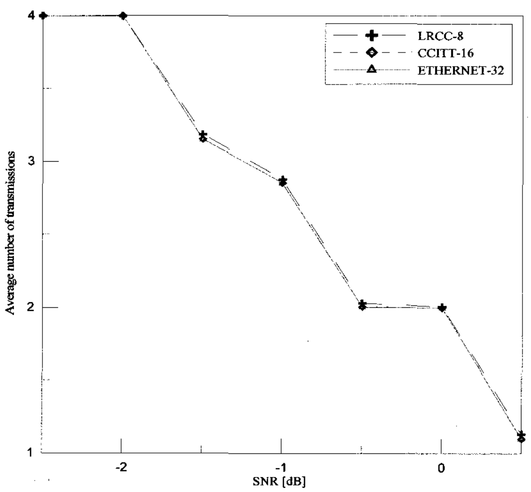


(b)

Fig. 9. Throughput and the average number of transmissions of three CRC codes. (a) Througnput, (b) Average number

than other codes from the simulation results. This is due to the fact that the average number of transmissions has nearly the same value as shown in Fig. 9(b).

The average number of iterations is represented in Table 1. The average number of iterations of ETHERNET-32 is nearly same as that of LRCC-8 even though that of ETHERNET-32 is a little bit lager because there is no incorrect iteration stop due to no undetected errors. The BER may be quite different even if the average number of iterations of the two CRC codes is almost same. For example, the BER of the ETHERNET-32 at the fourth transmission is about 10^{-7} at the SNR of -1.0dB as shown in the Fig. 8(a), but that of LRCC-8 is about 10^{-2} as shown in the Fig. 6(a).

Therefore, 32-bit CRC code should be used in order to avoid an incorrect stopping of iterations in the HARQ system with turbo code while satisfying error performance simultaneously.

Table 1. The average number of iterations of two CRC codes.

SNR	LRCC-8	ETHERNET-32
-2.5dB	78.8845	79.9566
-2.0dB	65.5722	66.3847
-1.5dB	48.3867	48.9972
-1.0dB	40.1080	40.7717
-0.5dB	23.4014	23.5982
0.0dB	21.6401	22.0177
0.5dB	6.7099	6.7936
1.0dB	-	2.1745

Three kinds of simulation are performed to check the effect of CRC code up to now. The effects of retransmission and iteration can be obtained regardless of CRC code under the assumption of perfect error detection. Up to 16-bit CRC codes show the undetected errors which result in no reduction of bit and frame error rate in the real circumstance where the CRC code is used to request retransmission only. On the other hand, such phenomenon is not observed when more than 32-bit CRC code is used. Thus, the assumption of perfect error detection is not valid if the length of CRC code is not sufficient.

In addition, the undetected errors are also found up to 16-bit CRC code when it is used for both the iteration stop of turbo decoding and retransmission request. But 32-bit CRC code shows no performance degradation due to no undetected errors. Also this code shows little performance difference as compared to the case of the perfect error detection. Therefore, at least 32-bit CRC code should be used for HARQ system with turbo code to avoid incorrect iteration stop and retransmission request because of undetected errors.

Ⅳ. Encoder structures and their performance

The most appropriate encoder structure for HARQ system is also investigated in this paper. The encoder structure of cdma2000 1x evolution-data optimized (1xEV-DO) system which is the most commonly used in the domestic mobile communication environment is adopted at first. Turbo encoder which is a standard of cdma2000 1x EV-DO system is consisted of two recursive systematic convolutional (RSC) encoders whose code rate is 1/3 and one interleaver between them. So it can provide the overall code rate down to 1/5.

And it is considered that the error performance of the system may be improved as the number of constituent RSC encoders is increased in general. So the simulation is performed while increasing the number of constituent RSC encoders. Therefore, three schemes of turbo encoder are presented with respect to the number of constituent encoders to determine the most appropriate encoder scheme for HARQ system. They are shown in Fig. 10.

The first encoder scheme is that of cdma2000 1xEV-DO system as shown in Fig. 10(a). The second scheme shown in the Fig. 10(b) is composed of 3 encoders with 1 RSC encoder whose code rate is 1/3 and 2 RSC encoders of rate 1/2 with two different interleavers. And the last scheme has 4 RSC encoders of rate 1/2 in parallel with three interleavers.

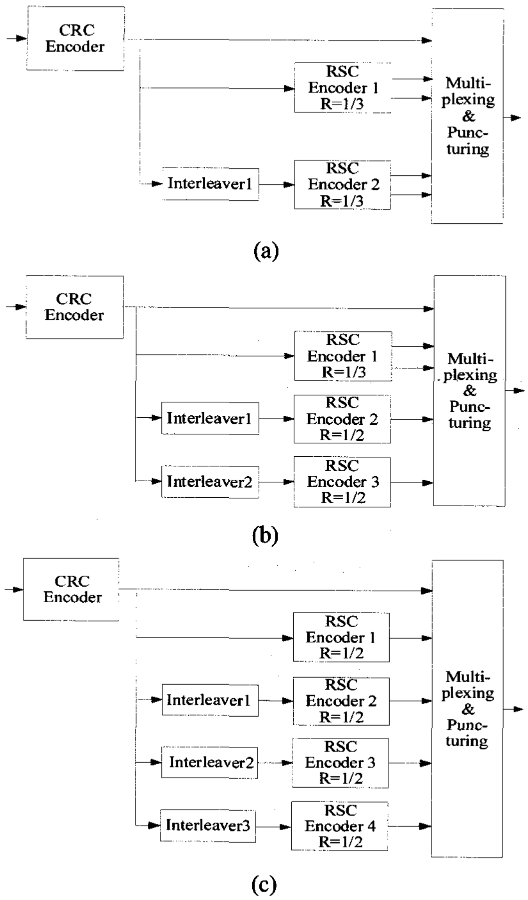
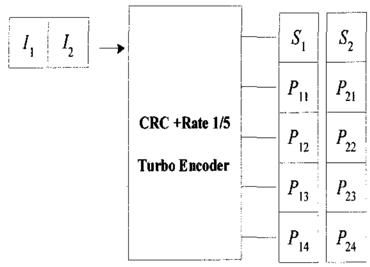


Fig. 10. Three schemes of turbo encoder for HARQ system. (a) Scheme 1, (b) Scheme 2, (c) Scheme 3

The puncturing patterns according to the three encoder schemes are shown in Fig. 11. The puncturing period is set to 2. So 10 output bits are generated by 2 input bits I_1 and I_2 because the code rate is 1/5. That is, S_1 and S_2 correspond to the information bits I_1 and I_2. And P_{11} to P_{14} are parity bits of I_1, and P_{21} to P_{24} are those of I_2. The information bits S_1,S_2 and parity bits P_{11}, P_{23} are transmitted at the first transmission in the first scheme. The puncturing pattern of the second scheme is similar to that of the first one. The transmitted bits until the second transmission are same as the first scheme. And P_{12}, P_{22} and P_{14}, P_{24} are transmitted at the third and fourth transmission. Finally, S_1, P_{11}, S_2, P_{22} are transmitted at the first transmission at the third scheme. And P_{12}, P_{21} and P_{13}, P_{23} and P_{14}, P_{24} are transmitted from the second to fourth transmission.

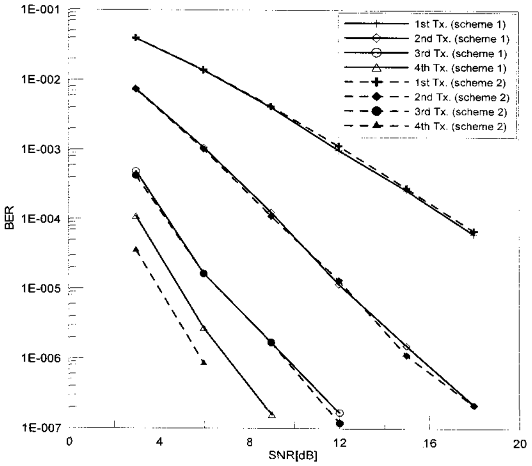


	Scheme 1	Scheme 2	Scheme 3
1st Tx.	S_1 P_{11} S_2 P_{23}	S_1 P_{11} S_2 P_{23}	S_1 P_{11} S_2 P_{22}
2nd Tx.	P_{13} P_{21}	P_{13} P_{21}	P_{12} P_{21}
3rd Tx.	P_{12} P_{24}	P_{12} P_{22}	P_{13} P_{23}
4th Tx.	P_{14} P_{22}	P_{14} P_{24}	P_{14} P_{24}

Fig. 11. Puncturing patterns of three schemes.

The simulation is carried out at Rayleigh fading channel. The 32-bit CRC code which is not influenced by undetected errors is used and the frame length is 512 bits including this CRC code. The BER according to the three kinds of encoders is shown in Fig. 12. BER of the first and second scheme is almost same till the third transmission. But the second scheme shows better error performance than the first one about 1dB at BER of 10^{-6} at the fourth transmission. This is due to the fact that the second scheme has one more constituent encoder than the first one.

BER of the second and third scheme has the same value till the second transmission as shown in the Fig. 12(b). On the other hand, the second scheme shows better error performance about 1dB and 4dB at the third and fourth transmission respectively to get the BER of 10^{-6}. The randomness among constituent encoders cannot be guaranteed if the number of interleavers is increased. So the third scheme which has 3 interleavers shows poor error performance than the second one which has only 2 interleavers. Therefore the encoder which has 3 constituent encoders shows the best error performance among 3 encoder schemes considered in this paper.



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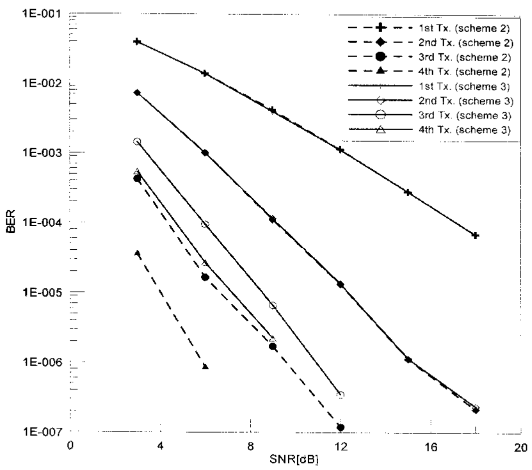

(b)

Fig. 12. BER of the three encoder schemes. (a) The fist and second, (b) The second and third

V. Conclusions

CRC code is conventionally used to decide retransmission request in the HARQ system. And it can also be used to stop the iterative decoding in order to reduce the computational complexity and delay of turbo code. Thus, CRC code can be used for both iteration stop and retransmission request in HARQ system with turbo code. Furthermore, perfect error detection is assumed in the conventional HARQ system in which CRC code is used for retransmission request only. So the performance of CRC-turbo concatenated code used to stop the iterative decoding of turbo code as well as request retransmission is analyzed according to the three kinds of simulation with various lengths of packet at AWGN channel.

The first simulation is performed under the conventional assumption of the perfect error detection, and the effects of retransmission and iteration are obtained. On the other hand, the undetected errors are found up to 16-bit CRC code when CRC code is used for retranasmission request only. So the error performance is not improved even if the number of transmissions is increased. But no undetected error is observed if 32-bit CRC code is used. So the assumption that any CRC code can detect errors perfectly is not valid. The same phenomenon is observed in the last simulation in which CRC code is used for both purposes. So at least 32-bit CRC code should be used to avoid the undetected errors and obtain the effects of retransmission and iteration. In addition, the encoder structure which uses 3 RSC encoders shows the best performance among 3 schemes considered in this paper for HARQ system with turbo code

Therefore, at least 32-bit CRC code should be used in the HARQ system with turbo code which has 3 constituent encoders to eliminate false iteration stop and retransmission request due to the undetected errors.

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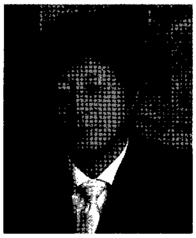
Woo Tae Kim Regular Member

Woo Tae Kim received the B.S., M.S. and Ph.D. degree in Electronics Engineering from Kyungpook National University, Daegu, Korea in 1998, 2000, and 2006, respectively. Since 2006, he has been working for Wireless Terminal Division, Samsung Electronics Co. LTD. as a senior Engineer. His research interests include digital communication systems, coding theory, and digital signal processing.

Jeong Goo Kim Lifelong Member



Jeong Goo Kim received the B.S, M.S, and Ph.D. degree in Electronics Engineering from Kyungpook National University, Daegu, Korea in 1988, 1991 and 1995, respectively. Since 2006, he has been an associate professor of School of Computer Science and Engineering, Pusan National University, Pusan, Korea. His research focuses on applications of information theory and coding to modern communication systems. Recently he is interested in signal transmission scheme for the next generation T-DMB.

Eon Kyeong Joo Lifelong Member

Eon Kyeong Joo received the B. S. degree in Electronics Engineering from Seoul National University, Seoul, Korea, in 1976, the M. S. and Ph. D. degree in Electrical Engineering from The Ohio State University, Columbus, Ohio, in 1984 and 1987, respectively. From 1976 to 1979, he was an Officer of Communication and Electronics, Republic of Korea Navy. From 1979 to 1982, he had worked for Korea Institute of Science and Technology (KIST) as a Researcher. In 1981, he was awarded the Korea Government Scholarship for graduate study in the USA. In 1987, he joined the faculty of the Department of Electronic Engineering, Kyungpook National University, Daegu, Korea, where he is now a Professor of the School of Electrical Engineering and Computer Science. His research interests include digital communication systems, coding and decoding, modulation and demodulation, statistical signal processing, and signal processing for communication systems.